15th Pisa meeting on Advanced Detectors

La Biodola – Isola d'Elba

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Ultra low noise readout with Travelling Wave Parametric Amplifiers: the DARTWARS project

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on behalf of the DARTWARS collaboration

1. INFN – Laboratori Nazionali di Frascati

DARTWARS

Detector Array Readout with Traveling Wave AmplifieRS

INFN LNF

MARIE CURIE ACTIONS

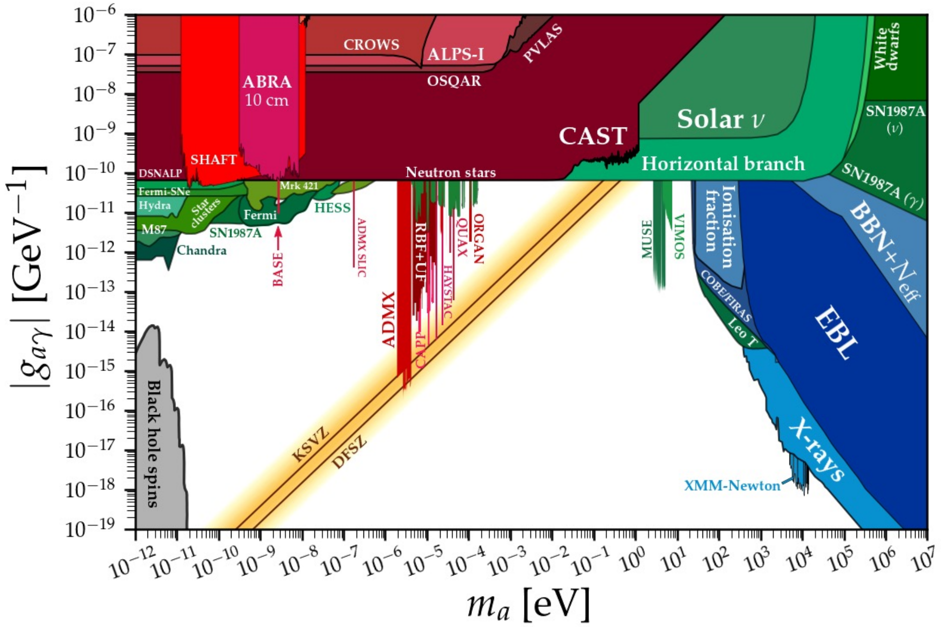
GA: 101027746

- Motivation: low-noise microwave detection
- Principles of operation of TWPA
  - J-TWPA
  - KI-TWPA
- The DARTWARS project
  - Goals
  - Preliminary results
- Conclusions

The frontier physics

Ultra-low noise detection and **amplification** is essential in many fields, from **fundamental physics** to quantum computing

- Dark matter (axions, dark photons…)
- Neutrinos
- CMB
- Qubit readout



Currently used detectors and amplifiers

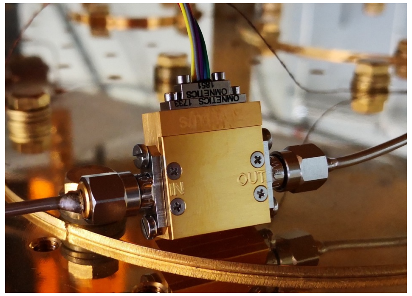
Large bandwidth and **lowest possible noise** required for reading **weak microwave signals** from multiple detectors

MKIDs Array of Microwave Kinetic Inductance Detectors

TESs Array of Transition Edge Sensors

HEMT

(High-electron-mobility transistor)

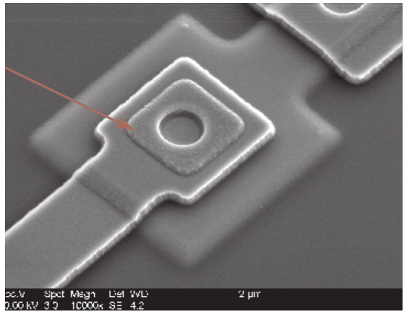


mw cavities mw signals from radiofrequency cavities

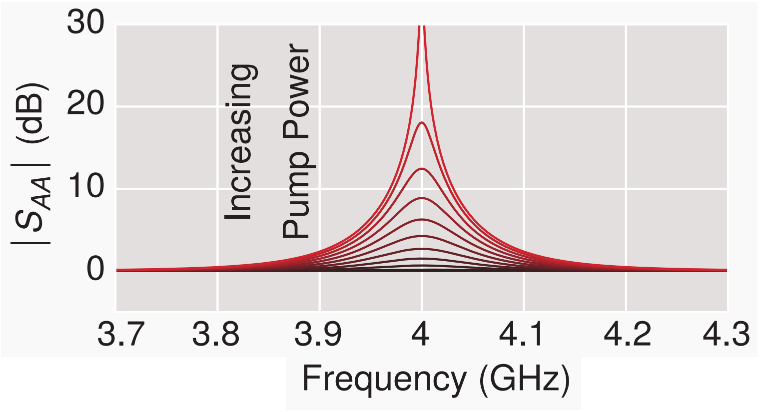
qubits mw resonators coupled to qubit circuit

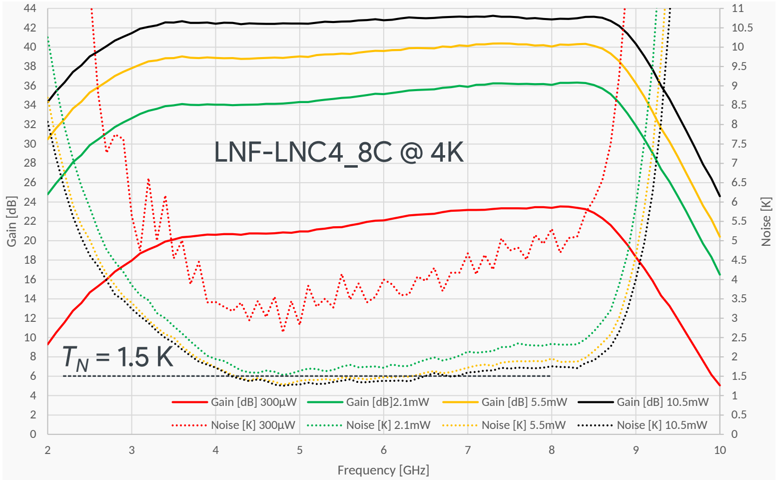
JPA

(Josephson parametric amplifier)



JPA vs HEMT – pro&cons





- Superconducting device
- High gain (~20 dB) but fixed gain-bandwidth product
- Small instantaneous bandwidth (~100 MHz)
- Small dynamic range (< –100 dBm)
- Noise at the quantum limit

- Semiconductor device
- High gain (30 dB or better)
- Large bandwidth
- High dynamic range
- Noise 10-40 times above quantum limit

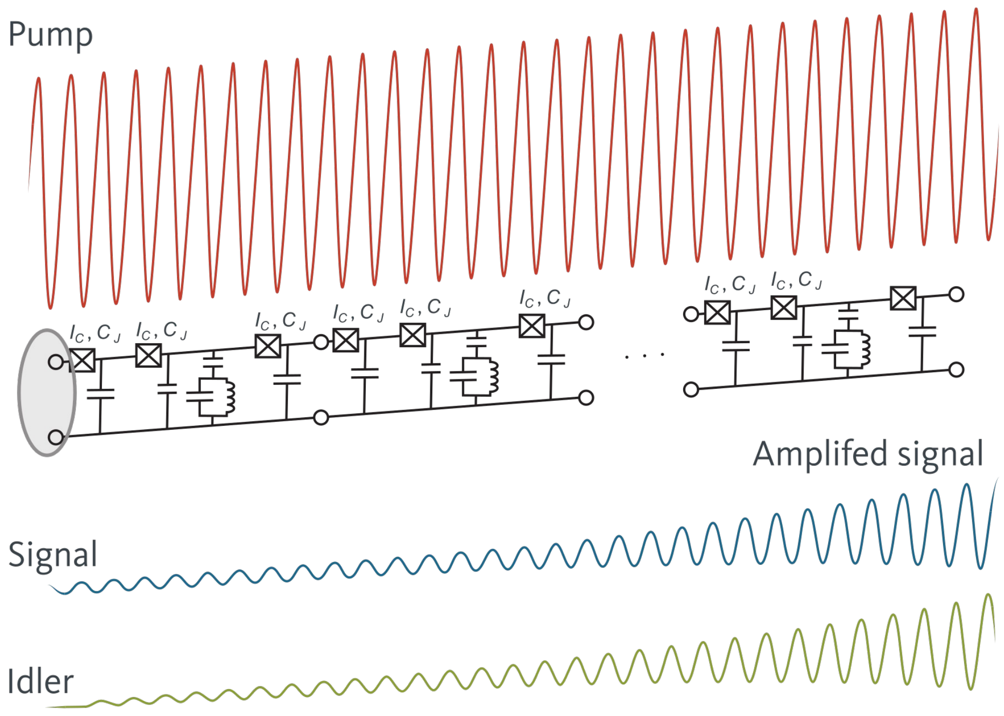
The frontier detector

Superconducting **Travelling Wave Parametric Amplifiers** (TWPAs):
transmission line with embedded nonlinear lumped elements

The **nonlinear current-inductance relation** is
responsible of the **mixing** and **parametric amplification**

$$L(I) \simeq L(0)\left(1 + \frac{I^2}{I_c^2}\right)$$

- Gain ($\lesssim$ 20 dB)
- Large bandwidth (few GHz)
- Noise at the quantum limit
- Dynamic range depending on technology



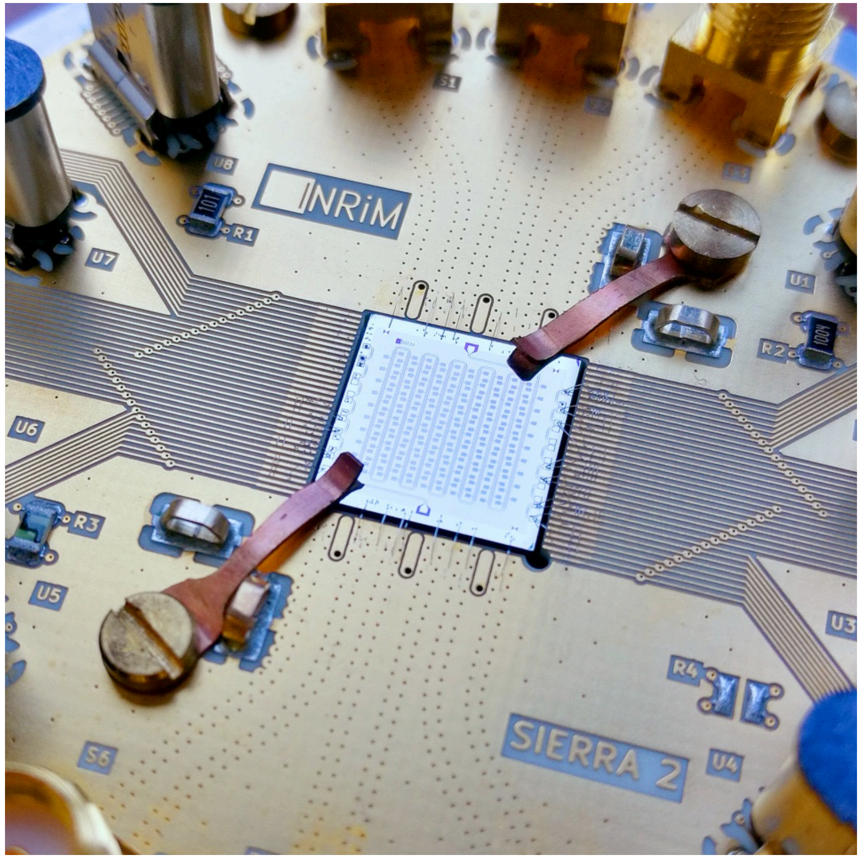
The DARTWARS project – goals

DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

1. **Development** of **high-performing parametric amplifiers** by exploring new design solutions, new materials and fabrication processes, to achieve:

    - High **gain** ($\gtrsim$ 20 dB)
    - Large **bandwidth** (in the 5-10 GHz range)
    - Large **saturation power** ($\sim$ 50 dBm)
    - Nearly quantum-limited **noise** ($\gtrsim$ 600 mK)
    - Reduction of **gain ripple**

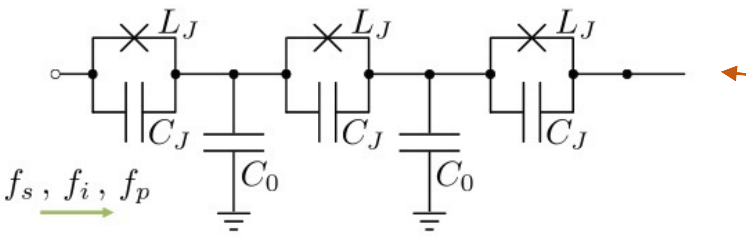
2. **Readout demonstration** of various detectos and devices, such as MKIDs, TESs, mw cavities and qubits

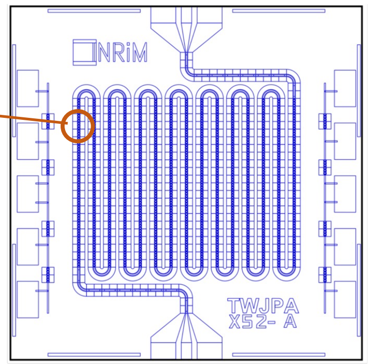


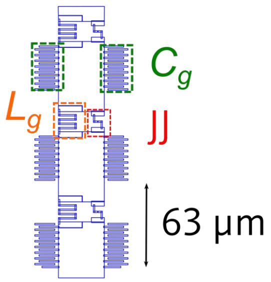
Courtesy of INRiM

Josephson Travelling Wave Parametric Amplifier

Mixing process due to the nonlinear inductance of the JJs







3 elementary cells

- Gain ($<$ 20 dB)
- Large bandwidth (few GHz)
- Quantum-limited noise level
- Small dynamic range (< -90 dBm)

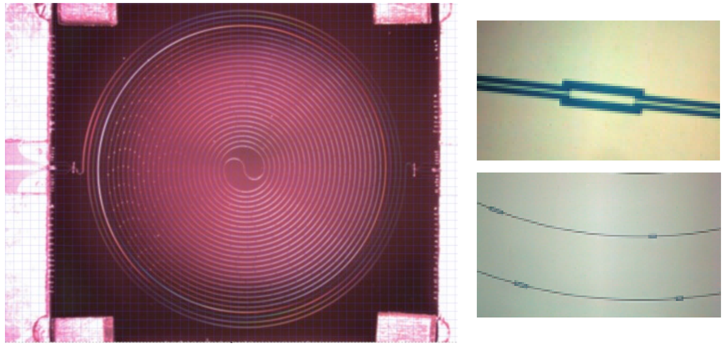
4-Wave Mixing (4WM):
$2fP = f_s + f_i$
unbiased transmission line

3-Wave Mixing (3WM):
$f_P = f_s + f_i$
biased transmission line

A. Giachero *et al.*, arXiv:2111.01512

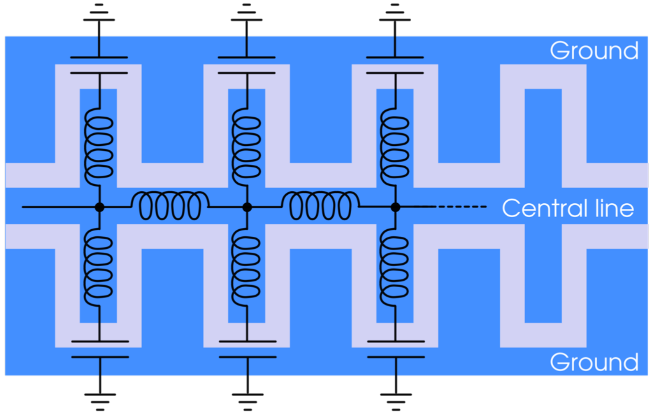
Kinetic Inductance Travelling Wave Parametric Amplifier

1) Spiral CPW transmission line with periodic impedance loadings



Eom et al., Nature Physics 8 (2012) 623–627

2) Artificial transmission line with lumped elements



Exploit the non-linear kinetic inductance of TiN or NbTiN

- Large ripples on gain profile
- Large bandwidth (few GHz)
- Near-quantum-limited noise level
- High dynamic range ($\gtrsim -50$ dBm)

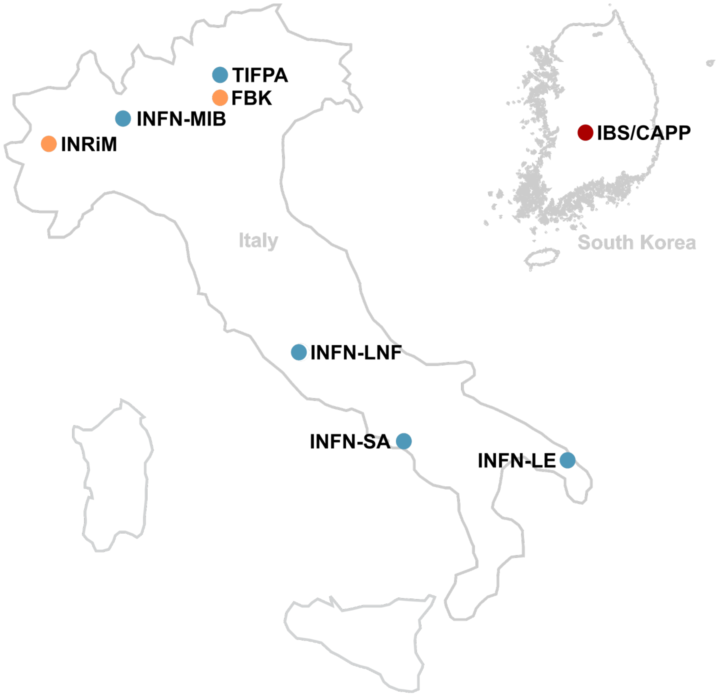
A. Giachero *et al.*, arXiv:2111.01512

The DARTWARS project – institutions

DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

CSN5 Ricerca Tecnologica

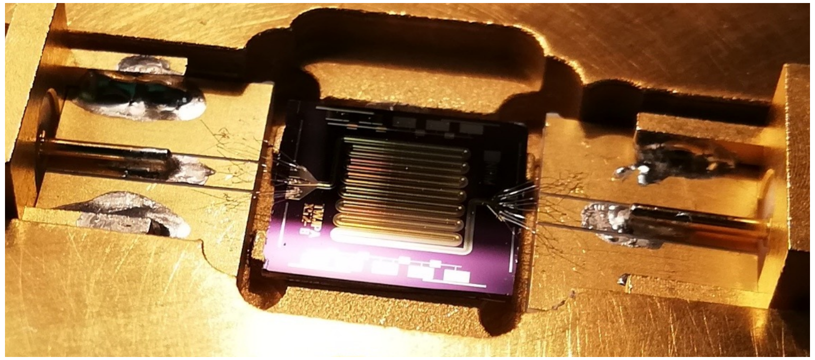
CSN5 project started in 2021

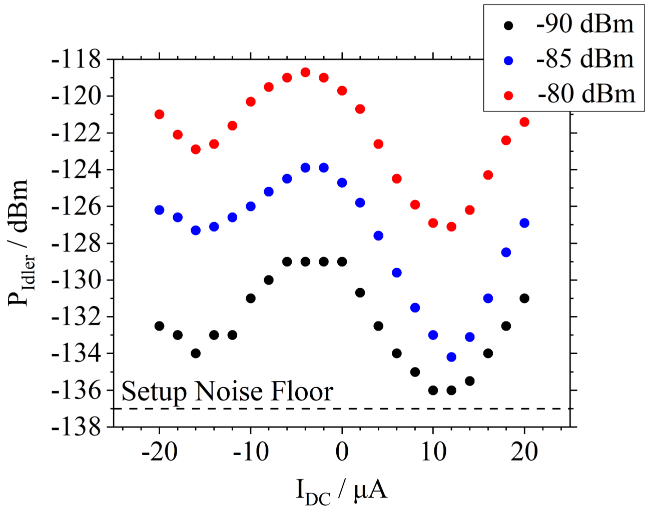


- **INFN-MIB**: project coordination; design and characterization of the devices (mainly KI-TWPA)
- **INFN-LNF**: J-TWPA fabrication supervision and characterization
- **INFN-LE**: investigation of magnon-cavity polaritons applied to quantum computing and quantum sensing
- **INFN-SA**: design and simulation of TWPAs; J-TWPA testing
- **INFN-TIFPA**: supervision of production at FBK; participation in the characterization (mainly KI-TWPA)

- **FBK**: fabrication of KI-TWPA prototypes
- **INRiM**: design and fabrication of J-TWPA prototypes
- **IBS-CAPP** (S. Korea): co-finances the production; participation in the characterization
- **NIST** (USA): participation in KI-TWPA design and test

J-TWPA preliminary measurements at LNF

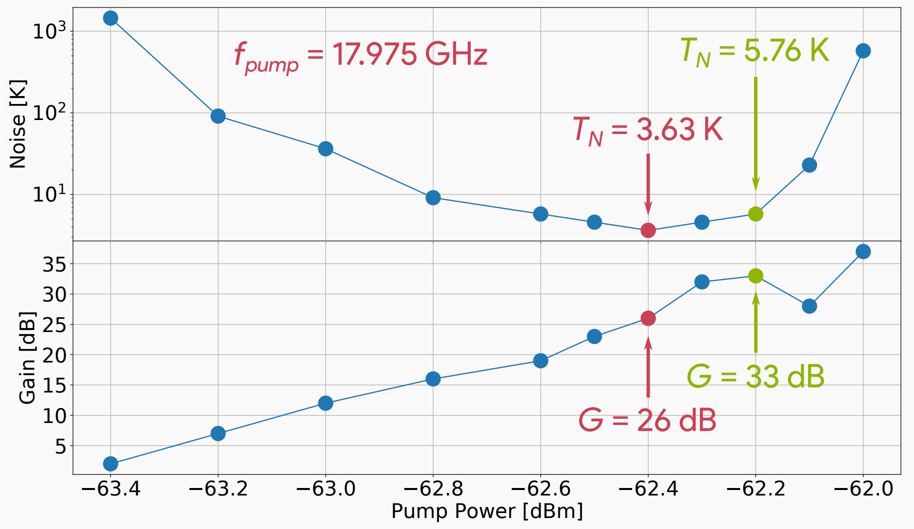




- measurements showed clear evidence of parametric amplification but with a nonhomogeneous behavior in frequency probably due to a nonhomogeneous fabrication of the ~900 JJs of the device

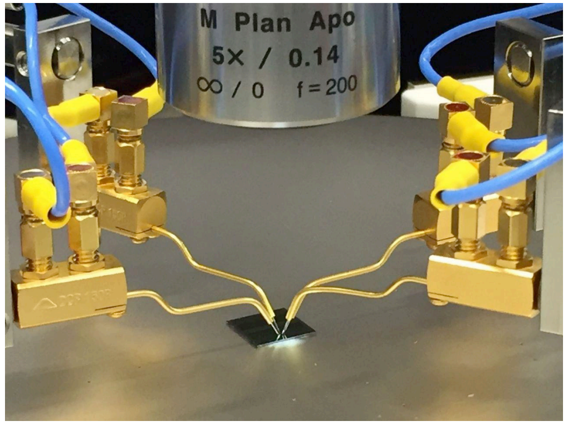
- Both 3-wave mixing and 4-wave mixings verified

- gain up to ~30 dB was observed at particular frequencies and with a minimum noise temperature of 3.63 K

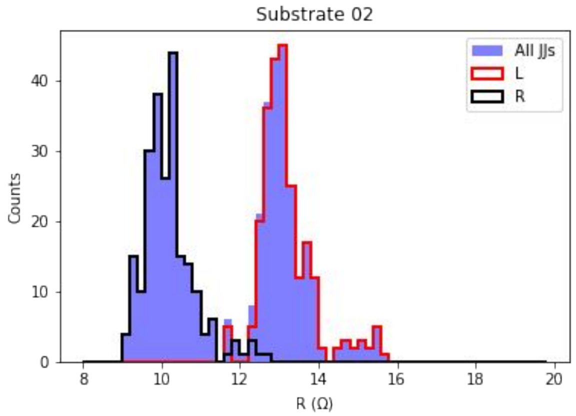


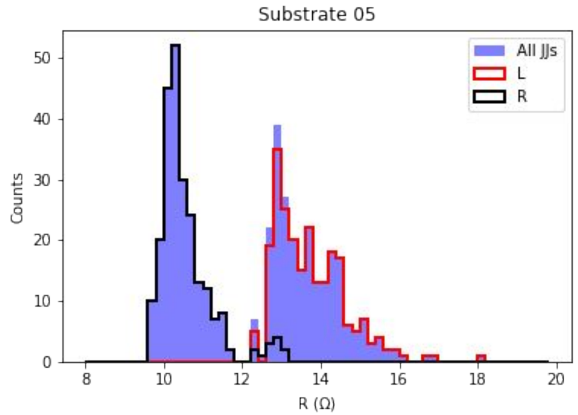
P. Livreri *et al.*, arXiv:2111.03409

JJs testing with probe station at uniMIB



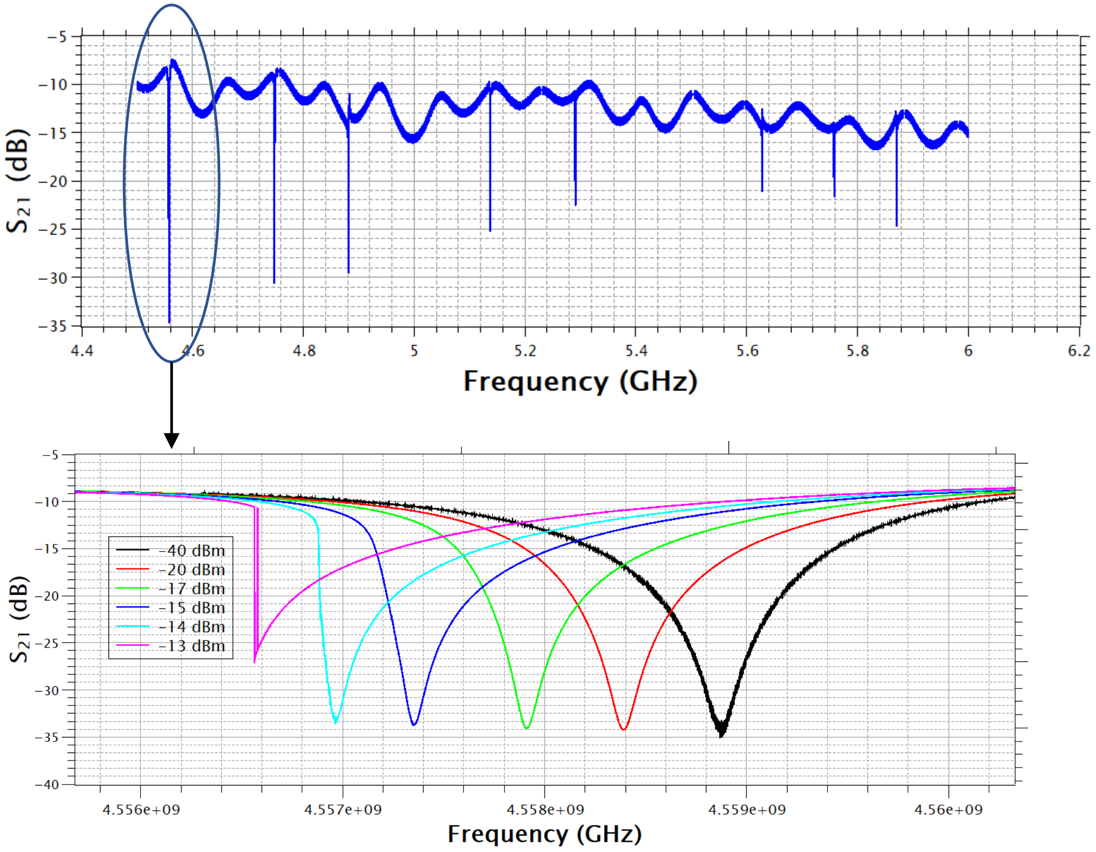
- JJs fabricated by INRiM, designed with $I_c = 4\ \mu A$ and $R_n = 80\ \Omega$
- 4-terminals measurements with a probe station
- Testing homogeneity of junctions: spread between 5% and 10%
- Detected position-dependent resistance





KI-TWPA materials preliminary characterization at FBK/TIFPA

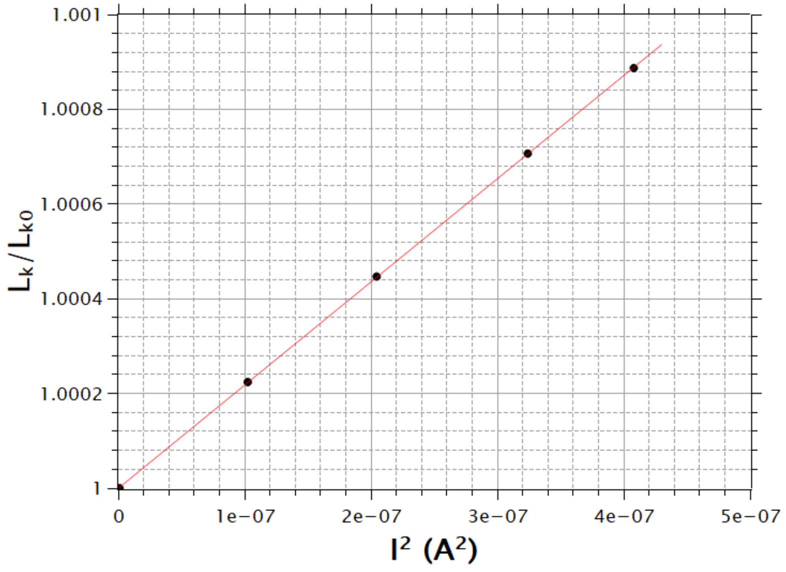
NbTiN patterned into micro-resonators



$$L_k = L_{k_0}\left(1 + \frac{I^2}{I_*^2}\right)$$

Kinetic inductance related to resonant frequency

$f_{\text{res}}^{-2} \propto (L_k + L_g)C$ and $I^2 \propto P_{\text{feed}}$



Courtesy of Marco Faverzani

Some Ads

For more details go see the **posters**:

Design and preliminary characterizations of traveling wave parametric amplifiers for DARTWARS

feat. **Matteo Borghesi**

Qub-IT: Quantum sensing with superconducting qubits for fundamental physics

feat. **Danilo Labranca**

Conclusions

- **TWPAs** are promising candidates of **quantum-limited microwave amplifiers** for applications in fundamental physics and quantum computing

- DARTWARS aims at:

  - **developing** (nearly-)**quantum limited Traveling Wave Parametric Amplifiers** with two approaches: **KI-TWPA**s and **J-TWPA**s, exploring new designs and materials
  - **demonstrating** the **readout** of several devices (TES/MKIDs/RF cavities/qubits)

- Preliminary measurements and characterizations done. There is **room for improvement** in terms of gain and bandwidth

- Design and fabrication improvements are ongoing