Josephson Photonics Devices for BREAD

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INSTITUT QUANTIQUE

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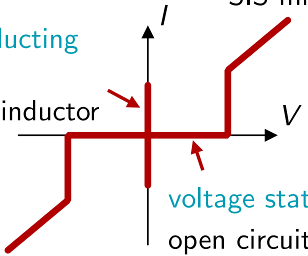
Josephson junction IV: Semi-classical view

Josephson junction in the voltage state is also dissipationless!

superconducting state:
nonlinear inductor

QP tunnelling:
SIS mixers



voltage state:
open circuit?

$$I = I_C \sin(\omega_J t)$$

$$\omega_J = \frac{2eV}{\hbar}, \quad I_C = \frac{2eE_J}{\hbar}$$

AC current but no DC current

Holst *et al.*, Phys. Rev. Lett. **73**, 3455 (1994)

Ingold, Nazarov, in Single Charge Tunnelling, cond-mat/0508728 (1992)

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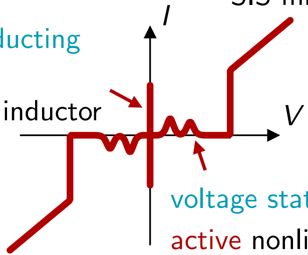
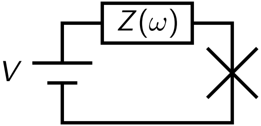


voltage state:
active nonlinear drive



$$I = I_\mathrm{C} \sin(\omega_\mathrm{J} t)$$

$$\omega_\mathrm{J} = \frac{2eV}{\hbar}, \qquad I_\mathrm{C} = \frac{2eE_\mathrm{J}}{\hbar}$$

Dissipated power

$$P = \mathrm{Re}\, Z(\omega_\mathrm{J}) \frac{{I_\mathrm{C}}^2}{2}$$

Power is drawn from bias:

$$I = \frac{P}{V} = \frac{2e}{\hbar} \frac{\mathrm{Re}\, Z(\omega_\mathrm{J})}{\omega_\mathrm{J}} \frac{{I_\mathrm{C}}^2}{2}$$

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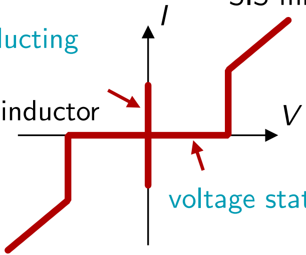
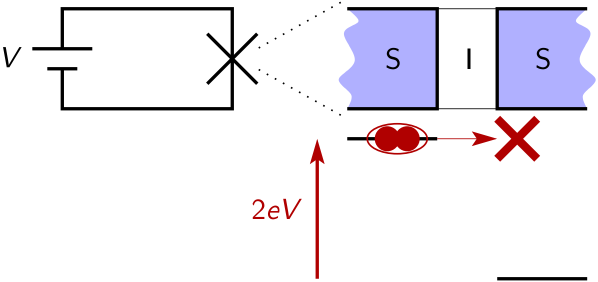


voltage state:



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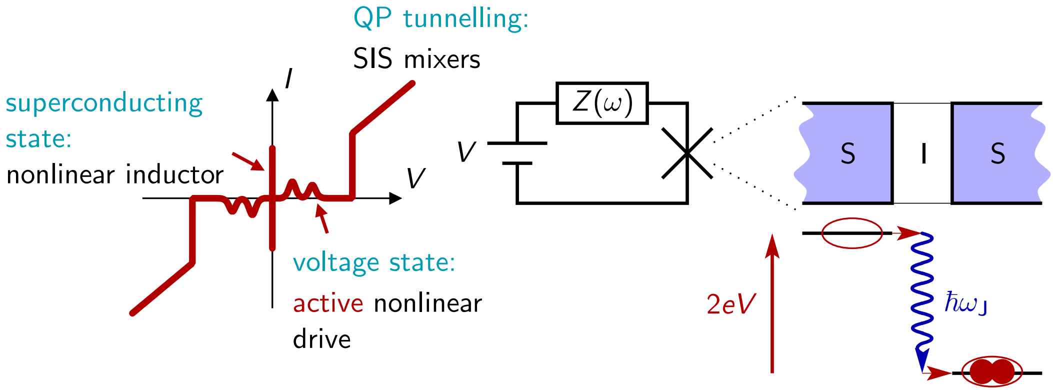

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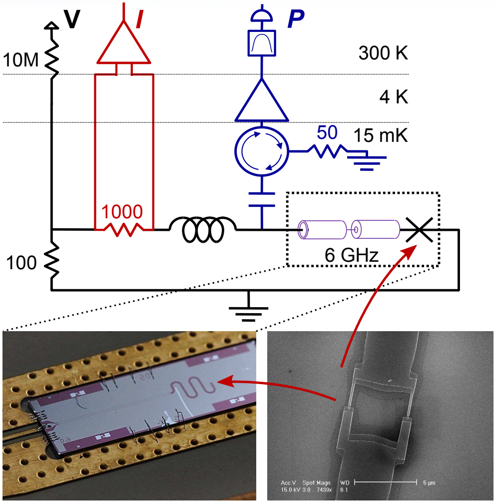
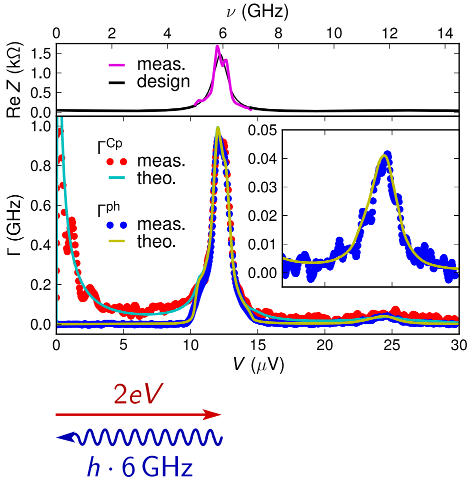
Bright side of inelastic Cooper-pair tunnelling





Hofheinz *et al.*, Phys. Rev. Lett. **106**, 217005 (2011)

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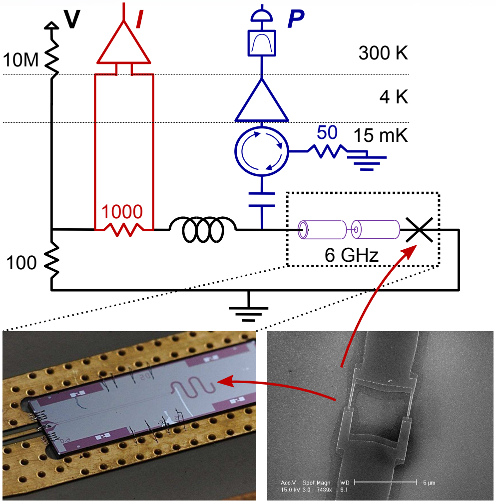

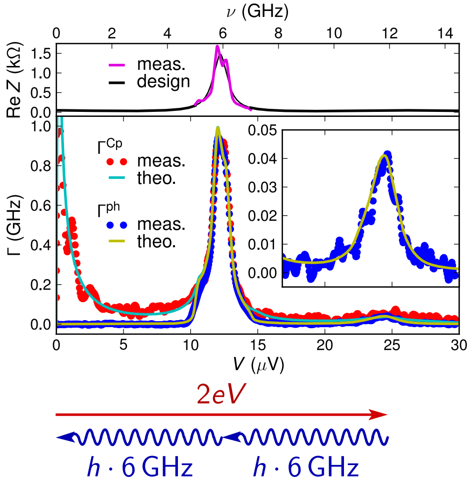

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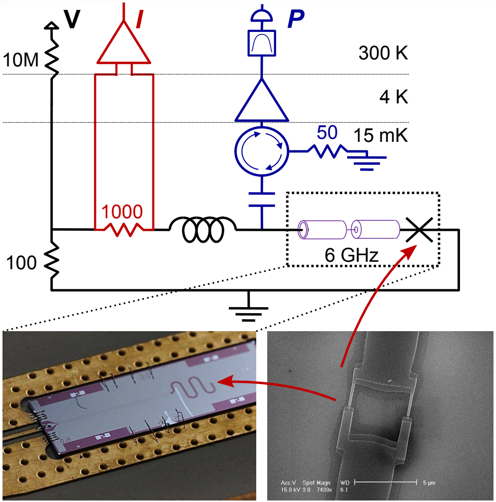

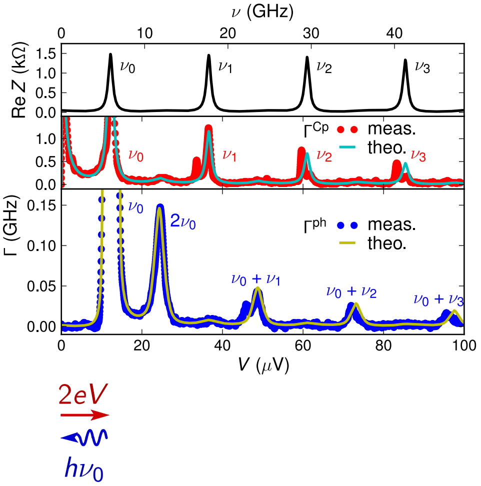

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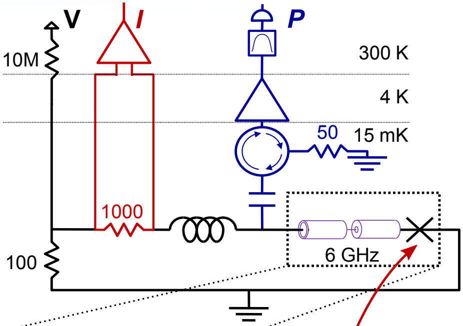

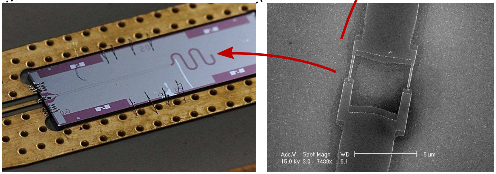

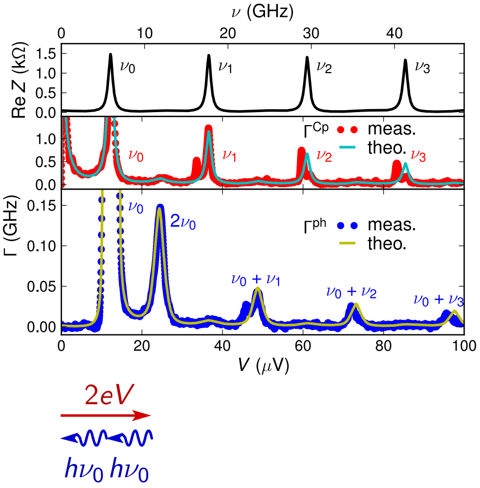

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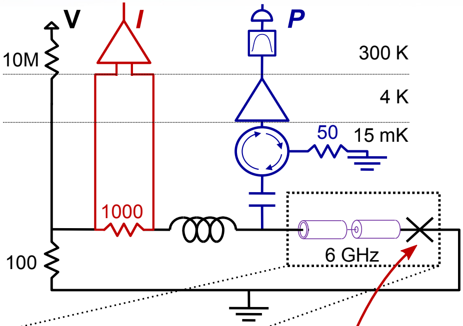

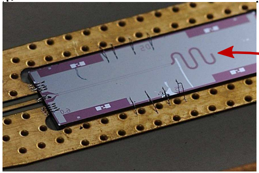

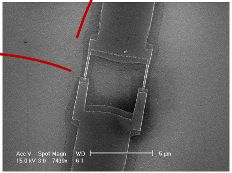

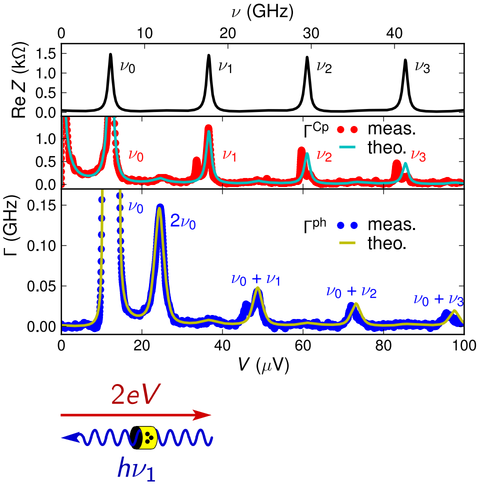

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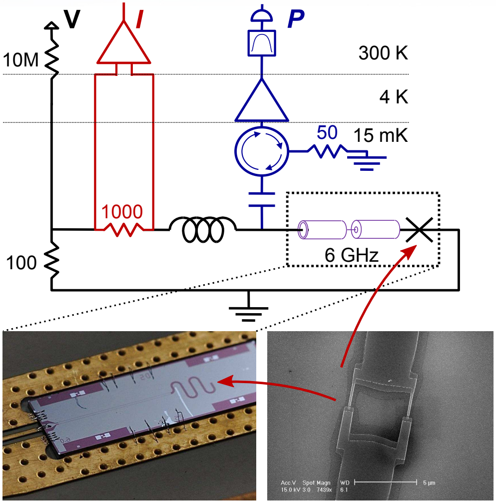

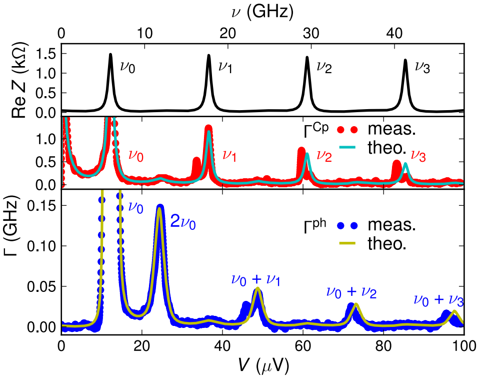

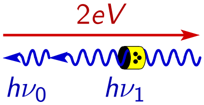

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Josephson photonics

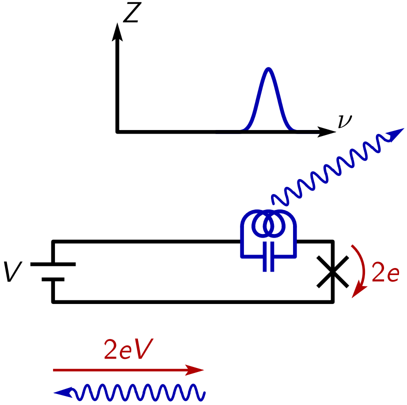
Engineering $Z(\nu)$ ⟶ Full toolbox for wideband quantum microwave devices

Sources

- **Coherent**
- Single photons
- Entangled photons

Measurement

- Amplifiers
- Frequency shifters
- Photomultipliers



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Hofheinz *et al.*,
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Gramich *et al.*,
Phys. Rev. Lett. **111** 247002 (2013)

Chen *et al.*,
Phys. Rev. B **90**, 020506(R) (2014)

Cassidy *et al.*,
Science **355** 939 (2017)

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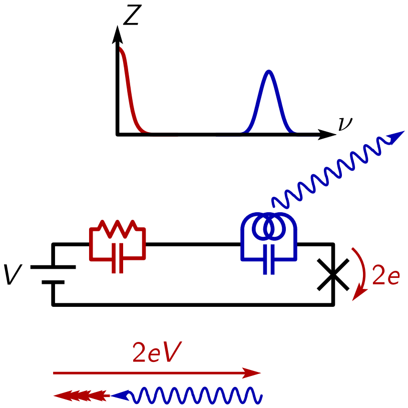

Leppäkangas *et al.*,
Phys. Rev. Lett. **115** 027004 (2015)

Armour *et al.*,
Phys. Rev. B **91** 184508 (2015)

Dambach *et al.*,
Phys. Rev. B **92** 054508 (2015)

Souquet *et al.*,
Phys. Rev. A **93** 060301 (2016)

Grimm *et al.*,
Phys. Rev. X **9** 021016 (2019)

Rolland *et al.*,
Phys. Rev. Lett. **122** 186804 (2019)

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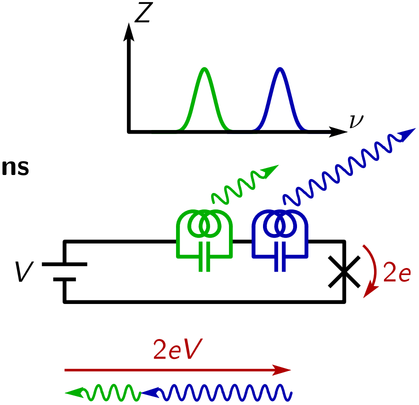

Padurariu *et al.*,
prb **86** 054514 (2012)

Leppäkangas *et al.*,
Phys. Rev. Lett. **110** 267004 (2013)

Trif *et al.*,
Phys. Rev. B **92** 014503 (2015)

Westig *et al.*,
Phys. Rev. Lett. **119** 137001 (2017)

Wood *et al.*,
Phys. Rev. B **104** 155424 (2021)

Peugeot *et al.*,
Phys. Rev. X **3** 031008 (2021)

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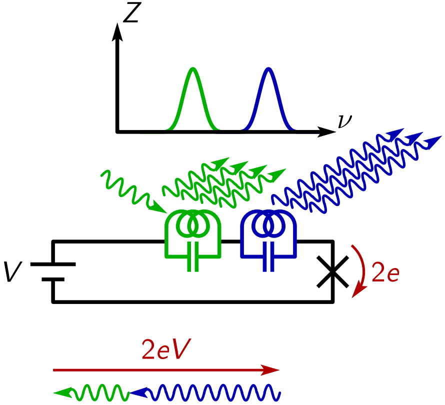

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Lähteenmäki *et al.*,
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Jebari *et al.*,
Nat. Electron. **1** 223 (2018)

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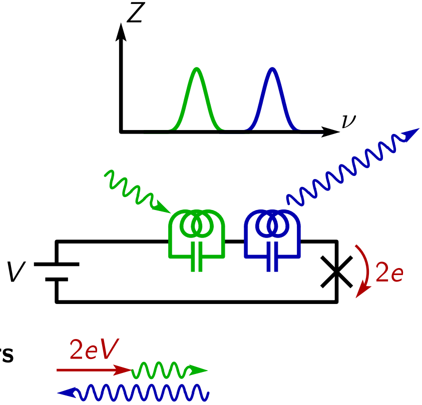

Leppäkangas *et al.*,
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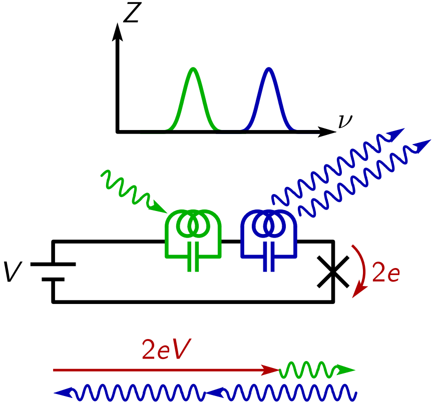

Leppäkangas *et al.*,
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Albert *et al.*,
Phys. Rev. X **14** 011011 (2024)

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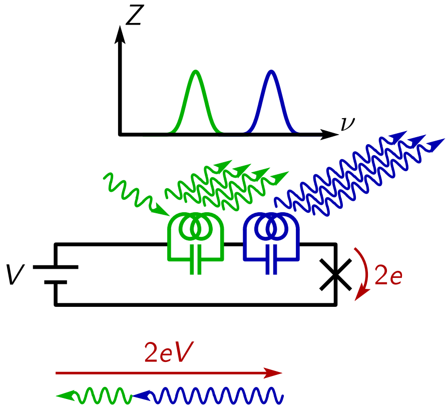

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The quantum limit of noise

Linear phase-preserving amplification:

$$\langle o \rangle = \sqrt{G}\langle a \rangle$$

Need additional idler mode b to satisfy commutation relations $[o, o^\dagger] = [a, a^\dagger] = 1$:

$$o = \sqrt{G}a + \sqrt{G-1}b^\dagger$$

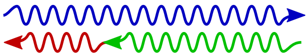
Minimal input-referred noise:

$$N_{\text{in}} = \frac{\langle o^\dagger o \rangle}{G} = \frac{(G-1)\langle b b^\dagger \rangle}{G} \geq \frac{G-1}{G}$$

Caves, Phys. Rev. D **26** 1817 (1982)

Limit reached by (Josephson) parametric amplifiers:

$$H = g c a^\dagger b^\dagger + \text{h.c.}$$



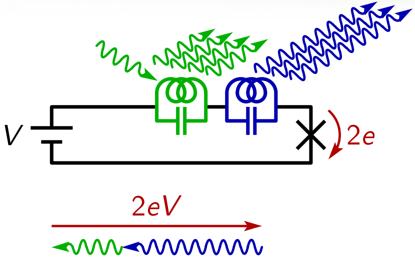
The Inelastic Cooper pair tunnelling amplifier (ICTA)

$$H = \hbar\omega_a a^\dagger a + \hbar\omega_b b^\dagger b - E_J\cos(\phi)$$

with

$$\phi = \omega_J t + \varphi_a\left(a^\dagger + a\right) + \varphi_b\left(b^\dagger + b\right)$$

$$\varphi_i = \sqrt{\pi\frac{4e^2}{h}Z_i}$$



- Suppose small fields $\varphi_a a$, $\varphi_b b \ll 1$ ➜ expand to second order in $\varphi_a a$ and $\varphi_b b$
- Suppose $\frac{\varphi_a E_J}{2\hbar}, \frac{\varphi_b E_J}{2\hbar} \ll |\omega_a - \omega_b|$ ➜ RWA at $\omega_J = \omega_a + \omega_b$

$$E_J\cos(\phi) = \frac{E_J}{2}\left(e^{i\phi} + \text{h.c.}\right) \approx \frac{E_J^*\varphi_a\varphi_b}{2}\left(e^{i\omega_J t}a^\dagger b^\dagger + \text{h.c.}\right)$$

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Usual parametric amplifier Hamiltonian

ICTA	↔	JPA
Josephson energy E_J	↔	pump power
0-point fluctuations φ_i	↔	participation ratio
voltage bias ω_J	↔	pump frequency

- Suppose small fields $\varphi_a a$, $\varphi_b b \ll 1$ ➔ expand to second order in $\varphi_a a$ and $\varphi_b b$
- Suppose $\frac{\varphi_a E_J}{2\hbar}$, $\frac{\varphi_b E_J}{2\hbar} \ll |\omega_a - \omega_b|$ ➔ RWA at $\omega_J = \omega_a + \omega_b$

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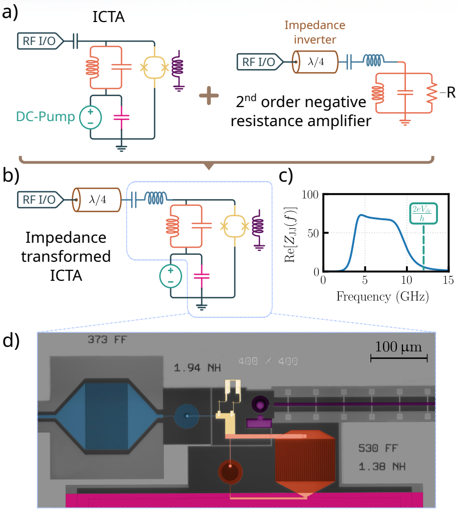
From there on standard JPA theory, e.g. Abdo *et al.* Phys. Rev. B **87** 014508 (2013):

Large gain when $E_J^* \varphi_a \varphi_b \to \hbar\sqrt{\gamma_a \gamma_b}$

Increasing bandwidth



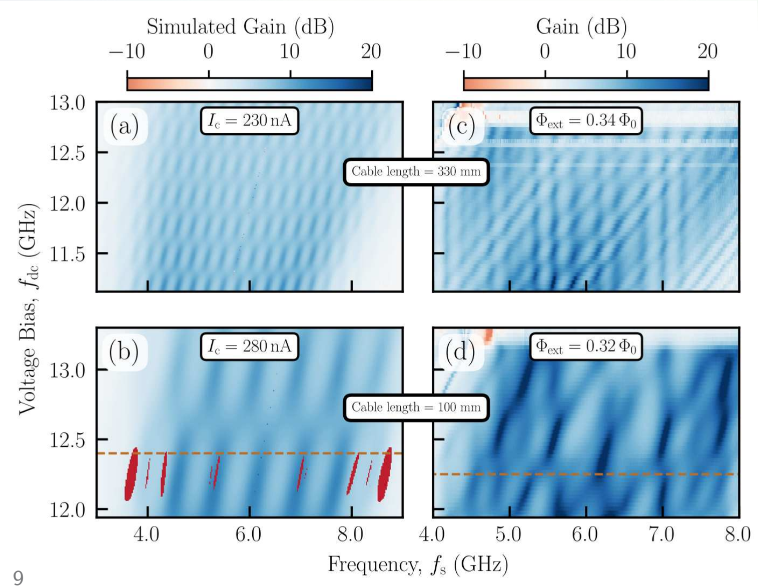
- Need low-Q low-impedance modes
- For 20 dB gain:

$$\xi = \frac{E_J^* \varphi_a \varphi_b}{\hbar\sqrt{\gamma_a \gamma_b}} \approx 0.8$$

Key challenge: parametric resonances

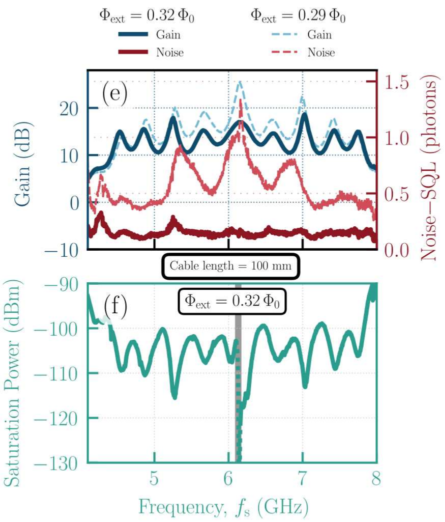
- Avoid $\xi > 1$ for any spurious signal–idler pair
- Fast out-of band roll-off of impedance

Broadband ICTA: Simulation vs Measurement



- Good agreement simulation/experiment
- Ripple due to standing waves in TL between circulator and amplifier
- Instability at some bias voltages

Broadband ICTA: Figures of merit



Bias: $2eV/h = 12.25\,\text{GHz}$

- ✔ average gain $\sim 13\,\text{dB}$
- ✔ near octave BW
- ✔ within 0.2 photons of QL
- saturation power $-106\,\text{dBm}$
- ✔ Power at $2eV/h$: $< -100\,\text{dBm}$
- ✗ reflection amplifier for now

Nehra *et al.*, arXiv:2512.19902

Inelastic Cooper-pair Tunnelling Amplifier

- ✔ Near quantum limited
- ✔ Useful saturation power
- ✔ Bandwidth close to TWPA
- Josephson inductance cancels
- → cleaner nonlinearity (no Kerr terms)
- → no plasma frequency
  - → ICTA should work up to gap
- ICTA does not need pump
- → Easier to operate at mm-wave frequencies

Jebari *et al.*, Nat. Electron. **1** 223 (2018)
Martel *et al.*, Appl. Phys. Lett. **126** 074001 (2025)
Nehra *et al.*, arXiv:2512.19902

Salha Jebari

Florian Blanchet

Ulrich Martel

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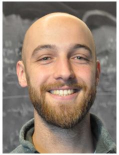
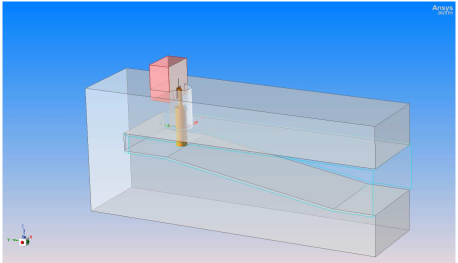


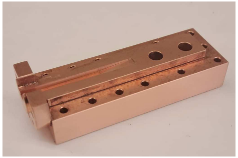
Baptiste Monge

mm-wave ICTA: where we are

W band (75 GHz to 110 GHz)

- ✔ Cryogenic W-band setup installed.
- ✔ HEMT amplifiers at 4 K and 300 K
- ✔ VNA extenders and custom receiver
- ✔ Device can be anchored to 100 mK or 1 K stage
  - Testing sample holder with WR10 – coax – CPW transition
  - Optimizing Y-factor calibration
  - First sample designs: resonators, narrowband (few GHz) ICTAs





Developing expertise with cryogenic mm-wave setups

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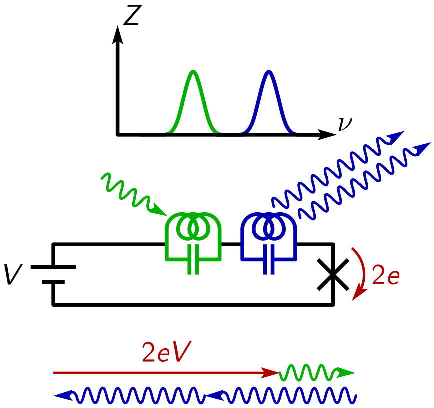
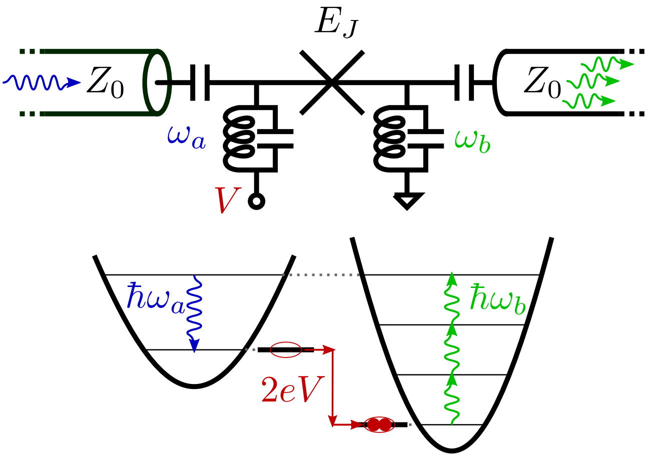


Leppäkangas *et al.*, Phys. Rev. A **97** 013855 (2018)

Albert *et al.*, Phys. Rev. X **14** 011011 (2024)

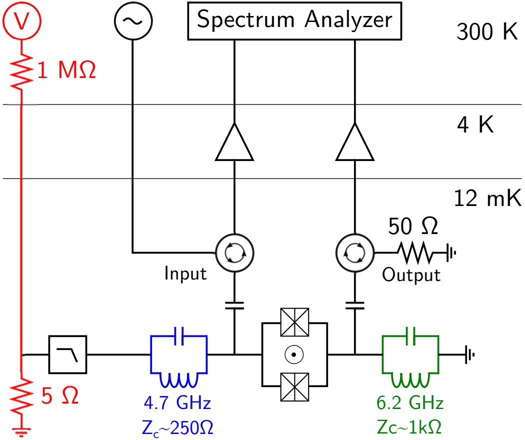
Strong nonlinearity: Photomultiplication



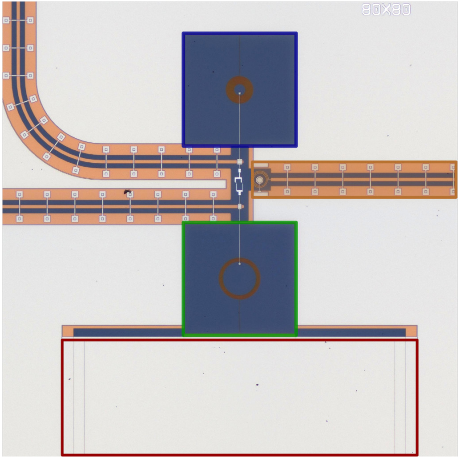
- spontaneous tunnelling forbidden
- incident photon provides energy complement
- → tunnelling creates several photons in other mode
- Preserves phase space volume
- Amplification of photon number by *n*
- *n* fold phase-symmetry

Leppäkangas *et al.*, Phys. Rev. A **97** 013855 (2018)

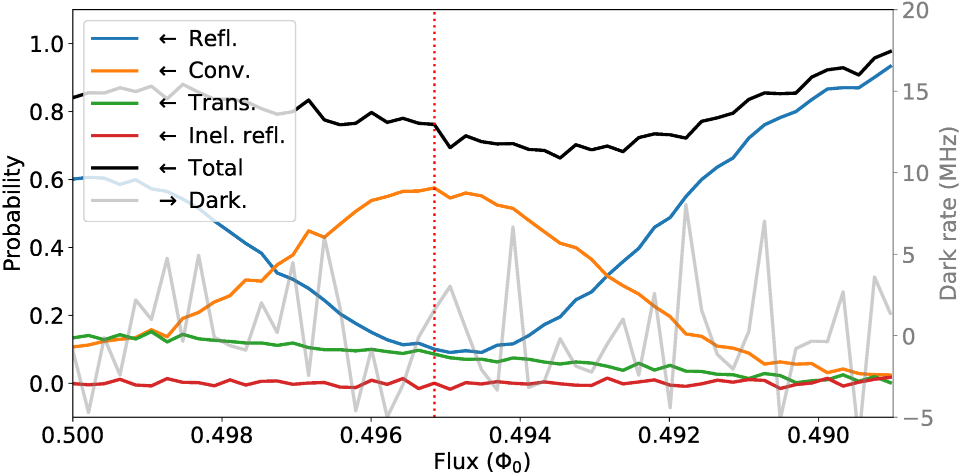
Device



Albert *et al.*, Phys. Rev. X **14** 011011 (2024)

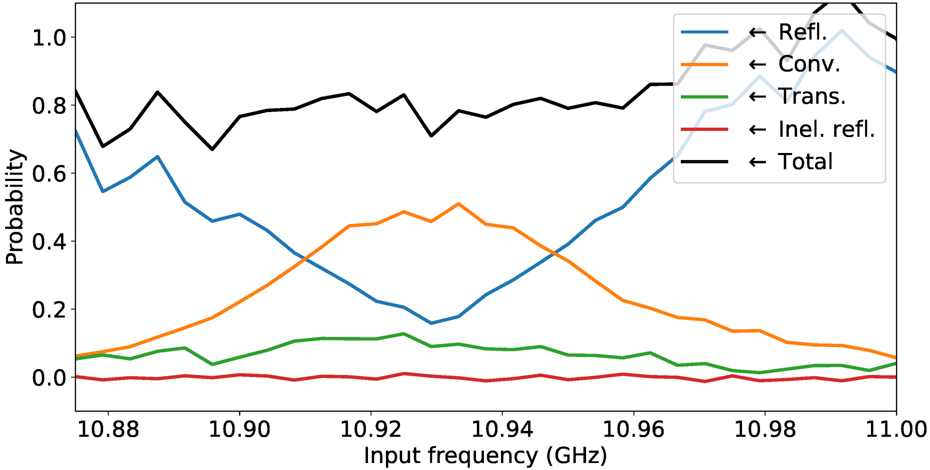


Conversion 1 ➡ 3



Input frequency	Input power	Bias $2eV/h$	Efficiency	Dark rate
10.933 GHz	−120 dBm	4.6 GHz	59 %	200 kHz

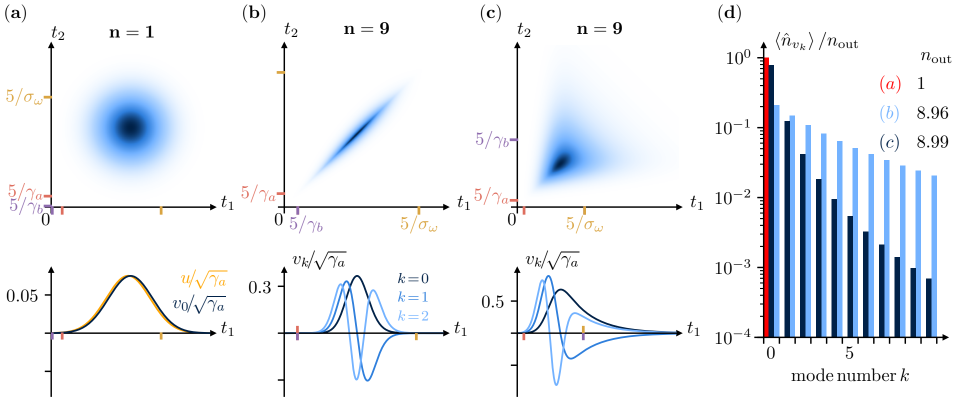
Bandwidth



Input power	Bias $2eV/h$	Flux	Efficiency	Bandwidth
-120 dBm	4.6 GHz	$0.497\,\phi_0$	0.59 %	50 MHz

Expected $G^{(1)}$ of output

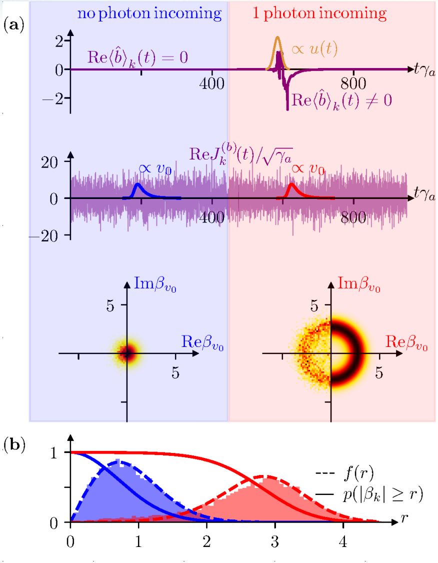
$\gamma_a = 10\sigma_w$, $\gamma_b = 100\sigma_w$ | $\gamma_a = 10\sigma_w$, $\gamma_b = 10\sigma_w$ | $\gamma_a = 10\sigma_w$, $\gamma_b = 1\sigma_w$



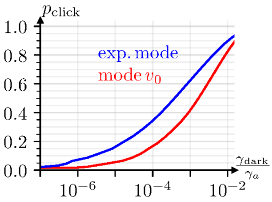
Danner *et al.*, arXiv:2510.08030

For $n > 1$ need $\gamma_b \approx \sigma_w$ to get photons in dominant mode

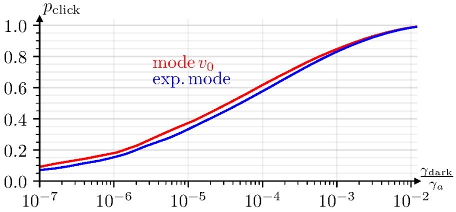
Towards single-photon detection: Filtering and Thresholding



Multimode ($\gamma_b = 10\sigma_w$):

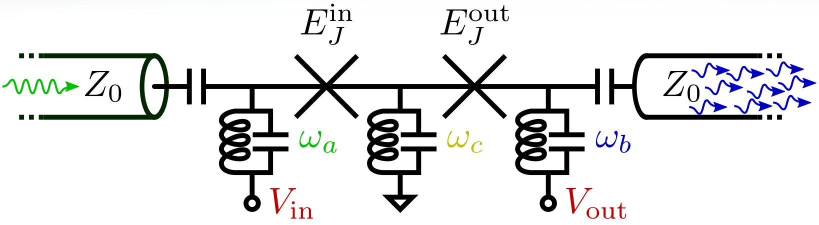


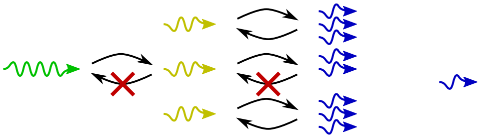
Dominant mode ($\gamma_b = \sigma_w$):



Danner *et al.*, arXiv:2510.08030

Cascaded photomultipliers

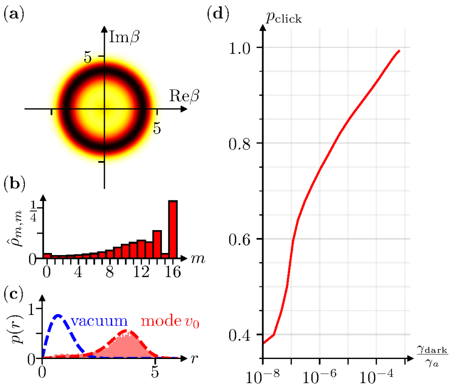




Leppäkangas *et al.*, Phys. Rev. A **97** 013855 (2018)

- photon is either fully converted or reflected
- impedance matching by tuning one Josephson energy

Detection efficiency



Danner *et al.*, arXiv:2510.08030

- Dynamics more complicated
- ➜ Difficult to get all photons in one mode
- ➜ Need somewhat more than 9 photons
- 4×4 gives good efficiency

For low dark count rate:

- 2 or 3 stages ➜ ICTA ➜ threshold detector
- Output bandwidth $\sim 10\,\text{MHz}$
- $\gamma_{\text{dark}} \sim 1\,\text{Hz}$ seems possible
- Adjust input band with bias voltage

Photomultiplier

Where we are at:

- linear to a few photons
- 0.6 quantum efficiency
- dark rate $\sim$ 200 kHz (down from 700 MHz)

Thresholding:

- expect dark *count* rate down to 1 Hz

Spectrum analyzer mode:

- Measure PSD of output^n
- Noise performance ???

Theory:

Juha Leppäkangas

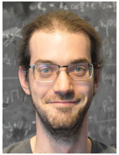
Lukas Danner

Björn Kubala

Exp.:

Romain Albert

Joël Griesmar



Nicolas Bourlet

Leppäkangas *et al.*, Phys. Rev. A **97** 013855 (2018)
Albert *et al.*, Phys. Rev. X **14** 011011 (2024)
Danner *et al.*, arXiv:2510.08030

Josephson photonic devices for BREAD

ICTA

- ✔ near quantum limited noise
- ✔ high bandwidth
- scaling to mm-wave frequencies underway

Jebari *et al.*, Nat. Electron. **1** 223 (2018)
Martel *et al.*, Appl. Phys. Lett. **126** 074001 (2025)
Nehra *et al.*, arXiv:2512.19902

Photo multiplier

- ✔ no dead time
- single photon detection: dark count rate $\sim 1\,\text{Hz}$ seems possible
- power spectrum analysis: not yet clear if any gain w/r to linear amplifier

Leppäkangas *et al.*, Phys. Rev. A **97** 013855 (2018)
Albert *et al.*, Phys. Rev. X **14** 011011 (2024)
Danner *et al.*, arXiv:2510.08030

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