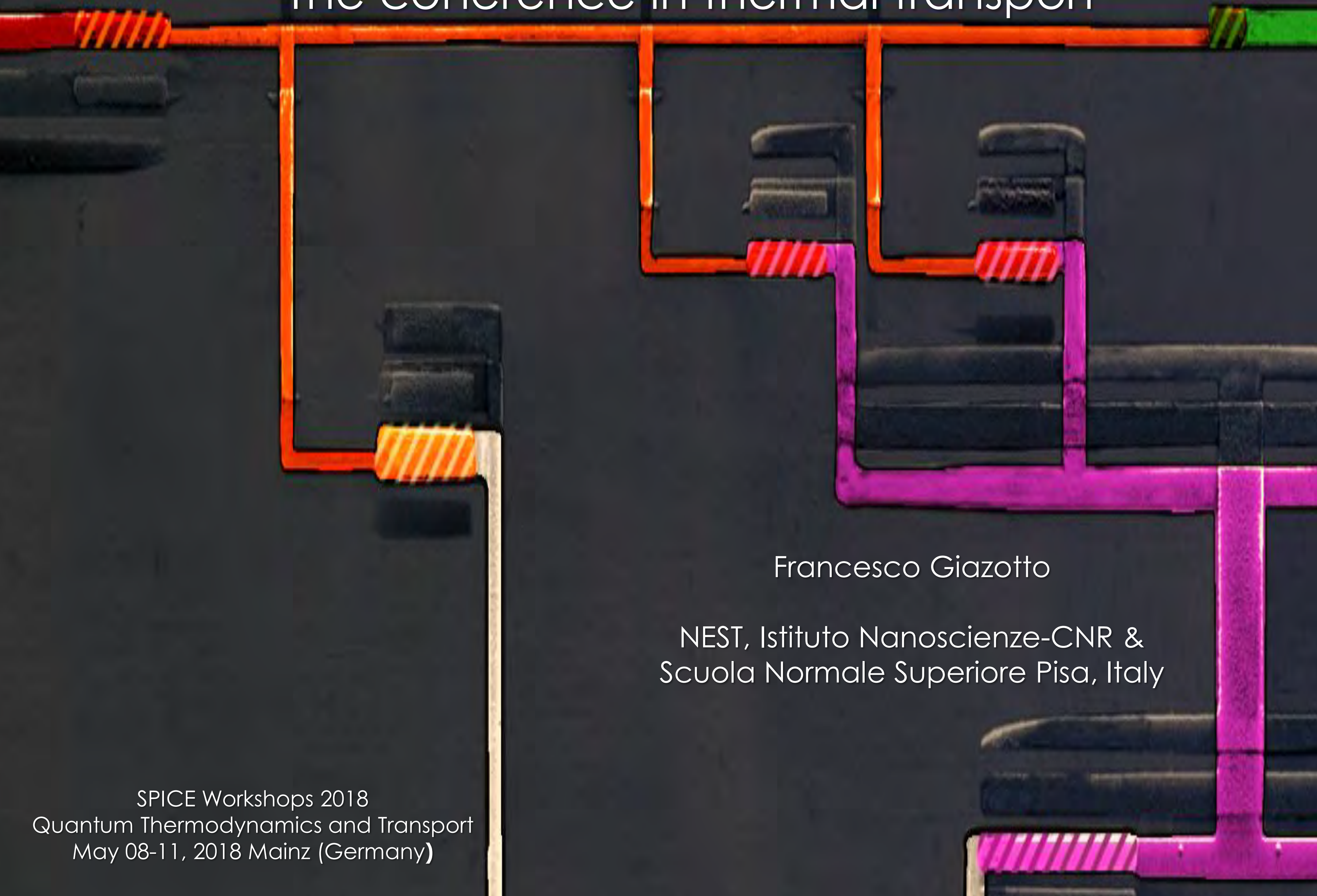
Tutorial: Superconductivity: The coherence in thermal transport



Francesco Giazotto

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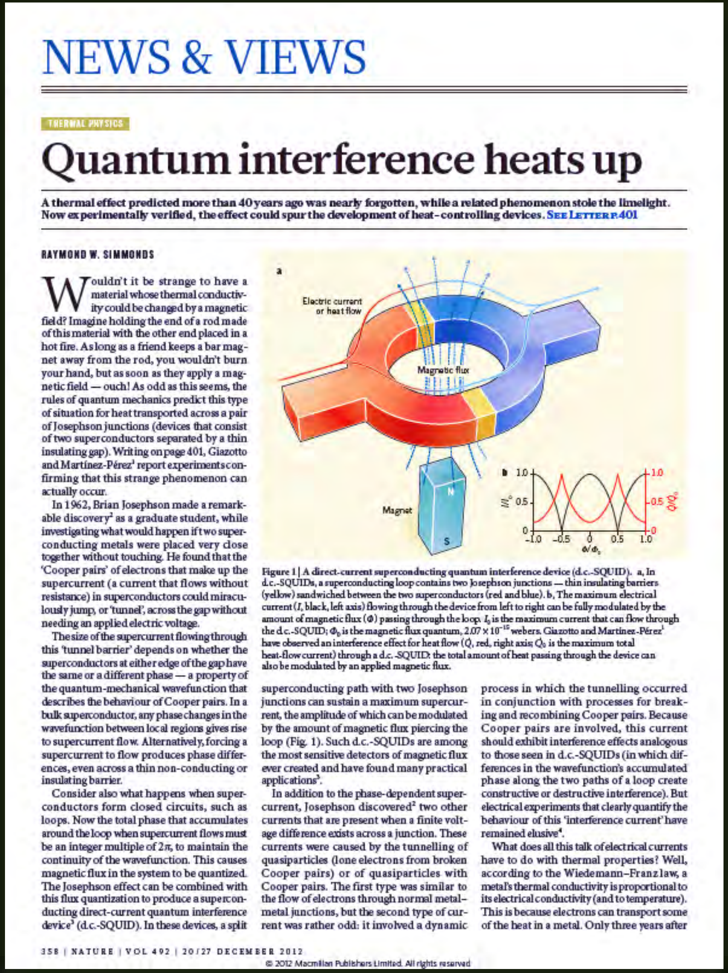
SPICE Workshops 2018
Quantum Thermodynamics and Transport
May 08-11, 2018 Mainz (Germany)

Outline

1. Motivation & mission
2. Overview
3. Basic concept of thermal transport in Josephson-based quantum circuits
4. Double & single-slit heat interferometers
5. Balanced thermal modulators
6. Josephson thermal π-junctions
7. Phase-tunable Josephson thermal routers

Motivations & mission

- Set the experimental ground for a challenging young branch of science: the *coherent caloritronics*, i.e., the complementary of coherent electronics
- *Phase*-manipulate & master heat transfer in a solid-state environment
- Provide original & novel approaches to realize *thermal devices* (heat transistors, splitters, diodes, refrigerators, exotic quantum circuits)
- Address & understand fundamental *energy- and heat-related phenomena* at nanoscale (coherent dynamics, heat interference, time-dependent effects, quantum thermodynamics, decoherence)



NEWS & VIEWS

THERMAL PHYSICS

Quantum interference heats up

A thermal effect predicted more than 40 years ago was nearly forgotten, while a related phenomenon stole the limelight. Now experimentally verified, the effect could spur the development of heat-controlling devices. SEE LETTER P.401

RAYMOND W. SIMMONDS

Wouldn't it be strange to have a material whose thermal conductivity could be changed by a magnetic field? Imagine holding the end of a rod made of this material with the other end placed in a hot fire. As long as a friend keeps a bar magnet away from the rod, you wouldn't burn your hand, but as soon as they apply a magnetic field — ouch! As odd as this seems, the rules of quantum mechanics predict this type of situation for heat transported across a pair of Josephson junctions (devices that consist of two superconductors separated by a thin insulating gap). Writing on page 401, Giazotto and Martínez-Pérez[1] report experiments confirming that this strange phenomenon can actually occur.

In 1962, Brian Josephson made a remarkable discovery[2] as a graduate student, while investigating what would happen if two superconducting metals were placed very close together without touching. He found that the 'Cooper pairs' of electrons that make up the supercurrent (a current that flows without resistance) in superconductors could miraculously jump, or 'tunnel', across the gap without needing an applied electric voltage.

The size of the supercurrent flowing through this 'tunnel barrier' depends on whether the superconductors at either edge of the gap have the same or a different phase — a property of the quantum-mechanical wavefunction that describes the behaviour of Cooper pairs. In a bulk superconductor, any phase changes in the wavefunction between local regions gives rise to supercurrent flow. Alternatively, forcing a supercurrent to flow produces phase differences, even across a thin non-conducting or insulating barrier.

Consider also what happens when superconductors form closed circuits, such as loops. Now the total phase that accumulates around the loop when supercurrent flows must be an integer multiple of 2π, to maintain the continuity of the wavefunction. This causes magnetic flux in the system to be quantized. The Josephson effect can be combined with this flux quantization to produce a superconducting direct-current quantum interference device[3] (d.c.-SQUID). In these devices, a split superconducting path with two Josephson junctions can sustain a maximum supercurrent, the amplitude of which can be modulated by the amount of magnetic flux piercing the loop (Fig. 1). Such d.c.-SQUIDs are among the most sensitive detectors of magnetic flux ever created and have found many practical applications[3].

In addition to the phase-dependent supercurrent, Josephson discovered[2] two other currents that are present when a finite voltage difference exists across a junction. These currents were caused by the tunnelling of quasiparticles (lone electrons from broken Cooper pairs) or of quasiparticles with Cooper pairs. The first type was similar to the flow of electrons through normal metal–metal junctions, but the second type of current was rather odd: it involved a dynamic process in which the tunnelling occurred in conjunction with processes for breaking and recombining Cooper pairs. Because Cooper pairs are involved, this current should exhibit interference effects analogous to those seen in d.c.-SQUIDs (in which differences in the wavefunction's accumulated phase along the two paths of a loop create constructive or destructive interference). But electrical experiments that clearly quantify the behaviour of this 'interference current' have remained elusive[4].

What does all this talk of electrical currents have to do with thermal properties? Well, according to the Wiedemann–Franz law, a metal's thermal conductivity is proportional to its electrical conductivity (and to temperature). This is because electrons can transport some of the heat in a metal. Only three years after

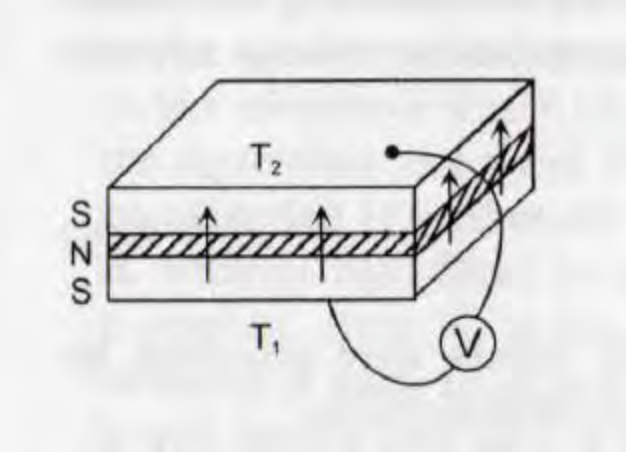
Figure 1 | A direct-current superconducting quantum interference device (d.c.-SQUID). **a**, In d.c.-SQUIDs, a superconducting loop contains two Josephson junctions — thin insulating barriers (yellow) sandwiched between the two superconductors (red and blue). **b**, The maximum electrical current (I, black, left axis) flowing through the device from left to right can be fully modulated by the amount of magnetic flux (Φ) passing through the loop. I_0 is the maximum current that can flow through the d.c.-SQUID; Φ_0 is the magnetic flux quantum, 2.07×10^{-15} webers. Giazotto and Martínez-Pérez[1] have observed an interference effect for heat flow ($\dot{Q}$, red, right axis; $\dot{Q}_0$ is the maximum total heat-flow current) through a d.c.-SQUID: the total amount of heat passing through the device can also be modulated by an applied magnetic flux.

358 | NATURE | VOL 492 | 20/27 DECEMBER 2012

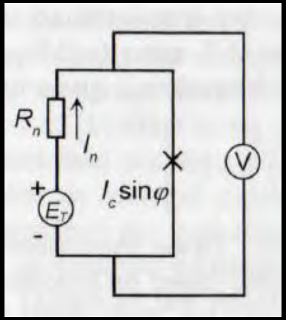
Main goal: develop **quantum technology** for managing **heat** in nanoscale circuits

Thermoelectric effects in Josephson junctions

dc & ac thermoelectric response



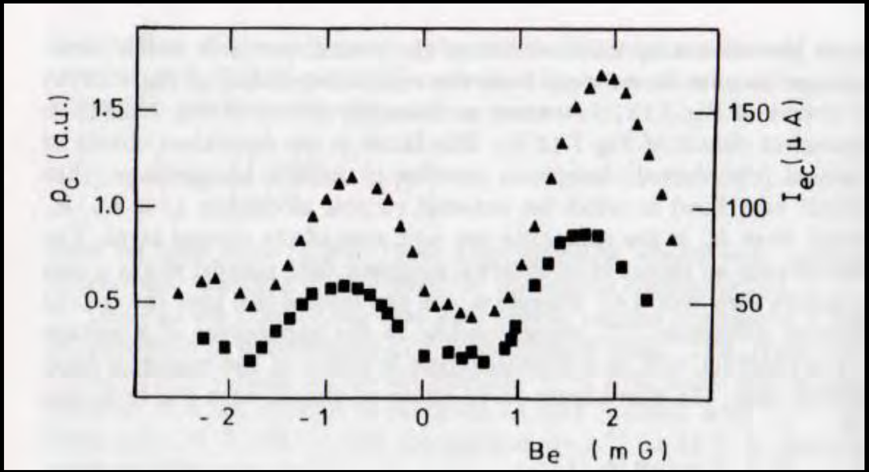
SNS-like Josephson junction



$$\omega = \frac{2e}{\hbar} R_n \left[\left(\frac{\alpha \Delta T}{R_n} \right)^2 - I_c{}^2 \right]^{1/2}$$

$\alpha \sim 10^{-8}$ V/K thermopower

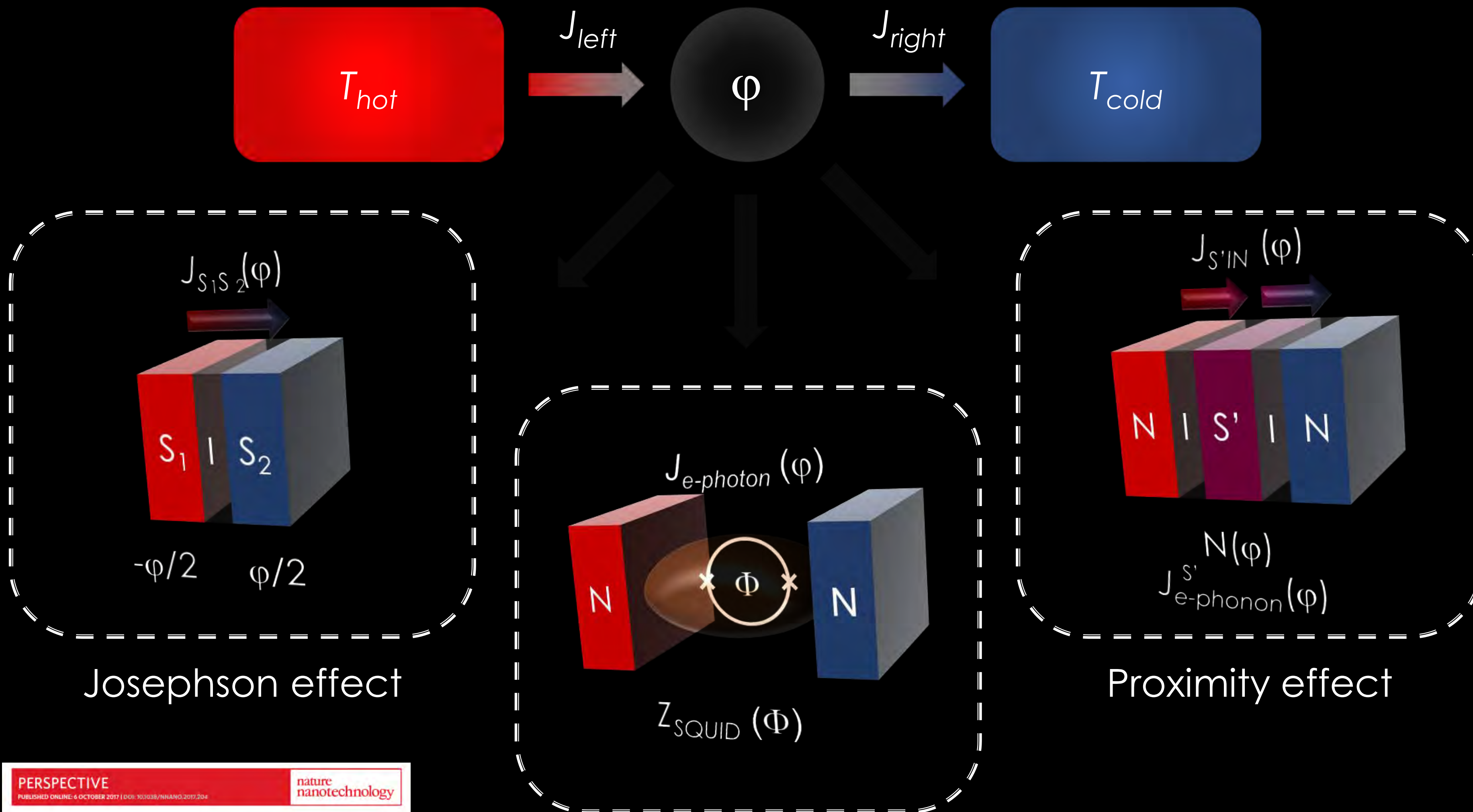
Presence of a magnetic field



Aronov and Galperin, JETP Lett. **19**, 165 (1974);
Kartsovnik, Ryazanov, and Schmidt, JETP Lett. **33**, 356 (1981);
Ryazanov and Schmidt, Solid State Commun. **40** 1055, (1981);
Clarke and Freake, Phys. Rev. Lett. **29**, 588 (1982).

Panaitov, Ryazanov, Ustinov, and Schmidt, Phys. Lett. **100A**, 301 (1984);
Schmidt, JETP Lett. **33**, 98 (1981);
Ryazanov and Schmidt, Solid State Commun. **42,** 733 (1982);
Huebener, Supercond. Sci. Technol. **8**, 189 (1995).

Physical basis of coherent caloritronics



Tuning
electron-photon interaction


PERSPECTIVE

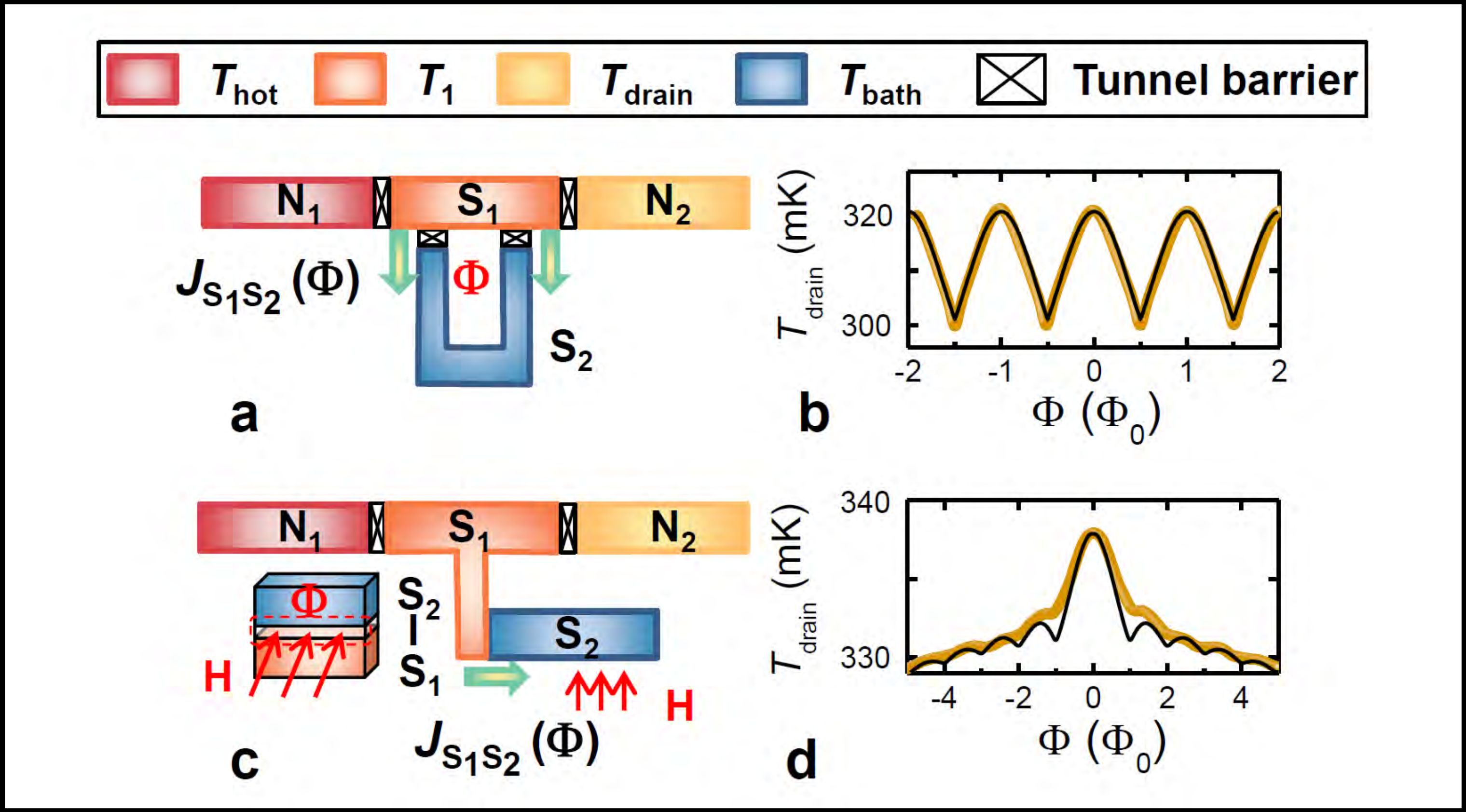
nature nanotechnology

Towards phase-coherent caloritronics in superconducting circuits

Antonio Fornieri and Francesco Giazotto

A. Fornieri and FG, Nat. Nanotechnol. **12** (2017)

Josephson tunnel circuits



Josephson heat interferometers

b – Double-slit Josephson interferometer

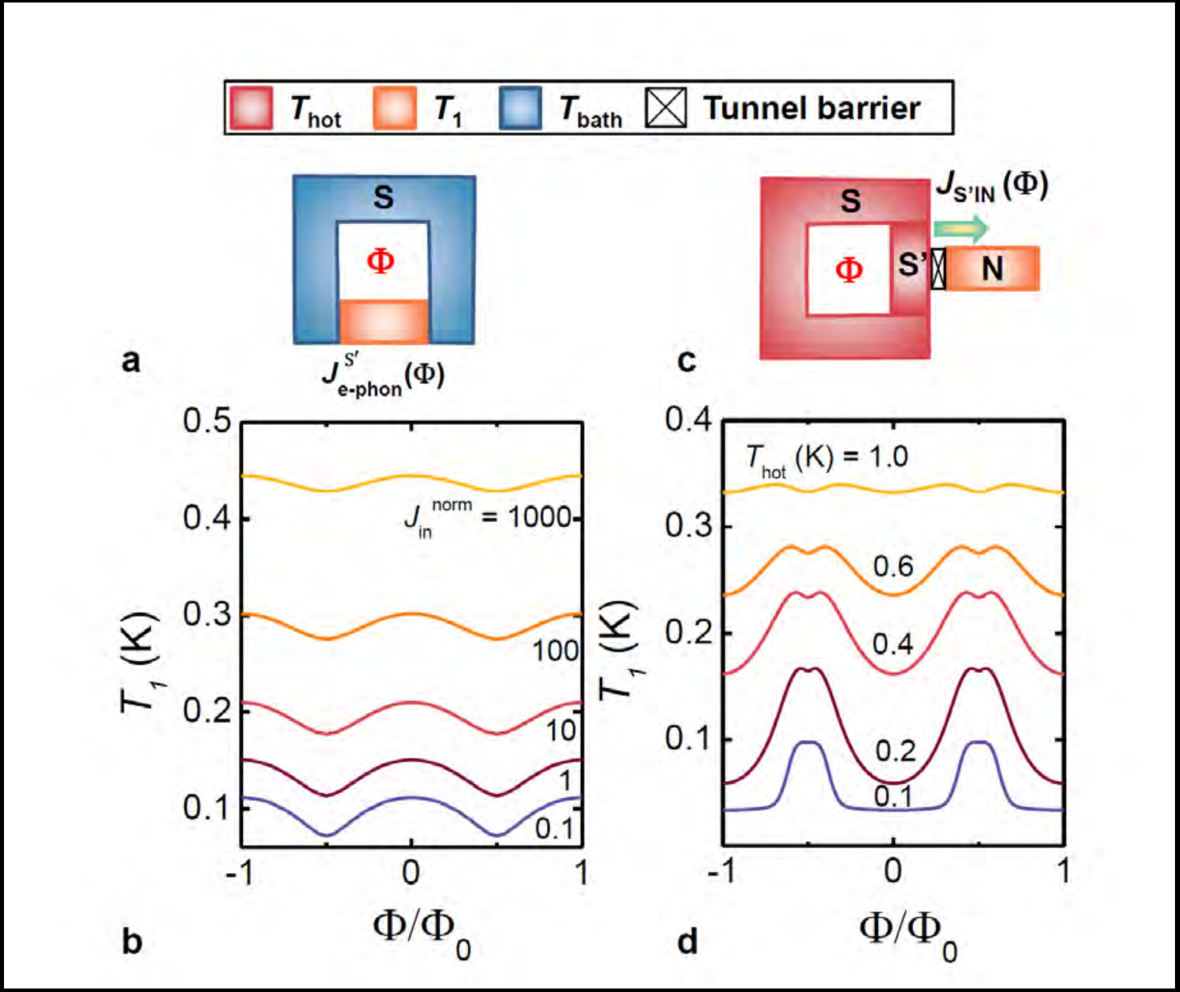
$$J_{\rm SQUID}(T_1, T_{\rm bath}, \Phi) = 2J_{\rm qp}(T_1, T_{\rm bath}) - 2J_{\rm int}(T_1, T_{\rm bath}) \left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|$$

c – Single-slit Josephson diffractor

$$J_{S_1S_2}(T_1, T_{\rm bath}, \Phi) = J_{\rm qp}(T_1, T_{\rm bath}) - J_{\rm int}(T_1, T_{\rm bath}) \left|\frac{\sin(\pi\Phi/\Phi_0)}{(\pi\Phi/\Phi_0)}\right|$$

A. Fornieri and FG, Nat. Nanotechnol. **12** (2017)

Superconducting proximity structures

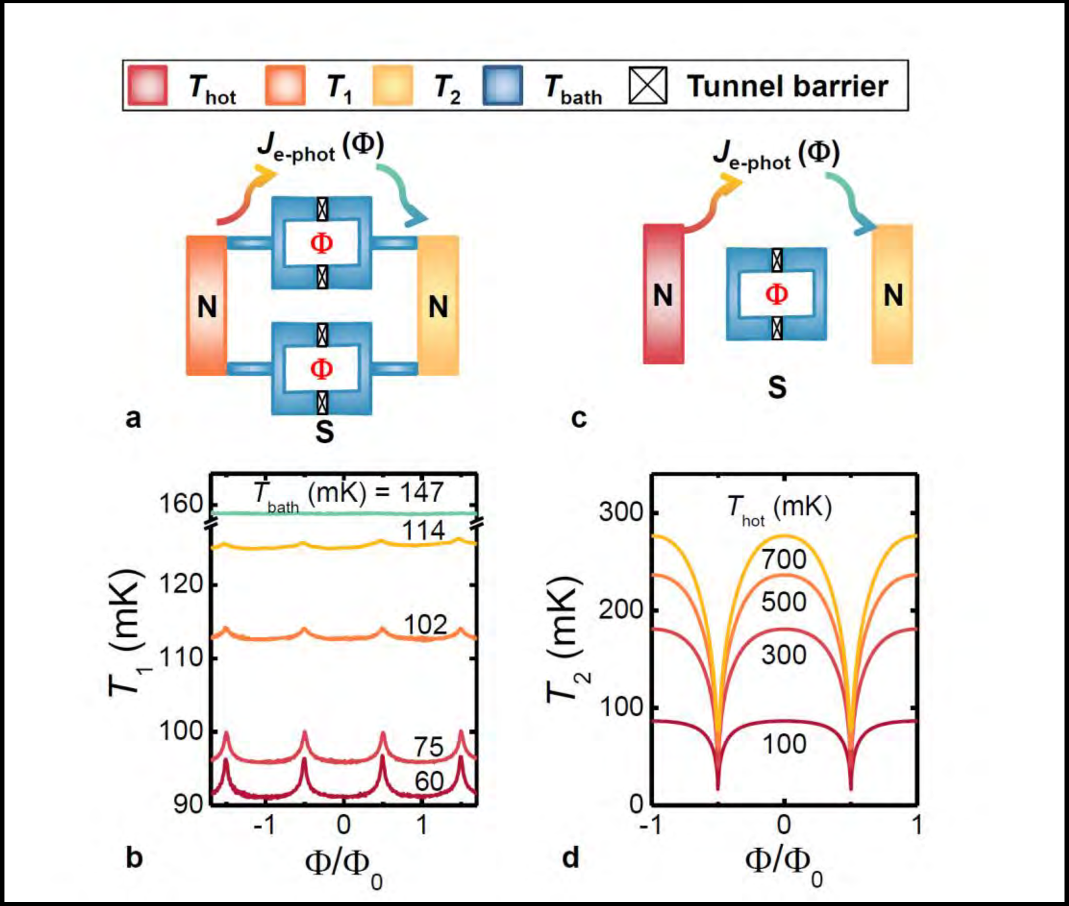


a– Phase-dependent electron-phonon coupling, entropy, specific heat

c – Phase-tunable proximity thermal valve

A. Fornieri and FG, Nat. Nanotechnol. **12** (2017)

Photonic heat transistors



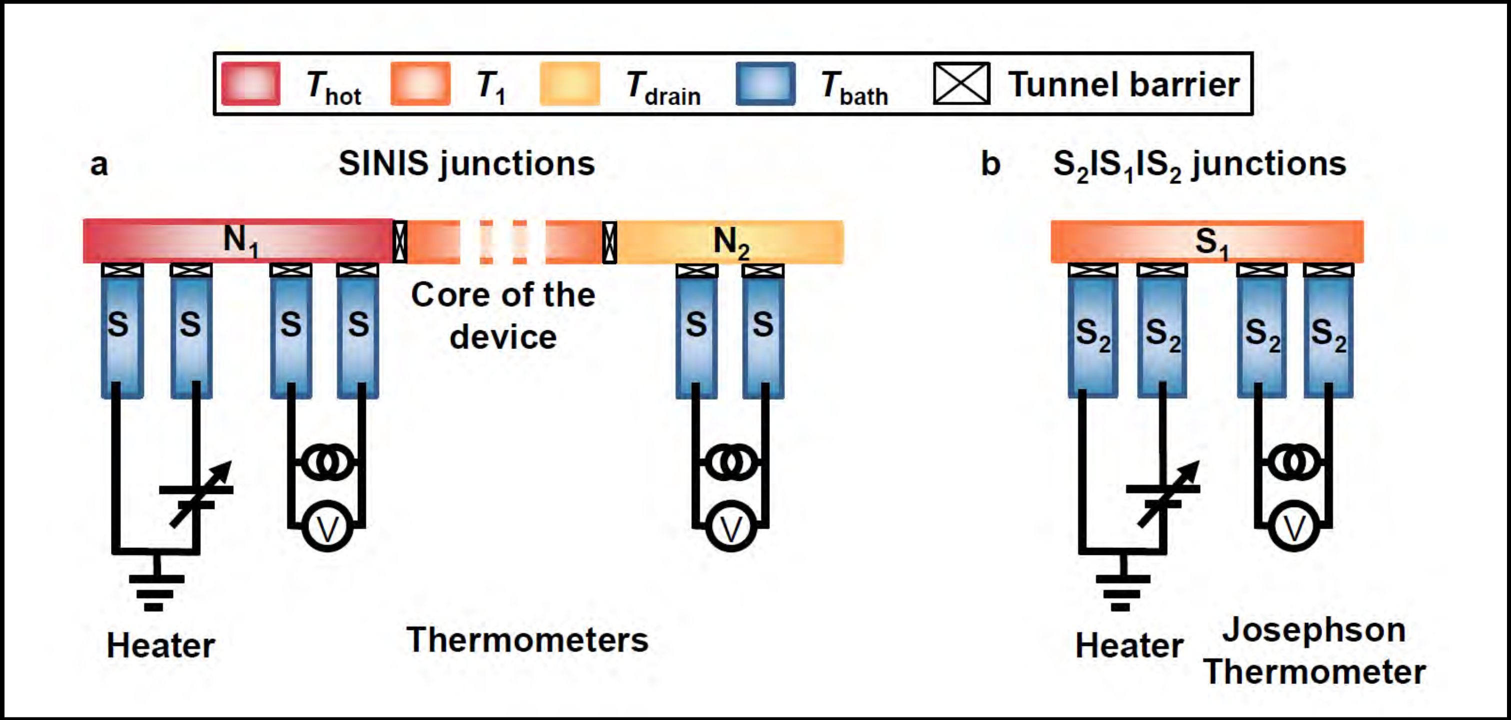
a – First demonstration of phase-dependent photonic heat conduction

c – Design for a *non-galvanic* photonic thermal transistor

$$\mathcal{T}(\omega) = \frac{4\Re[Z_1(\omega)]\Re[Z_2(\omega)]}{|Z_{\text{tot}}(\omega)|^2}$$

M. Meschke, *et al.*, Nature **444**, 187 (2006);
A. Fornieri and FG, Nat. Nanotechnol. **12** (2017);
A. Ronzani, *et al.*, arXiv:1801.09312.

Experimental setups



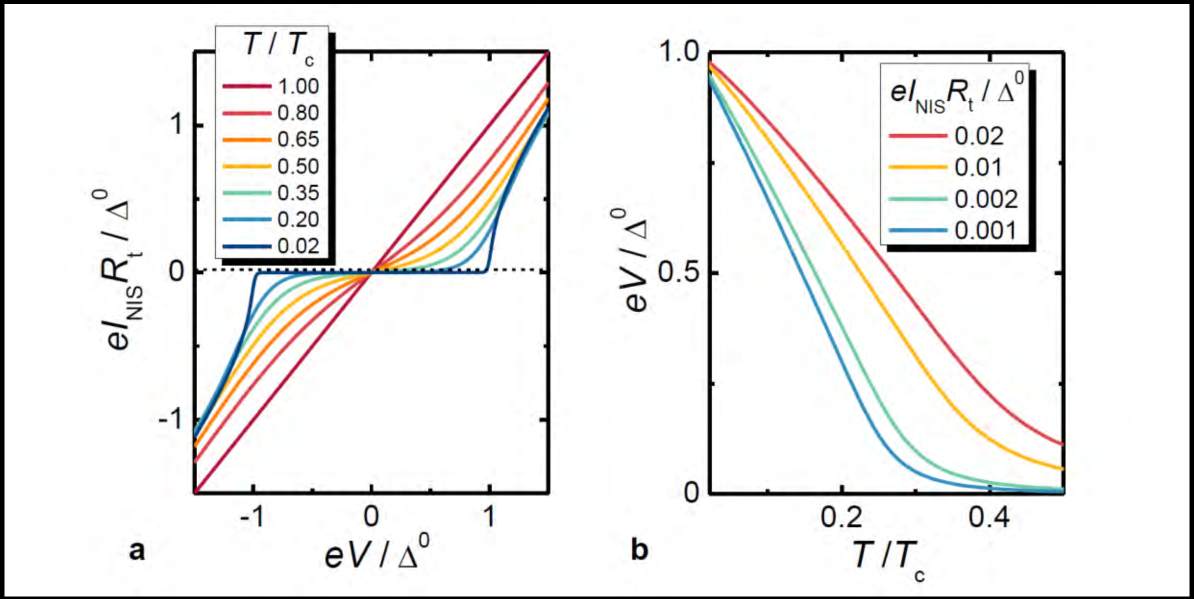
b – DC & RF electron thermometry through SINIS tunnel junctions

c – Electron thermometry through temperature dependence of the critical current, or through quasiparticle current

FG, T. T. Heikkila, A. Luukanen, A. M. Savin, and J. P. Pekola, Rev. Mod. Phys. **78**, 217 (2006)

S. Gasparinetti, *et al*., Phys. Rev. Appl. **3**, 014007 (2015);
K. L. Viisanen and J. P. Pekola, Phys. Rev. B **97**, 115422 (2018);
O.-P. Saira, *et al*., Phys. Rev. Applied **6**, 024005 (2016);
J. Govenius, *et al*., Phys. Rev. Lett. **117**, 030802 ()2016.

Electric transport in superconducting tunnel junctions (NIS)



$$I_{\mathrm{NIS}}(V,T_1,T_2) = \frac{1}{eR_{\mathrm{t}}}\int_{-\infty}^{\infty} \mathrm{d}E\mathcal{N}(E,T_2)[f_1(E-eV,T_1)-f_2(E,T_2)],$$
$$= \frac{1}{2eR_{\mathrm{t}}}\int_{-\infty}^{\infty} \mathrm{d}E\mathcal{N}(E,T_2)[f_1(E-eV,T_1)-f_1(E+eV,T_1)]$$

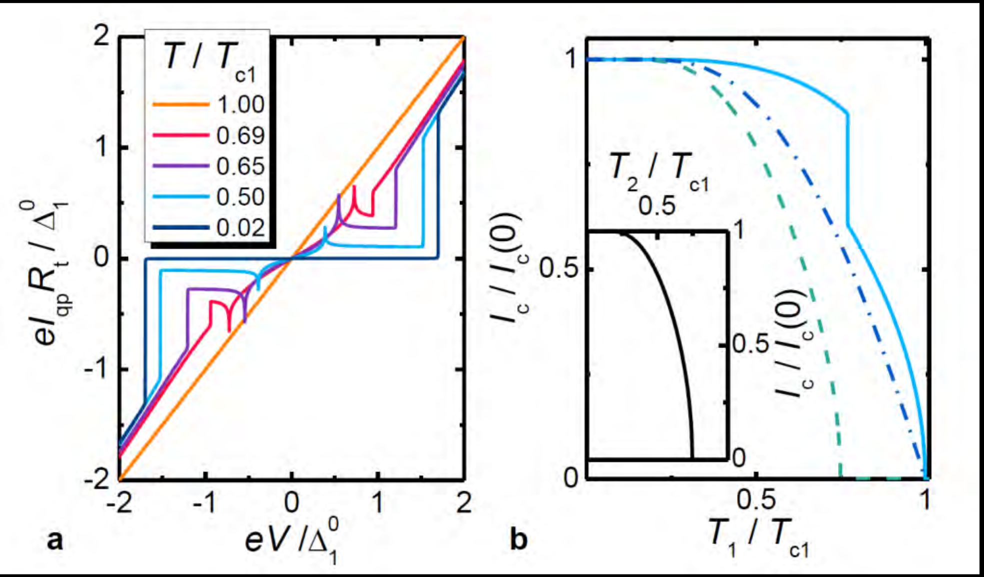
a – *I*/*V* characteristics of a NIS junction

b – Voltage response of the junction vs *T* at given I_{bias}: sensitive electron thermometry

FG, T. T. Heikkila, A. Luukanen, A. M. Savin, and J. P. Pekola, Rev. Mod. Phys. **78**, 217 (2006)

S. Gasparinetti, *et al.*, Phys. Rev. Appl. **3**, 014007 (2015);
K. L. Viisanen and J. P. Pekola, Phys. Rev. B **97**, 115422 (2018);
O.-P. Saira, *et al.*, Phys. Rev. Applied **6**, 024005 (2016);
J. Govenius, *et al.*, Phys. Rev. Lett. **117**, 030802 ()2016.

Electric transport in superconducting tunnel junctions (SIS)



$$I_j(V, T_1, T_2, \varphi) = I_c(T_1, T_2)\sin\varphi + I_{int}(V, T_1, T_2)\cos\varphi$$

$$I_c(T_1, T_2) = \frac{1}{2eR_t}\left|\int_{-\infty}^{\infty} dE\{\mathbf{f}(E, T_1)\Re[\mathcal{F}_1(E, T_1)]\Im[\mathcal{F}_2(E, T_2)] + \mathbf{f}(E, T_2)\Re[\mathcal{F}_2(E, T_2)]\Im[\mathcal{F}_1(E, T_1)]\right|,$$

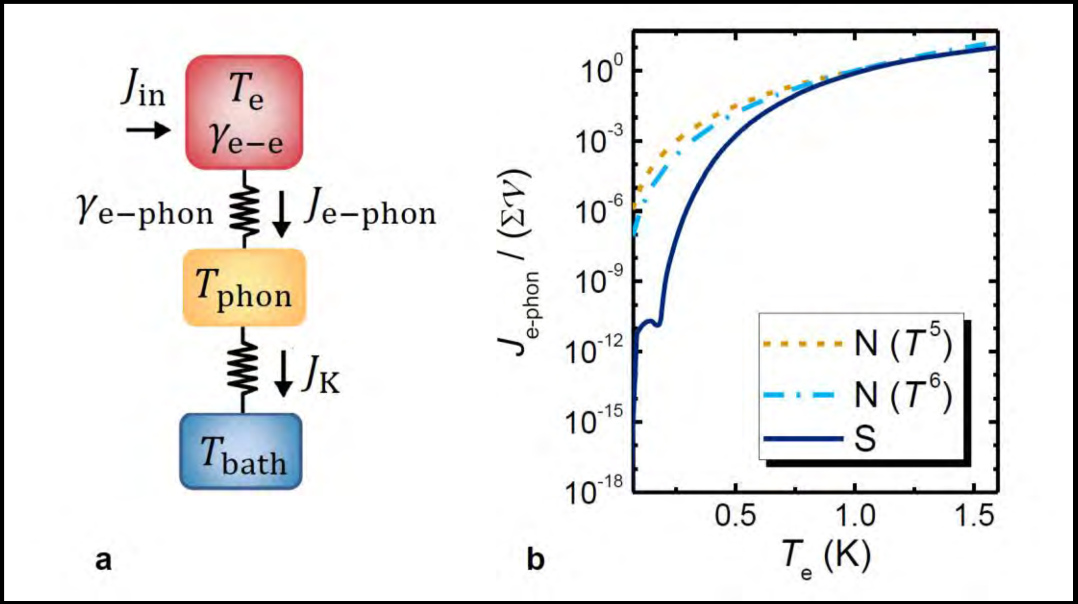
a – *I/V* quasiparticle characteristics of a SIS junction: more complicated thermometry

b – Temperature dependence of the Josephson current: non-dissipative thermometry

FG, T. T. Heikkila, A. Luukanen, A. M. Savin, and J. P. Pekola, Rev. Mod. Phys. **78**, 217 (2006)

S. Gasparinetti, *et al.*, Phys. Rev. Appl. **3**, 014007 (2015);
K. L. Viisanen and J. P. Pekola, Phys. Rev. B **97**, 115422 (2018);
O.-P. Saira, *et al.*, Phys. Rev. Applied **6**, 024005 (2016);
J. Govenius, *et al.*, Phys. Rev. Lett. **117**, 030802 ()2016.

Quasiequilibrium regime in mesoscopic circuits



$$J^{\rm N}_{\rm e-phon} = \Sigma \mathcal{V} (T_{\rm e}^5 - T_{\rm bath}^5)$$

clean metal

$$J^{\rm AlMn}_{\rm e-phon} = \Sigma_{\rm AlMn} \mathcal{V} (T_{\rm e}^6 - T_{\rm bath}^6)$$

disordered metal

$$J^{\rm S}_{\rm e-phon}(T_{\rm e}, T_{\rm bath}) = -\frac{\Sigma \mathcal{V}}{96\zeta(5) k_{\rm B}^5} \int_{-\infty}^{\infty} dE E \int_{-\infty}^{\infty} d\epsilon \epsilon^2 {\rm sgn}(\epsilon) {\rm L}({\rm E}, {\rm E}+\epsilon, {\rm T_e}) \left\{ \coth\left(\frac{\epsilon}{2k_{\rm B}T_{\rm bath}}\right) [f^{(1)}(E, T_{\rm e}) - f^{(1)}(E+\epsilon, T_{\rm e})] - f^{(1)}(E, T_{\rm e}) f^{(1)}(E+\epsilon, T_{\rm e}) + 1 \right\}.$$

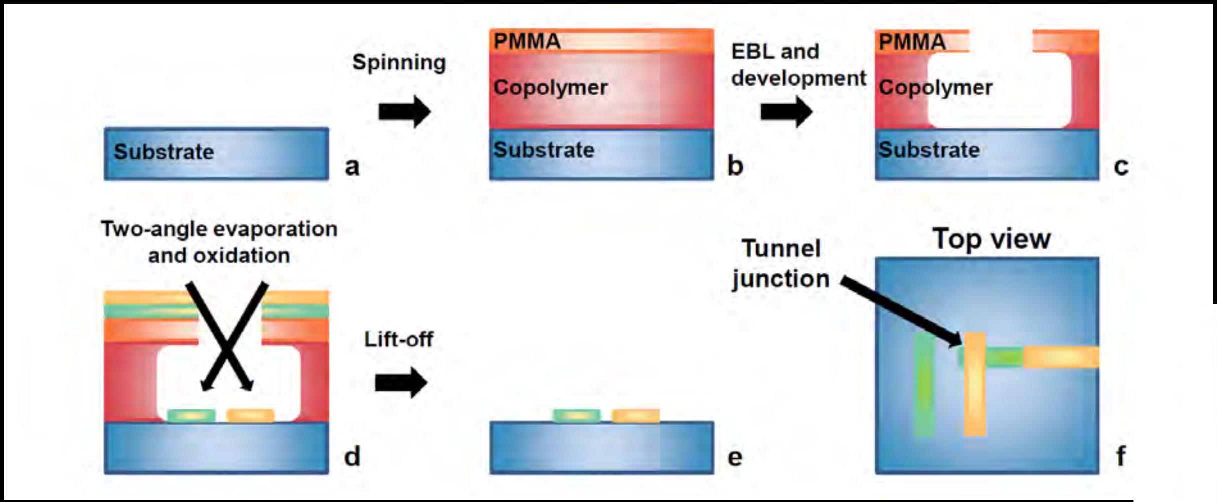
superconductor

a – Scheme of N or S film on a substrate

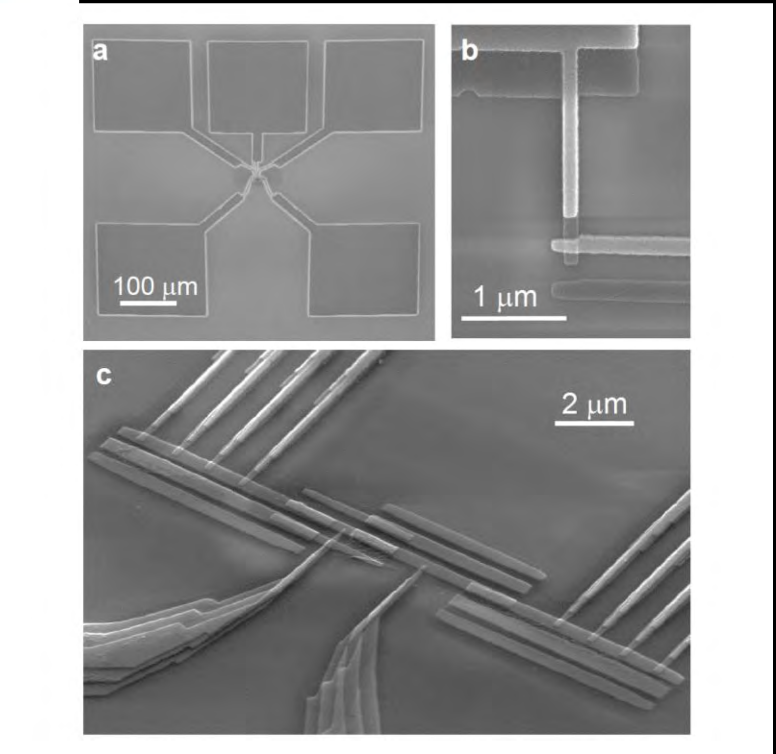
b – Electron-phonon coupling in N and S

FG, T. T. Heikkila, A. Luukanen, A. M. Savin, and J. P. Pekola, Rev. Mod. Phys. **78**, 217 (2006);
A. Fornieri and FG, Nat. Nanotechnol. **12** (2017);
A. V. Timofeev, *et al.*, Phys. Rev. Lett. **102**, 017003 (2009)

Nanofabrication techniques

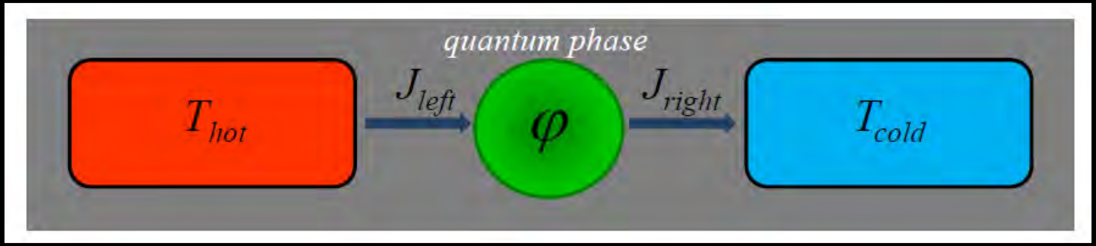


Angle evaporation and *in-situ* oxidation

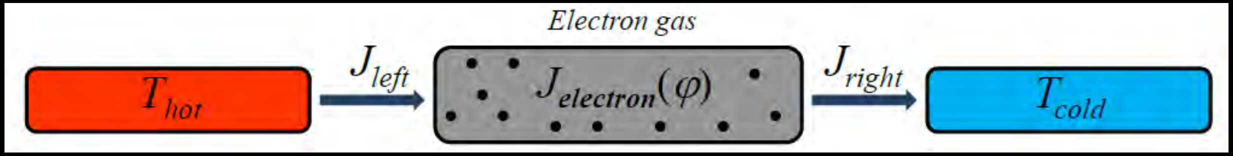


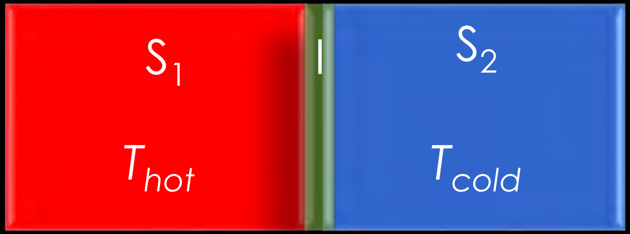
Typical shadow-mask evaporated structures

Principle of phase-dependent heat current control



Exploitation of quantum phase to control heat current flow





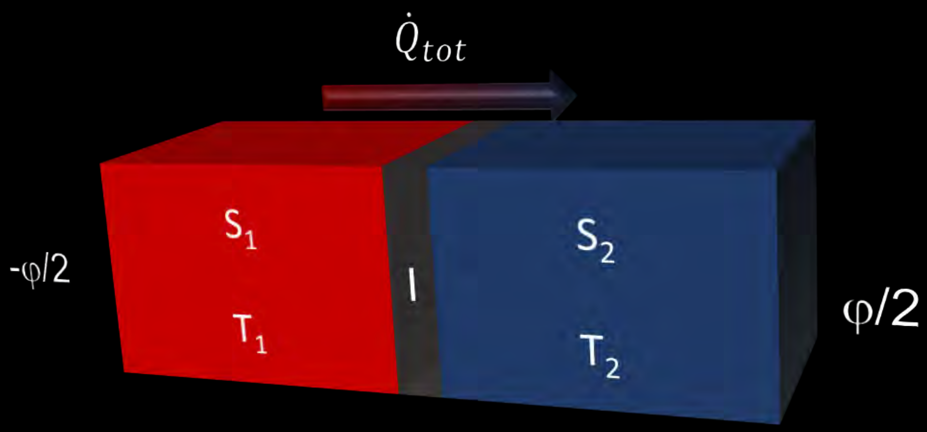
Temperature-biased Josephson tunnel junction

↓

Heat current is predicted to be phase dependent and stationary

Maki and Griffin, PRL **15**, 921 (1965);
Zhao et al., PRL **91**, 077003 (2003);
Zhao et al., PRB **69**, 134503 (2004)

Heat current in a temperature-biased JJ



Maki and Griffin, PRL **15**, 921 (1965);
Zhao et al., PRL **91**, 077003 (2003);
Zhao et al., PRB **69**, 134503 (2004

$$\dot{Q}_{tot} = \dot{Q}_{qp}(T_1, T_2) - \dot{Q}_{int}(T_1, T_2\,)\cos\varphi$$

$$\dot{Q}_{qp}(T_1, T_2) = \frac{2}{e^2 R_T}\int_0^{\infty} E\aleph_1(E, T_1)\aleph_2(E, T_2)[f_1(E, T_1) - f_2(E, T_2)]dE$$ quasiparticle

$$\dot{Q}_{int}(T_1, T_2) = \frac{2}{e^2 R_T}\int_0^{\infty} E\mathcal{M}_1(E, T_1)\mathcal{M}_2(E, T_2)[f_1(E, T_1) - f_2(E, T_2)]dE$$ interference

$$\aleph_{1,2}(E, T_{1,2}) = |E|/\sqrt{E^2 - \Delta_{1,2}(T_{1,2})^2}\,\theta\left[E^2 - \Delta_{1,2}(T_{1,2})^2\right]$$

$$\mathcal{M}_{1,2}(E, T_{1,2}) = |\Delta_{1,2}(T_{1,2})|/\sqrt{E^2 - \Delta_{1,2}(T_{1,2})^2}\,\theta\left[E^2 - \Delta_{1,2}(T_{1,2})^2\right]$$

$$f_{1,2}(E, T_{1,2}) = \left[1 + e^{E/k_B T_{1,2}}\right]^{-1}$$

$$\begin{cases}\dot{Q}_{qp} = 0 \\ \dot{Q}_{int} = 0\end{cases} \quad if\ T_1 = T_2$$

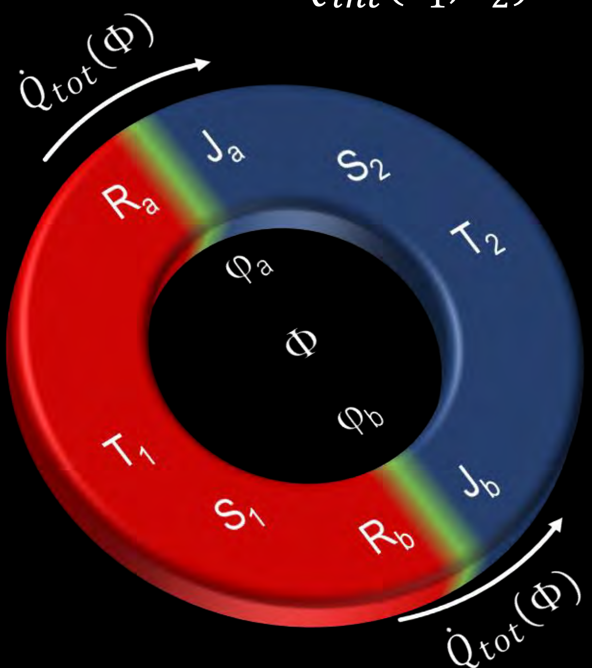
$$\dot{Q}_{int} = 0 \quad if\ S_1\ or\ S_2\ in\ normal\ state$$

Temperature-biased DC-SQUID: theory (i)

$$\dot{Q}_{tot} = \dot{Q}_{qp}(T_1, T_2) - \dot{Q}_{int}(T_1, T_2, \varphi_a, \varphi_b)$$

$$\dot{Q}_{qp}(T_1, T_2) = \dot{Q}^{a}_{qp}(T_1, T_2) + \dot{Q}^{b}_{qp}(T_1, T_2)$$

$$\dot{Q}_{int}(T_1, T_2) = \dot{Q}^{a}_{int}(T_1, T_2)\cos\varphi_a + \dot{Q}^{b}_{qp}(T_1, T_2)\cos\varphi_b$$



$\varphi_a + \varphi_b + 2\pi\,\Phi/\Phi_0 = 2k\pi$ Flux quantization

$I^a_j \sin\varphi_a = I^a_j \sin\varphi_b$ Current conservation

$$\cos\varphi_a = \frac{r + \cos(2\pi x)}{\sqrt{1 + r^2 2r\cos(2\pi x)}}$$ $x = \Phi/\Phi_0$

$$\cos\varphi_b = \frac{1 + \cos(2\pi x)}{\sqrt{1 + r^2 2r\cos(2\pi x)}}$$ r= I^a_j/I^b_j

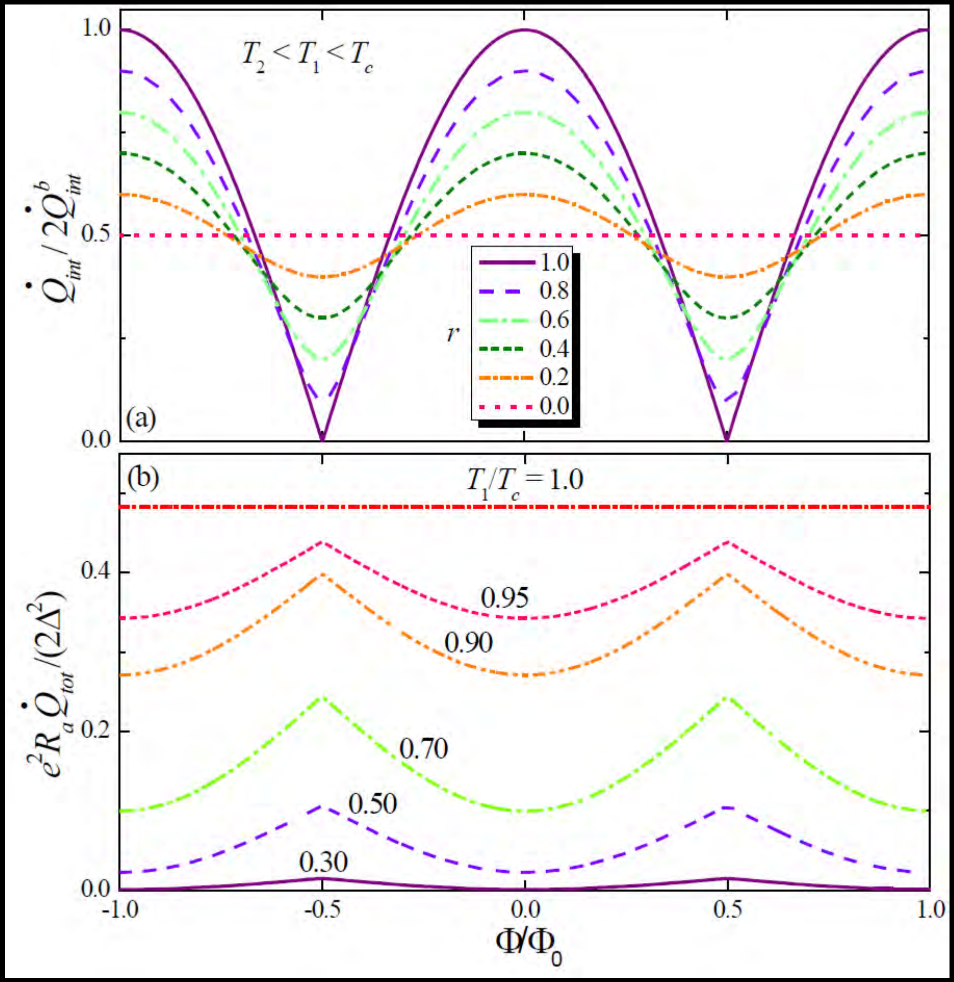
$$\dot{Q}_{int} = \dot{Q}^{b}_{int}(T_1, T_2)\sqrt{1 + r^2 + 2r\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$

Symmetric SQUID

$$\dot{Q}_{int} = 2\dot{Q}^{b}_{int}(T_1, T_2)\left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|$$

FG and M. J. Martinez-Perez, APL **101**, 102601 (2012)

Temperature-biased DC-SQUID: theory (ii)



Role of critical current asymmetry

Maximum $\dot{Q}^b_{int}(1+r)$

Minimum $\dot{Q}^b_{int}(1-r)$

Total heat current behavior (symmetric SQUID)

$T_2 = 0.1T_c$

FG and M. J. Martinez-Perez, APL **101**, 102601 (2012)

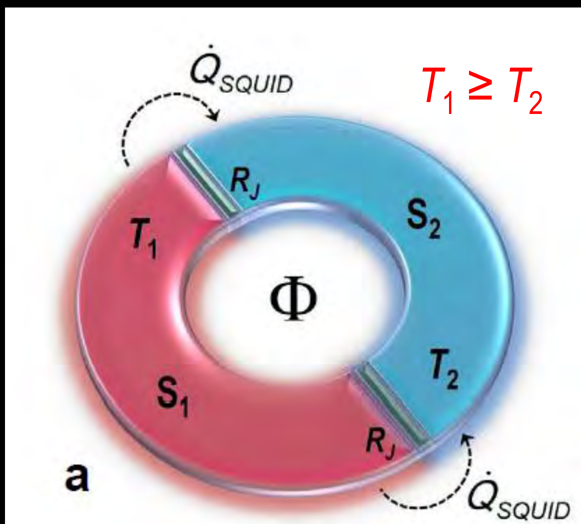
"Josephson heat interferometer": setup (i)


LETTER

doi:10.1038/nature11702

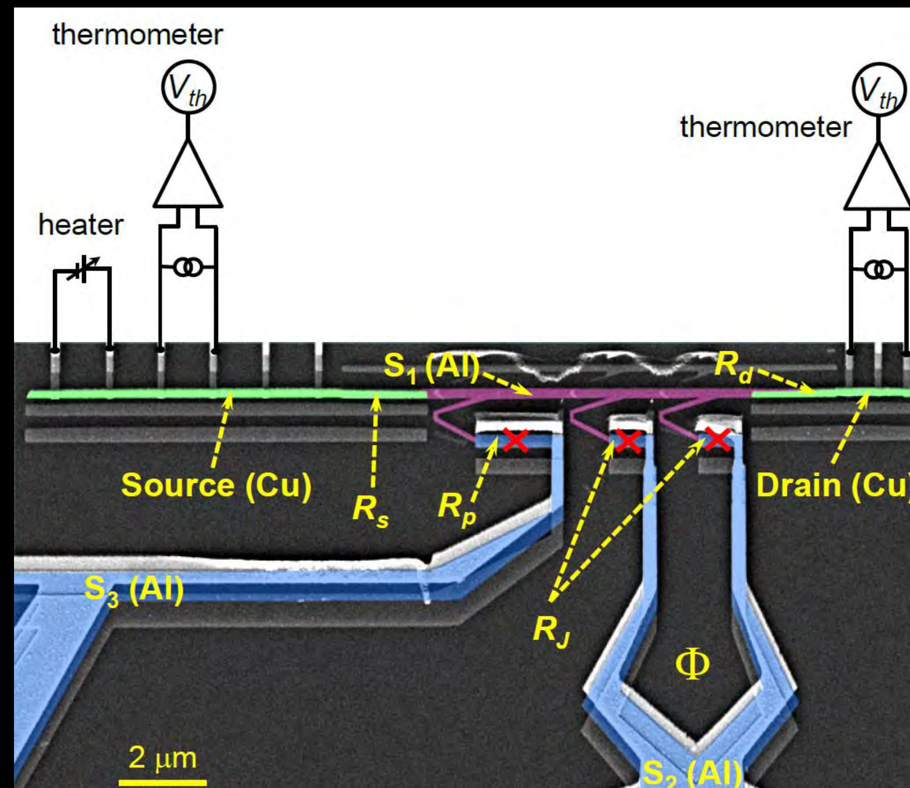
The Josephson heat interferometer

Francesco Giazotto[1] & María José Martínez-Pérez[1]



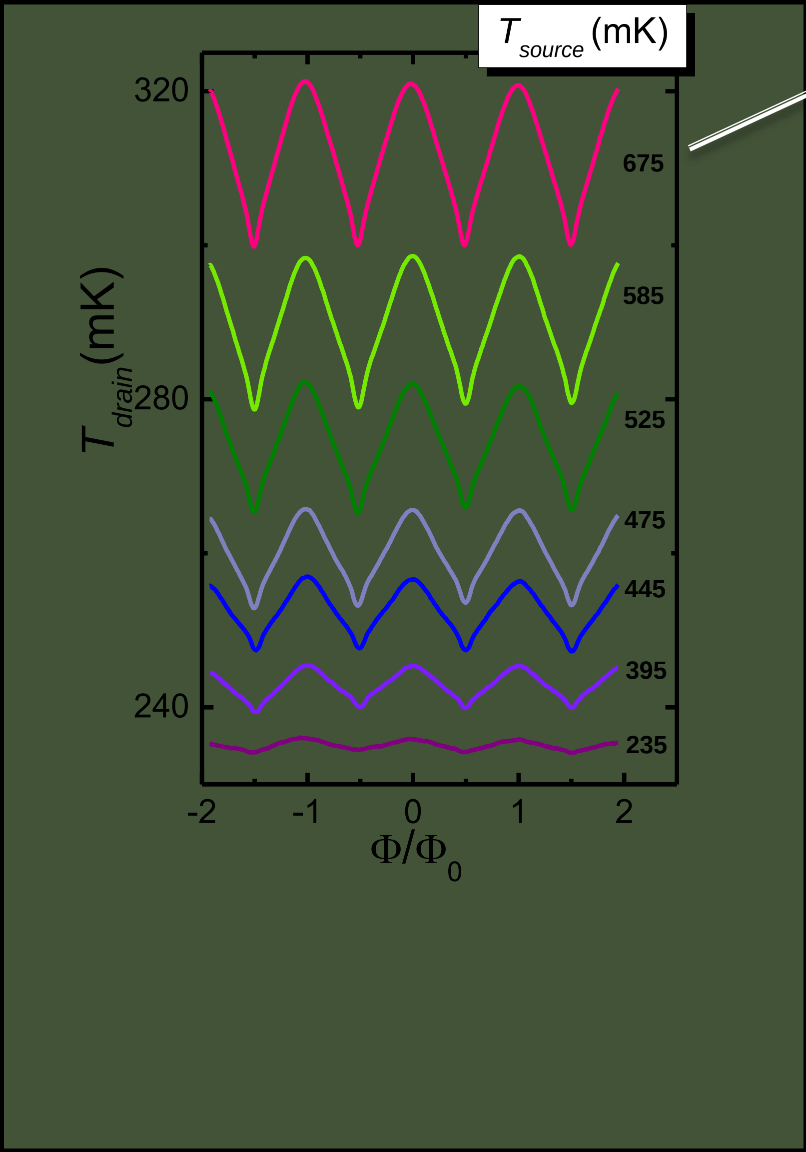
Symmetric SQUID (r = 1)

$$\dot{Q}_{SQUID}(\Phi) = 2\dot{Q}_{qp} - 2\dot{Q}_{int}\left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|$$

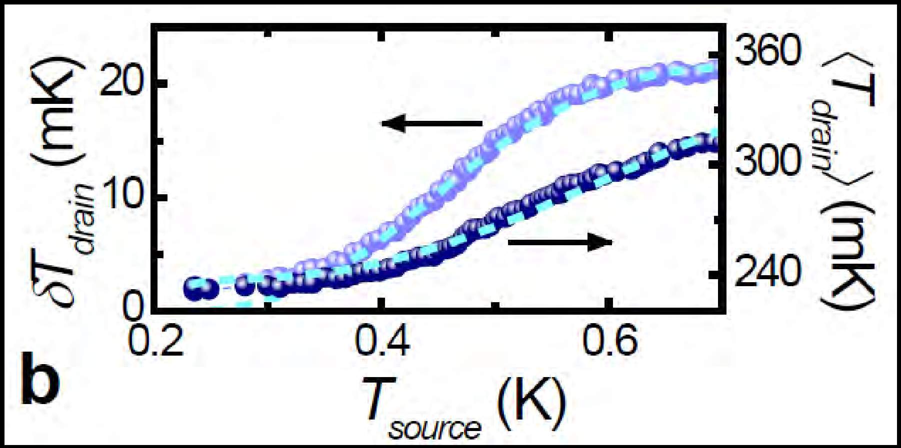


FG and M. J. Martinez-Perez, Nature **492**, 401 (2012)

Behavior @ 235 mK (i)

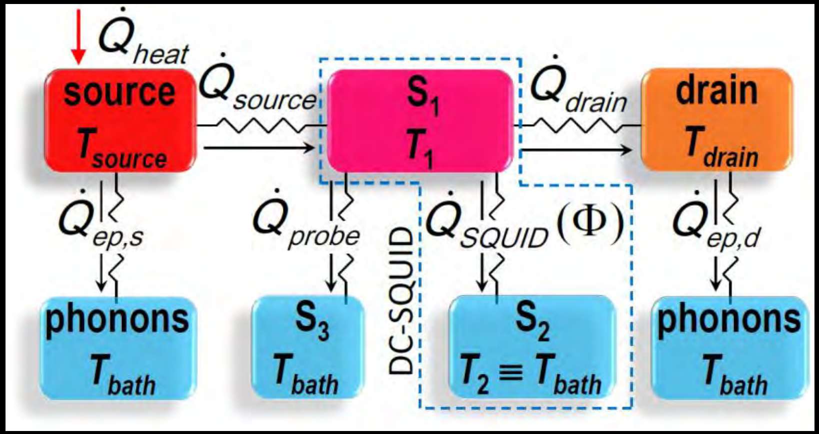


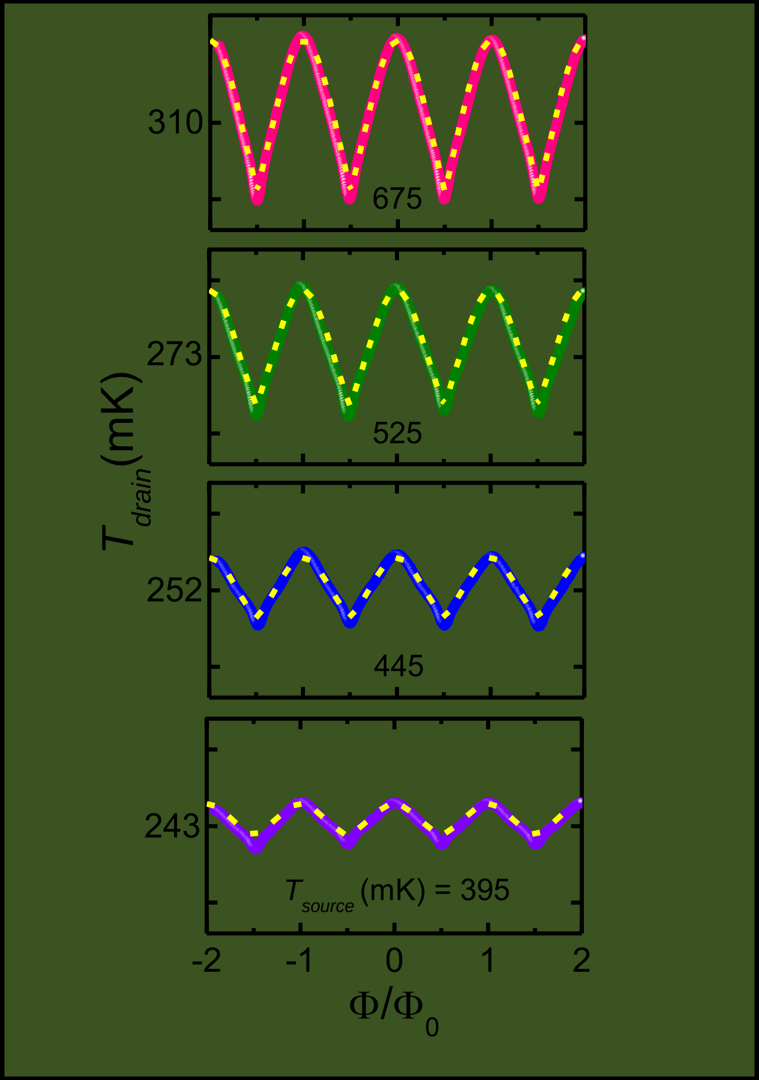
δT_{drain} ~ 21 mK
9% relative
modulation amplitude

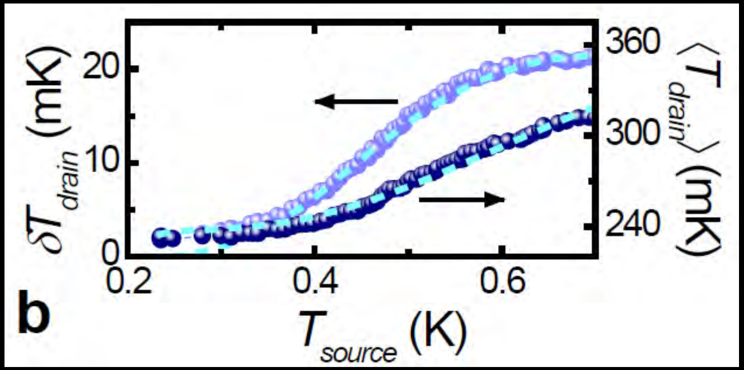


FG and M. J. Martinez-Perez, Nature **492**, 401 (2012)

Comparison to theory

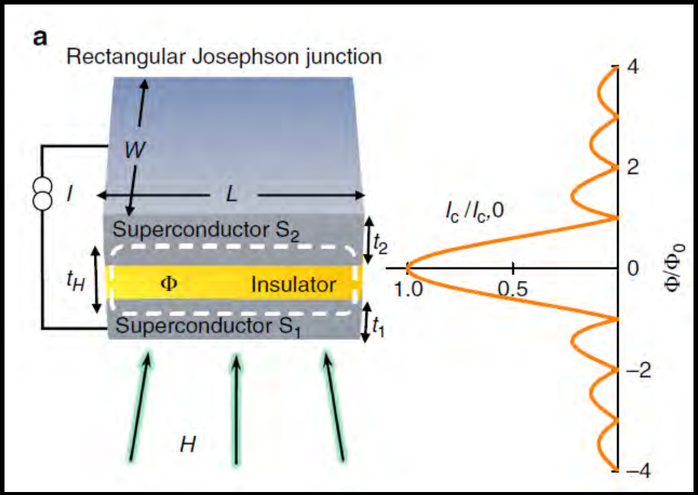




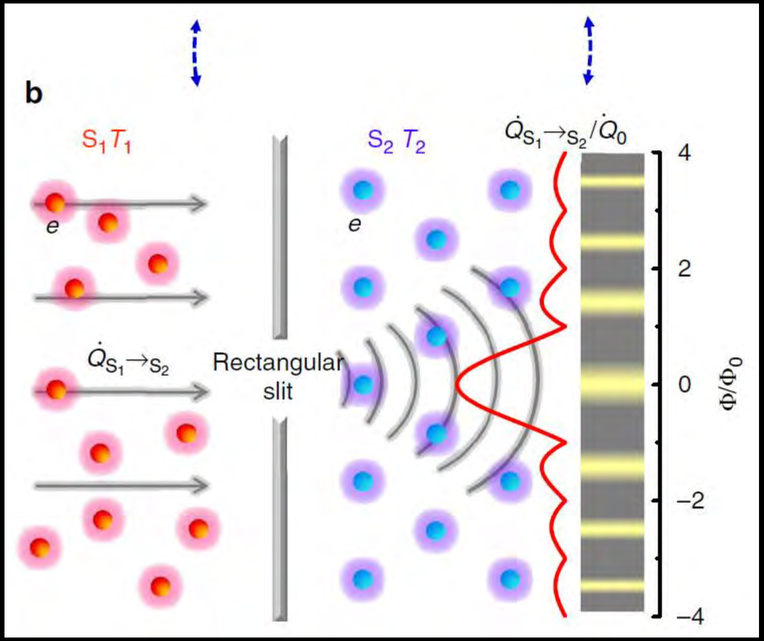


Good agreement with theoretical prediction

Electric vs thermal quantum diffraction

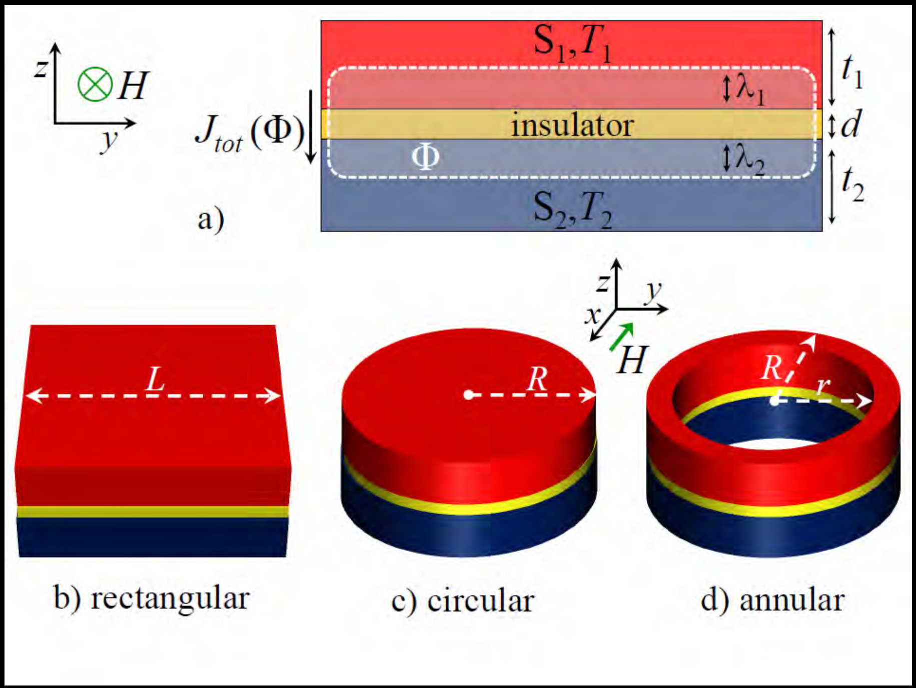


Electric diffraction through a rectangular slit



Diffraction of heat current through a rectangular slit

Heat current quantum diffraction in extended short JJs



$$\tilde{t} = d + \lambda_1 \tanh\frac{t_1}{2\lambda_1} + \lambda_2 \tanh\frac{t_2}{2\lambda_2}$$

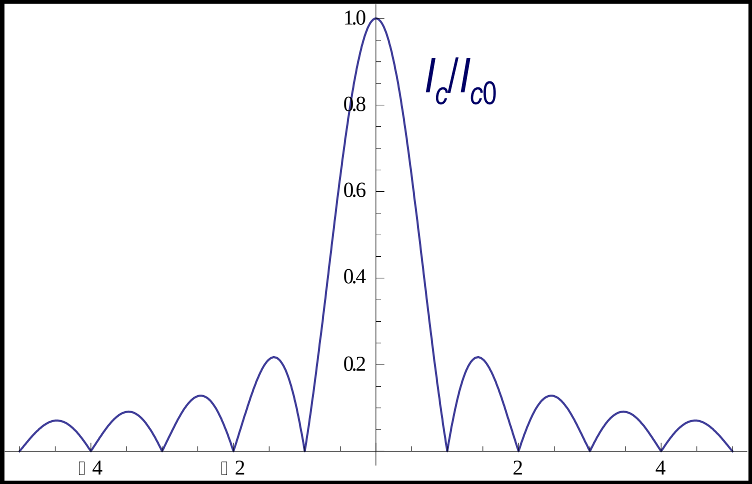
$$L \ll \lambda_J \equiv \sqrt{\frac{\Phi_0 W L}{2\mu_0 I_c \tilde{t}}}$$

Josephson critical current

$$I_c(\Phi) = \left|2 I_{c0} \int_{-\infty}^{\infty} f(y) \cos\left(\frac{2\pi\Phi}{\Phi_0}\frac{y}{L}\right) dy\right|$$

Critical current Fraunhofer pattern for a rectangular JJ

$$\frac{I_c}{I_{c0}} = |\sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)|$$



Φ/Φ_0

FG, M. J. Martinez-Perez, and P. Solinas, Phys. Rev. B **88**, 094506 (2013)

A “quantum diffractor” for thermal flux: experimental setup


nature COMMUNICATIONS

ARTICLE

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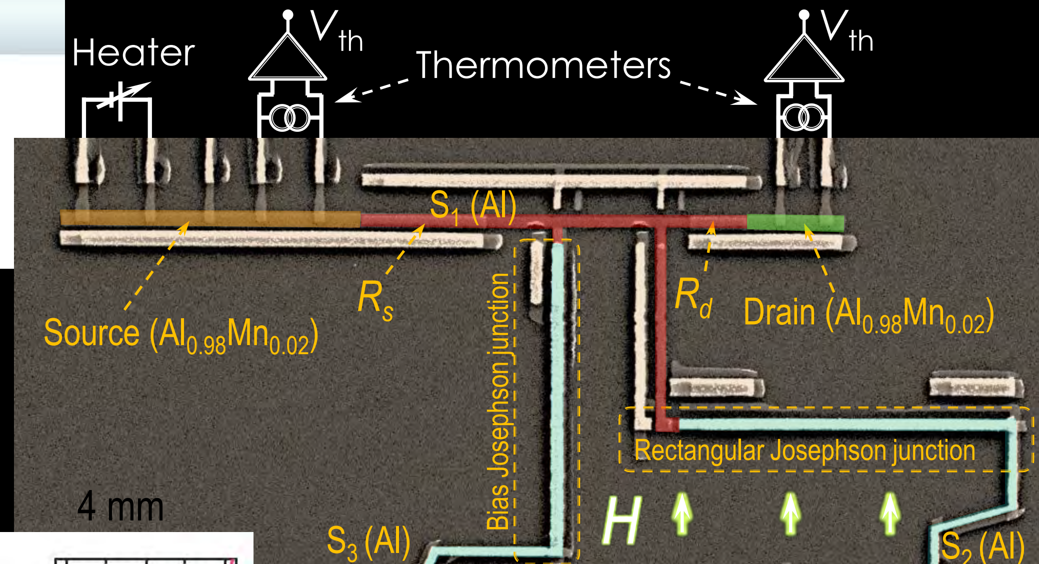
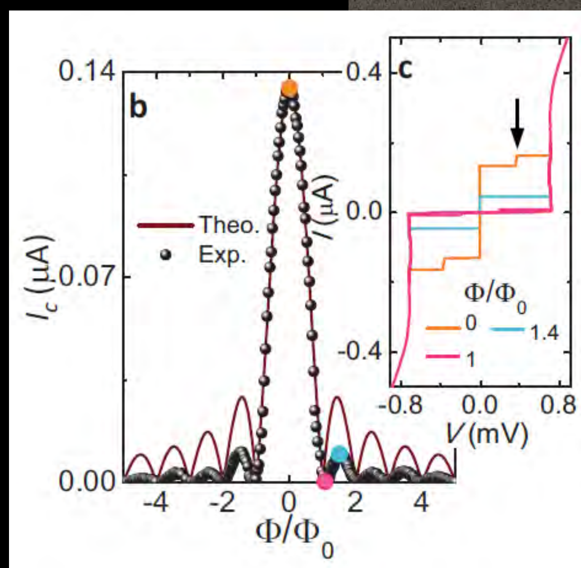
A quantum diffractor for thermal flux

Maria José Martínez-Pérez[1] & Francesco Giazotto[1]

Rectangular JJ

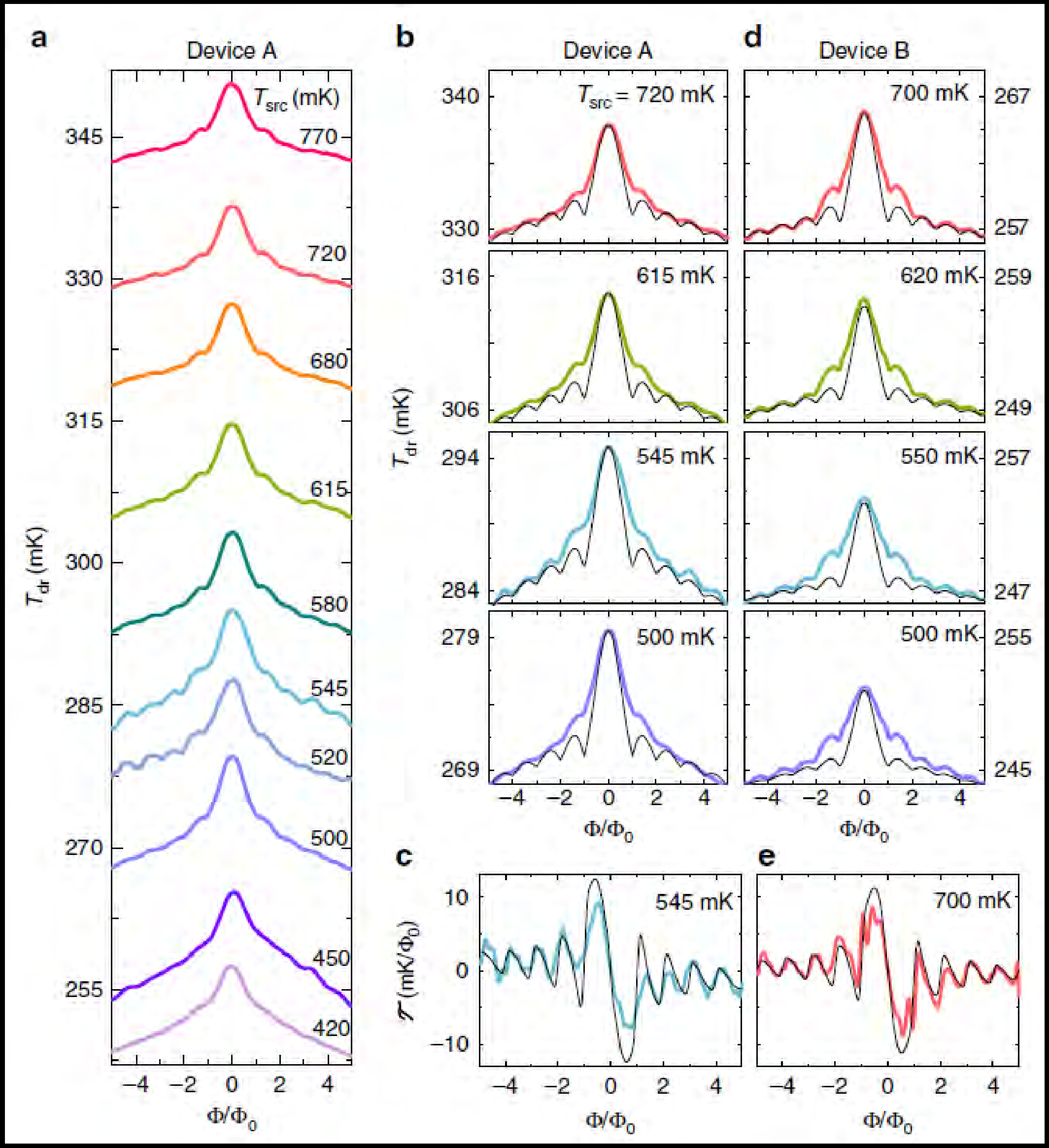


Magnetic interference pattern



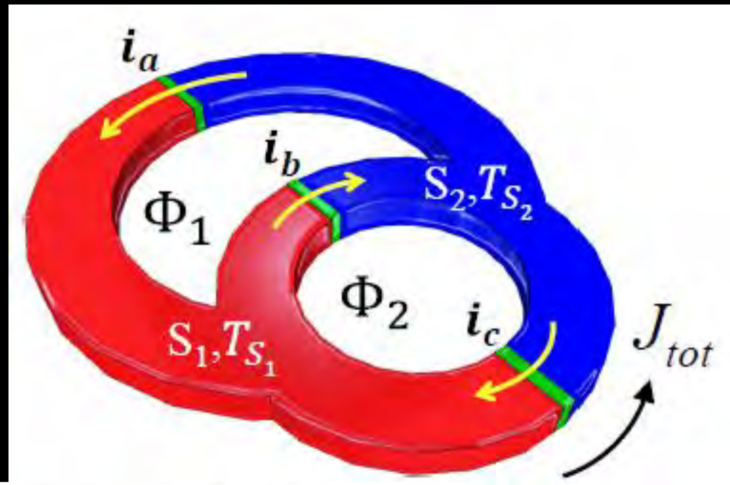
Josephson current behavior

Temperature diffraction pattern @ 240 mK



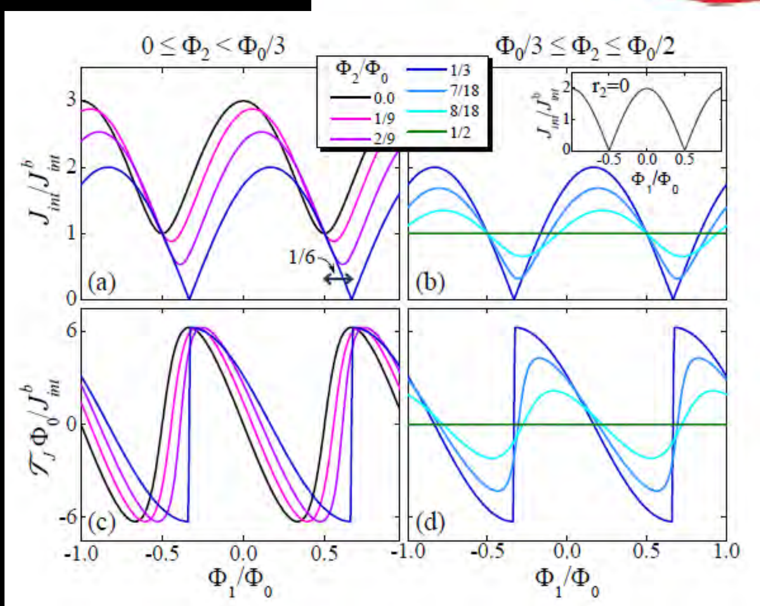
M. J. Martinez-Perez and FG, Nat. Commun. **5**, 3579 (2014)

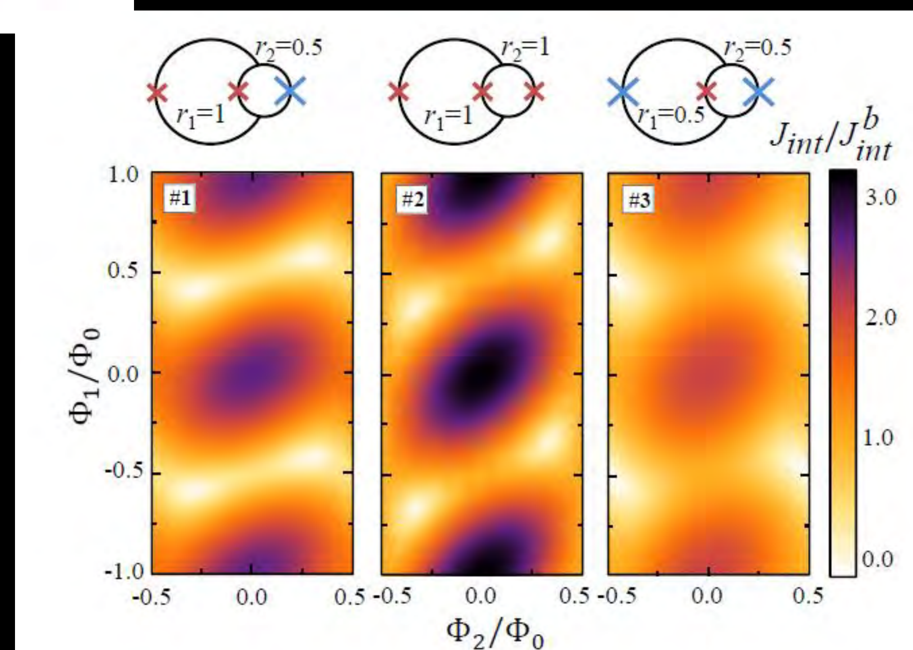
Fully-balanced heat interferometer



- Enhanced control over the flux-to heat current transfer function
- Complete suppression of the phase-coherent part

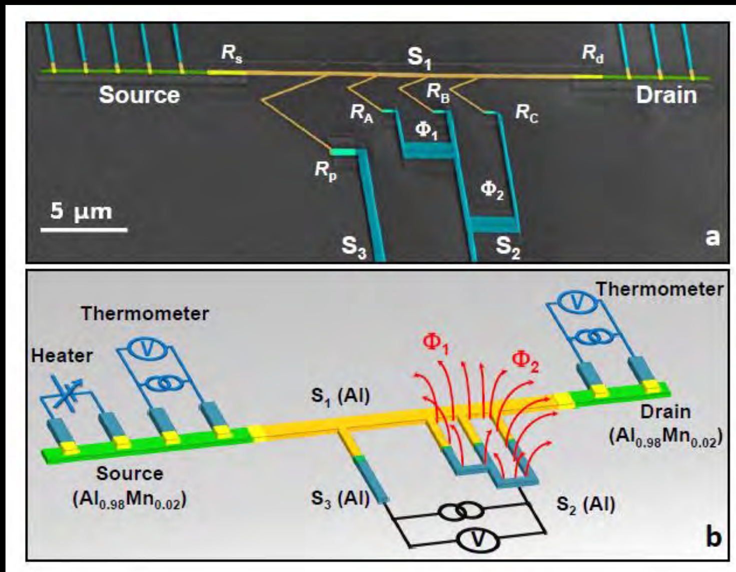
$$i_a - i_c \leq i_b \leq i_a + i_c$$





M. J. Martinez-Perez and FG, APL **102**, 401 (2013)

Nanoscale phase-engineering of thermal transport
i) Electrical response

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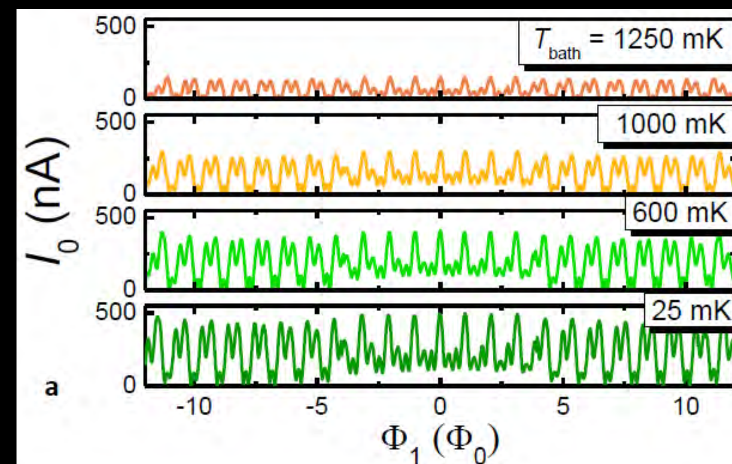
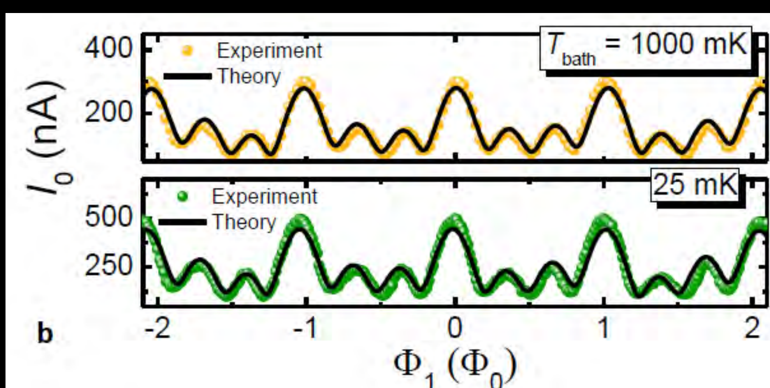
nature nanotechnology

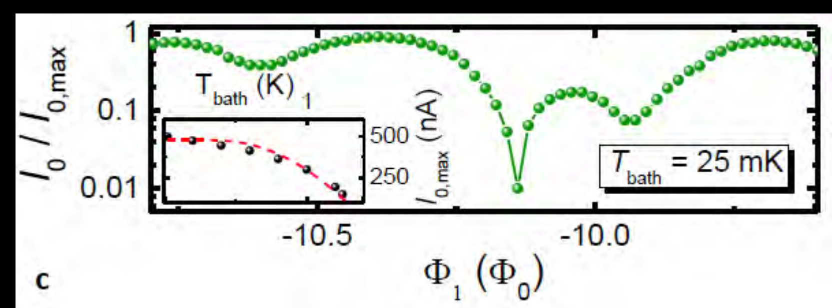
Nanoscale phase engineering of thermal transport with a Josephson heat modulator

Antonio Fornieri[1], Christophe Blanc[1], Riccardo Bosisio[1,2], Sophie D'Ambrosio[1] and Francesco Giazotto[1*]

Fully-balanced quantum thermal modulator structure: full phase-engineering of heat currents

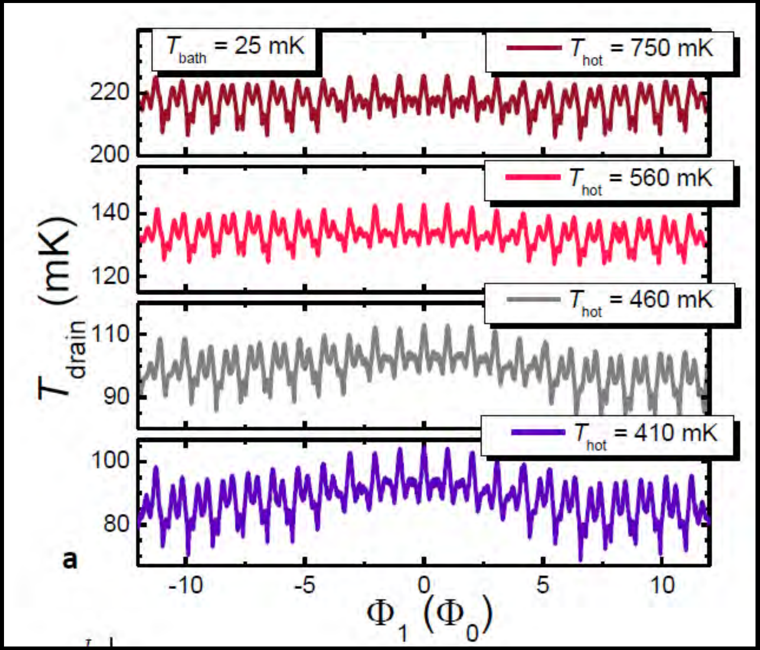






I_c suppression ~ 99%

Nanoscale phase-engineering of thermal transport
ii) Thermal response at base T_{bath}

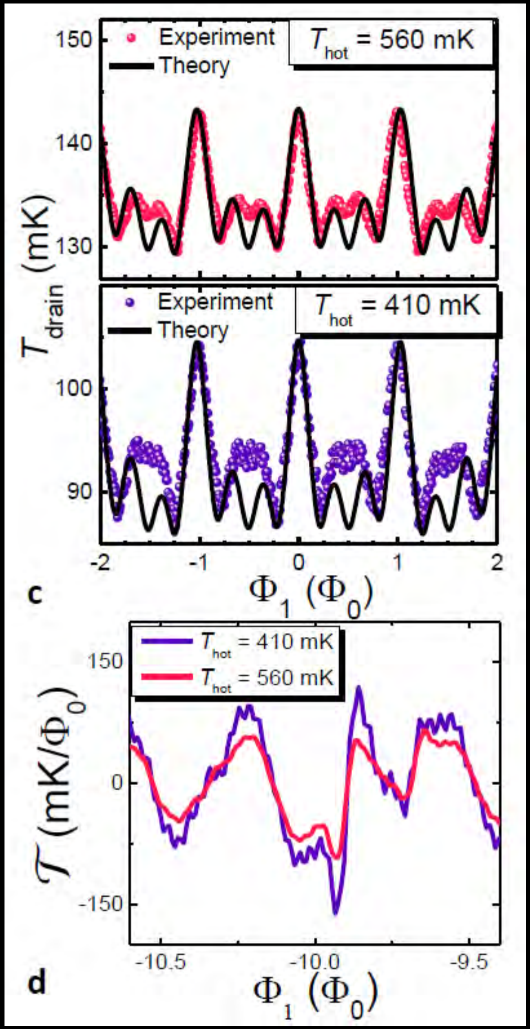


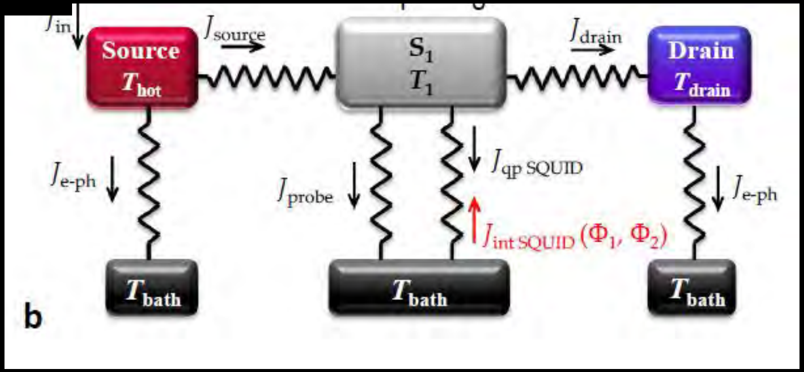
~ 40mK temperature swing

J_{int} suppression ~ 99%

τ ~ 200mK/Φ_0 @ 25mK

X 3 previous exps

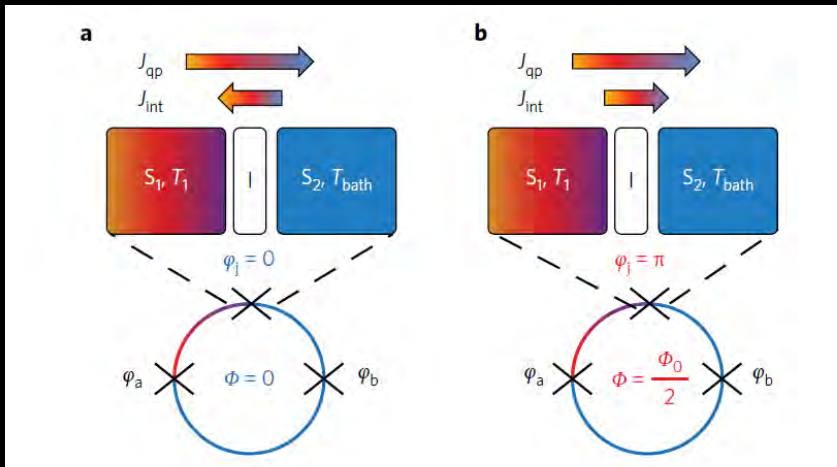




Thermal model

A. Fornieri, C. Blanc, R. Bosisio, S. D'Ambrosio, and FG, Nat.Nanotech. **11**, 258 (2016)

Phase-controllable 0-π *thermal* Josephson junction

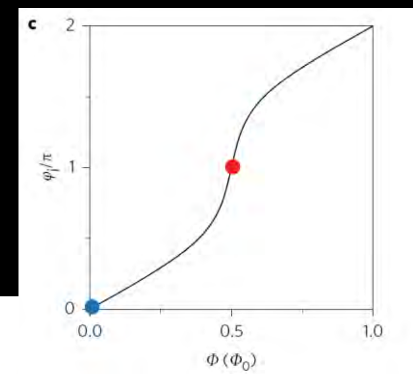


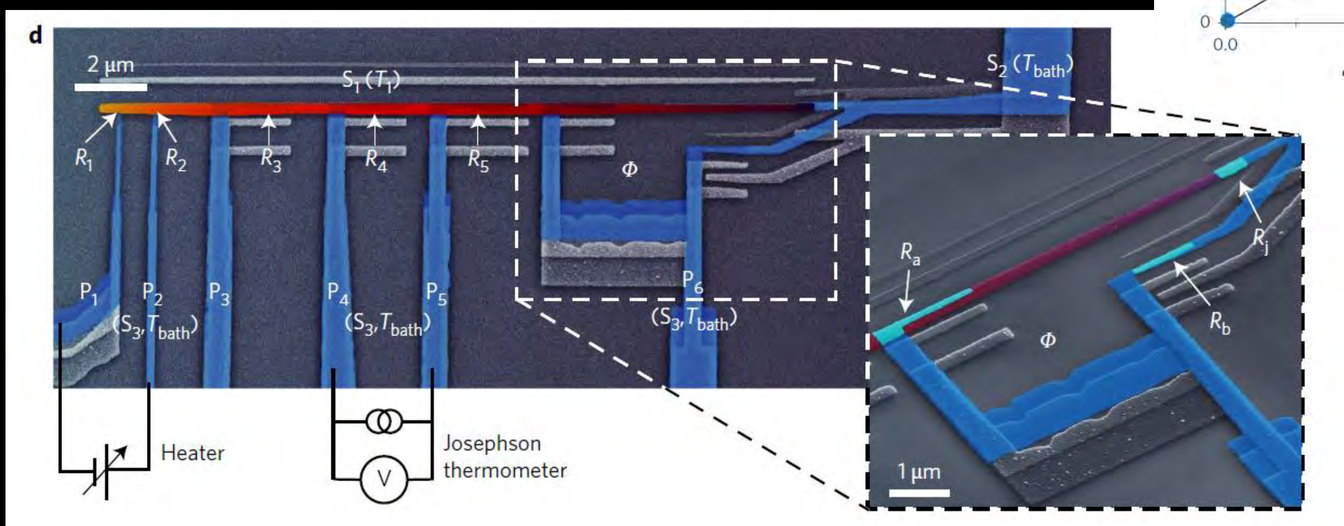

nature nanotechnology LETTERS

PUBLISHED ONLINE: 13 MARCH 2017 | DOI: 10.1038/NNANO.2017.25

0–π phase-controllable thermal Josephson junction

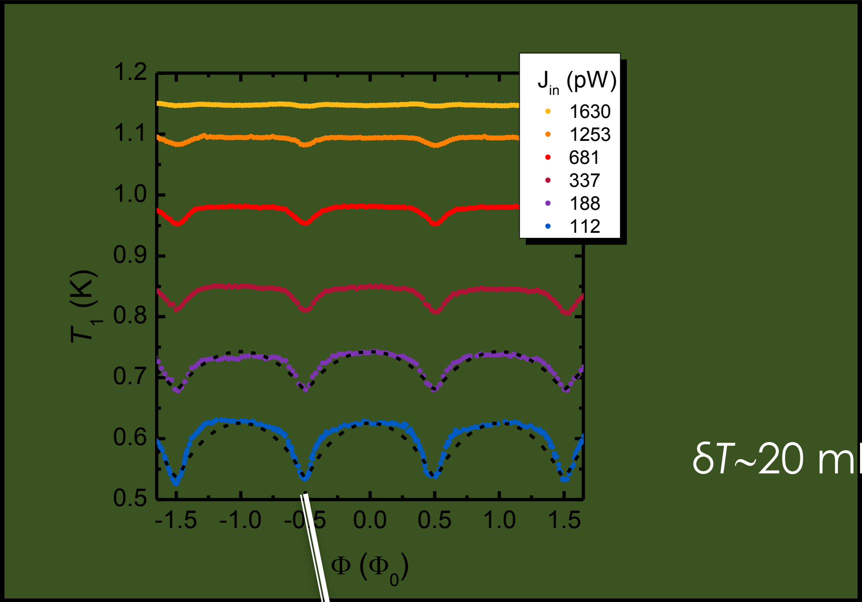
Antonio Fornieri[1], Giuliano Timossi[1], Pauli Virtanen[1], Paolo Solinas[2] and Francesco Giazotto[1]*

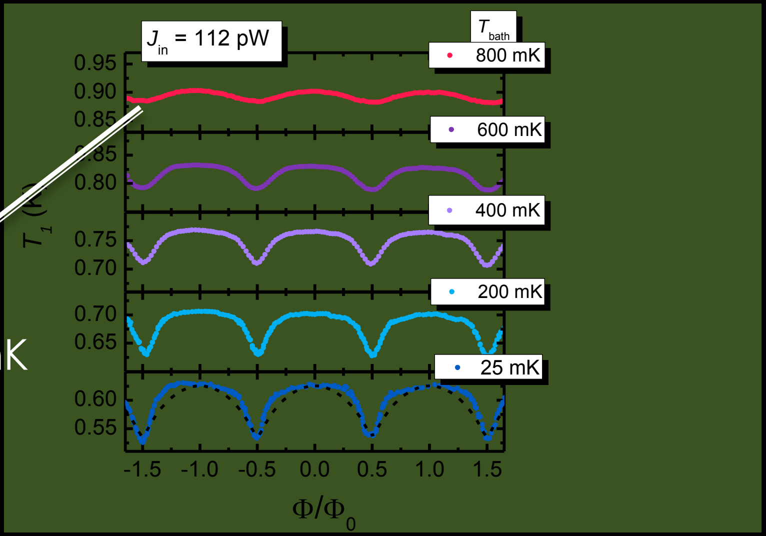




A. Fornieri, G. Timossi, P. Solinas, P. Virtanen, and FG, Nat. Nanotechnol. **12**, 425-429 (2017);
A. Fornieri, G. Timossi, R. Bosisio, P. Solinas, and FG, Phys. Rev. B **93**, 134508 (2016)

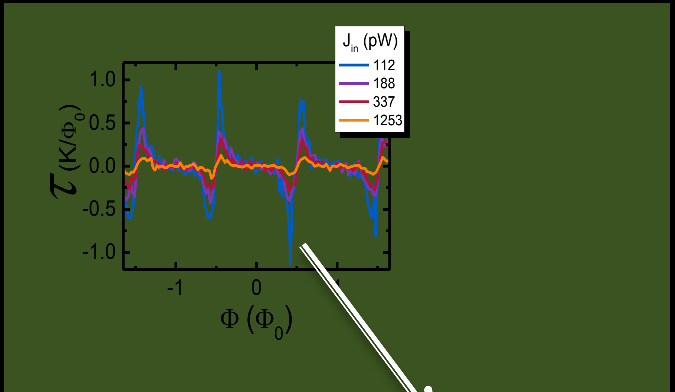
0-π *thermal* Josephson junction: thermal behavior





δT~20 mK @ 800 mK

δT up to 100 mK @ 25 mK

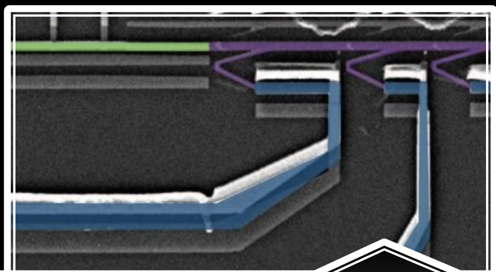


$$\mathcal{T} \equiv \partial T_{drain}/\partial\Phi$$

~1 mK/Φ_0 @ 550 mK

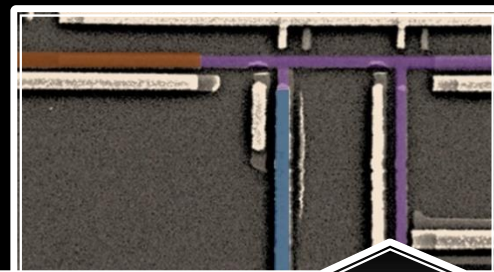
A. Fornieri, G. Timossi, P. Solinas, P. Virtanen, and FG, Nat. Nanotechnol. **12**, 425-429 (2017);
A. Fornieri, G. Timossi, R. Bosisio, P. Solinas, and FG, Phys. Rev. B **93**, 134508 (2016)

Single output caloritronic devices



The Josephson heat interferometer

Nature **492**, 401 (2012)



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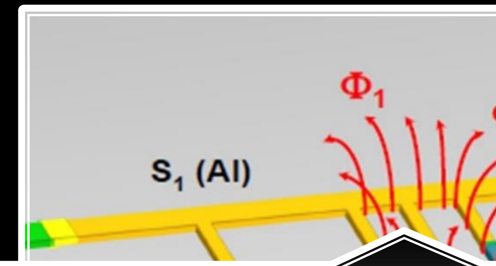
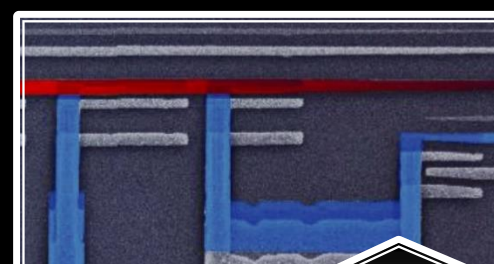


Nanoscale phase engineering of thermal transport with a Josephson heat modulator

Nat. Nanotech. **11**, 258 (2016)

Rectification of electronic heat current by a hybrid thermal diode

Nat. Nanotech. **10**, 303 (2015)

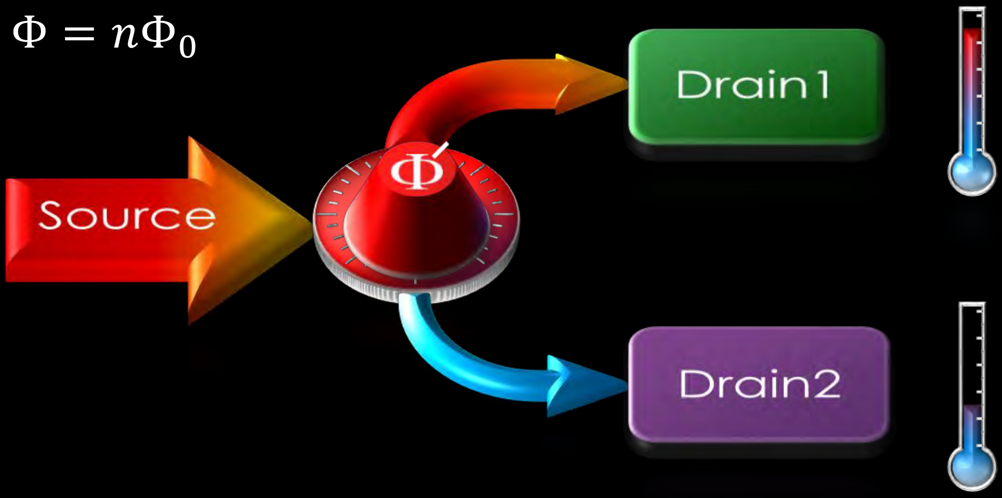


0-π phase-controllable thermal Josephson junction

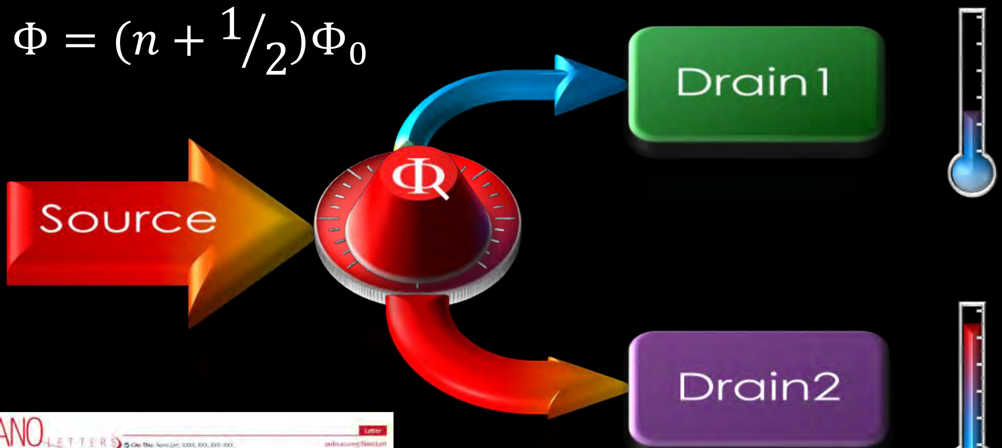
Nat. Nanotech. **12**, 425 (2017)

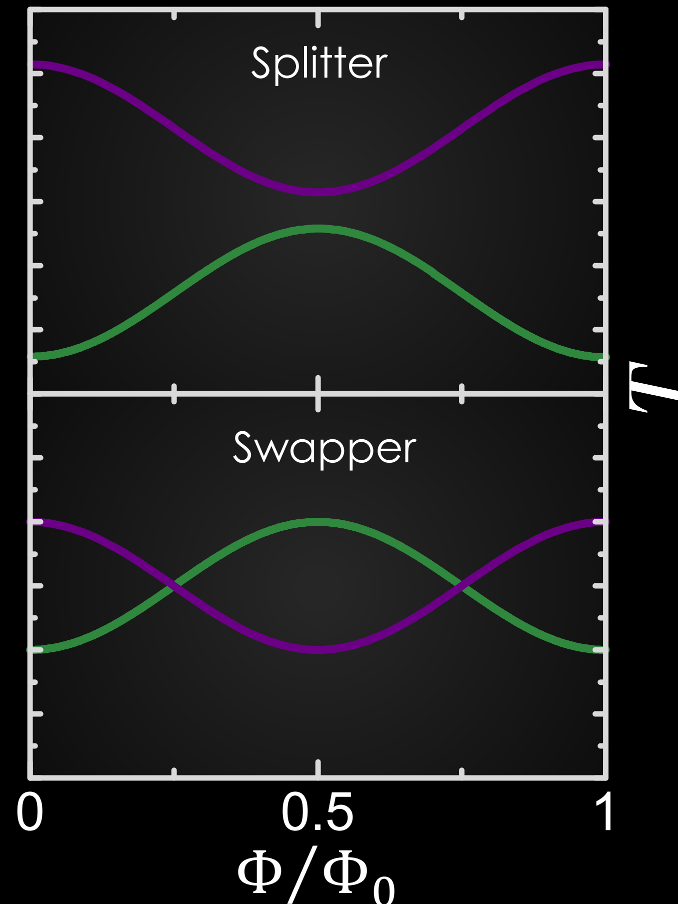
Phase-tunable thermal router: General scheme

$\Phi = n\Phi_0$



$\Phi = (n + {}^{1}/_{2})\Phi_0$





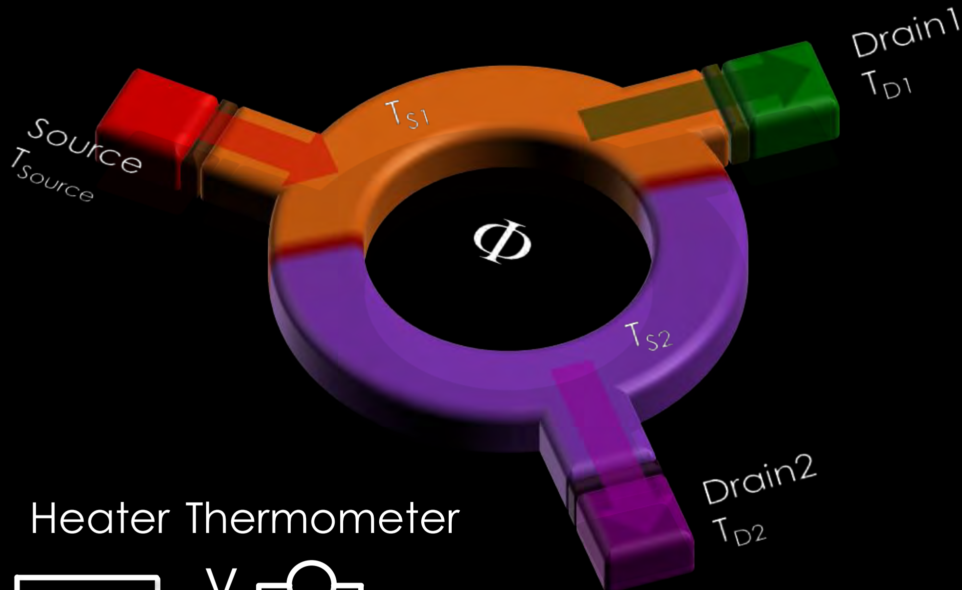

NANO LETTERS

Phase-Tunable Josephson Thermal Router

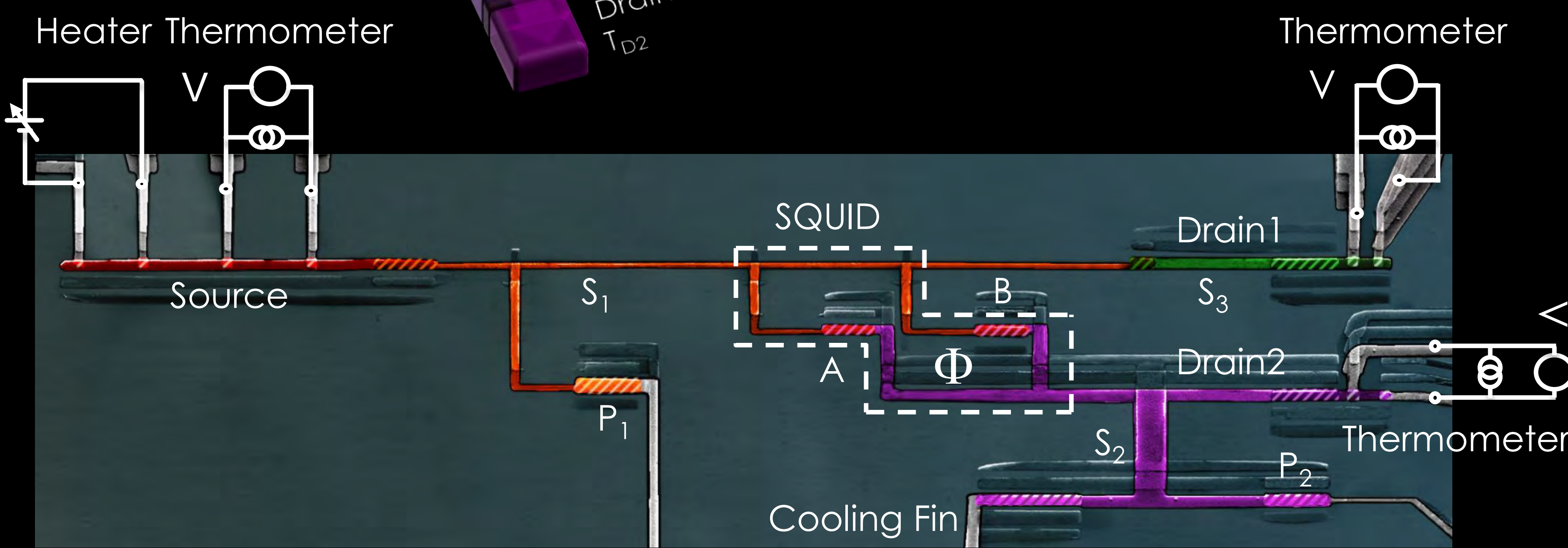
Giuliano Francesco Timossi, Antonio Fornieri, Federico Paolucci, Claudio Puglia, and Francesco Giazotto
NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Piazza S. Silvestro 12, I-56127 Pisa, Italy
Dipartimento di Fisica dell'Università di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy

DOI: 10.1021/acs.nanolett.7b04906

Phase-tunable thermal router: Device structure

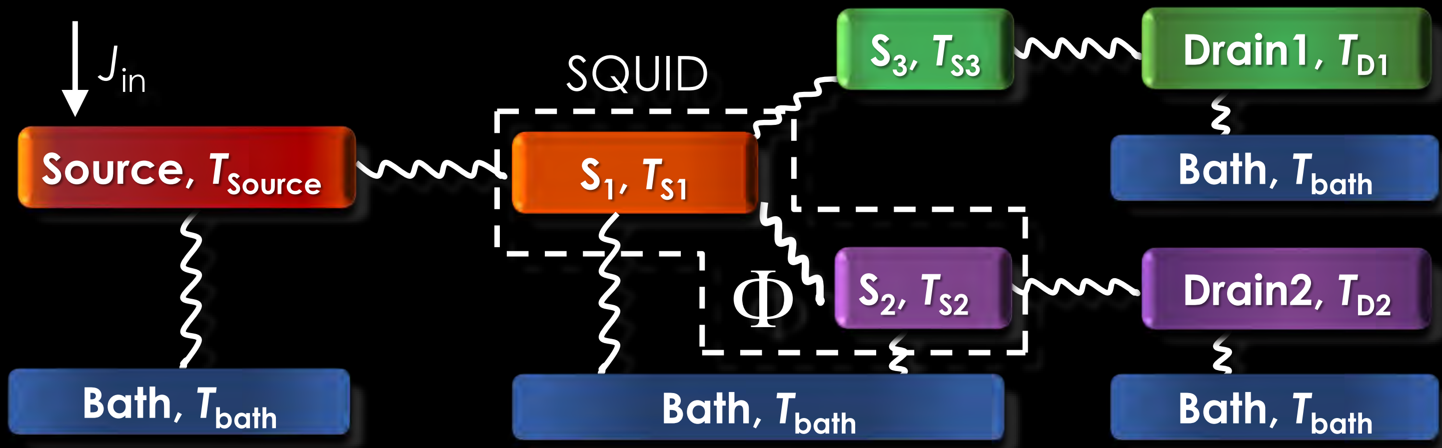


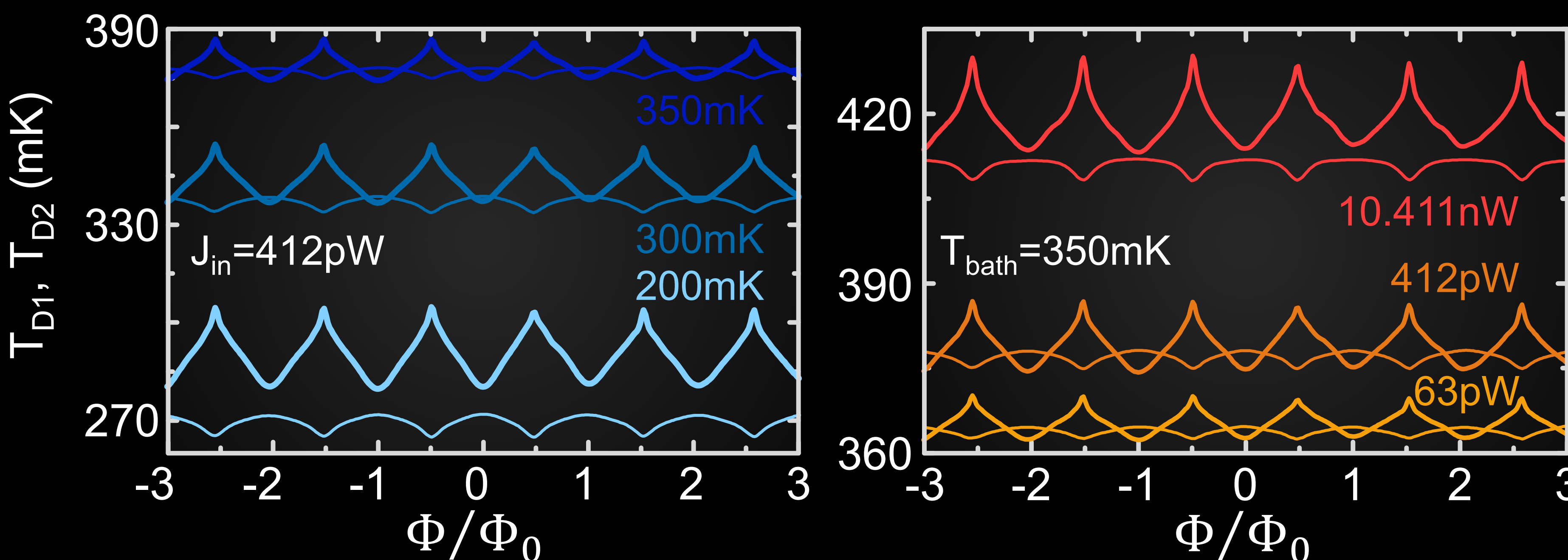
$$\dot{Q}_{int} = \dot{Q}^{A}_{int}(T_{S1}, T_{S2})\sqrt{1 + r^2 + 2r\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$



G. Timossi, A. Fornieri, F. Paolucci, C. Puglia, and FG, Nano Lett. **18**, 1764 (2018)

Phase-tunable thermal router: Experiment





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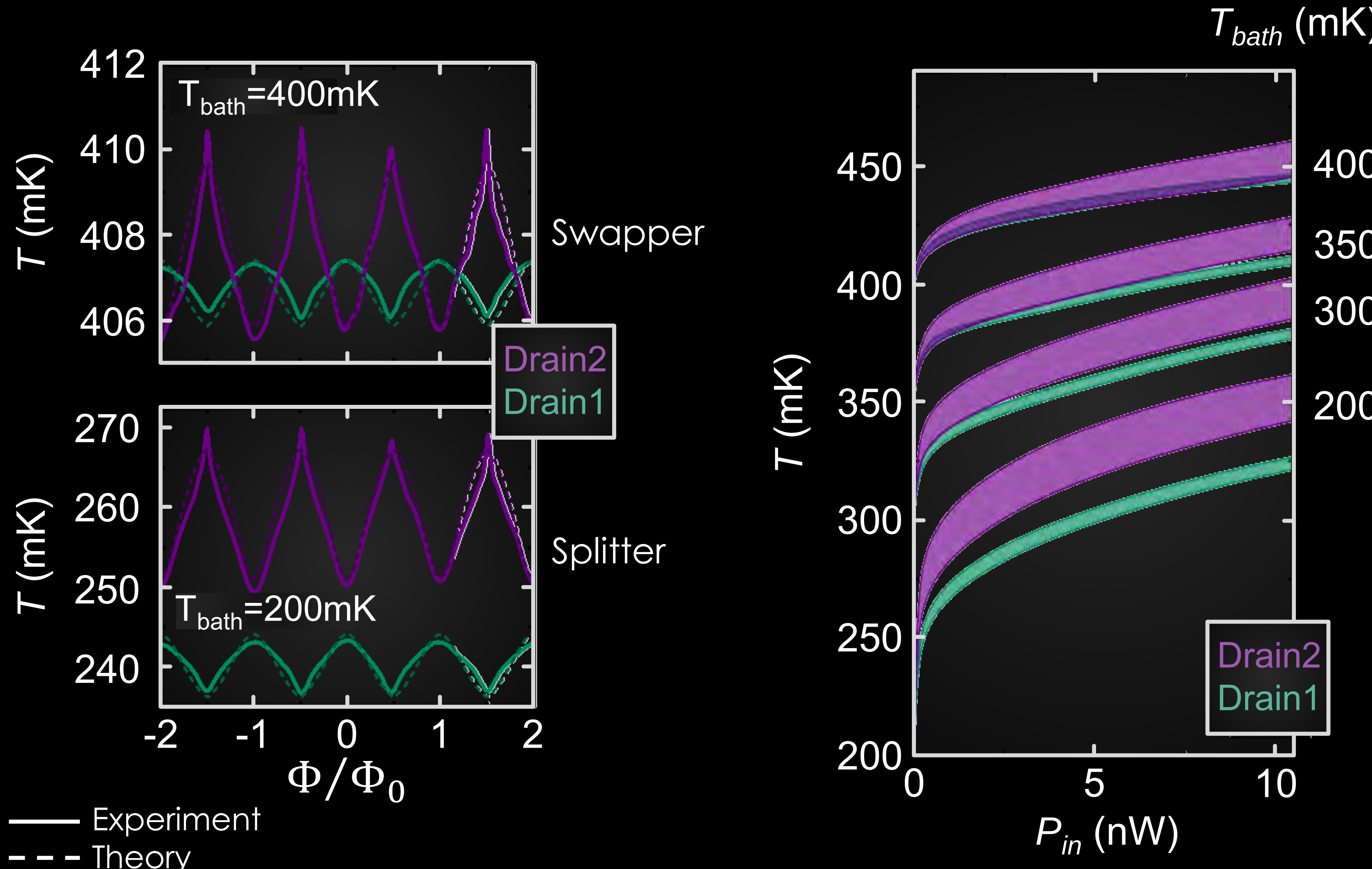
Phase-tunable thermal router: Experiment



G. Timossi, A. Fornieri, F. Paolucci, C. Puglia, and FG, Nano Lett. **18**, 1764 (2018)

Conclusions

1. Realization of the first heat interferometer
2. Confirmation of the existence, magnitude and sign of the phase-dependent heat current
3. Realization of the first quantum diffractor for thermal flux, complementary proof of the "thermal" Josephson effect
4. Double-loop Josephson thermal modulator: complete phase-engineering of electronic heat current at the nanoscale
5. Realization of the first controllable 0-π thermal Josephson junction
6. Realization of the first phase-tunable Josephson thermal router with large T separation and sizeable T inversion: gateway to realize mesoscopic "thermal machines"

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M. J. Martinez-Perez
P. Solinas
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C. Blanc
P. Virtanen
C. Puglia

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