Quantum-limited amplification and photon counting based on Josephson photonics

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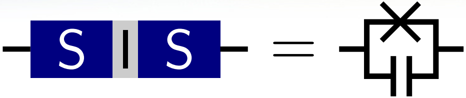
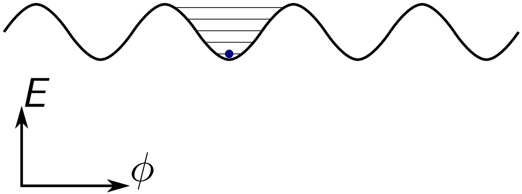
The Josephson junction in quantum circuits





$$H = \; - E_{\mathrm{J}} \cos(\phi)$$

$$V = \frac{\hbar}{2e} \frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- Josephson junction forms anharmonic oscillator ➔ qubit

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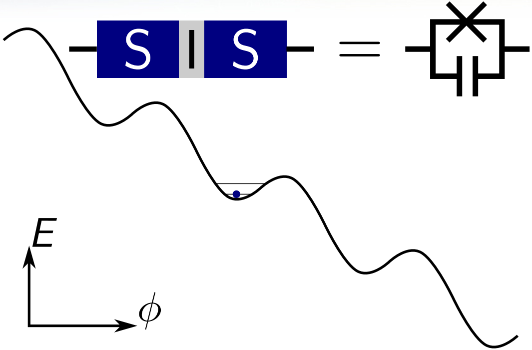

- Josephson junction forms anharmonic oscillator ➔ qubit
- DC current tilts potential

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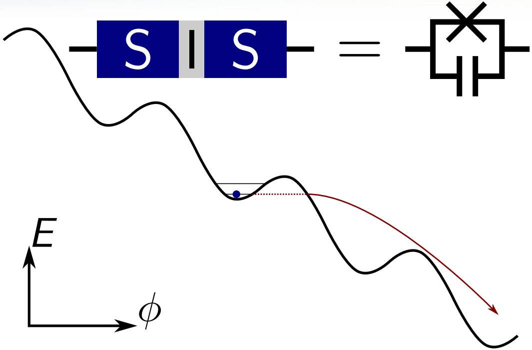


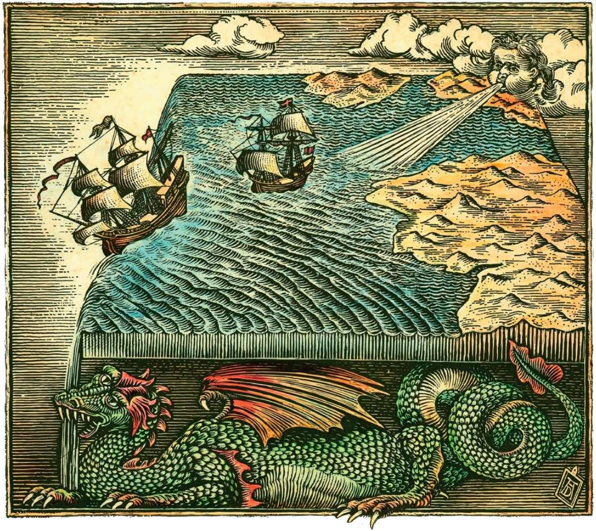
$$H = -E_J \cos(\phi)$$

$$V = \frac{\hbar}{2e}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- Josephson junction forms anharmonic oscillator ➔ qubit
- DC current tilts potential
- current too high ➔ phase runs down potential
  - $V > 0$
  - energy gets dissipated somewhere
  - qubit is gone

Stay below the critical current!

The Josephson junction in quantum circuits



Artist: Antar Dayal

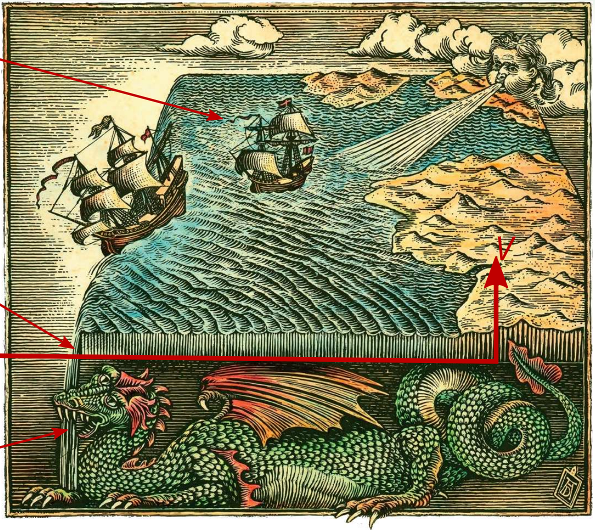
The Josephson junction in quantum circuits

phase particle

I_C

I

monster of instant decoherence



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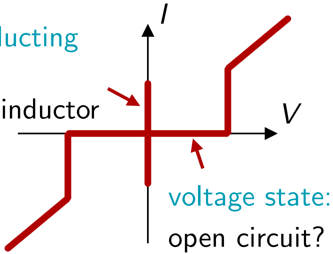
Voltage state of the Josephson junction: Semi-classical view

Josephson junction in the voltage state is also dissipationless!



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

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

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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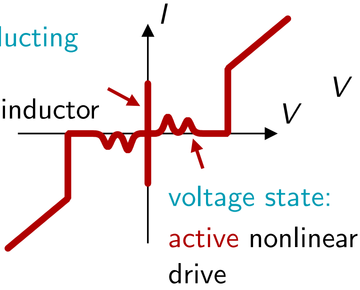

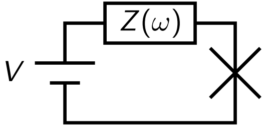

$$I = I_C \sin(\omega_J t)$$

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

Dissipated power

$$P = \mathrm{Re}\, Z(\omega_J)\frac{I_C{}^2}{2}$$

Power is drawn from bias:

$$I = \frac{P}{V} = \frac{2e}{\hbar}\frac{\mathrm{Re}\, Z(\omega_J)}{\omega_J}\frac{I_C{}^2}{2}$$

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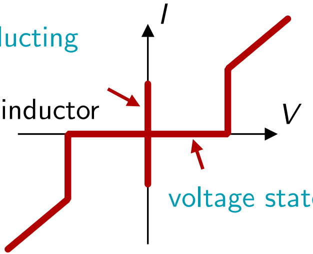
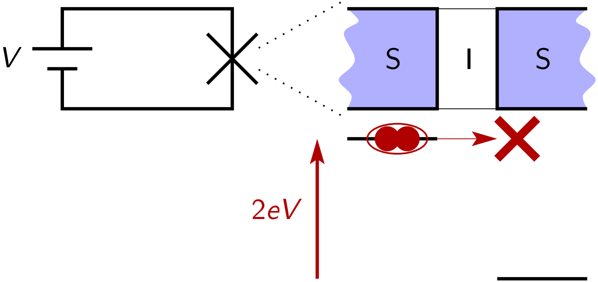
superconducting state:
nonlinear inductor



voltage state:



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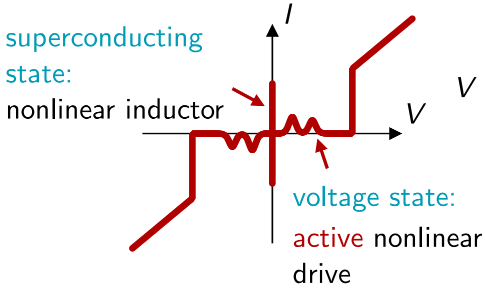

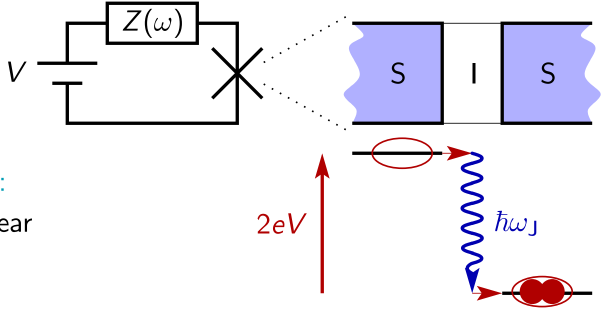

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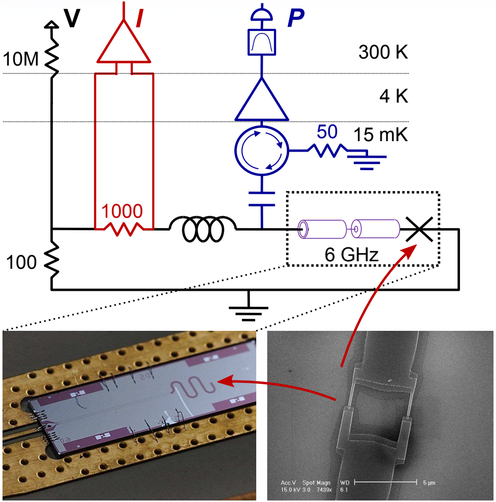
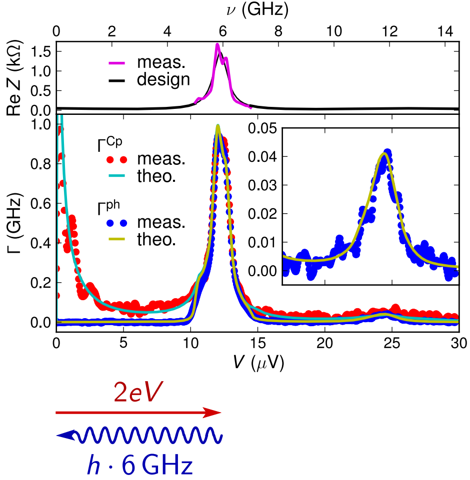
Bright side of inelastic Cooper-pair tunnelling





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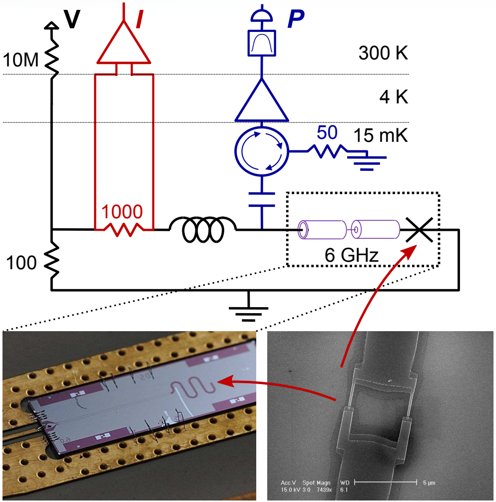

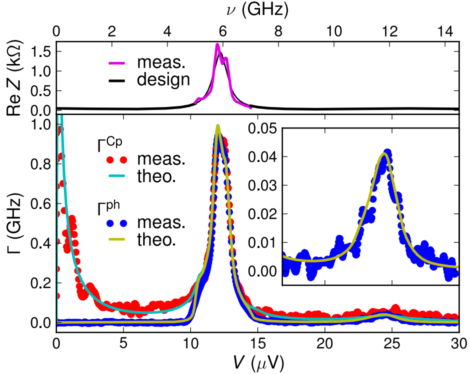

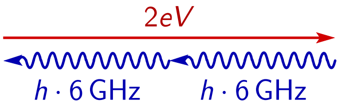

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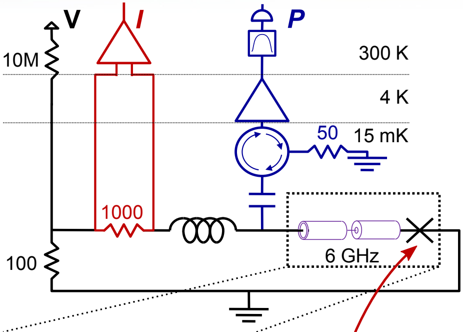

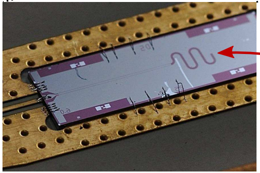

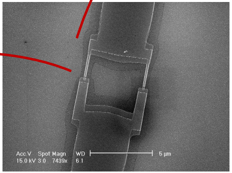

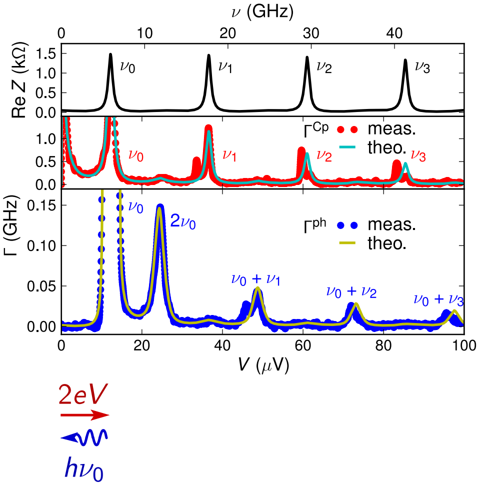

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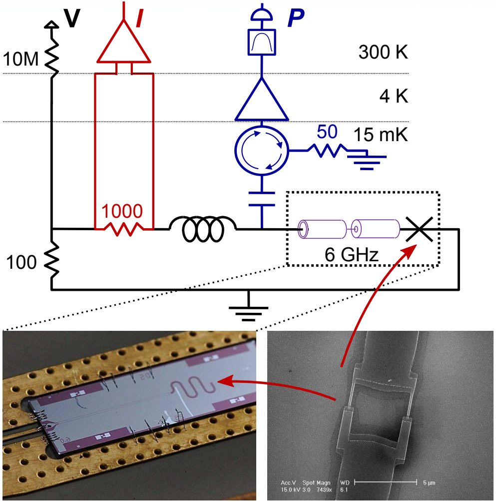

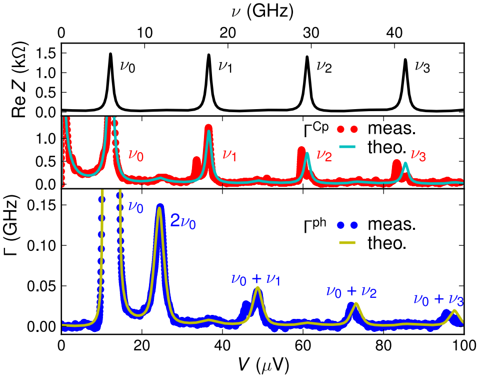

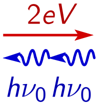

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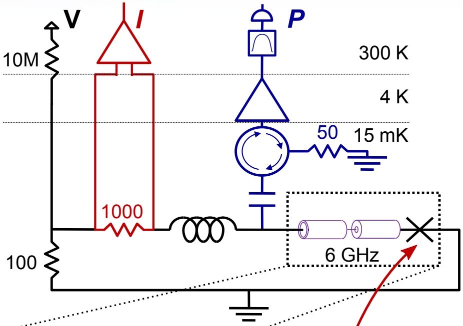

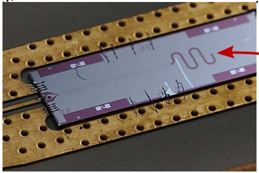

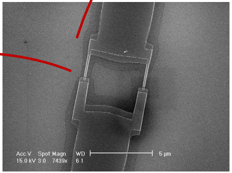

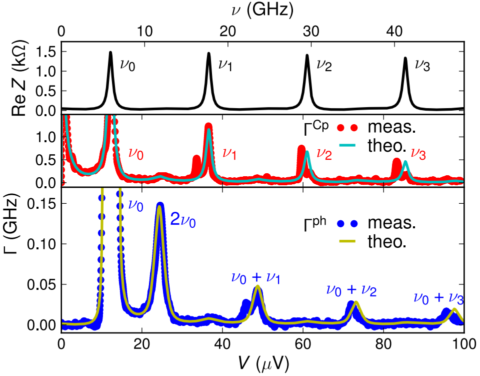

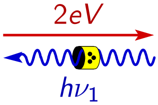

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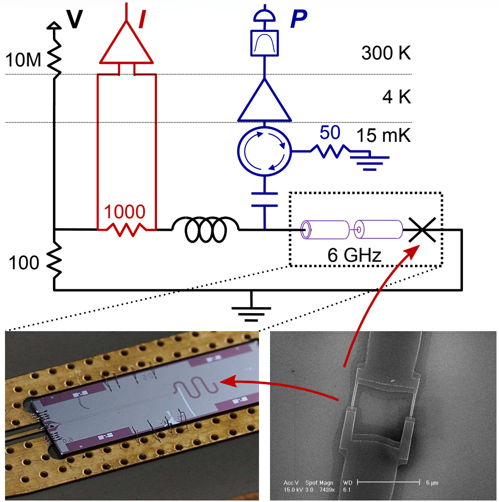

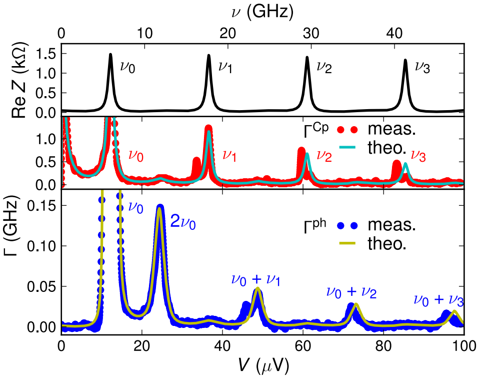

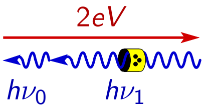

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Josephson photonics

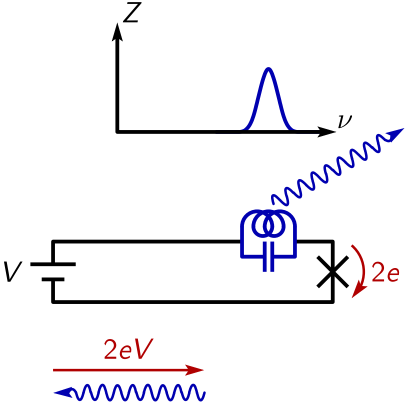
Engineering $Z(\nu)$ ➡ Full toolbox for wideband quantum microwave devices

Sources

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

Measurement

- Amplifiers
- Frequency shifters
- Photomultipliers



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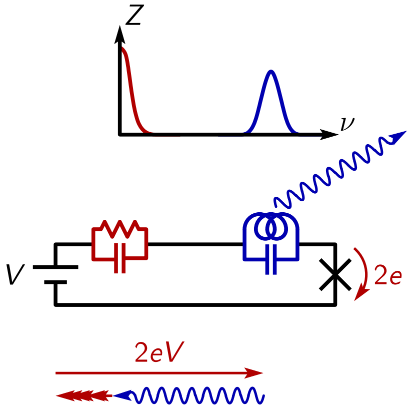

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Phys. Rev. X **9** 021016 (2019)

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Phys. Rev. Lett. **122** 186804 (2019)

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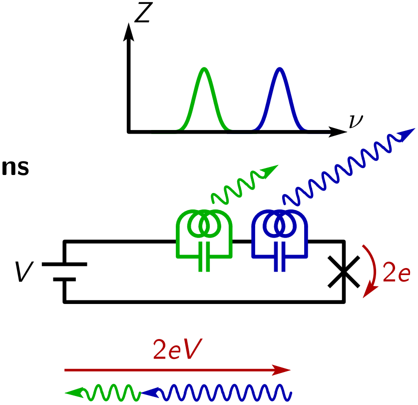

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prb **86** 054514 (2012)

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

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Phys. Rev. B **92** 014503 (2015)

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Phys. Rev. Lett. **119** 137001 (2017)
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prb **104** 155424 (2021)

Josephson photonics

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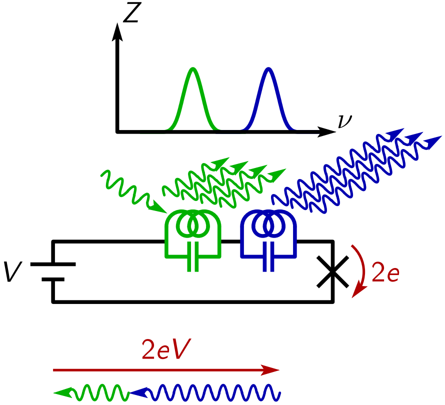


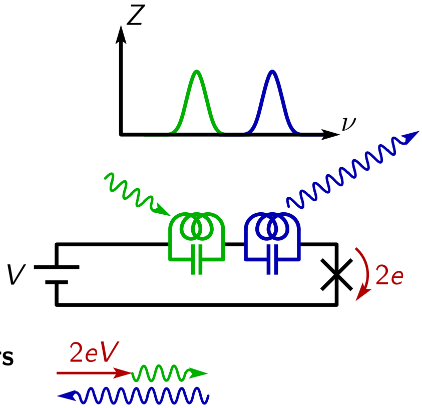
Safi *et al.*,
Phys. Rev. B **84** 205129 (2011)

Lähteenmäki *et al.*,
Sci. Rep. **2** 276 (2012)

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

Josephson photonics

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



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Leppäkangas *et al.*,
Phys. Rev. B **98** 224511 (2018)

Josephson photonics

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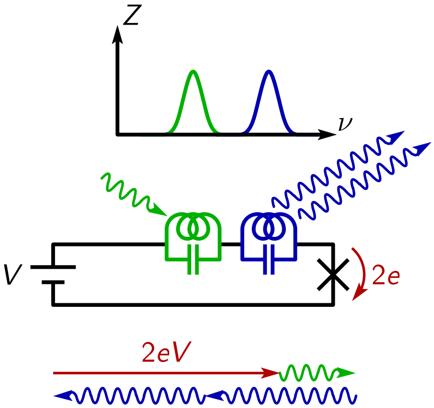

Leppäkangas *et al.*,
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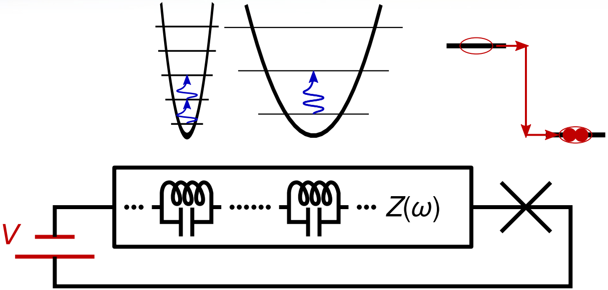
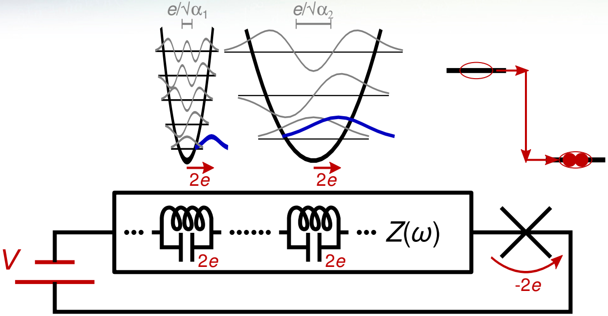
Inelastic Cooper pair tunnelling: Nonlinearity depends on impedance



$$\Gamma \propto E_J^2 \delta(2eV - n_1\hbar\omega_1 - n_2\hbar\omega_2 \ldots)$$

- One or several modes can absorb $2eV$ as photons

Inelastic Cooper pair tunnelling: Nonlinearity depends on impedance



$$M_n^{(k)} = \left|\langle n | e^{i\sqrt{\alpha_k}(a+a^\dagger)} | 0\rangle\right|^2 = \frac{\alpha_k^n e^{-\alpha_k}}{n!}$$

$$\alpha_k = \pi \frac{4e^2}{h} Z_k$$

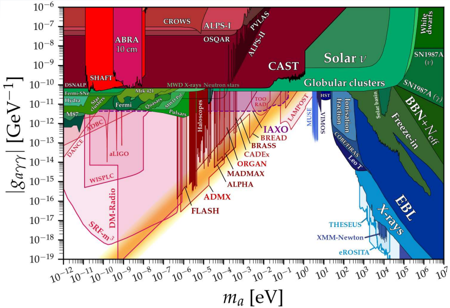
$\sqrt{\alpha_k}$: 0-point phase fluctuations

$$\Gamma \propto E_J^2 M_{n_1}^{(1)} M_{n_2}^{(2)} \cdots \delta(2eV - n_1\hbar\omega_1 - n_2\hbar\omega_2 \ldots)$$

- One or several modes can absorb $2eV$ as photons
- Z_k determine **how** $2eV$ is split up into photons

$Z(\omega)$ can be engineered, V controlled ➔ very versatile

Quantum measurement devices for THz blind spot



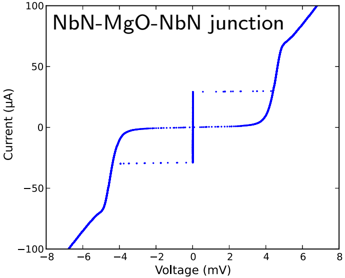
Ciaran O'Hare, cajohare.github.io/AxionLimits

Gap frequencies $2\Delta/h$

Al: 90 GHz
Nb: 700 GHz
NbN: 1.2 THz

Josephson photonics at high frequency

- no microwave pump needed
- Josephson inductance cancels
- Frequency only limited by gap



Grimm *et al.*, Supercond. Sci. Technol. **30** 105002 (2017)

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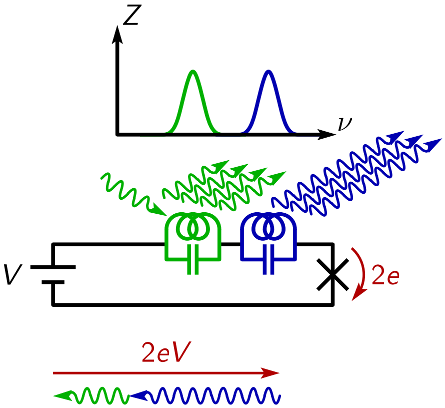

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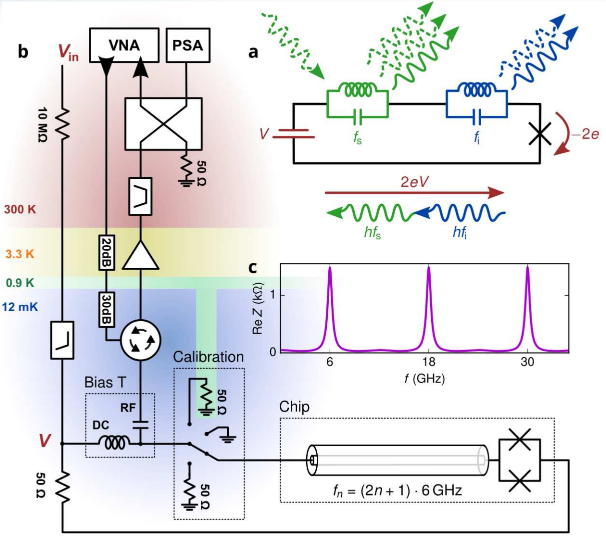
Weak nonlinearity: Amplification

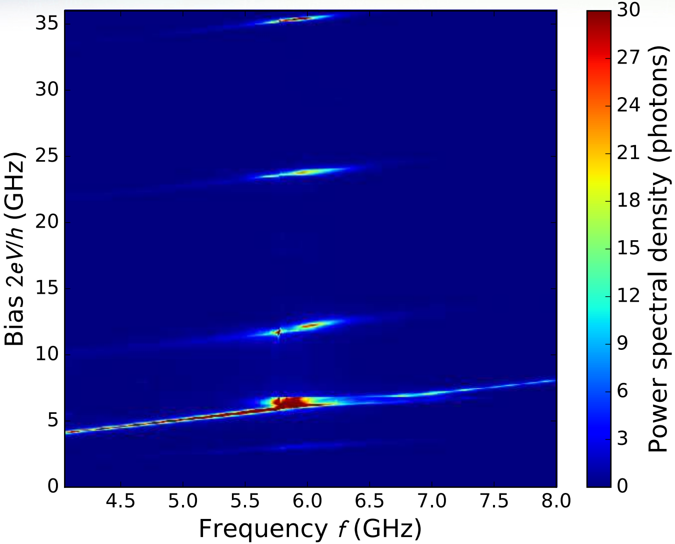


- send signal to one of the modes
- chose any mode as idler
- bias at the sum of the two modes
- Adjust E_J for large gain:

$$\frac{E_J}{\hbar\sqrt{\Gamma_a\Gamma_b}}\pi\frac{4e^2}{h}\sqrt{Z_a Z_b} \to 1_-$$

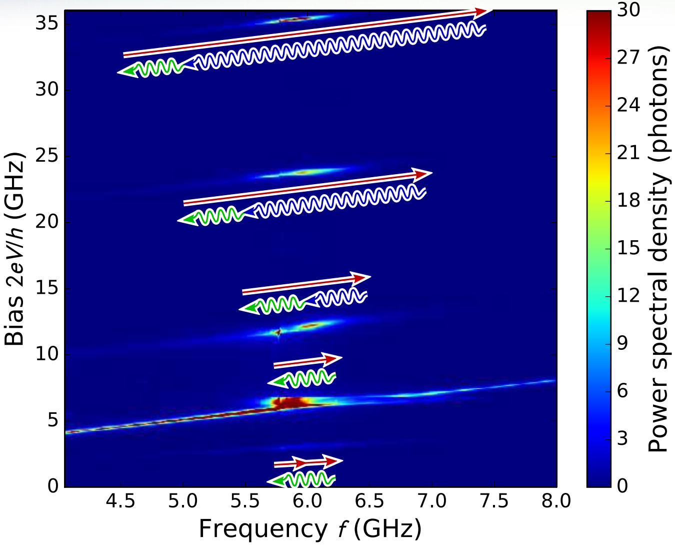
➜ quantum limited amplification?

Power spectral density



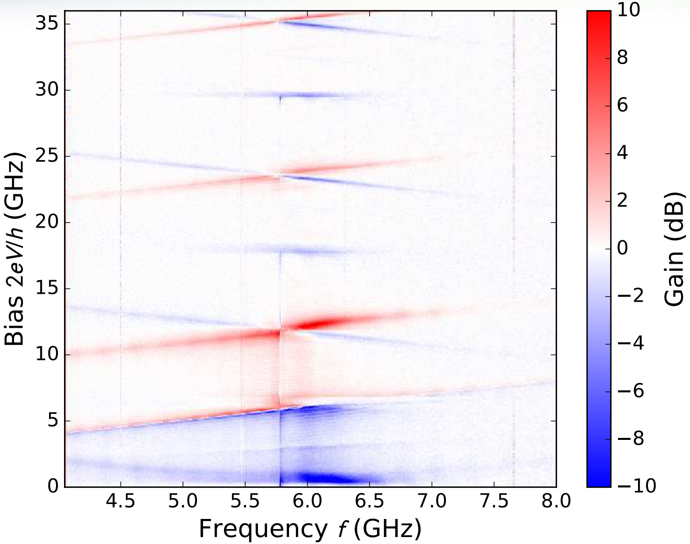
- Same sample as in the beginning
- Resolve photon emission rate in frequency

Power spectral density



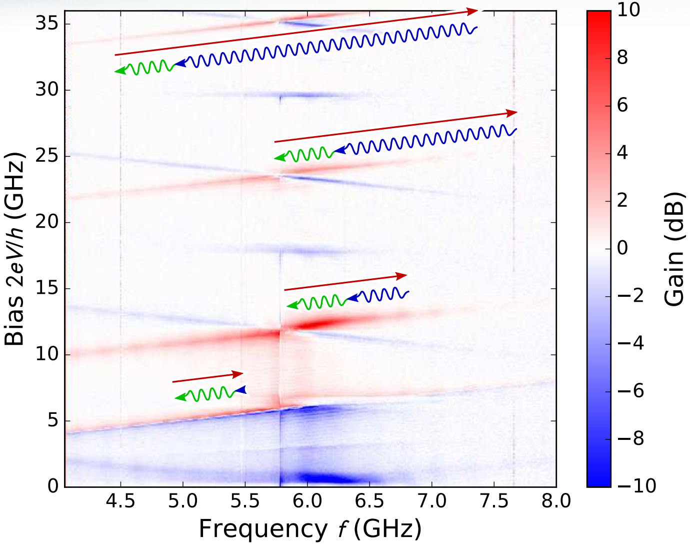
- Same sample as in the beginning
- Resolve photon emission rate in frequency
- → Amplifier noise

Gain



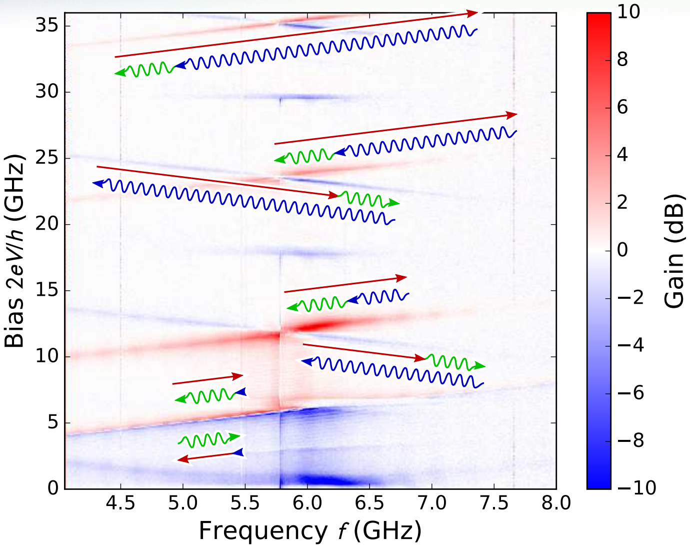
Bias 2eV/h (GHz)
0
5
10
15
20
25
30
35
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
Frequency f (GHz)
Gain (dB)
10
8
6
4
2
0
−2
−4
−6
−8
−10

Gain



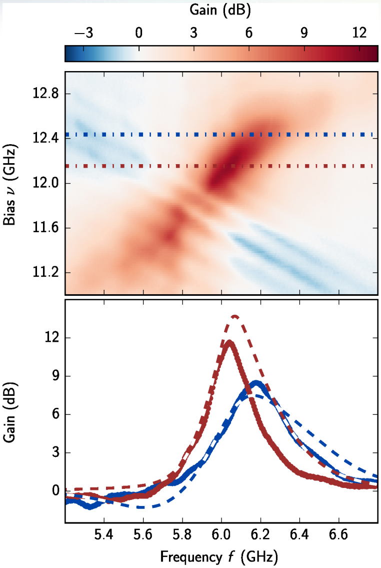
- Down conversion
- Gain

Gain



- Down conversion
- Gain
- Frequency conversion
- Loss

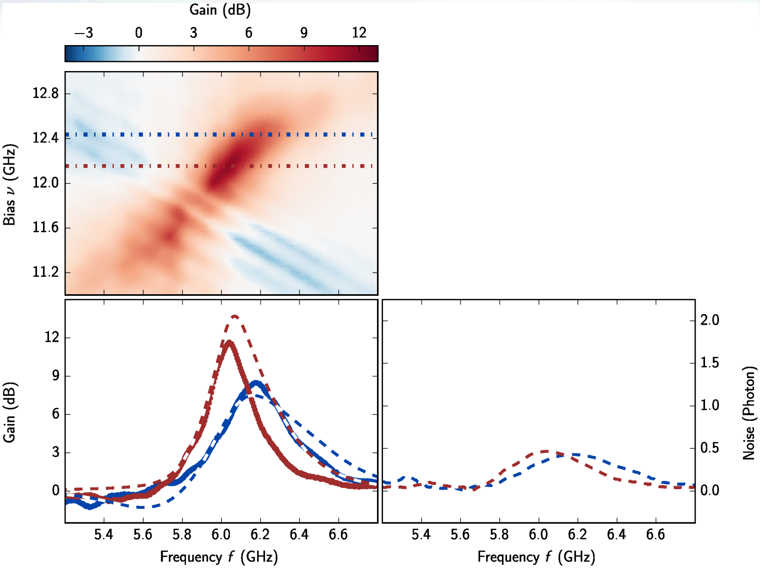
Amplification close to the quantum limit



- Gain $> 10\,\mathrm{dB}$ for sample not designed as amplifier
- Qualitatively explained by $P(E)$ theory

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

Amplification close to the quantum limit



- Gain $> 10\,\mathrm{dB}$ for sample not designed as amplifier
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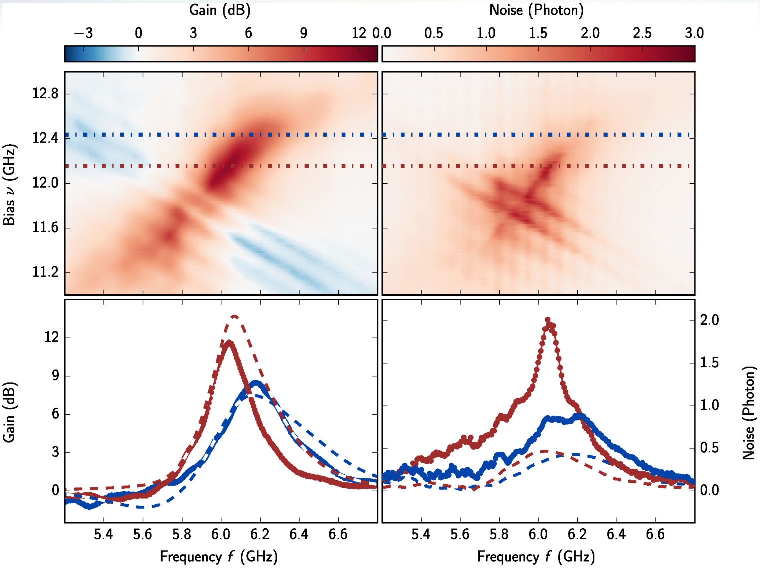
- quantum limit $\frac{1}{2}|1 - G^{-1}|$

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

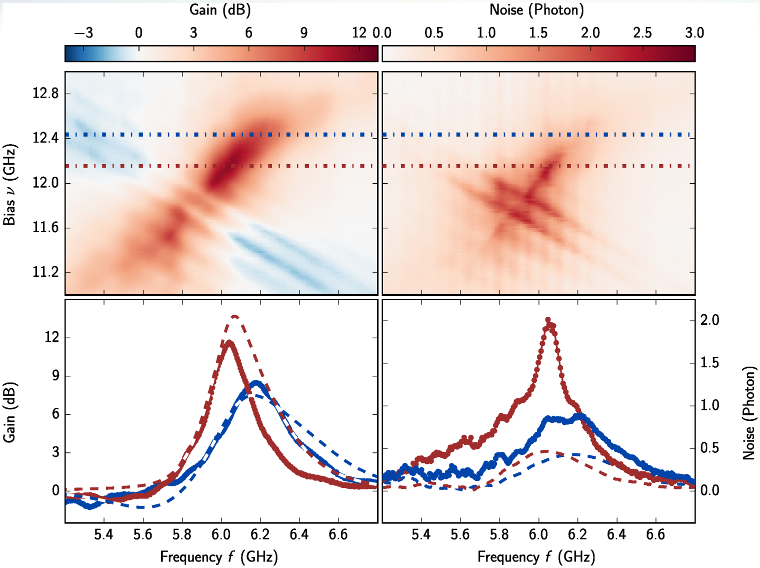
Amplification close to the quantum limit



- Gain $> 10\,$dB for sample not designed as amplifier
- Qualitatively explained by $P(E)$ theory
- quantum limit $\frac{1}{2}|1 - G^{-1}|$
- Best noise $\sim 2 \times$ QL

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

Amplification close to the quantum limit

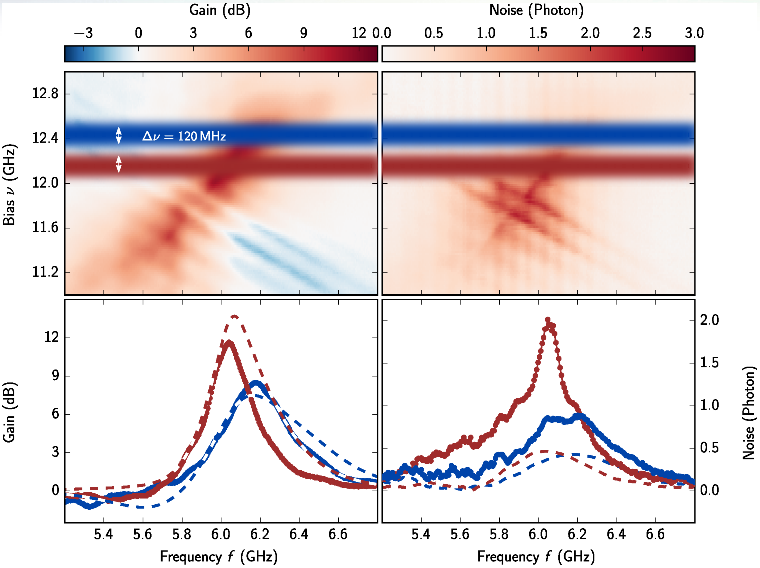


Limited performance

- Gain limited to $\sim 10\,\mathrm{dB}$
- Best noise $\sim 2 \times \mathrm{QL}$

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

Amplification close to the quantum limit



Limited performance

- Gain limited to $\sim 10\,\mathrm{dB}$
- Best noise $\sim 2 \times$ QL

Reason: Pump fluctuations $\Delta\nu$

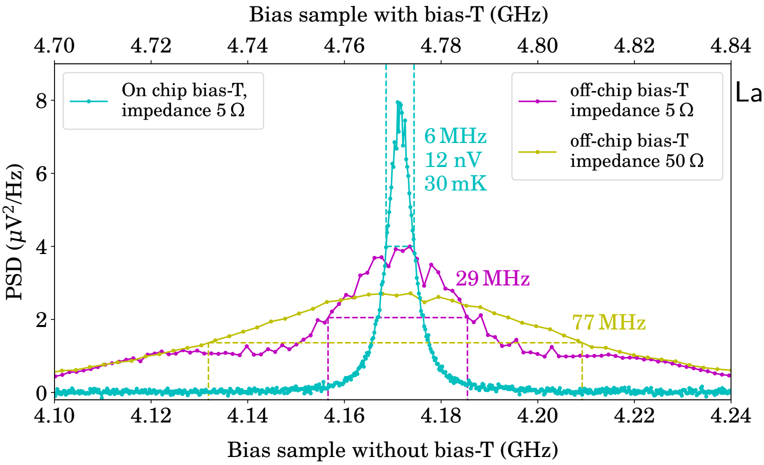
- JPA: $\sim 1\,\mu\mathrm{Hz}$
- ICTA: $\sim 100\,\mathrm{MHz}$

Optimize:

- reduce voltage noise
- increase bandwidth

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

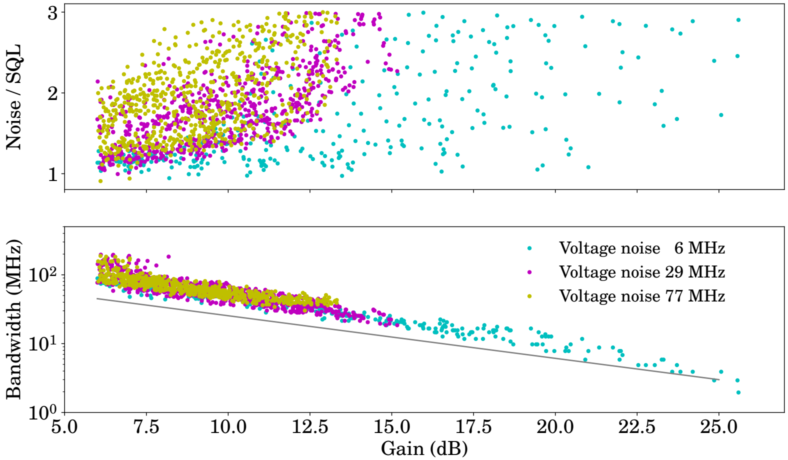
Reducing voltage-bias noise



Last filter generation:

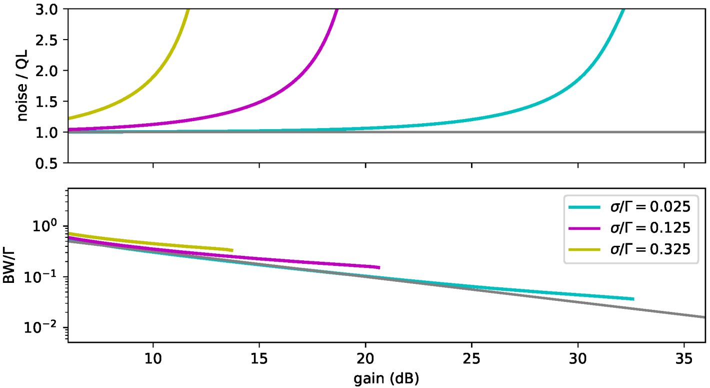
- 3 discrete LCR stages + silver epoxy
- 700 Hz cutoff
- flat 5 Ω output impedance up to 1 GHz
- effective temperature of 5 Ω: 30 mK

Gain is limited by voltage noise



- Various operating points
- BW reduces with gain: $\sqrt{G} \cdot \mathrm{BW} = \Gamma$
- Need bandwidth > voltage noise
- Lower bias noise allows for larger gain

JPA theory with adiabatic pump-frequency fluctuations



- JPA theory on resonance
- average over Gaussian distribution of bias frequency
- qualitative agreement with measurement

Inelastic Cooper-pair Tunneling Amplifier

- Near quantum limited noise
- GBWP $\sim 100\,\text{MHz}$
- $P_{\text{in}}^{-1\,\text{dB}} \sim -130\,\text{dBm}$ @ $G = 20\,\text{dB}$
- Less hardware overhead
- No pump tone required
- Should work to gap of superconductor
- Expect easy scaling to mm-wave to THz frequencies

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

Salha Jebari

Florian Blanchet

Ulrich Martel

Naveen Nehra

Josephson photonics

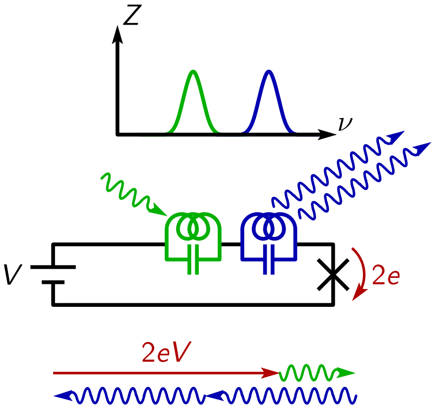
Engineering $Z(\nu)$ → **Full toolbox for wideband quantum microwave devices**

Sources

- Coherent
- Single photons
- Entangled photons

Measurement

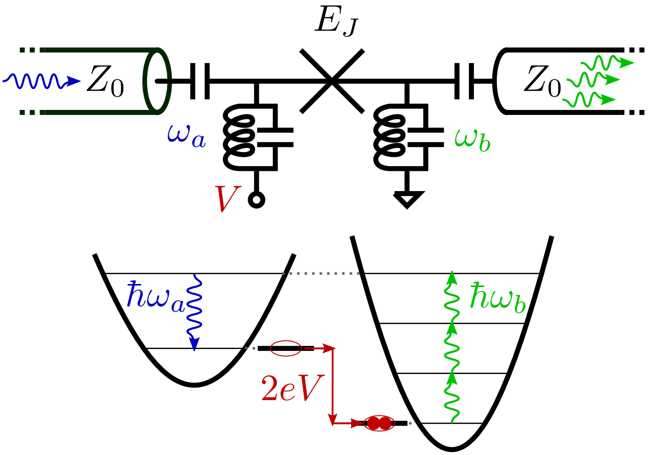
- Amplifiers
- Frequency shifters
- **Photomultipliers**



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

Albert *et al.*,
arxiv:2303.03173 (2023)

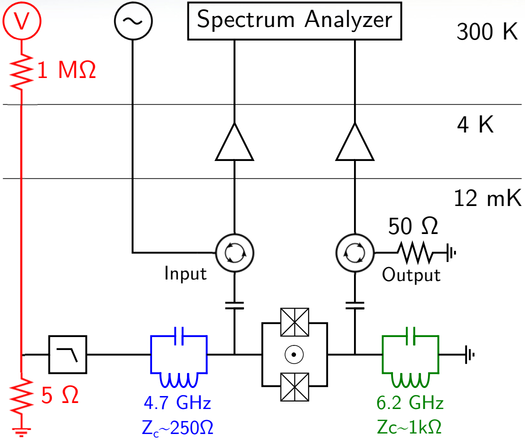
Strong nonlinearity: Photomultiplication

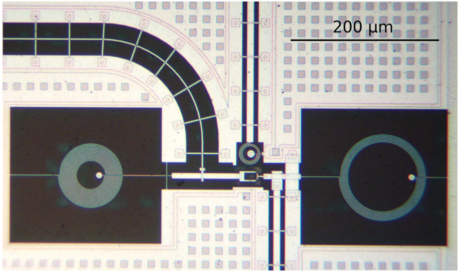


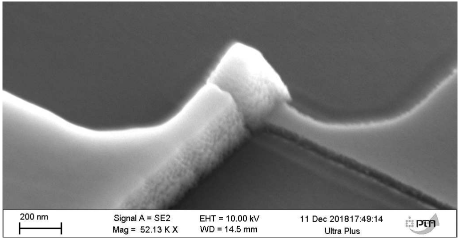
- spontaneous tunneling forbidden
- incident photon provides energy complement
- tunneling creates several photons in other mode
- process involving ≥ 3 photons
- need $Z_{\text{out}} \sim 2\,\text{k}\Omega$
- adjust E_J to cancel reflection

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

Device



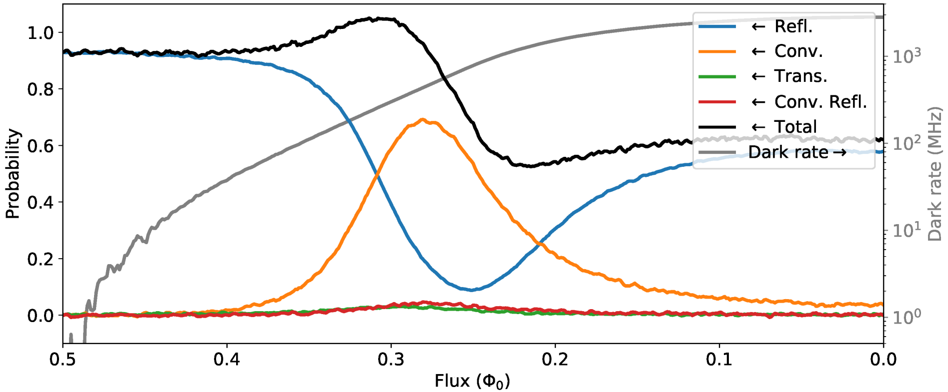




Josephson junctions: Nb/Al/AlOx/Nb

Albert *et al.*, arxiv:2303.03173

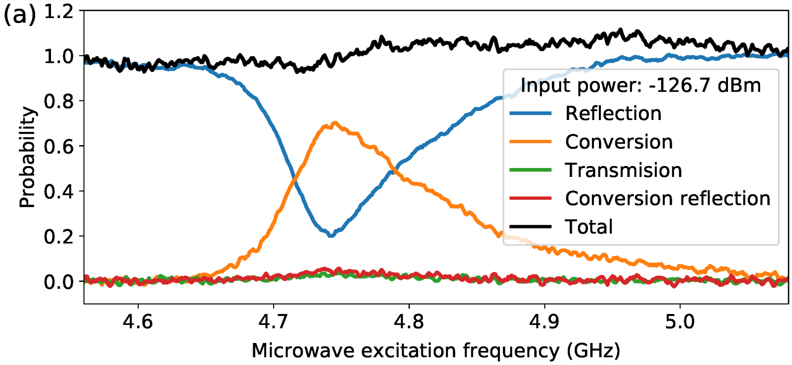
Conversion 1 ➔ 3



Input frequency	Input power	Bias $2eV/h$
4.74 GHz	-127 dBm	13.37 GHz

Albert *et al.*, arxiv:2303.03173

Bandwidth



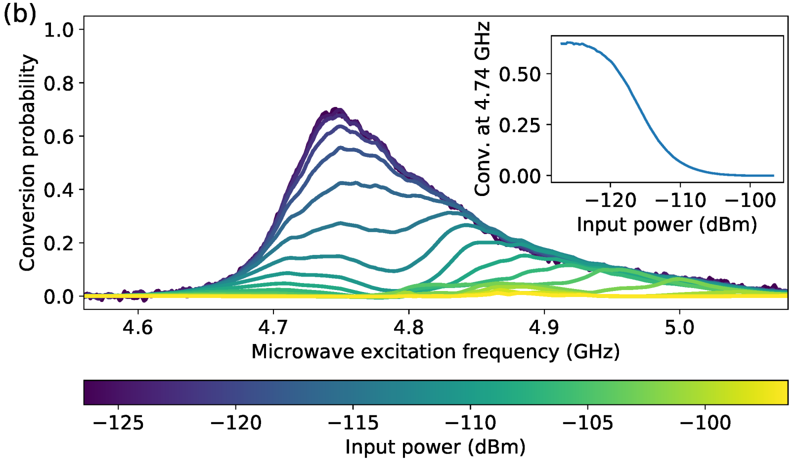
Input power : $-127\,\mathrm{dBm}$

Bias voltage: $13.37\,\mathrm{GHz}$

SQUID flux : $0.28\,\phi_0$

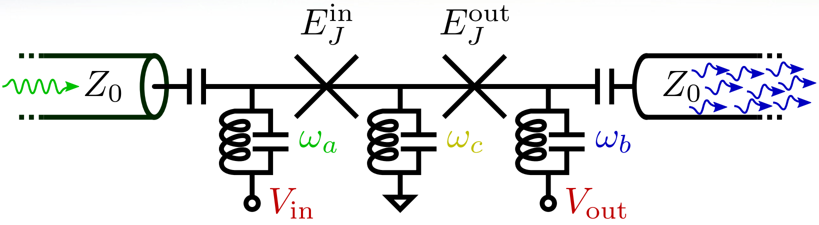
Efficiency : $73\,\%$

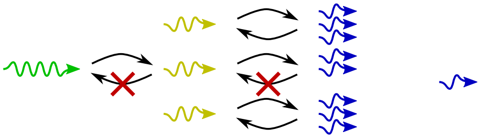
Power handling



Bias voltage: 13.37 GHz
SQUID flux : 0.28 ϕ_0
Efficiency : 73 %
Saturation : 6 photons

Cascaded photomultipliers ➔ single photon detector





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

- photon is either fully converted or reflected
- impedance matching by tuning one Josephson energy
- need 2 to 3 stages followed by quantum limited amplifier
- number resolving, no dead time

Photomultiplier

Where we are at:

- ✔ linear to a few photons
- ✔ 0.7 quantum efficiency
- ✗ high dark rate

Reasons for high dark rate:

- high E_J ➔ non RWA processes
- understood with $P(E)$

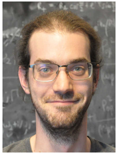
Much lower dark rate with:

- lower BW
- $2eV < \hbar\omega_{\text{output}}$
- preliminary result: $< 1\,\text{MHz}$

Juha Leppäkangas

Romain Albert

Joël Griesmar



Nicolas Bourlet

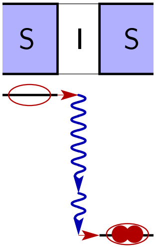
Leppäkangas *et al.*, Phys. Rev. A **97** 013855 (2018)

Albert *et al.*, arxiv:2303.03173, to appear in Phys. Rev. X

Quantum measurement devices based on Josephson photonics

New physics

- Nonlinearity in drive, not modes
- very open systems



Useful devices

- no microwave pump needed
- very strong nonlinearities
- not limited by plasma frequency
- good candidate for covering THz blind spot in quantum measurement

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

Albert *et al.*, arxiv:2303.03173, to appear in Phys. Rev. X