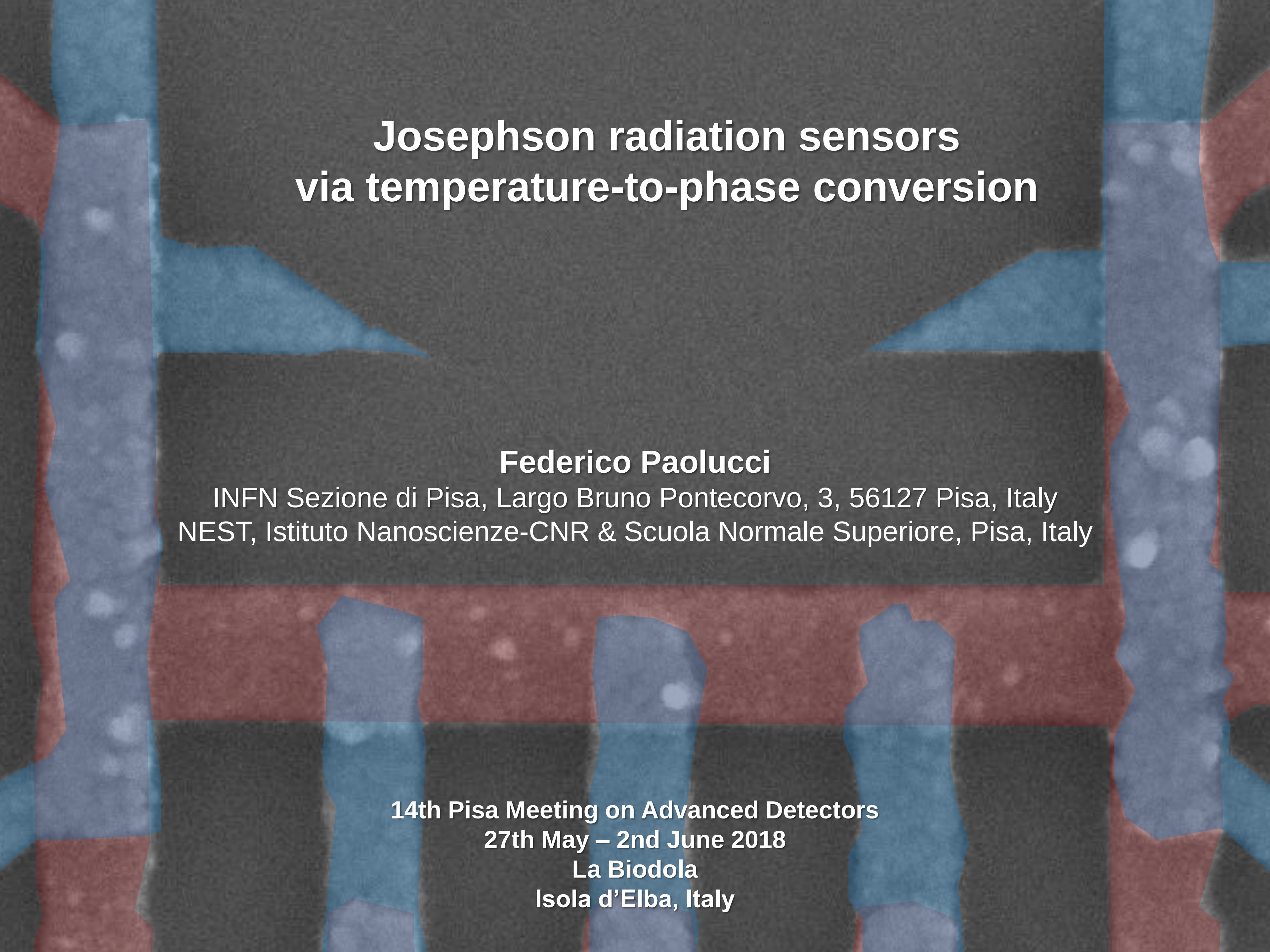

Josephson radiation sensors via temperature-to-phase conversion

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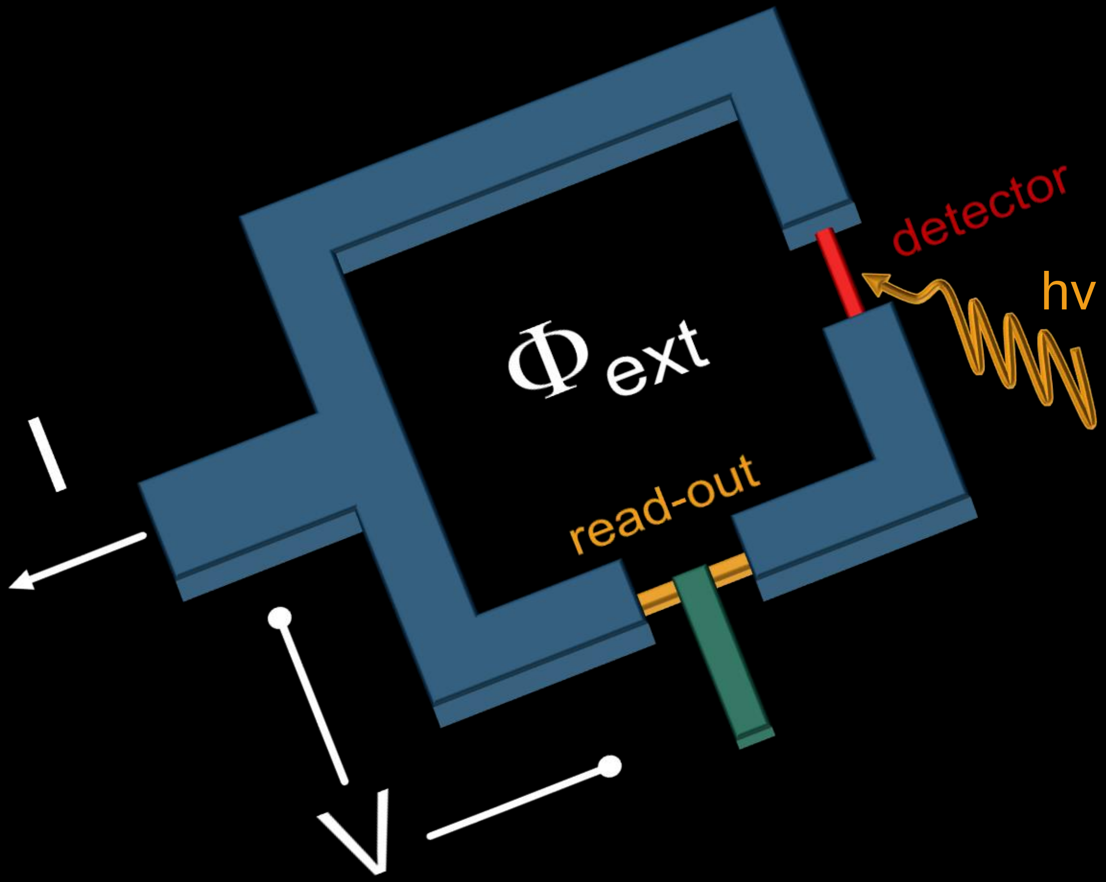
La Biodola
Isola d’Elba, Italy

Outline

- Principle of photonic sensing based on T-to-ϕ transduction
- Theoretical model
- Superconducting Quantum Interference Proximity Transistor (SQUIPT)
- Thermometer
- Nanocalorimeter operation
    - Thermal model, S/N ration, resolving power
- Bolometer operation
    - Thermal model, NEP
- Performances

Temperature-to-phase conversion: principle



Radiation absorption ($h\nu$)

↓

T_e enhancement in detector JJ

↓

Suppression of circulating J current

↓

Variation of phase drop across the WLs

↓

Modification of DOSs

↓

SQUIPT readout

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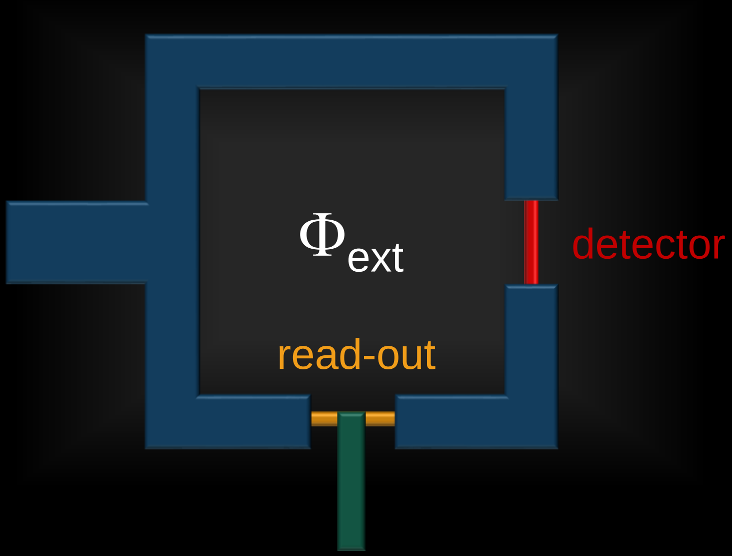
Temperature-to-phase conversion: principle



Assumptions:

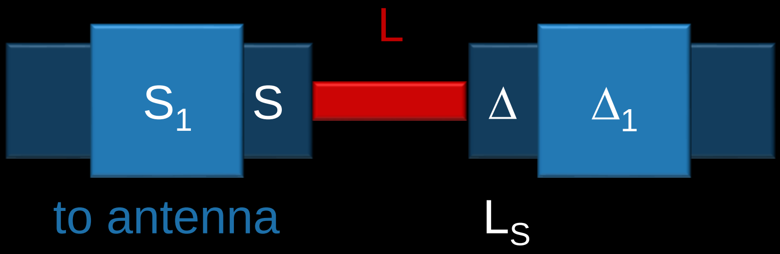
- **Short** ($\Delta \leq \hbar D/L^2$) SNS JJ junctions:
  - Drastic reduction of detector volume V
  - Known analytical solutions for I and DOS
  - Enhanced response in the readout JJ
- Fluxoid quantization

$$\varphi_d + \varphi_r = 2\pi\frac{\Phi_{ext}}{\Phi_0} + 2k\pi$$

Andreev Mirror: $\Delta_1 \gg \Delta$

Heat is confined in the detector region

Appl. Phys. Lett. **63**, 3075 (1993)



$L_S \gg \xi_0$

Proximity only due to S

Good acoupling with radiation when:

$$\upsilon > \frac{2\varepsilon_{gap}}{\hbar}$$

where the wire energy gap is

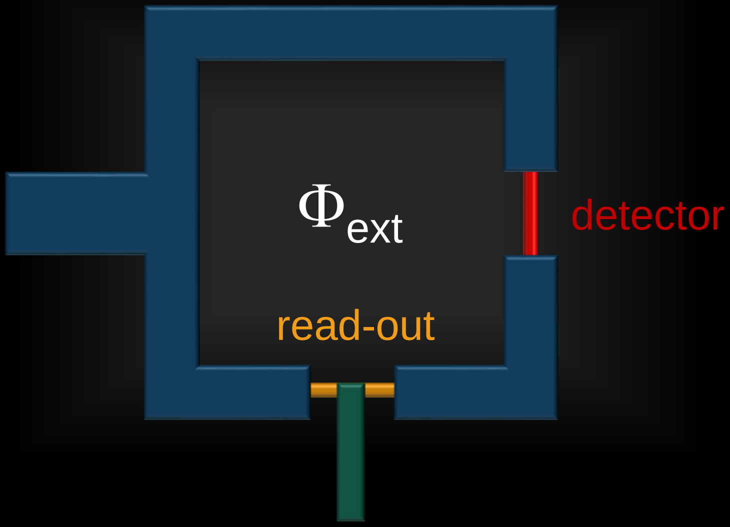
$$\varepsilon_{gap}^{d,r} = \Delta(T)\cos\left({}^{\varphi_{d,r}}/_{2}\right)$$

For $\varepsilon_{gap} = 50\mu eV$

$\nu > 15\mathrm{GHz}$

Phys. Rev. Appl. **9**, 054027 (2018)

Temperature-to-phase conversion: model



$$I_C^{d,r}(T,\varphi_{d,r}) =$$

$$= \frac{\pi\Delta(T)}{eR_N^{d,r}}\cos\left(\frac{\varphi_{d,r}}{2}\right)\int_{\Delta(T)\cos(\varphi_{d,r}/2)}^{\Delta(T)} d\varepsilon$$

$$\times \frac{1}{\sqrt{\varepsilon^2+\Delta^2(T)\cos^2\left(\frac{\varphi_{d,r}}{2}\right)}}\tanh\left(\frac{\varepsilon}{2k_BT}\right)$$

T_e-induced suppression of supercurrent for $\Phi_{ext} \neq 0$

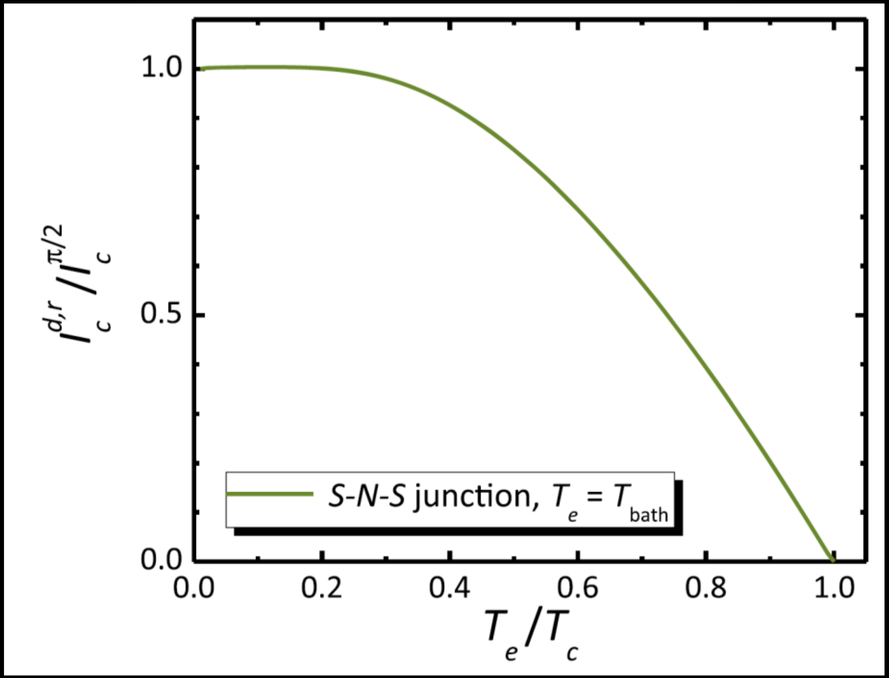
↓

Variation finite phase drop across the WLs

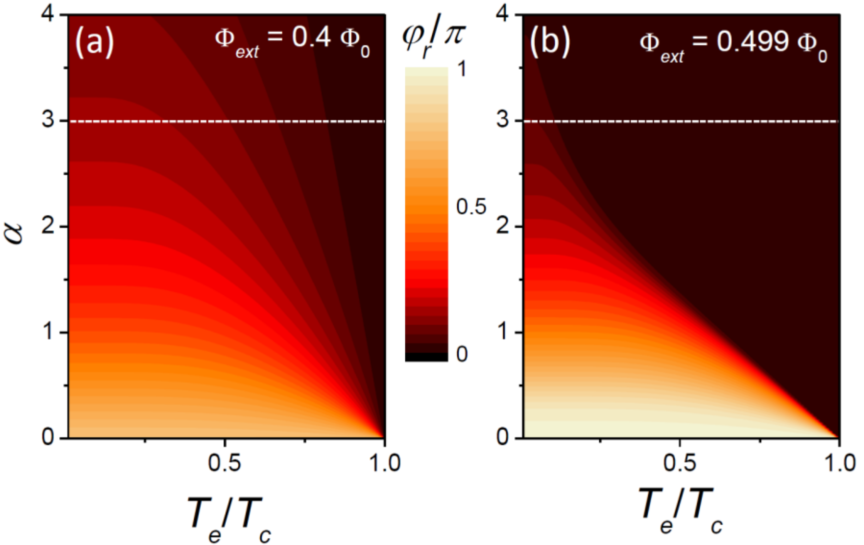
↓

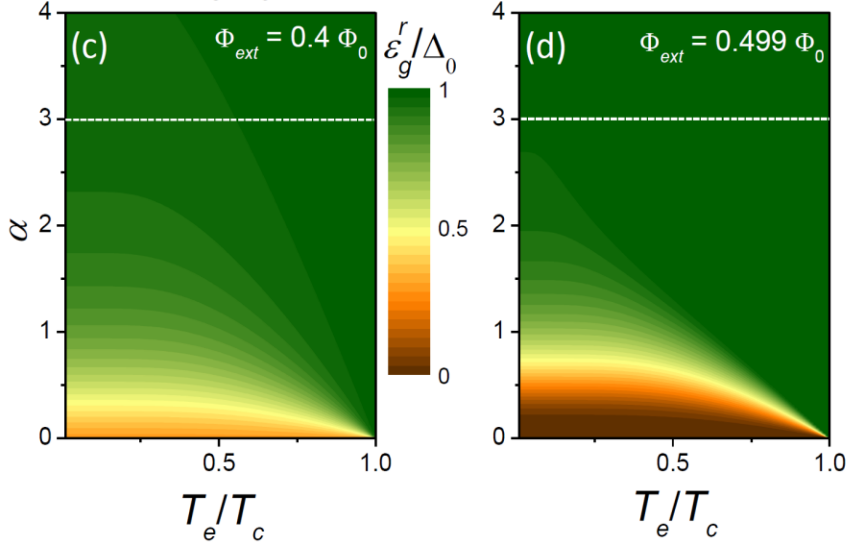
Conservation of circulating supercurrent

$$I_C^d(T_e,\varphi_d) = I_C^r(T_{bath},\varphi_r)$$



Temperature-to-phase conversion: model





$$\alpha = \frac{R_N^d}{R_N^r} = \frac{L_J^d}{L_J^r}$$

$$\varepsilon_{gap}^{d,r} = \Delta(T)\cos\left(\varphi_{d,r}/2\right)$$

- For <u>**α>>1**</u>, phase drop will occur predominantly across <u>**read-out**</u> JJ
- For <u>**α<<1**</u>, phase drop will occur predominantly across <u>**detector**</u> JJ

<u>**Gapped**</u> metal (φ = 0)

<u>**Gapless**</u> metal (φ = π)

Phys. Rev. Appl. **9**, 054027 (2018)

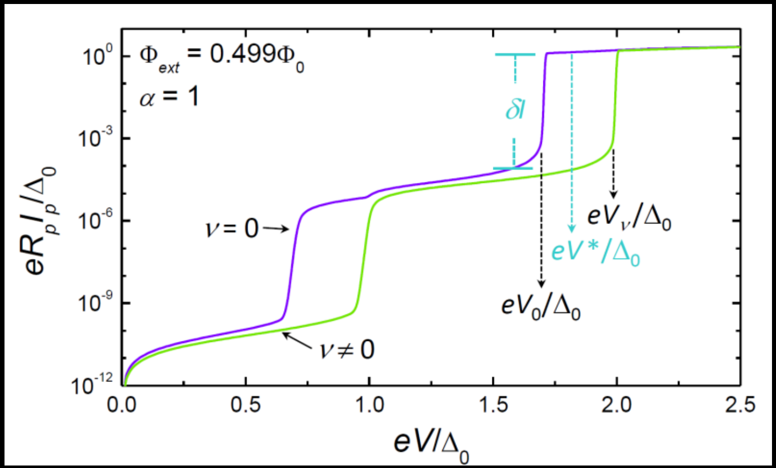
Temperature-to-phase conversion: SQUIPT response

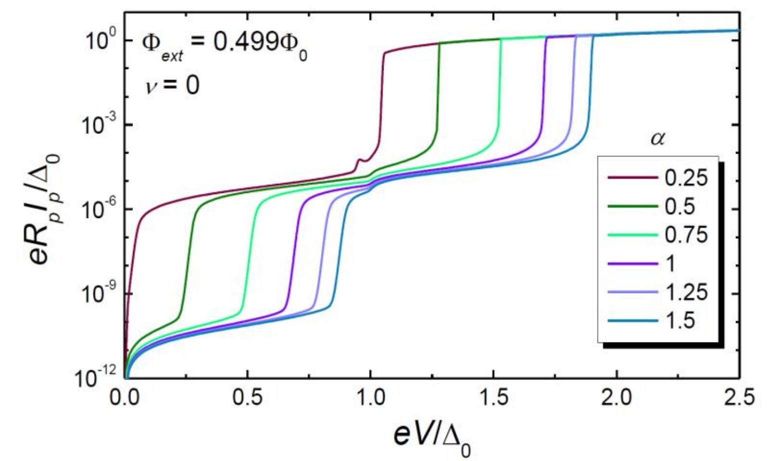
$$I_P(V) = \frac{1}{ewR_N}\int_{\frac{L-w}{2}}^{\frac{L+w}{2}} dx \int_{-\infty}^{\infty} d\varepsilon\, \aleph_N^r(x,\varepsilon,\varphi_r)\,\aleph_S^p(\tilde{\varepsilon})\,F(\varepsilon,\tilde{\varepsilon})$$

$$\aleph_S^p(\mathcal{E},T_e) = \left| Re\left[\frac{(\mathcal{E}+i\Gamma)}{\sqrt{(\mathcal{E}+i\Gamma)^2-\Delta^2(T_e)}}\right]\right|$$

$$F(\varepsilon,\tilde{\varepsilon}) = [f_0(\tilde{\varepsilon}) - f_0(\varepsilon)]$$

Nature Phys. (2010), PRB (2011), PRB (2011), PRAppl (2014), APL (2015)





Absorption of a photon:

reduction of tunneling current

Different α:

selection of operation voltage

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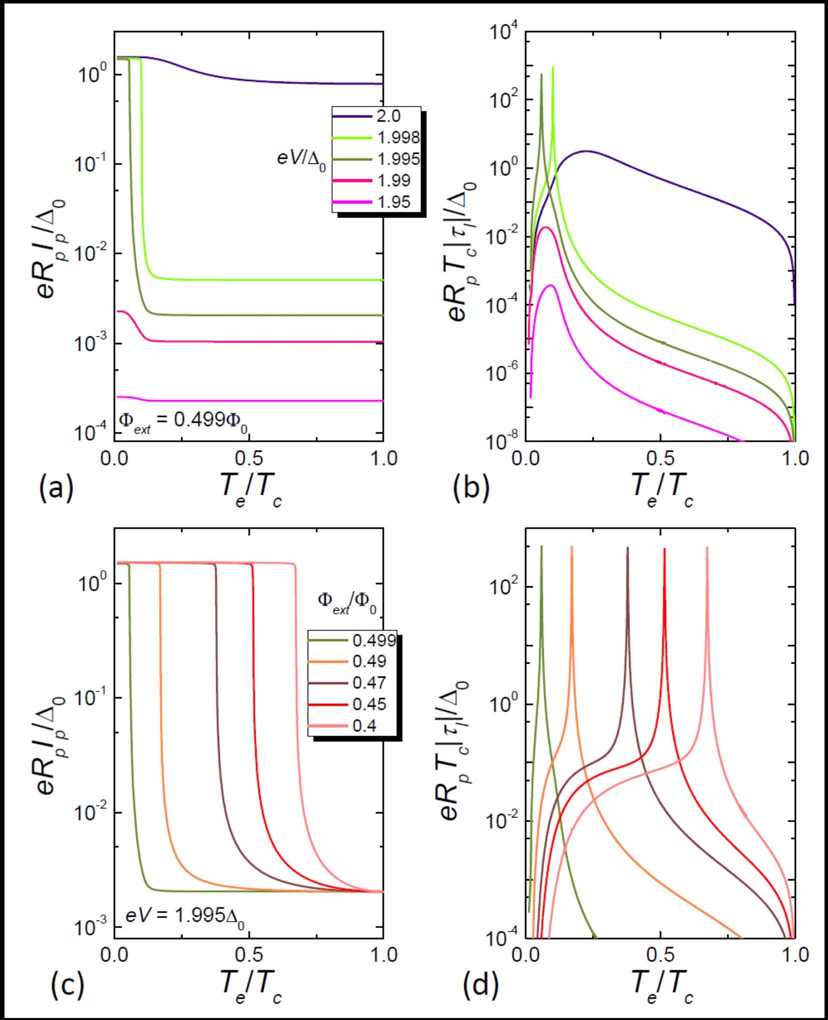
Temperature-to-phase conversion: thermometer

Current

Transfer function

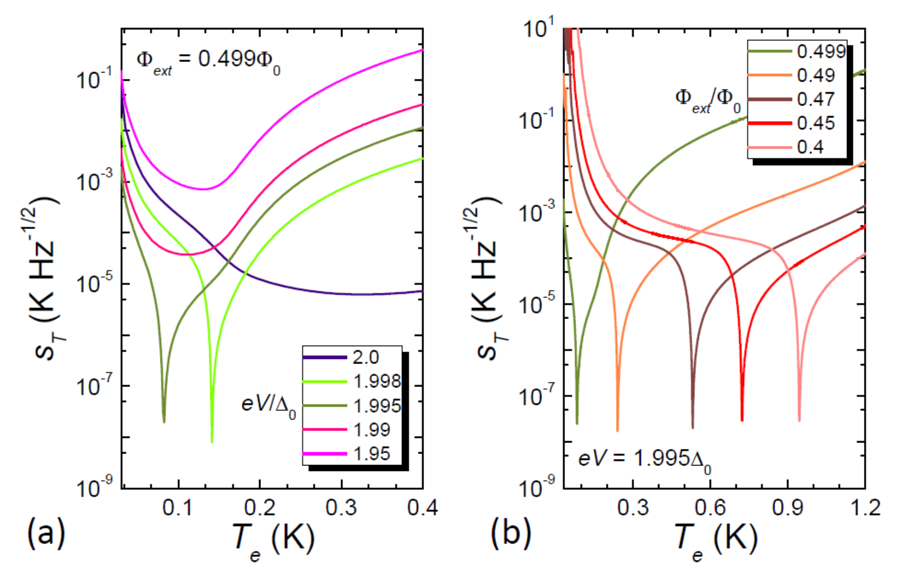


Temperature noise per unit of bandwidth

$$s_T = \frac{\sqrt{S_I}}{|\tau_I|}$$

Low frequency current noise

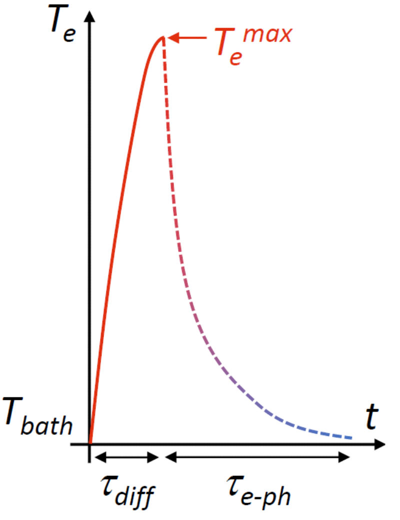
$$S_I(V) = 2eI_P(V)\coth\left(\frac{eV}{2k_BT_{bath}}\right)$$



$$s_T \sim tens\ \mathrm{nK}/\sqrt{Hz}$$

Phys. Rev. Appl. **9**, 054027 (2018)

Temperature-to-phase conversion: calorimeter



$$\tau_{diff} = \frac{L^2}{D} \sim 10^{-12} s$$

$$\tau_{e-ph} \approx \frac{k_B^2 v_F}{0.34\Sigma} T_{bath}^{-3} \sim$$
$$\sim [10^{-4} - 10^{-7}] s$$

Photon energy

$$\delta U = h\nu$$

Energy required to change T$_e$ in the detection junction:

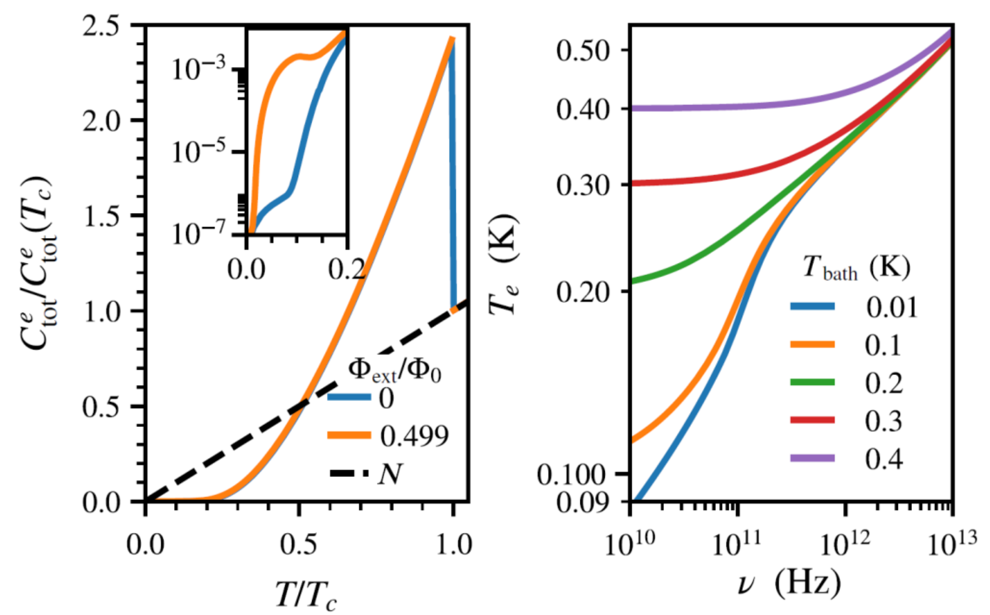
$$\delta U(T_e, T_{bath}) = \delta Q^d(T_e, T_{bath}) + \delta W^d(T_e, T_{bath}) + \delta W^r(T_{bath})$$

δQ: heat of quasiparticles

δW: work to change phase difference

Total electron heat capacity

$$C_{tot}^e(T_e, T_{bath}) = \frac{d}{dT_e} \delta U(T_e, T_{bath})$$



Temperature-to-phase conversion: calorimeter

e-ph relaxation haltime

$$\tau_{1/2}(\nu, T_{bath}) = \int_{[T_e^{max}(\nu)+T_{bath}]/2}^{T_e^{max}(\nu)} dT_e \frac{C_{tot}^e(T_e)}{\dot{Q}_{e-ph}^{tot}(T_e, T_{bath})}$$

$$\dot{Q}_{e-ph} = -\frac{\Sigma_d V_d}{96\zeta(5)k_B^5}\int_{-\infty}^{\infty} dEE \int_{-\infty}^{\infty} d\varepsilon M_{E,E+\varepsilon}(\Delta_0(T_e), \Gamma_0)$$

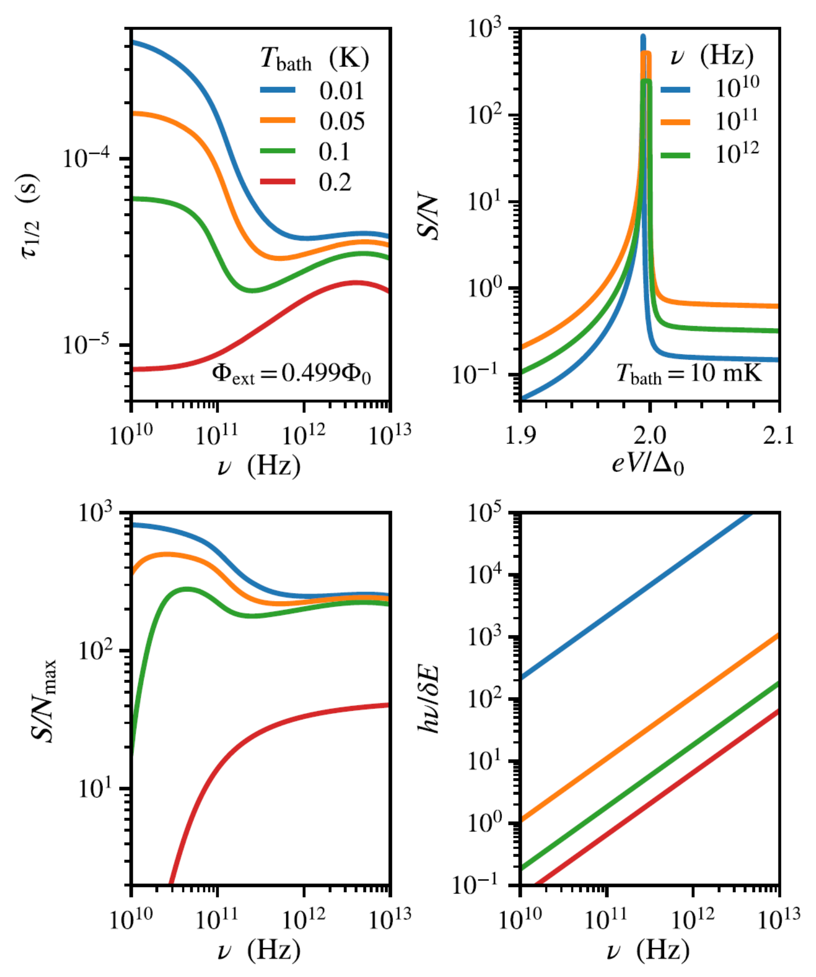
$$\times\, \varepsilon|\varepsilon| \left[coth\left(\frac{\varepsilon}{2k_B T_{bath}}\right)(f_E - f_{E+\varepsilon}) - f_E f_{E+\varepsilon} + 1 \right]$$

signal to noise ratio

$$\frac{S}{N}(T_e(h\nu)) = \frac{I_P(V, T_{bath}) - I_P(V, T_e(h\nu))}{\sqrt{S_I(V, T_{bath})}\sqrt{\omega}}$$

resolving power

$$\frac{h\nu}{\delta E}(\nu, T_{bath}) = \frac{h\nu}{4\sqrt{2\ln 2\, k_B T_{bath}^2 C_{tot}^e(\varphi_d, T_{bath})}}$$



Resolving power > 100 for frequencies above 100GHz at 10mK

Suited for microwave and Far InfraRed single-photon detection

Phys. Rev. Appl. **9**, 054027 (2018)

Temperature-to-phase conversion: bolometer

energy balance equation

$$P_{opt} + \dot{Q}^{tot}_{e-ph}(T_e, T_{bath}) = 0$$

$$\dot{Q}_{e-ph} = -\frac{\Sigma_d V_d}{96\zeta(5)k_B^5}\int_{-\infty}^{\infty} dEE \int_{-\infty}^{\infty} d\varepsilon M_{E,E+\varepsilon}(\Delta_0(T_e),\Gamma_0)$$

$$\times\, \varepsilon|\varepsilon|\left[coth\left(\frac{\varepsilon}{2k_B T_{bath}}\right)(f_E - f_{E+\varepsilon}) - f_E f_{E+\varepsilon} + 1\right]$$

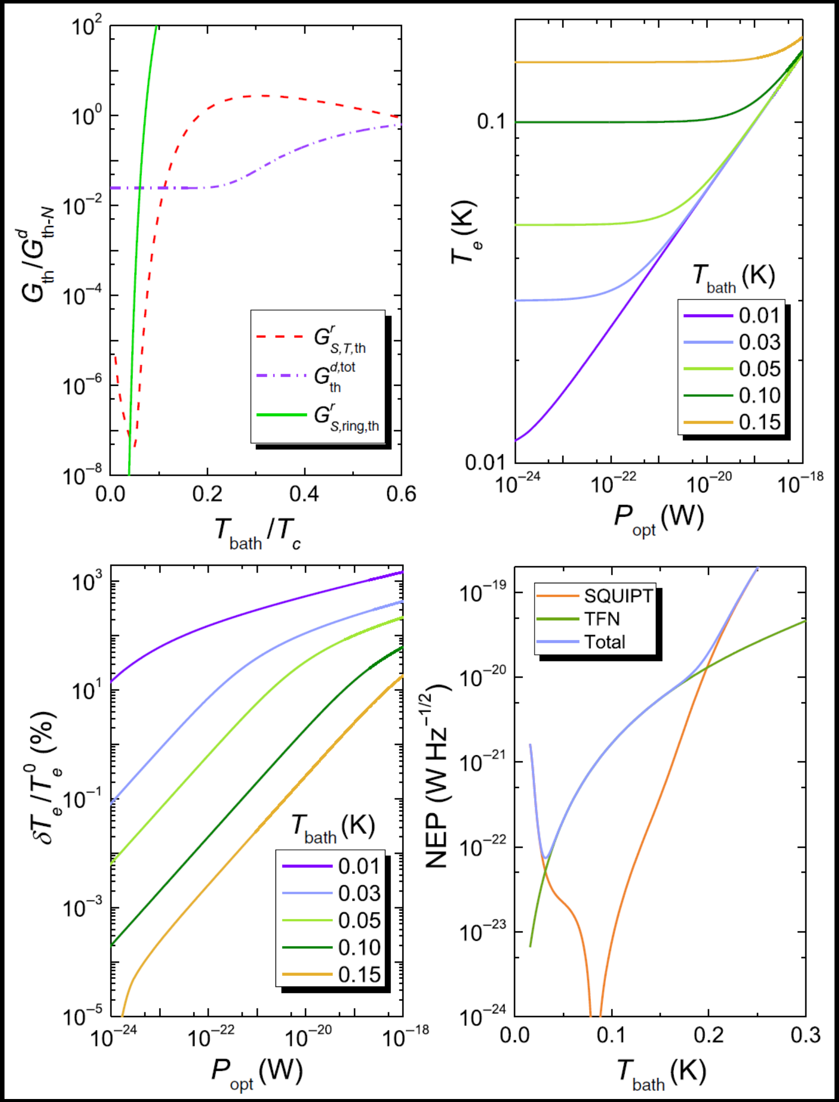
noise equivalent power

$$NEP = \sqrt{4k_B T_{bath}^2 G_{th}^{tot}}$$

e-ph thermal conductance

$$G_{th}^{tot} = \frac{\partial \dot{Q}_{e-ph}}{\partial T_e}$$

NEP below 10-22WHz-1/2 at 50mK



Phys. Rev. Appl. **9**, 054027 (2018)

Temperature-to-phase conversion: performances

- T-to-ϕ conversion due to kinetic inductance changes & SQUIPT spectroscopy
- Thermal sensitivity amplified by small thermal capacity (superconductivity & small volume)
- As electron thermometer: sensitivity up to tens of nK/Hz$^{1/2}$ tunable with Φ in the 10mK…1K temperature range
- Calorimetric mode: resolving power $h\nu/\delta E > 10^2$ for 50GHz…10THz photons
- Bolometric mode: NEP $\sim 10^{-22}$ W/Hz$^{1/2}$ below 50 mK
- Attractive as MW and FIR radiation detector for open problems in **astrophysics** & **quantum electronic circuits**

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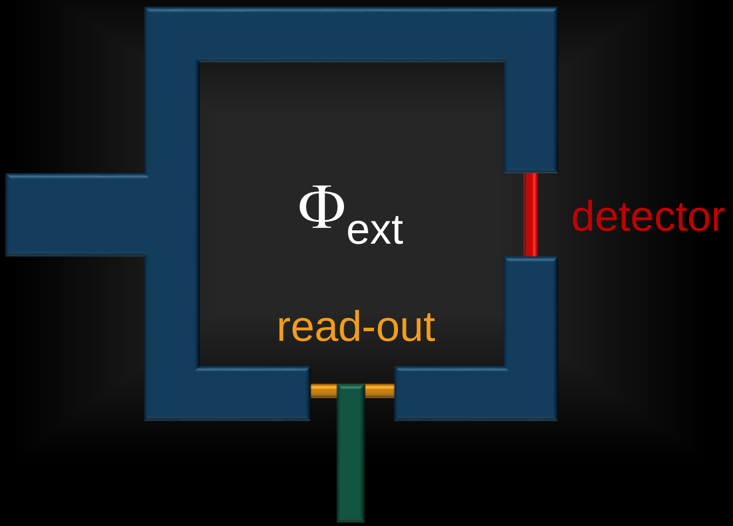

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