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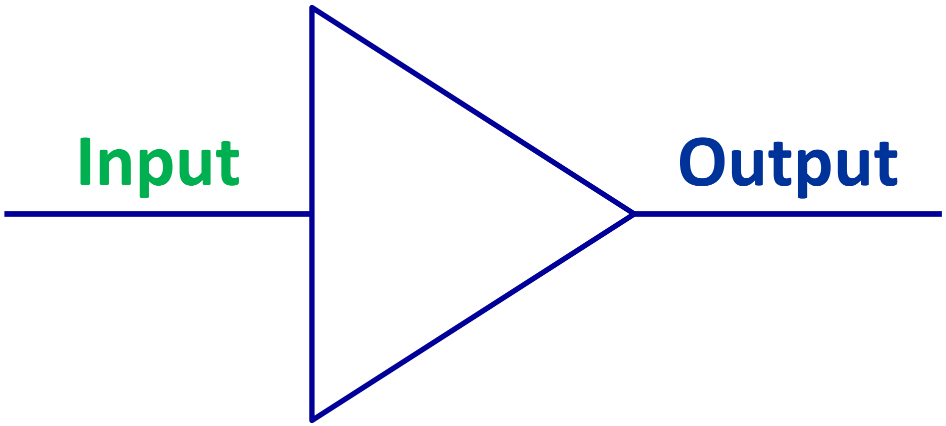
Pheliqs: PHotonique - ELectronique - Ingénierie - QuantiqueS

Near quantum-limited amplification and conversion based on a voltage-biased Josephson junction

Salha JEBARI, Florian Blanchet, Romain Albert, Dibyendu Hazra, Alexander Grimm, Fabien Portier and Max Hofheinz

Ideal amplifier

- **Ultra Low Noise Amplification** is a must in superconducting qubit experiments
  - Qubit read out
  - Quantum feedback



High gain

Large bandwidth

High dynamic range

Low noise

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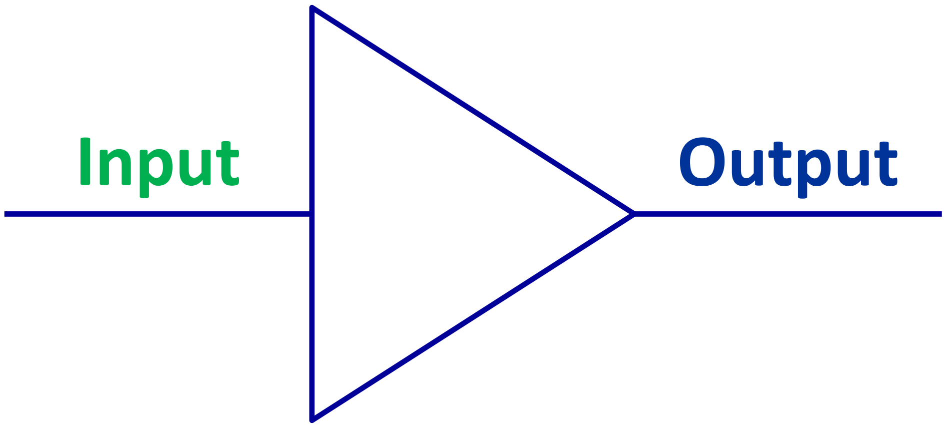


Easy to use

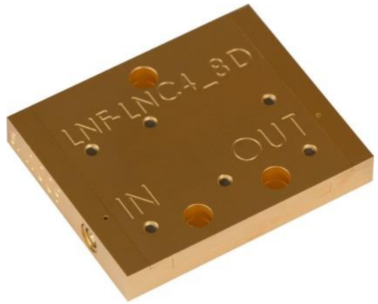
High gain

Large bandwidth

High dynamic range

Low noise

Commercial amplifiers



http://www.lownoisefactory.com

http://www.caltechmicrowave.org

Advantages

- Simple to use
- Large bandwidth
- High dynamic range
- High gain

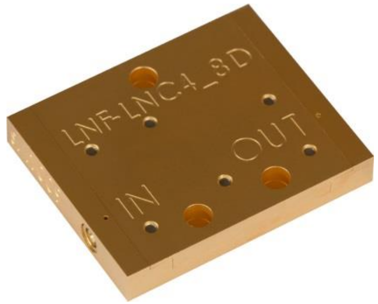
Disadvantages

- High noise

2K at 6 GHz = 10 photons of noise

- Power dissipation

Commercial amplifiers

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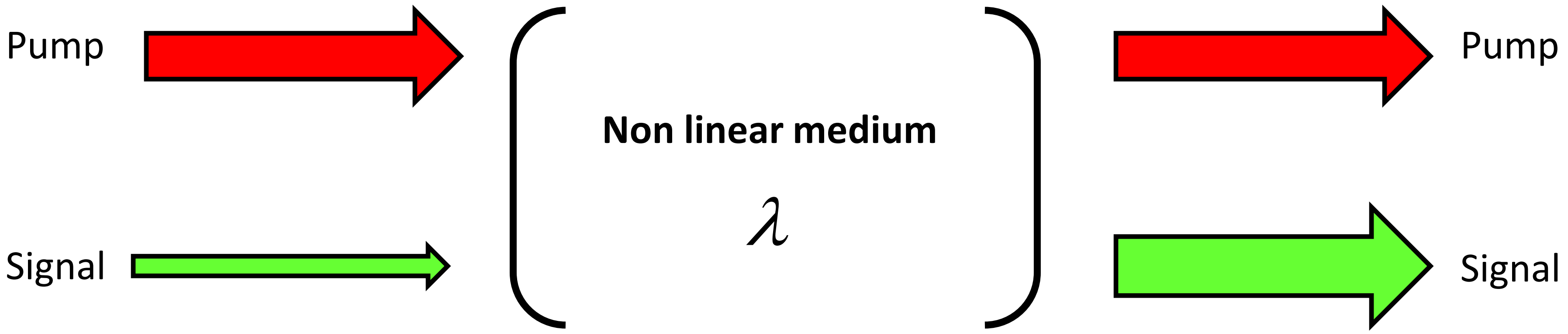
Parametric amplifier: new type of amplifier that can amplify without or with very **low noise**

Parametric amplification



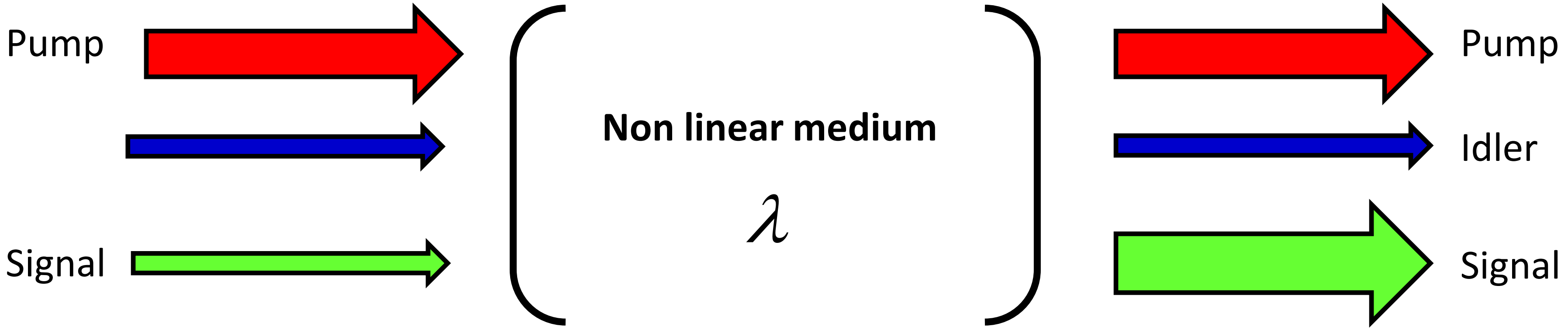
Principle of parametric amplification

$$\omega_p = \omega_s + ?$$

Why?

- Any dissipation at a frequency less than $\frac{k_B T}{\hbar}$ necessarily introduces a noise
- Only parametric amplifier is able to control exactly the origin of frequency dissipation

Parametric amplification



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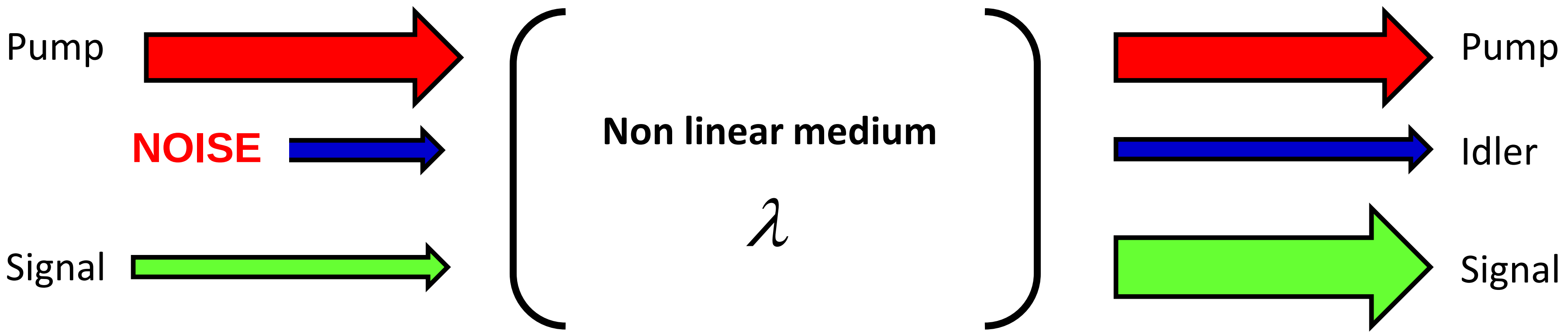

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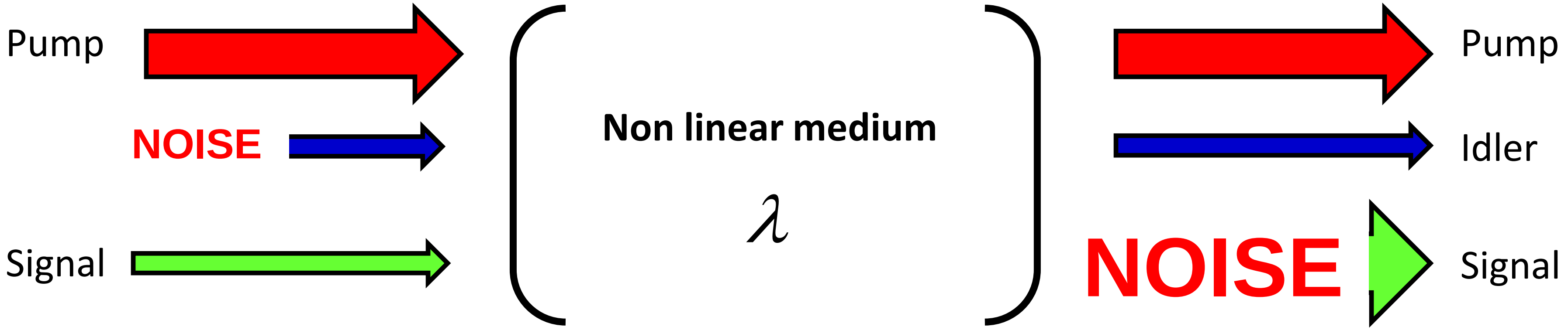

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The challenge

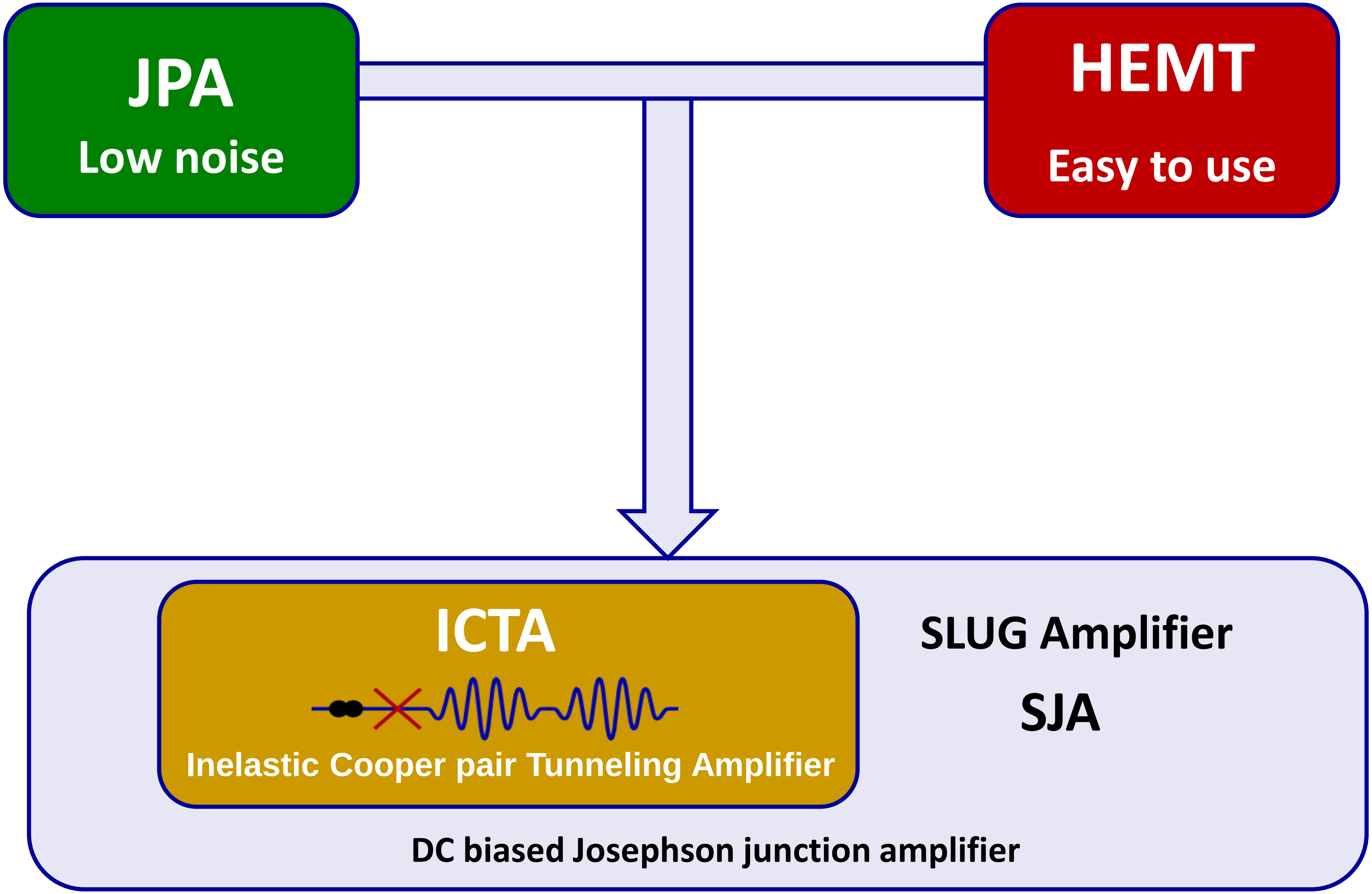
JPA

Low noise

HEMT

Easy to use

The challenge



Outline

Part 1

From dynamic Coulomb blockade physics to Josephson parametric amplifier physics:

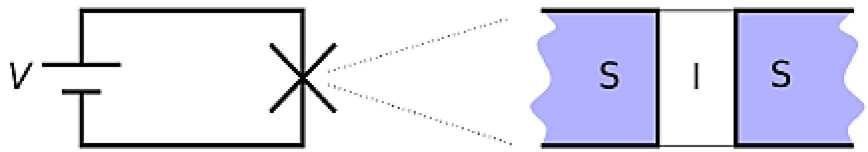
Theory, Measurement results with Aluminium (Al) sample

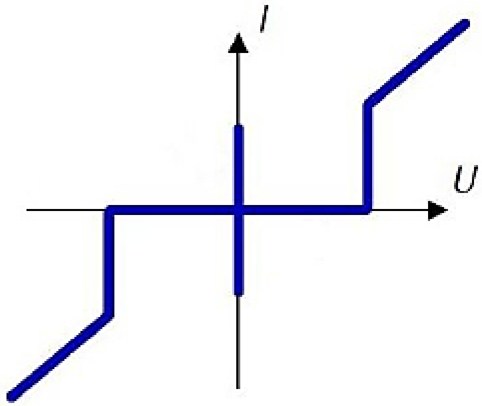
Part 2

Optimization of parameters of ICTA samples:

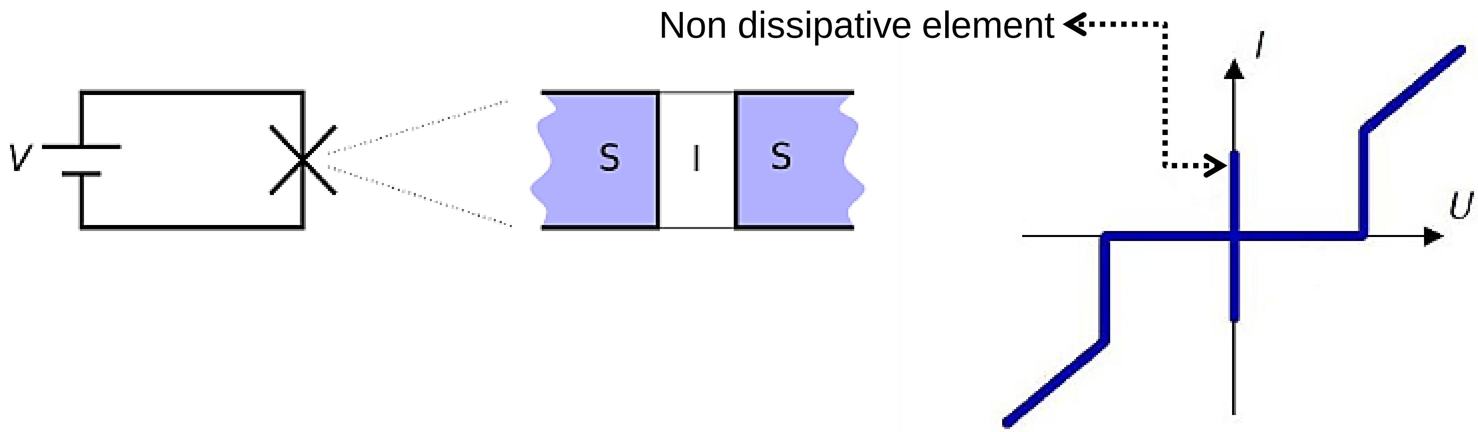
Niobium Nitride (NbN) sample

Inelastic Cooper pair tunneling





Inelastic Cooper pair tunneling



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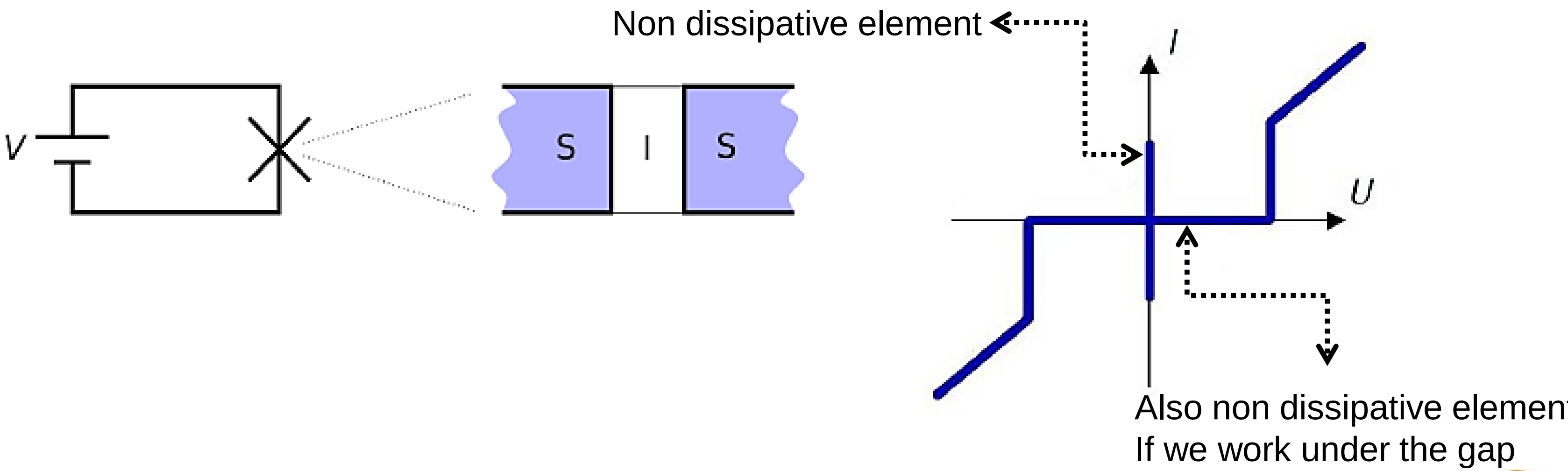
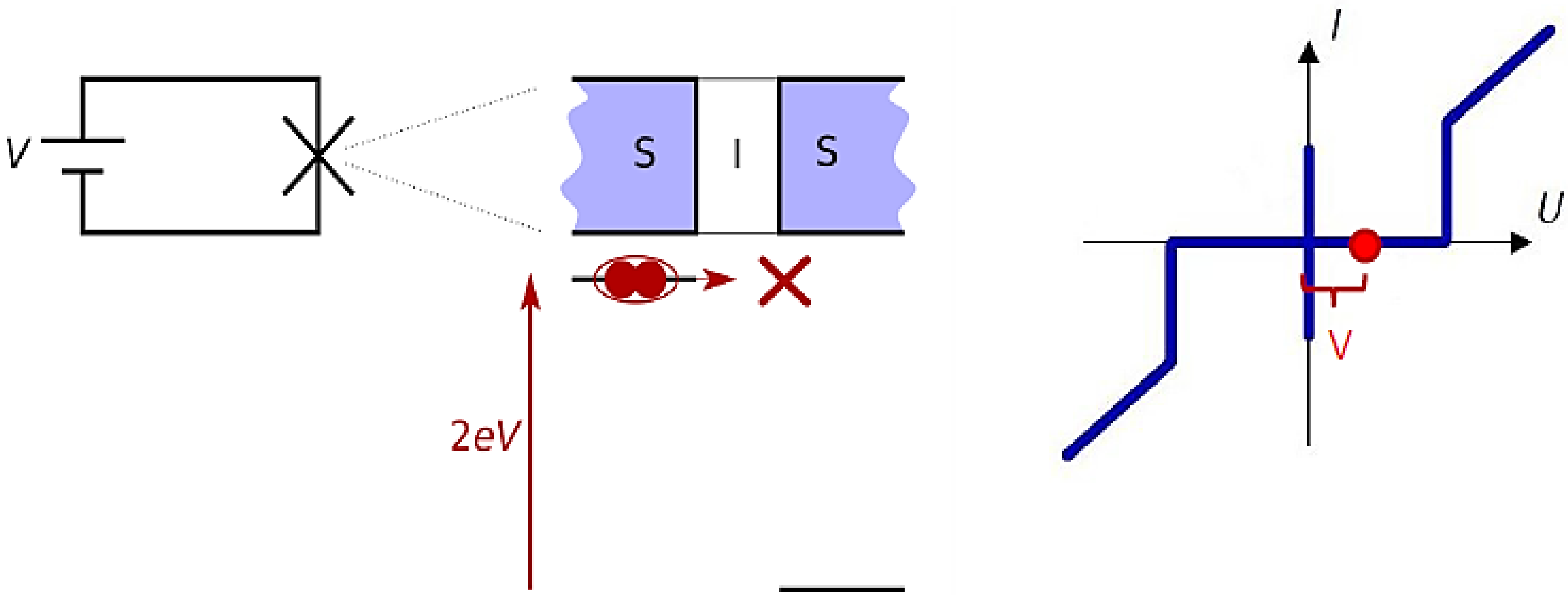


Fun physics

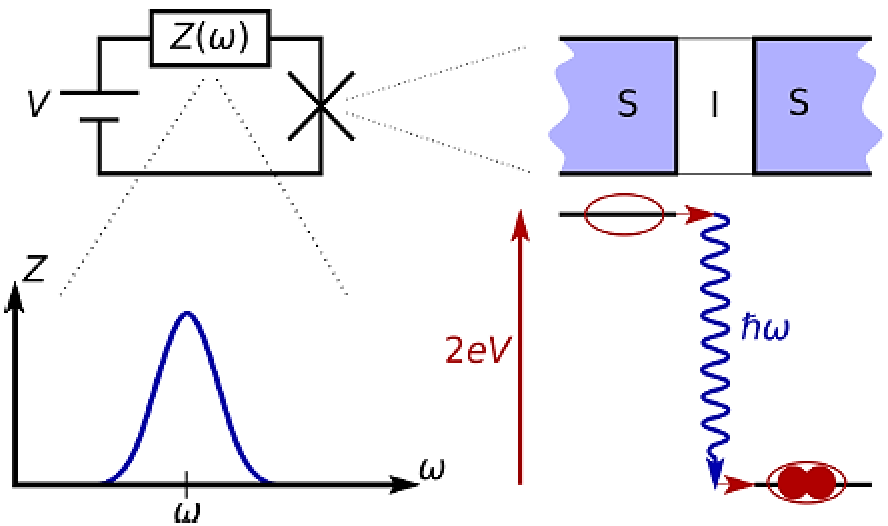
Inelastic Cooper pair tunneling

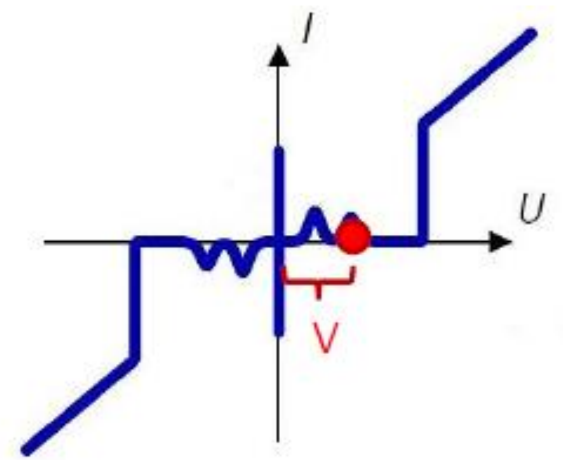


- **A Cooper pair can only tunnel if it can lose its energy 2eV**
- **No density of states on the other side: No Cooper pair current**

G.-L. Ingold and Y. V. Nazarov, Single Charge Tunneling 294, 21 (1992)
T. Holst, D. Esteve, C. Urbina, and M. H. Devoret, Physical Review Letters 73, 3455 (1994)

Inelastic Cooper pair tunneling





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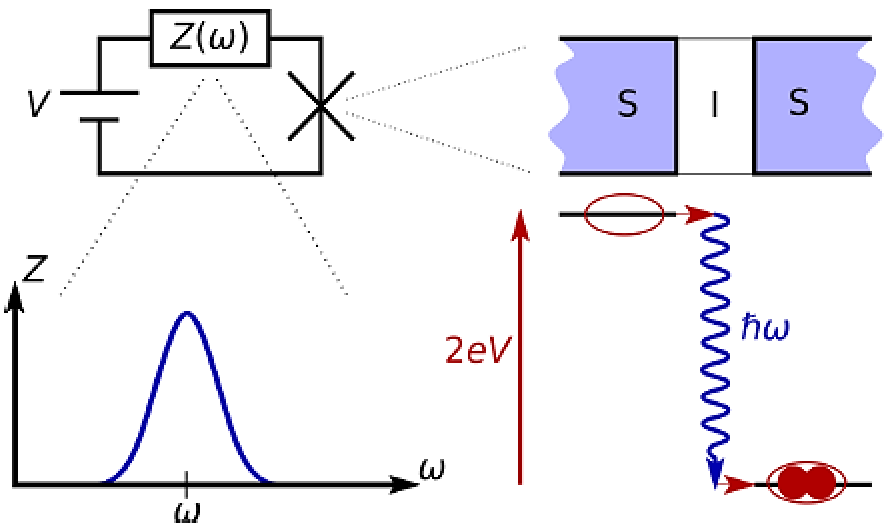

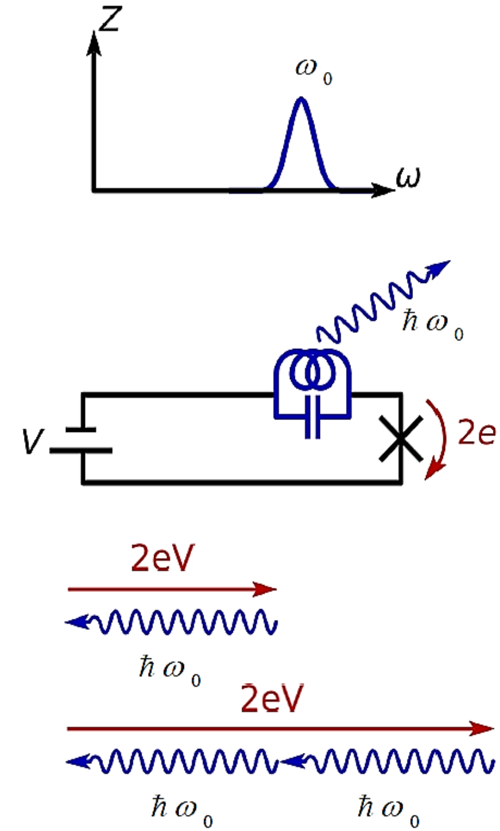

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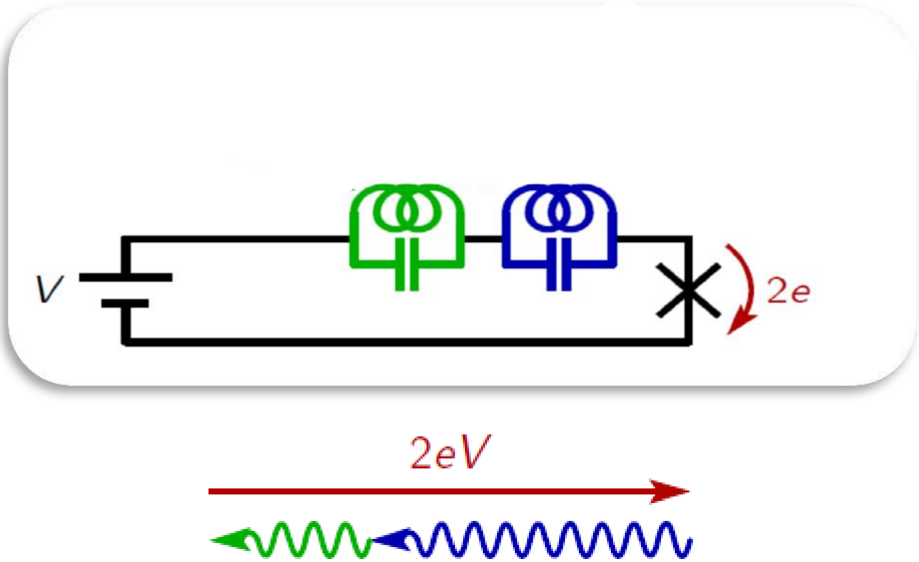

Resonance condition

$$2eV \cong \hbar\omega_a + \hbar\omega_b$$

Inelastic Cooper pair Tunneling Amplifier: ICTA

Resonance condition

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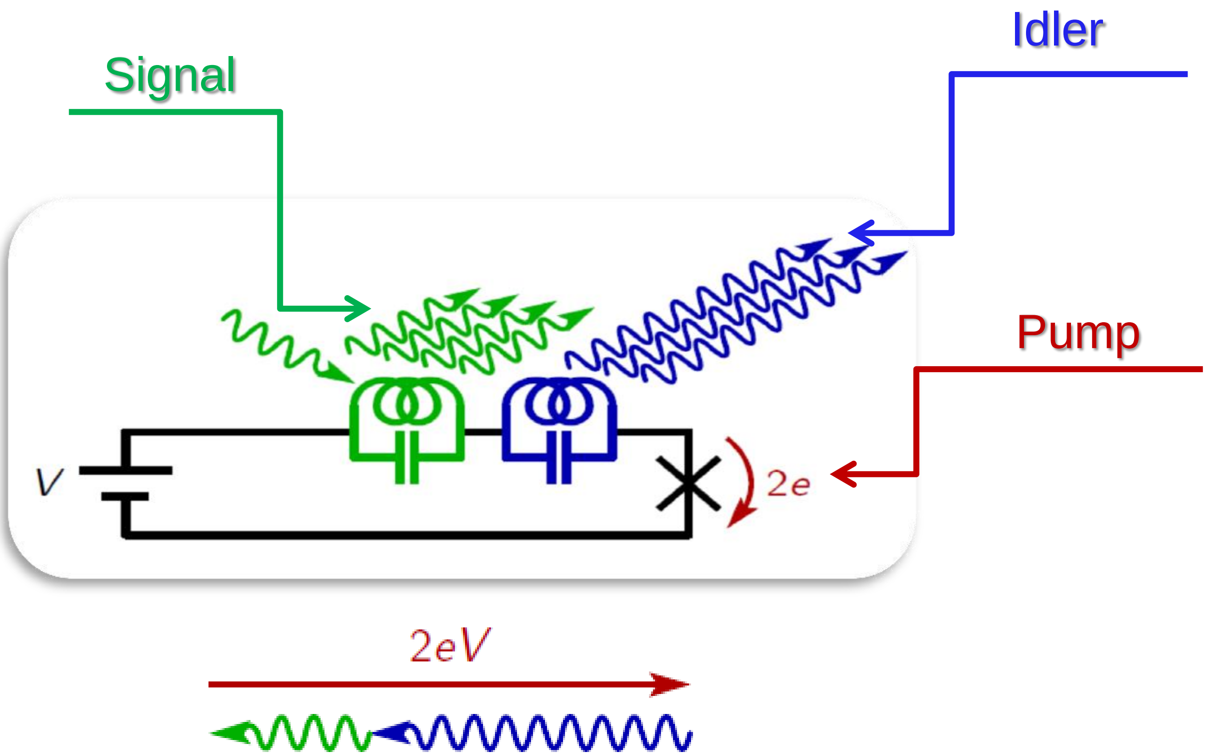
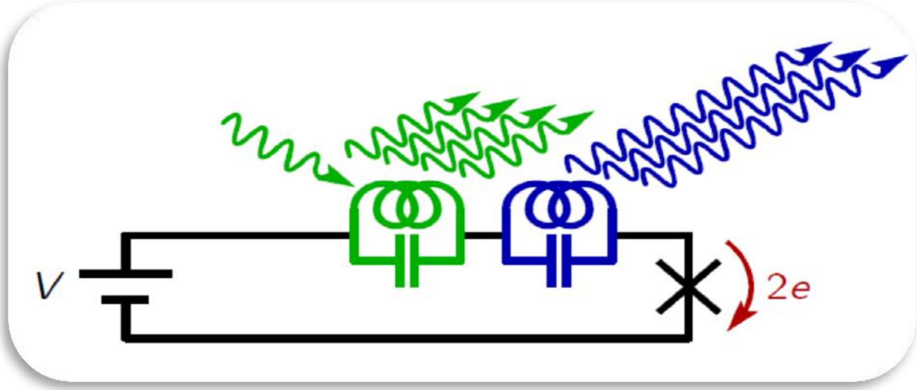


- Use parametric down-conversion process
- Send signal at one of the modes
- Process accelerated due to stimulated emission
- Quantum limited amplification

ICTA theory



$$2eV \cong \hbar\omega_a + \hbar\omega_b$$

$$\rho_{a,b} = \sqrt{\frac{\pi Z_{a,b}}{\hbar / 4e^2}}$$

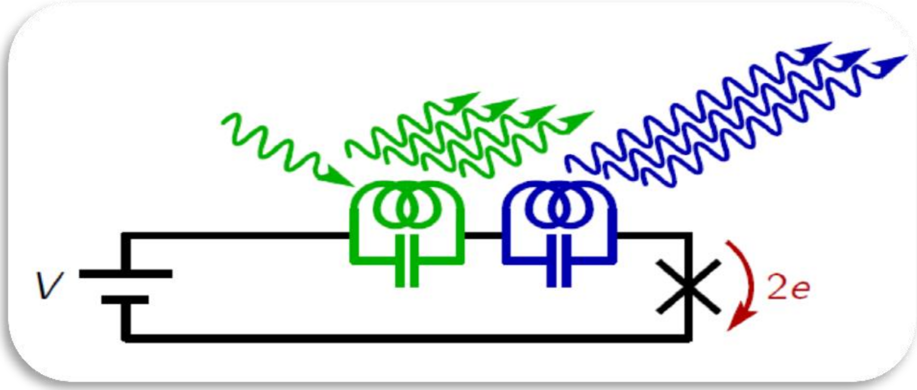
$$H_{sys} \approx \hbar\omega_a a^+ a + \hbar\omega_b b^+ b - E_J \cos\left(\frac{2eVt}{\hbar} + \rho_a (a^+ + a) + \rho_b (b^+ + b)\right)$$

Isolated resonators a,b

Josephson junction energy

Kirchhoff’s law

ICTA theory



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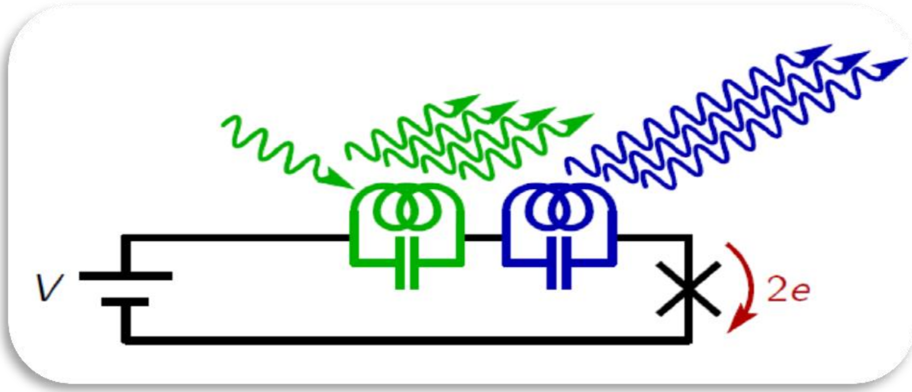
Rotating wave approximation

$$|\omega_J - \omega_a - \omega_b| < E_J$$

ICTA theory



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$$|\omega_J - \omega_a - \omega_b| < E_J$$

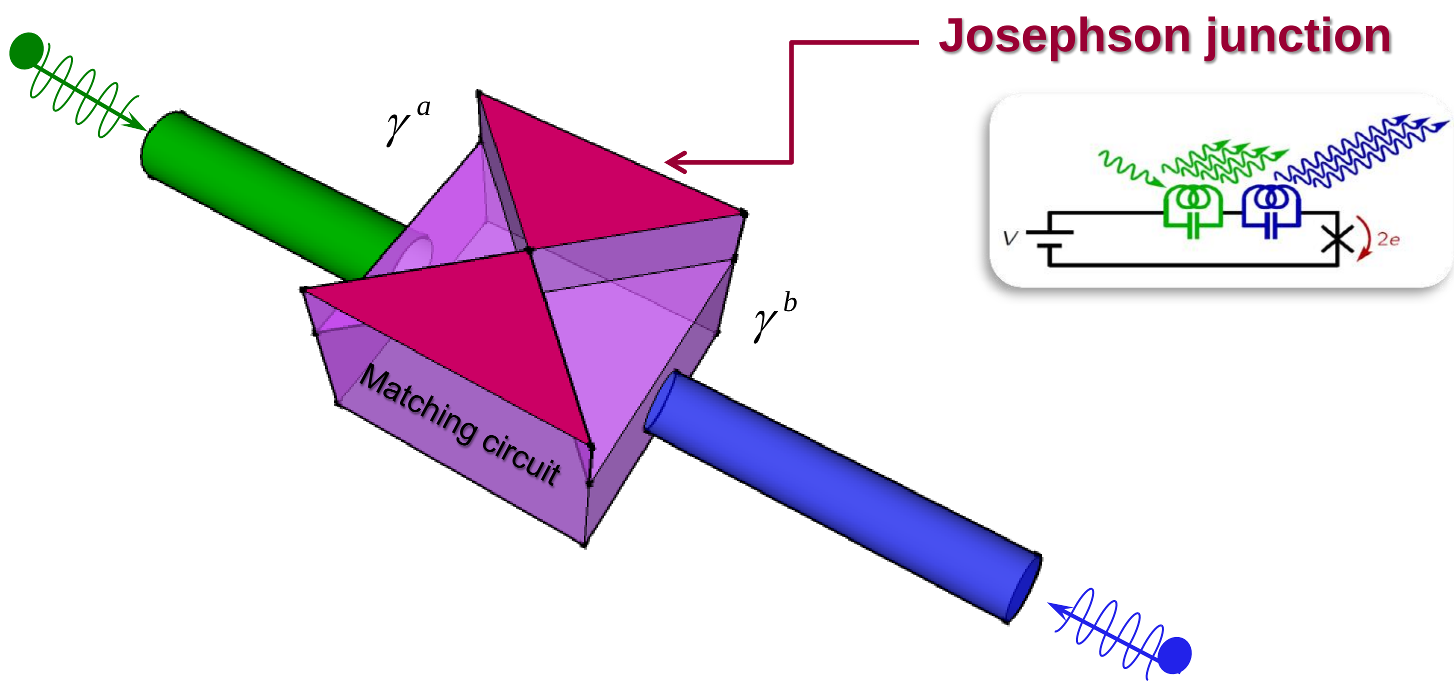
$$H_{sys} = \hbar\omega_a a^+ a + \hbar\omega_b b^+ b + \hbar\lambda(a^+ b^+ e^{-i\omega_J t} + h.c.)$$

Isolated resonators a,b

Coupling term

$$\lambda = E_J \frac{\rho_a \rho_b}{2\hbar}$$

ICTA theory: scattering matrix



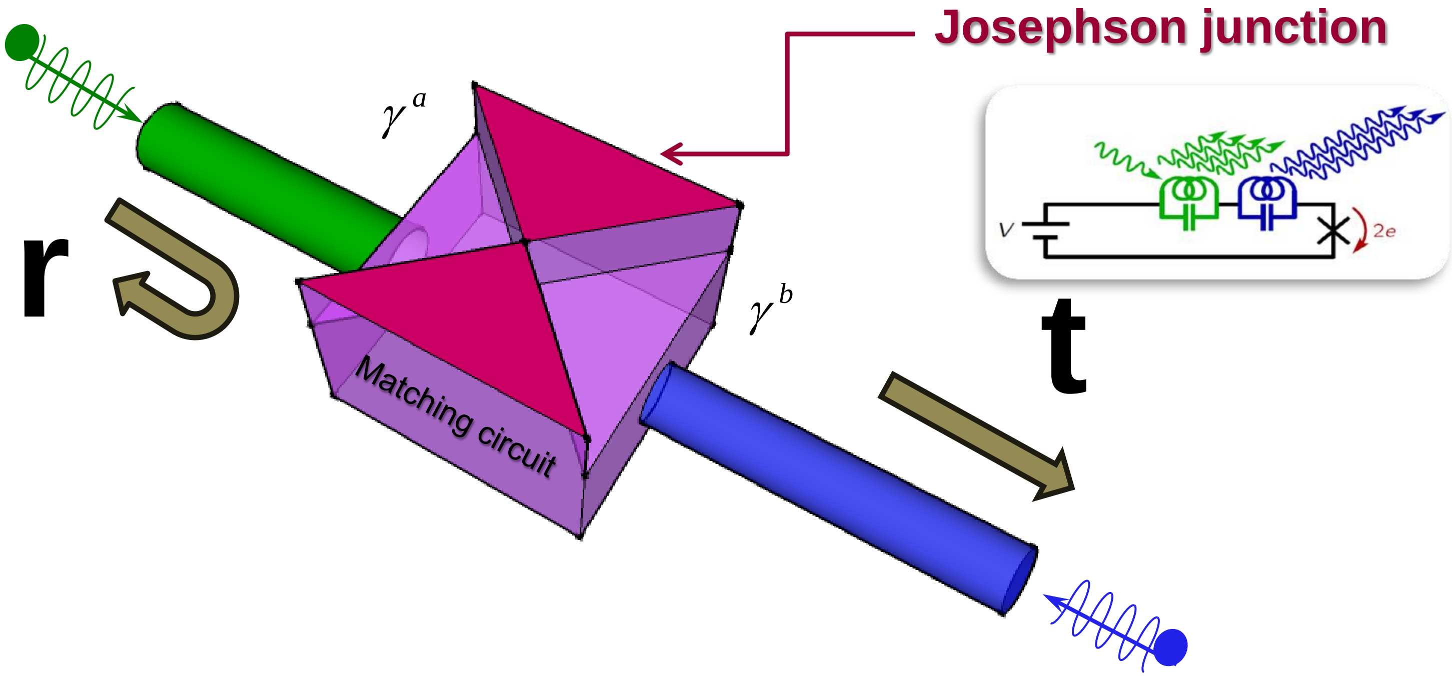
$$\gamma^a, \gamma^b : \text{Damping terms}$$

$$\lambda : \text{Coupling frequency}$$

$$\omega_\text{a} \approx \omega_s : \text{Signal frequency}$$

$$\omega_\text{b} \approx \omega_i : \text{Idler frequency}$$

ICTA theory: scattering matrix



γ^a, γ^b : Damping terms

λ : Coupling frequency

$\omega_a \approx \omega_s$: Signal frequency

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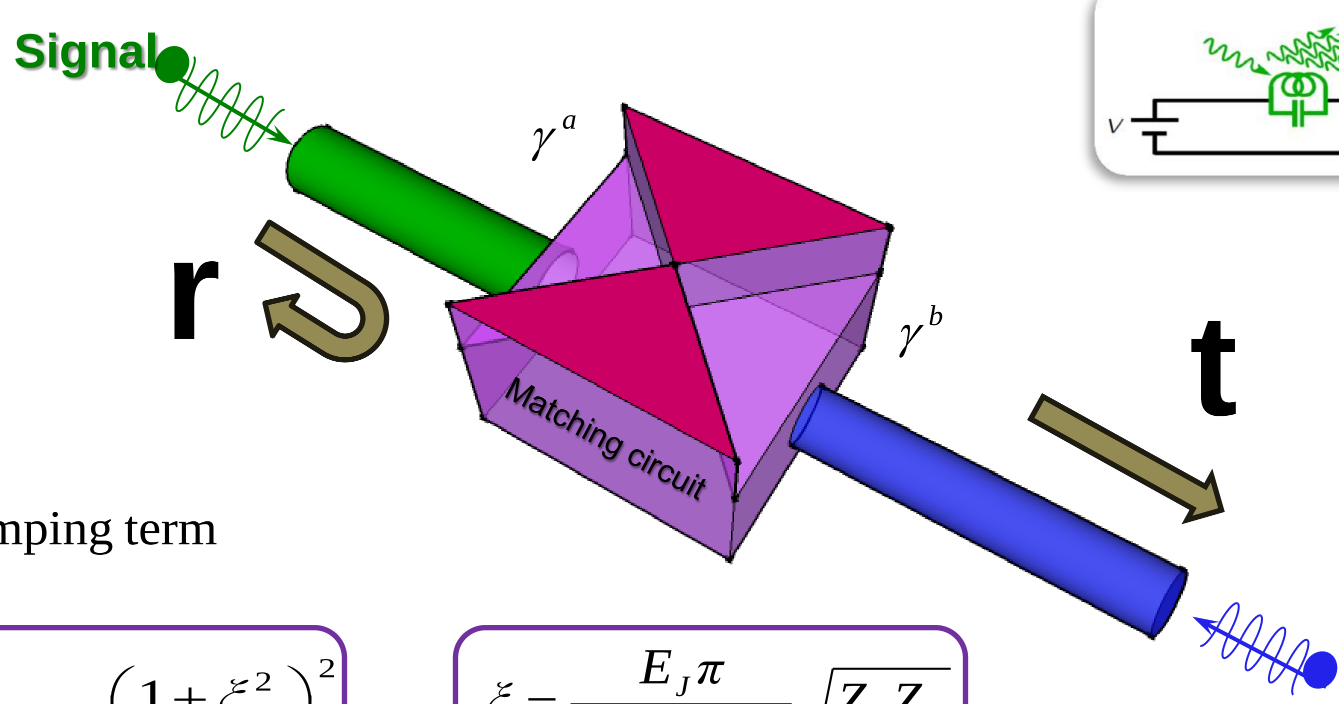
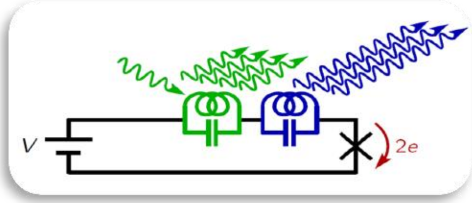
ICTA gain





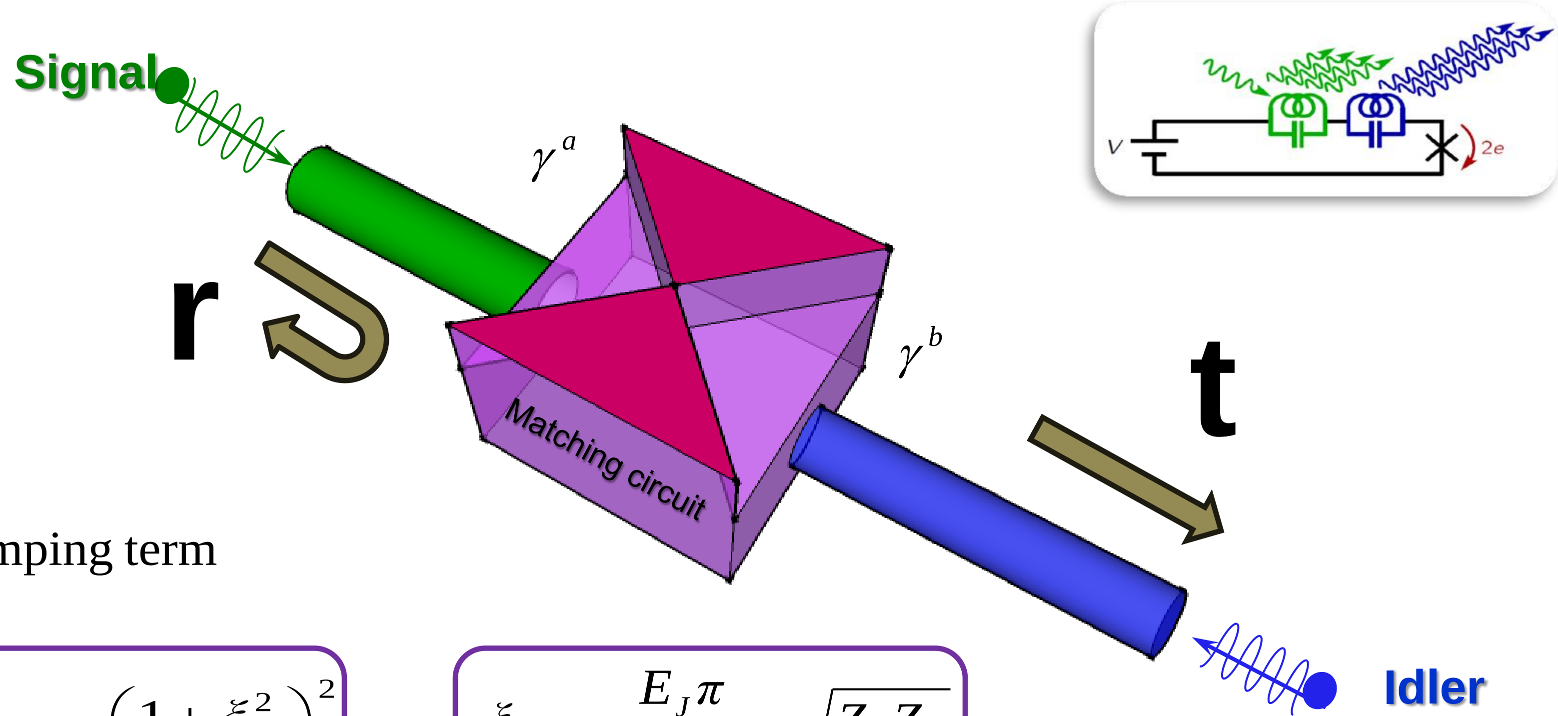
γ : damping term

$$r^2 = G = \left(\frac{1+\xi^2}{1-\xi^2}\right)^2$$

$$\xi = \frac{E_J \pi}{R_Q \hbar \sqrt{\gamma_a \gamma_b}} \sqrt{Z_a Z_b}$$

See more: B.Abdo et al., Physical Review B **87**, 014508 (2013)

ICTA gain



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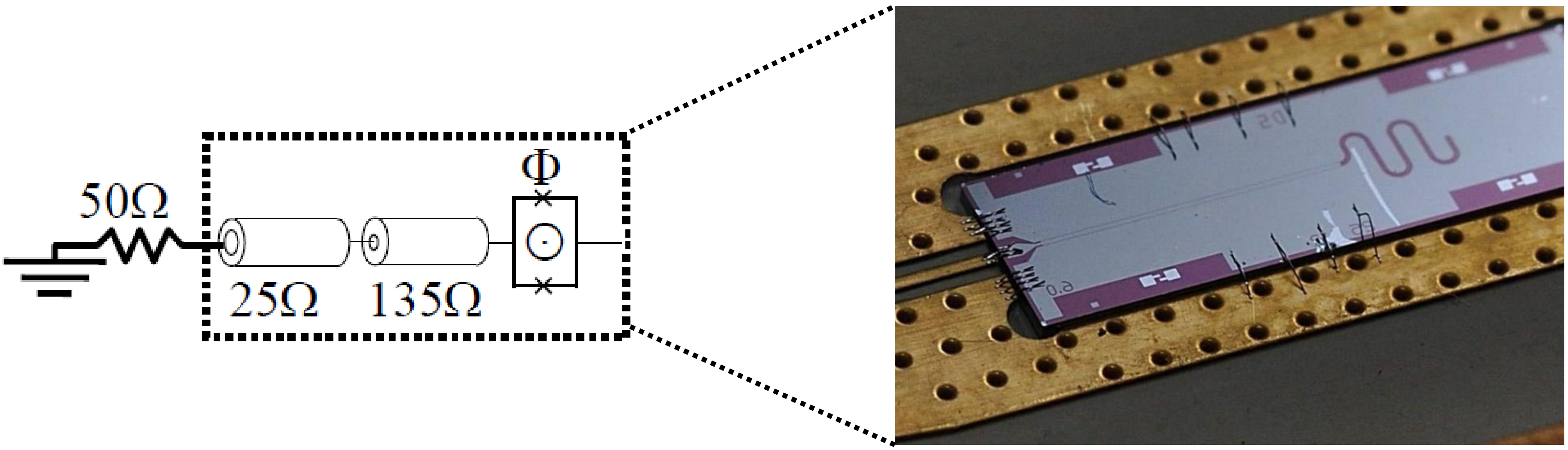
Our case

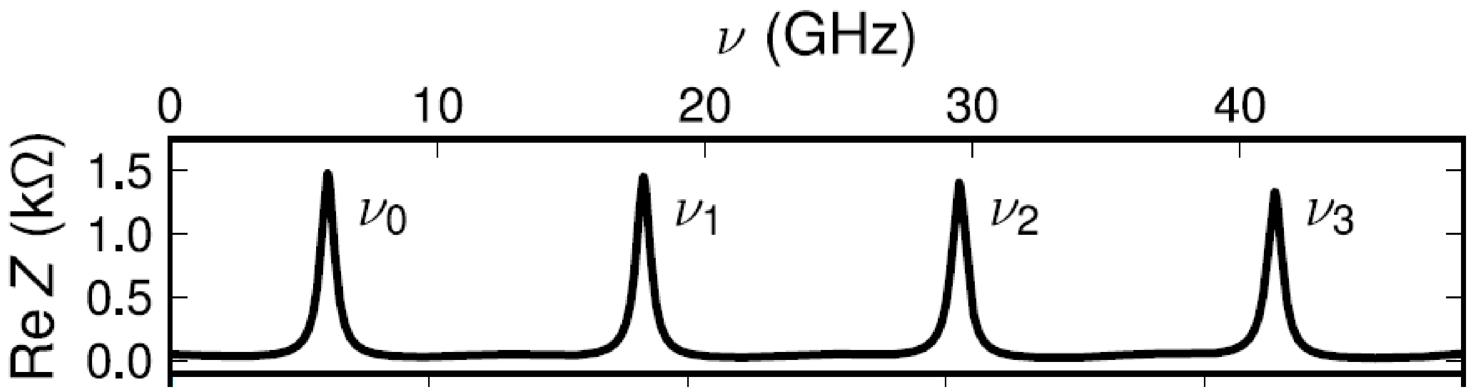
$$\xi \propto E_J$$

JPA

$$\xi \propto \frac{1}{\mathrm{E_J}}$$

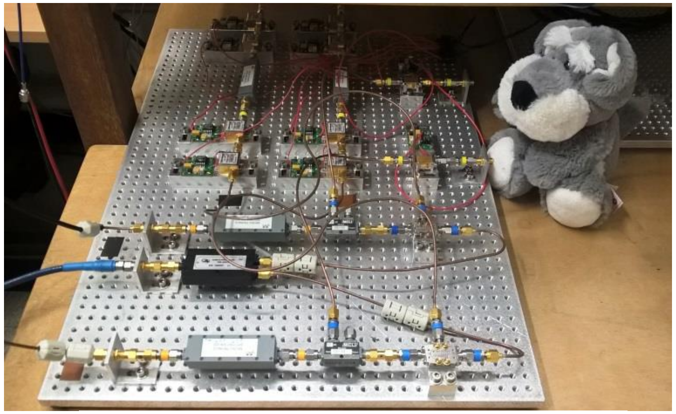
Sample

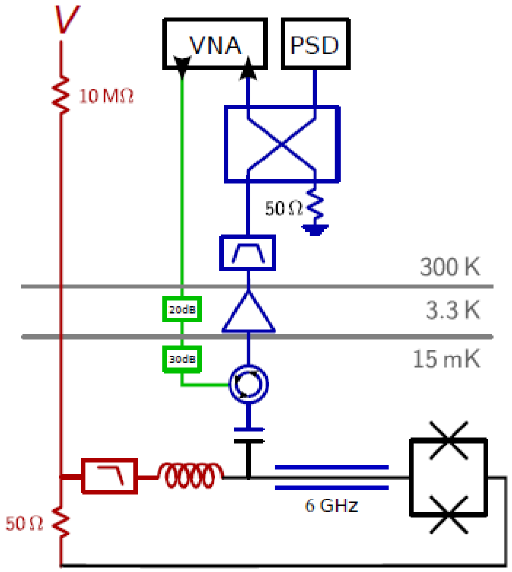


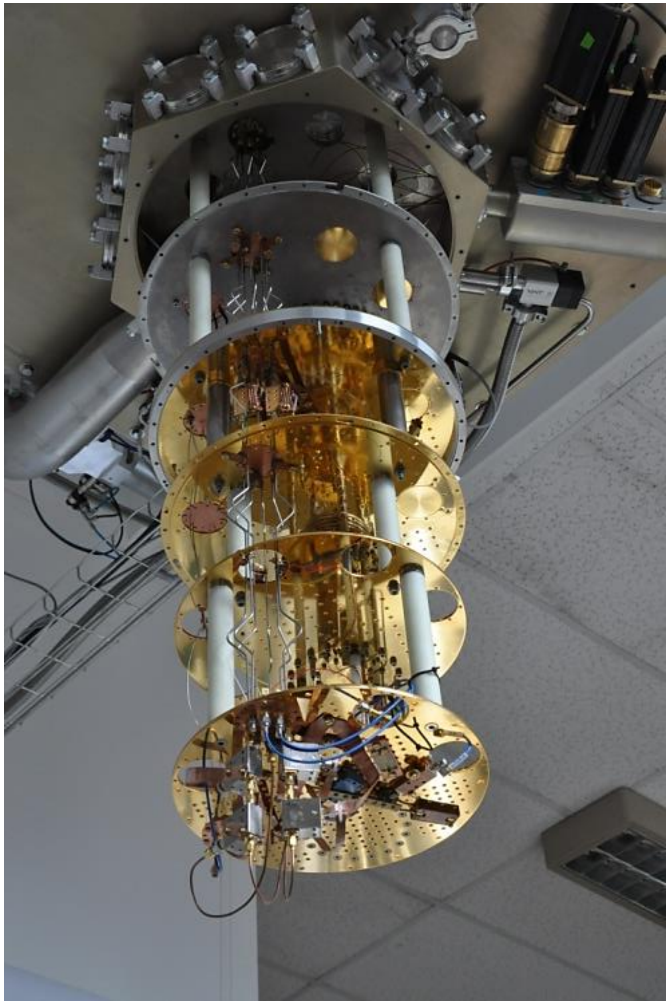


Fabricated in Quantronic group
CEA Saclay

Experimental setup







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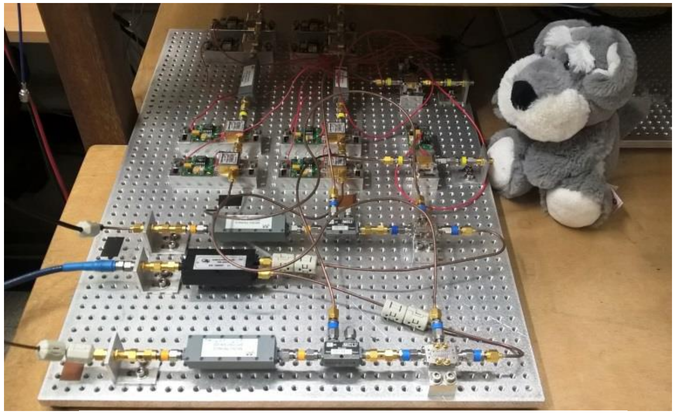

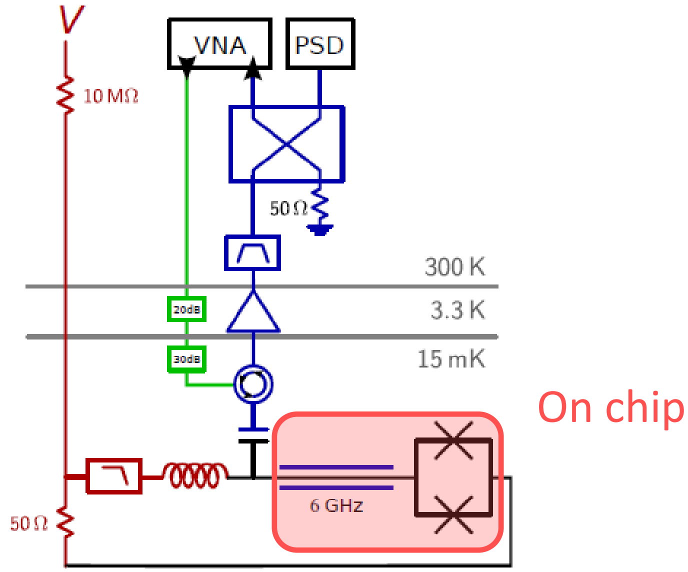

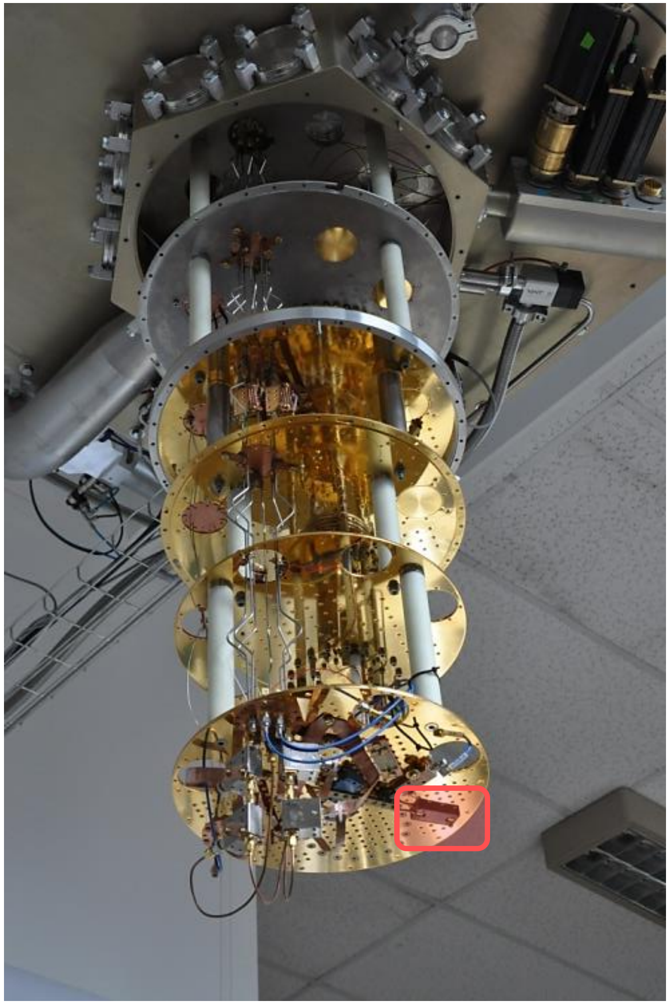

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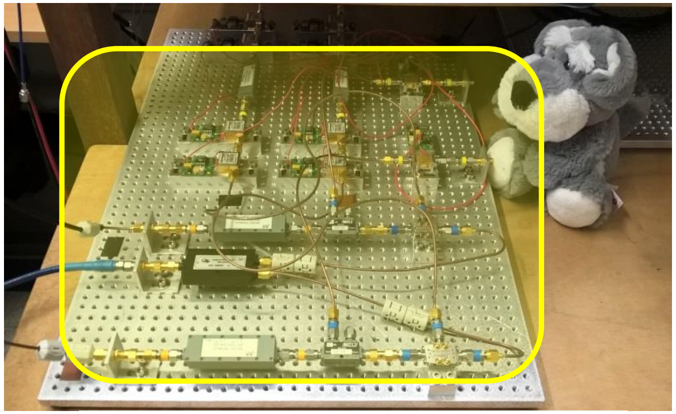
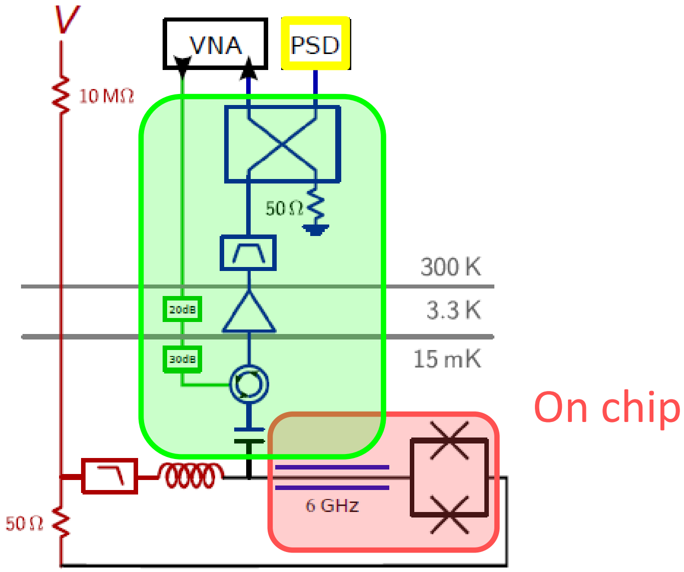
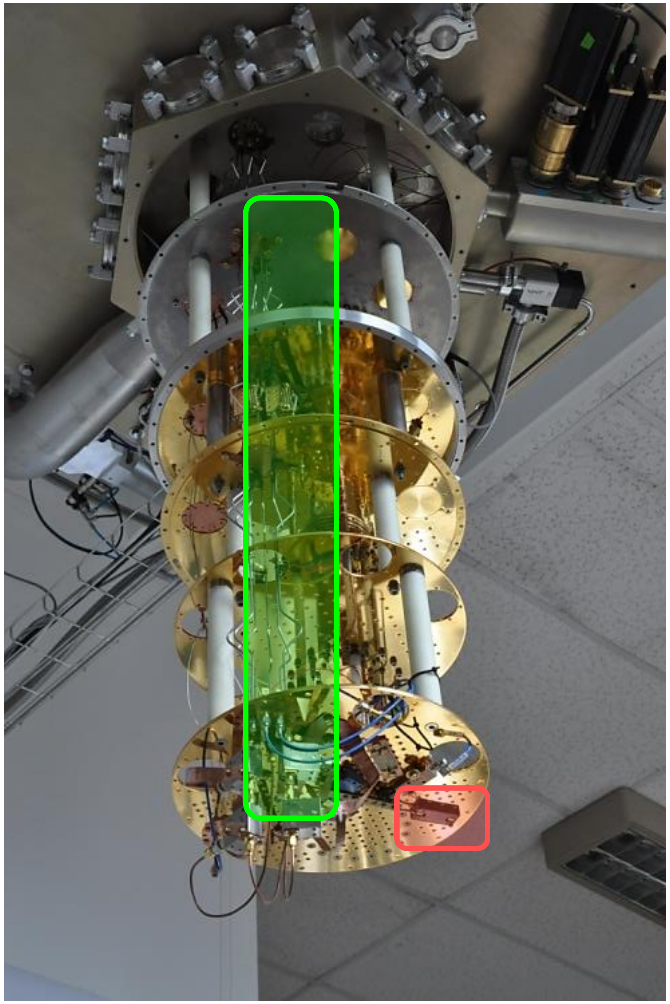
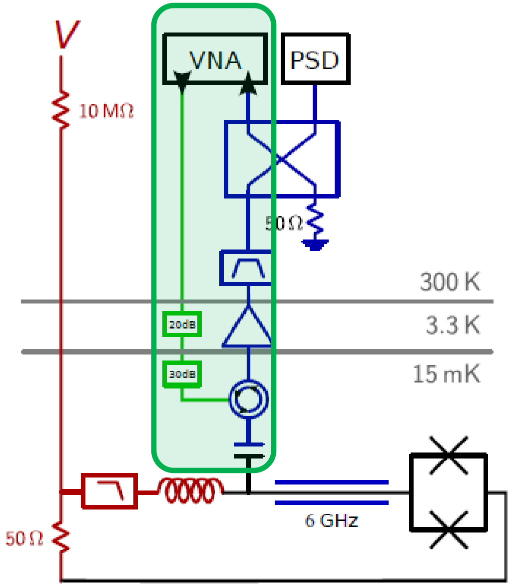
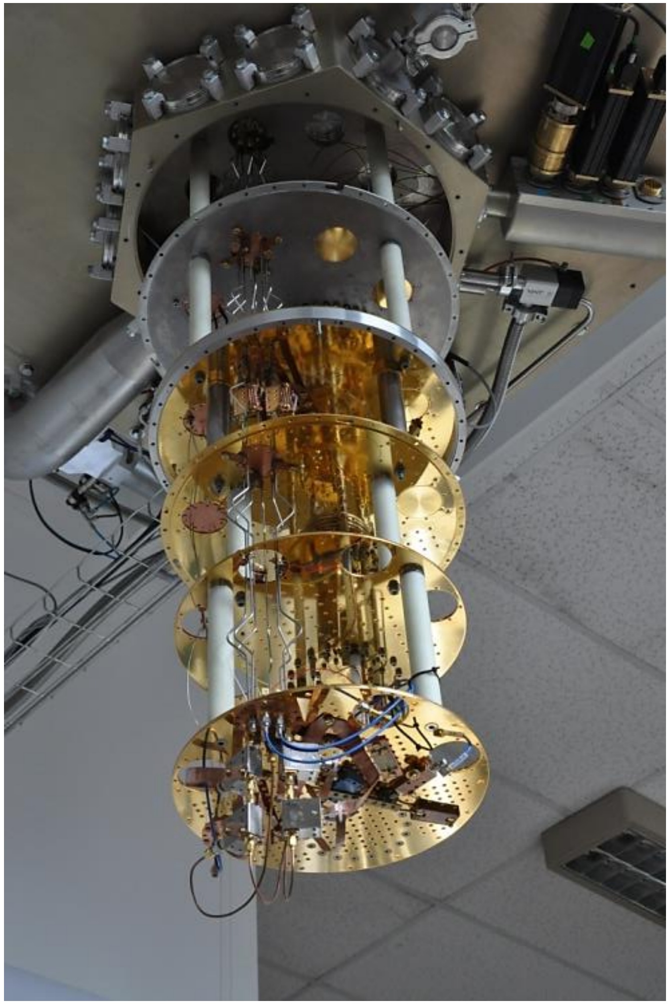






VNA measurement

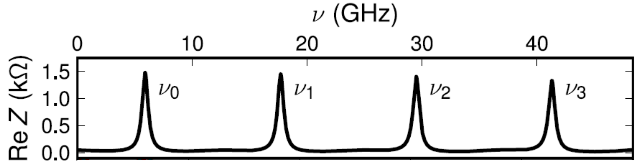


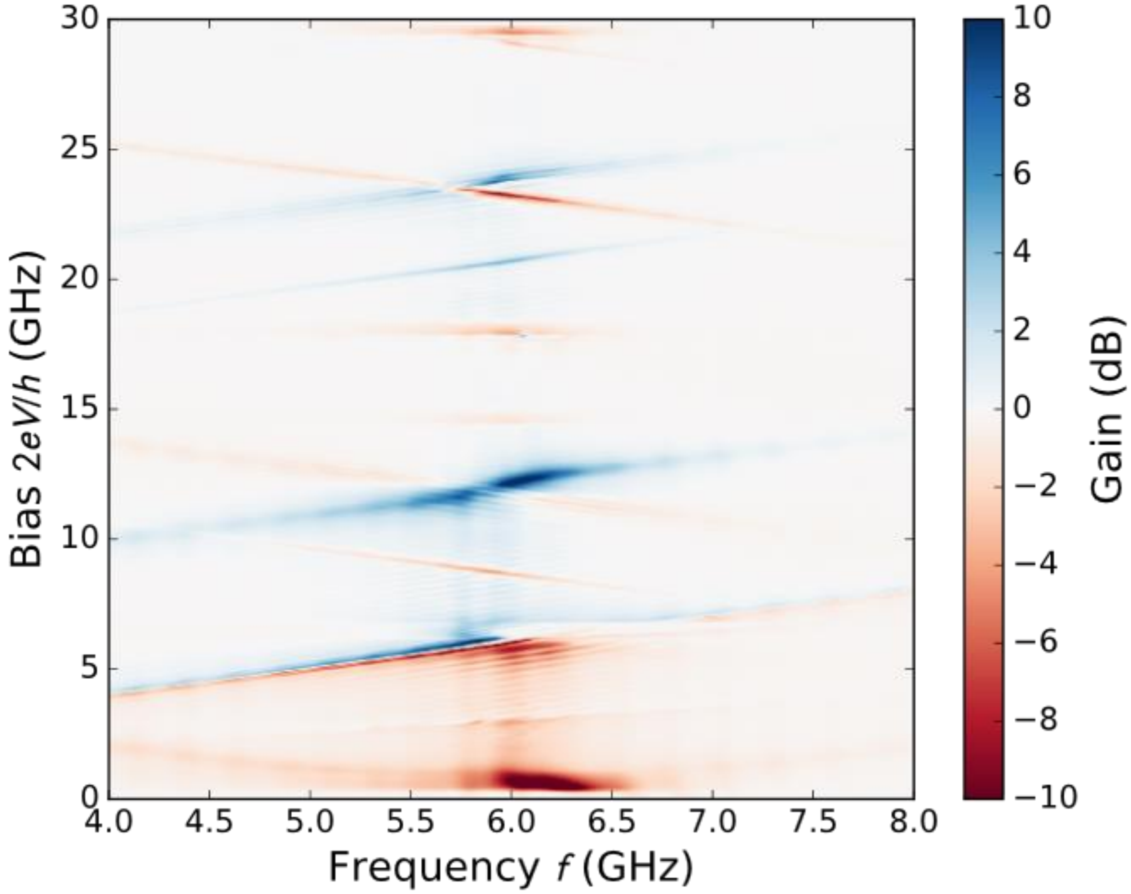


Conversion with gain: amplification

Measurement @

$I_c = 17.5\,\text{nA}$ Signal power = -125 dBm





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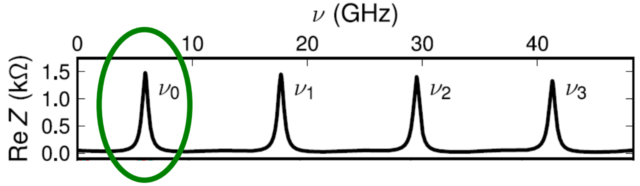

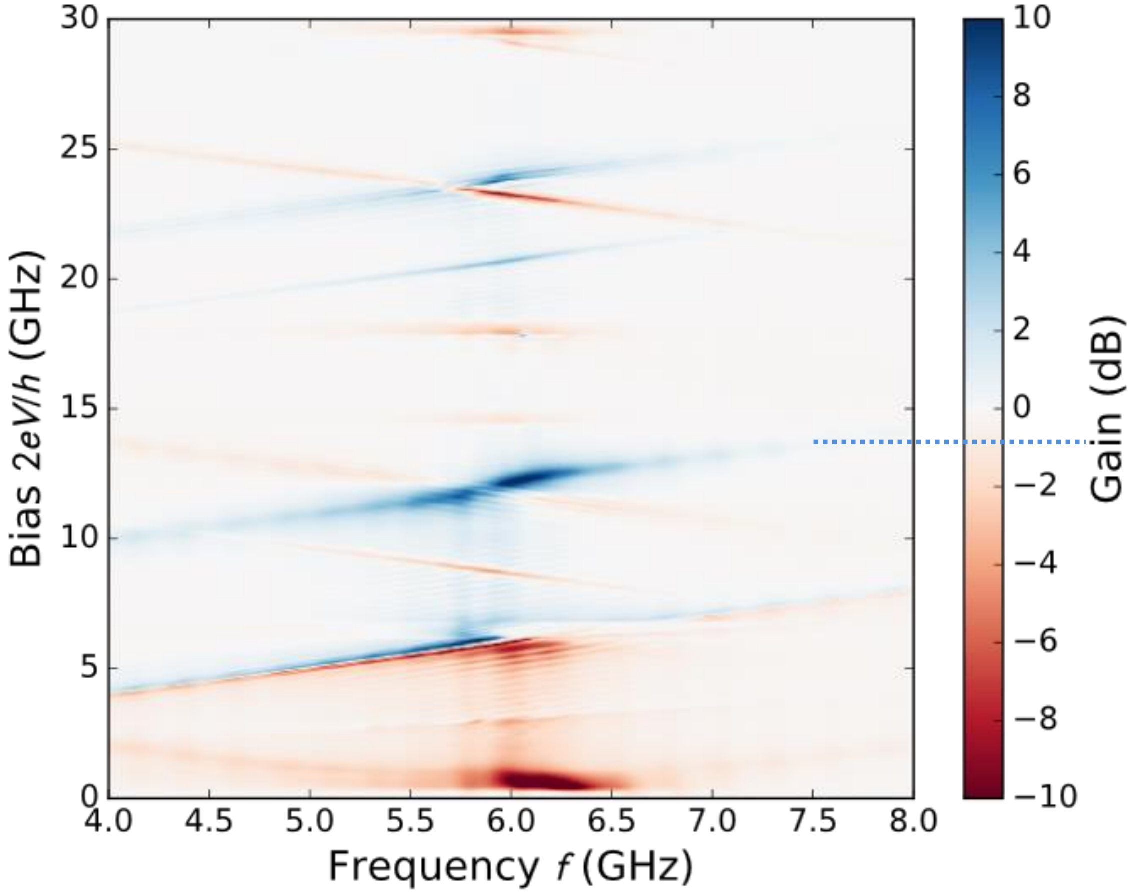

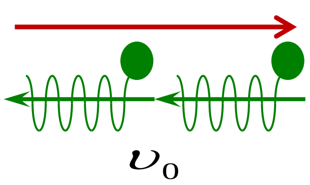

G > 0 dB
To preserve

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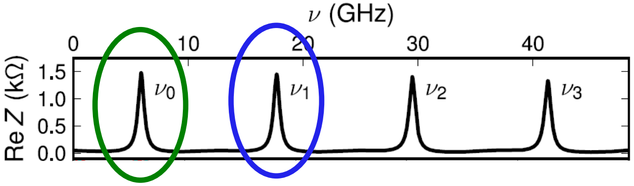

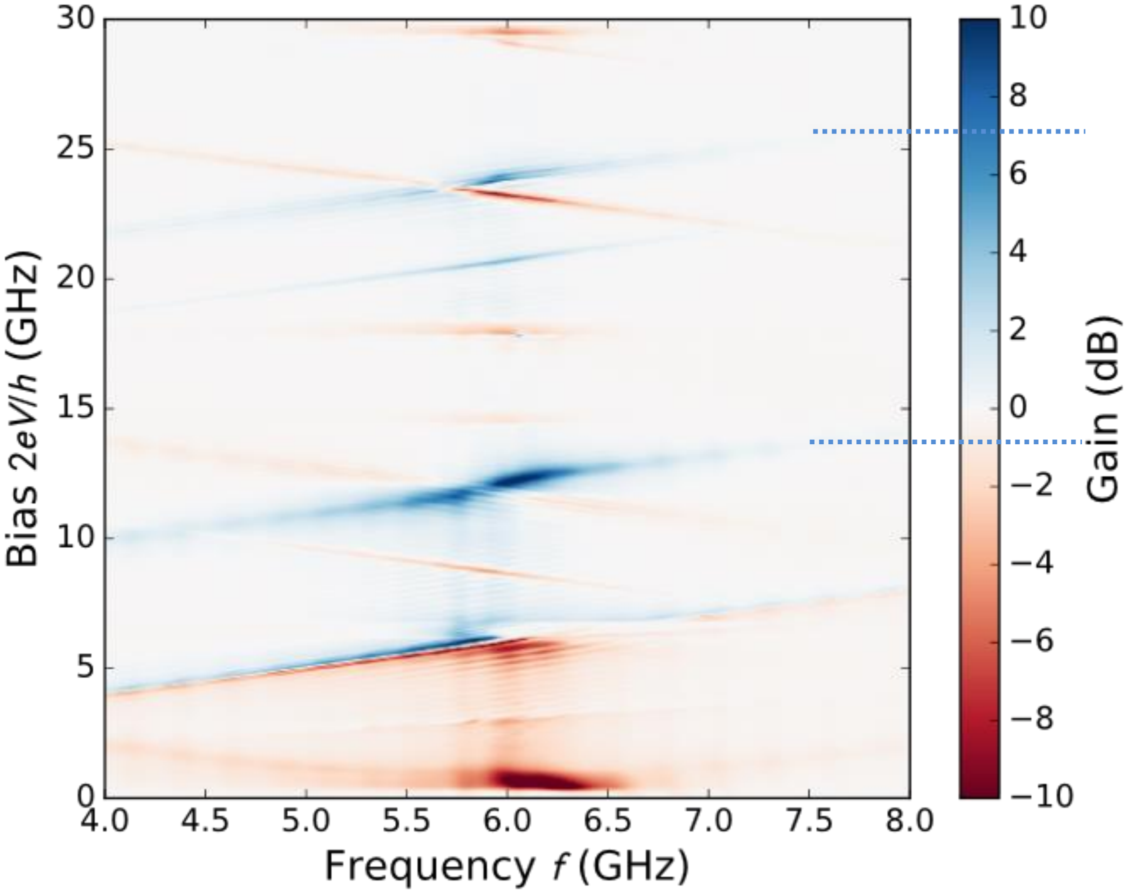

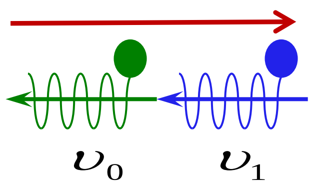

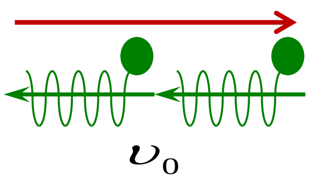

G > 0 dB
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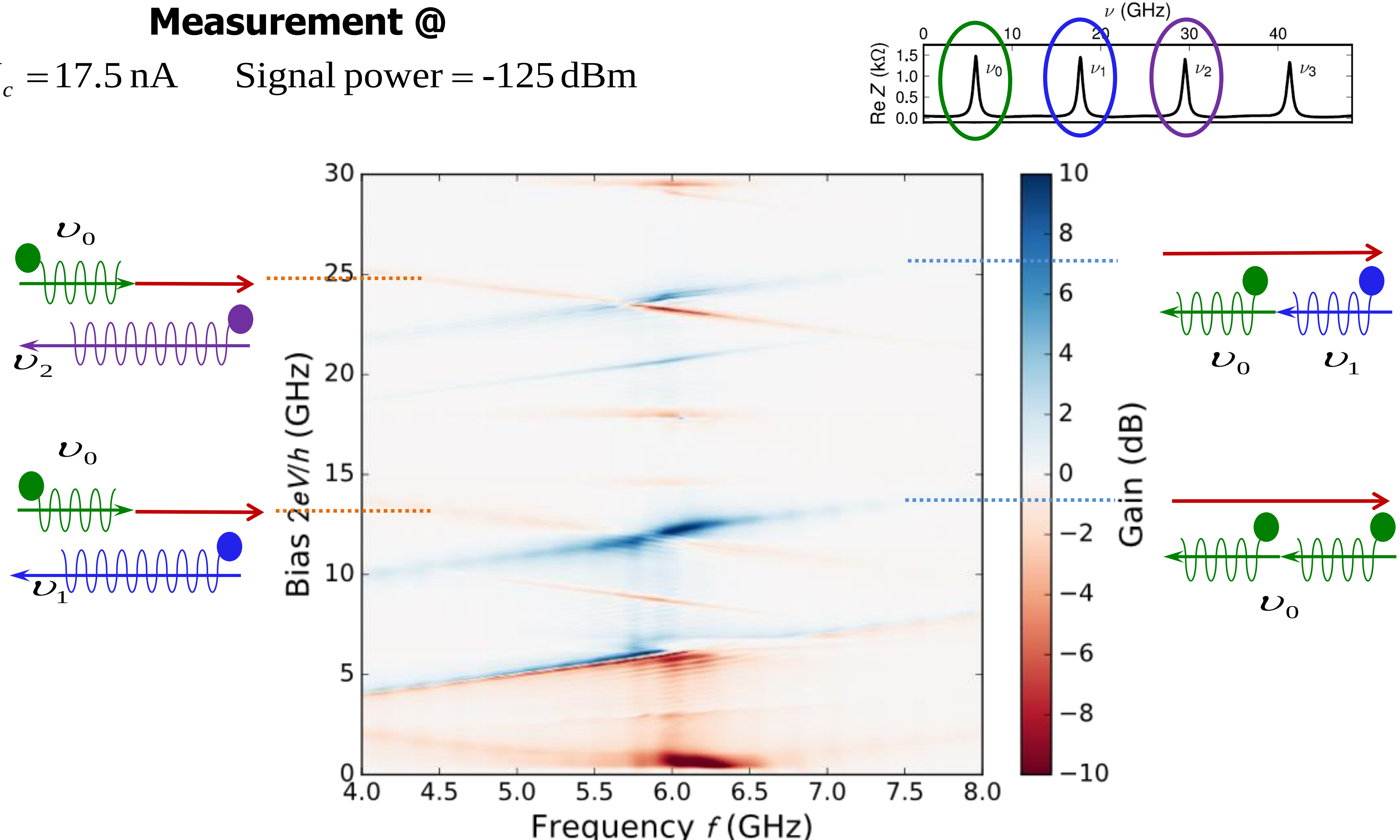

G < 0 dB
To eliminate

G > 0 dB
To preserve

Measurement of higher order terms

$$H_{sys} \approx \hbar\omega_a a^+ a + \hbar\omega_b b^+ b - E_J \cos(\frac{2eVt}{\hbar} + \rho_a (a^+ + a) + \rho_b (b^+ + b))$$

$$\Downarrow$$

$$H_{sys} = \hbar\omega_a a^+ a + \hbar\omega_b b^+ b + \hbar\lambda (a^+ b^+ e^{-i\omega_J t} + h.c.)$$

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$$H_{sys} \approx \hbar\omega_a a^+ a + \hbar\omega_b b^+ b - E_J \cos\left(\frac{2eVt}{\hbar} + \rho_a (a^+ + a) + \rho_b (b^+ + b)\right)$$

$$H_{sys} \approx \hbar\omega_a a^+ a + \hbar\omega_b b^+ b - \frac{E_J}{2}\left\{ e^{-i\omega_j t} e^{-\frac{i}{2}\rho_a} e^{-\frac{i}{2}\rho_b} \right\}\left\{ \sum_{n=0}^{\infty} \frac{1}{n!} (-i\rho_a a^+)^n \sum_{m=0}^{\infty} \frac{1}{m!} (-i\rho_b b^+)^m \sum_{p=0}^{\infty} \frac{1}{p!} (-i\rho_a a)^p \sum_{q=0}^{\infty} \frac{1}{q!} (-i\rho_b b)^q \right\} + h.c.$$

$$H = \ldots\alpha (a^+)^2 b e^{-i(\omega_j - 2\omega_a + \omega_b)} + \ldots + \beta a b (c^+)^3 e^{-i(\omega_j + \omega_b - 3\omega_c)} + \ldots$$

$$H_{sys} = \hbar\omega_a a^+ a + \hbar\omega_b b^+ b + \hbar\lambda (a^+ b^+ e^{-i\omega_J t} + h.c.)$$

Measurement of higher order terms

$$H_{sys} \approx \hbar\omega_a a^+ a + \hbar\omega_b b^+ b - E_J \cos\left(\frac{2eVt}{\hbar} + \rho_a (a^+ + a) + \rho_b (b^+ + b)\right)$$

$$H_{sys} \approx \hbar\omega_a a^+ a + \hbar\omega_b b^+ b - \frac{E_J}{2}\left\{ e^{-i\omega_J t} e^{-\frac{i}{2}\rho_a} e^{-\frac{i}{2}\rho_b} \left\{ \sum_{n=0}^{\infty} \frac{1}{n!}(-i\rho_a a^+)^n \sum_{m=0}^{\infty} \frac{1}{m!}(-i\rho_b b^+)^m \sum_{p=0}^{\infty} \frac{1}{p!}(-i\rho_a a)^p \sum_{q=0}^{\infty} \frac{1}{q!}(-i\rho_b b)^q \right\} \right\} + h.c.$$

$$H = \ldots\alpha (a^+)^2 b e^{-i(\omega_j - 2\omega_a + \omega_b)} + \ldots + \beta a b (c^+)^3 e^{-i(\omega_j + \omega_b - 3\omega_c)} + \ldots$$

High signal power

$$H_{sys} = \hbar\omega_a a^+ a + \hbar\omega_b b^+ b + \hbar\lambda (a^+ b^+ e^{-i\omega_J t} + h.c.)$$

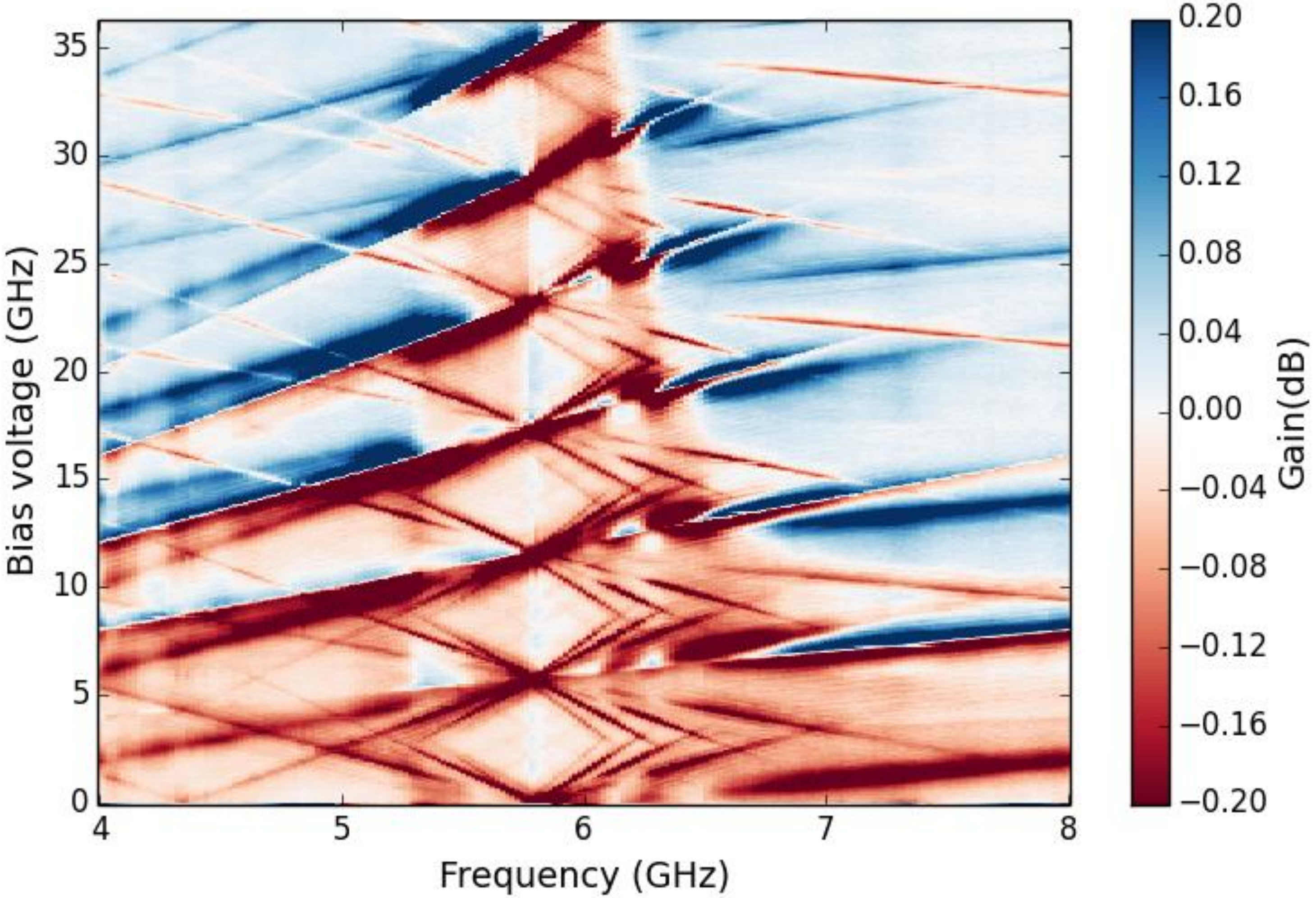
Low signal power

QUESTION !

Measurement of higher order terms

Measurement @

$I_c = 17.5\,\text{nA}$ Signal power = -90 dBm

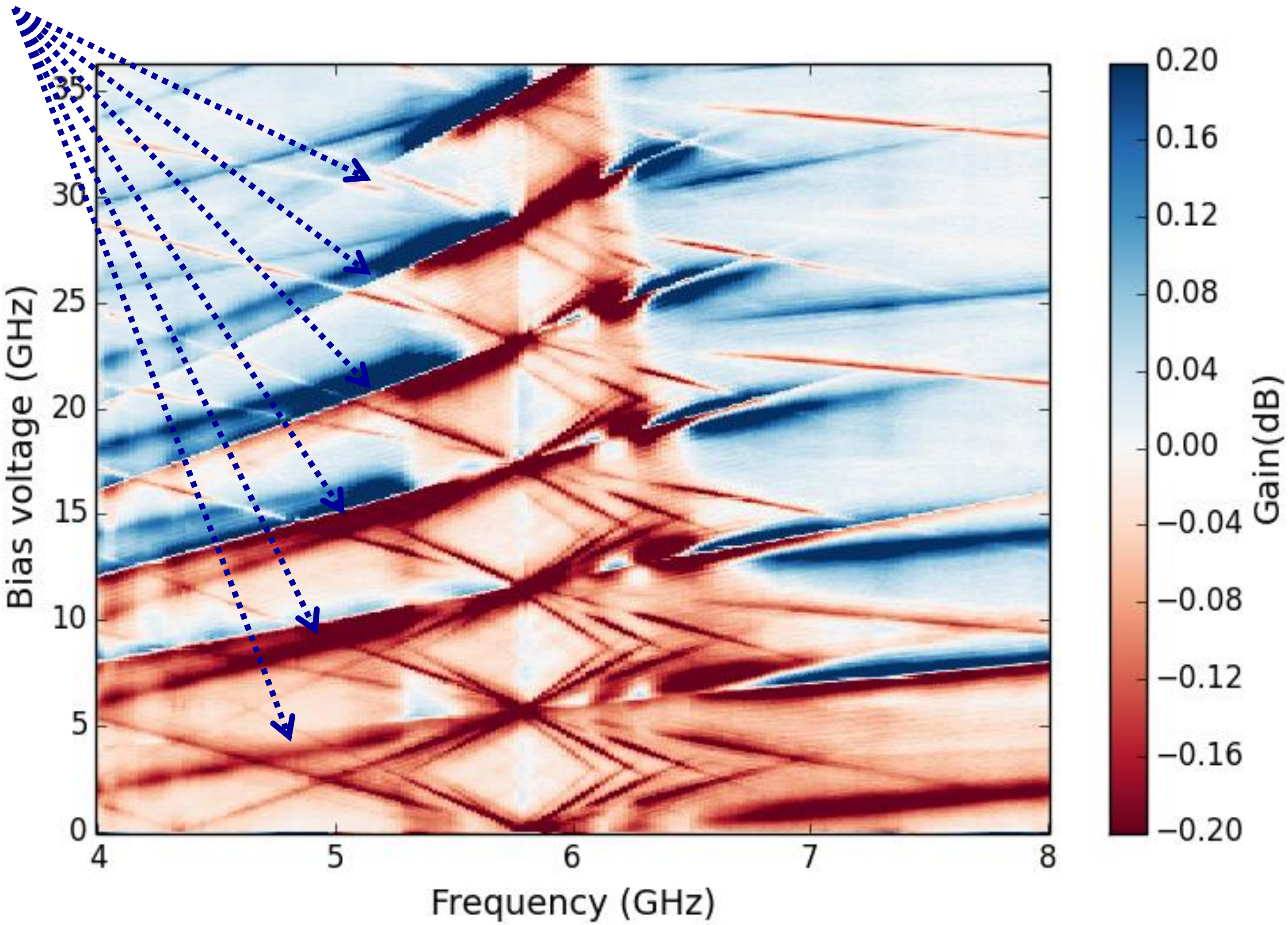


Measurement of higher order terms

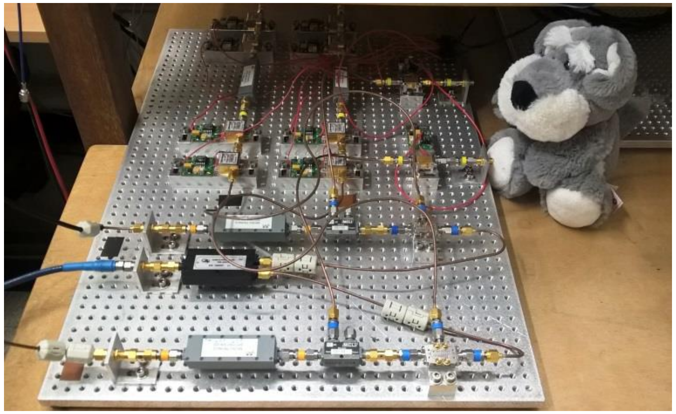
$$\tilde{I}(2eV) = \delta(0)\sum_n \left| J_n\left(\frac{2eU}{\hbar\omega_0}\right) \right|^2 I(2eV - n\hbar\omega_0)$$

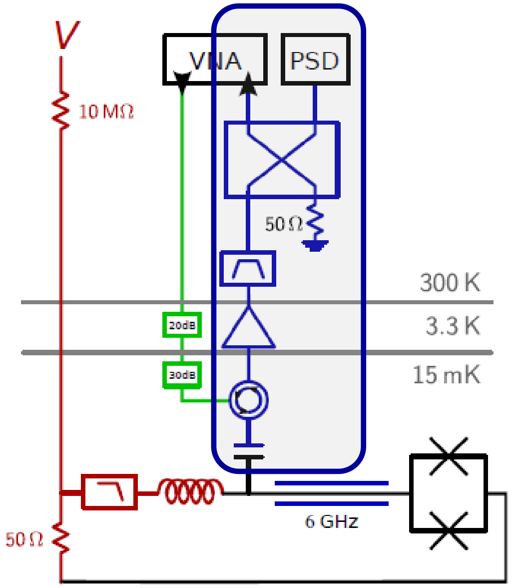
Measurement @

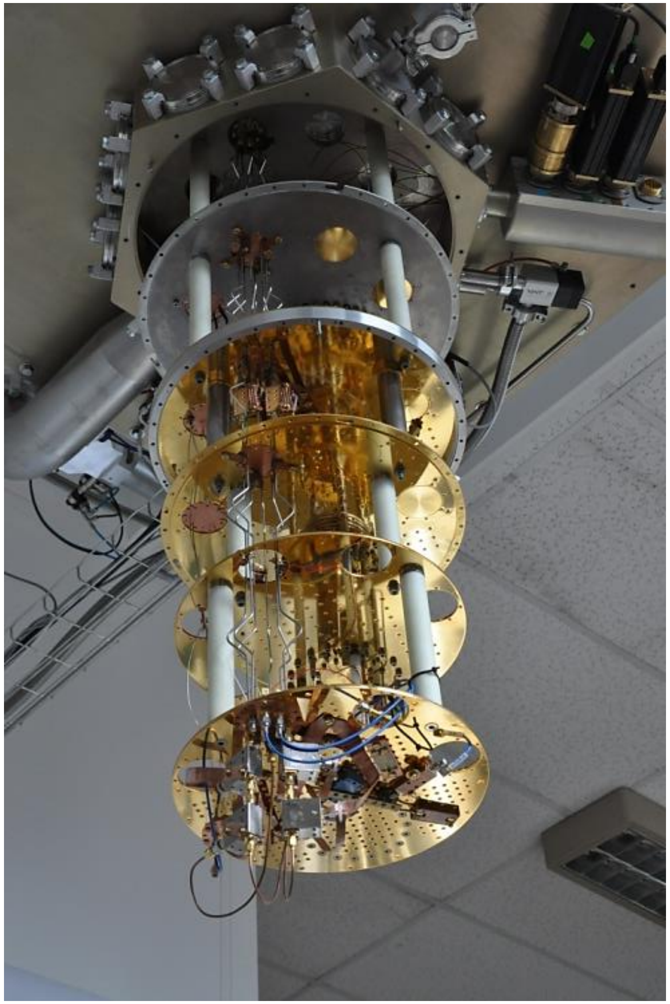
$I_c = 17.5\,\text{nA}$ Signal power = -90 dBm



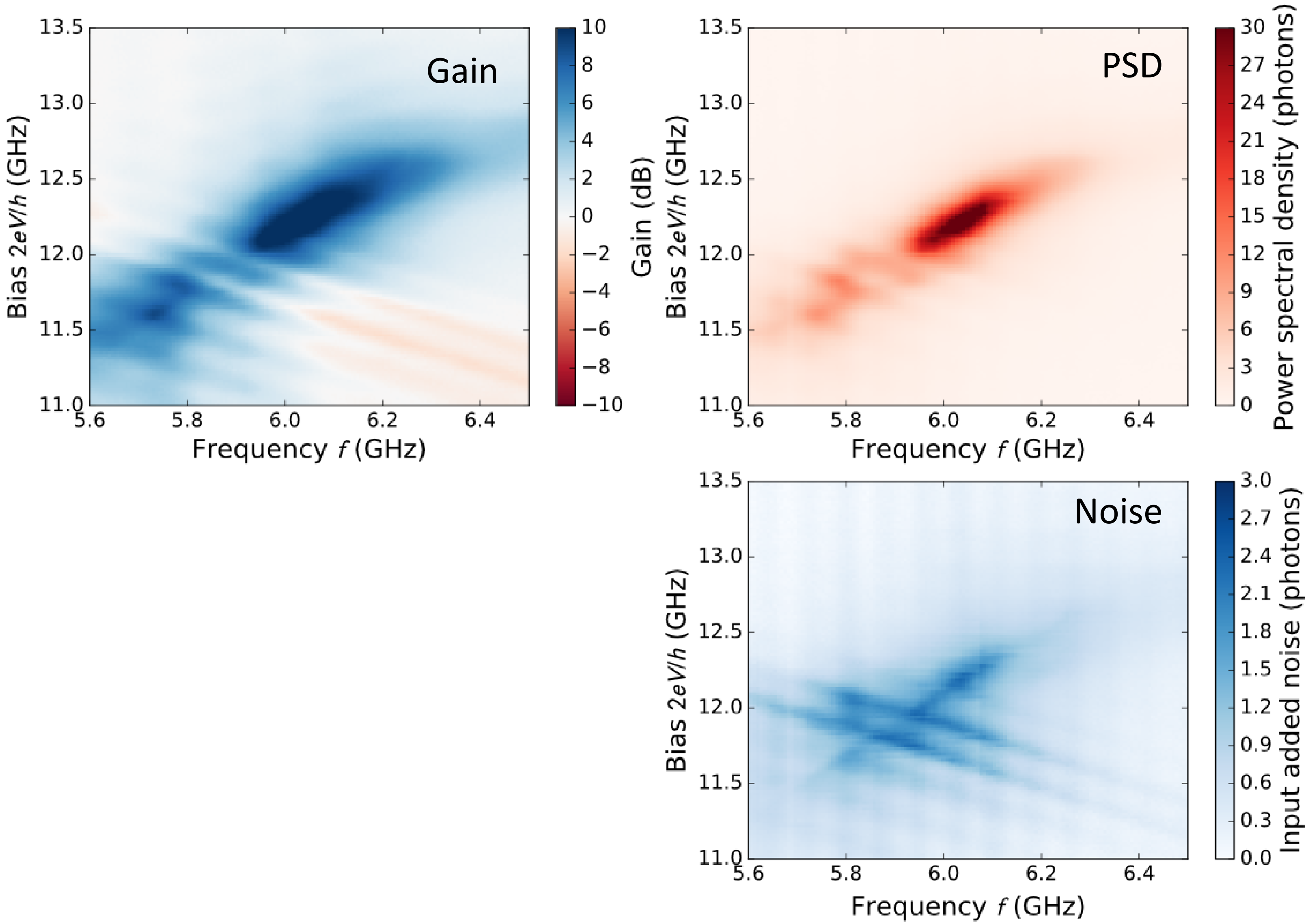
PSD measurement



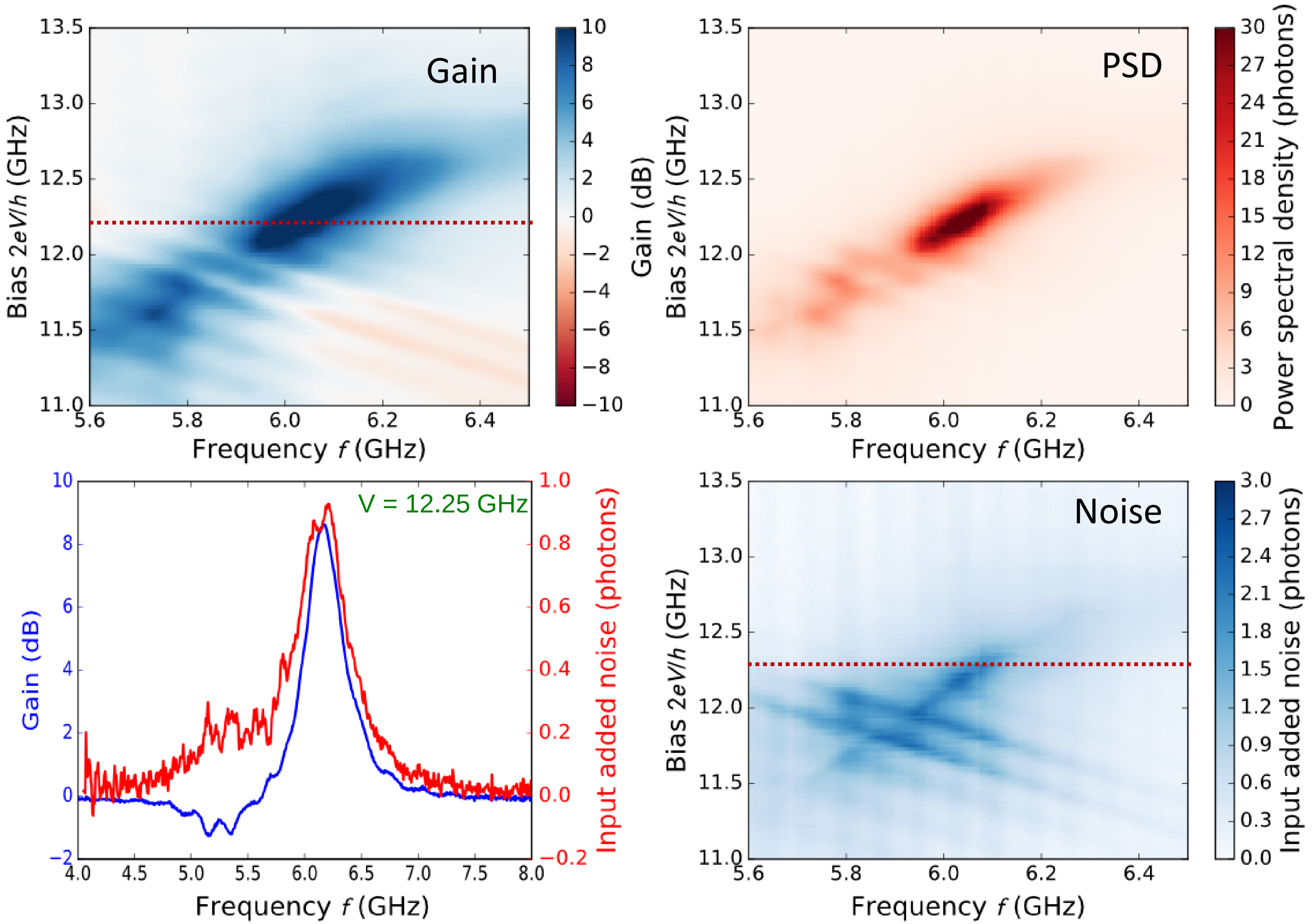




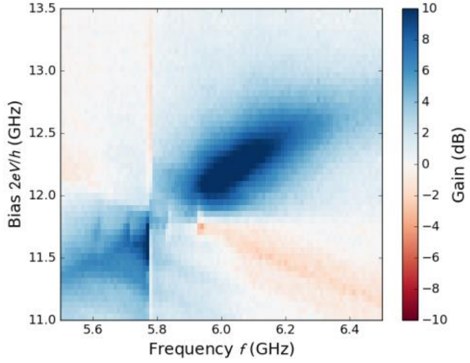
Noise measurement



Noise measurement



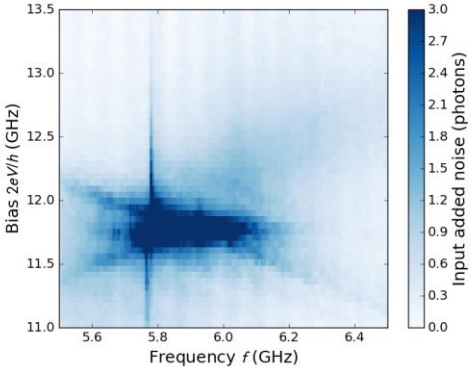
Summary



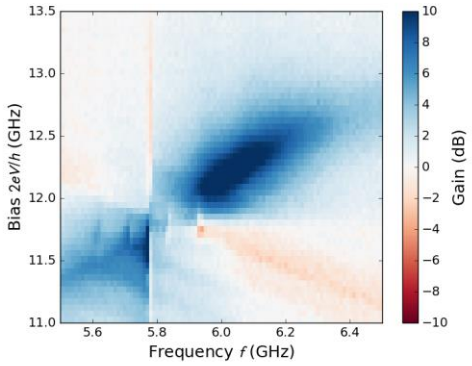
First generation of ICTA
Test sample

Sample **NOT** designed for amplification:

- ➢ 10 dB gain over 280 MHz
- ➢ Noise 0.9 photons: 1.8 * quantum limit

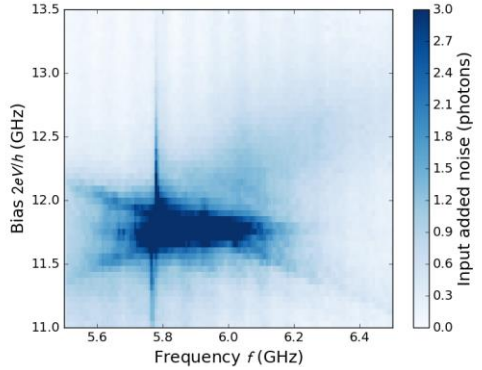


Summary



First generation of ICTA
Test sample

Sample **NOT** designed for amplification:
- ➢ 10 dB gain over 280 MHz
- ➢ Noise 0.9 photons: 1.8 * quantum limit

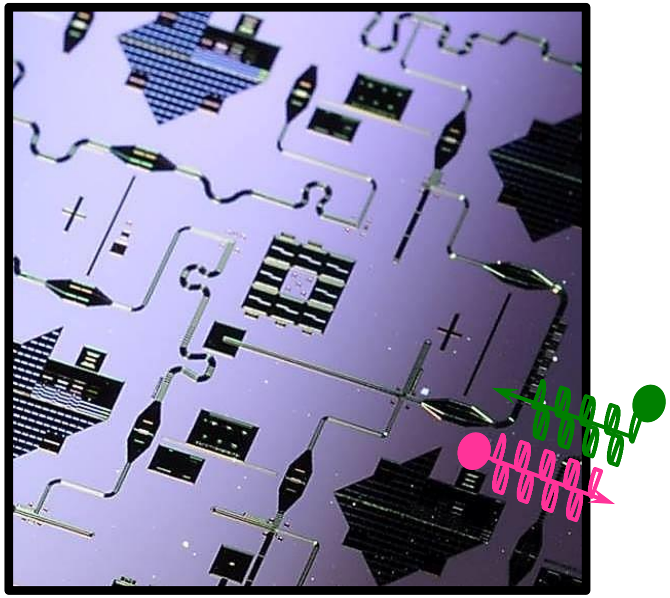


Second generation of ICTA
Real sample

Points to optimize
- ❖ Eleminate frequency conversion process
- ❖ Increase junction size
- ❖ Lower resonator quality factor
- ❖ Reduce voltage noise
- ❖ Idler @ 100 GHz

By using NbN superconductor

Salha Jebari and Max Hofheinz ,
patent application FR 16 58429
Submitted on 09-09-2016



Outline

Part 1

From dynamic Coulomb blockade physics to Josephson parametric amplifier physics:

Theory, Measurement results with Aluminium (Al) sample

Part 2

Optimization of parameters of ICTA samples:

Niobium Nitride (NbN) sample

Single Cooper pair photonics group

DE LA RECHERCHE À L'INDUSTRIE cea

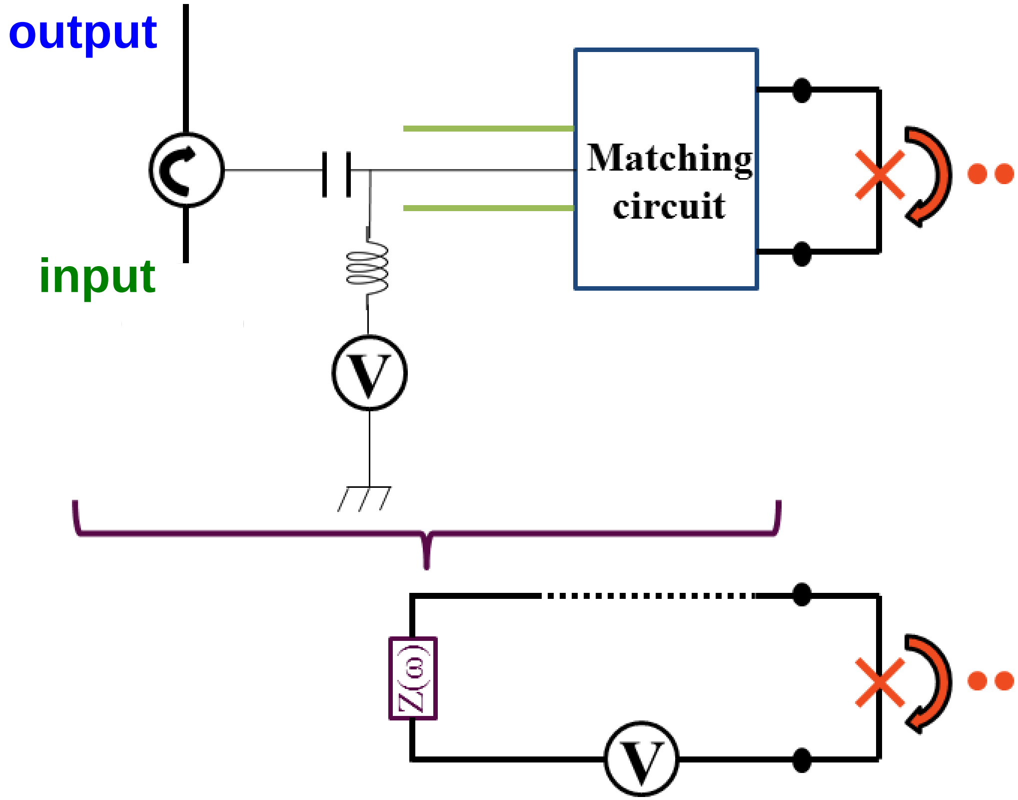
INAC INSTITUT NANOSCIENCES ET CRYOGÉNIE

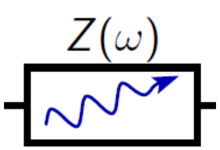
nanoSCIENCES FONDATION

erc

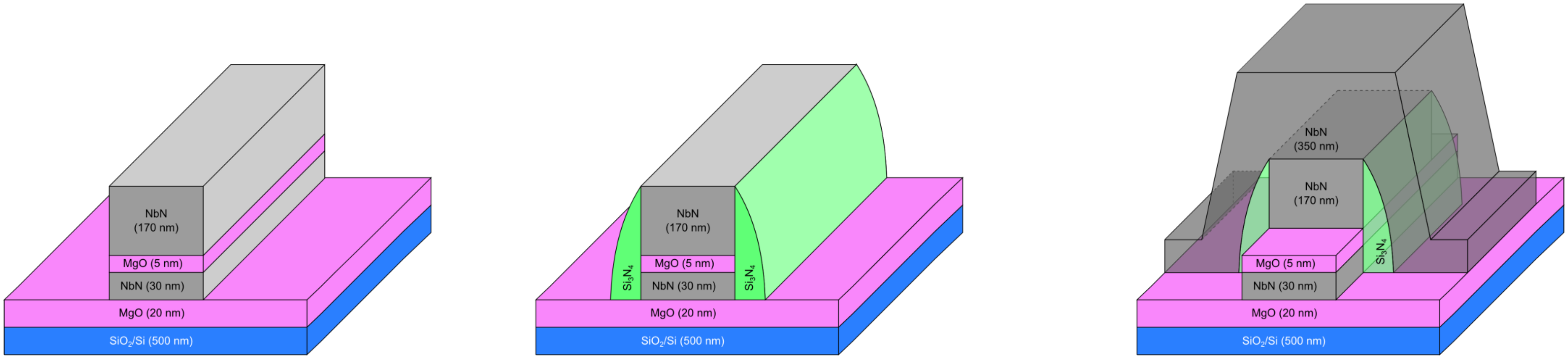
UNIVERSITÉ GRENOBLE ALPES

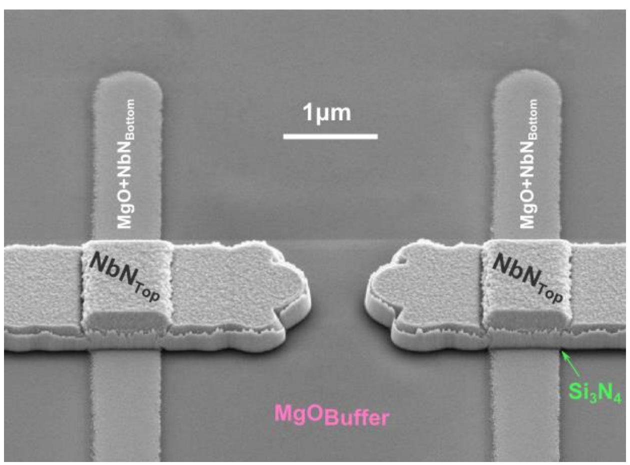
Our ICTA implementation



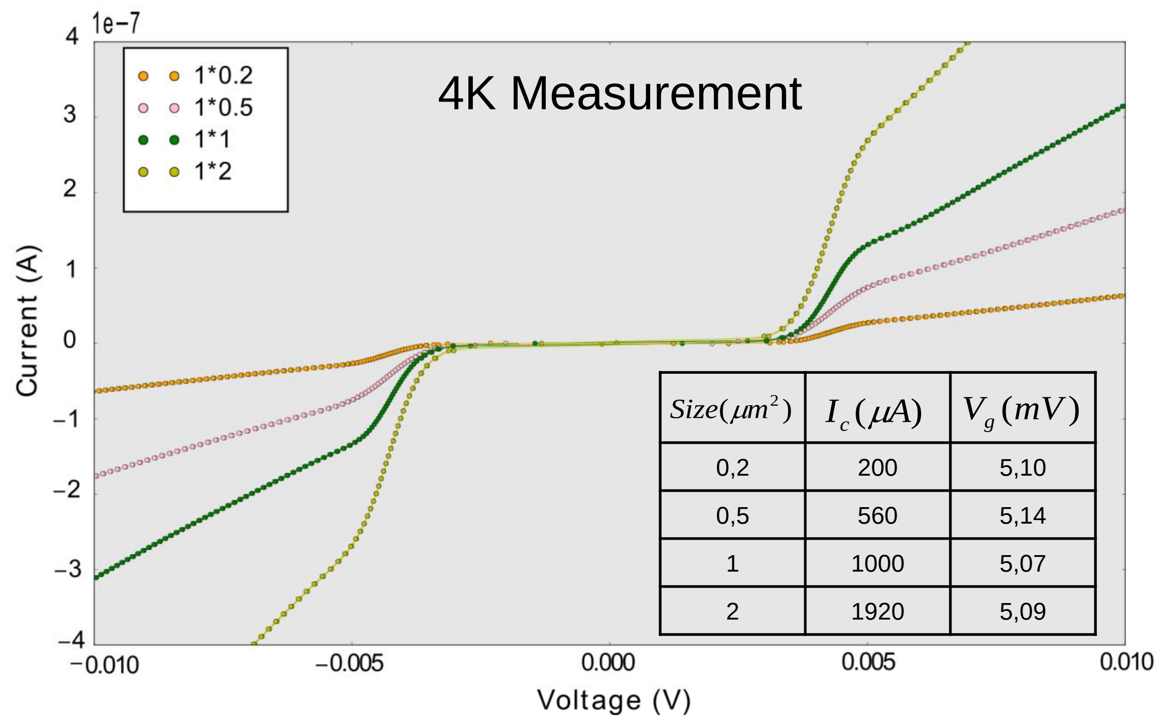


NbN/MgO/NbN Josephson junction





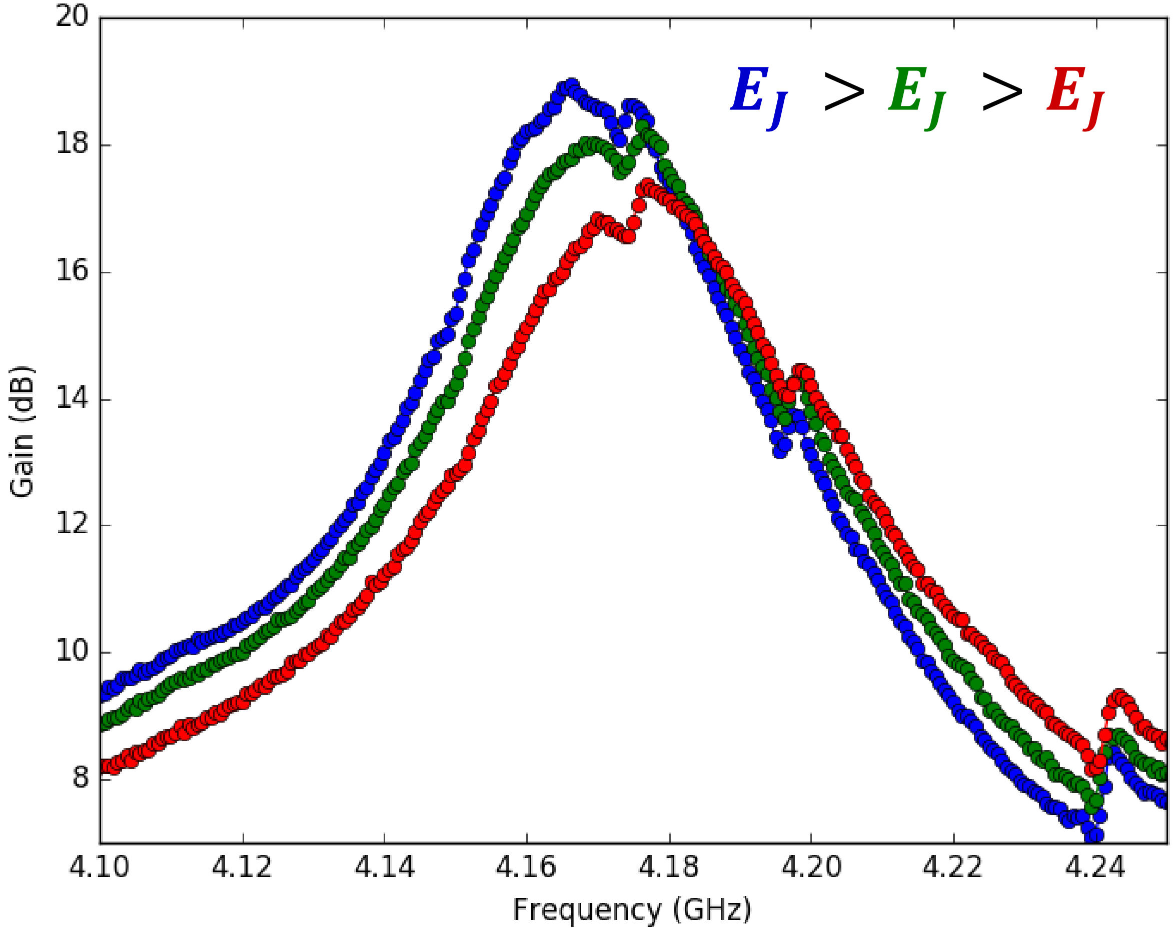
SEM of SQUID



$Size(\mu m^2)$	$I_c(\mu A)$	$V_g(mV)$
0,2	200	5,10
0,5	560	5,14
1	1000	5,07
2	1920	5,09

First proof of amplification using NbN samples

Similaire sample with big Josephson junction

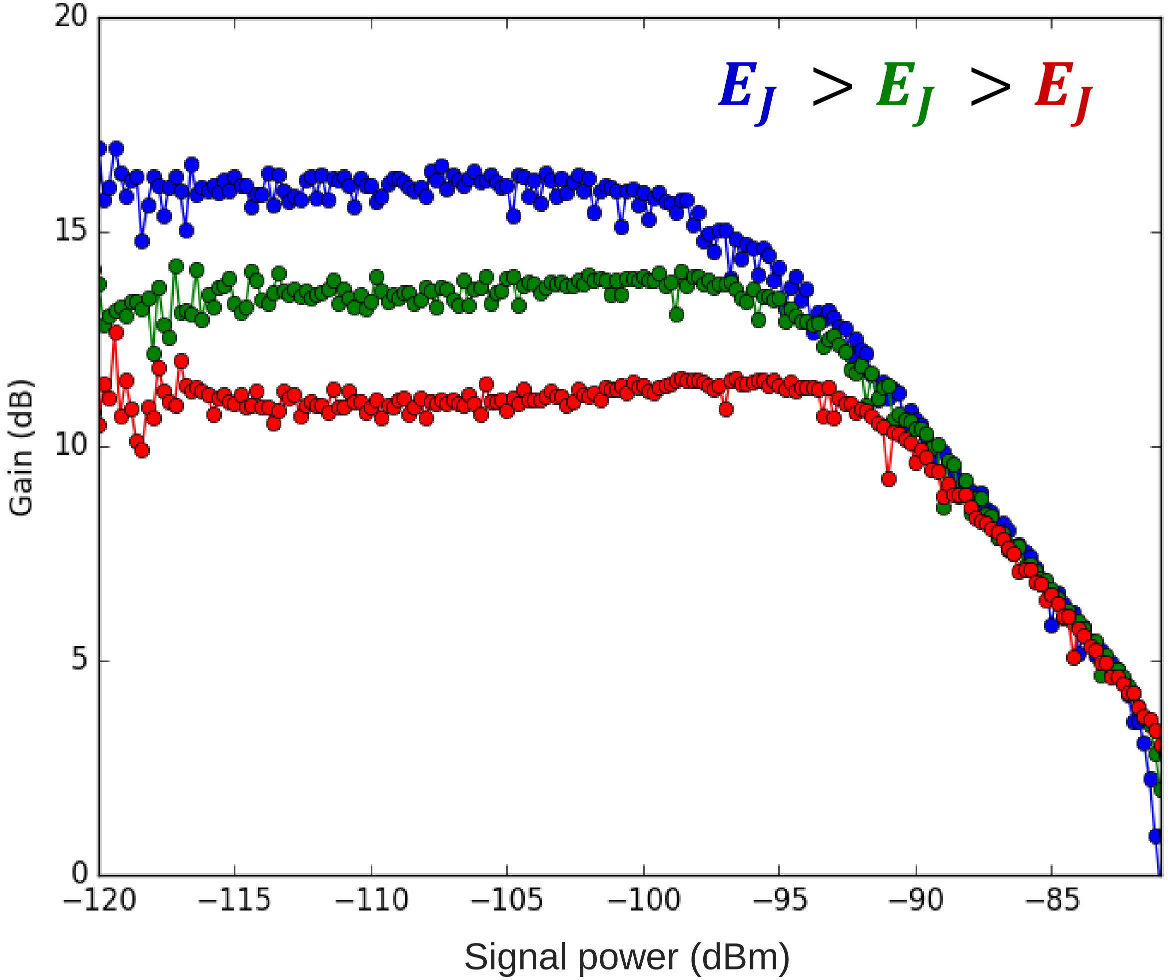


Maximum of measured gain is 22.5 dB over 50 MHz

Josephson junction energy ↗ Gain ↗

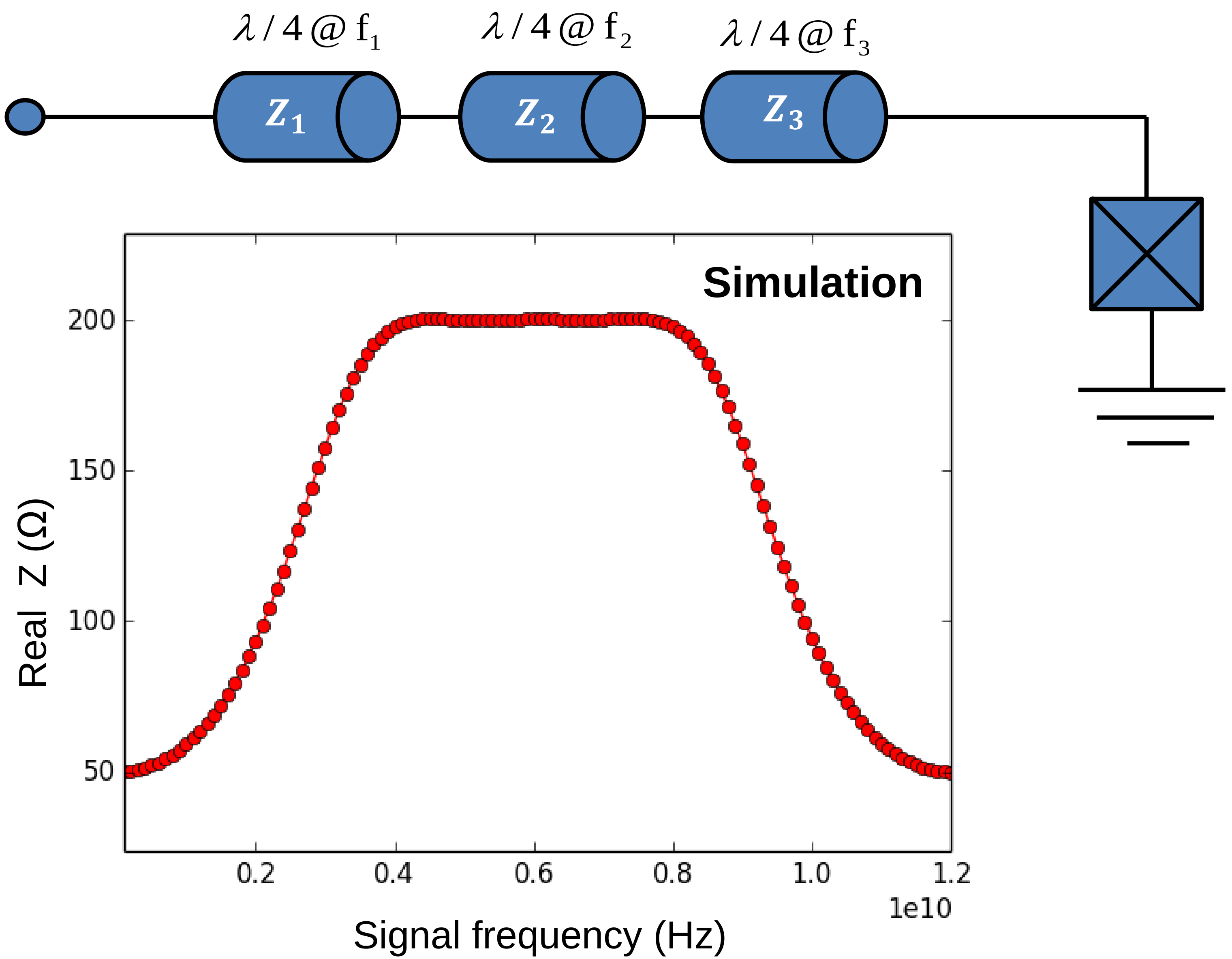
First proof of amplification using NbN samples

Similaire sample with big Josephson junction

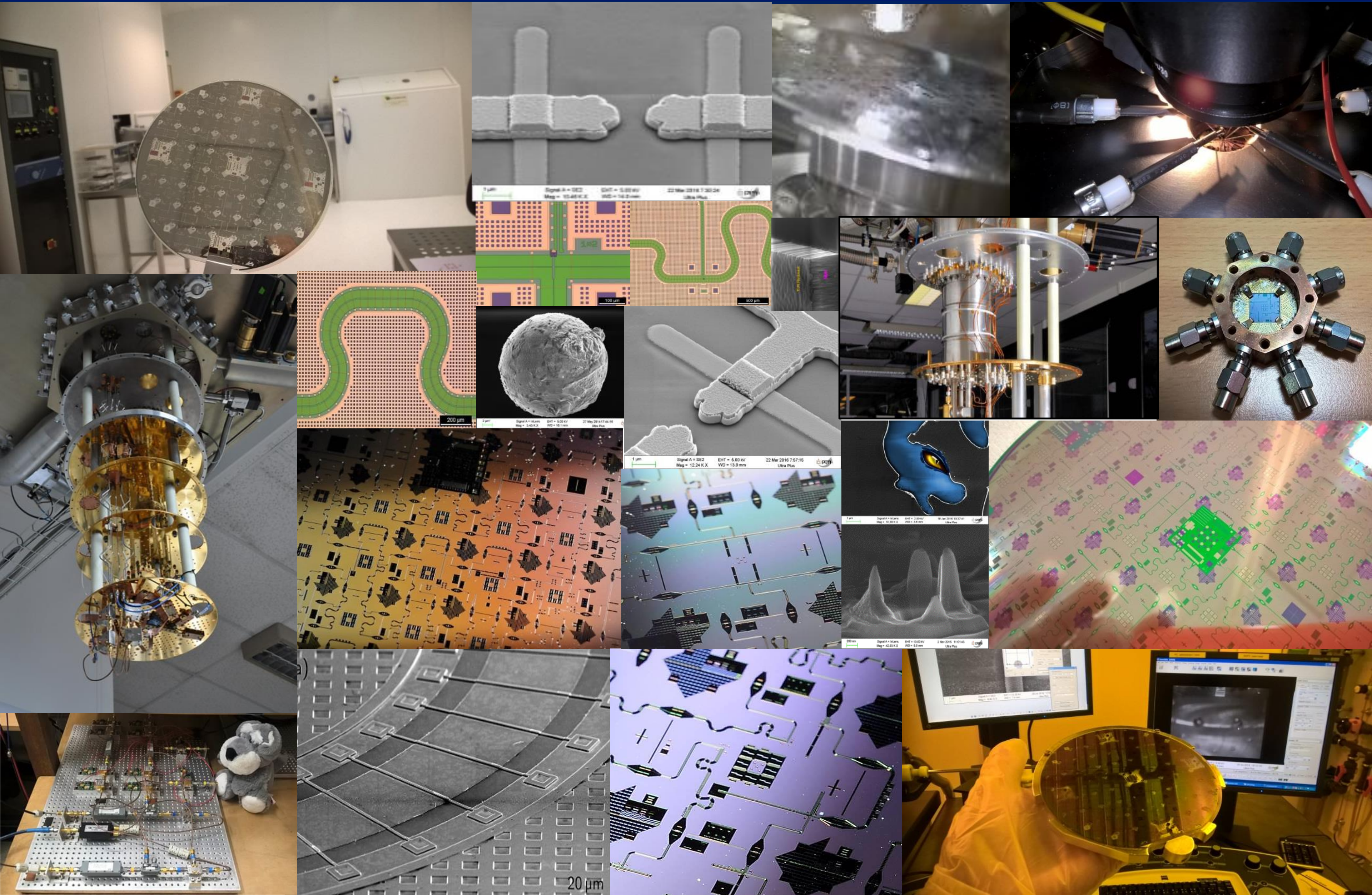


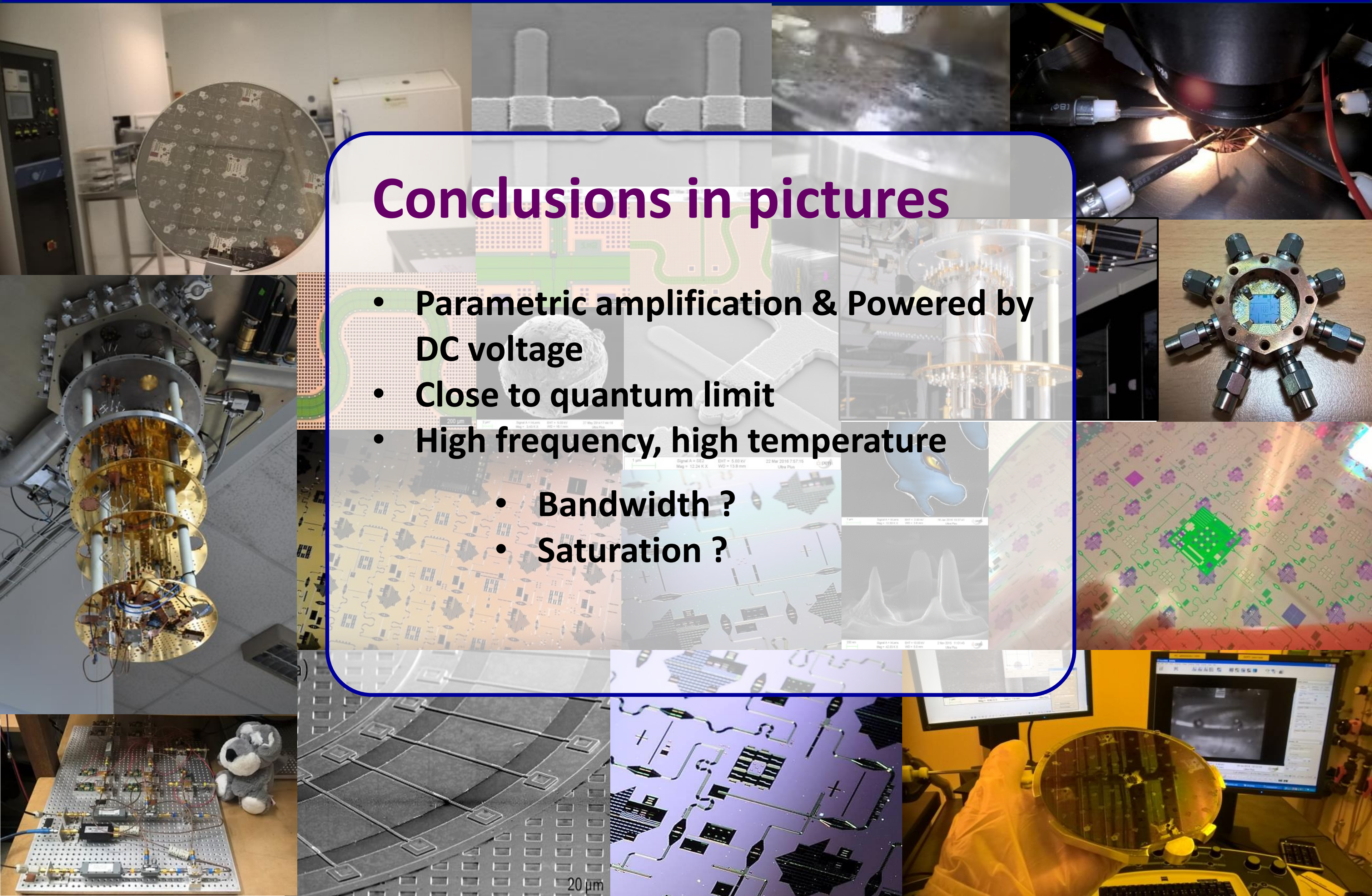
1 dB compression point : -97 dBm

First proof of amplification using NbN samples



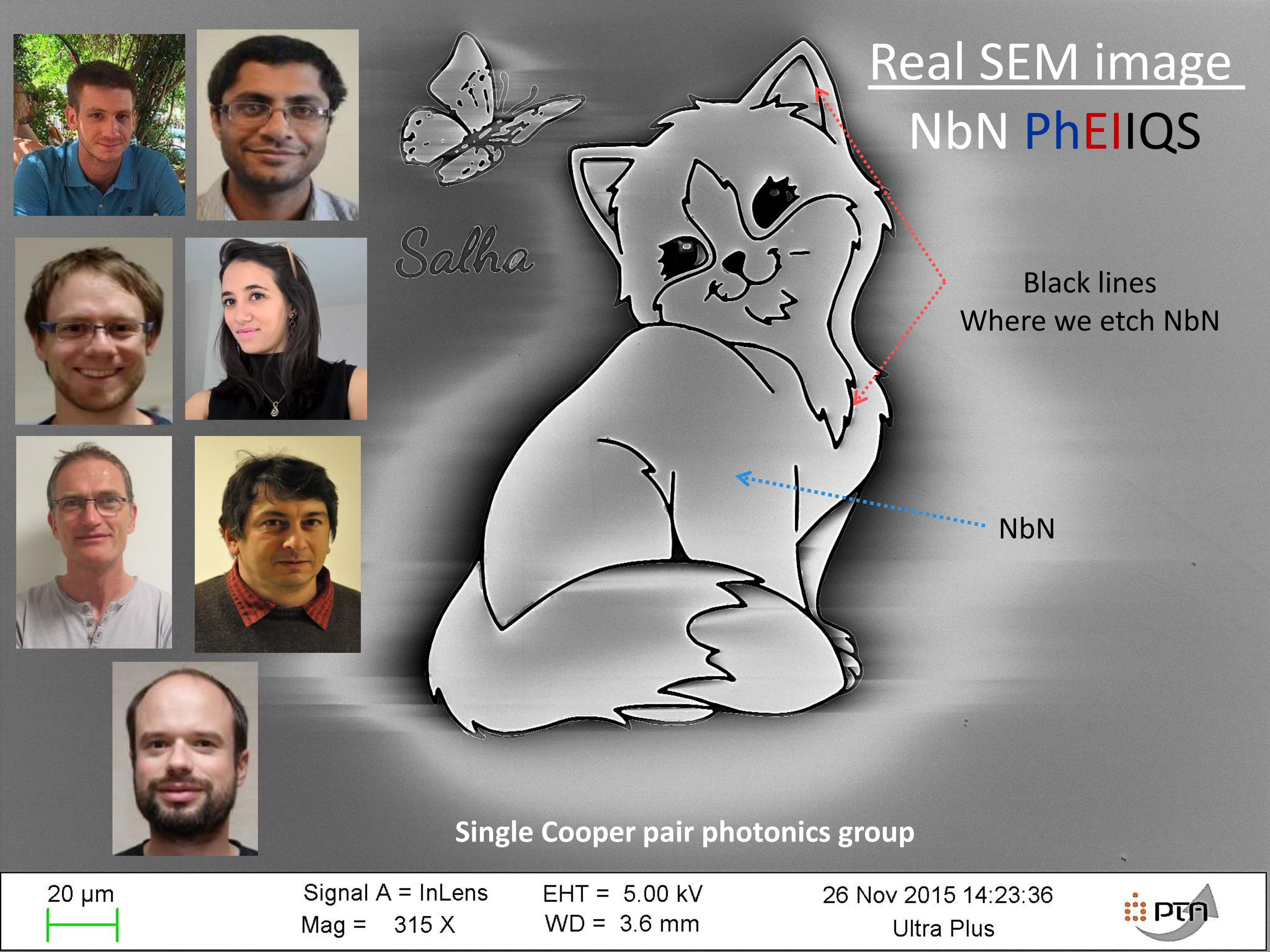
Single Cooper pair photonics group : ICTA project





Conclusions in pictures

- Parametric amplification & Powered by DC voltage
- Close to quantum limit
- High frequency, high temperature
    - Bandwidth ?
    - Saturation ?



Real SEM image
NbN PhEIIQS
Salha
Black lines
Where we etch NbN
NbN
Single Cooper pair photonics group
20 µm
Signal A = InLens
Mag = 315 X
EHT = 5.00 kV
WD = 3.6 mm
26 Nov 2015 14:23:36
Ultra Plus