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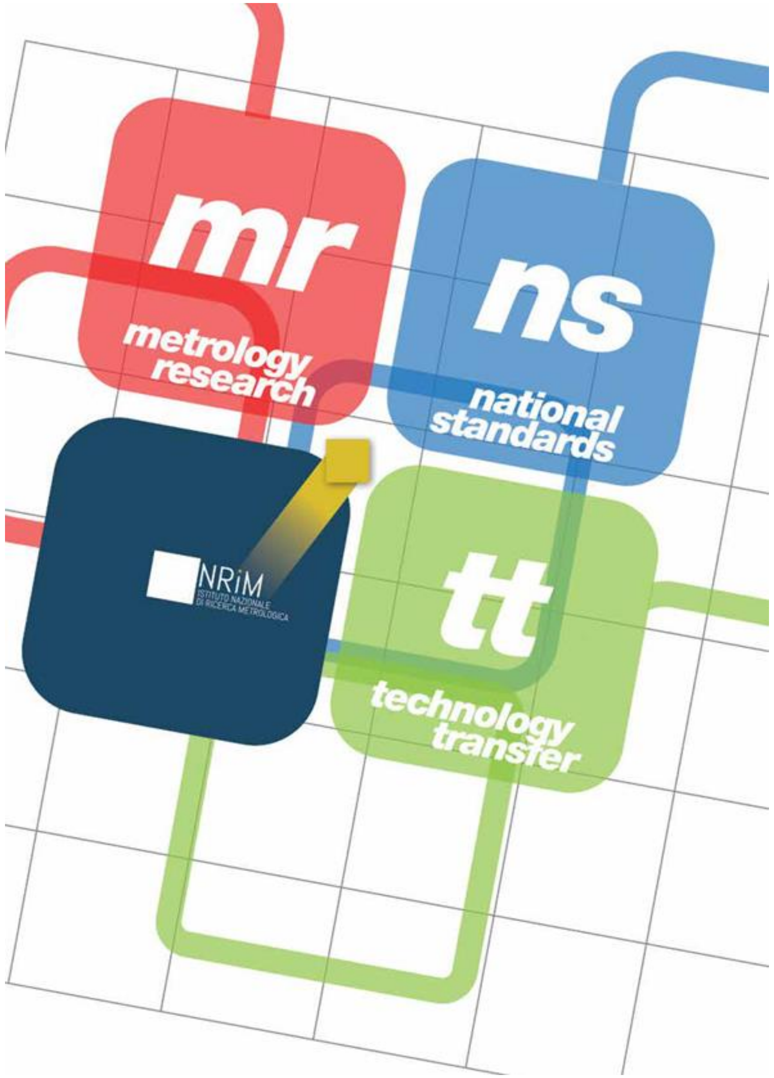
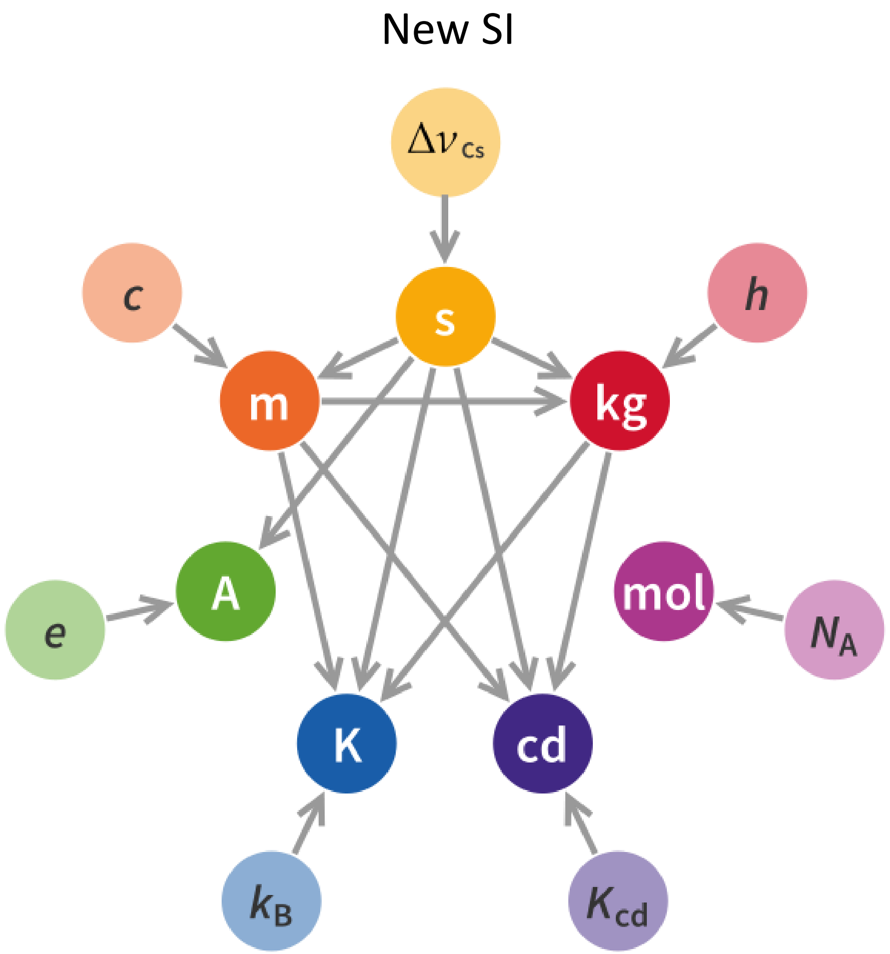
# Josephson metamaterials: properties and fabrication

Circuit QED: from Quantum Devices to Analogues on Superconducting Circuits - Trento, October 3-5

*Emanuele ENRICO*

# Introduction



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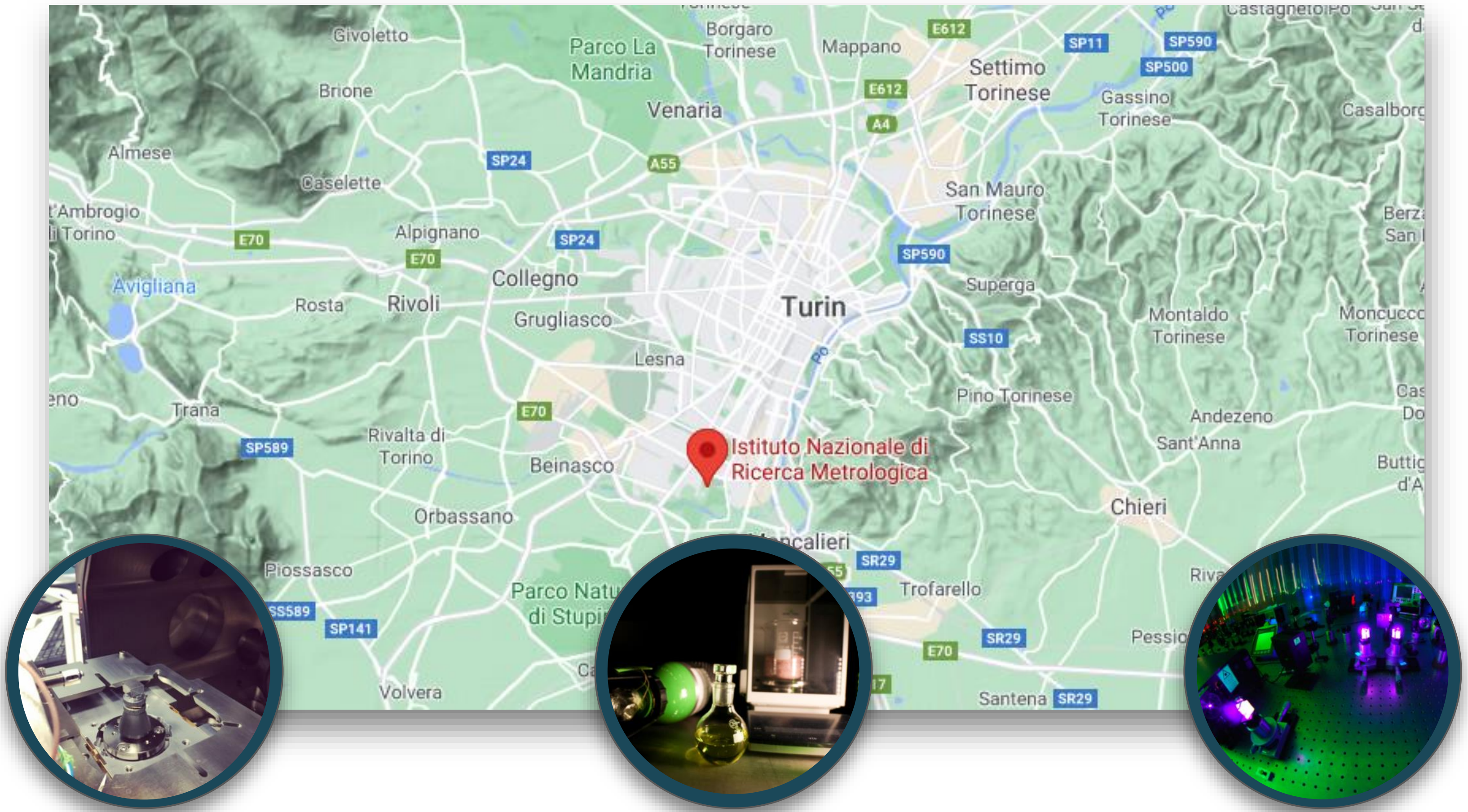
# Introduction




Advanced materials metrology and life science

Applied metrology and engineering

Quantum metrology and nano technologies

# Introduction

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Quantum metrology and nano technologies

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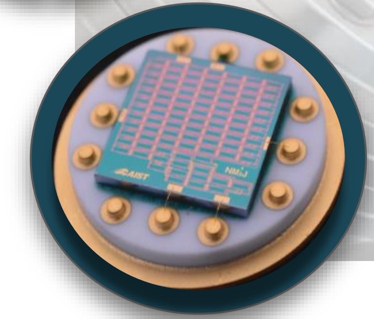
# Quantum Electronics - NanoTech

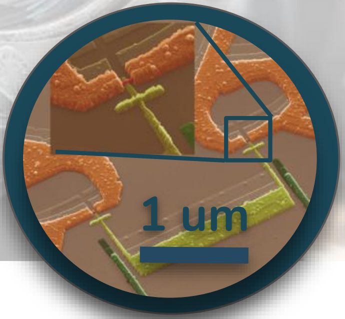


Quantum Hall Array Resistance Standard

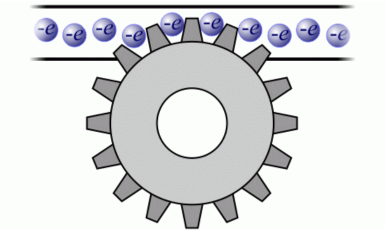
$R_H = R_K/i$

with $R_K = h/e^2$

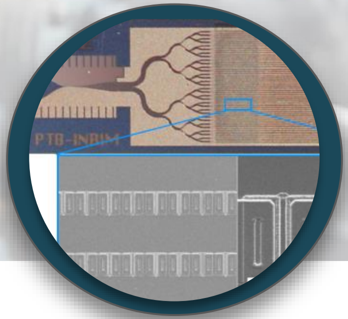
and $i = 1, 2, 3, 4, \ldots$




Single-electron transistor low DC current standard



$I=nef$

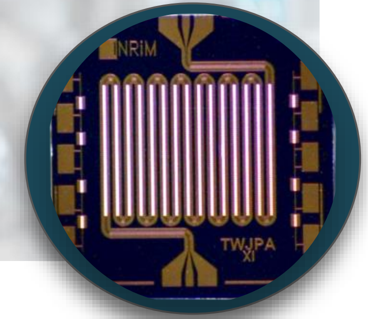


Josephson Voltage Standard

$V_J = n\, K_J\, f$

with $K_J = h/2e$

and $k = 1, 2, 3, 4, \ldots$




Microwave photonics

| | |
|---|---|
| $\nu$ | 1 GHz → 20 GHz |
| $\lambda=c/\nu$ | 300 cm → 15 cm |
| $E=h/\nu$ | 4 µeV → 80 µeV |
| $T=E/k_B$ | 50 mK → 1K |

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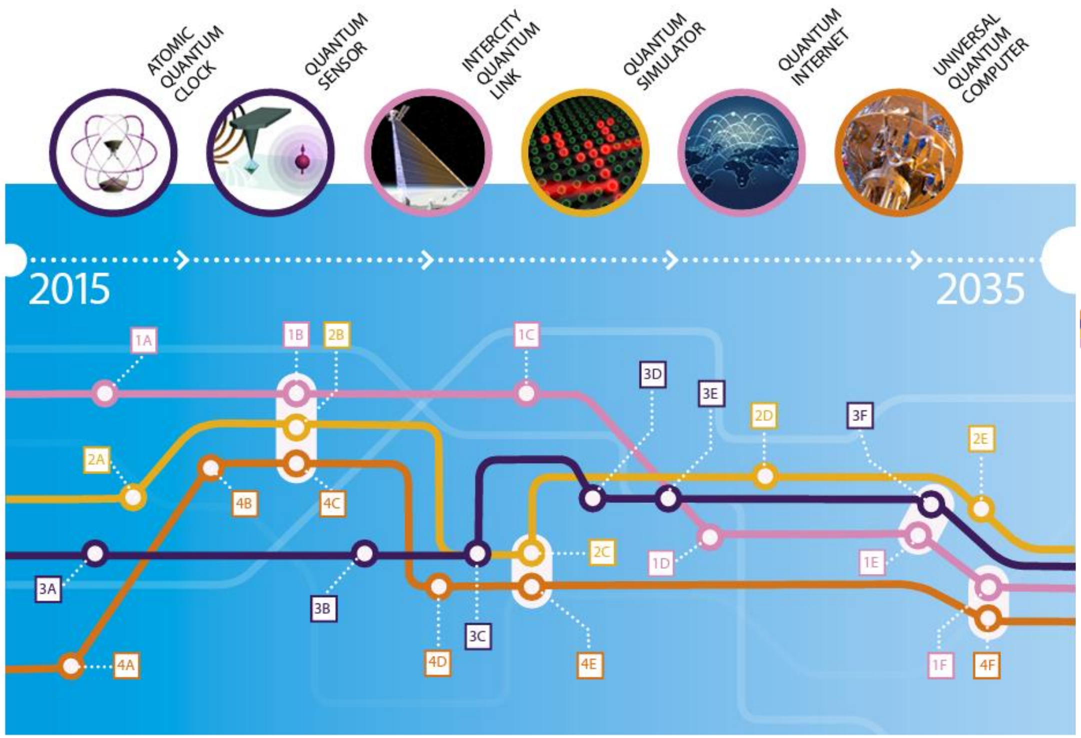
# Quantum Electronics - Applications




*Quantum Manifesto, A New Era of Technology*
May 2016

Pillars share **quantum states** experimental access, evidence and advantage

| | 1. Communication | 2. Simulators | 3. Sensors | 4. Computers |
|---|---|---|---|---|
| 0 – 5 years | A Core technology of quantum repeaters<br>B Secure point-to-point quantum links | A Simulator of motion of electrons in materials<br>B New algorithms for quantum simulators and networks | A Quantum sensors for niche applications (incl. gravity and magnetic sensors for health care, geosurvey and security)<br>B More precise atomic clocks for synchronisation of future smart networks, incl. energy grids | A Operation of a logical qubit protected by error correction or topologically<br>B New algorithms for quantum computers<br>C Small quantum processor executing technologically relevant algorithms |
| 5 – 10 years | C Quantum networks between distant cities<br>D Quantum credit cards | C Development and design of new complex materials<br>D Versatile simulator of quantum magnetism and electricity | C Quantum sensors for larger volume applications including automotive, construction<br>D Handheld quantum navigation devices | D Solving chemistry and materials science problems with special purpose quantum computer > 100 physical qubit |
| > 10 years | E Quantum repeaters with cryptography and eavesdropping detection<br>F Secure Europe-wide internet merging quantum and classical communication | E Simulators of quantum dynamics and chemical reaction mechanisms to support drug design | E Gravity imaging devices based on gravity sensors<br>F Integrate quantum sensors with consumer applications including mobile devices | E Integration of quantum circuit and cryogenic classical control hardware<br>F General purpose quantum computers exceed computational power of classical computers |

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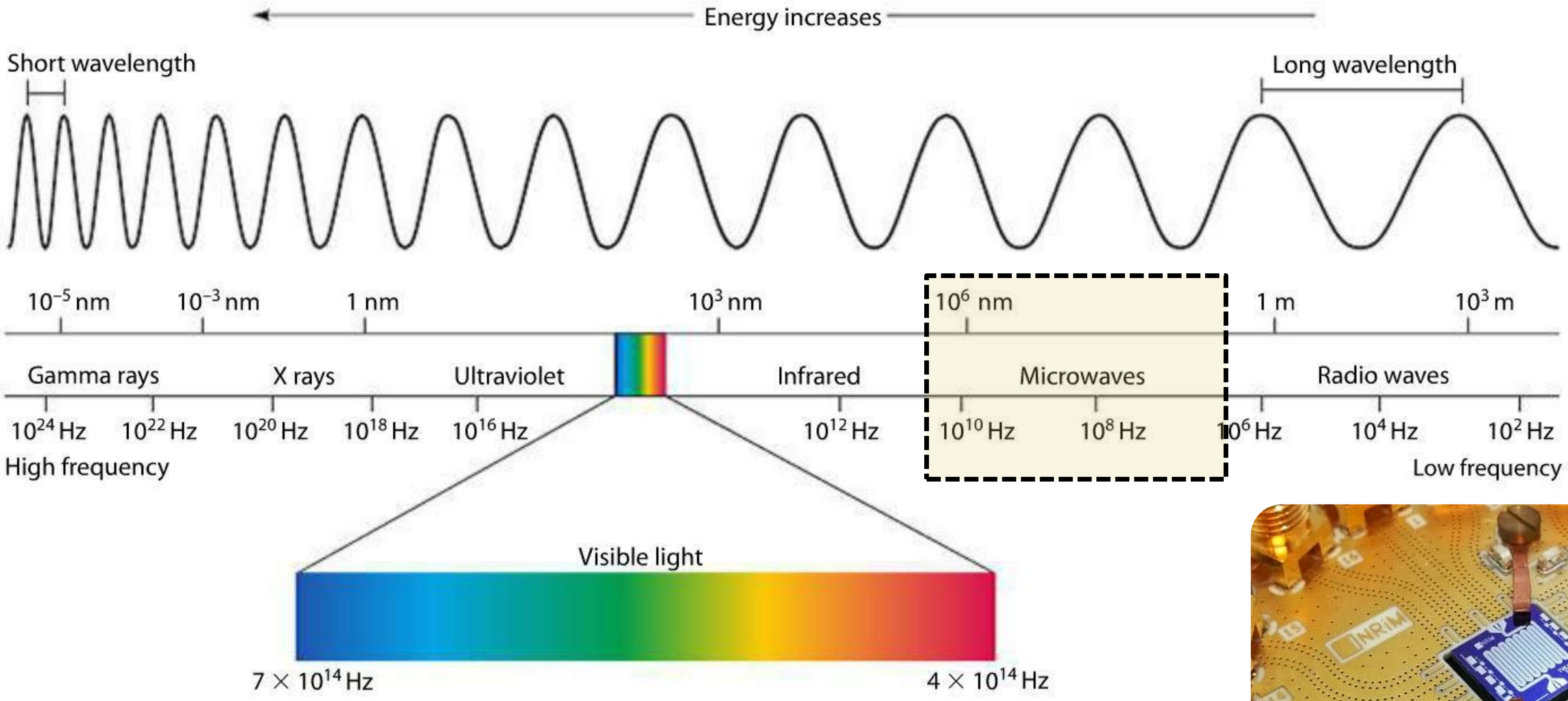
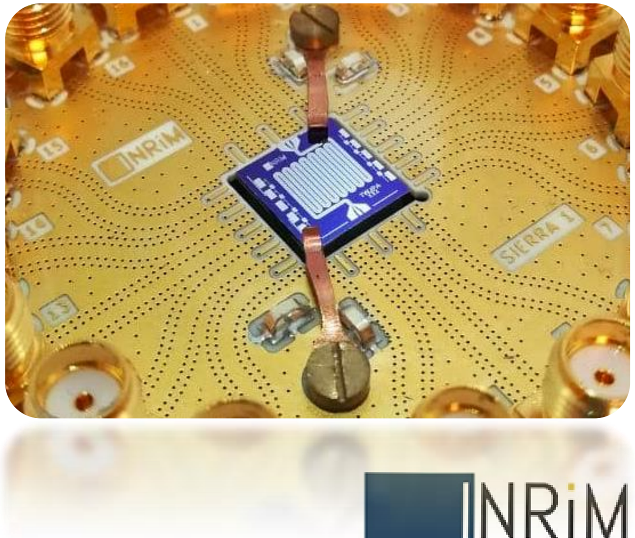
# Quantum states – Energy scale



Circuit QED gives access to the **tuneability** of quantum states interactions with **chip-scale** technologies

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# Metrology perspective and current status of cQED related quantities

| Quantity | Traceability protocols | Calibration Standards | Uncertainty budget |
|---|---|---|---|
| *Temperature* | | | |
| *Frequency* | | | |
| *Voltage* | | | |
| *Current* | | | |
| *Impedance* | | | |
| *S-parameters* | | | |
| *Gain/Attenuation* | | | |
| *Power* | | | |

# Circuit QED Toolbox

- Transmission lines
- Resonators / Cavities
- Qubits
- Isolators / Circulators
- Bias-tee
- Directional couplers
- Quantum limited linear amplifiers
- Detectors (transducers or counters eg. single microwave photon detectors)
- Nonclassical radiation sources

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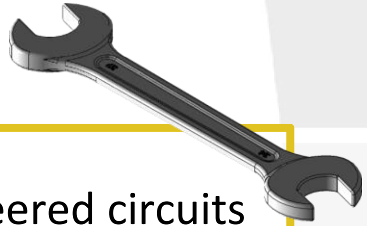

**Josephson metamaterials** are engineered circuits characterized by mixing processes promoting:

- Parametric amplification
  Quantum limited added-noise
- Parametric downconversion
  Nonclassical radiation



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# Nonlinear (meta) materials

Dipole electric momentum of a nonlinear material under electromagnetic stimulus

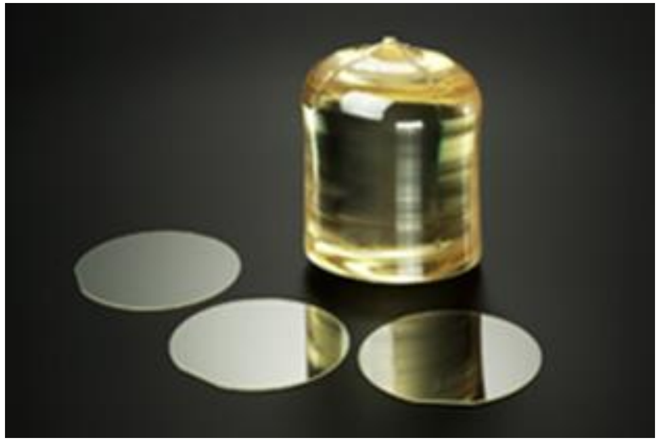
$$P(t)=\varepsilon_0 \left(\chi^{(1)}E(t)+\chi^{(2)}E^2(t)+\chi^{(3)}E^3(t)+\ldots\right)$$

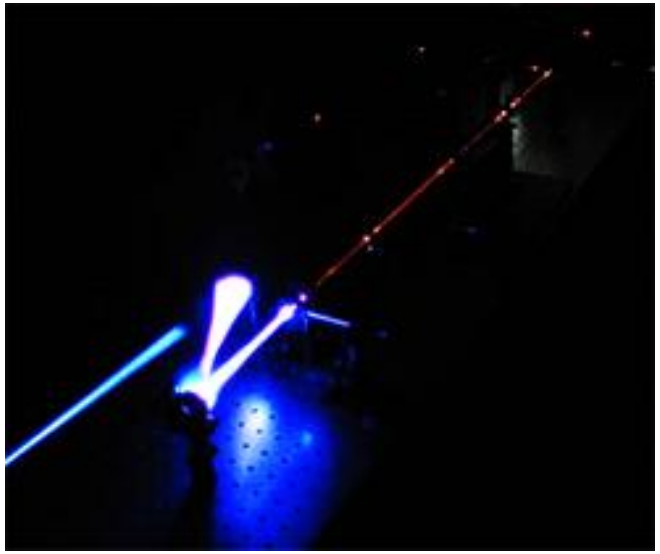
When a (weak) signal is pumped by a (strong) one

$$E(t)=E_p\cos(\omega_p t)+ E_s\cos(\omega_s t)$$

It generates

- Second harmonics (SHG)
- Sum frequency
- Different frequency or Parametric Down Conversion (PDC)







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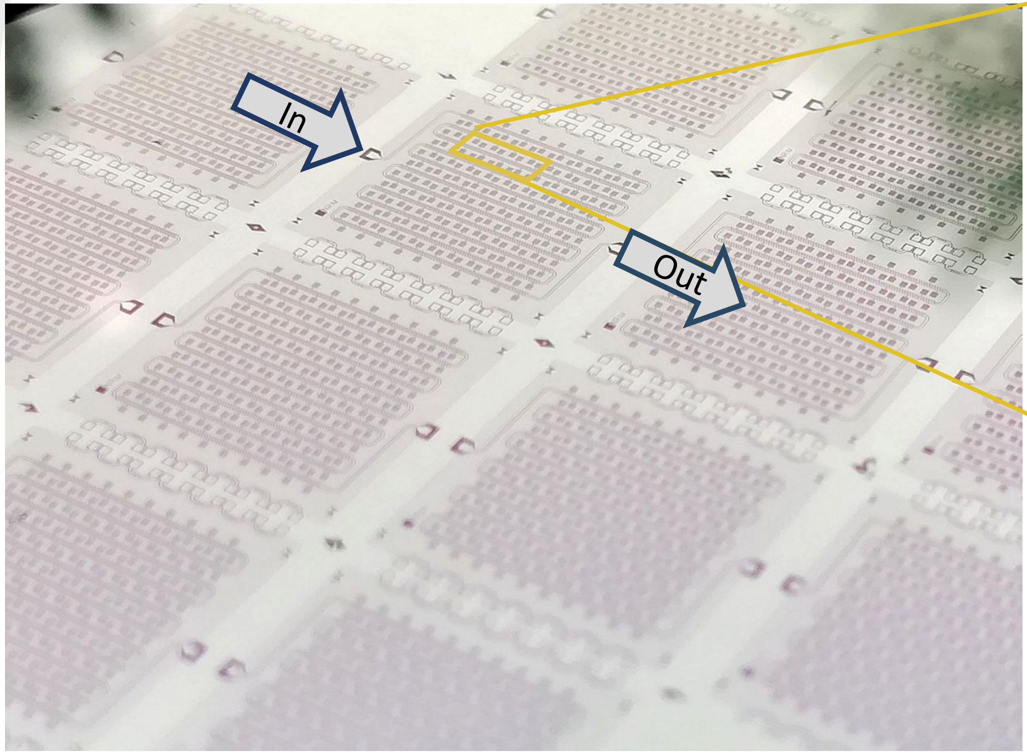
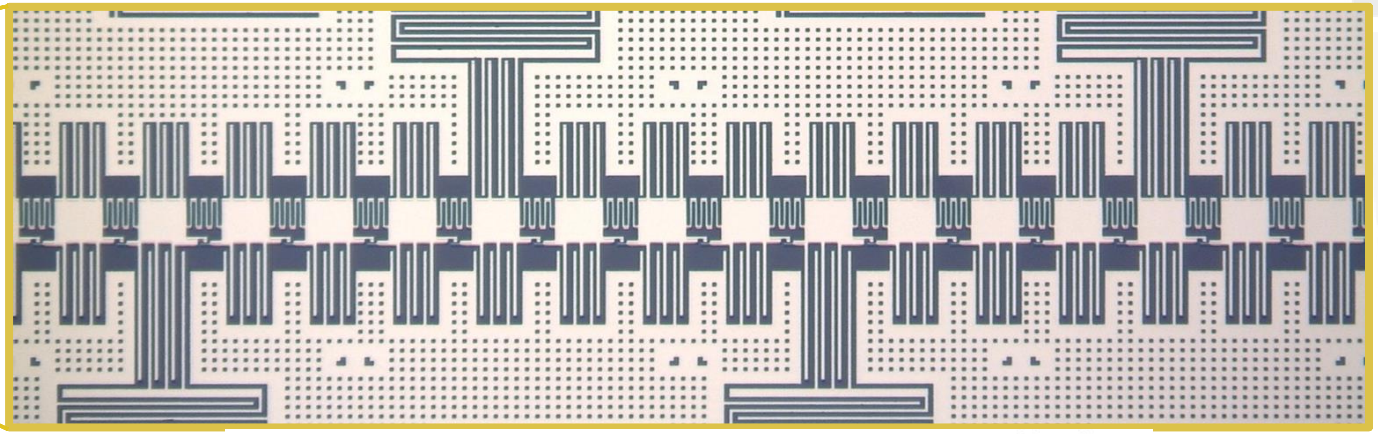
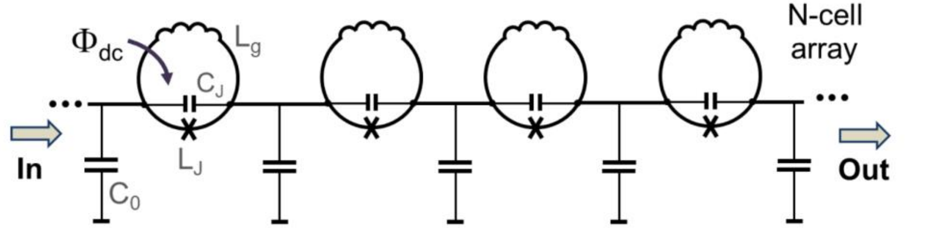
# Nonlinear (meta) materials - µWaves

- Transmission line (eg. CPW or stripline) + **identical** meta-atom (with JJ nonlinearity)
- Effects of the interaction with the single cell are perturbative -> avoid abrupt changes that acts like point defects or scattering sites (crystal analogy)

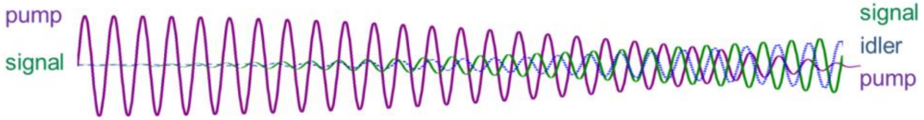


S. Pagano et al., *Development of Quantum Limited Superconducting Amplifiers for Advanced Detection*, IEEE Trans. Appl. Supercond, **32**, 4 (2022)



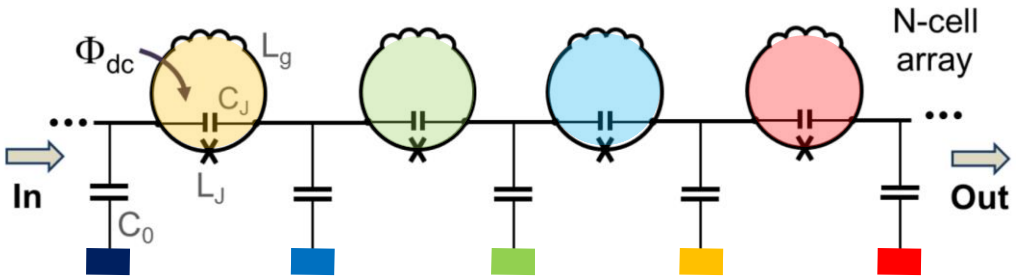

Very small phase mismatch $\Rightarrow$ almost exponential gain, $\sqrt{G} \propto e^{gN}$

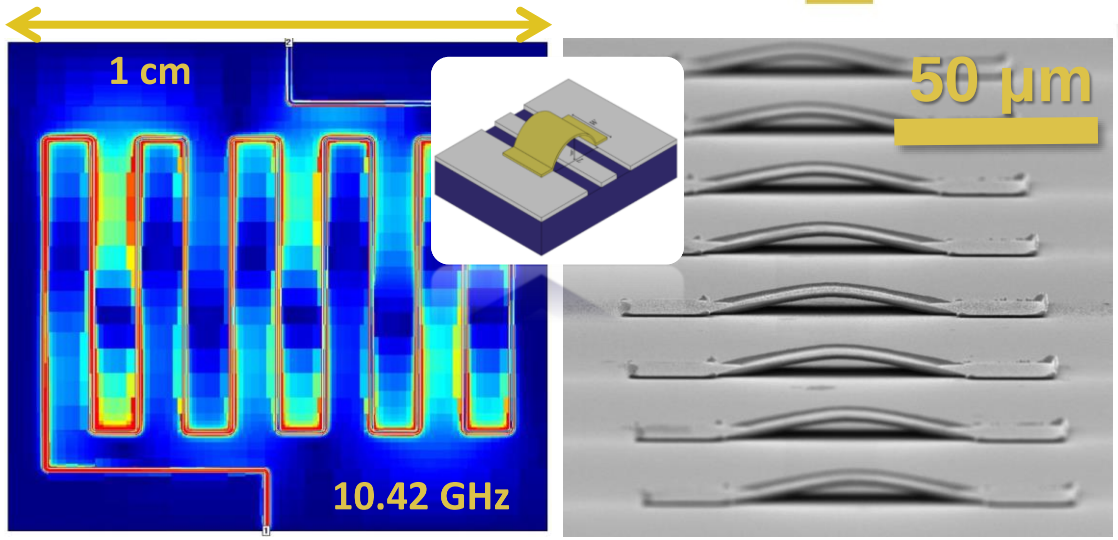


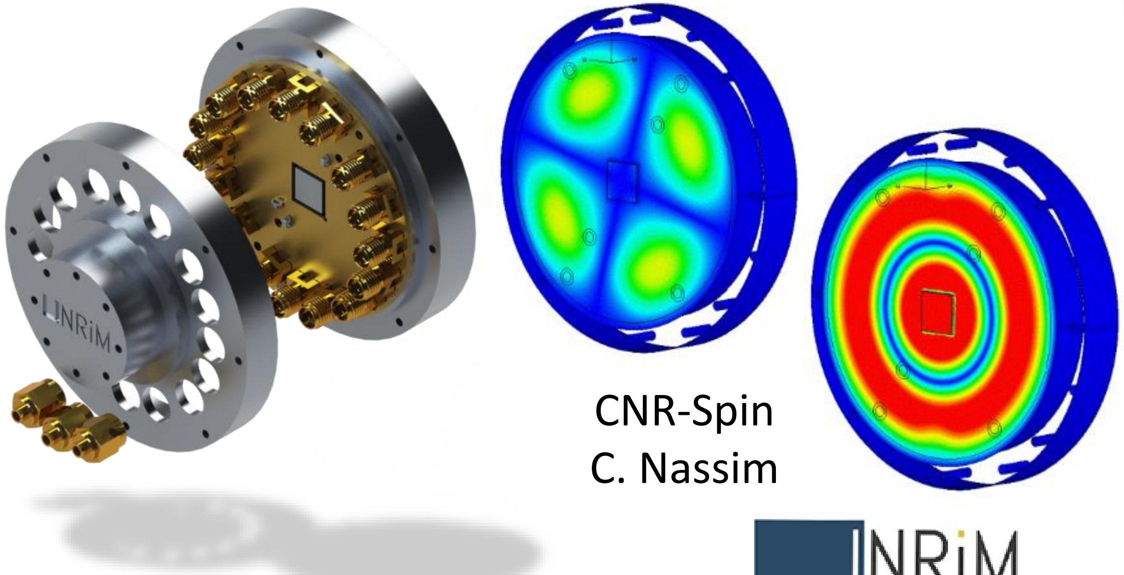

Zorin, *Phys. Rev. Appl.* **6**, 034006 (2016)

# Transmission lines peculiarities

- Packed CPW/stripline
- Influenced by substrate/dielectrics choice
  **materials** losses (eg. TLS)
- Total size vs. chip size
  **slotline** modes -> Airbridges
- Chip and connectors size influence packaging
  **cavity** modes




CNR-Spin
C. Nassim

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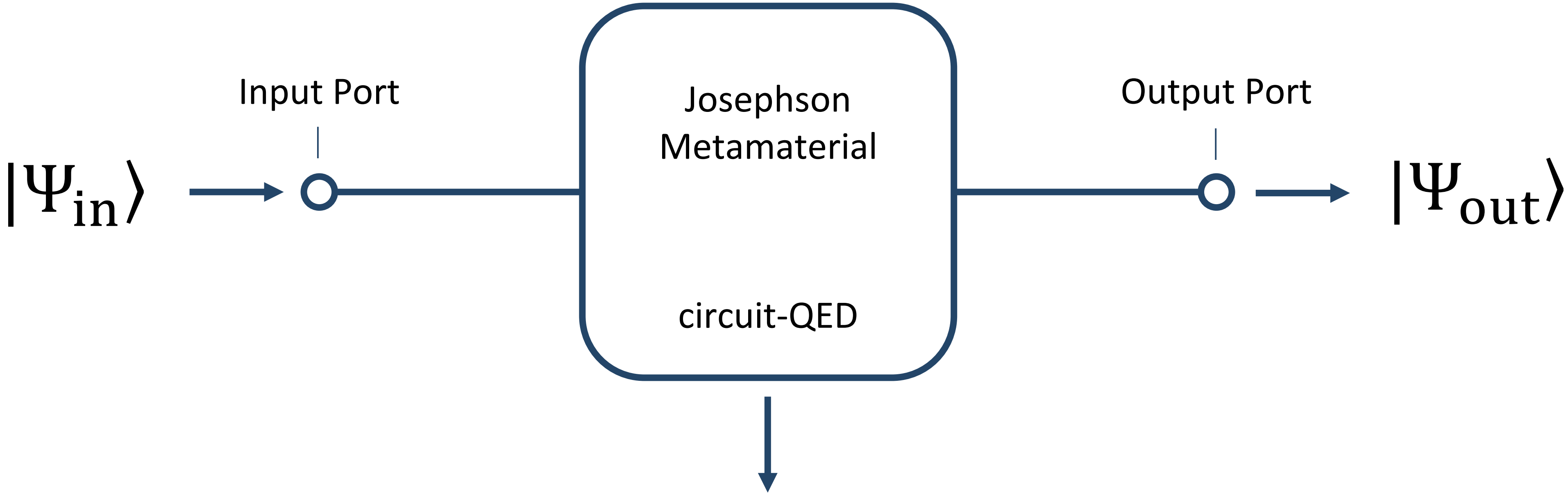
# Modelling



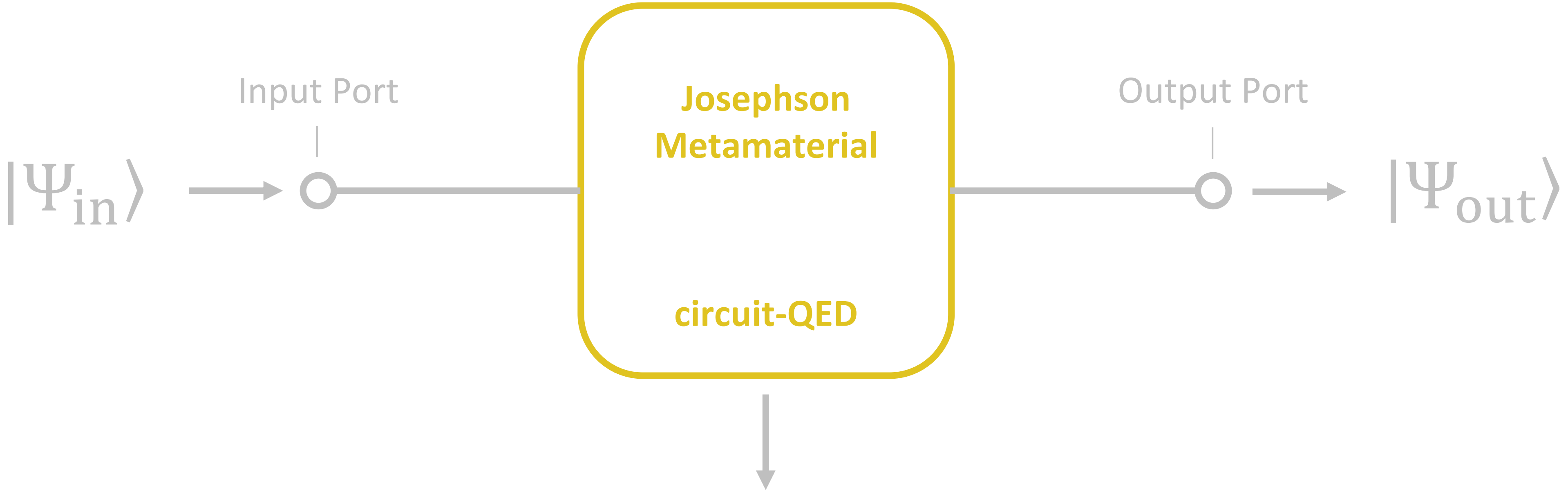

Classic observables:

- Gain
- Noise Figure
- Noise Temperature

Quantum behavior:

- Occupancy probability distribution

# Modelling




Classic observables:

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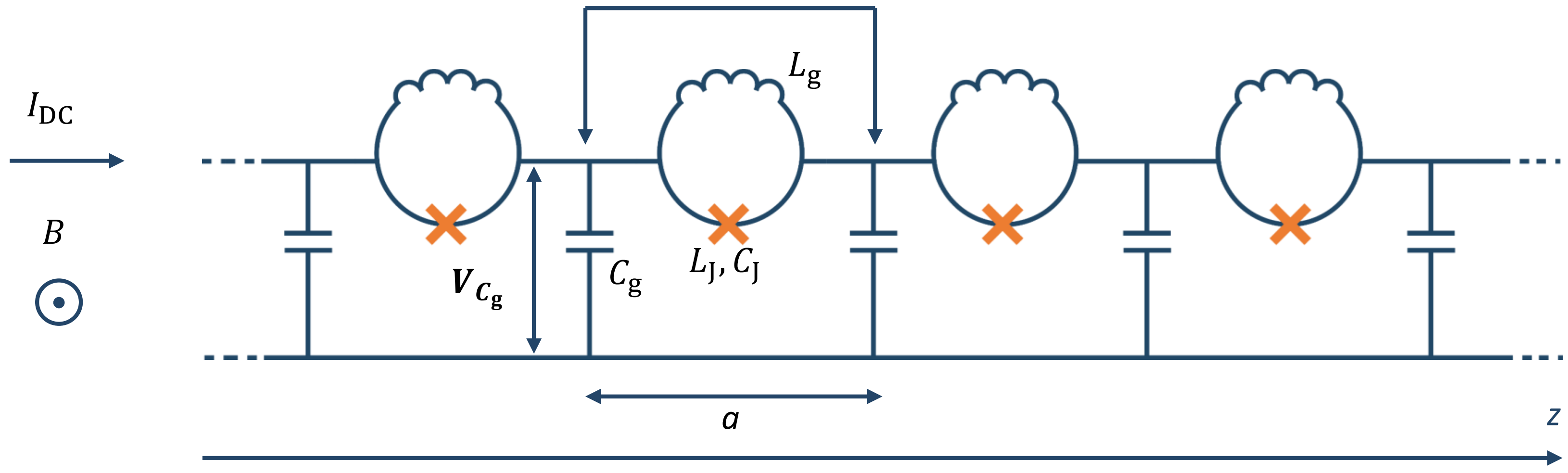
# First Quantization Hamiltonian

We adapt and further extend the work presented in [1] to an **rf-SQUID based Josephson Traveling Wave Parametric Amplifier** [2]

$$\Delta\Phi(z,t) = \Delta\Phi_{DC} + \delta\Phi(z,t)$$




$\Delta\Phi_{DC}$ is the **constant** flux difference due to external bias

$\delta\Phi(z,t)$ is the **time-dependent** flux difference induced by the travelling waves

The **first quantization Hamiltonian** can be written as the sum of the electromagnetic energy stored in each component of the transmission line

$$H = \frac{1}{a}\int_0^{aN} \left[\frac{1}{2L_g}\Delta\Phi(z,t)^2 + \varphi_0 I_c\left(1 - \cos\left(\frac{\Delta\Phi(z,t)}{\varphi_0}\right)\right) + \frac{C_J}{2}\left(\frac{\partial\Delta\Phi(z,t)}{\partial t}\right)^2 + \frac{C_g}{2}V_{C_g}^2(z,t)\right] dz$$


[1] T. H. A. van der Reep, "Mesoscopic Hamiltonian for Josephson traveling-wave parametric amplifier", Phys. Rev. A **99**, 063838 (2019)
[2] A. B. Zorin, "Josephson Traveling-Wave Parametric Amplifier with Three-Wave Mixing", Phys. Rev. App. **6**, 034006 (2016)

# Second Quantization Hamiltonian

$$H(\delta\Phi, V_{C_g}) \xrightarrow[V_{C_g} = V_{C_g}(\hat{a}_n, \hat{a}_n^\dagger)]{\delta\Phi = \delta\Phi(\hat{a}_n, \hat{a}_n^\dagger)} \hat{H}(\hat{a}_n, \hat{a}_n^\dagger)$$

First Quantization

Second Quantization

# Second Quantization Hamiltonian

The Hamiltonian describes all the **energy preserving interactions** between 3 or 4 traveling waves (i.e., the **parametric down conversion**, the **sum frequency generation**, the **high order harmonics generation**, etc.. )

$$H = \hbar\chi_0 + \sum_n \hbar\chi_1^{(n)}\left(\hat{a}_n^\dagger \hat{a}_n + \frac{1}{2}\right) + \sum_{n,l,m} \hbar\,\chi_3^{(n,l,m)}\{\hat{a} + \hat{a}^\dagger\}_{n,l,m} \cdot \delta_{\Delta_{n,l,m},0} + \sum_{n,l,m,s} \hbar\,\chi_4^{(n,l,m,s)}\{\hat{a} + \hat{a}^\dagger\}_{n,l,m,s} \cdot \delta_{\Delta_{n,l,m,s},0}$$

Energy from **external bias**

Energy of the **propagating waves**

All 3-wave mixing energy-preserving processes

All 4-wave mixing energy-preserving processes

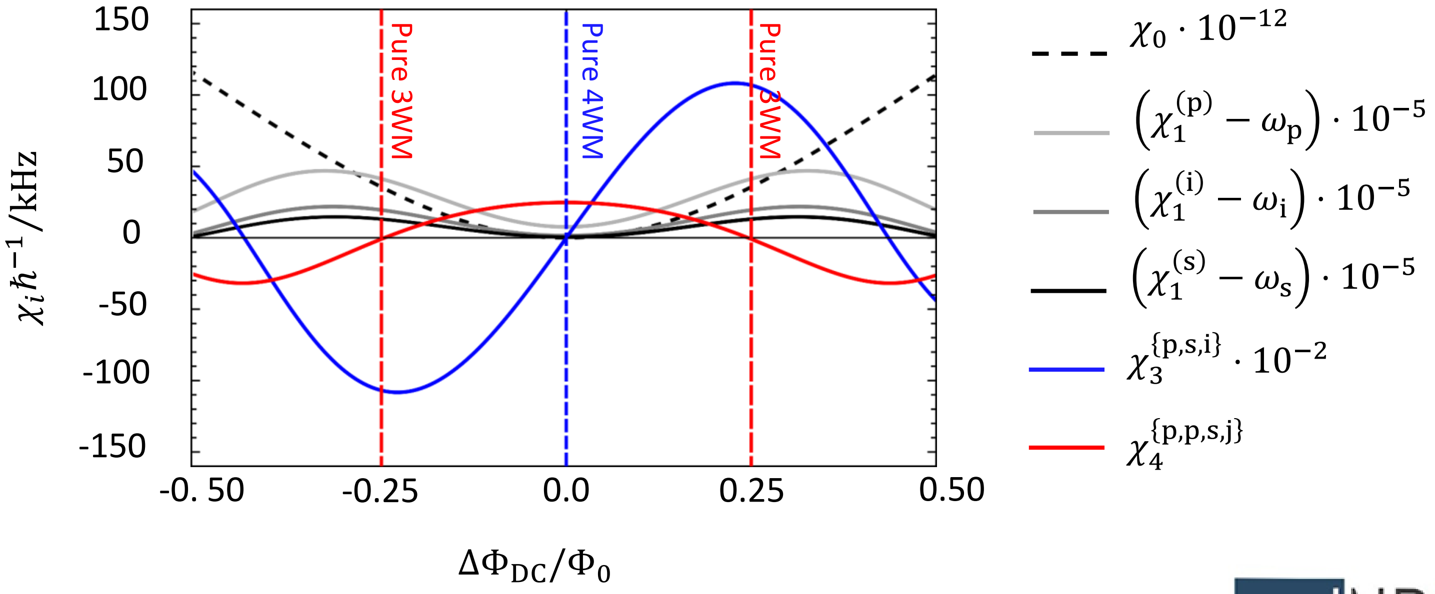
For **parametric down-conversion**

- **3WM** $n, l, m = \{\mathrm{p,s,i}\}$

  with $\omega_\mathrm{p} = \omega_\mathrm{s} + \omega_\mathrm{i}$

- **4WM** $n, l, m, s = \{\mathrm{p,s,j}\}$

  with $2\omega_\mathrm{p} = \omega_\mathrm{s} + \omega_\mathrm{j}$

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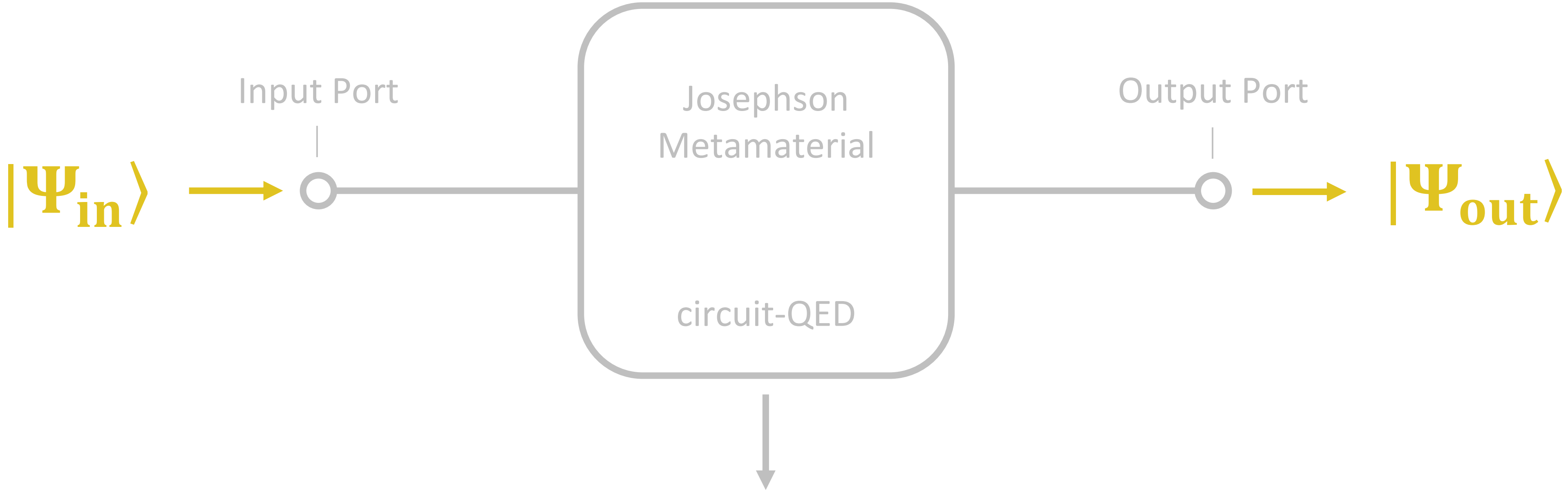
# Quantum states evolution




Classic observables:

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# CMEs from Heisenberg Equation

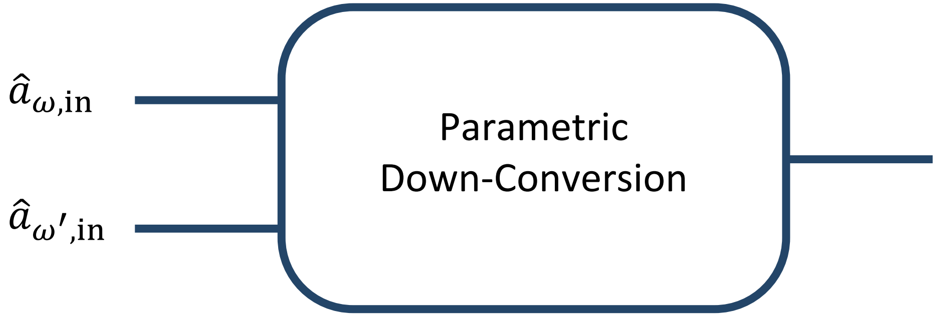
Selecting a proper bias condition, the amplifier can work as a pure 3-Wave Mixer or 4-Wave Mixer ($H_{3WM}$, $H_{4WM}$).
In this condition the **evolution of propagating modes** can be derived solving the **Heisenberg equation**:

$$\frac{d\hat{a}_n}{dt} = \frac{i}{\hbar}\left[H_{3WM(4WM)}, \hat{a}_n\right] + \frac{\partial \hat{a}_n}{\partial t} \qquad \text{where } n = \{\mathrm{p,s,i,j}\}$$

Under the **undepleted and classical pump** approximation, the output field at the **signal frequency ω** is:

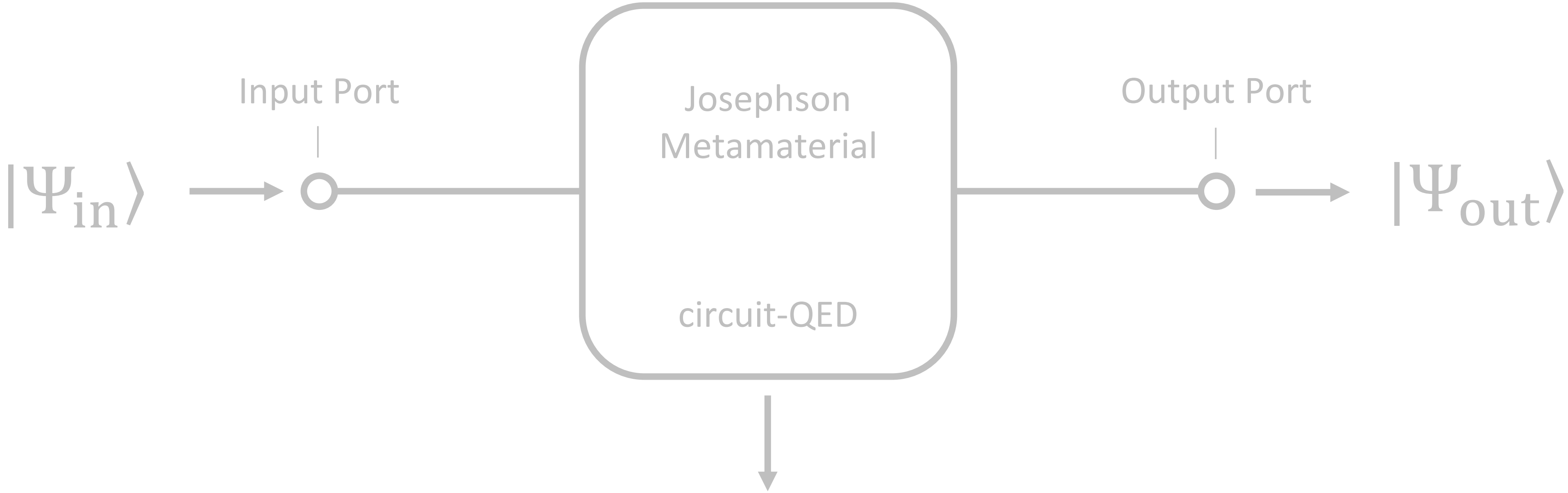
$$\hat{a}_\omega(t) = \left[\left(\cosh(gt) + \frac{i\Psi}{2g}\sinh(gt)\right)\hat{a}_{\omega,\mathrm{in}} - \left(\frac{i\Upsilon}{g}\sinh(gt)\right)\hat{a}^{\dagger}_{\omega',\mathrm{in}}\right] e^{-i\left(\frac{\Psi}{2}\right)t}$$

where $g$ is the ***complex gain factor***, $\Psi$ is the ***density phase mismatch*** and $\Upsilon$ is the ***interaction parameter***.




$$\hat{a}_{\omega,\mathrm{out}} = u(\omega)\hat{a}_{\omega,\mathrm{in}} - v(\omega)\hat{a}^{\dagger}_{\omega',\mathrm{in}}$$

# Classical quantities




**Classic observables:**

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# Signal photon number at output

$$\langle \hat{n}_{\omega,out}\rangle = \langle \hat{a}^{\dagger}{}_{\omega,\,\mathrm{out}}\, \hat{a}_{\omega,\mathrm{out}}\rangle =$$

$$= |u(\omega)|^2 \langle \hat{n}_{\omega,\,\mathrm{in}}\rangle + |v(\omega)|^2 \langle \hat{n}_{\omega',\mathrm{in}}\rangle + i\left(u^*(\omega)v(\omega)\left\langle \hat{a}^{\dagger}_{\omega,\mathrm{in}}\, \hat{a}^{\dagger}_{\omega',\mathrm{in}}\right\rangle - u(\omega)v^*(\omega)\left\langle \hat{a}_{\omega',\mathrm{in}}\, \hat{a}_{\omega,\mathrm{in}}\right\rangle\right) + |v(\omega)|^2$$

**Amplification** of the input field at ω frequency

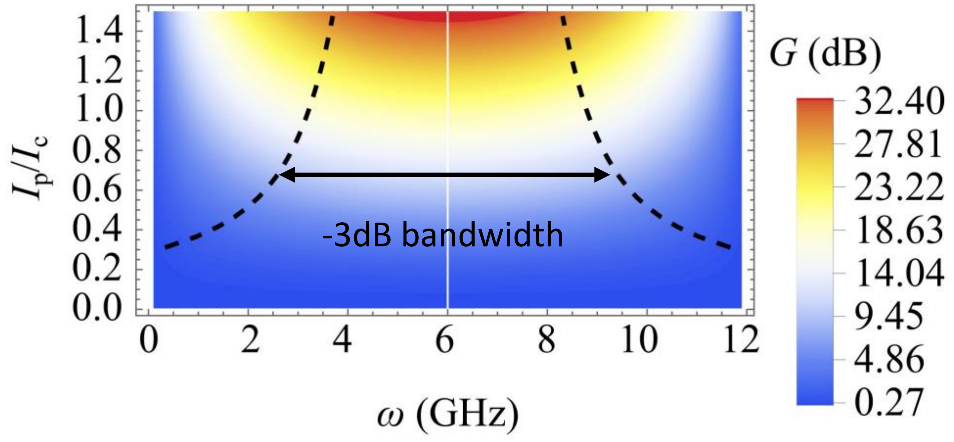
**Contribution** to the amplification of the **input field at ω** frequency due to the presence of an input signal at **ω' frequency**

Contribution from the **spontaneous annihilation** of a pump photon

Contribution from the **spontaneous creation** of a pump photon

**Added noise photons** $(\langle \mathrm{vac}|\hat{n}_{\omega,out}|\mathrm{vac}\rangle)$

$$G(\omega) \equiv \frac{\langle \hat{n}_{\omega,\mathrm{out}}\rangle}{\langle \hat{n}_{\omega,\mathrm{in}}\rangle} = |u(\omega)|^2$$

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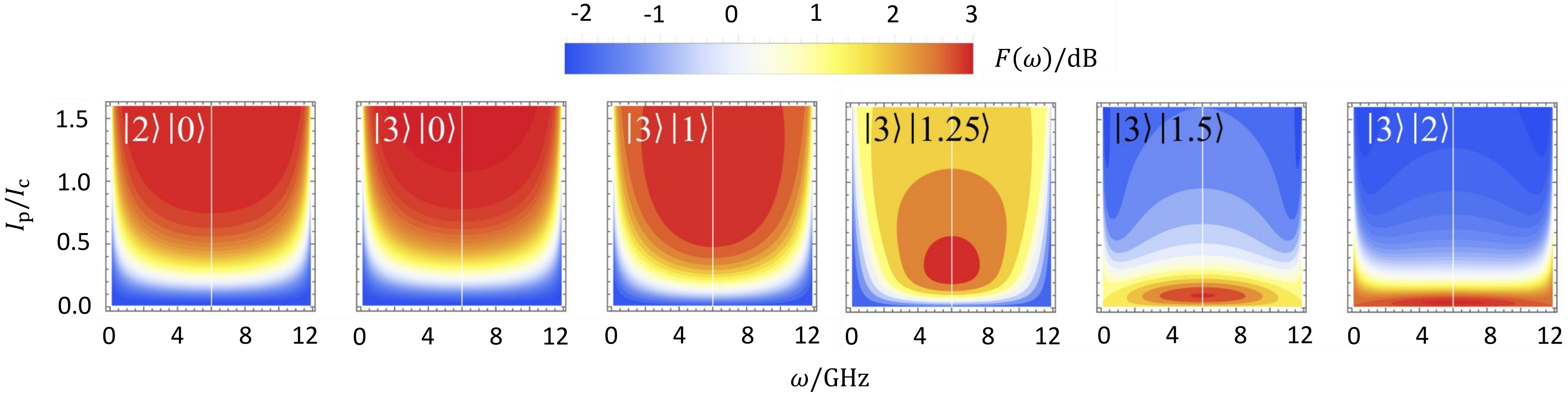
# Noise figure and Signal to Noise Ratio

$$F(\omega) \equiv \frac{\mathrm{SNR_{in}}(\omega)}{\mathrm{SNR_{out}}(\omega)} \qquad \mathrm{SNR_{in}}(\omega) \equiv \frac{\langle \hat{n}_{\omega,\mathrm{in}} \rangle^2}{\left\langle (\Delta \hat{n}_{\omega,in})^2 \right\rangle} \qquad \mathrm{SNR_{out}}(\omega) \equiv \frac{\langle \hat{n}_{\omega,\mathrm{out}} \rangle^2 - \langle \hat{n}^{\mathrm{vac}}_{\omega,\mathrm{out}} \rangle^2}{\left\langle (\Delta \hat{n}_{\omega,\mathrm{out}})^2 \right\rangle}$$ [4]

Variance of the input/output photon number

Supposing at the input a **Bimodal Coherent state**: $|\Psi_C\rangle = D(\alpha_\omega)|0_\omega\rangle D(\alpha_{\omega'})|0_{\omega'}\rangle = |\alpha_\omega\rangle|\alpha_{\omega'}\rangle$




An **idler** tone at the input port **influences the Noise figure** $F(\omega)$ of the amplifier

[4] Z. Shi *et al.*, "Quantum noise properties of non-ideal optical amplifiers and attenuators", *J. Opt.* **13** (2011)



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# Noise Temperature

The **effective temperature $T_{\mathrm{eff}}(\omega)$** of the amplifier is the temperature that a **Bose-Einstein distribution** should have to equal the output $\omega$ mode occupancy generated by a vacuum input state [5]:

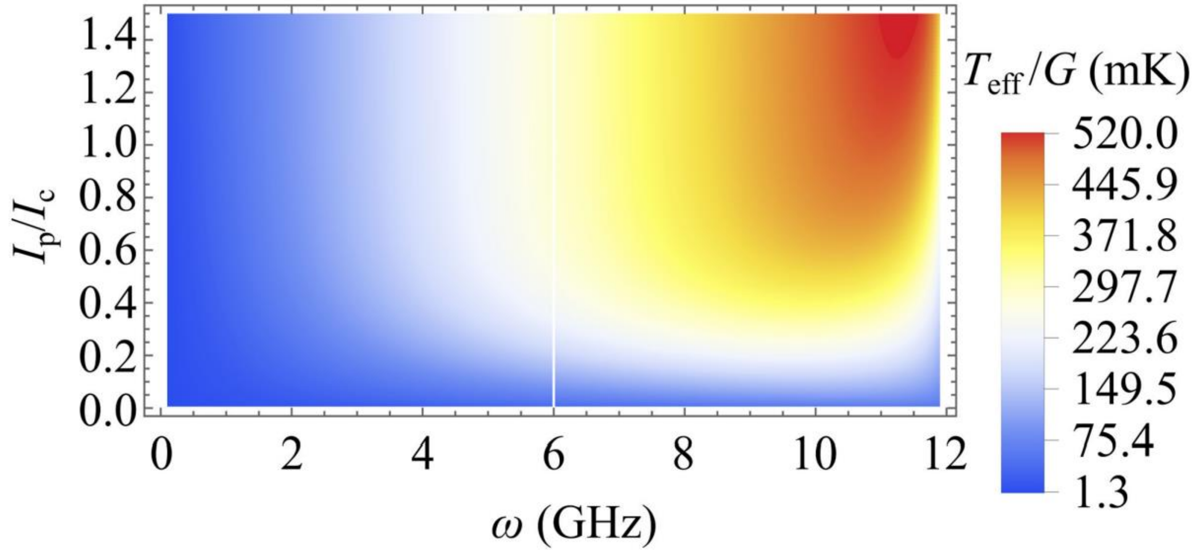
$$\frac{1}{e^{\hbar\omega/k_B T_{\mathrm{eff}}(\omega)} - 1} = |v(\omega)|^2$$

The **noise temperature $T_{\mathrm{n}}(\omega)$** is the effective temperature normalized on the gain minus the contribution given by the fluctuation of the input vacuum state:

$$T_{\mathrm{n}}(\omega) = \frac{T_{\mathrm{eff}}(\omega)}{G(\omega)} - \frac{1}{2}\frac{\hbar\omega}{k_B}$$

For high gain $T_{\mathrm{n}}(\omega)$ approaches the **Standard Quantum Limit**:

$$T_{\mathrm{n,SQL}} = \frac{1}{2}\frac{\hbar\omega}{k_B}$$





[5] A. A. Clerk *et al.*, "Introduction to quantum noise, measurement, and amplification", *Rev. Mod. Phys.* **82,** 1155 (2010)

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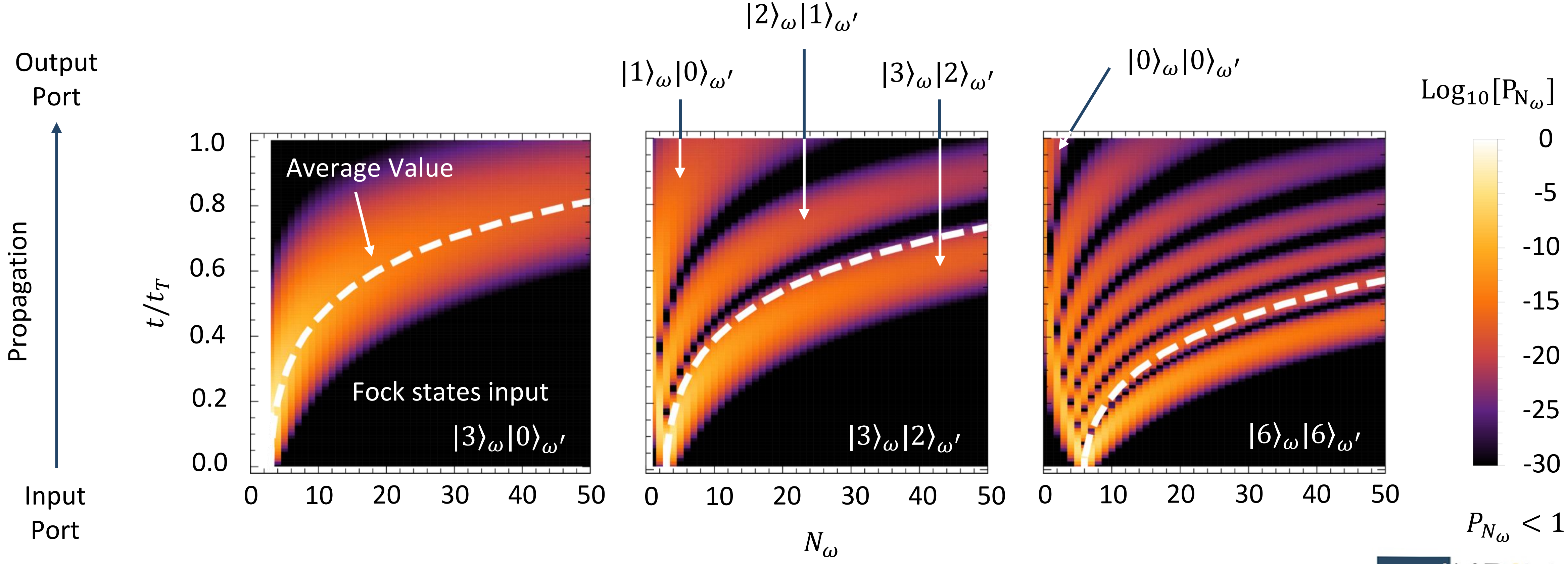
# Time-evolution of bimodal Fock states

The average photon number at frequency ω at a certain time *t* can be written in terms of the **probability $P_{N_\omega}$** to find $N_\omega$ photons at a given time

$$\langle n_\omega(t)\rangle = \sum_{N_\omega} P_{N_\omega}(t)\cdot N_\omega$$



# For more details …

PHYSICAL REVIEW B **104**, 184517 (2021)

**Quantum model for rf-SQUID-based metamaterials enabling three-wave mixing and four-wave mixing traveling-wave parametric amplification**

Angelo Greco and Luca Fasolo
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Alice Meda and Luca Callegaro
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Emanuele Enrico*
*INRiM, Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, 10135 Torino, Italy*
*and INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*

(Received 30 April 2021; revised 22 October 2021; accepted 25 October 2021; published 24 November 2021)

A quantum model for Josephson-based metamaterials working in the three-wave mixing (3WM) and four-wave mixing (4WM) regimes at the single-photon level is presented. The transmission line taken into account, namely Josephson traveling wave parametric amplifier (JTWPA), is a bipole composed of a chain of rf-SQUIDs, which can be biased by a DC current or a magnetic field to activate the 3WM or 4WM nonlinearities. The model exploits a Hamiltonian approach to analytically determine the time evolution of the system both in the Heisenberg and interaction pictures. The former returns the analytic form of the gain of the amplifier, while the latter allows recovering the probability distributions vs time of the photonic populatio[...] Fock and coherent input states. The dependence of the metamaterial's nonlinearities [...] circuit parameters in a lumped model framework while evaluating the effects of the [...] the model validity.

DOI: 10.1103/PhysRevB.104.184517

A. Greco *et al.*, Phys. Rev. B (2021)

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 4, JUNE 2022 1700306

**Bimodal Approach for Noise Figures of Merit Evaluation in Quantum-Limited Josephson Traveling Wave Parametric Amplifiers**

L. Fasolo, C. Barone, M. Borghesi, G. Carapella, A. P. Caricato, I. Carusotto, W. Chung, A. Cian, D. Di Gioacchino, E. Enrico, P. Falferi, M. Faverzani, E. Ferri, G. Filatrella, C. Gatti, A. Giachero, D. Giubertoni, A. Greco, Ç. Kutlu, A. Leo, C. Ligi, P. Livreri, G. Maccarrone, B. Margesin, G. Maruccio, A. Matlashov, C. Mauro, R. Mezzena, A. G. Monteduro, A. Nucciotti, L. Oberto, S. Pagano, V. Pierro, L. Piersanti, M. Rajteri, A. Rettaroli, S. Rizzato, Y. K. Semertzidis, S. Uchaikin, and A. Vinante

***Abstract*—The advent of ultra-low noise microwave amplifiers revolutionized several research fields demanding quantum-limited technologies. Exploiting a theoretical bimodal description of a linear phase-preserving amplifier, in this contribution we analyze some of the intrinsic properties of a model architecture (i.e., an rf-SQUID based Josephson Traveling Wave Parametric Amplifier) in terms of amplification and noise generation for key case study input states (Fock and coherent). Furthermore, we present an analysis of the output signals generated by the parametric amplification mechanism when thermal noise fluctuations feed the device.**

***Index** [...]ve photonics, noise figure, super[...]es.*

[...]N

[...]gress in several fields [...]um computation and [...][4], radio detection

the amplifier is considered as a two-ports black-box driven at a pump frequency $\omega_p$ that amplifies a bosonic input mode at frequency $\omega$. The amplification is associated with the creation of a second mode at frequency $\omega' = \omega_p - \omega$ (the so-called idler mode of a three-wave mixing parametric amplification [15]) that is commonly considered as an internal mode of the amplifier that causes the onset of noise at the output port. Here, we extend and give a different perspective of this description considering the case in which an uncorrelated idler mode is already present at the input port (i.e., considering a bimodal input field), analyzing the effect of the interaction between these modes inside the amplifier in terms of typical noise estimators. This operative condition may arise in real measurement setups where the amplifier is exploited, for instance, for the multiplexed readout of broadband signals [16] or for the joint detection and amplification of probing signals in a microwave quantum illumination

L. Fasolo *et al.*, IEEE TAS (2022)

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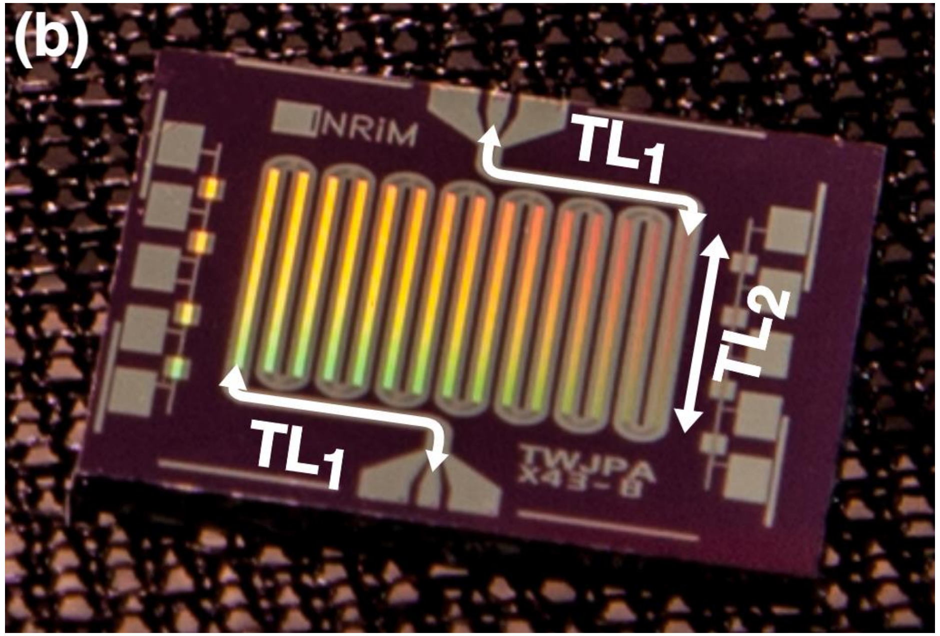
# Fabrication Example
# JTWPA – DARTWARS Project




Preliminary samples

- Poor impedance matching of TL1, TL2 and 50 Ω
- No dispersion engineering
- High Josephson Junctions parameters spread
- No sloline modes rejection techniques

DART WARS

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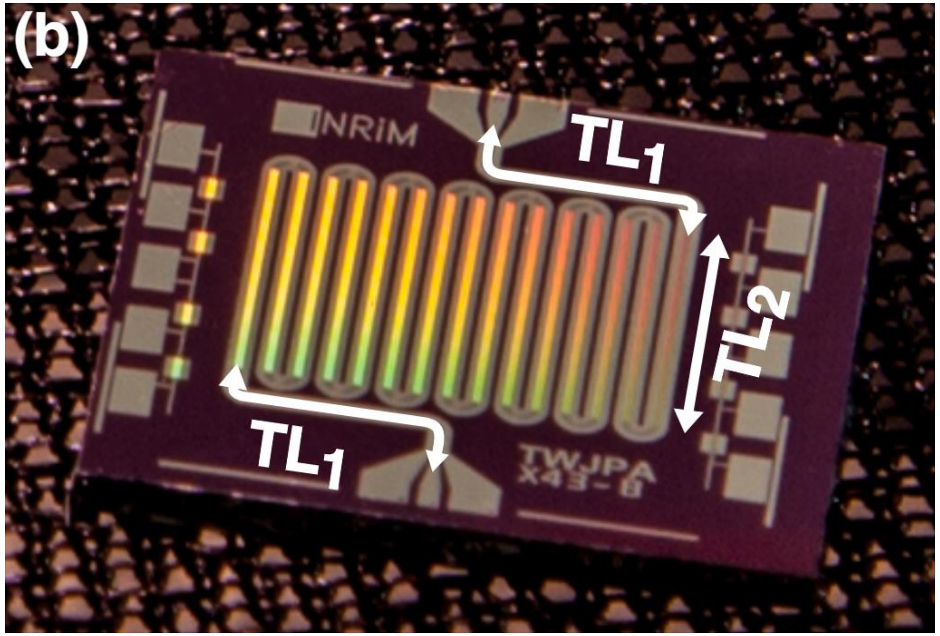
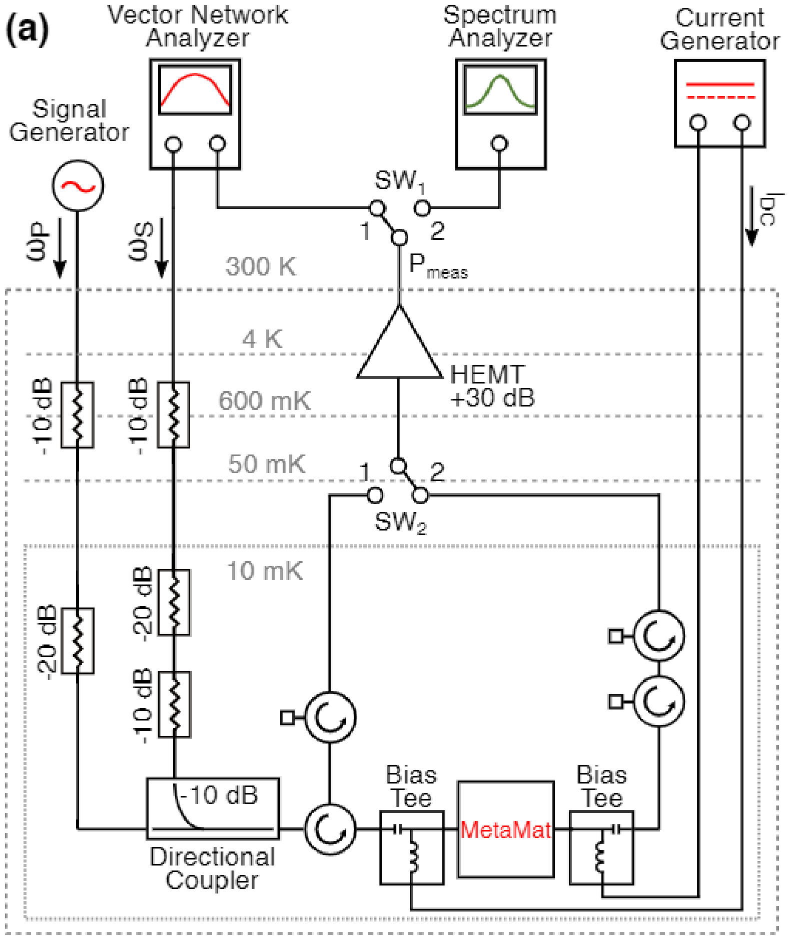
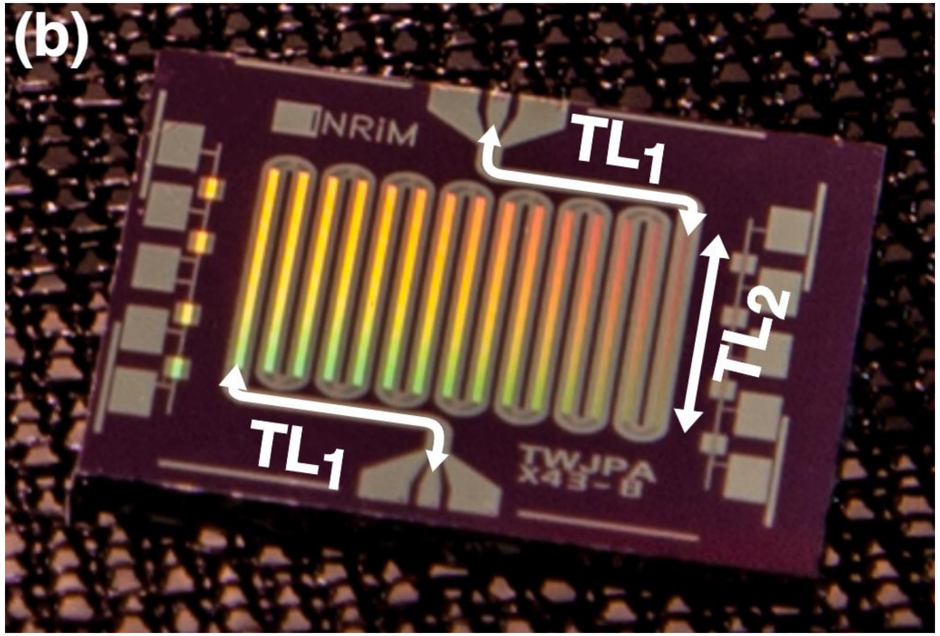
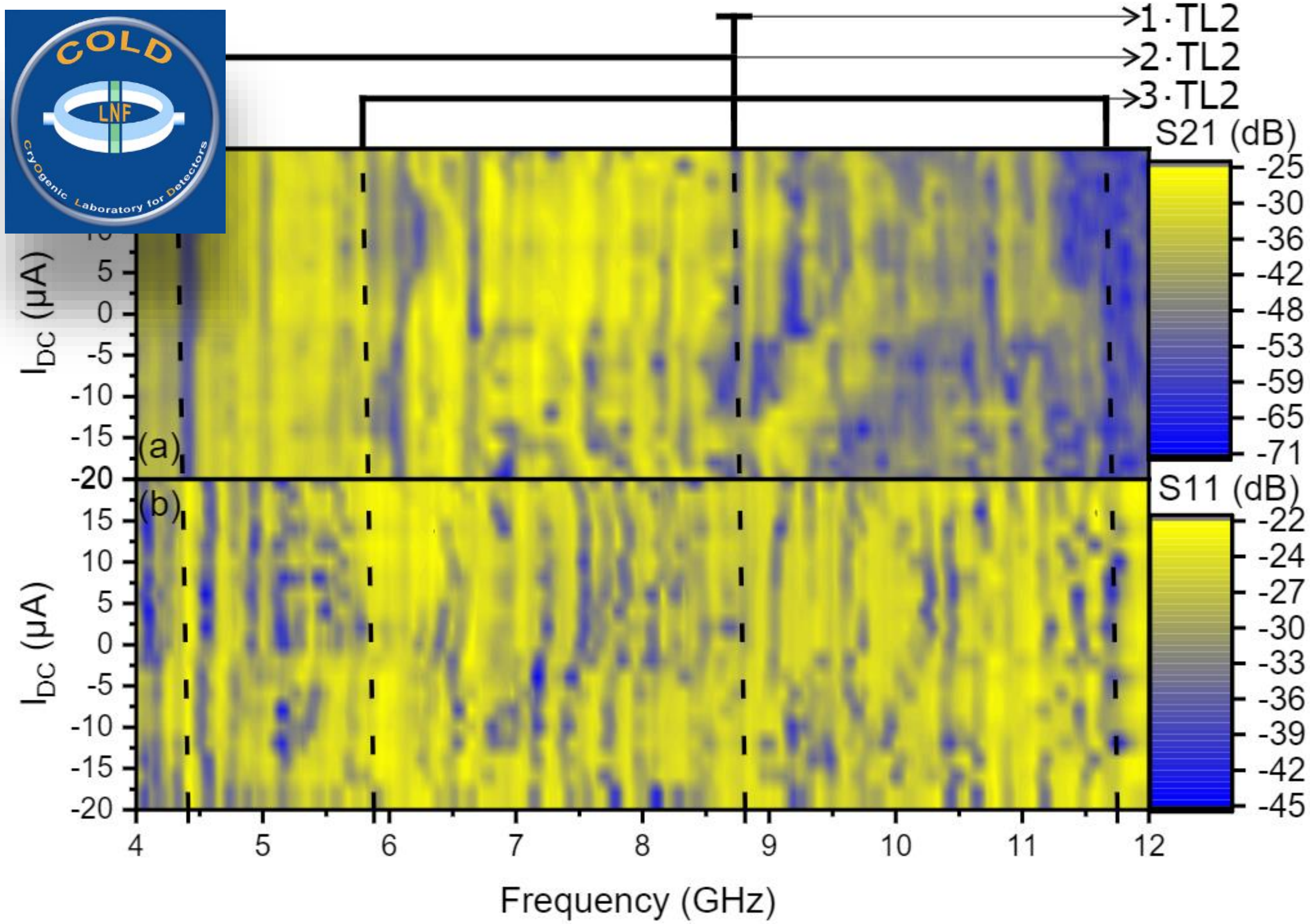
# JTWPA – DARTWARS Project



# Fabrication Example
# JTWPA – DARTWARS Project

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# Fabrication Example

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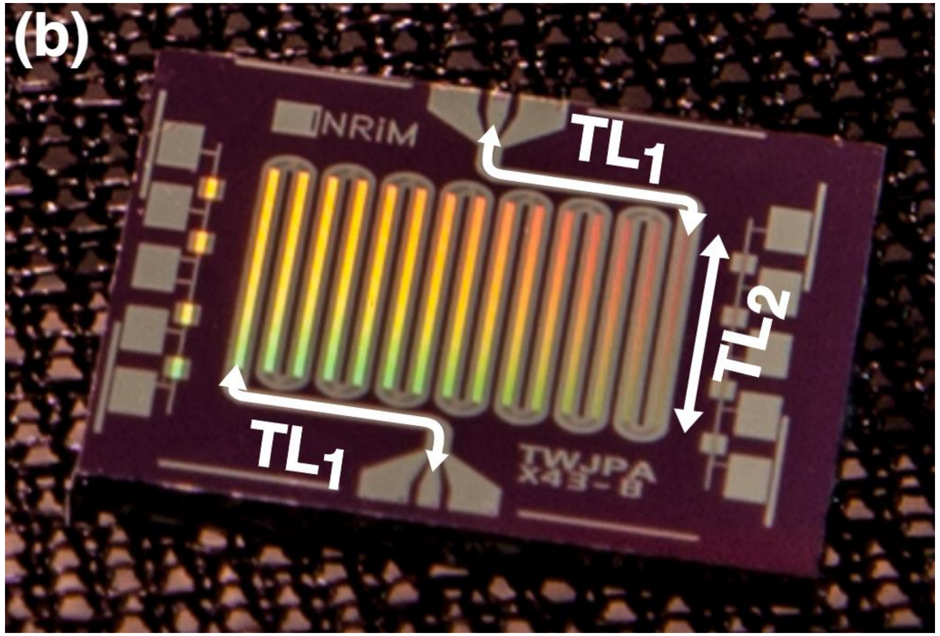
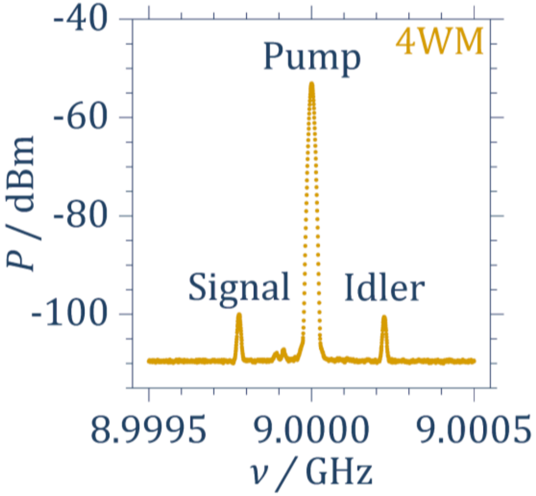
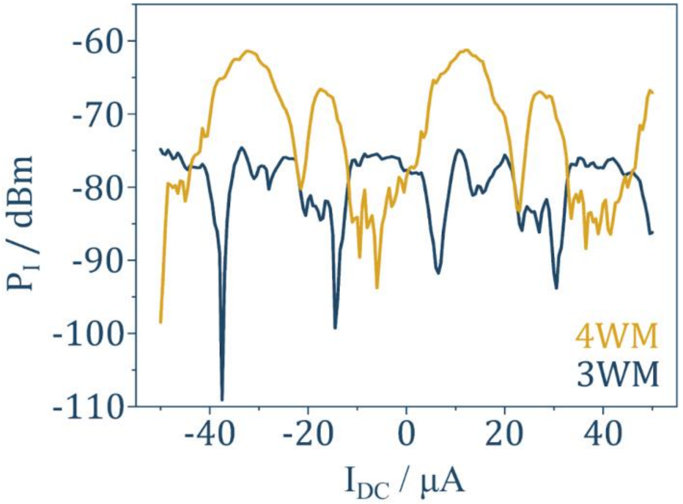
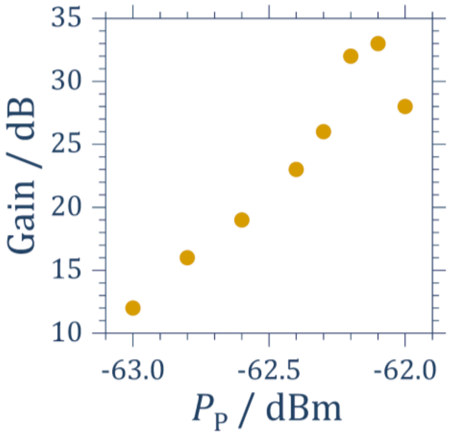
$\nu_p$ = 6.8 GHz
$\nu_s$ = 3.3 GHz
$\nu_{i,3WM}$ = 3.5 GHz   $\nu_{i,4WM}$ = 10.3 GHz

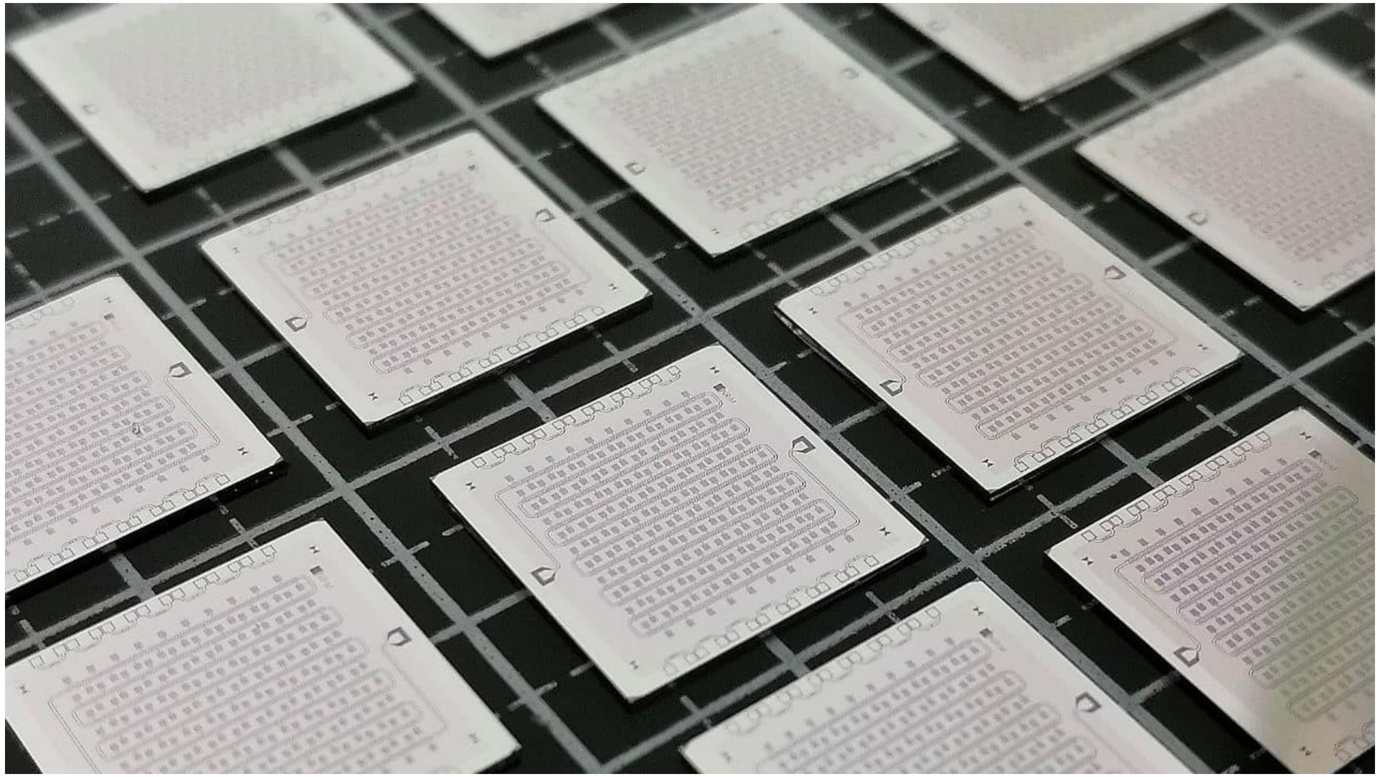


# Fabrication Example
# JTWPA – DARTWARS Project



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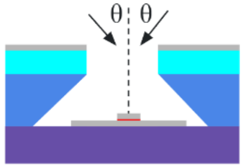
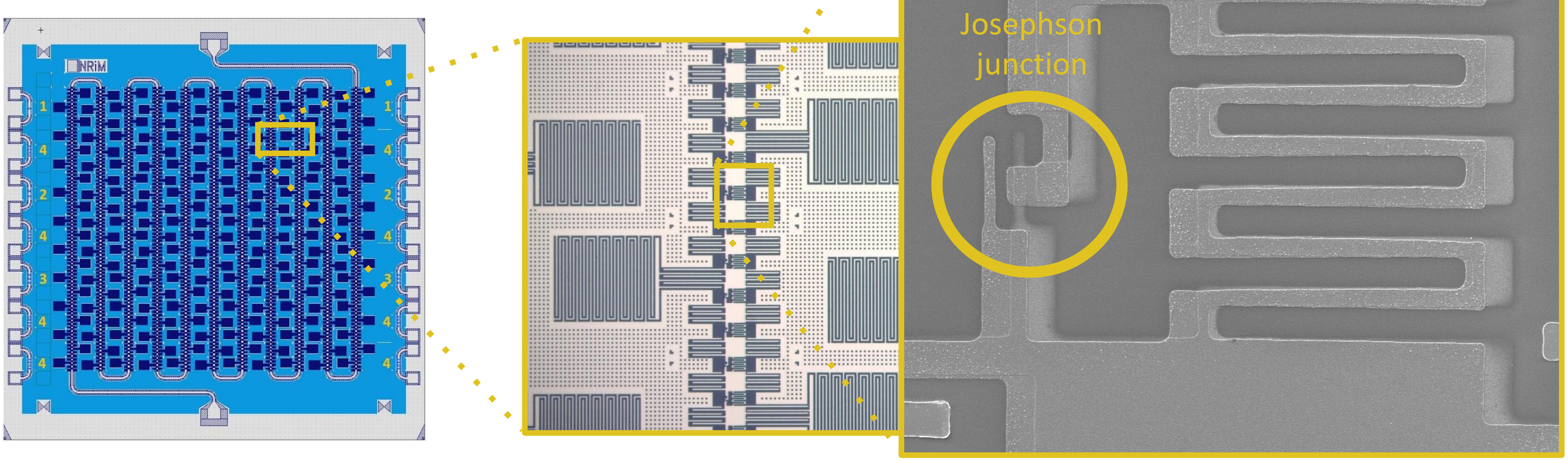
# Fabrication Example
# JTWPA – DARTWARS Project

Conventional double angle evaporation




S. Pagano et al., *Development of Quantum Limited Superconducting Amplifiers for Advanced Detection*, IEEE Trans. Appl. Supercond, **32**, 4 (2022)

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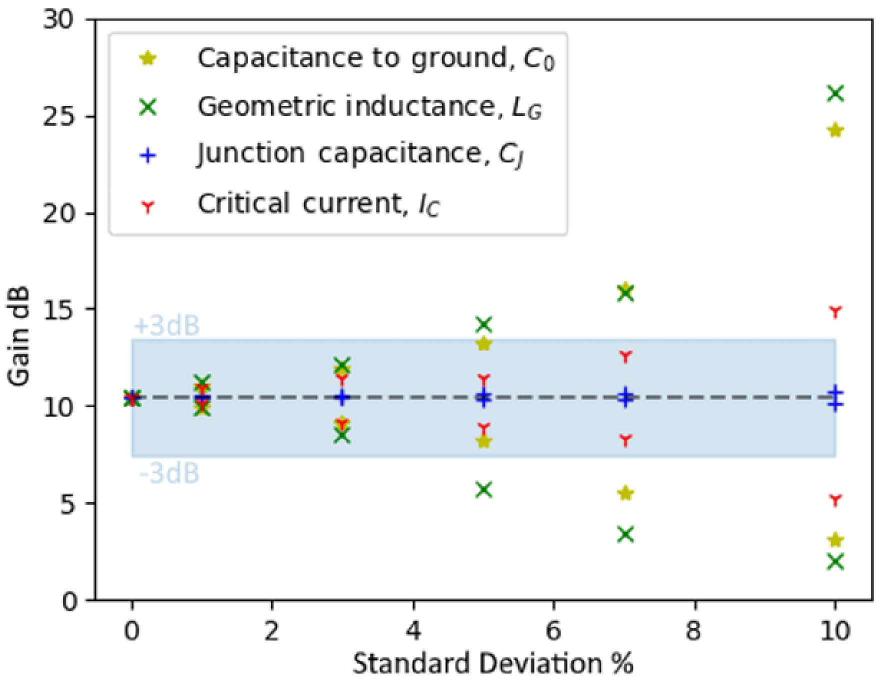
# The role of Josephson Junction parameters spread

- Josephson Junction **spread** of parameters deeply affect the amplifiers performances (eg. Gain)

- Due to the exponential dependence of its properties, Josephson tunnel junctions are the **bottleneck** of the whole JTWPAs operation




*The Effect of Parameter Variations on the Performance of the Josephson Travelling Wave Parametric Amplifiers, https://arxiv.org/abs/2112.07766*

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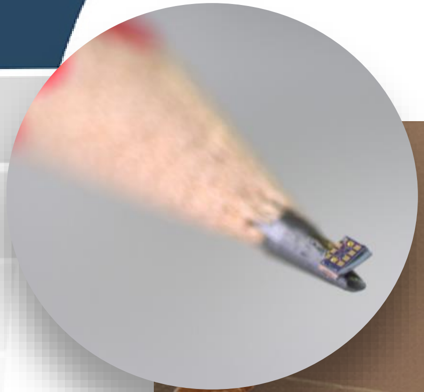
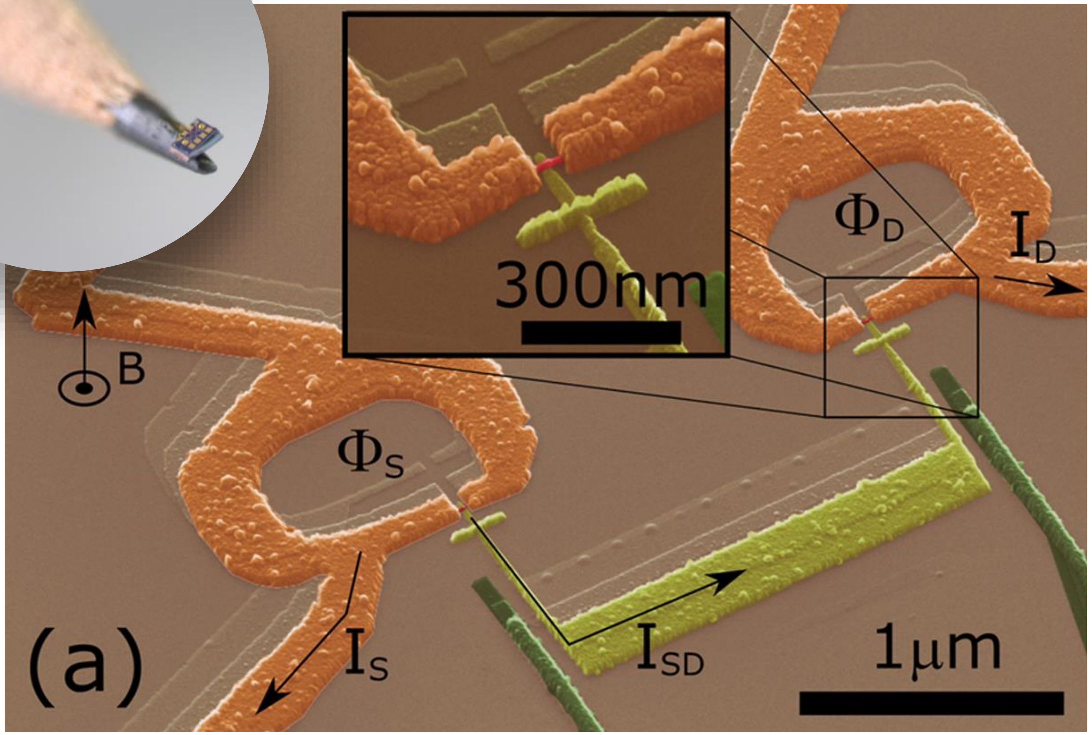
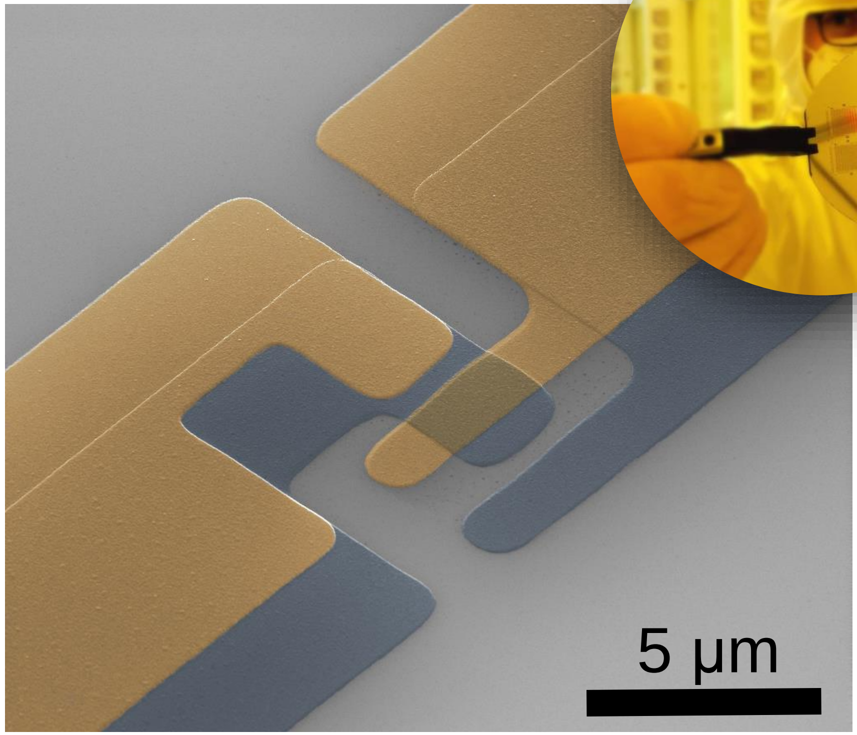
# Technological challange

Need for **reproducibility** and **stability** of Josephson Junctions on a large scale approach






E. Enrico, et al., *Single charge transport in a fully superconducting SQUISET locally tuned by self-inductance effects*, AIP Advances **12**, 055122 (2022)




UV shadow lithography based Josephson Junction

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# PiQuET Cleanroom facility

## 500 $m^2$ of ISO 5-6 laboratories




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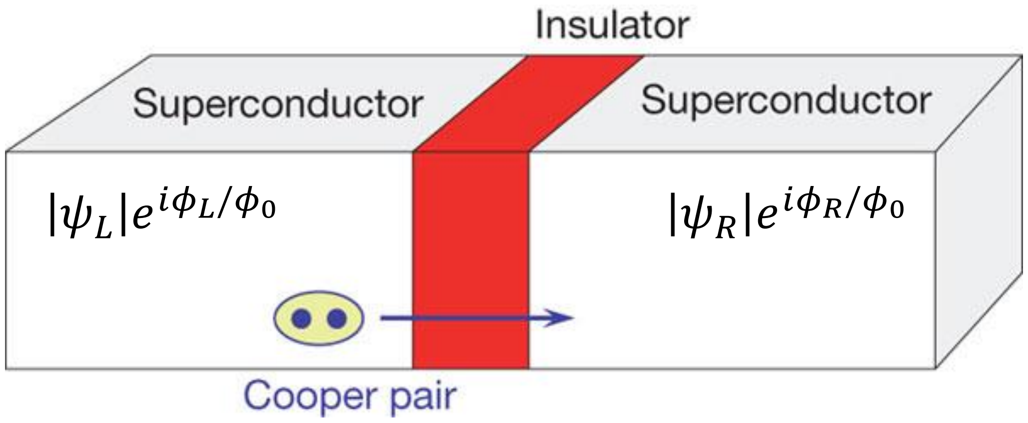
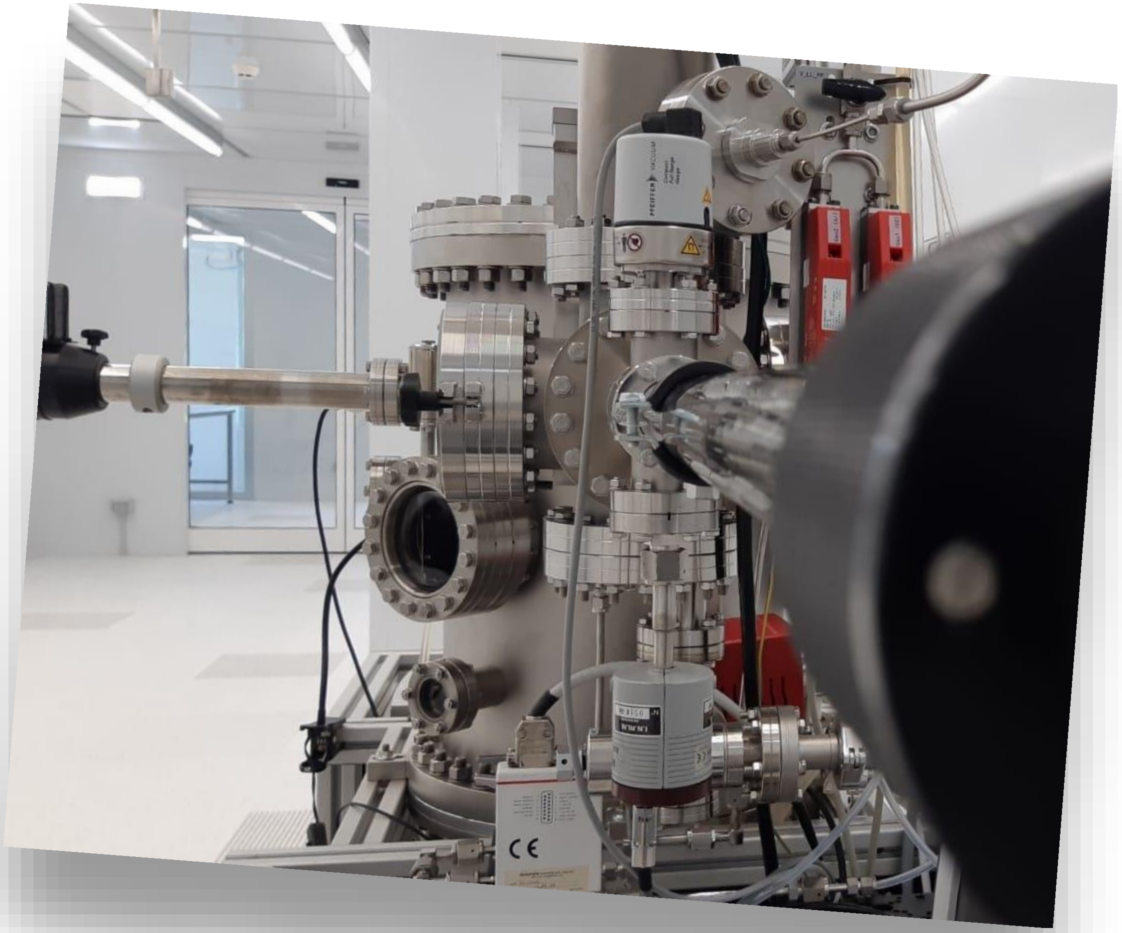
# Tunnel junctions in real life

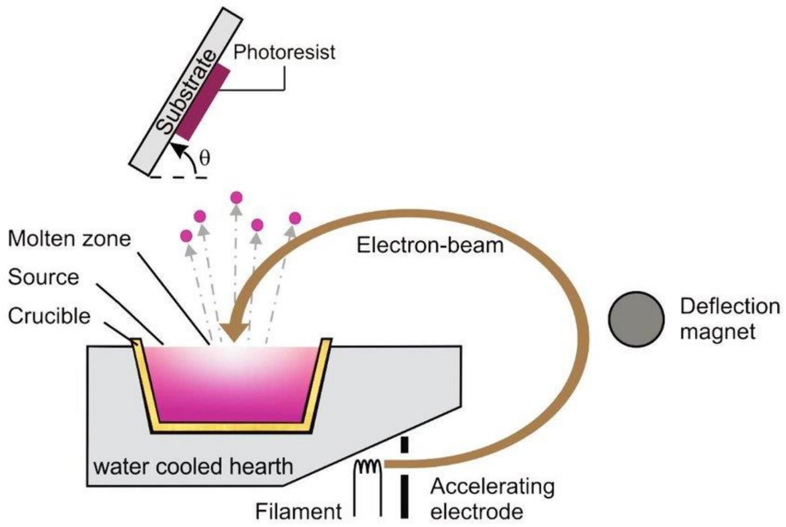



- Niobium technology
  Multi-step sputtering-based process
  (Nb/Al/AlOx/Nb Technique, '80)

- Aluminum technology
  Single step e-beam evap-based process
  (Niemeyer-Dolan Technique, 1987)



# Tunnel junctions in real life



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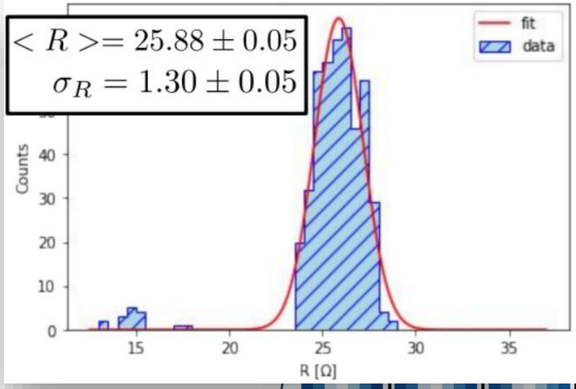
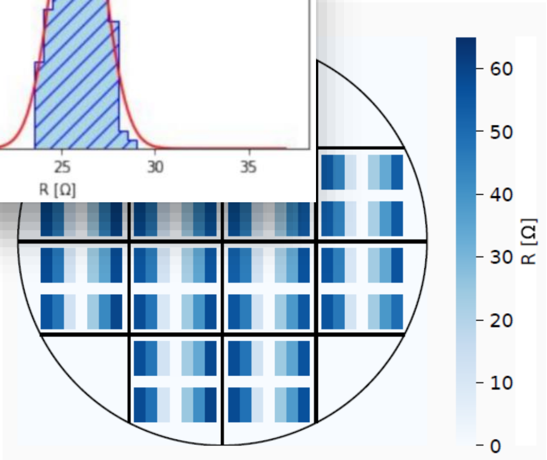
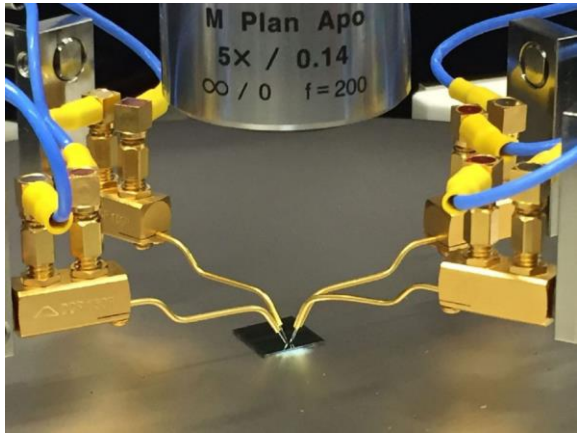
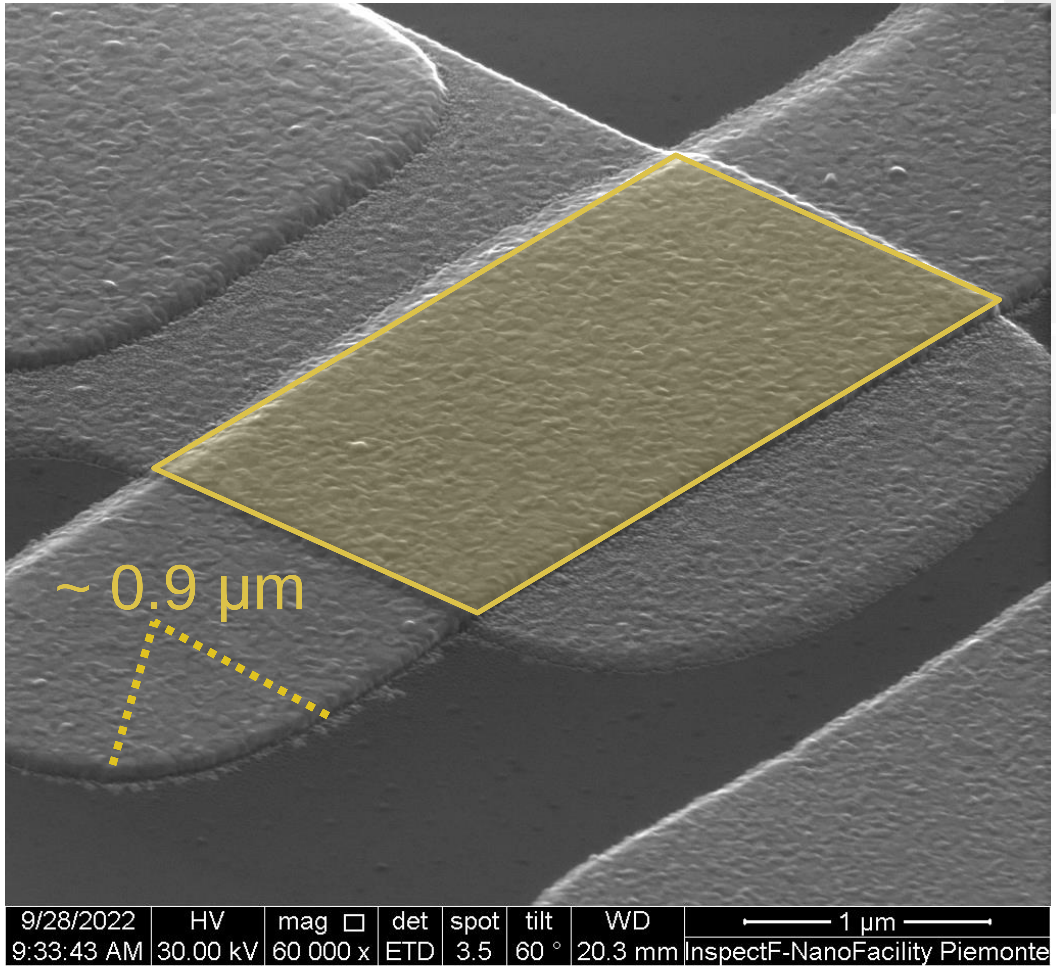
# UV shadow mask lithography

- Thick and robust mask
  - compatible with $O_2$ ashing process
  - reduced *hillocks* formation
  - increased dielectric barrier uniformity
- Compatible with low-conductivity substrates
- Reasonable fast and reproducible process on wafer-scale
  - tested with RT semi-automatic measurements on JJs series

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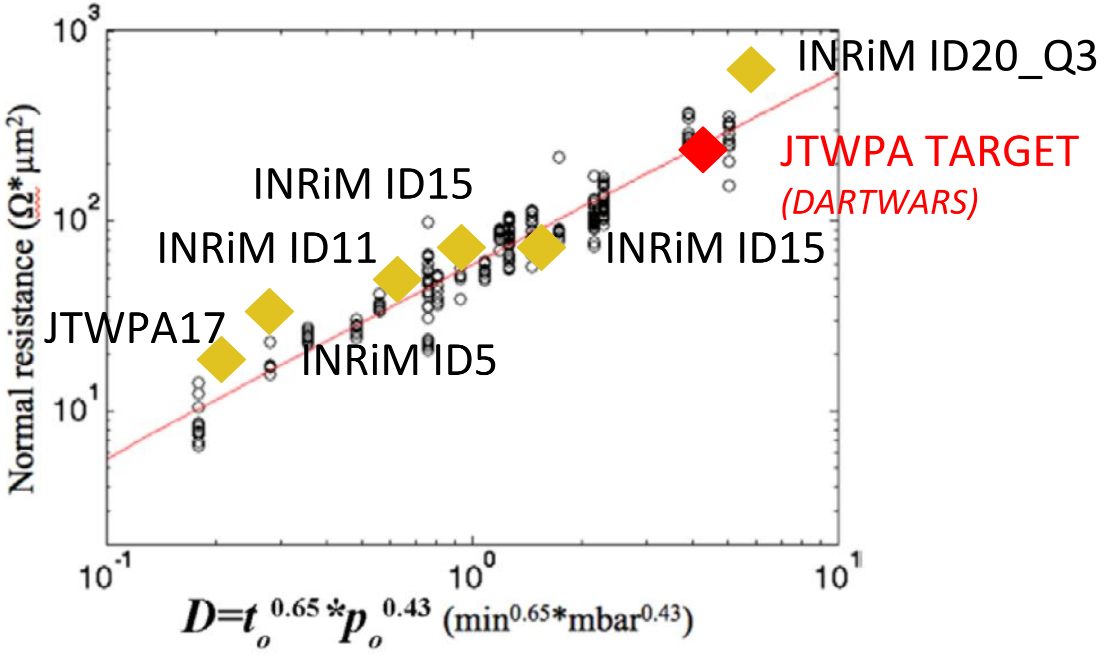
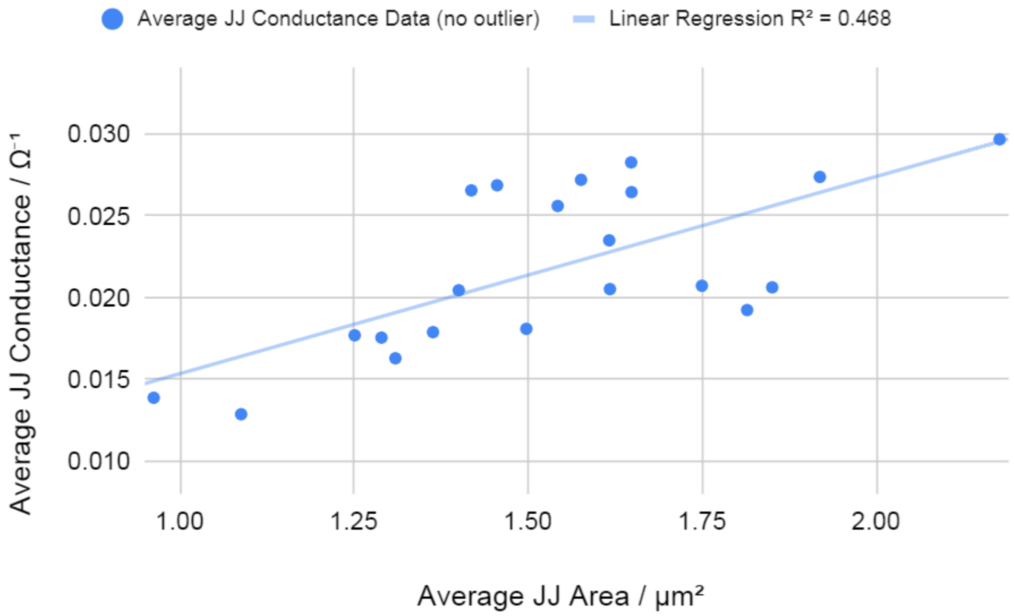
# Josephson Junctions - area/oxidation interplay

Calibration points following the model presented in L J Zeng *et al* 2015 *J. Phys. D: Appl. Phys.* **48** 395308)




Run to run predictability and repeatability

INRiM ID15 - Area vs. Conductance correlation




On-Wafer reproducibility and homogeneity

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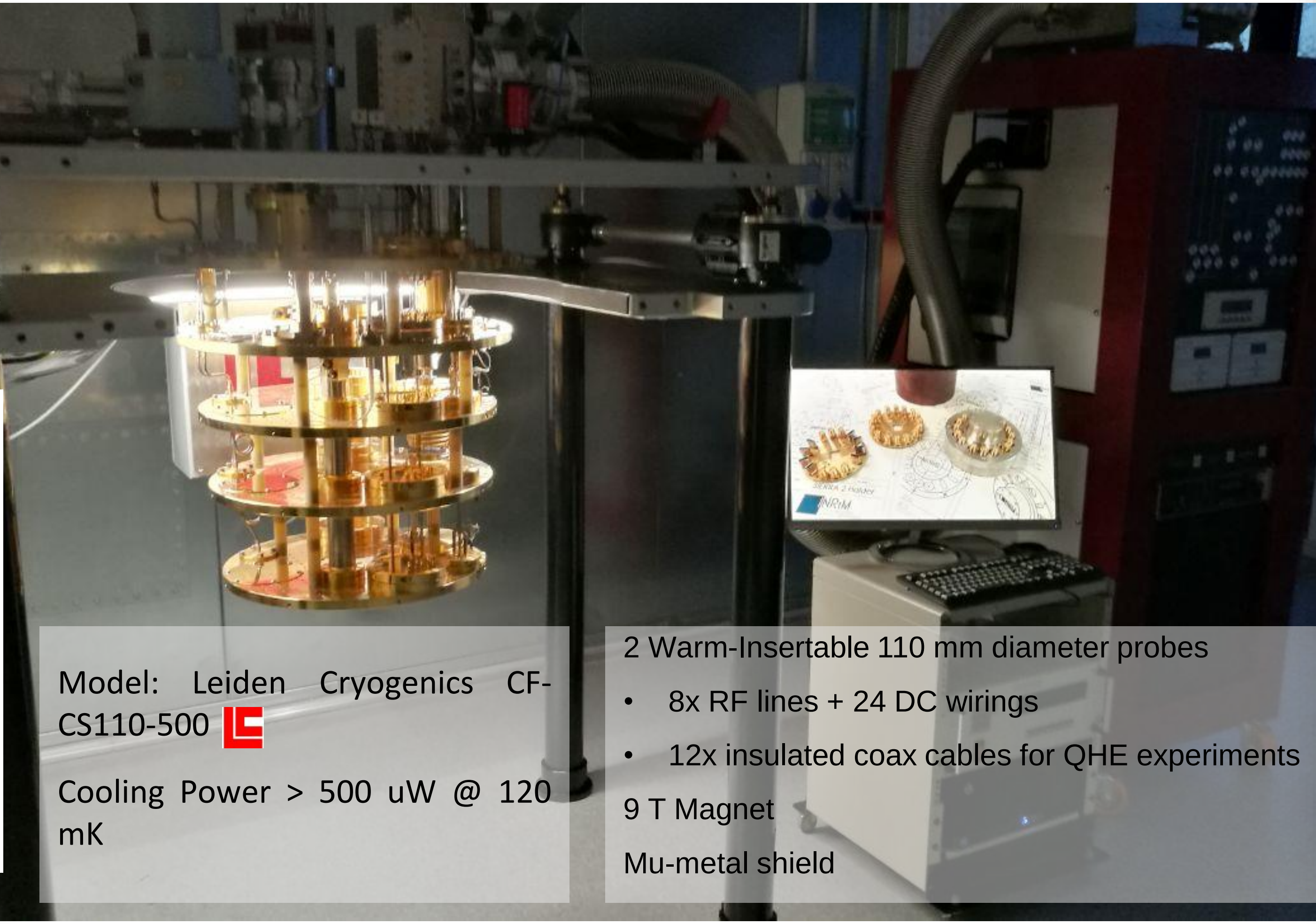
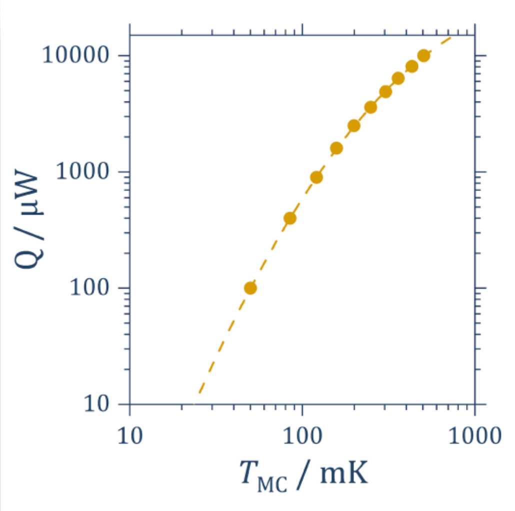
# Quantum Signals Processing Lab.






Model: Leiden Cryogenics CF-CS110-500

Cooling Power > 500 uW @ 120 mK

2 Warm-Insertable 110 mm diameter probes

- 8x RF lines + 24 DC wirings
- 12x insulated coax cables for QHE experiments

9 T Magnet

Mu-metal shield

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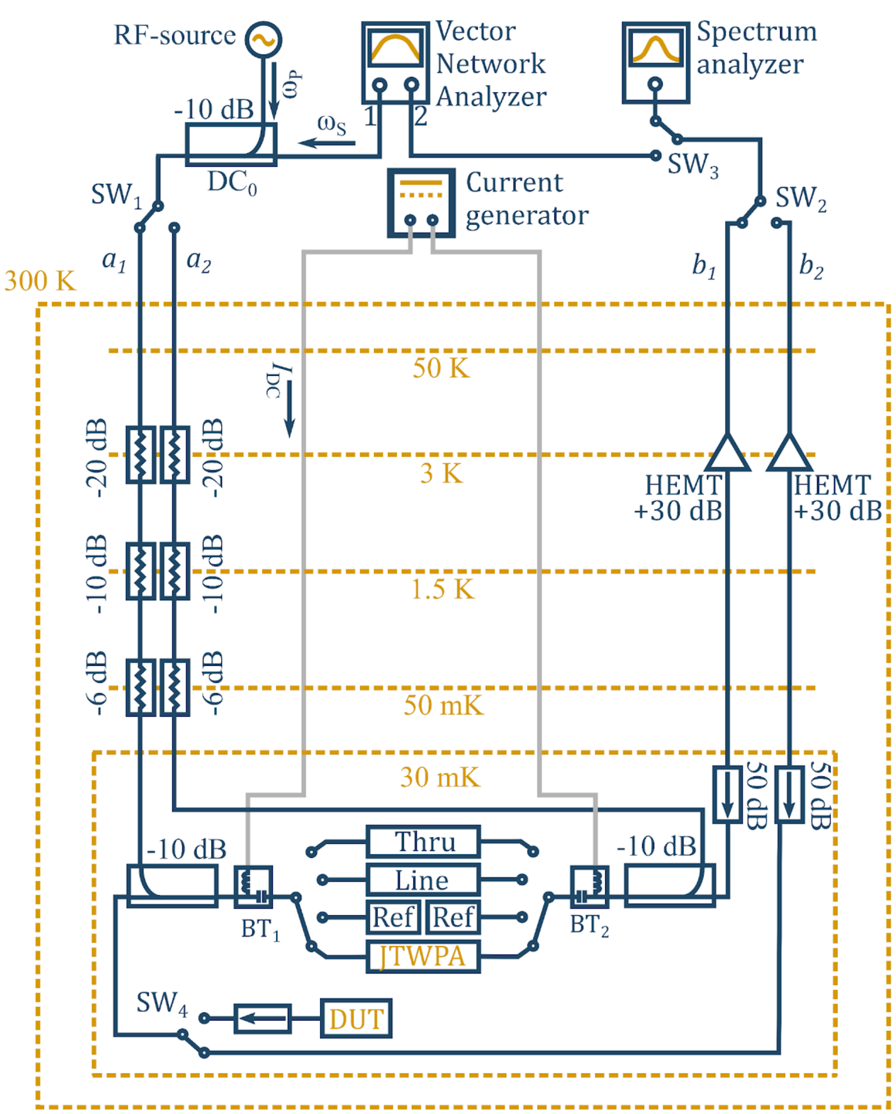
# Quantum Signals Processing Lab.




Two-ports microwave **S-parameters calibration** scheme at cryogenic temperature

Uncertainty budget contributions:
- Reproducibility
- Stability
- Standards

SuperQuant

Luca Oberto (INRiM)

**Microwave metrology for superconducting quantum circuits (20FUN07 SuperQuant)**

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Ranzani L., Spietz L., Popovic Z., *and* Aumentado J., “Two-port microwave calibration at millikelvin temperatures”, *Review of Scientific Instruments* **84**, 034704 (2013)

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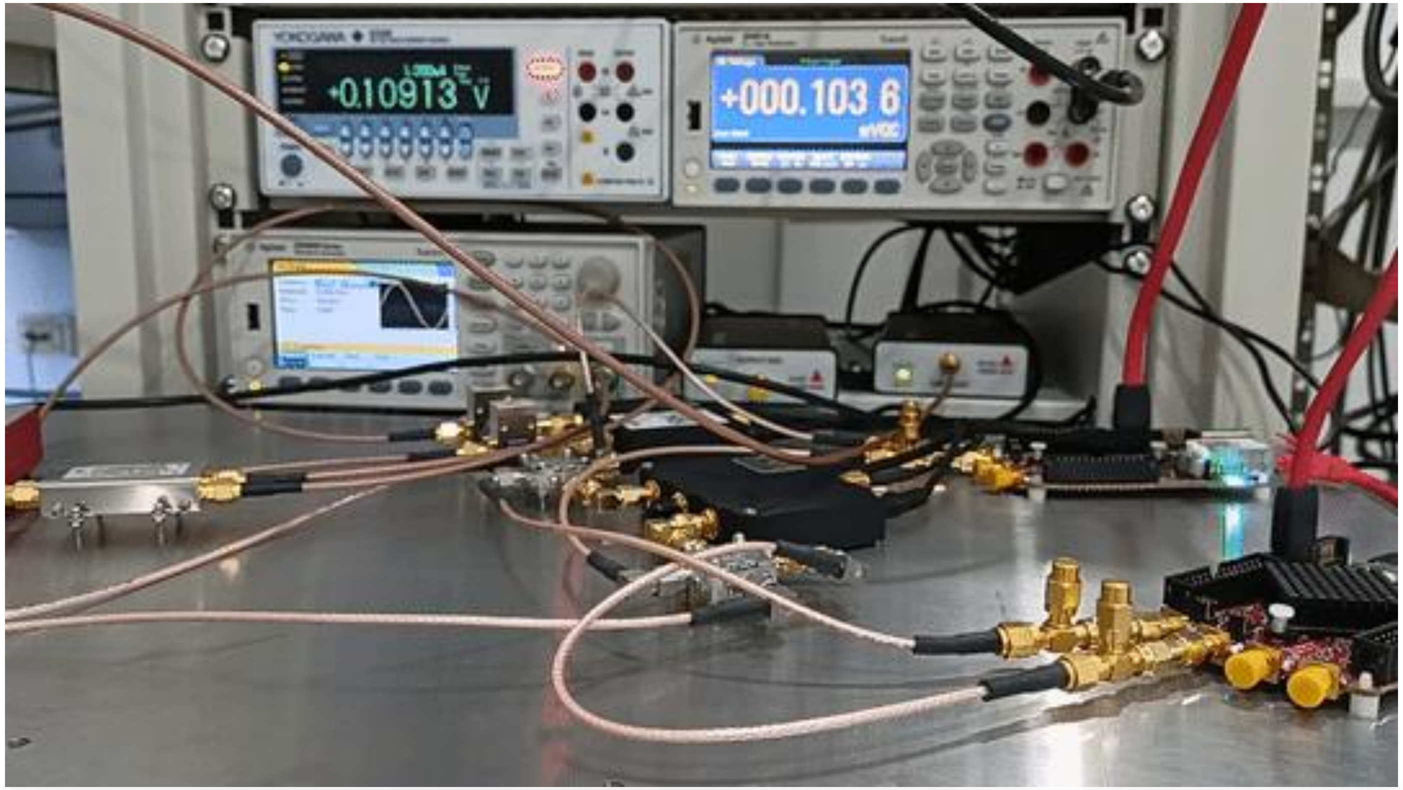
# Signal processing + Control electronics

## Quantum Signals Processing Laboratory



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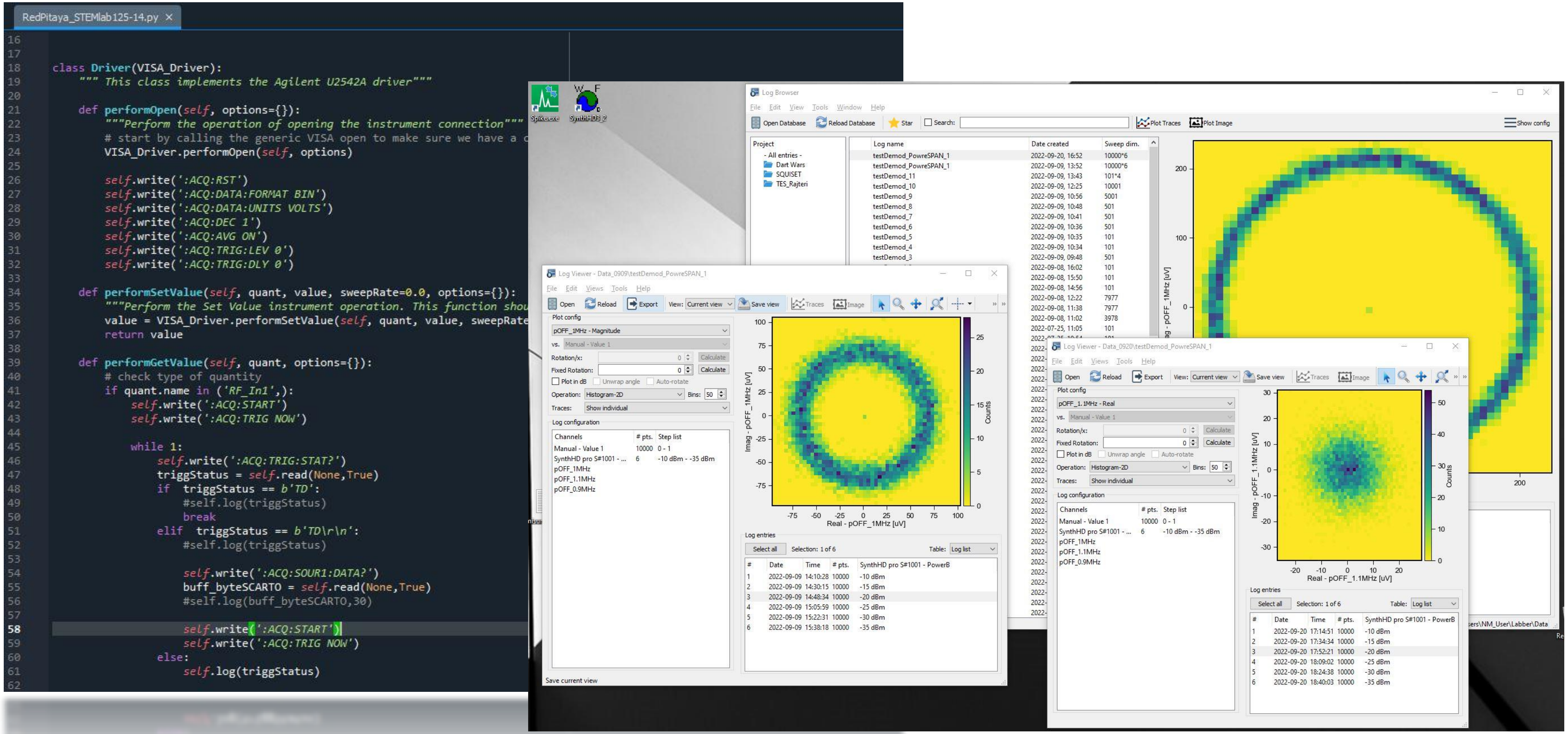
# Control software

## Quantum Signals Processing Laboratory



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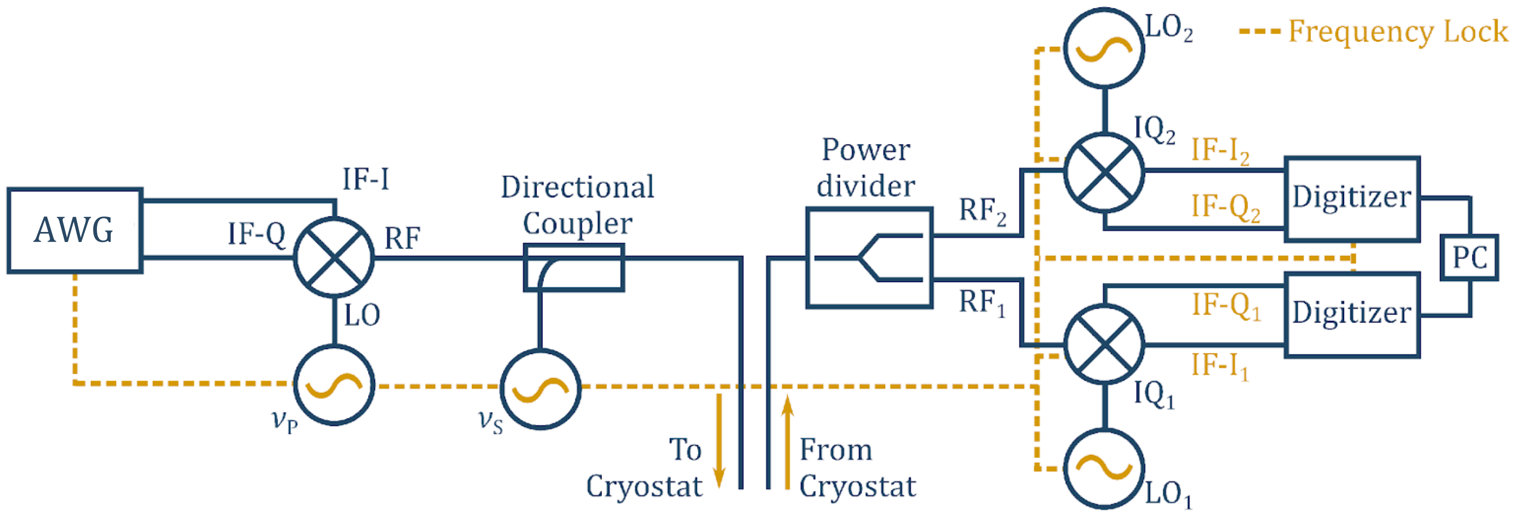
# Squeezing as a resource

Principle scheme for detecting quantum correlations in the output signals of a JTWPA




Esposito M., Ranadive A., Planat A., Leger S., Fraudet D., Jouanny V., Buisson O., Guichard W., Naud C., Aumentado J., Lecocq F., *and* Roch N., "Observation of Two-Mode Squeezing in a Traveling Wave Parametric Amplifier", *Phys. Rev. Lett.* **128**, 153603 (2022)

SUPERGALAX

Highly sensitive detection of single microwave photons with coherent quantum network of superconducting qubits for searching galactic axions

H2020-FETOPEN-2018-2019-2020-01

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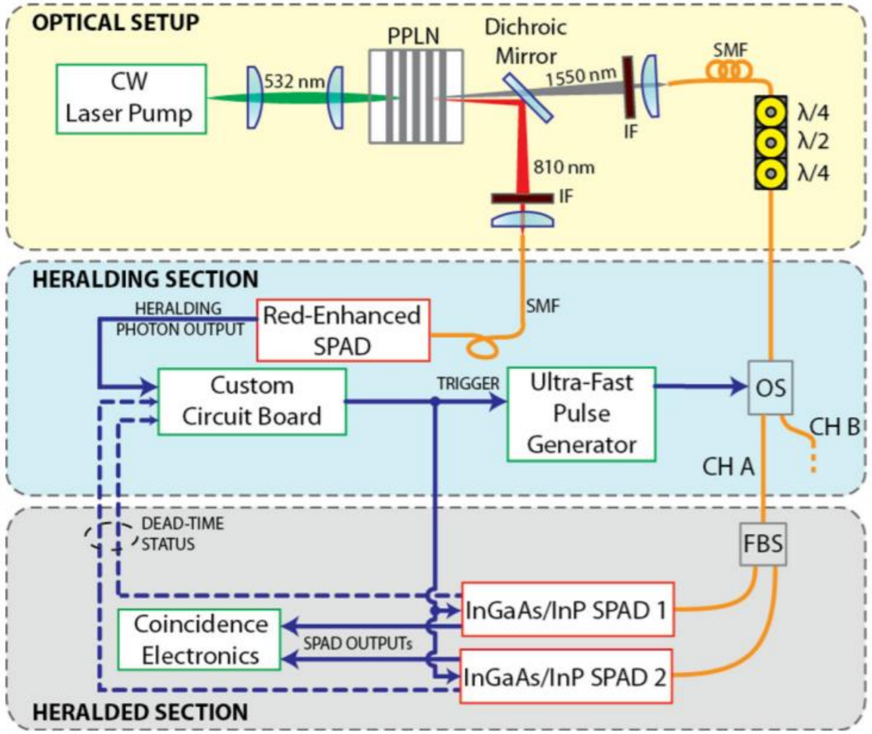
# Future perspectives

Single Microwave Photon Detectors (SMPD) **Calibration** via Heralding




SPAD analogue in the microwave regime

G. Brida et al., An extremely low-noise **heralded single-photon source:** A breakthrough for quantum technologies Appl. Phys. Lett. 101, 221112-1-11 (2012). doi:10.1063/1.4768288

SUPERGALAX

Highly sensitive detection of single microwave photons with coherent quantum network of superconducting qubits for searching galactic axions

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# Thanks for your attention!