# Perspectives on Broadband Quantum-Limited Traveling-Wave Microwave Parametric Amplifiers for Fundamental Physics Measurements

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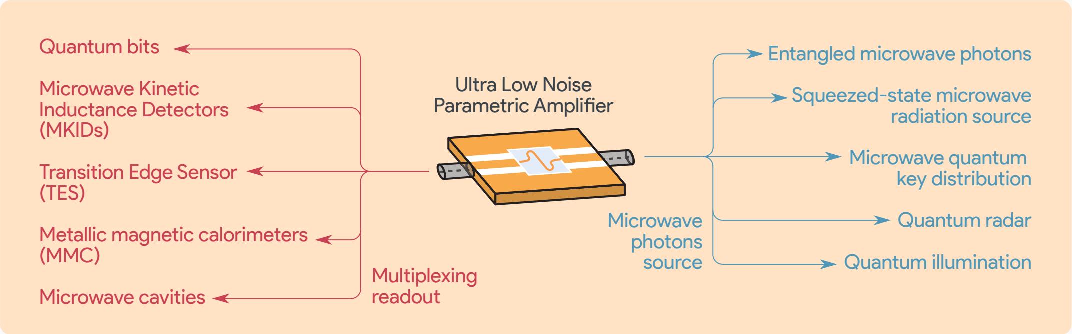
Frontier Detectors
for Frontier Physics
16th Pisa Meeting on
Advanced Detectors

# Low-noise microwave amplifiers play a central role in different applications

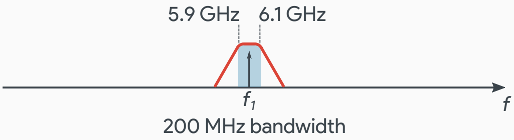
Ultralow-noise broadband amplifiers are suitable readout devices for cryogenic detectors, superconducting qubits, and have a variety of applications in quantum sensing and quantum communication.



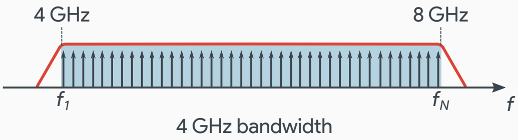
These applications needs broadband operation, minimum added noise, and perfect information preservation;

# Broadband requirement

Narrowband
Amplifier

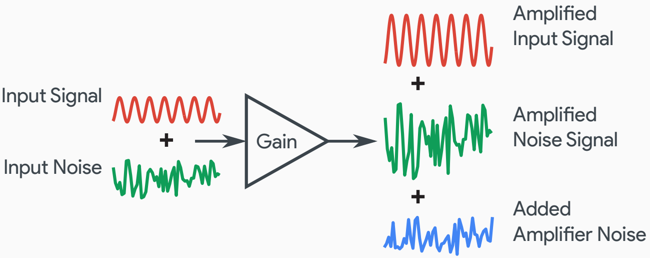


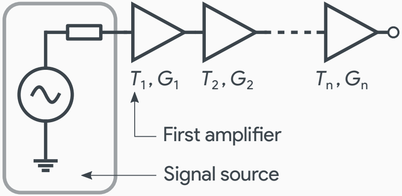
Broadband
Amplifier



- Multiplexing readout involves the simultaneous measurement of multiple signals or parameters using a single measurement system ⇒ multitone readout
- Multitone readout ⇒ amplifiers that can efficiently amplify multiple signals across a broad frequency range;
- Crucial in communications systems (like radar) ⇒ simultaneous readout of signals with different frequencies;
- The microwave frequency-division multiplexing also allows to read out several detectors/qubits at the same time in a common feedline;

# Low Noise requirement



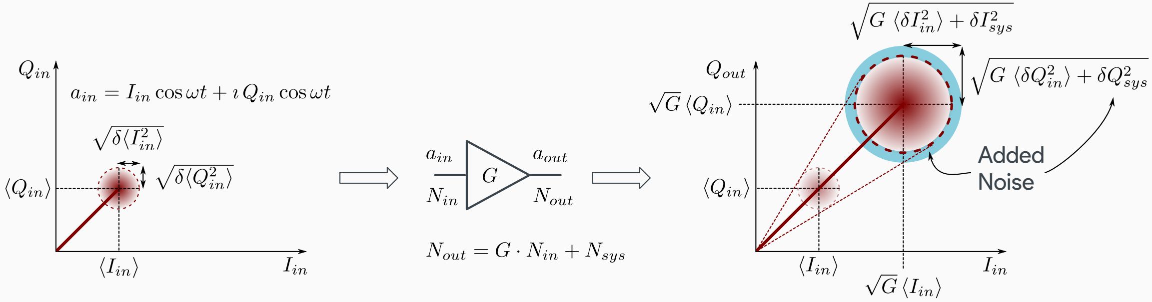


- The input of the amplifier is sensitive to both the noise and the signal present at its input;
- The amplifier added noise can come from many different sources (thermal fluctuations, electron-hole recombination, etc)
- The first amplifier in a chain has the most significant effect on the total noise figure (Friis' formula)

$$T_{\text{tot}} = T_1 + \frac{T_2 - 1}{G_1} + \frac{T_3 - 1}{G_1 G_2} + \frac{T_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{T_n - 1}{G_1 G_2 G_3 \cdots G_{n-1}}$$

- Heisenberg uncertainty principle puts a fundamental limit of an added noise for a "phase-insensitive amplifier";

# Standard Quantum Limit (SQL)



Luca Planat Ph.D thesis, 2020

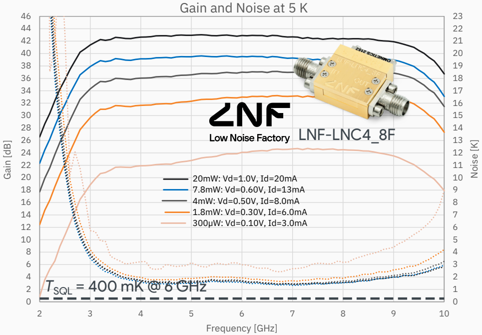
- Heisenberg uncertainty principle puts a fundamental limit of an added noise for a "phase-insensitive amplifier";
- A quantum limited amplifier is an amplifier with added noise: $N_{\text{SQL}} = \frac{\hbar f}{k T}$ (1 quanta) $\Rightarrow$ $T_N \geq \frac{\hbar f}{k} = T_{\text{SQL}} \sim \frac{50\ \text{mK}}{\text{GHz}}$

A quantum limited amplifier (QLA):

- Is indispensable for reading out qubits with high fidelity (reliability of computations in the presence of noise and errors);
- Could provide improved sensitivity for detectors that use frequency-multiplexed readout.

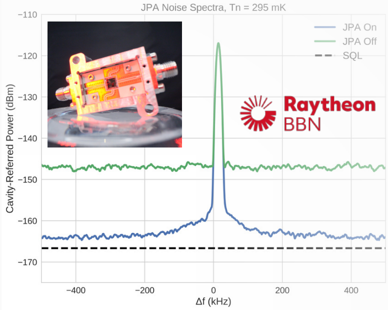
# Are amplifiers broadband and quantum limited?

## High-electron-mobility transistor (HEMT)



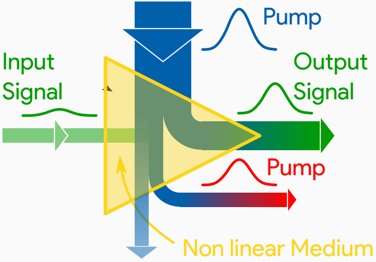
- Low Noise Amplifier in semiconductor technology;
- Gain: $G = 44$ dB;
- Bandwidth: 4 GHz;
- Noise temperature: $T_N = 1.5$ K @ 6 GHz;
- Broadband Amplifier but not Quantum Limited;

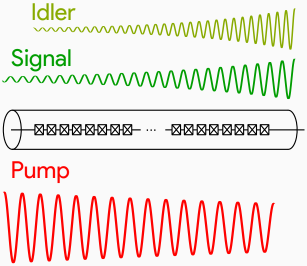
## Josephson Parametric Amplifier (JPA)

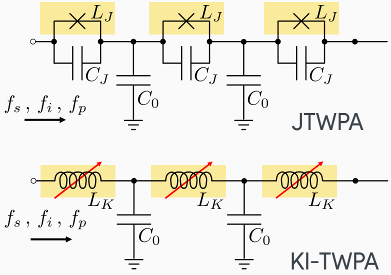


- Low Noise Amplifier in superconducting technology;
- Gain: $G = 20$ dB;
- Bandwidth: 300 MHz;
- Noise temperature: $T_N = 300$ mK @ 6.8 GHz;
- Quantum Limited Amplifier but not broadband;

# Traveling Wave Parametric Amplifiers (TWPAs)





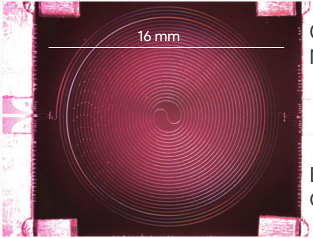


Appl. Phys. Lett. 119, 120501 (2021)

- Microwaves travelling along a transmission line with embedded non-linear medium;
- The non-linear medium can be implemented by Josephson Junction (JJ) or Kinetic Inductance (KI) of superconductors;
- A large pump tone modulates this element, coupling the pump ($f_p$) to a signal ($f_s$) and idler ($f_i$) tones via frequency mixing;
- The non-linear medium to convert the energy of the pump into an amplified signal;
- The total system noise target is the standard quantum limit (SQL) over a large bandwidth.

# TWPA: two different approaches

Kinetic inductance traveling wave amplifier (KI-TWPA)

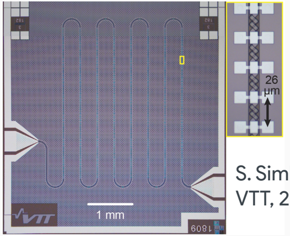


0.8 m length of NbTiN CPW line

Byeong Ho Eom *et al.*
Caltech, 2012.

Nature Phys 8, 623–627 (2012)

Josephson traveling wave parametric amplifiers (JTWPA)



1632 SNAILs
4.2 cm length

S. Simbierowicz *et al.*
VTT, 2021

Rev. Sci. Instrum. 92, 034708 (2021)

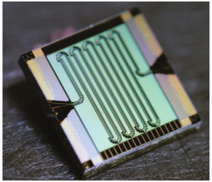
- Parametric amplification ⇒ periodic variation of a parameter generates amplification
- Tunable element ⇒ inductance ⇒

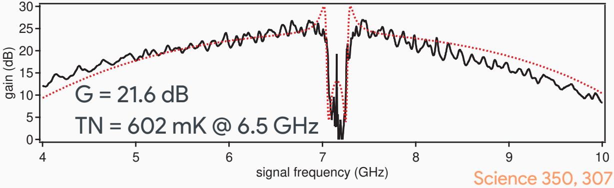
$$\begin{cases} \text{Josephson junction (JJ):} & L_J(I) = L_{J_0} \dfrac{\arcsin\left(I/I_c\right)}{I/I_c} \\ \text{Kinetic inductance (KI):} & L_K(I) = L_{K_0}\left(1 + \dfrac{I^2}{I_*^2}\right) \end{cases}$$

# TWPA: two different approaches (cont.)

Josephson traveling-wave parametric amplifier (JTWPAs):

- have become important for superconducting-circuit experiments such as multiplexed qubit readouts and sensing;
- are commercially available from QuantWare (www.quantware.com) and Silent-Wave (silent-waves.com) ;





Science 350, 307-310 (2015)

... however, the development of Kinetic Inductance TWPA (KI-TWPA or KIT) is particularly significant because they

- are simple to fabricate and require only few lithography and etching steps, without overlapping structures;
- provide a high dynamic range, high gain, and operate near the SQL;
- can operated also at higher temperatures, from millikelvin to 4 K (space application, spin-qubit, ...);
- are resilient to high magnetic fields (spin-qubit, axion search, ...);

# Kinetic Inductance Traveling Wave Amplifier (KI-TWPA)

## Kinetic Inductance

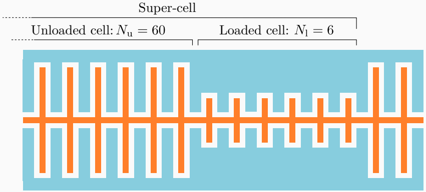
- Superconducting materials, such as NbTiN and NbN, exhibit a nonlinearity that is uniquely dissipationless in their kinetic inductance;
- Kinetic inductance per unit length $L_k$ of a superconducting transmission line can be expanded as

$$L_k(I) = L_d \left(1 + \varepsilon I + \xi I^2\right) \quad \text{with} \quad L_d = L_0 \left(1 + \frac{I_{dc}^2}{I_*^2}\right)$$

$$\text{and} \quad \varepsilon = \frac{2\, I_{dc}}{I_*^2 + I_{dc}^2} \quad , \quad \xi = \frac{1}{I_*^2 + I_{dc}^2}$$

- $\xi I^2$ permits the 4-wave-mixing: $2\, f_p = f_s + f_i$
- $\varepsilon I$ permits the 3-wave-mixing: $f_p = f_s + f_i$
- The scaling current $I_*$ sets the scale of the nonlinearity

## Dispersive lumped element line



- Lumped element line with stubs for tuning the characteristic impedance to $Z_0 = 50\, Omega$;
- Periodic loading with $Z_0 > 50\,\Omega$ along the line:
- Dispersive line $\Rightarrow$ modified phase velocities;
- Extra delay at the pump frequency to create phase-matching:
- Exponential gain: $G_s = \left|\frac{I_s(x)}{I_s(0)}\right|^2 = \cosh^2\left(\frac{\delta_L\, k_p\, x}{8}\right)$

# KI-TWPA projects in Italy

The Milano-Bicocca Unimib/INFN group is involved in two different projects in this field with similar aims

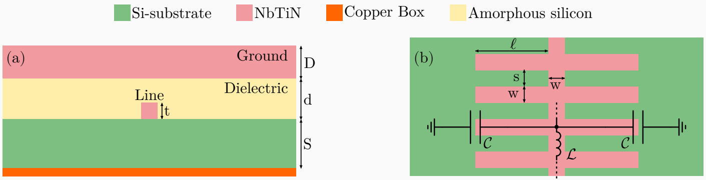
## DARTWARS Project

- Goal: develop state-of-art JTWPA and KI-TWPA for detector and qubit array;
- Funded by the Italian Institute of Nuclear Physics (INFN) through a competitive call;
- Involved institutions: INFN (Bicocca, LNF, Lecce, Salerno, TIFPA), Italian National Institute of Metrology (INRiM), and Bruno Kessler Foundation (FBK);

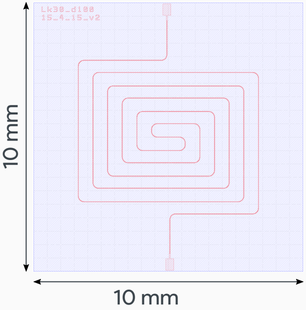
## MSCA Project

- Goal: develop innovative KI-TWPA for detector and qubit array;
- Funded by the European Union through a competitive H2020-MSCA-IF-2020 call;
- Involved institutions: University of Milano-Bicocca, University of Colorado Boulder (CO, USA), National Institute of Standards and Technology (NIST, CO, USA);

# KI-TWPA @ NIST: High Kinetic Inductance TWPA



- NbTiN line with higher kinetic inductance $L_k = 30$ pH/sq (instead of 10 pH/sq)
  IEEE Trans. Appl. Supercond. 33,5 (2023) 1700905;
- Inverted-microstrip lines provide higher capacitance due to the amorphous silicon (a-Si) dielectric;

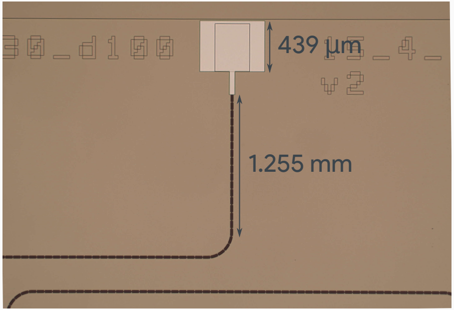


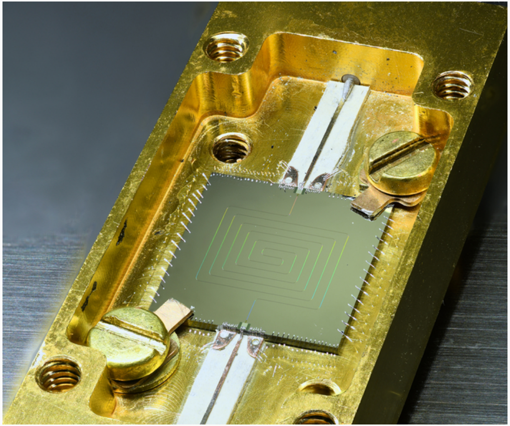
30-4 version

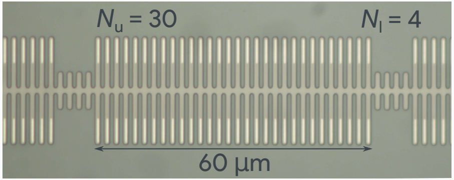
$N_u = 30$
$N_l = 4$

- Two-arm spiral layout to optimize the chip size;
- Each supercell composed by:
  $N_u = 30$ unloaded cells and $N_l = 6$ loaded cells;
- Total number of supercells: $N_{sc} = 1200$;
- Total number of cells: $N_c = 40800 \Rightarrow$ Total line length: $L_{tot} \sim 8.2\,\mathrm{cm}$
  (for the previous CPW version: $L_{tot} \sim 33\,\mathrm{cm}$);
- Chip sizes: $1 \times 1\,\mathrm{cm}^2$ (for the previous CPW version: $2 \times 2\,\mathrm{cm}^2$);
- Expected gain: $G > 25\,\mathrm{dB}$, centered at 6 GHz;
- Expected pump frequency: $f_p \sim 12\,\mathrm{GHz}$;

# KI-TWPA @ NIST: devices production







- First version (v1) published in J. Low. Temp. Phys. (2024);
- Improved version (v2) presented at the last APS March Meeting;

# KI-TWPA @ NIST: characterization Results

12 prototypes tested:

- 10/12 amplifiers showed a gain $G > 20$ dB;
- Fabrication yield: 83% (2 not working devices)
- $G = (20 - 27)$ dB ✓☺;

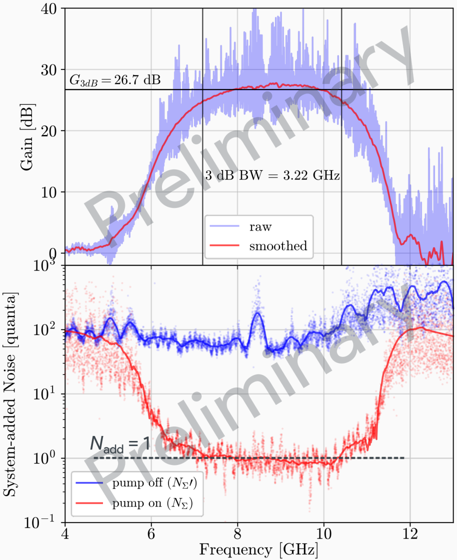
For the best devices:

Critical current: $I_c \sim 0.8$ mA
Scaling current around: $I_* \sim 2.8$ mA ($I_*^{\mathrm{CPW}} \sim 7$ mA)
Bias current around: $I_{dc} \sim 0.5$ mA ($I_{dc}^{\mathrm{CPW}} \sim 1.5$ mA)
Pump power: $P_p \sim -40$ dBm ($P_p^{\mathrm{CPW}} \sim -28$ dBm) ✓☺
1 dB compression point: $P_{1\mathrm{dB}} \sim -70$ dBm
3 dB bandwidth: $B = 3.2$ GHz

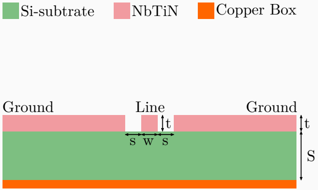
KI-TWPA performance creeping up on the SQL ✓☺:

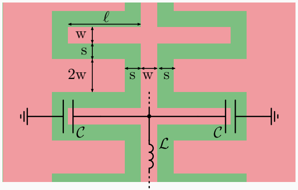
$$N_{\mathrm{add}} \simeq 1\,\text{quanta} \Rightarrow T_N = 400\,\text{mK @ 8 GHz}$$

Production of a new improved version with bandwidth centered at 6 GHz in progress at NIST

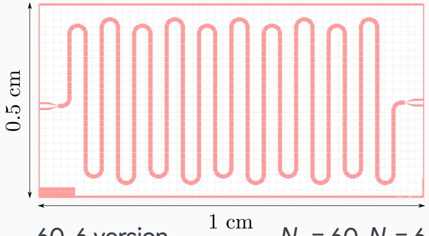


# KI-TWPA @ INFN: design





- NbTiN line with kinetic inductance $L_k = 8.5$ pH/sq produced in collaboration with FBK;
- Conservative stub-loaded CPW line (inspired by PRX Quantum 2 (2021) 010302 )

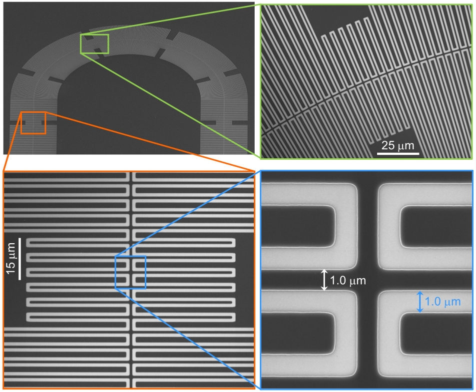


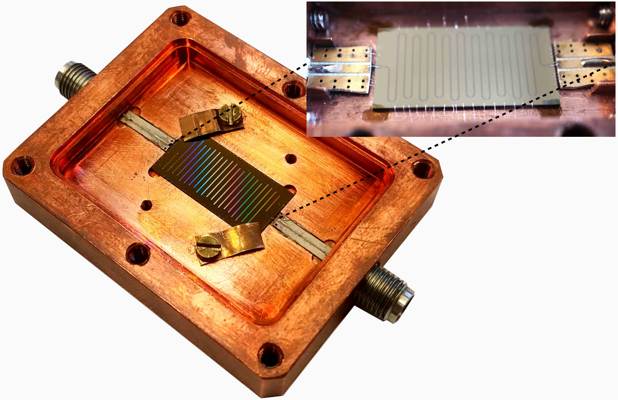
60-6 version

$N_u = 60, N_l = 6$

- Meander-shaped line to simplify the design
- Each supercell composed by: $N_u = 60$ unloaded cells and $N_l = 6$ loaded cells;
- Total number of supercells: $N_{sc} = 523 \Rightarrow$ *half-size*;
- Total number of cells: $N_c = 34518 \Rightarrow$ Total line length: $L_{tot} \sim 17.3\,\text{cm}$;
- Chip sizes: $0.5 \times 1\,\text{cm}^2$;
- Expected gain: $G \sim 10\,\text{dB}$, centered at 6 GHz;
- Expected pump frequency: $f_p \sim 12\,\text{GHz}$;

# KI-TWPA @ INFN: production of the *half-size* amplifier



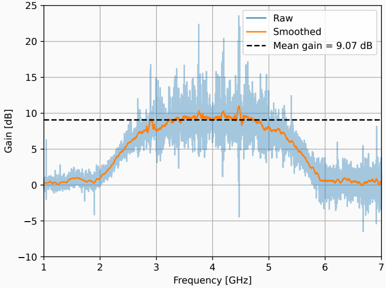


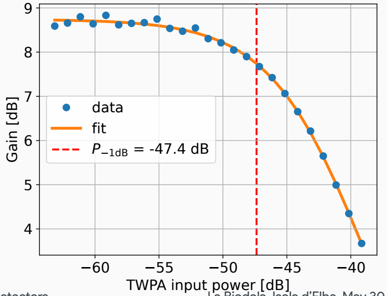
Design, production and characterization published in:

- Phys. Scripta 98 (2023) 12, 125921;
- IEEE Trans. Appl. Supercond. 34,3 (2024) 1700605
- J. Low. Temp. Phys. (2024)

# KI-TWPA @ INFN: gain measurements

- Amplification bandwidth centered around 4 GHz (lower than expected);
- Maximum gain measured around 9 dB in the 3 dB bandwidth, which aligns with the expected value;
- Critical current of $I_c = (1.41 \pm 0.01)$ mA and a scaling current of $I^* = (6.72 \pm 0.03)$ mA, as expected and compatible with literature;
- 1 dB compression point estimated at $P_{-1\mathrm{dB}} = -47.4$ dB;
- Higher pump power yields higher gain, but it also introduces larger ripples in the gain curve:
  $\Rightarrow$ not optimized box, local heating on the chip (hot-spots) not optimized grounding, etc
- Very encouraging performances for this first prototypes production





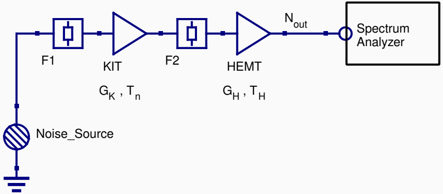
# KI-TWPA @ INFN: noise measurements

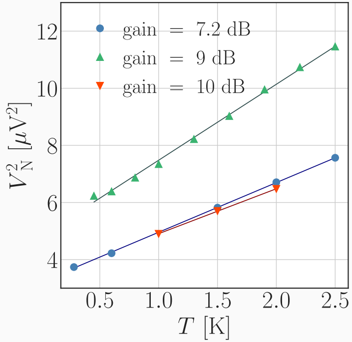
- Measurement of noise using the Y-factor method ⇒ Johnson-Nyquist noise of a 50 Ω resistor at various known temperatures;
- Noise source with an adjustable temperature range between 0.28 and 2.5 Kelvin.
- Noise measurements at three different gain settings: 7 dB, 9.2 dB, and 10 dB;
- Previous calibration of all system attenuation (including the line and RF components) and gains (HEMT and warm amplifiers) during dedicated cooling cycles.

| Noise measurements results @ 4 GHz | | | |
|---|---|---|---|
| $G_K$ (dB) | 7.2 | 9.0 | 10 |
| $T_{sys}$ (K) | 1.78 | 1.72 | 2.06 |
| $T_n$ (K) | 0.5 | 0.7 | 1.0 |
| $N_q$ | 2.5 | 3.4 | 4.9 |

Noise temperature $T_n \leq$ 600 mK

DARTWARS goal accomplished in the first prototype

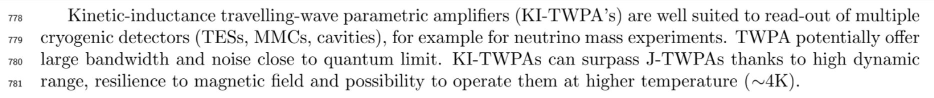




# TWPA amplifier and DRD5/RDq

DRD5: European Committee for Future Accelerators (ECFA) detector R&D roadmap
for quantum sensing and emerging technologies for particle physics

**Proposal on R&D on quantum sensors: the DRD5/RDq proto-collaboration**



Kinetic-inductance travelling-wave parametric amplifiers (KI-TWPA's) are well suited to read-out of multiple cryogenic detectors (TESs, MMCs, cavities), for example for neutrino mass experiments. TWPA potentially offer large bandwidth and noise close to quantum limit. KI-TWPAs can surpass J-TWPAs thanks to high dynamic range, resilience to magnetic field and possibility to operate them at higher temperature ($\sim$4K).

Ultralow-noise applications:

- RF cavities, and qubits, for probing the axion-photon coupling with haloscope;
- Transition-edge sensor (TESs) and Metallic magnetic calorimeters (MMCs) for many spectroscopic applications:
  astrophysics observations, neutrino mass measurements, dark matter search, exotic atoms spectroscopy, ...
- Microwave Kinetic Inductance Detectors (MKIDs) camera for millimeter-wave and exoplanet searches;

# Conclusion

- Travelling Wave Parametric Amplifiers (TWPAs) can provide broadband gain and operate at the quantum limit for noise.
- TWPAs have emerged as the leading technology for wideband pre-amplifiers.
- Kinetic Inductance TWPAs (KI-TWPAs) based on NbTiN film have shown promising near-quantum-limit noise.
- KI-TWPA amplifiers are simple to fabricate, provide a high dynamic range, can operate at higher temperatures, and are resilient to high magnetic fields.

  ... are the perfect amplifiers for many applications in fundamental physics measurements.

- KI-TWPAs developed at NIST showed lower pump operation, high gain, broad bandwidth, and noise close to the quantum limit.
- Preliminary KI-TWPAs developed by the INFN showed encouraging performance, and the design of the full-size device is in progress.

# Collaboration

**Unimib group**
M. Borghesi, P. Campana, R. Carobene, M. Faverzani, E. Ferri, A. Giachero, M. Gobbo, A. Irace, D. Labranca, R. Moretti, A. Nucciotti, L. Origo,

**FBK/Trento group**
F. Ahrens, N. Crescini, P. Falferi, F. Mantegazzini, B. Margesin, R. Mezzena, A. Vinante

**NIST/CU group**
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**INFN-LNF group**
A. D’Elia, D. Di Gioacchino, C. Gatti, C. Ligi, G. Maccarrone, A.S. Piedjou Komnang, L. Piersanti, A. Rettaroli, S. Tocci

MARIE CURIE ACTIONS
GA: 101027746