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## Towards a Long-Range Microwave Quantum Radar

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University of Palermo, Italy

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Technologies for  
Defense and Security

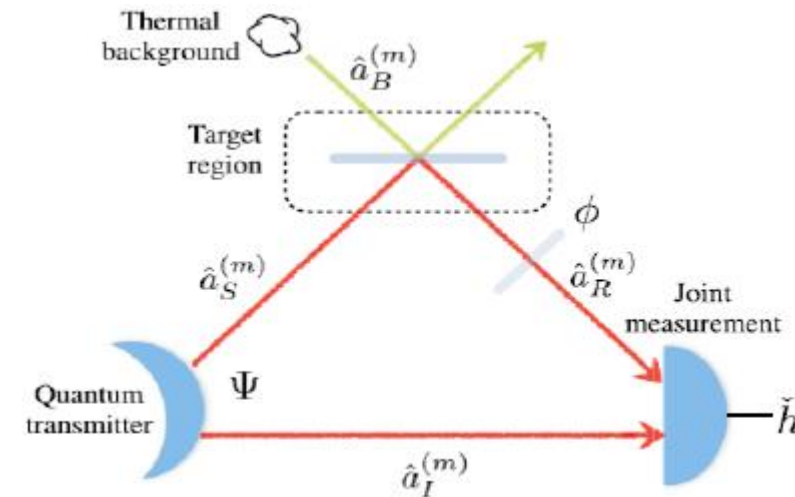


# Outline

- Motivation: From Classical to Quantum Radar
- Quantum Illumination Protocol
- Microwave Quantum Radar state of the art
- Josephson Traveling Wave Parametric Amplifier as a non-classical quantum source
- Microwave Quantum Radar based on JTWPA
- JTWPA vs JPA Performance Comparison: Receiver operating characteristics (ROCs)
- Conclusions

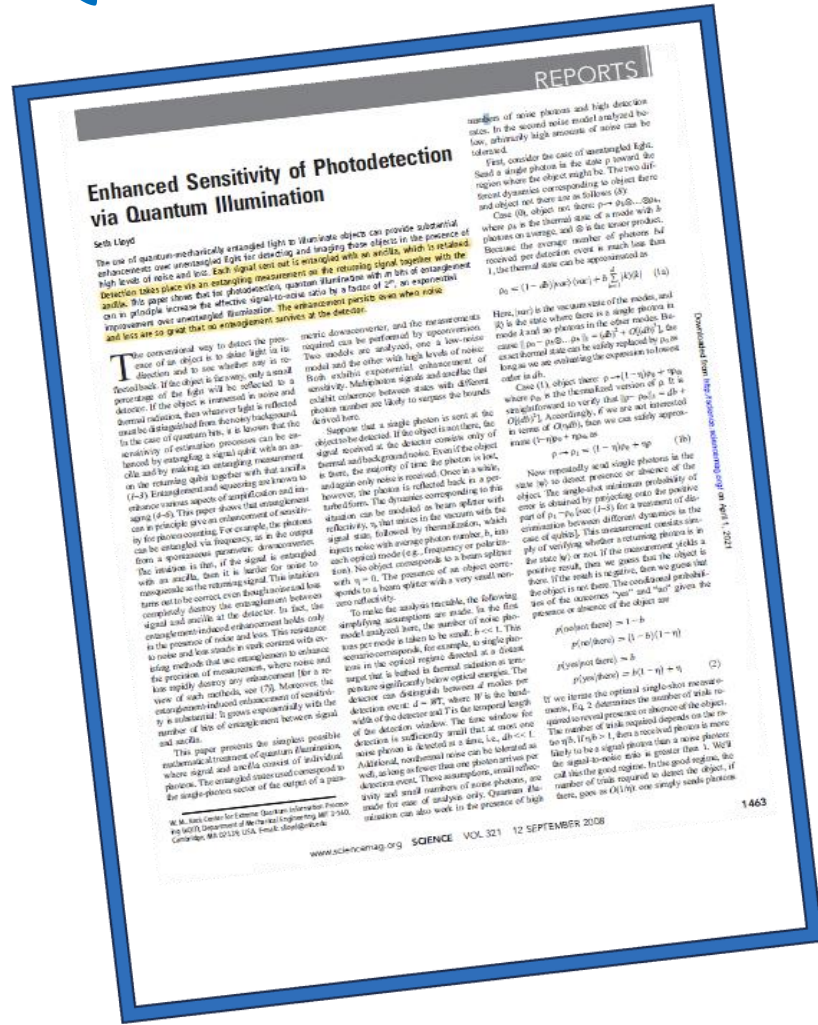
# Motivation

Quantum radar promises to reveal what classical radar cannot: the detection of low-reflectivity targets.



# Quantum Illumination Protocol - I

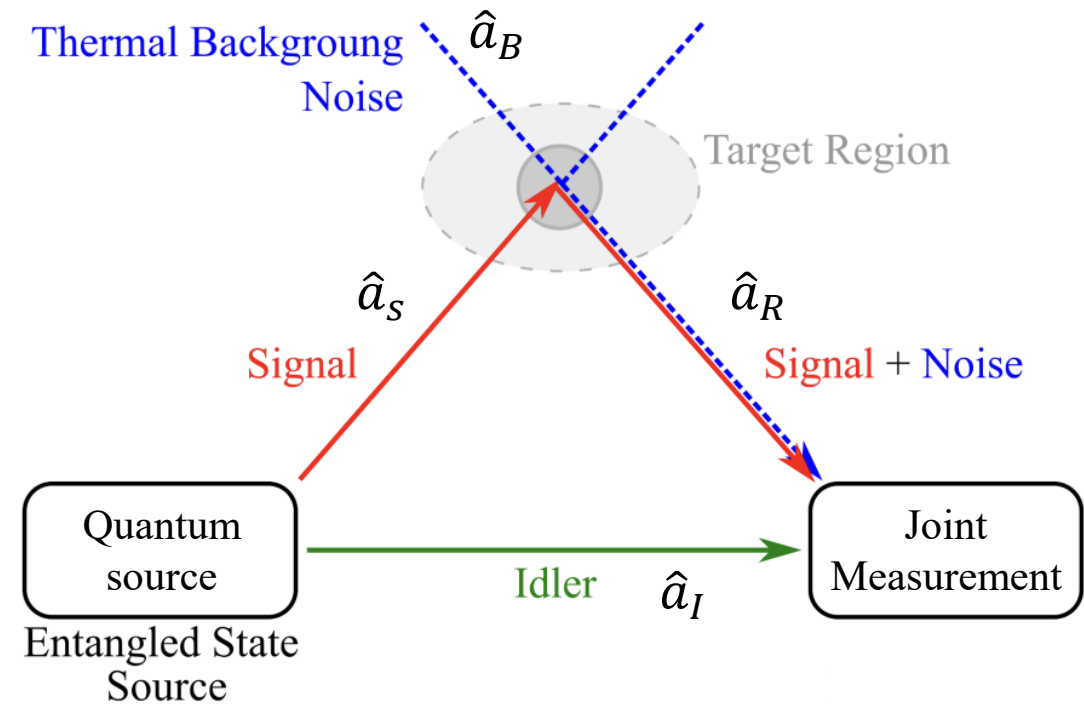
- In 2008, Lloyd proposed **Quantum illumination (QI)**: a photonics remote quantum sensing, in which entanglement, between a signal interrogating a target region and a locally held idler, is exploited as a detection protocol to enhance sensitivity of photodetection.



S.Lloyd, "Enhanced sensitivity of photodetection via quantum illumination," Science, vol. 321, no. 5895, pp. 1463–1465, Sep. 2008.

# Quantum Illumination Protocol - II

- **Quantum source of photons**, where a spontaneous parametric down-conversion (SPDC) process does occur, produces **entangled photon** beams traveling along separate paths.
- **Signal photons** are transmitted toward a target region. **Idler photons** are locally held in a **phase-matching delay line**.
- **Detection process** of QI is based on a **quantum receiver station** performing a **joint measurement** of the scattered signal photons and idler photons arriving simultaneously at the receiver.



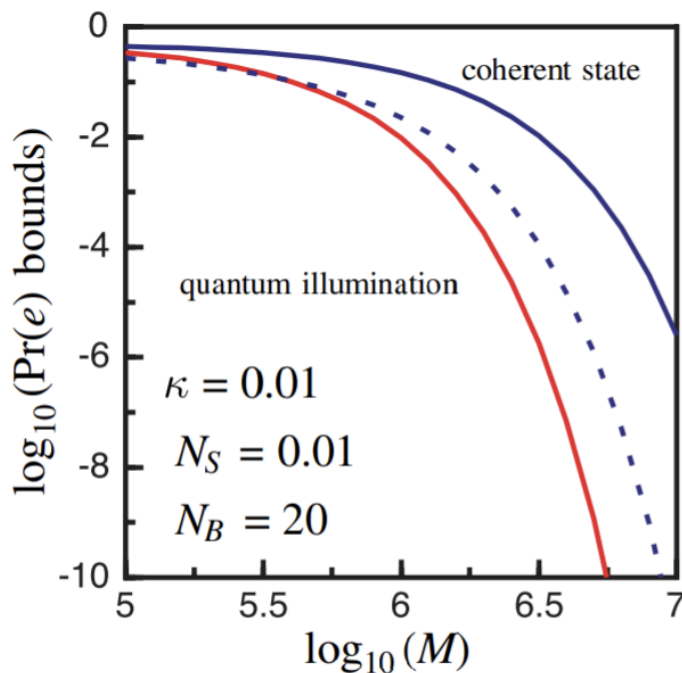
$$\hat{a}_s = \text{signal mode}$$

$$\hat{a}_R = \sqrt{\kappa} \hat{a}_s + \sqrt{1 - \kappa} \hat{a}_B = \text{return mode}$$

where:  $\kappa$  = reflection coefficient and  $a_B$  = background noise



# Quantum Illumination Error-Probability



- In 2008, Tan found using multiple signal-idler modes prepared in the **Two-Mode Squeezed Vacuum (TMSV)** state, Quantum Illumination allows a **6 dB** improvement for the error-probability exponent compared to the classical radar
- The **6 dB quantum advantage** occurs when the target is bathed in thermal background noise, due to which initial signal-idler entanglement is lost



S.-H. Tan, B. I. Erkmen, V. Giovannetti, S. Guha, S. Lloyd, L. Maccone, S. Pirandola, and J. H. Shapiro, "Quantum illumination with Gaussian states," Physical Review Letters, vol. 101, Art. no. 253601, Dec. 2008

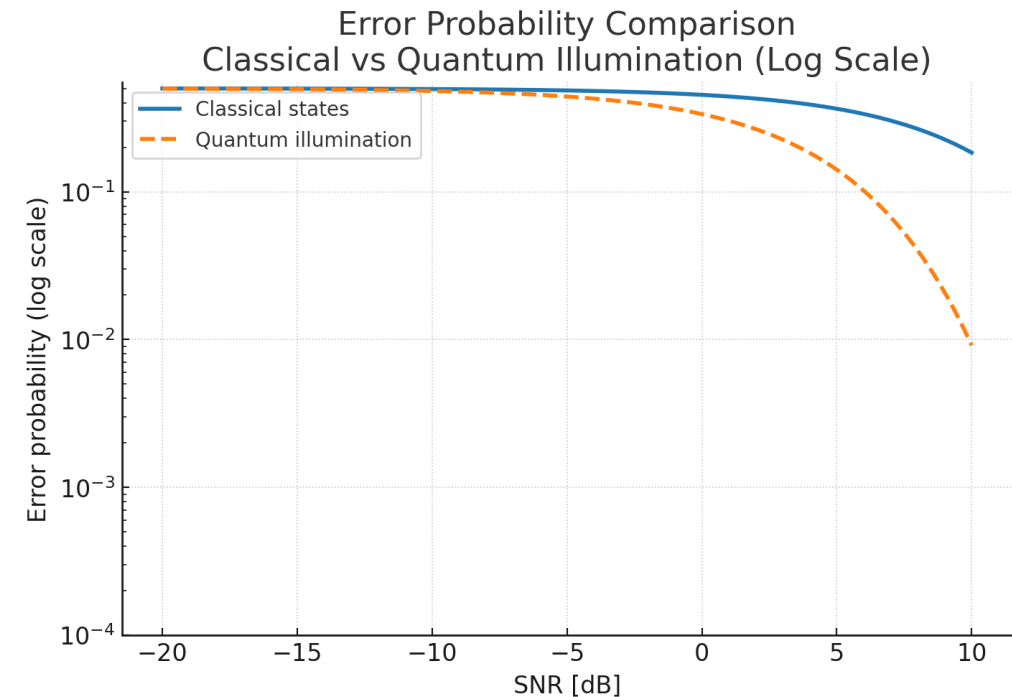
# Error-Probability Comparison

In the presence of many background photons  $N_B$ , QI allows an error probability  $P_e$  significant reduction, with the same signal photon number  $N_S$ .

$$P_e^{CS} \leq e^{-M\kappa N_S / 4N_B} / 2$$

$$P_e^{QI} \leq e^{-M\kappa N_S / N_B} / 2$$

QI provides an improvement by a factor of **4 (i.e., 6 dB)** in the error rate exponent compared to the classical protocol,



- Error probability  $P_e$  consists of the convex combination of the probability  $P_F$  of an incorrect identification of the target (false positive) and  $P_M$  of non-identification of the target (miss probability):

$$P_e = \lambda P_F + (1 - \lambda) P_M$$

# Josephson Junctions

Volume 1, number 7

PHYSICS LETTERS

1 July 1962

## POSSIBLE NEW EFFECTS IN SUPERCONDUCTIVE TUNNELLING \*

B. D. JOSEPHSON  
Cavendish Laboratory, Cambridge, England

Received 8 June 1962

We here present an approach to the calculation of tunnelling currents between two metals that is sufficiently general to deal with the case when both metals are superconducting. In that case new effects are predicted, due to the possibility that electron pairs may tunnel through the barrier leaving the quasi-particle distribution unchanged.

number on the other side unchanged, and pair creation operators  $S_k^{\dagger\dagger}$  which add a pair of electrons on one side leaving the quasi-particle distribution unchanged. The Hermitean conjugate destruction operators have similar definitions. The  $S$  operators, referring to macroscopically occupied states, may be treated as time dependent  $c$ -numbers  $^{\dagger\dagger}$ ,



Brian Josephson – Nobel Prize

Josephson discovered that a DC supercurrent can flow *without any applied voltage*, purely because of quantum phase coherence difference between two superconducting metals separated by a thin insulator.

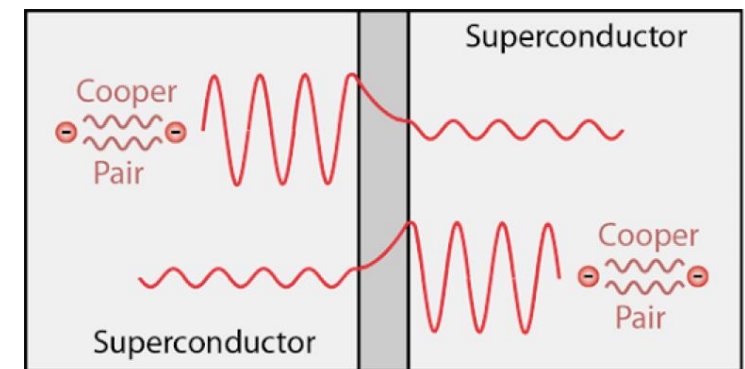
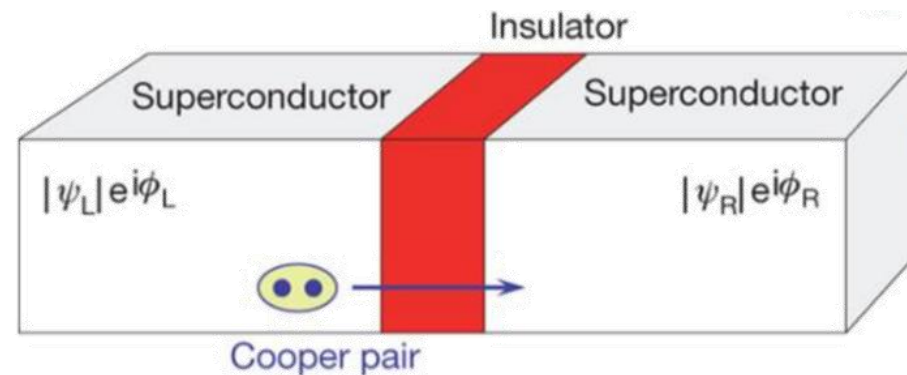
# Josephson Junction

Josephson Junction consists of two weakly coupled superconductors separated by a thin insulator.

Superconducting wavefunction

$\Psi(r,t) = |\Psi|e^{i\phi}$  where:

- $|\Psi| \rightarrow$  Cooper pairs density
- $\phi \rightarrow$  quantum phase common to the entire condensate of Cooper pairs

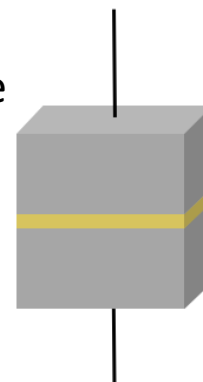


1<sup>st</sup> Josephson relation, or weak-link current-phase relation: Relative phase difference

$$I = I_C \sin[(\phi_L - \phi_R) / \phi_0]$$

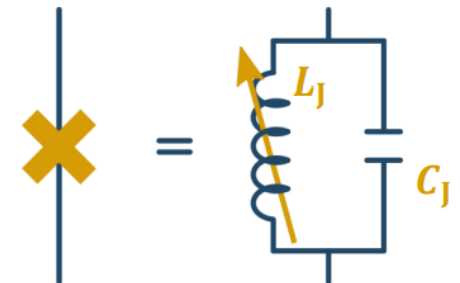
$I_C$  is the **critical current** - the maximum supercurrent the junction can carry

$\phi_0$  is the quantum flux



Tunnel junction

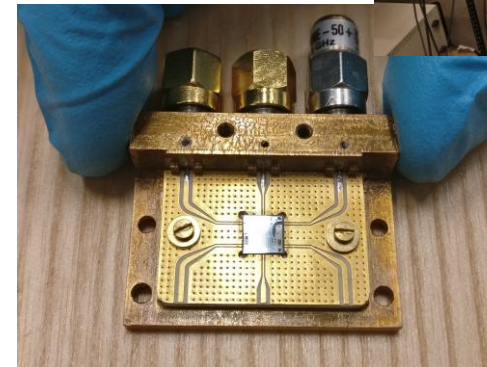
S  
I  
S  
superconductor  
insulator  
superconductor



# JPA-based Microwave Quantum Radar



In 2019, David Luong et al. proposed the first MQR based on JPA.



The transmit and receive horns were mounted facing each other with a separation of **0.5 m**.

D. Luong, et al., and B. Balaji, "Receiver operating characteristics for a prototype quantum two-mode squeezing radar," IEEE Trans on Aerospace and Electronic Systems, vol. 56, pp. 2041–2060, Nov. 2019.

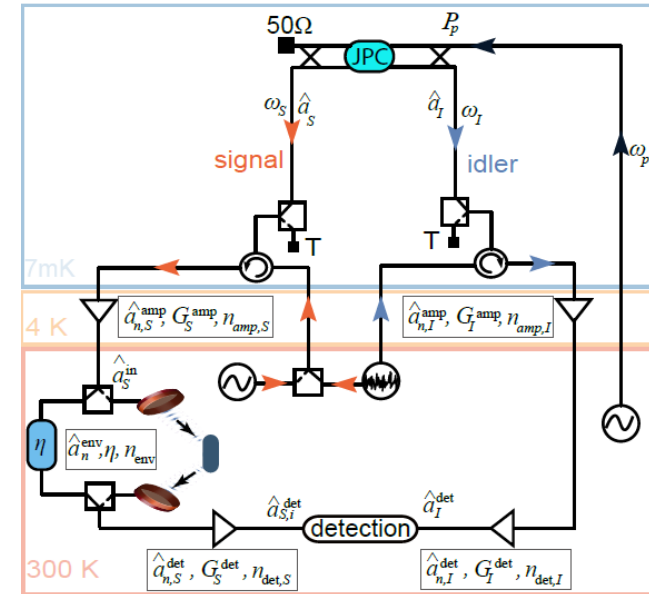
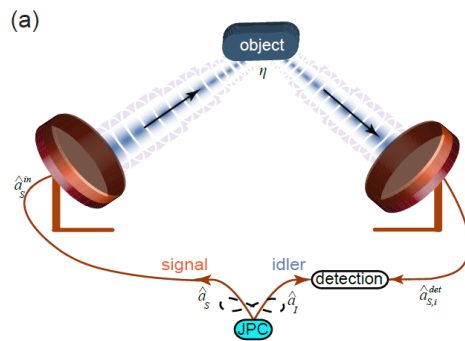
Built and evaluated a prototype quantum radar, called TMSV radar.

# JPC-based Microwave Quantum Radar



S. Barzanjeh, S. Pirandola, D. Vitali, J. M. Fink, Microwave quantum illumination using a digital phase-conjugated receiver. Sci. Adv. 2020

In 2020, Barzanjeh et al. proposed an MQR based on JPC and Phase Conjugated Receiver.



Experimentally investigated the concept of quantum illumination at microwave frequencies, by generating entangled fields using a **Josephson Parametric Converter (JPC)** which are then amplified to illuminate a room-temperature object at a **distance of 1 meter**.



# What's the JPA limit?

- Transmit power  $P$  with one photon per mode

$$P = EW$$

$E$  single photon energy  
Advantage of QR over CR  
disappears for more than  
five photons per mode

$W$  quantum source bandwidth  
JPA shows a narrow  
bandwidth limited to roughly  
tens of megahertz

- The time-bandwidth product

$$M = TW$$

$M$  = Number of modes

For quantum illumination, the **bandwidth** is determined by the **phase-matching bandwidth** of the SPDC process used to generate the entangled signal idler pulses.

«Radar engineers should note that the phase matching bandwidth of SPDC simply tells us over which range of frequencies we can produce entangled photons, but it does not correspond to a known temporal modulation of the frequency content of the signal»

Giacomo Sorelli, et al., Detecting a target with quantum entanglement, arXiv:2005.07116v5 [quant-ph] 21 Jul 2021.



# MQR: state of the art

MQR PARAMETERS	JPA [1]	JRC [2]	Unit
Antenna operating band	X-band	X-band	GHz
Antenna gain (G)	15	15	dB
Target radar cross section ( $\sigma$ )	1.0	1.0	m <sup>2</sup>
Bandwidth (W)	<b>1.0</b>	<b>20</b>	<b>MHz</b>
JPA power gain (Gp)	20	30	dB
Signal power (Ps)	-82	-128	dBm
Pump frequency fp=fs+fi	13.6821	16.89	GHz
Signal frequency (fs)	7.5376	10.09	GHz
Idler frequency (fi)	6.1445	6.8	GHz
Signal-to-noise ratio (SNR <sup>QR</sup> )	-19	-18	dB
<b>Maximum Range (Rmax) (Ns = 0.1)</b>	<b>0.5</b>	<b>1</b>	<b>m</b>

QTMS radar very similar to conventional noise radar  
 QTMS range equation can be obtained as follows:

$$R_{max} = \left( \frac{GA_e \sigma P_s}{(4\pi)^2 P_n (SNR)_{min}^Q} \right)^{1/4}$$

where:

G antenna gain

Ae effective antenna area

$\sigma$  target radar cross-section

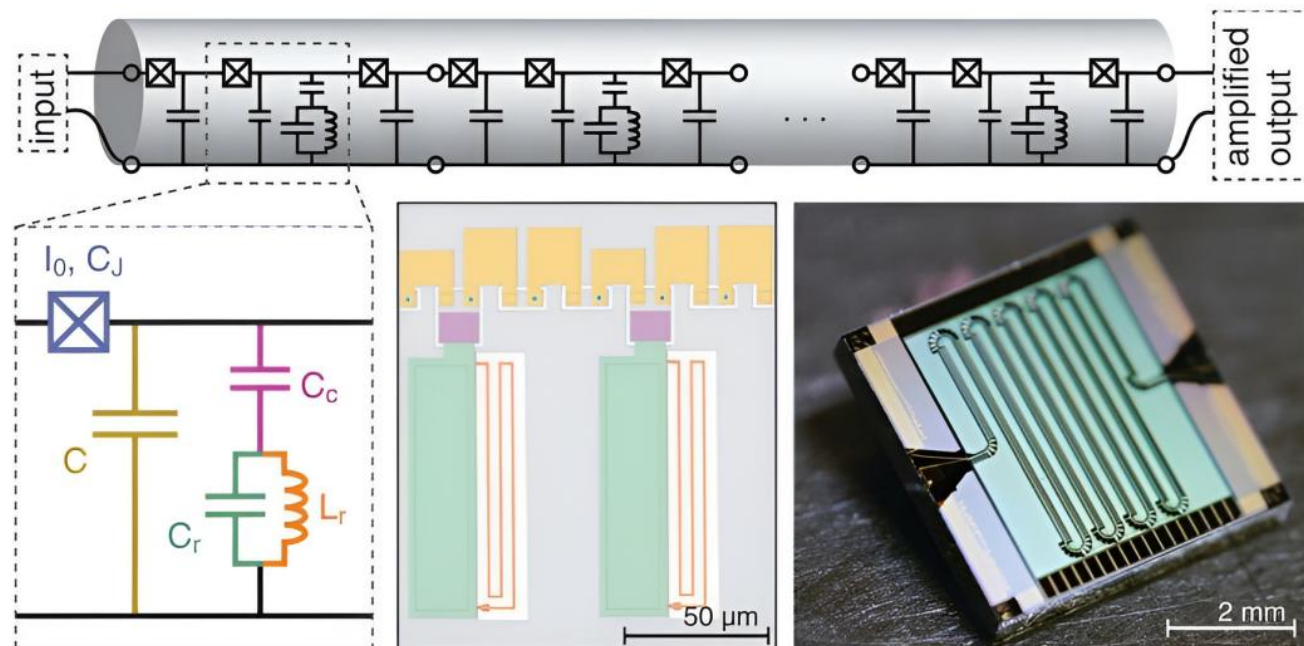
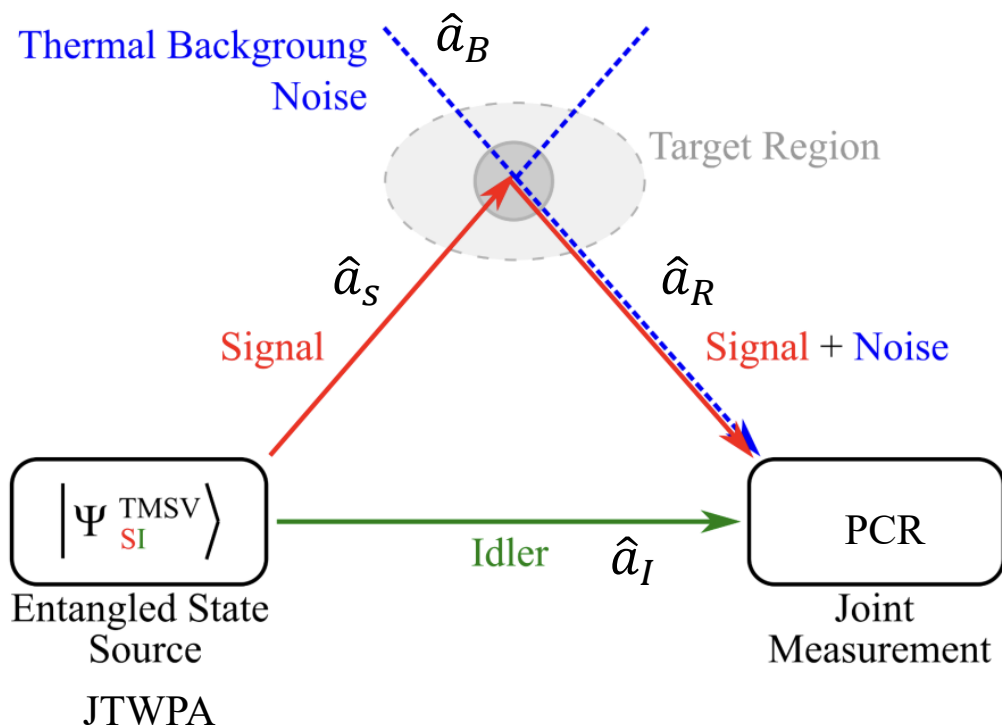
Ps, Pn signal and noise power

SNR signal to noise ratio at the input of the receiver

[1] D. Luong, et al, "Receiver operating characteristics for a prototype quantum two-mode squeezing radar," IEEE TAES, vol. 56, pp. 2041–2060, Nov. 2019.

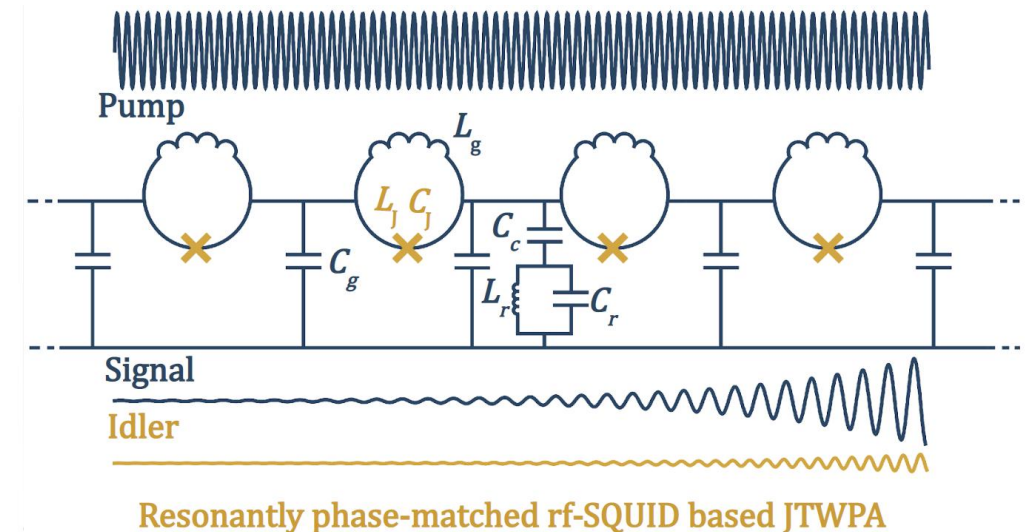
[2] S. Barzanjeh, et al, "Microwave quantum illumination using a digital phase conjugated receiver", Science Adv. 2020.

# JTWPA as an entangled photons source



# What's a JTWPA

- JTWPA is a **nanostructured superconducting** device composed of the repetition of several **Josephson junctions (JJs)** embedded in a **coplanar waveguide (CPW)**.
- The central conductor of the coplanar waveguide is composed of a chain of rf-SQUIDs with a geometric inductor  $L_g$  and a JJ with an inductance  $L_j$  and a capacitance  $C_j$ . The line is capacitively shunted to ground by capacitors  $C_g$ .
- The **energy of the pump** is partially transferred to a **traveling wave signal**, together with the creation of an energy-preserving **idler wave**.

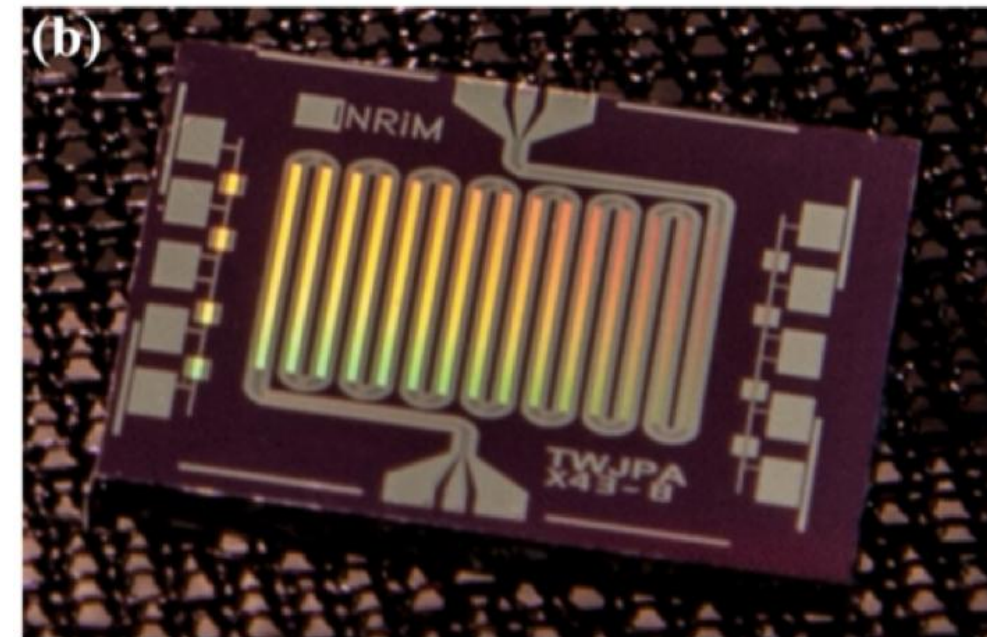


Electrical Equivalent circuit

# Why JTWPA?

Key advantages:

- **phase-matching bandwidth (W)** of the JTWPA in the GHz range, the W phase matching bandwidth can be largely increased, overcoming the narrow bandwidth of the JPA.
- purity of the nonlinearity of the Josephson elements provides the capability of **amplifying microwave signals close to the minimum amount** of added noise allowed **by quantum mechanics**
- high-fidelity and ultra low-noise heterodyne measurements of microwave signals at the single photon level
- brightest source of entangled fields across all of the electromagnetic spectrum
- simple on-chip integration with coherent quantum systems



# Can a JTWPA work as a quantum entangled source?

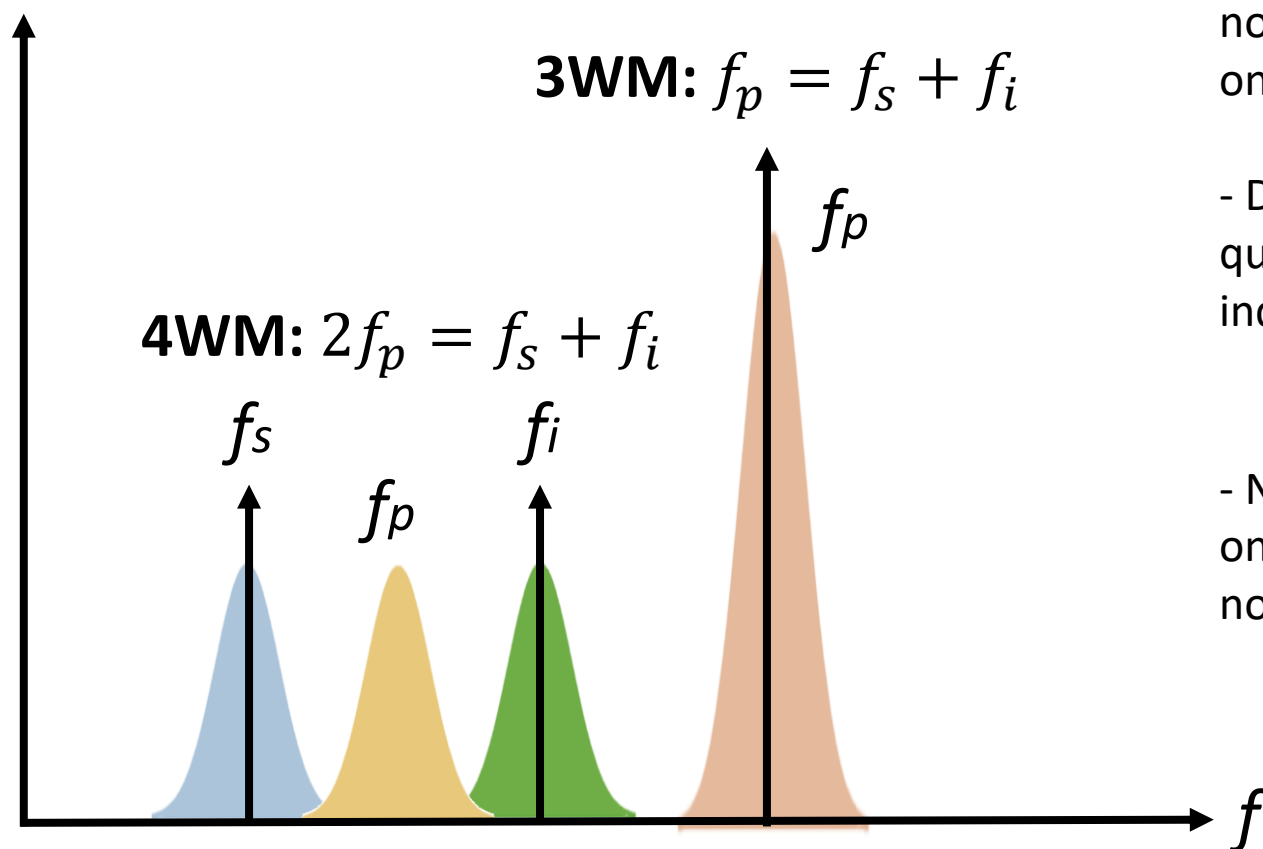
Two different mixing processes, depending on the nonlinearity of the dependence of the cell inductance on the current  $I$ :

- Degenerate four-wave mixing (4WM), triggered by a quadratic current dependence of the nonlinear inductance:

$$2f_p = f_s + f_i$$

- Non degenerate three-wave mixing (3WM), depends on the presence of a linear current dependence of the nonlinear inductance:

$$f_p = f_s + f_i$$





# Where JTWPA fabrication

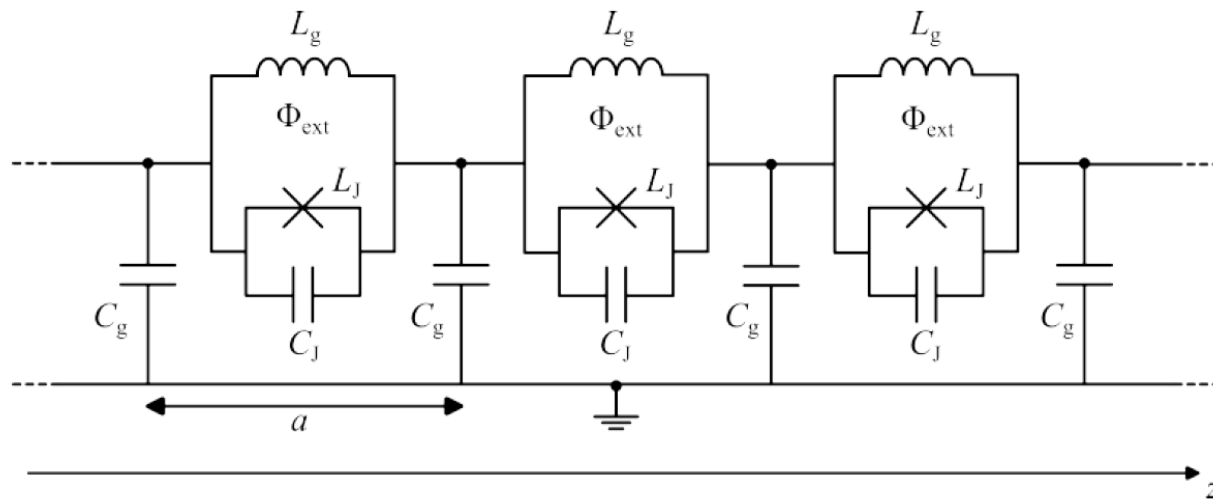


Quantum Circuits for Metrology Laboratory, located in INRiM, was inaugurated in March 2022.

It hosts a cryostat CF-CS110-500 from Leiden Cryogenics, equipped with two warm insertable probes, a 1.5 W cryocooler, and a 9 T superconducting magnet.

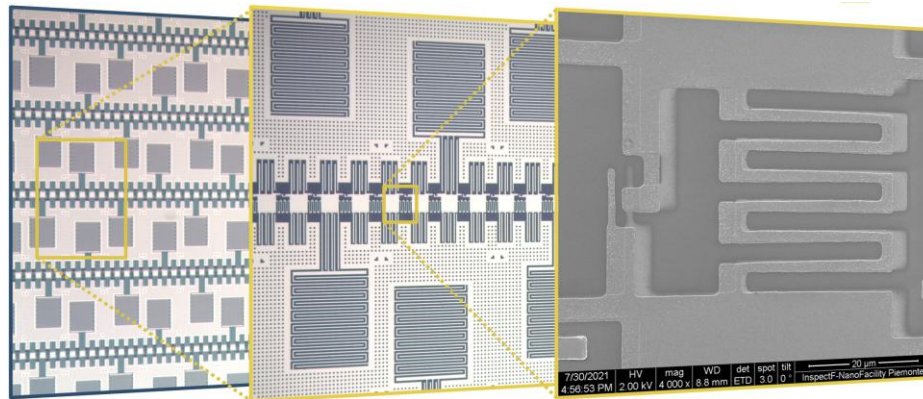
The system has a base temperature  $T = 10 \text{ mK}$  and a cooling power, on the mixing chamber plate, of  $900 \mu\text{W}@120 \text{ mK}$ .

# Electrical Equivalent Model



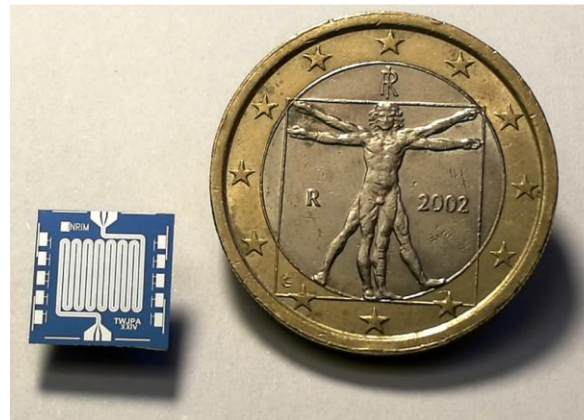
Electrical Parameter	Value	Description
$C_J$	$60 \text{ fF}$	Junction capacitance
$L_g$	$47.5 \text{ pH}$	Geometrical inductance
$C_g$	$11 \text{ fF}$	Ground capacitance
$a$	$60 \text{ }\mu\text{m}$	Unit cell length
$N$	1000	Number of unit cells
$I_c$	$5 \text{ }\mu\text{A}$	Critical current of the junction

# JTWPA fabrication

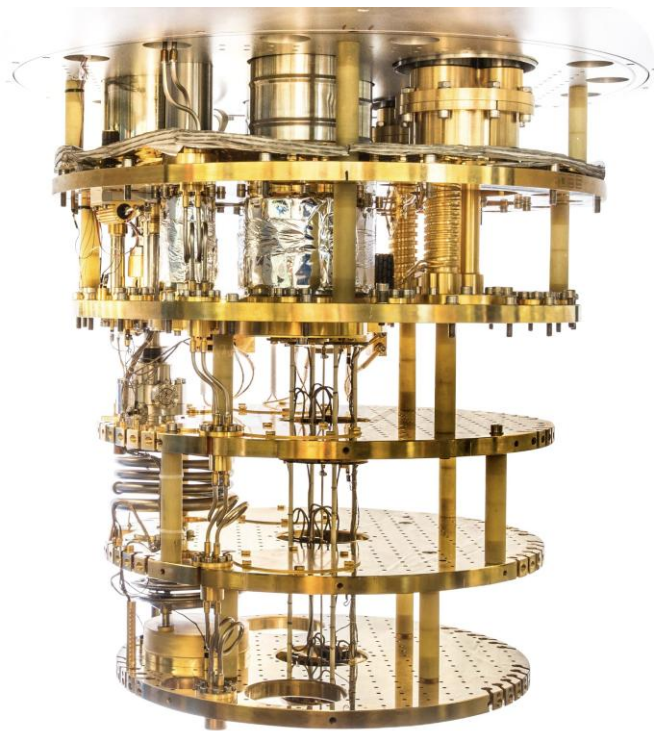


JTWPA's are fabricated with a highly reproducible multi-step workflow for the manufacturing of high-integrated **thin-film circuits on 2-inch Si wafers**.

The core of the fabrication process are two UV lithographs (resolution of  $0.8 \mu\text{m}$ ) followed by aluminum e-beam evaporations.



# Cryogenic set-up

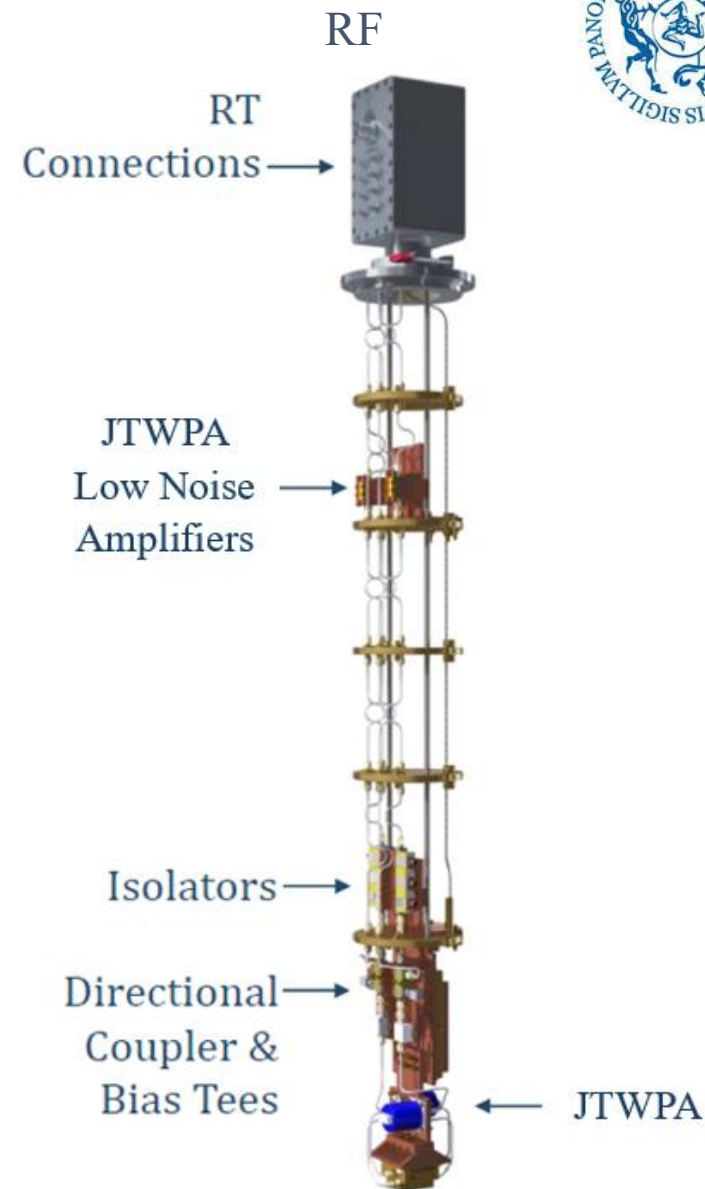
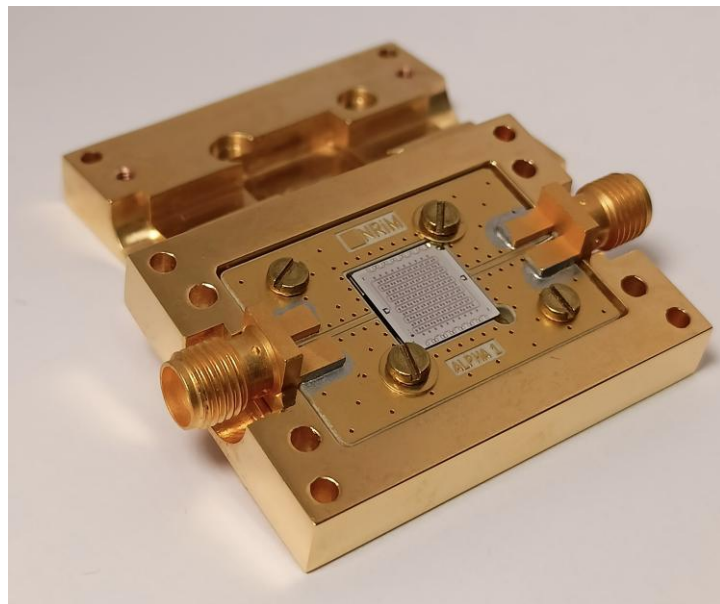


Dilution refrigerator

Model: Leiden Cryogenics CF-CS110-500

Cooling Power > 500  $\mu$ W @ 120 mK

Two-port sample holder



# Measurement set-up

The signal and pump frequencies are provided by a VNA and a signal generator and pass through several attenuation stages.

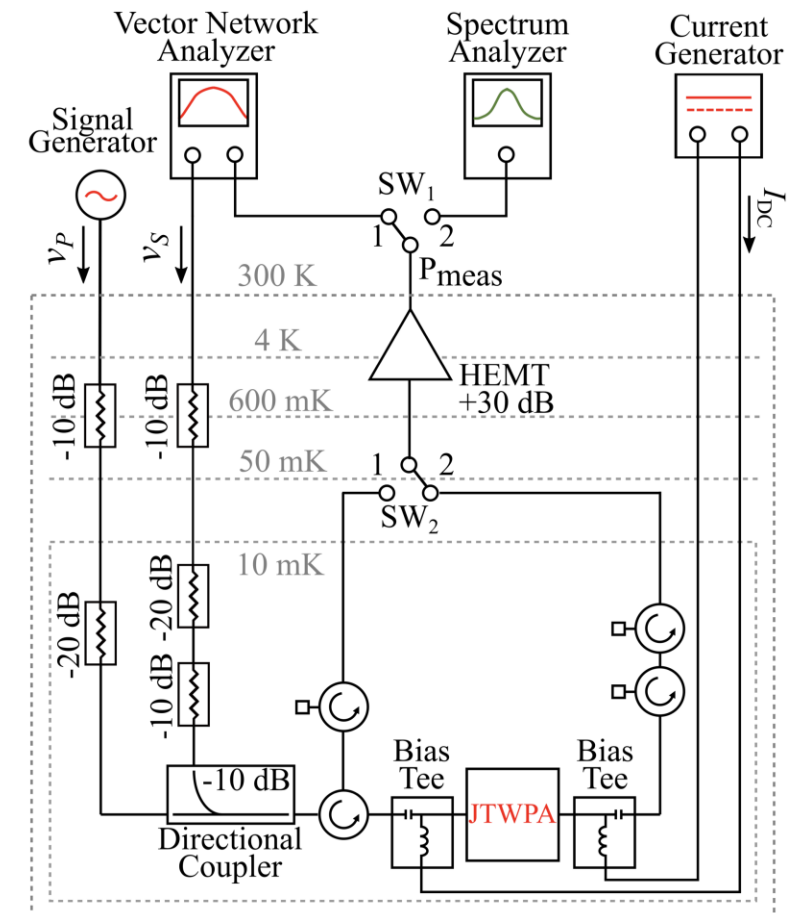
The signal and pump frequencies arrive at a directional coupler that injects the frequencies into the JTWPA after a first isolation stage provided by a circulator.

An electromechanical switch (SW2) in the output line allows to perform reflection (position 1) or transmission (position 2) measurements.

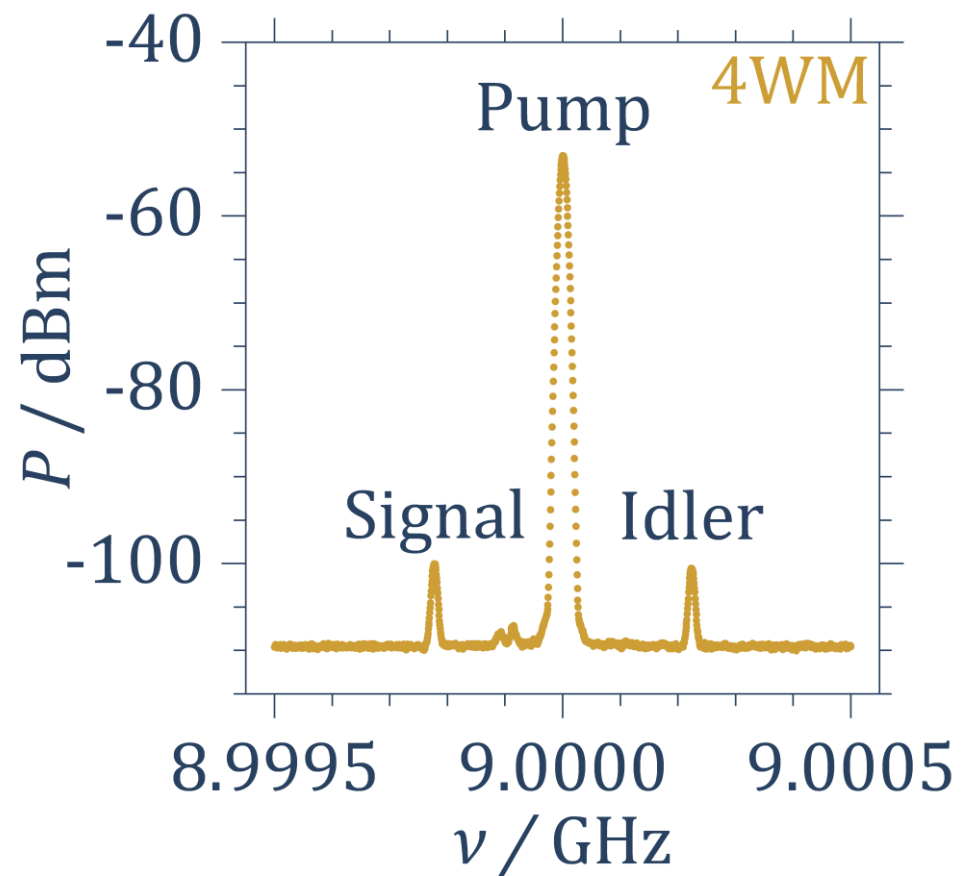
The output signal is amplified by a 30 dB HEMT LNA placed on the 4K stage.

Switch (SW1) allows to change the detector at room temperature between the VNA (position 1) and the spectrum analyser (position 2).

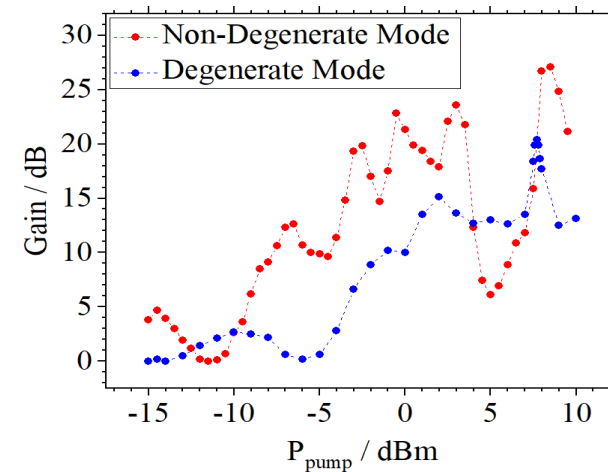
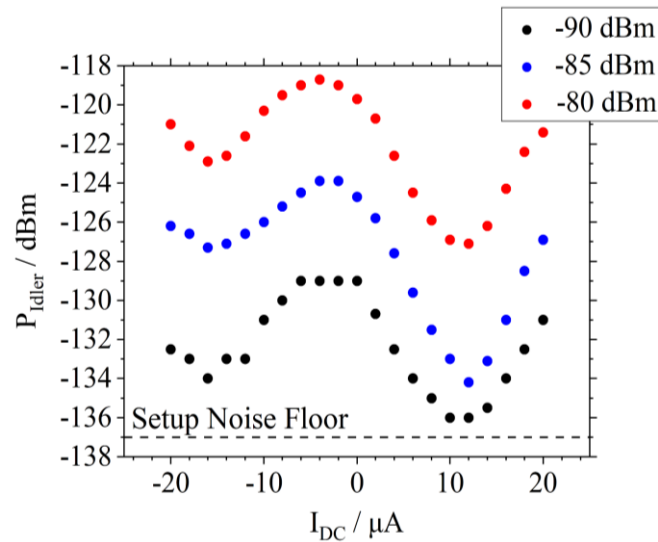
A current generator supplies a DC current which is injected into the central conductor of the JTWPA through two bias tees.



# JTWPA: generation of idler



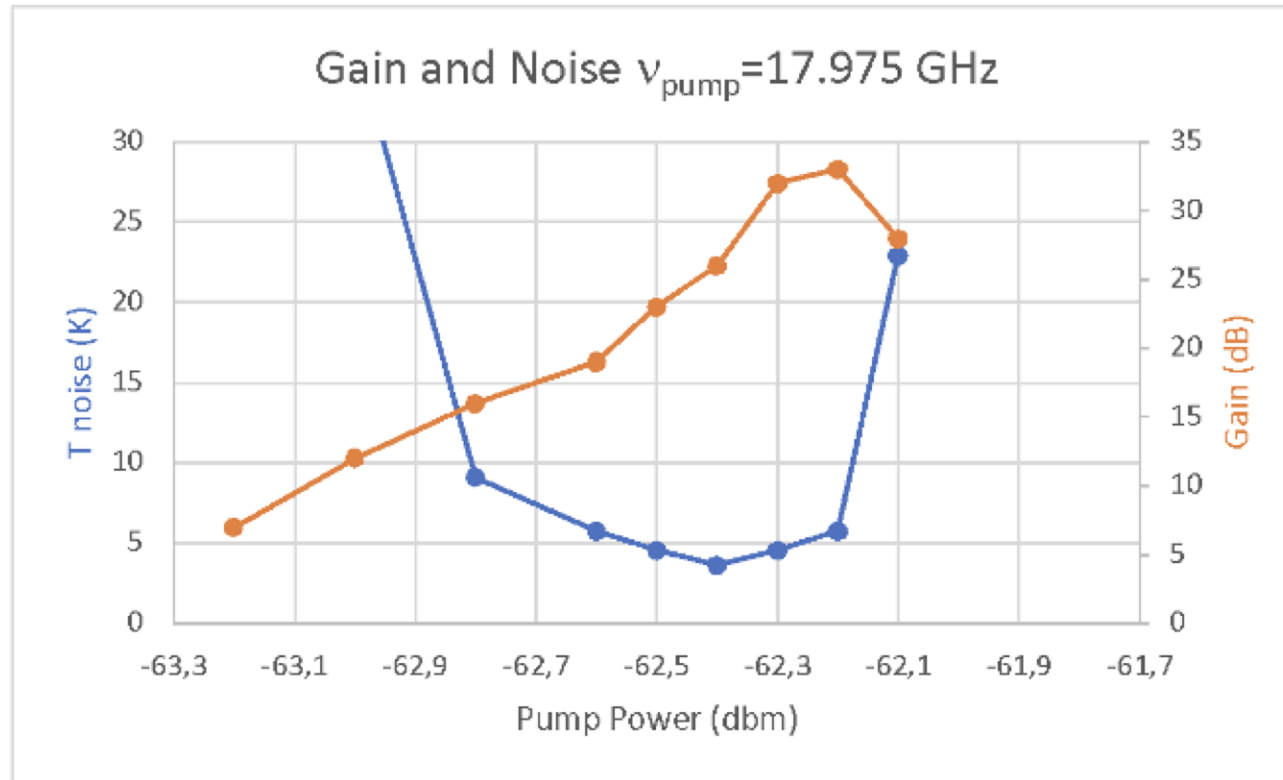
# Measurement Set-up and Results



✓ A first characterization of the JTWPA was performed measuring the output idler tone power ( $P_{\text{idler}}$ ), generated via 3WM, as a function of the DC bias current  $I_{\text{DC}}$ . The device was fed with a  $\nu_p = 6.75$  GHz driving pump tone, with three different power values  $P_p$  and a  $\nu_s = 3.3$  GHz signal tone with  $P_s = -84$  dBm power. For this mixing process the idler is expected to be generated at  $f_i = f_p - f_s = 3.45$  GHz.

✓ Signal power Gain as a function of pump power ( $P_{\text{pump}}$ ) for degenerate ( $\nu_p = 18$  GHz) and non-degenerate ( $\nu_p = 13.4$  GHz) regimes. The power gain induced by Josephson non-linearities reaches values around 25 dB, showing that the JTWPA acts as a metamaterial efficiently promoting 3WM processes, the key enabler for the preparation of TMSV state.

# JTWPA: amplifier characterization



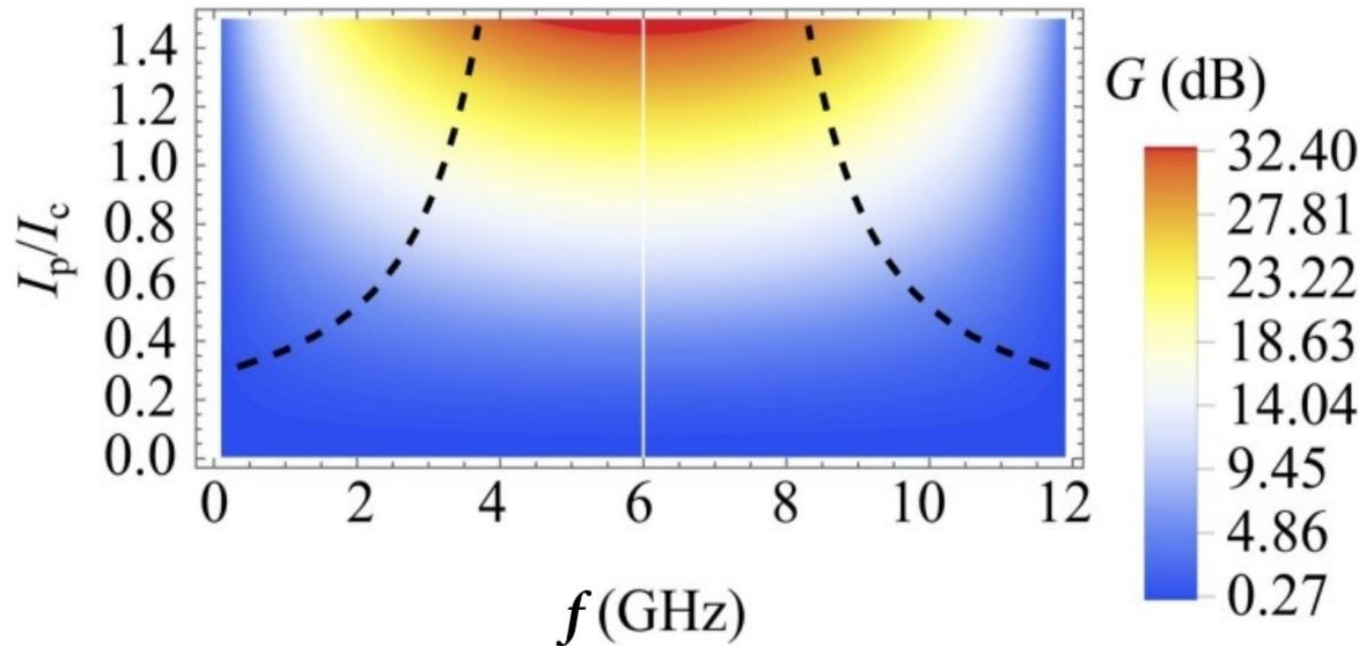
Signal gain and noise have been calibrated by measuring the coaxial lines attenuation and HEMT gain both at room temperature and during cryostat operation.

The best resulting value in terms of noise temperature is 4 K with a gain of 25 dB.

Signal gain (yellow curve and right axis)

Noise temperature of the whole RF chain (blue curve and left axis)

# JTWPA: gain vs frequency



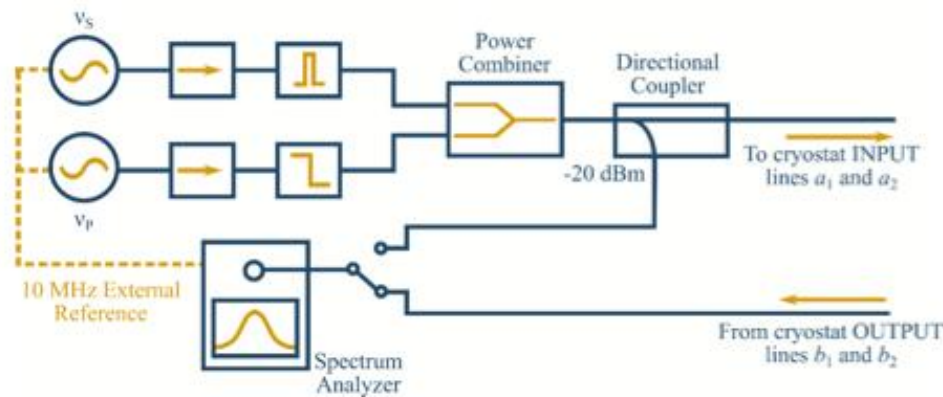
Experimental results in terms of  $G$  vs freq over the 0 to 12 GHz frequency band, as a function of the pump current  $I_p$  normalized on the critical current  $I_c$  of Josephson junctions composing the referenced device.

For a signal central frequency equal to 6 GHz, a maximum gain of 32.40 dB and maximum bandwidth equal to 4 GHz at 3 dB threshold level, identified with the dashed lines, are obtained.

# JTWPA characterization

## ROOM TEMPERATURE SETUP

- ✓ The setup's room temperature part is responsible for generating both the pump and the seeding signal tones, and for detecting the frequency-correlated tones generated in the dilution refrigerator by the JTWPA through the parametric down-conversion mechanism.
- ✓ A schematic of the electronics is presented on the left, while on the right its implementation is presented.





# JTWPA-based MQR Performance

Parameters	JTWPA	Unit
Antenna operating band	X-band	GHz
Antenna gain (G)	15	dB
Antenna effective area (Ae)	2.79×10 <sup>-3</sup>	m <sup>2</sup>
Target radar cross section (σ)	1.0	m <sup>2</sup>
Phase-Matching Bandwidth (W)	<b>3000</b>	MHz
Josephson power gain (Gp)	32.40	dB
HEMT gain (at 4K) (GHEMT)	30	dB
Signal gain (G <sub>S</sub> )	88.32	dB
Detection gain (G <sub>D</sub> )	16.82	dB
Amplifier gain (G <sub>A</sub> )	71.5	dB
Signal Power (P <sub>s</sub> )	-100	dBm
Pump power (P <sub>p</sub> )	-62.4	dBm
Noise power (P <sub>n</sub> )	-137	dBm
Pump frequency (f <sub>p</sub> )	18	GHz
Signal frequency (f <sub>s</sub> )	8.9998	GHz
Idler frequency (f <sub>i</sub> )	9.0002	GHz
Signal-to-noise ratio (SNR <sup>QR</sup> )	-8.23	dB
<b>Range (R) (N<sub>s</sub> = 0.1 η = 1 dB )</b>	<b>82.2</b>	<b>m</b>

QTMS radar very similar to conventional noise radar

QTMS range equation can be obtained as follows

$$R_{max} = \left( \frac{GA_e \sigma P_s}{(4\pi)^2 P_n (SNR)_{min}^Q} \right)^{1/4}$$

where:

G antenna gain

Ae effective antenna area

σ target radar cross-section

P<sub>s</sub>, P<sub>n</sub> signal and noise power

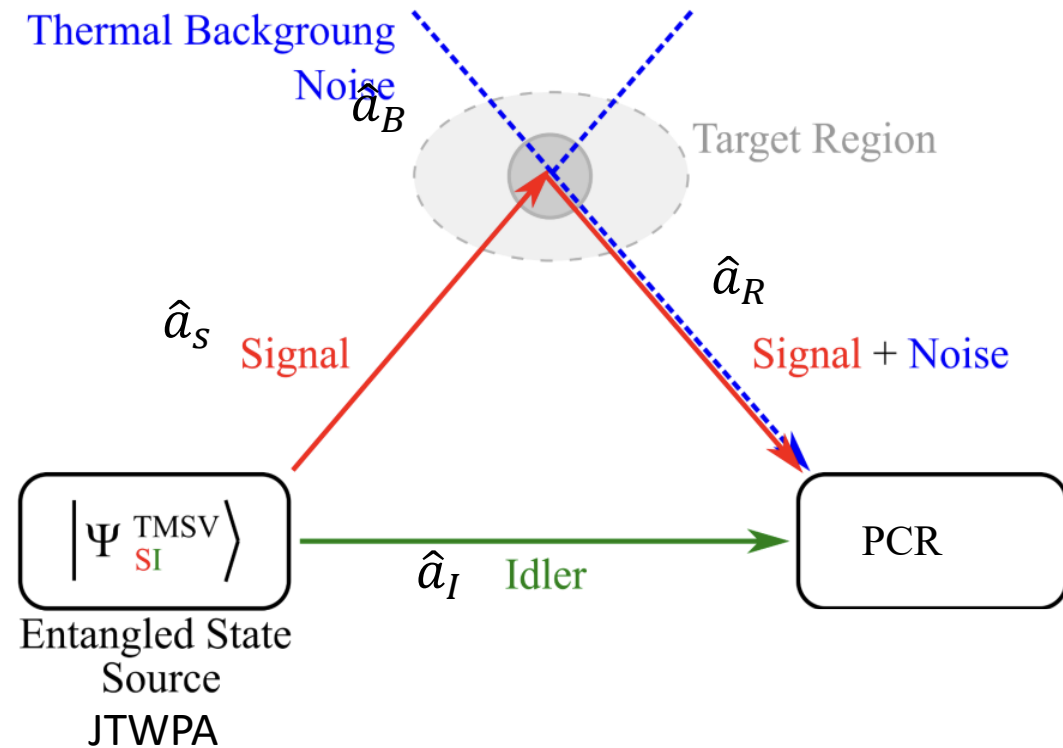
SNR signal to noise ratio at the input of the receiver

# Josephson Traveling Wave Parametric Amplifier as a non-classical quantum source

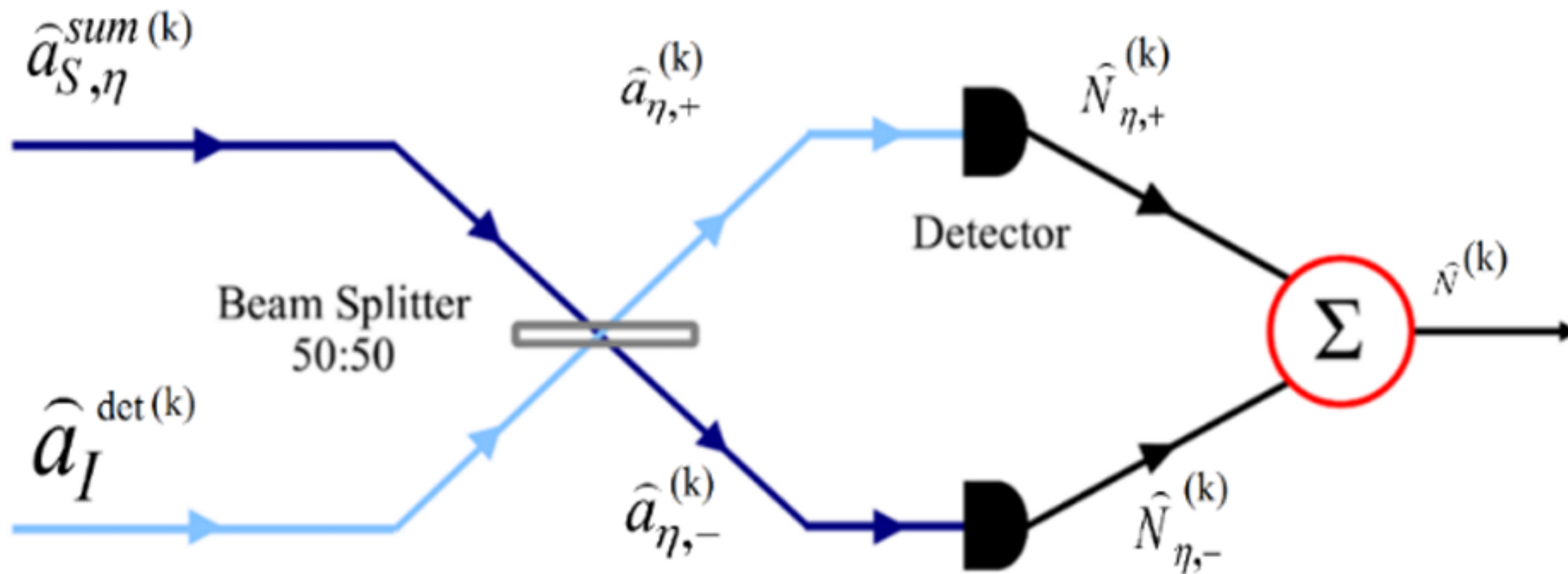
Error Probability for the QI protocol using a TMSV state is well below the classical minimum value, up to the limit:

$$P_e^{\text{TMSV}} \simeq \exp[-\eta N_s / N_B]$$

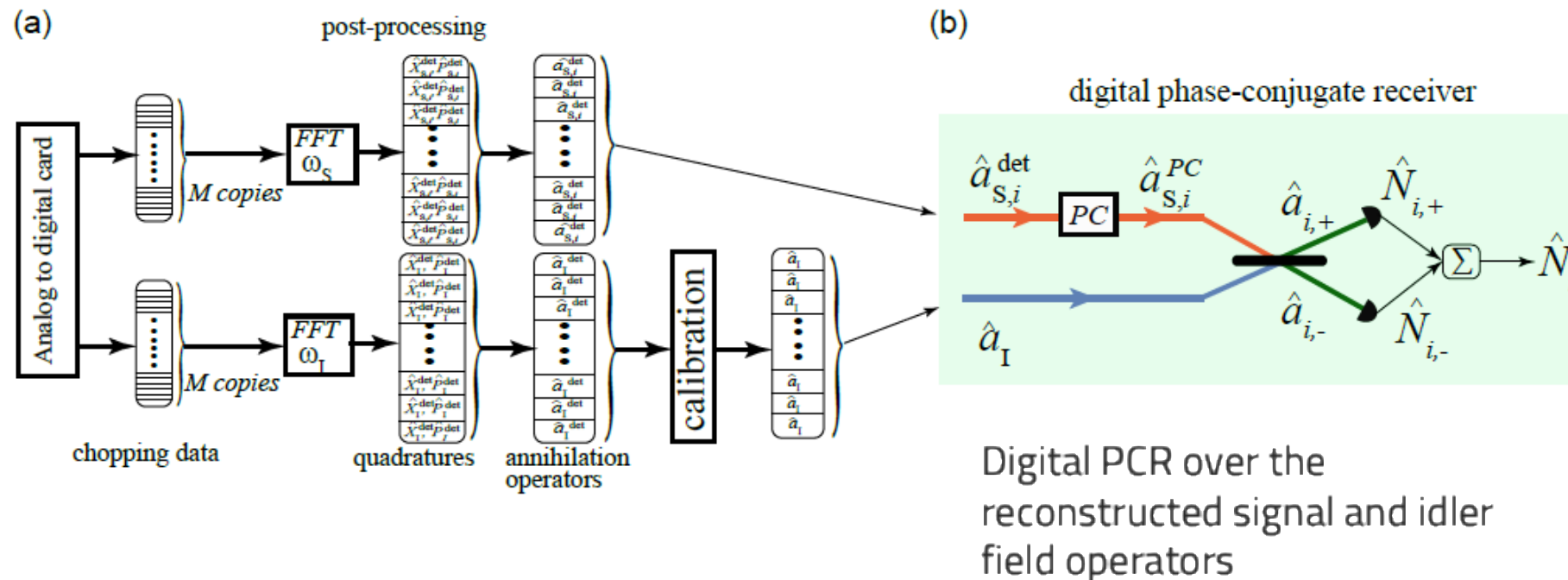
- $\eta$  reflectance of the signal scattered when target is present
- $N_s$  number of signal photons
- $N_B$  number of background thermal photons at the same frequency of the signal one.



# Phase Conjugate Receiver



# Phase conjugate receiver with digital post-processing

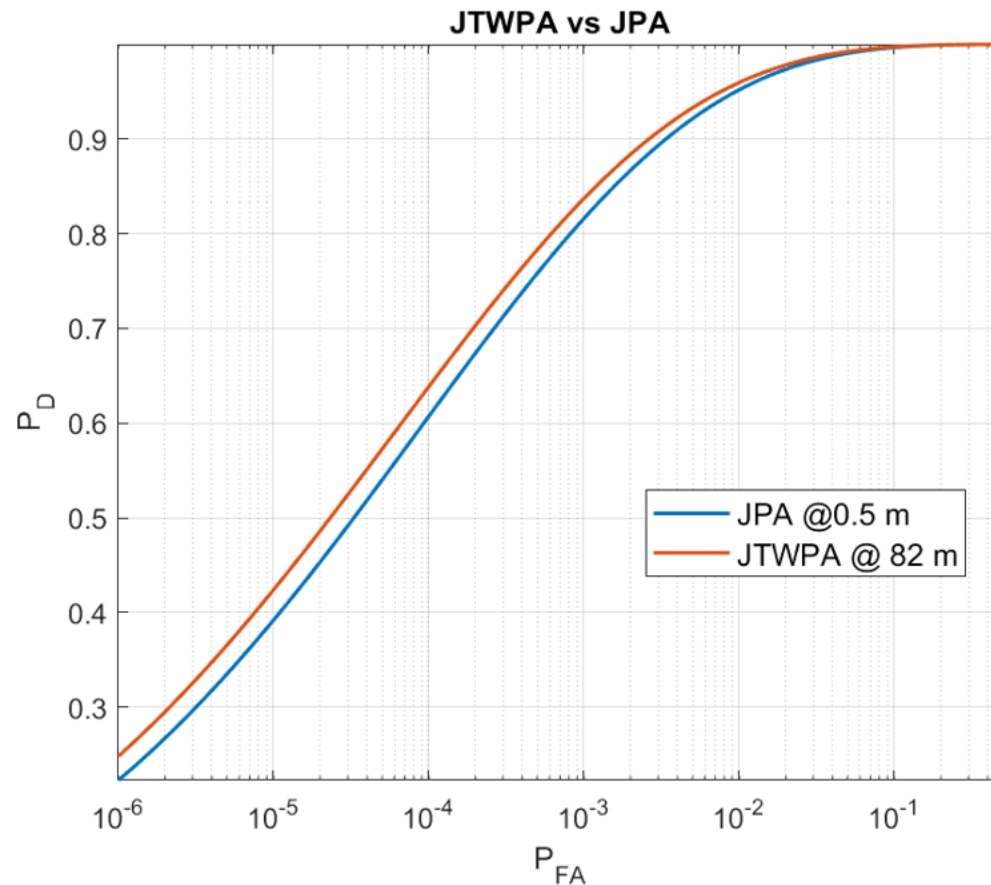


The outputs are amplified, down-converted, heterodyned, and digitized simultaneously and independently for both channels.

- Digital PCR: data postprocessing **with the ideal “calibrated” idler  $\hat{a}_I$** , obtained rescaling by the measured gain and subtracting the added amplifier noise



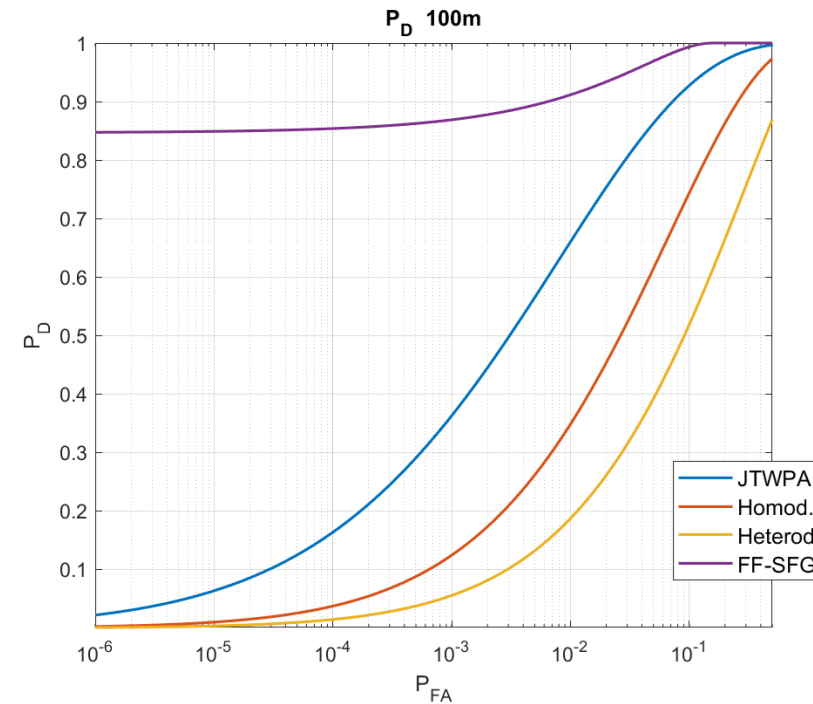
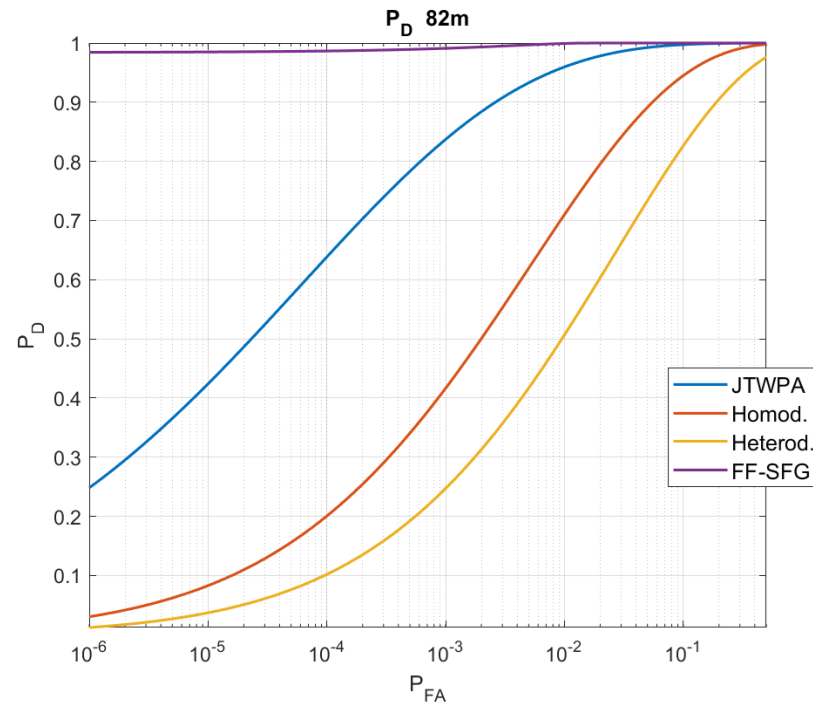
# Performance and Comparison: Receiver operating characteristic (ROC)



For a range equal to **82 m**, we have  $P_D > 80\%$  with a **PFA of  $10^{-3}$**  with JTWPA.

To obtain same performances with JPA, we must go down to less than **1 m**.

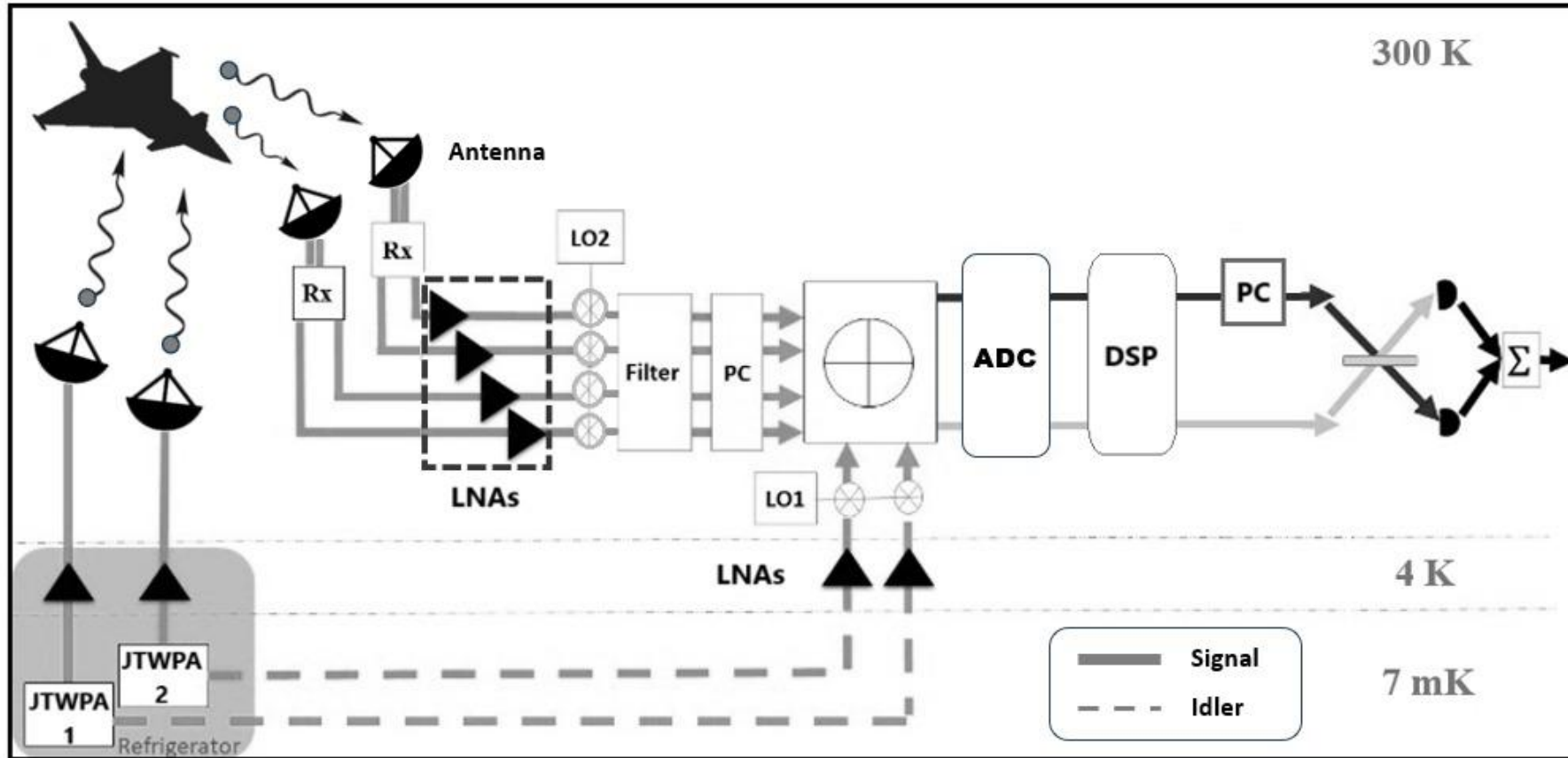
# Receiver operating characteristic (ROC)



Figs.1 and 2: ROC JTWPA vs classic coherent receivers with same setup and FF-SFG Feed Forward Sum Frequency Generation.

At **82 m**, we have already a  $P_D > 80\%$  with a  $P_{FA}$  of  **$10^{-3}$**  with JTWPA, big advantage to classical coherent receivers, performances begin to degrade at 100 m: target still detectable with more  $P_{FA}$ , less advantage to classic coherent receivers.

# MIMO Microwave Quantum Radar

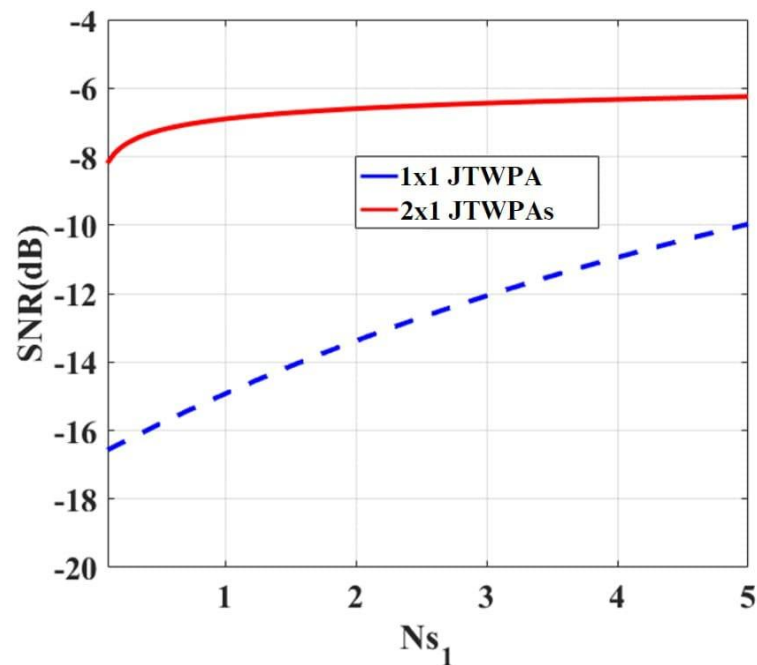




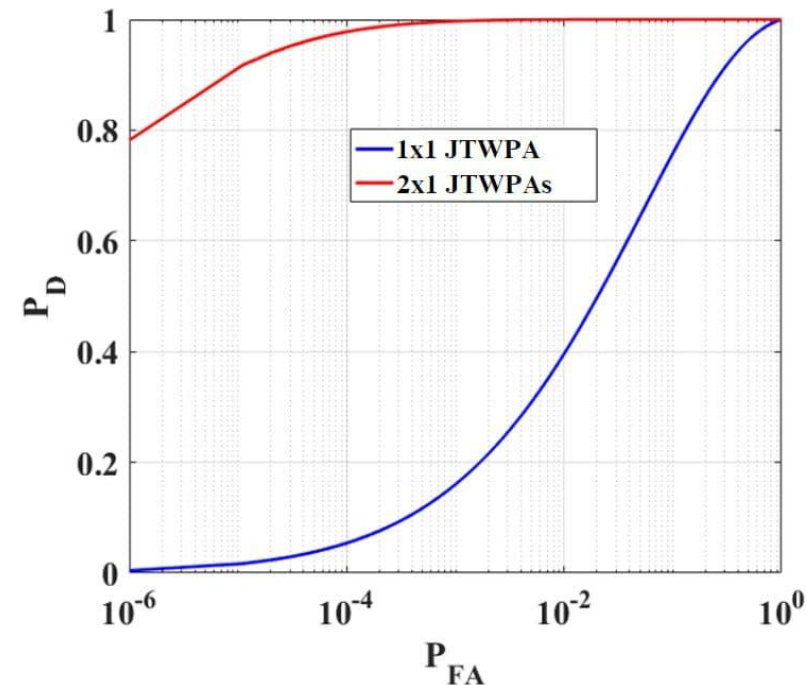
# MQR parameters with an array of two JTWPA quantum sources

Quantity	Parameter	Value	Units
Pump frequency	$f_p$	18	GHz
Signal frequency	$f_s$	8.9998	GHz
Idler frequency	$f_i$	9.0002	GHz
JTWPA bandwidth	$W$	3	GHz
JTWPA power gain	$G_P$	27.81	dB
JTWPA1 signal gain	$G_{S1}$	88.32	dB
JTWPA2 signal gain	$G_{S2}$	88.32	dB
JTWPA1 Idler gain	$G_{I1}$	88.15	dB
JTWPA2 Idler gain	$G_{I2}$	88.15	dB
HEMT-LNA gain (at 4 K)	$G_{amp}$	16.82	dB
Antenna operating bandwidth	$B$	X-Band	GHz
Antenna gain	$G_A$	15	dB

# Performance 2x1 JTWPAs vs 1x1 JTWPA



*SNRs for a single JTWPA and 2x1 JTWPAs vs signal photon numbers*



*ROC curves for a single JTWPA and 2x1 JTWPAs for cross-correlations equals 0.820,  $N = 80$*



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November 21, 2024

Professor Patrizia Livreri  
Department of Engineering  
University of Palermo

Dear Prof. Livreri:

Thank you for your inquiry regarding visiting me while you are in the United States this autumn. Given our mutual interest in microwave quantum illumination — and your group's expertise in Josephson-junction traveling-wave parametric amplifiers (JTWPAs), which is the essential technology for microwave quantum illumination — I believe that such a meeting will be mutually beneficial. Thus I am happy to invite you to MIT on December 5<sup>th</sup> to share our perspectives on quantum illumination and JTWPAs.

I look forward to meeting you.

Sincerely,

Jeffrey H. Shapiro



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# Conclusions

- Our proposed JTWPA quantum source represents a significant milestone in the evolution of Microwave Quantum Radar
- The good performance of the JTWPA in terms of wide bandwidth and increased transmit power makes it an ideal candidate for a long-range Microwave Quantum Radar

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# Thank you for your attention

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