

Thermal Quantum Devices



Francesco Giazotto

NEST, Istituto Nanoscienze-CNR &
Scuola Normale Superiore Pisa, Italy



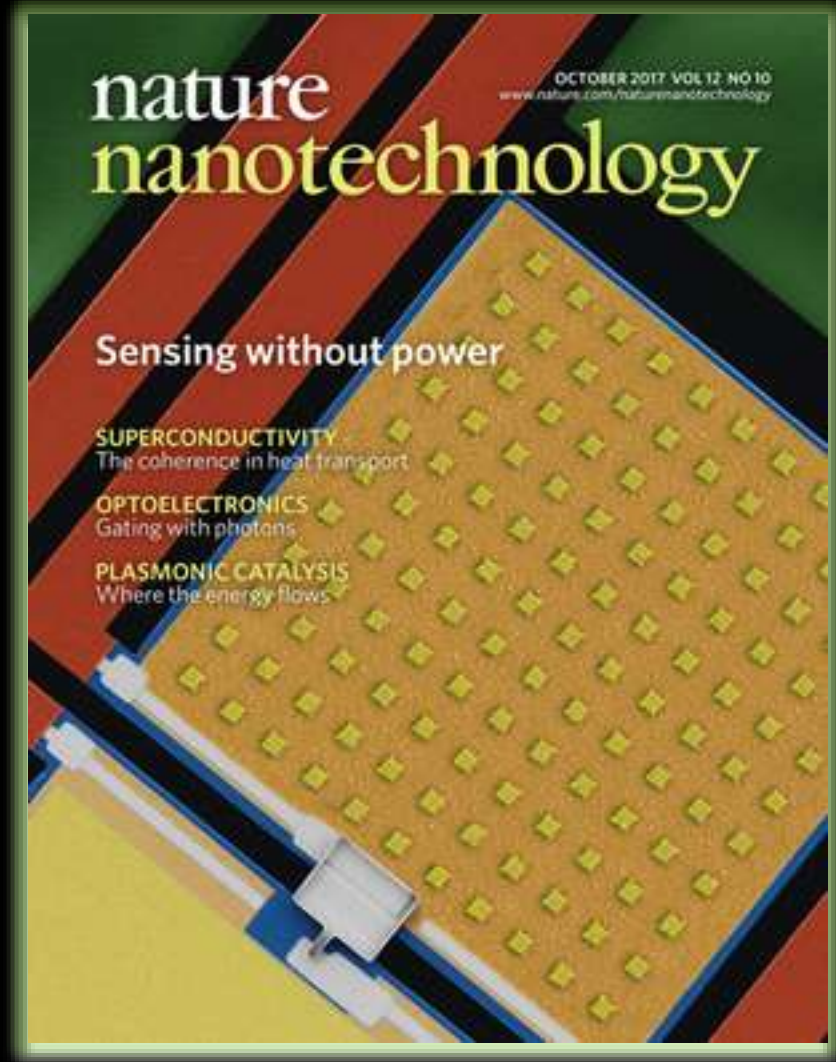
EASISchool

CNR-SPIN, Genoa, Italy

28 September – 6 October 2020

Outline

1. Motivations & mission
2. Overview
3. Basic properties of the electric Josephson effect
4. Basic concepts of thermal transport in Josephson-based quantum circuits
5. Double & single-slit heat interferometers
6. Balanced thermal modulators
7. Josephson thermal π -junctions
8. 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

Quantum interference heats up

A thermal effect predicted more than 40 years ago was nearly forgotten, with a related phenomenon stole the limelight. Now an experimentally verified, the effect could spur the development of heat-controlling devices. [SEE LETTERS, 631](#)

RAYMOND W. SIMMONS

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 466, Giustino and Mariani-Finzi¹ report experiments confirming that this strange phenomenon can actually occur.

In 1962, Brian Josephson made a remarkable discovery² 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 intrinsically tunnel or 'tunnel' across the gap without needing an applied electric voltage.

The sense 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 device³ (d.c.-SQUID). In these devices, a split

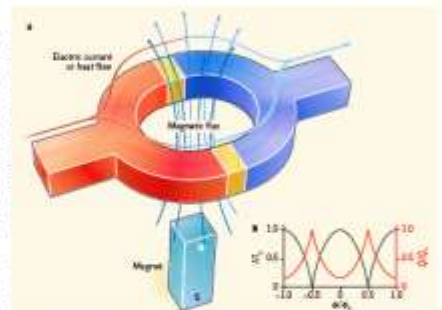


Figure 1 | A direct-current superconducting quantum interference device (d.c.-SQUID), a loop of superconducting material containing two Josephson junctions (yellow) and a magnetic field (blue) passing through the loop. The maximum current I_c^{\max} (red line) and the maximum heat flow Q_c^{\max} (blue line) can be fully modulated by the amount of magnetic flux Φ_0 passing through the loop. I_c^{\max} is the maximum current that can flow through the d.c.-SQUID, Φ_0 is the magnetic flux quantum, 2.87×10^{-15} webers. Giustino and Mariani-Finzi¹ have observed an interference effect for heat flow Q_c , red, right axis. Q_c is the maximum heat flow through a d.c.-SQUID. The total amount of heat passing through the device can also be modulated by an applied magnetic flux.

superconducting path with two Josephson junctions can sustain a stationary supercurrent, the amplitude of which can be modulated by the amount of magnetic flux passing through the loop (Fig. 1). Such d.c.-SQUIDs are among the most sensitive detectors of magnetic flux ever created and have found many practical applications⁴.

In addition to the phase-dependent supercurrent, Josephson discovered² two other currents that are present when a finite voltage difference exists across a junction. These currents were caused by the tunnelling of quasiparticles (free 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 accumulated phase along the two paths of a loop cause constructive or destructive interference). But electrical experiments that clearly quantify the behaviour of this 'interference current' have remained elusive⁵.

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

156 | NATURE | VOL 482 | 2017 DECEMBER 2017

© 2017 Macmillan Publishers Limited. All rights reserved.

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

Electric Josephson effect: tunnel junction



Josephson tunnel junction

$$I_c = I_0 \sin \varphi \quad \text{where} \quad I_0 = (\pi \Delta / 2eR_T) \tanh(\Delta / 2kT)$$

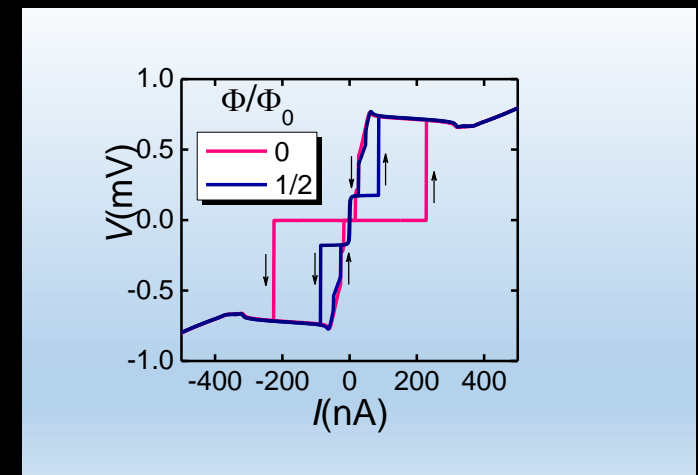
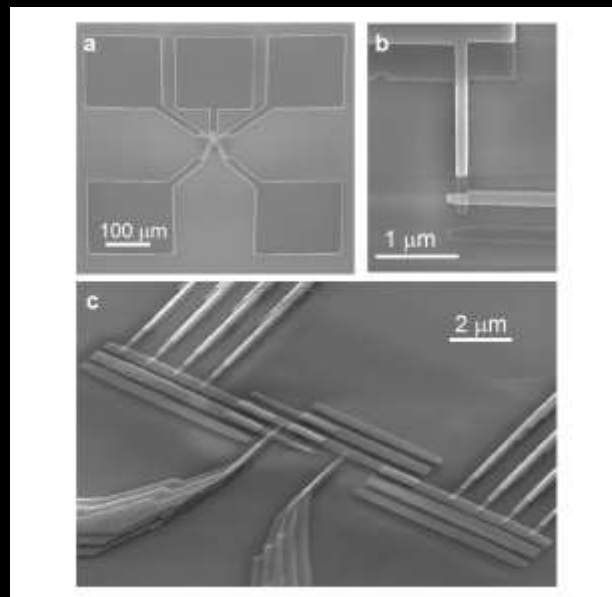
1st Josephson equation

$$V = (\Phi_0 / 2\pi) d\varphi / dt \quad \text{where} \quad \Phi_0 = h / 2e$$

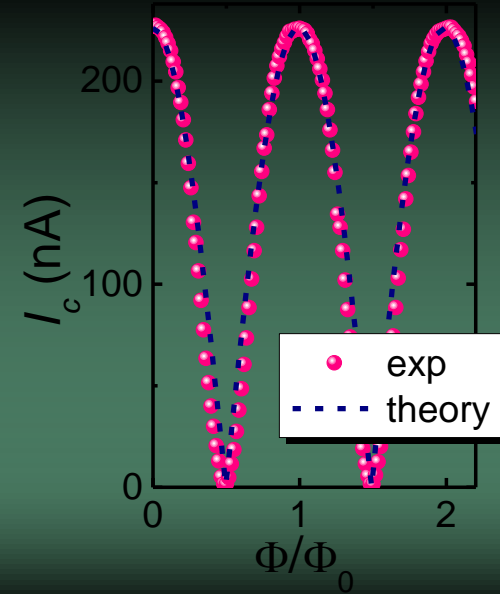
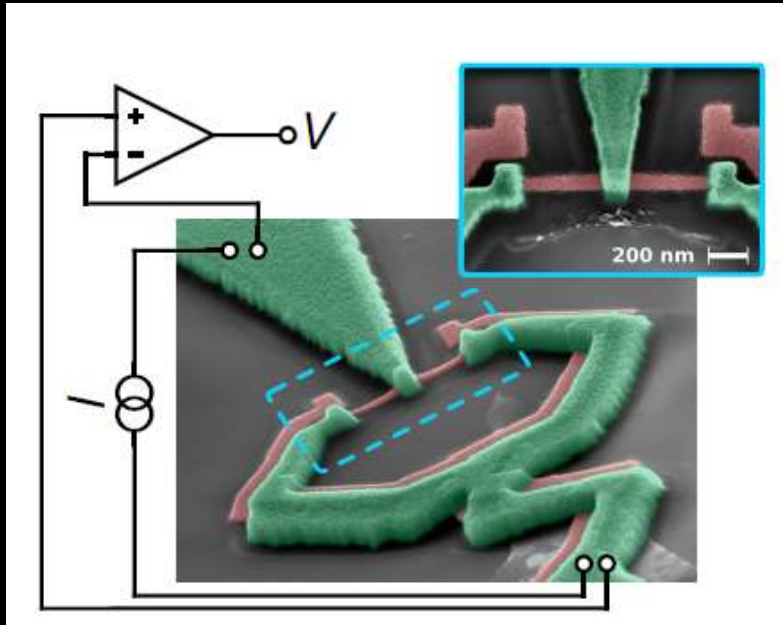
2nd Josephson equation

$$\nu_j = V / \Phi_0 \quad \text{Josephson frequency}$$

$$\nu_j \sim 484 \text{ GHz/mV}$$



Electric Josephson effect: SQUIDS

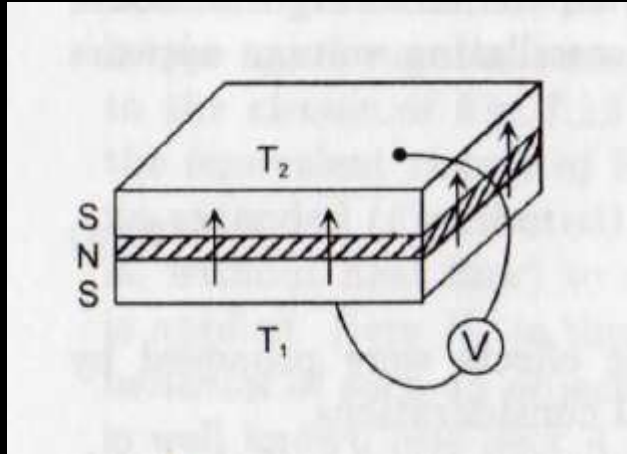


$$I_c = I_1 \sqrt{1 + r^2 + 2r \cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$

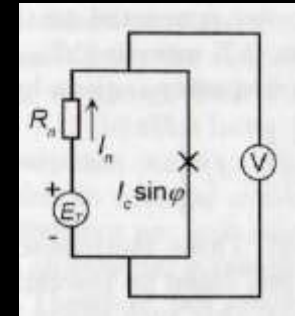
$$I_c = 2I_0 \left| \cos\left(\frac{\pi\Phi}{\Phi_0}\right) \right|$$

Thermoelectric effects in Josephson junctions

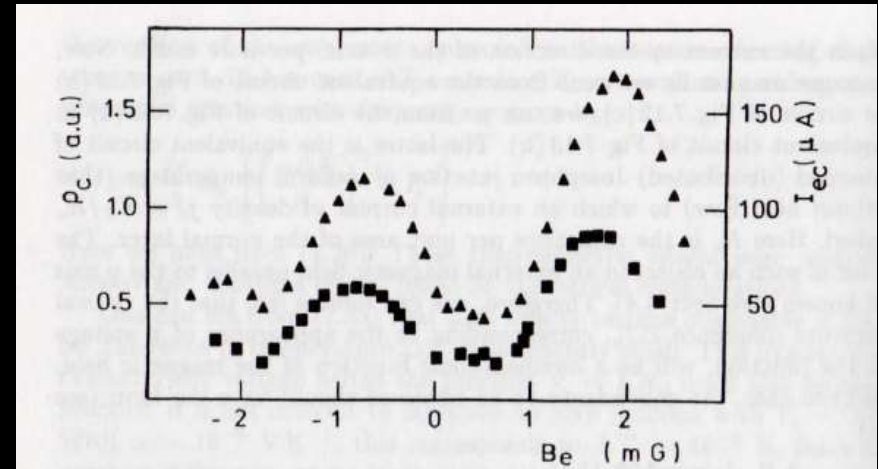
dc & ac **thermoelectric** response



SNS-like Josephson junction



Presence of a magnetic field



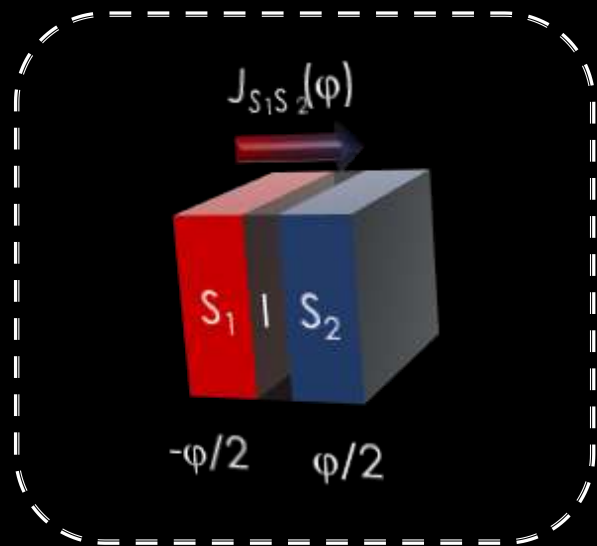
$$\omega = \frac{2e}{\hbar} R_n \left[\left(\frac{\alpha \Delta T}{R_n} \right)^2 - I_c^2 \right]^{1/2}$$

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

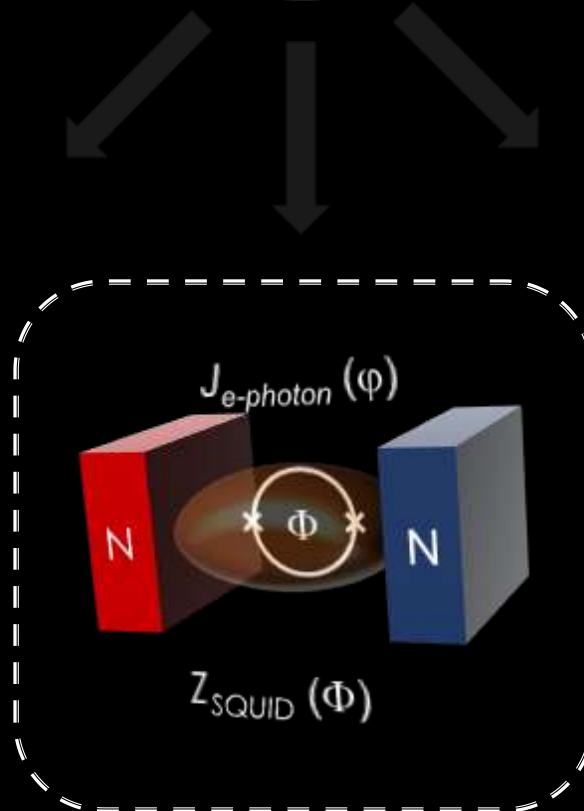
Aronov and Galperin, JETP Lett. **19**, 165 (1974);
 Kartsovnik, Ryazanov, and Schmidt, JETP Lett. **33**, 356 (1981);
 Ryazanov and Schmidt, Solid State Commun. **40**, 1055 (1981);
 Clarke and Freake, Phys. Rev. Lett. **29**, 588 (1982).

Panaïtov, 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).

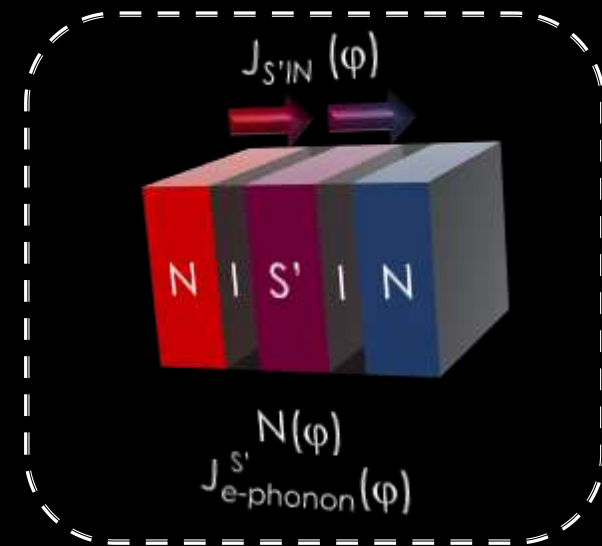
Physical basis of coherent caloritronics



Josephson effect



Tuning electron-photon interaction

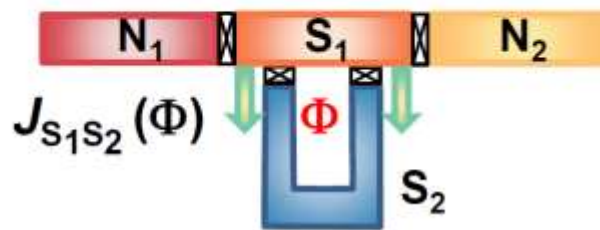


Proximity effect

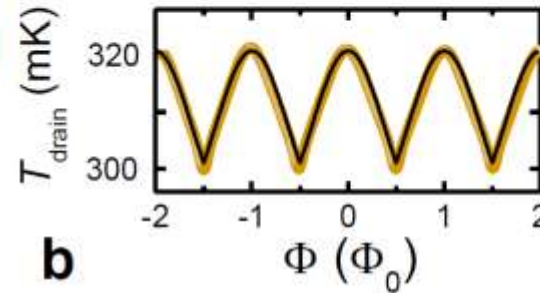
PERSPECTIVE nature nanotechnology
 TOWARDS ONLINE 6 OCTOBER 2017 | DOI: 10.1038/nnano.2017.124
Towards phase-coherent caloritronics in superconducting circuits
 Antonio Fornieri* and Francesco Giazotto*

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

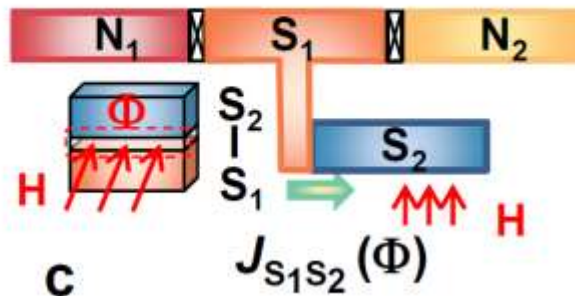
Josephson tunnel circuits



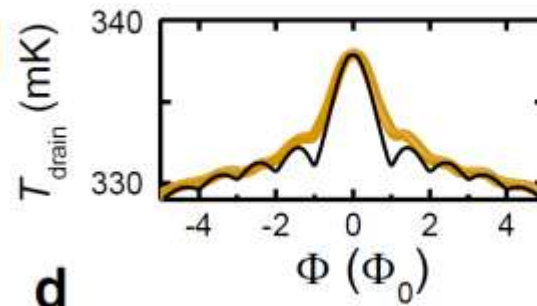
a



b



c



d

Josephson heat interferometers

b – Double-slit Josephson interferometer

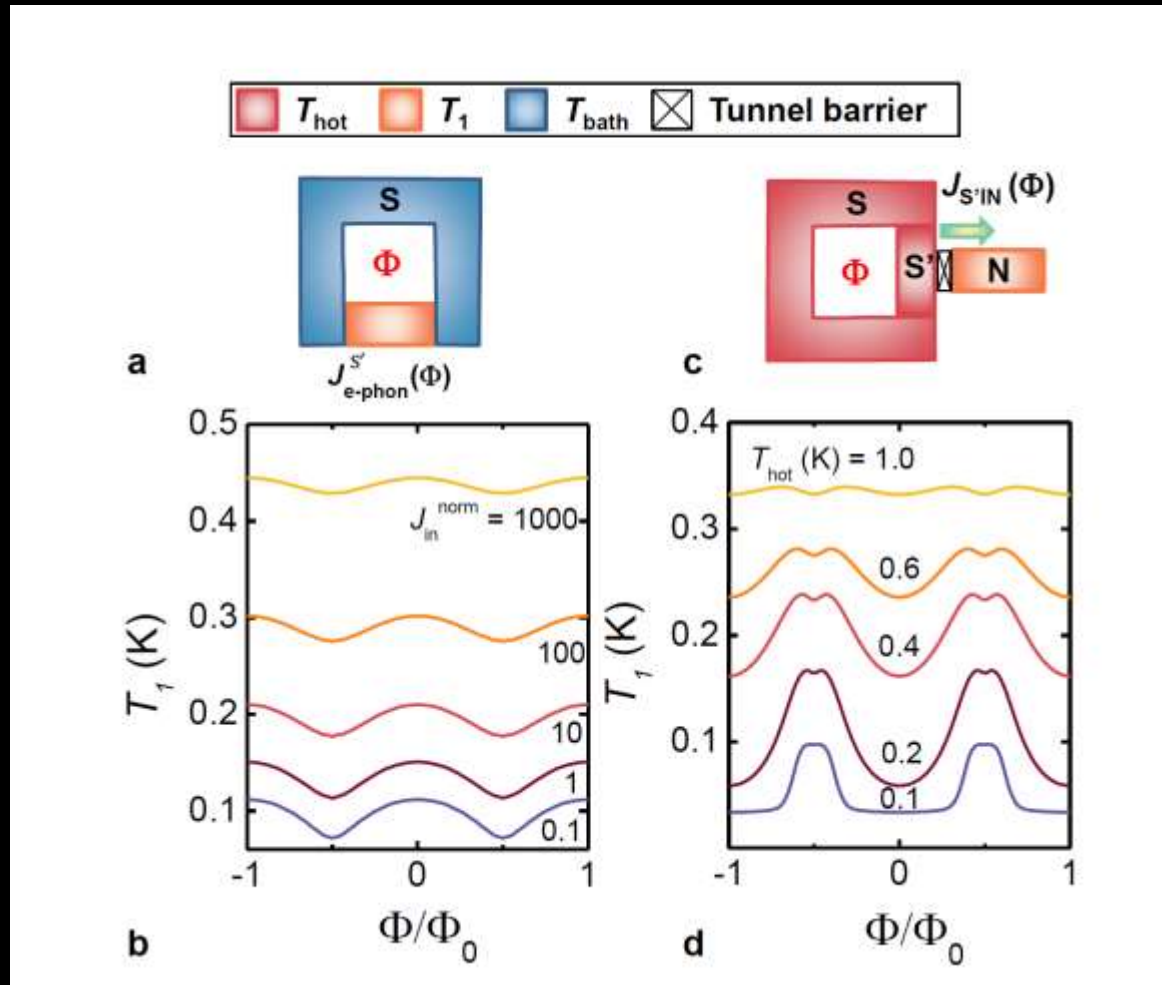
$$J_{\text{SQUID}}(T_1, T_{\text{bath}}, \Phi) = 2J_{\text{qp}}(T_1, T_{\text{bath}}) - 2J_{\text{int}}(T_1, T_{\text{bath}}) \left| \cos\left(\frac{\pi\Phi}{\Phi_0}\right) \right|$$

c – Single-slit Josephson diffractor

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

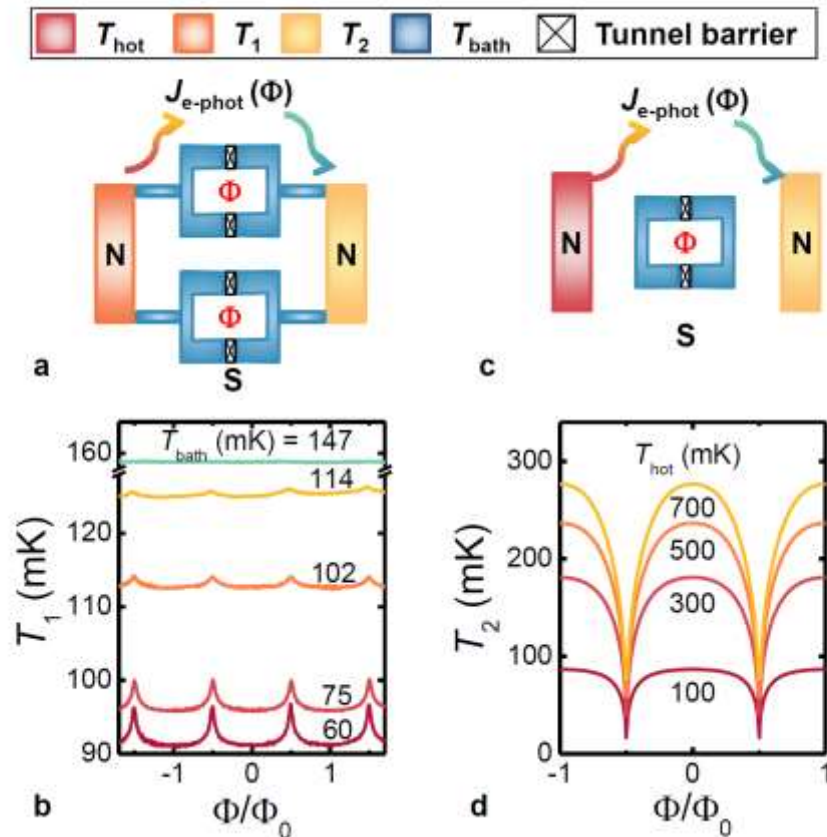
A. Fornieri and FG, Nat. Nanotechnol. **12** (2017)

Superconducting proximity structures



a– Phase-dependent electron-phonon coupling, entropy, specific heat
c – Phase-tunable proximity thermal valve

Photonic heat transistors



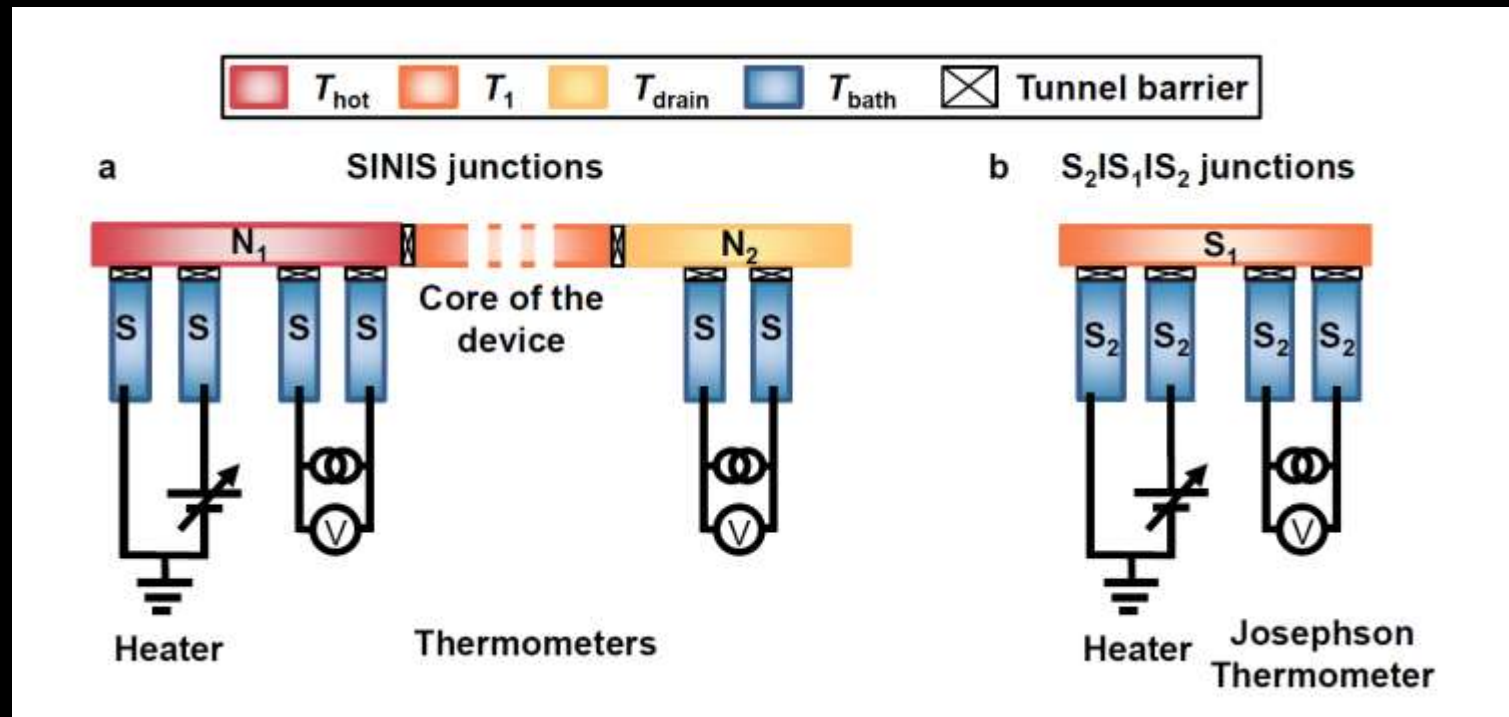
a – First demonstration of phase-dependent photonic heat conduction

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

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

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

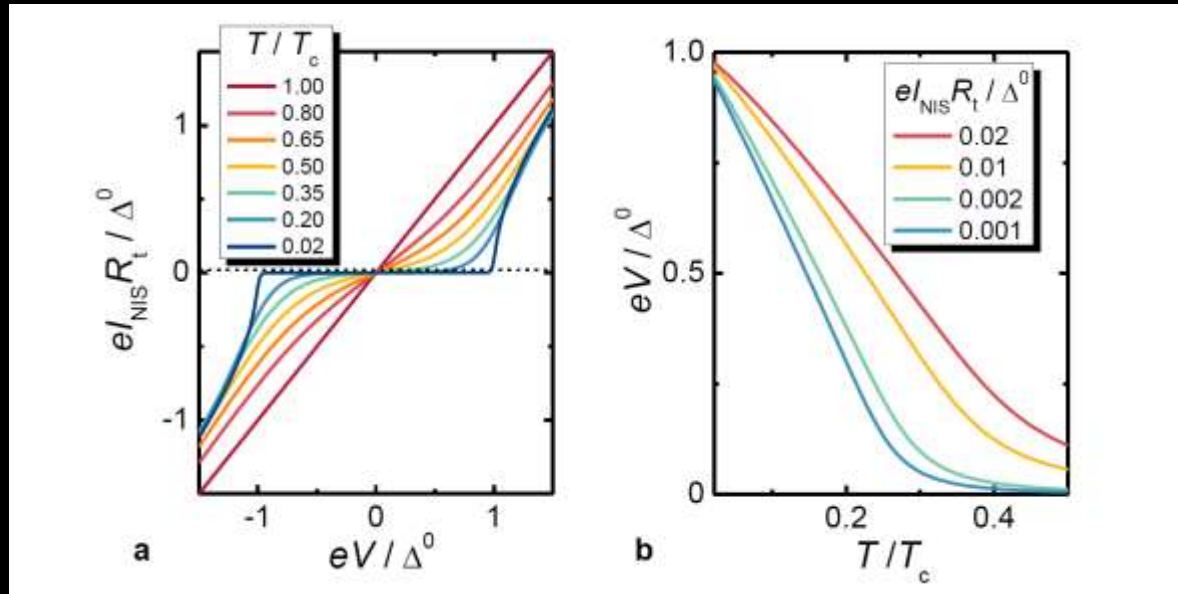
Experimental setups



a – DC & RF electron thermometry through SINIS tunnel junctions

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

Electric transport in superconducting tunnel junctions (NIS)

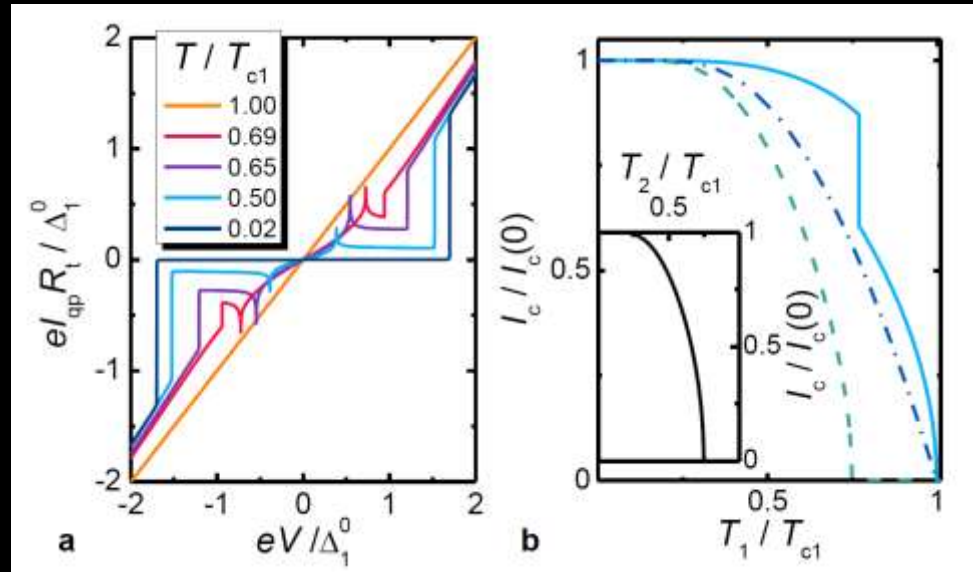


$$\begin{aligned}
 I_{\text{NIS}}(V, T_1, T_2) &= \frac{1}{eR_t} \int_{-\infty}^{\infty} dE N(E, T_2) [f_1(E - eV, T_1) - f_2(E, T_2)], \\
 &= \frac{1}{2eR_t} \int_{-\infty}^{\infty} dE N(E, T_2) [f_1(E - eV, T_1) - f_1(E + eV, T_1)]
 \end{aligned}$$

a – I/V characteristics of a NIS junction

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

Electric transport in superconducting tunnel junctions (SIS)



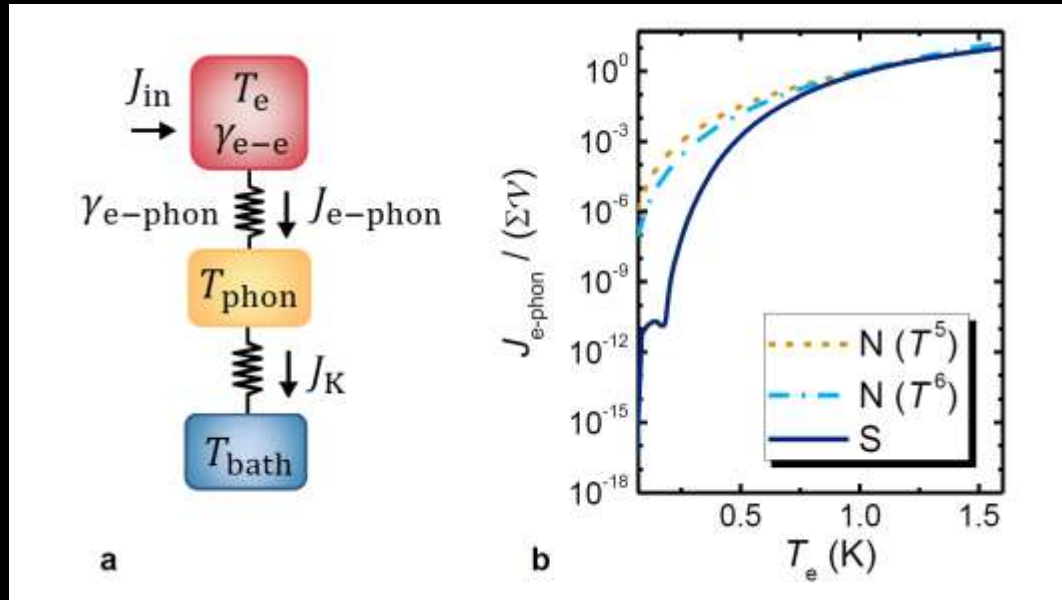
$$I_j(V, T_1, T_2, \varphi) = I_c(T_1, T_2) \sin \varphi + I_{int}(V, T_1, T_2) \cos \varphi$$

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

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

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

Quasiequilibrium regime in mesoscopic circuits



a

b

$$J_{e-phon}^N = \Sigma V (T_e^5 - T_{bath}^5)$$

clean metal

$$J_{e-phon}^{AlMn} = \Sigma_{AlMn} V (T_e^6 - T_{bath}^6)$$

disordered metal

a – Scheme of N or S film on a substrate

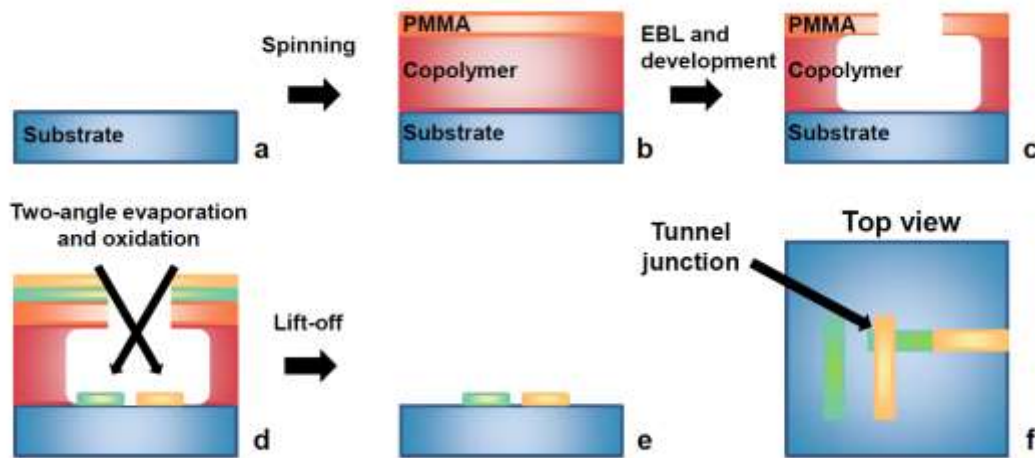
b – Electron-phonon coupling in N and S

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

superconductor

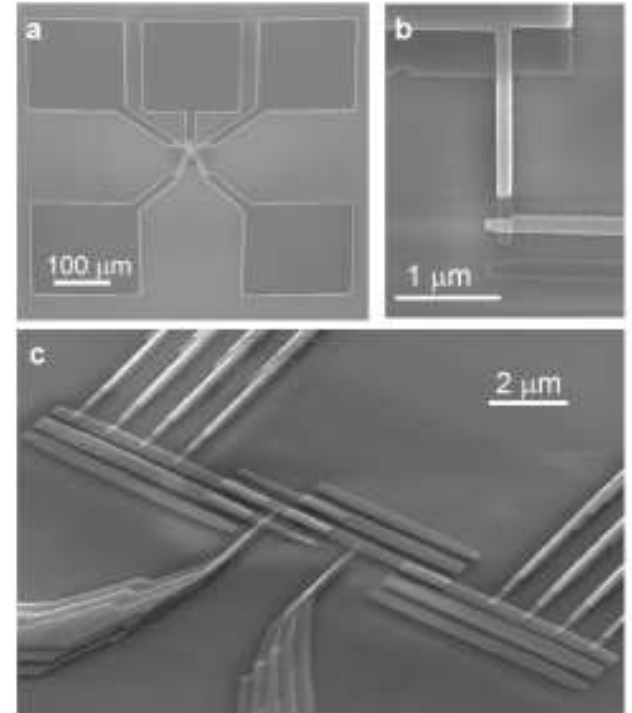
FG, T. T. Heikkilä, A. Luukanen, A. M. Savin, and J. P. Pekola, Rev. Mod. Phys. **78**, 217 (2006);
 A. Forni and FG, Nat. Nanotechnol. **12** (2017);
 A. V. Timofeev, et al., Phys. Rev. Lett. **102**, 017003 (2009)

Nanofabrication techniques

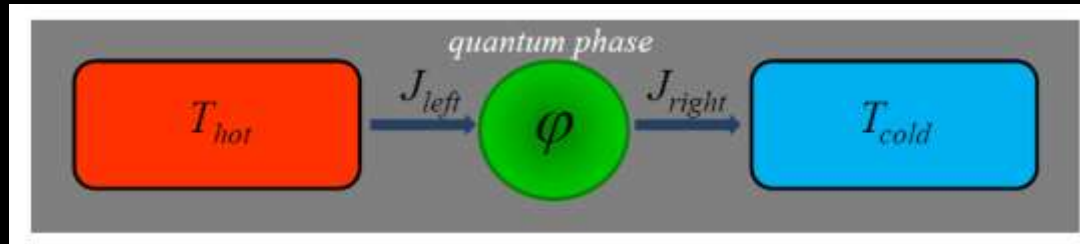


Angle evaporation and *in-situ* oxidation

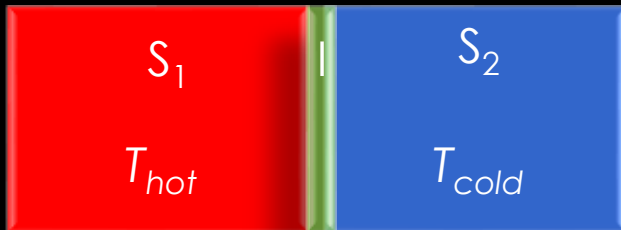
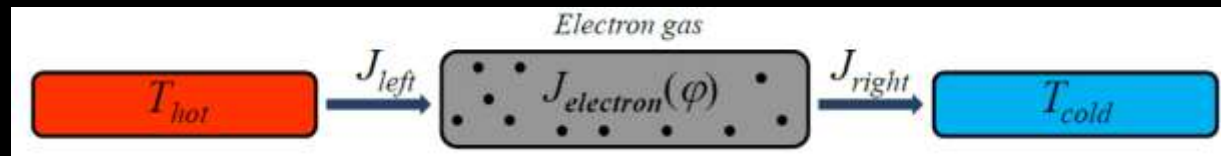
Typical shadow-mask evaporated structures



Principle of phase-dependent heat current control



Exploitation of superconducting phase to control heat current flow



Temperature-biased Josephson tunnel junction

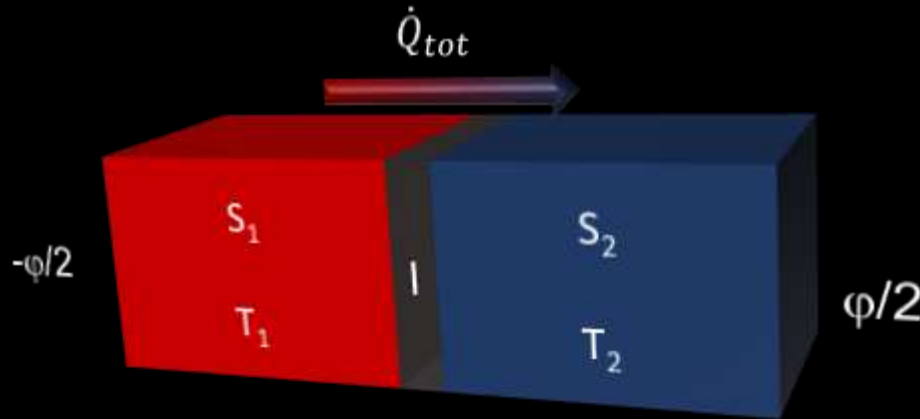


Heat current is predicted to be phase dependent and stationary

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

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

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

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

$$\left\{ \begin{array}{l} \dot{Q}_{qp} = 0 \\ \dot{Q}_{int} = 0 \end{array} \right. \quad \text{if } T_1 = T_2$$

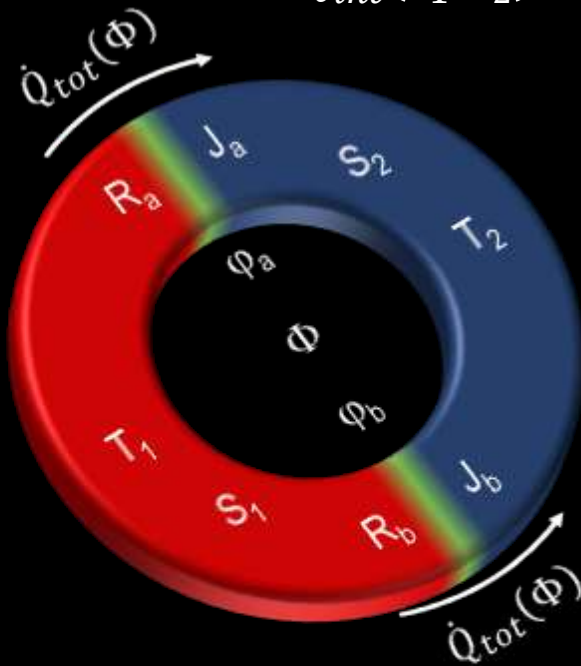
$$\dot{Q}_{int} = 0 \quad \text{if } S_1 \text{ or } S_2 \text{ in normal state}$$

Temperature-biased DC-SQUID: theory (i)

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

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

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



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

Flux quantization

$$I_j^a \sin \varphi_a = I_j^b \sin \varphi_b$$

Circulating charge
current conservation

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

$$x = \Phi / \Phi_0$$

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

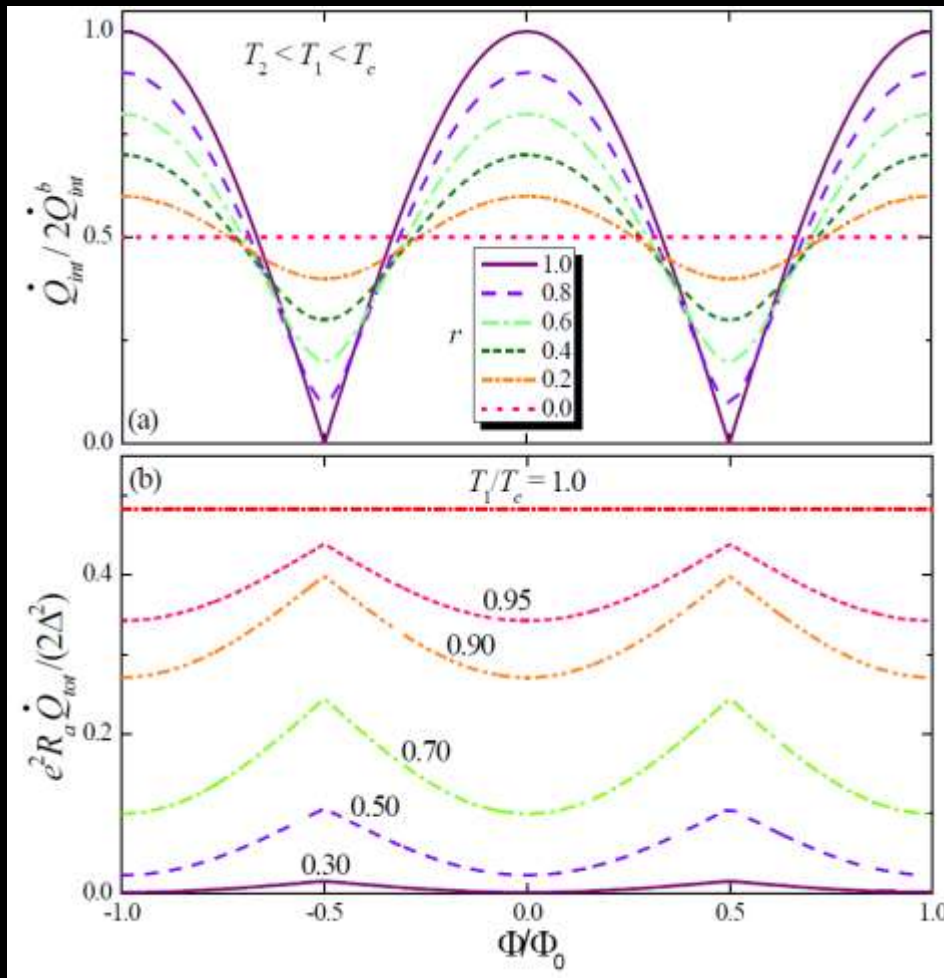
$$r = I_j^a / I_j^b$$

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

Symmetric SQUID

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

Temperature-biased DC-SQUID: theory (ii)



Role of critical current asymmetry

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

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

Total heat current behavior
(symmetric SQUID)

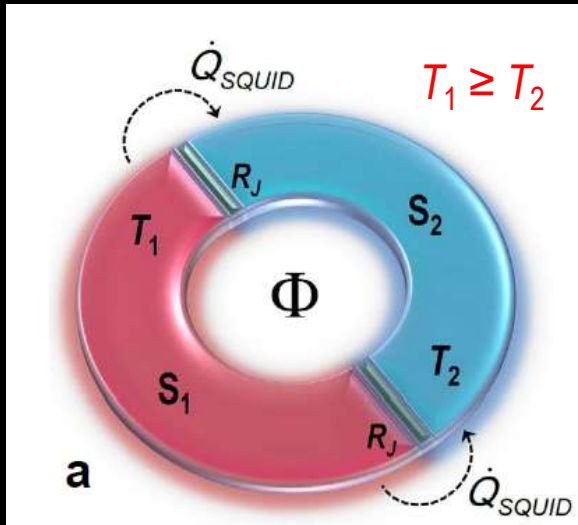
$$T_2 = 0.1T_c$$

“Josephson heat interferometer”: setup (i)

LETTER

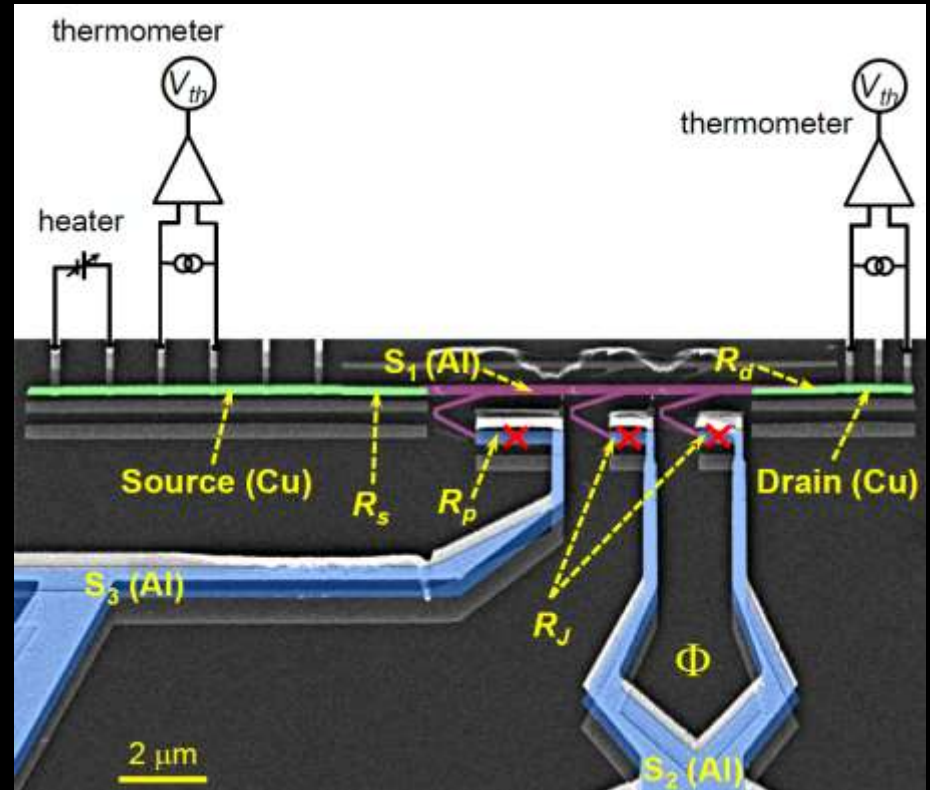
The Josephson heat interferometer

Francois Giazotto¹ & Marco José Martínez-Pérez¹

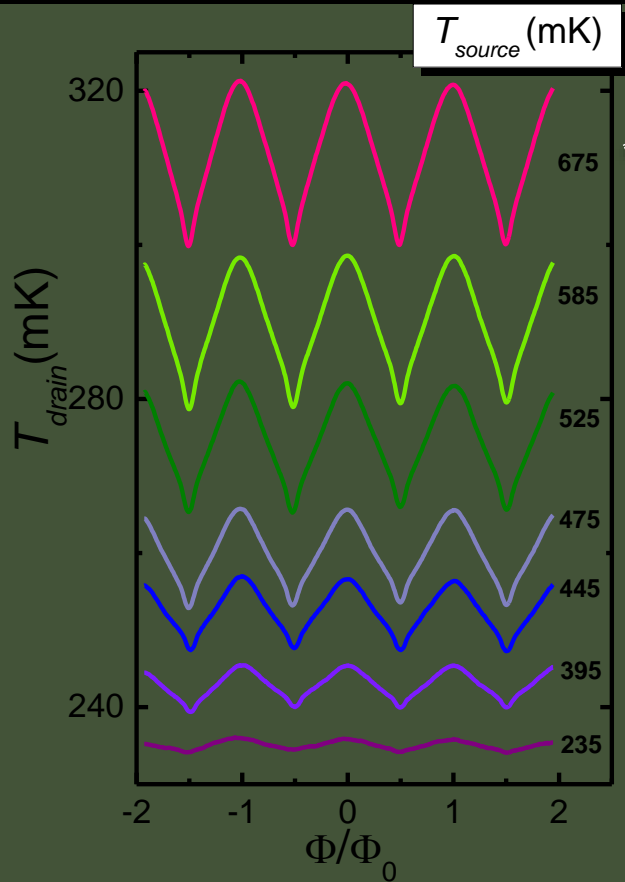


Symmetric SQUID ($r = 1$)

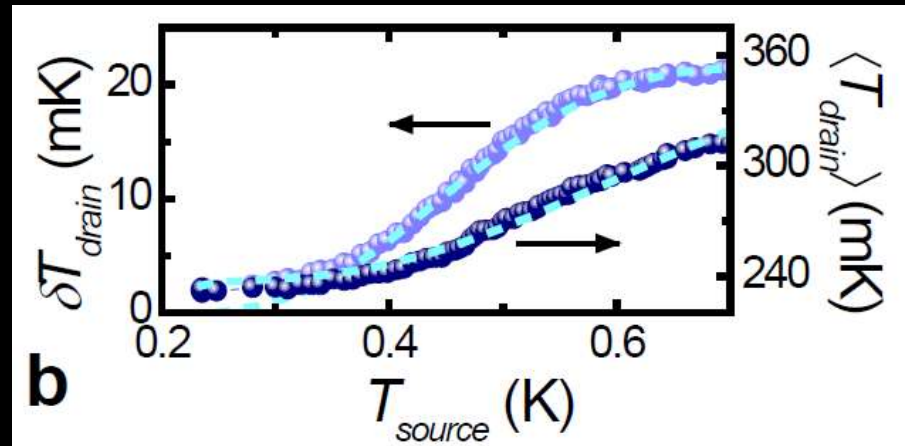
$$\dot{Q}_{SQUID}(\Phi) = 2\dot{Q}_{qp} - 2\dot{Q}_{int} \left| \cos \left(\frac{\pi\Phi}{\Phi_0} \right) \right|$$



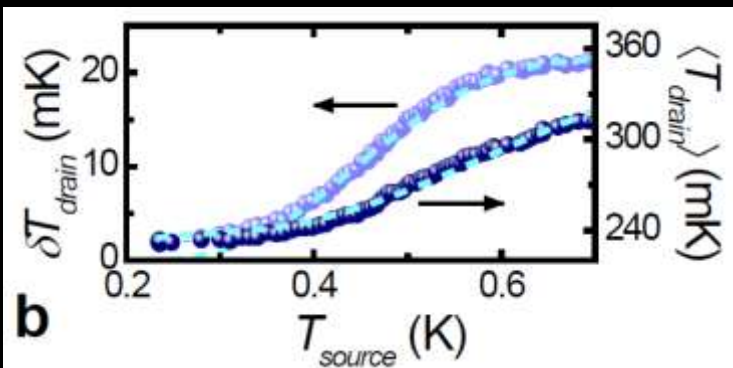
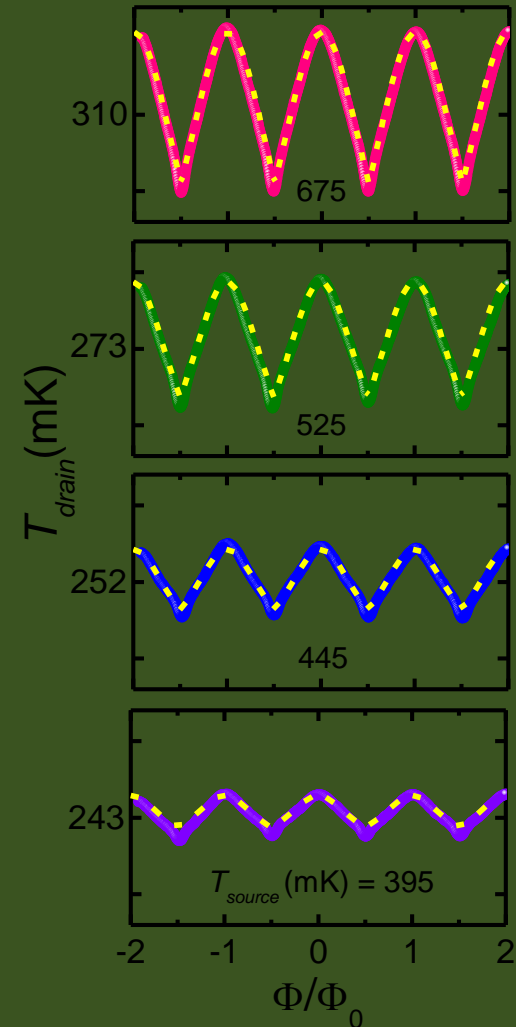
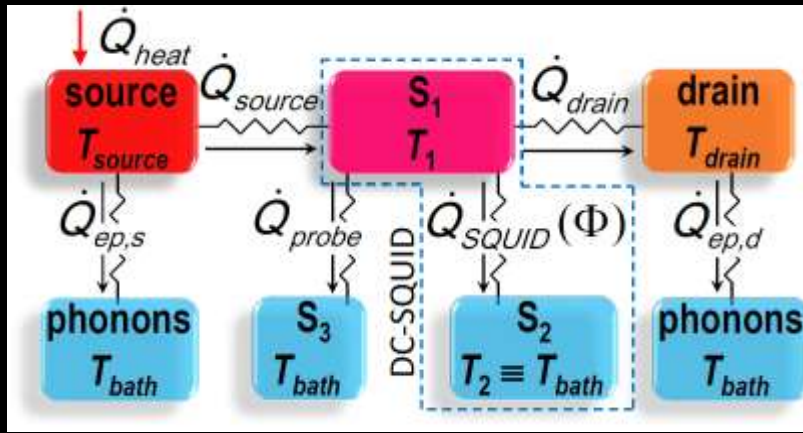
Behavior @ 235 mK (i)



$\delta T_{\text{drain}} \sim 21$ mK
9% relative
modulation amplitude

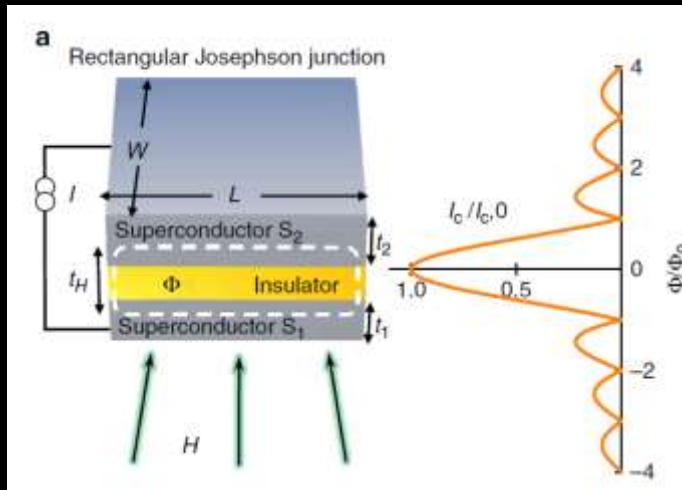


Comparison to theory

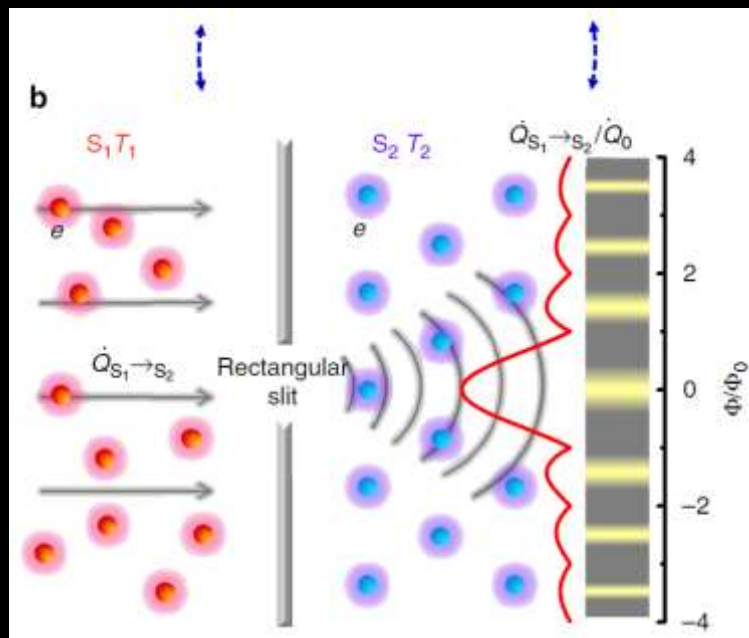


Good agreement with theoretical prediction

Electric vs thermal quantum diffraction

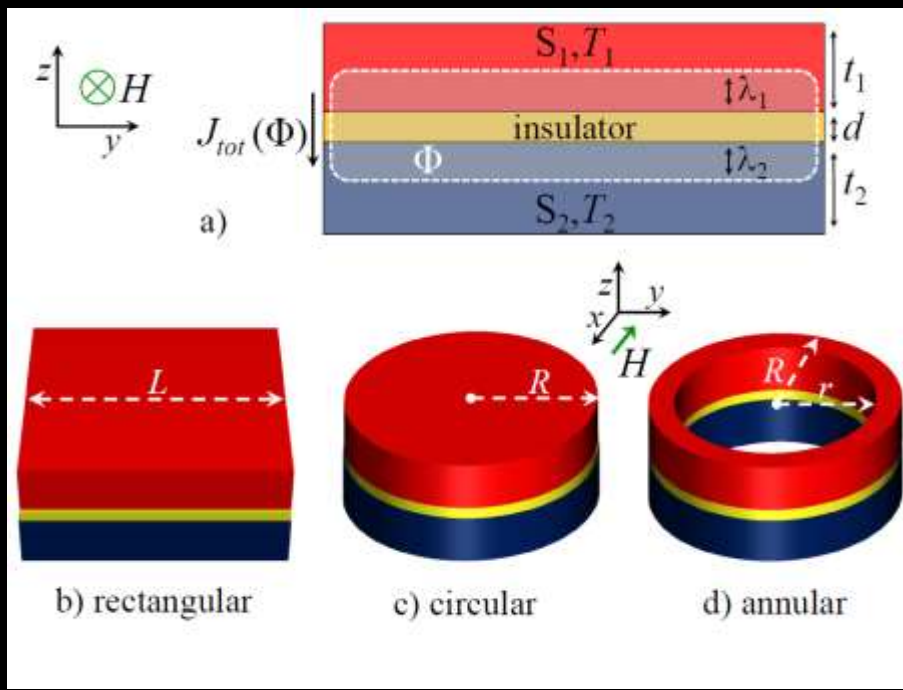


Electric diffraction through a rectangular slit



Diffraction of heat current through a rectangular slit

Heat current quantum diffraction in extended short JJs



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

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

Josephson critical current

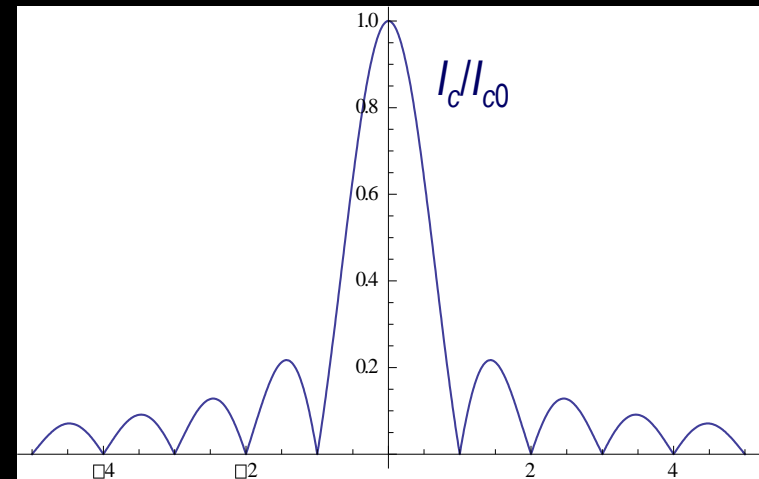
$$I_c(\Phi) = |2I_{c0} \int_{-\infty}^{\infty} f(y) \cos\left(\frac{2\pi\Phi}{\Phi_0} \frac{y}{L}\right) dy|$$

Critical current Fraunhofer pattern for a rectangular JJ

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



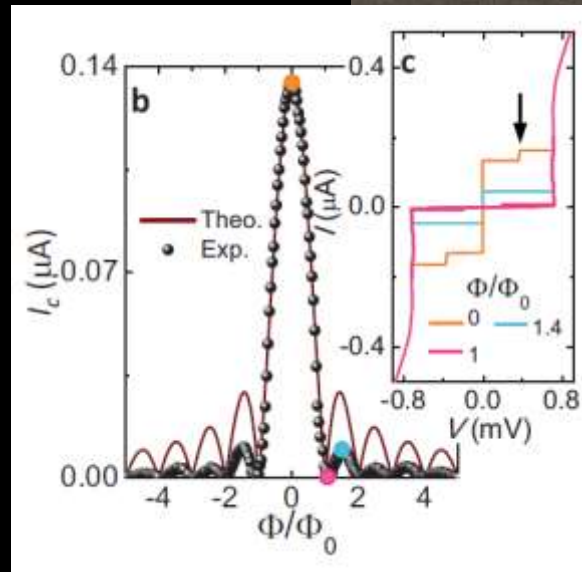
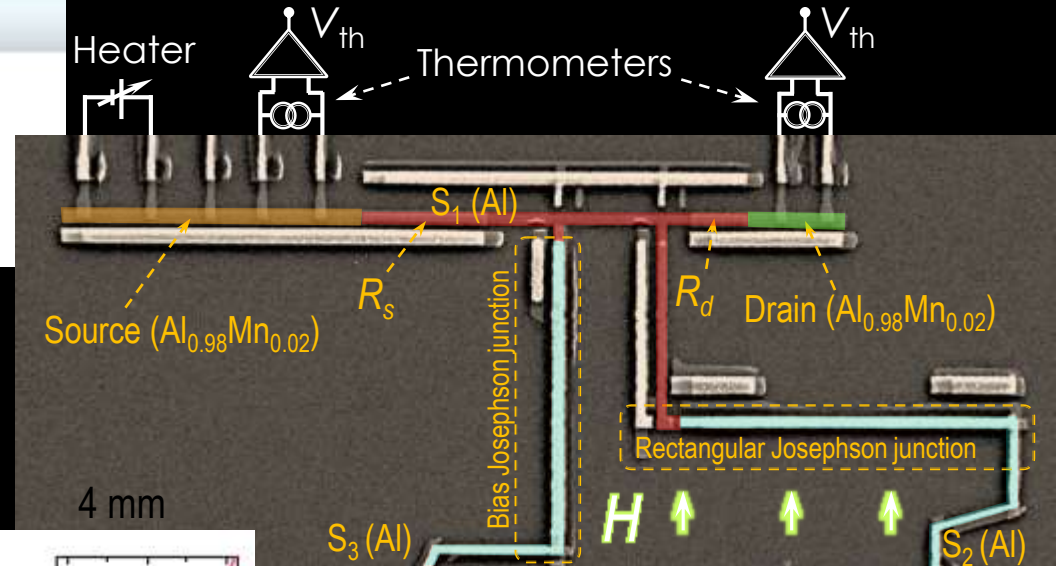
Φ/Φ_0



A "quantum diffractor" for thermal flux: experimental setup



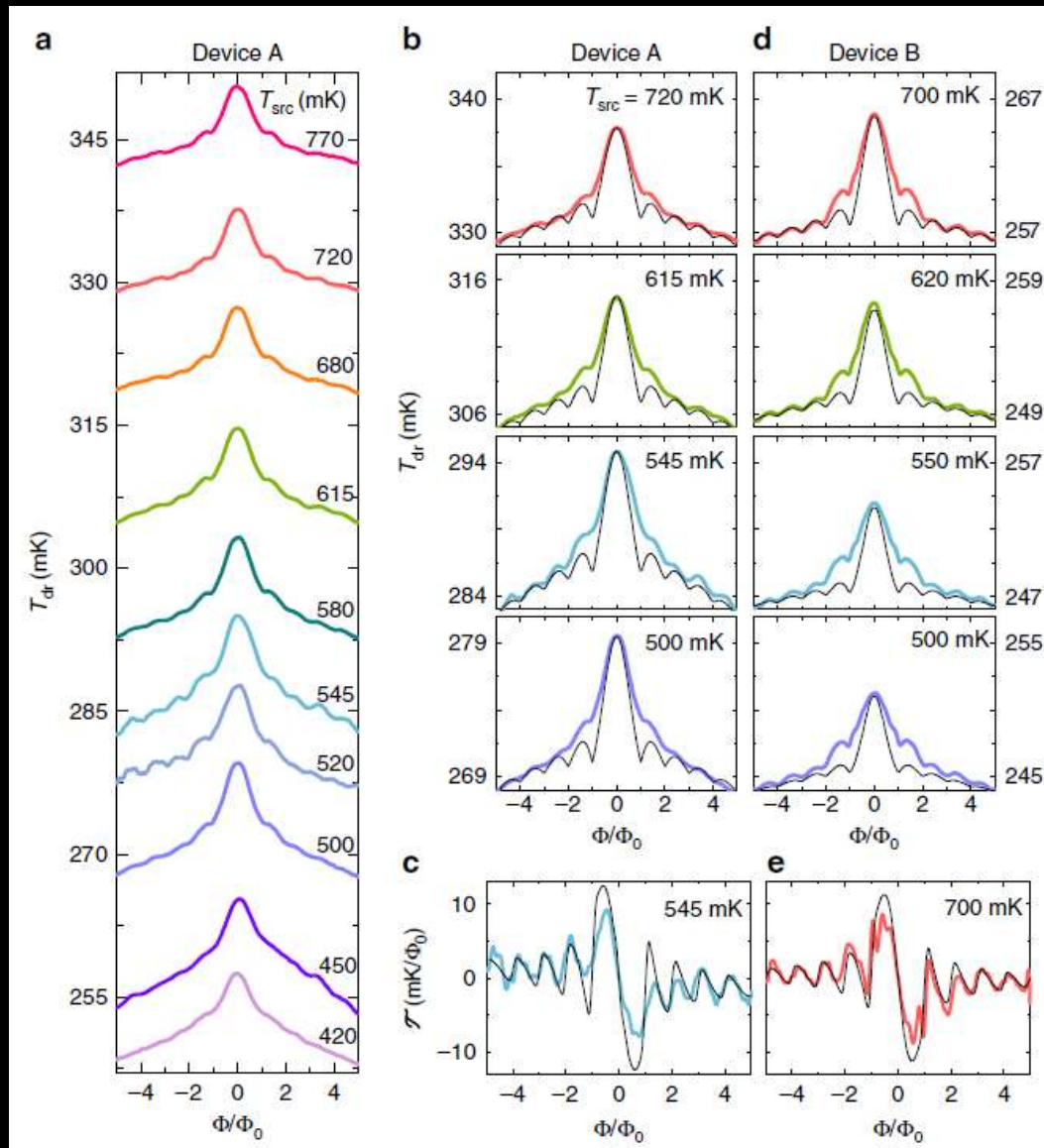
Rectangular JJ



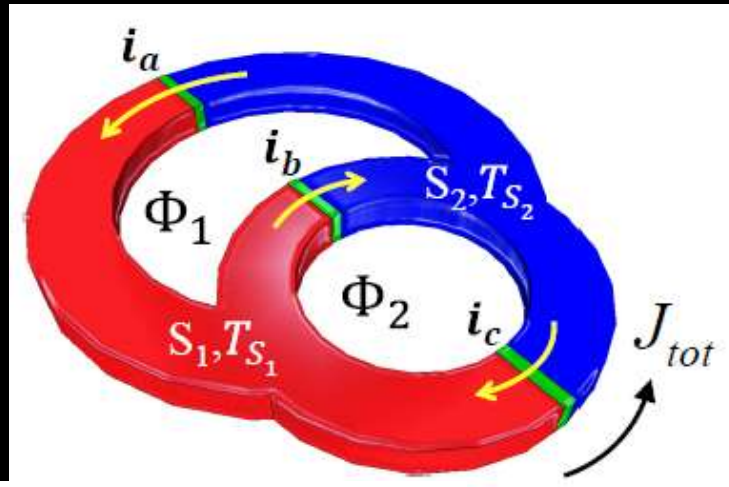
Josephson current behavior

Magnetic interference pattern

Temperature diffraction pattern @ 240 mK

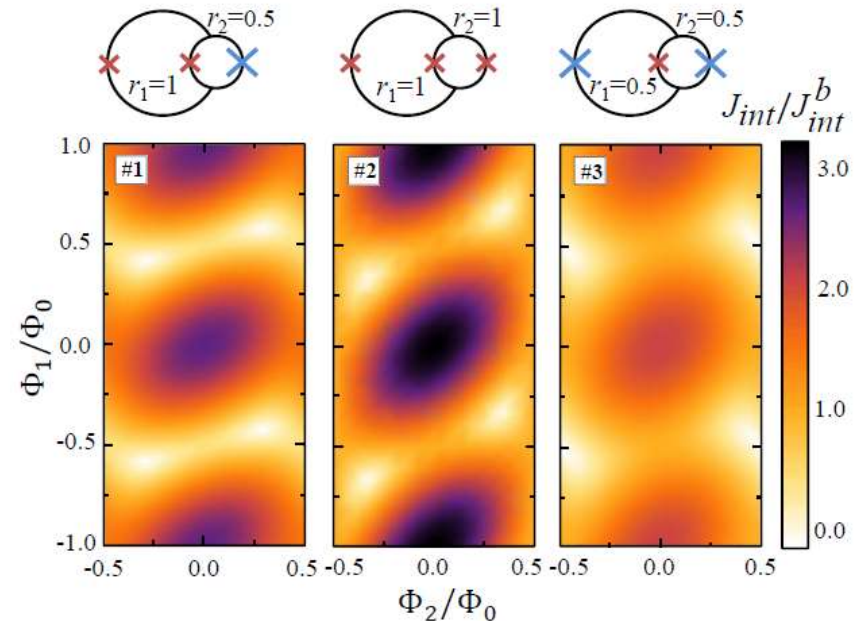
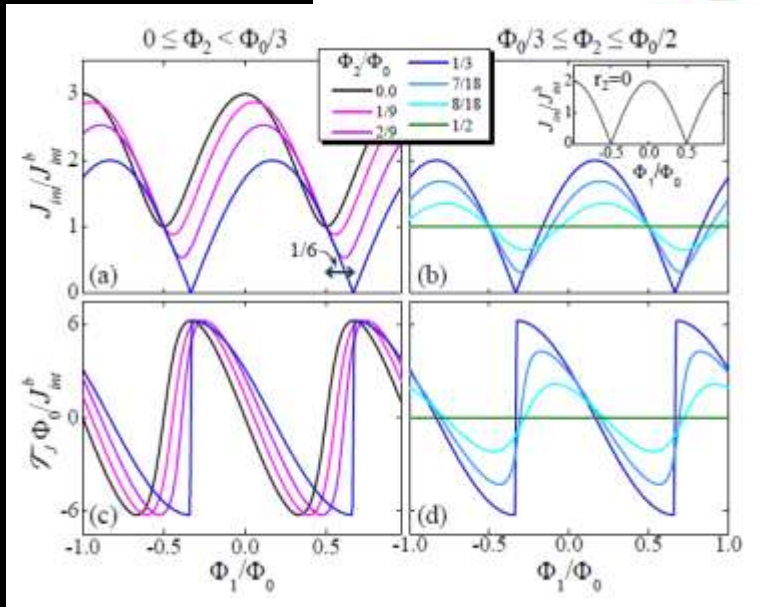


Fully-balanced heat interferometer



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

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

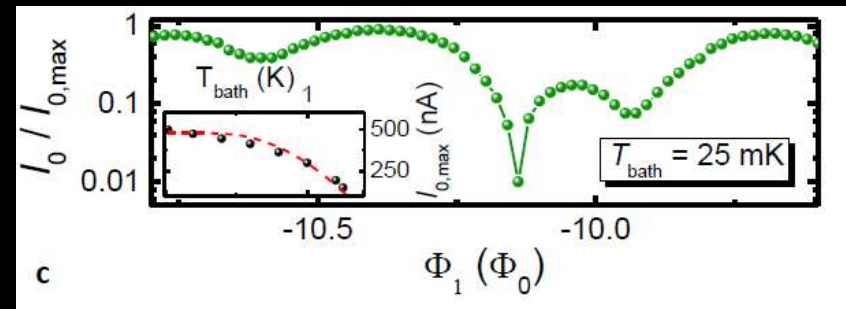
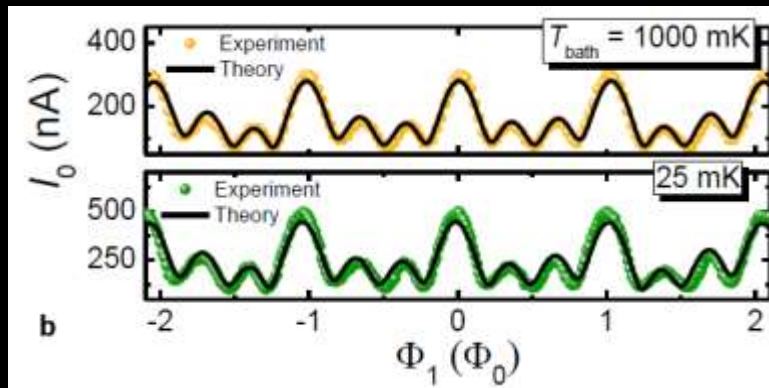
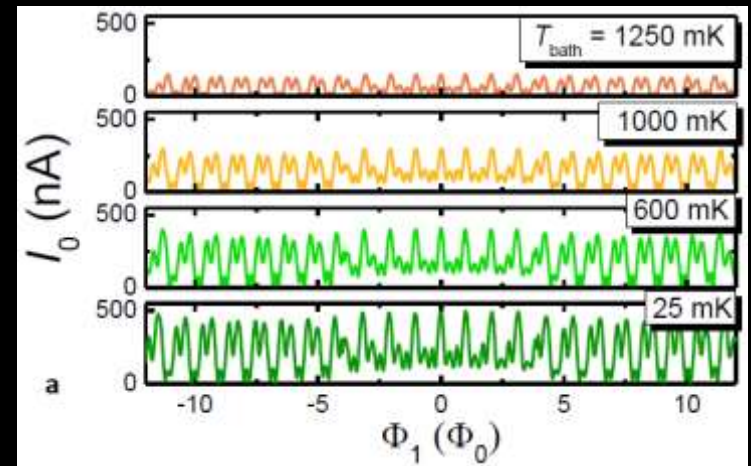
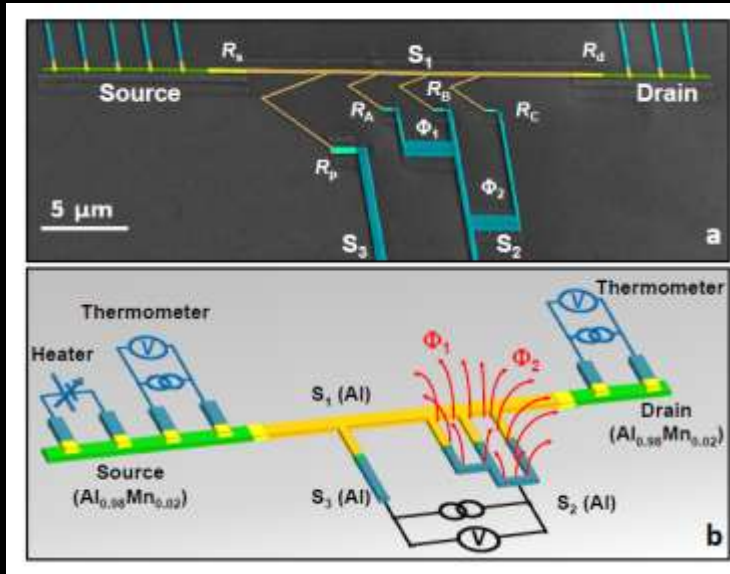


Nanoscale phase-engineering of thermal transport

i) Electrical response



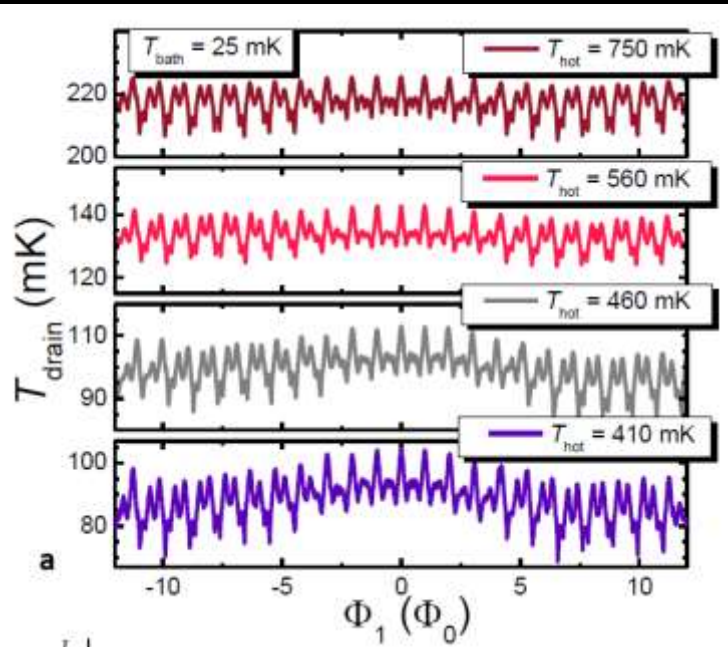
Fully-balanced quantum thermal modulator structure: full phase-engineering of heat currents



I_c suppression $\sim 99\%$

Nanoscale phase-engineering of thermal transport

ii) Thermal response at base T_{bath}

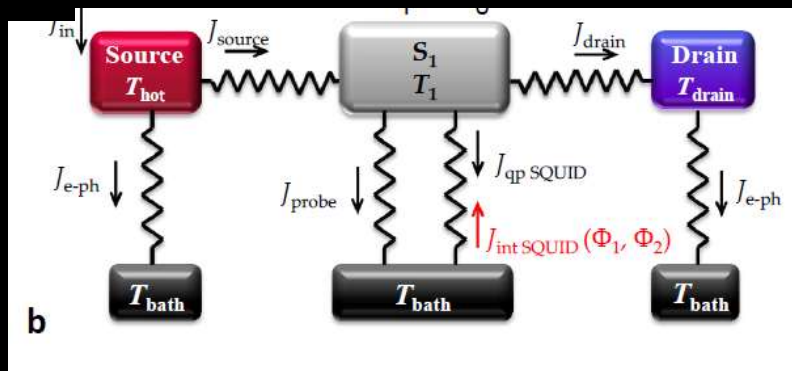


~ 40mK temperature swing

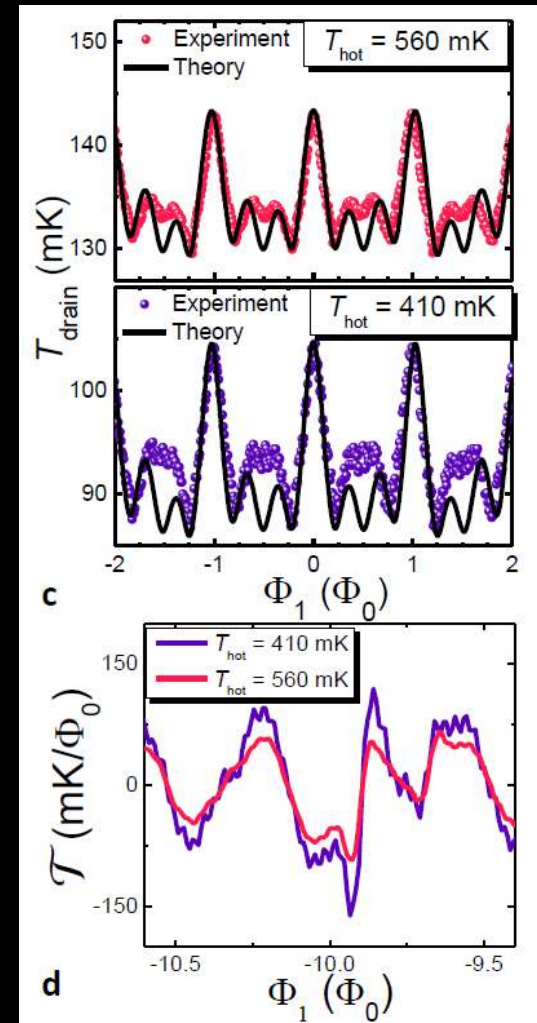
J_{int} suppression ~ 99%

$\tau \sim 200\text{mK}/\Phi_0 @ 25\text{mK}$

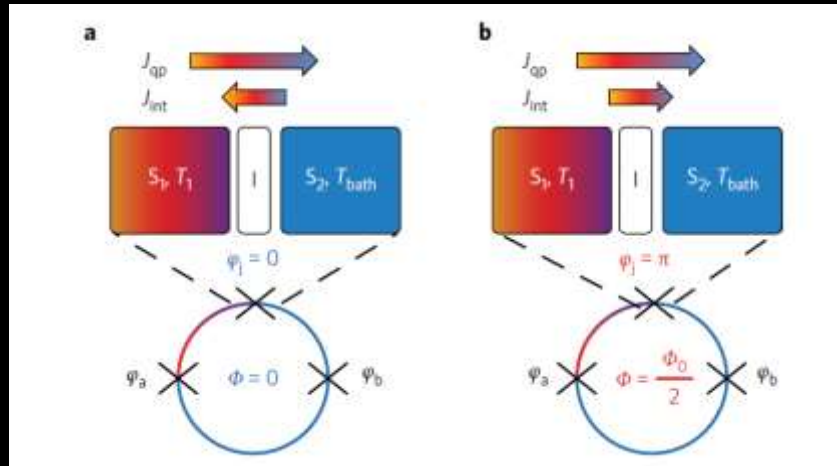
X 3 previous exps



Thermal model



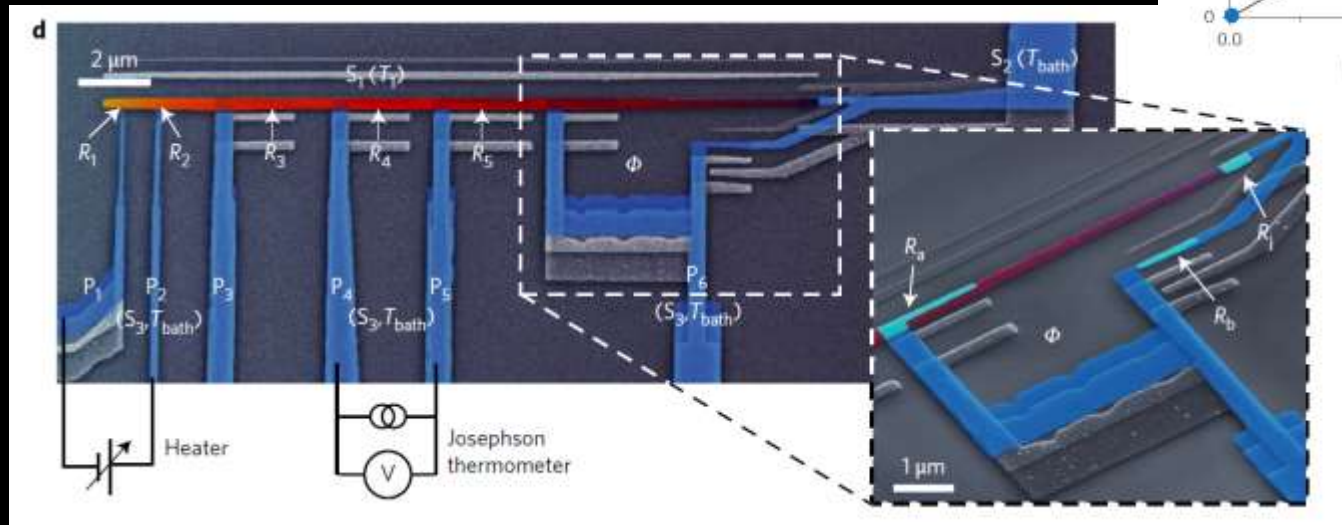
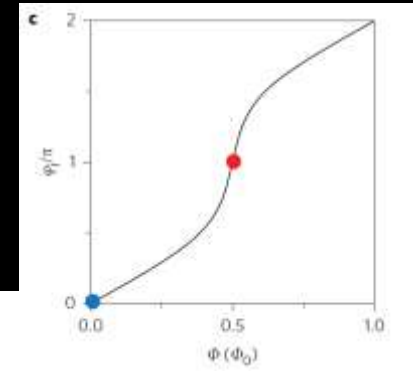
Phase-controllable $0-\pi$ thermal Josephson junction



nature nanotechnology LETTERS
 PUBLISHED ONLINE: 13 MARCH 2017 | DOI: 10.1038/NNANO.2017.26

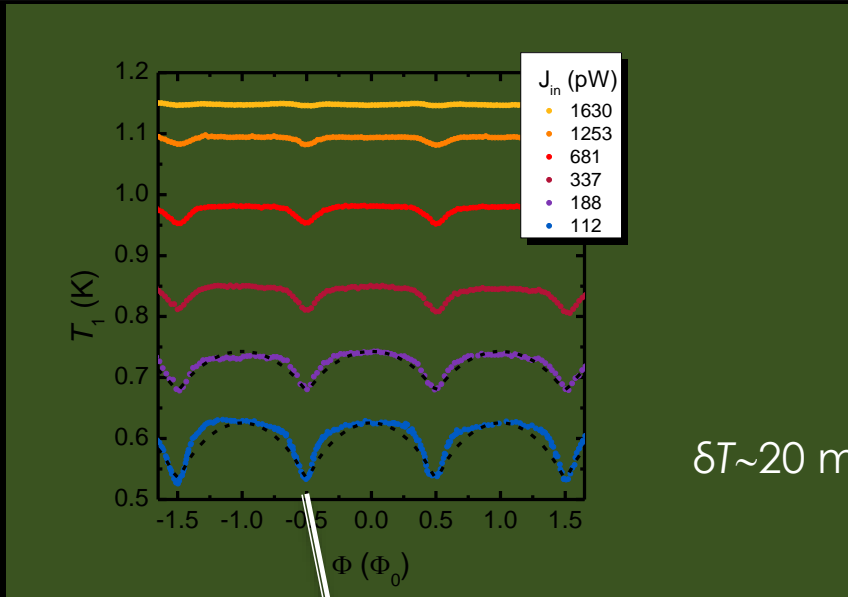
$0-\pi$ phase-controllable thermal Josephson junction

Antonio Fornieri¹, Giuliano Timossi¹, Pauli Virtanen¹, Paolo Solinas² and Francesco Giazotto^{1*}

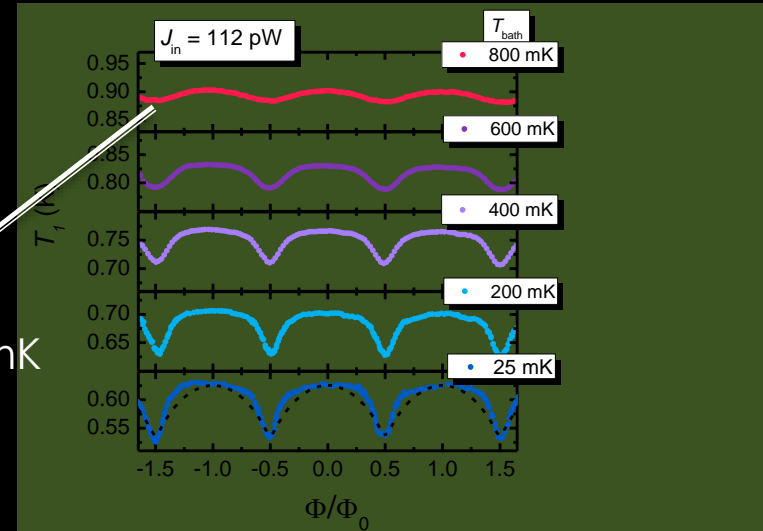


A. Fornieri, G. Timossi, P. Solinas, P. Virtanen, and FG, Nat. Nanotechnol. **12**, 425-429 (2017);
 A. Fornieri, G. Timossi, R. Bosisio, P. Solinas, and FG, Phys. Rev. B **93**, 134508 (2016)

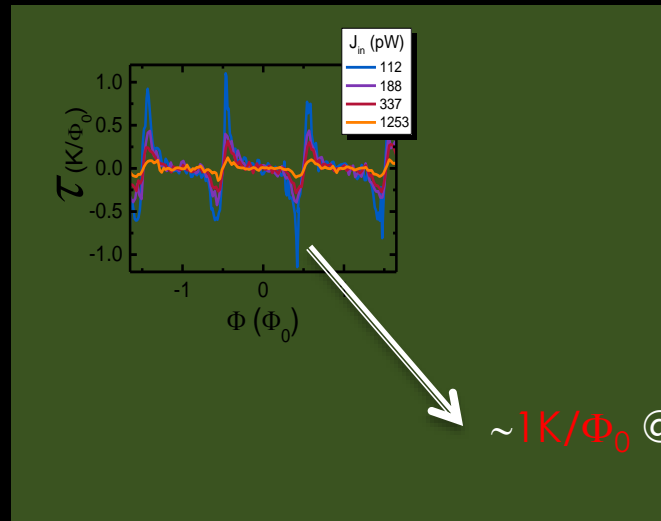
0- π thermal Josephson junction: thermal behavior



$\delta T \sim 20$ mK @ 800 mK



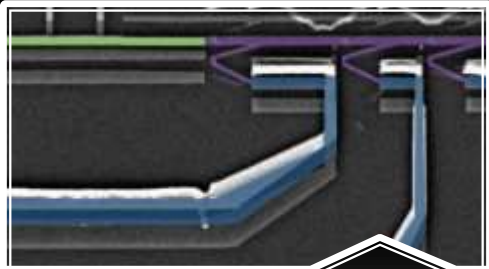
δT up to 100 mK @ 25 mK



~ 1 K/ Φ_0 @ 550 mK

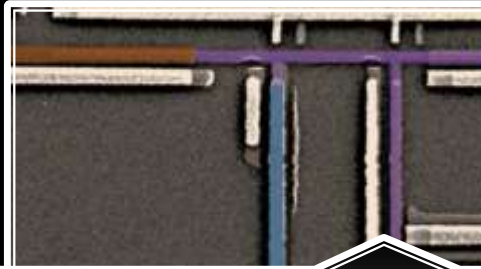
$$\mathcal{T} \equiv \partial T_{drain} / \partial \Phi$$

Single output caloritronic devices



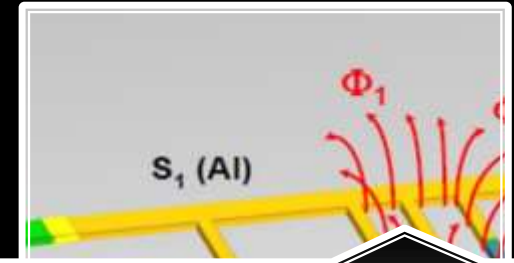
The Josephson heat interferometer

Nature **492**, 401 (2012)



A quantum diffractor for thermal flux

Nat. Commun. **5**, 3579 (2014)



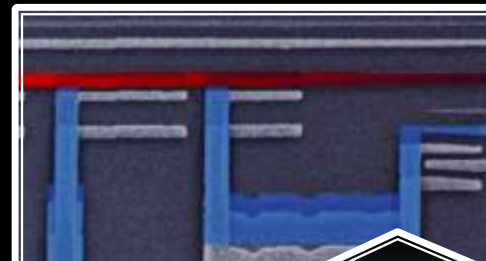
Nanoscale phase engineering of thermal transport with a Josephson heat modulator

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



Rectification of electronic heat current by a hybrid thermal diode

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



$0-\pi$ phase-controllable thermal Josephson junction

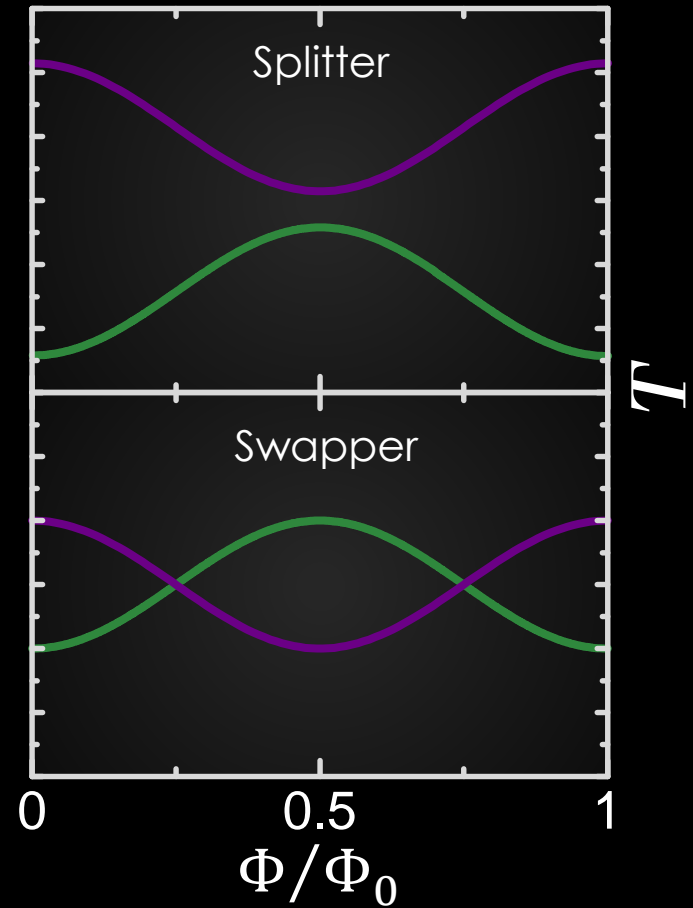
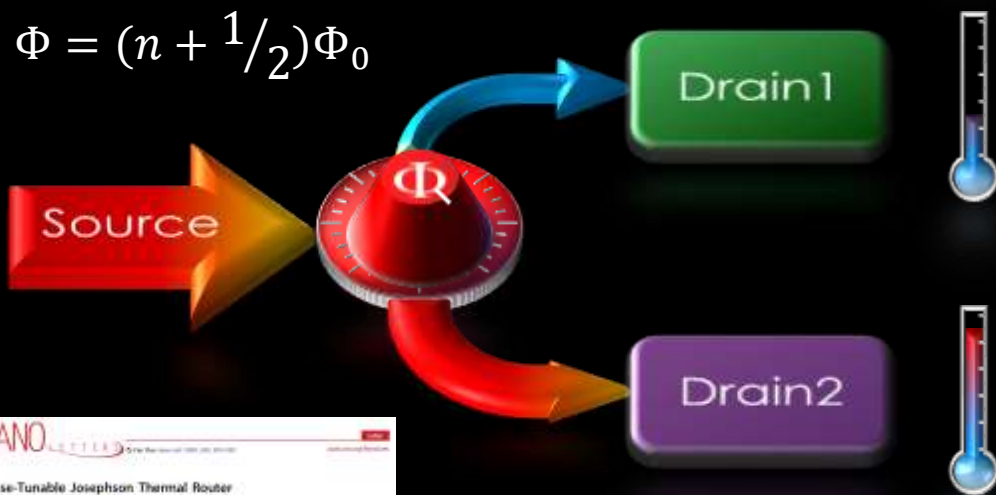
Nat. Nanotech. **12**, 425 (2017)

Phase-tunable thermal router: General scheme

$$\Phi = n\Phi_0$$

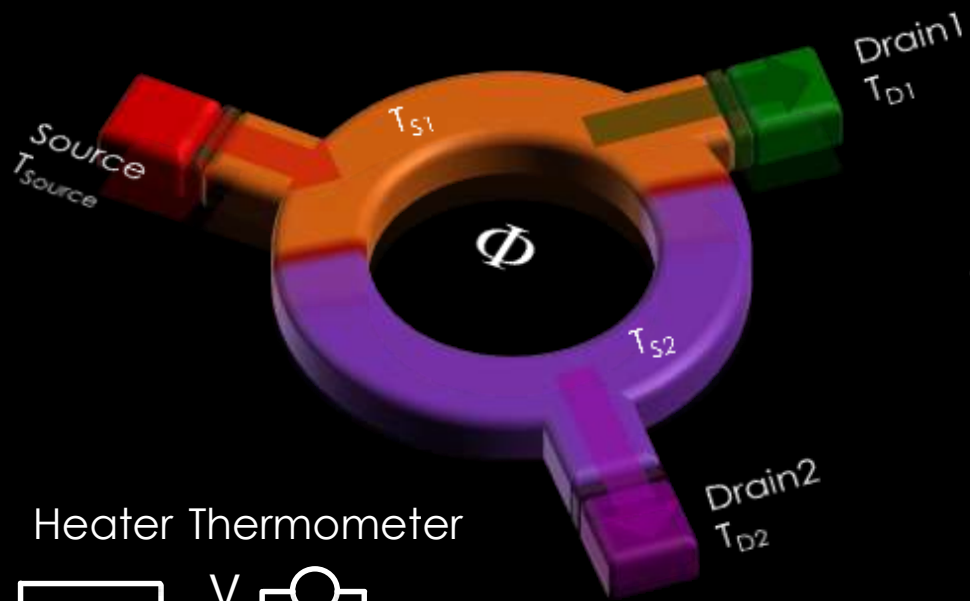


$$\Phi = (n + 1/2)\Phi_0$$



DOI: 10.1021/acs.nanolett.7b04906

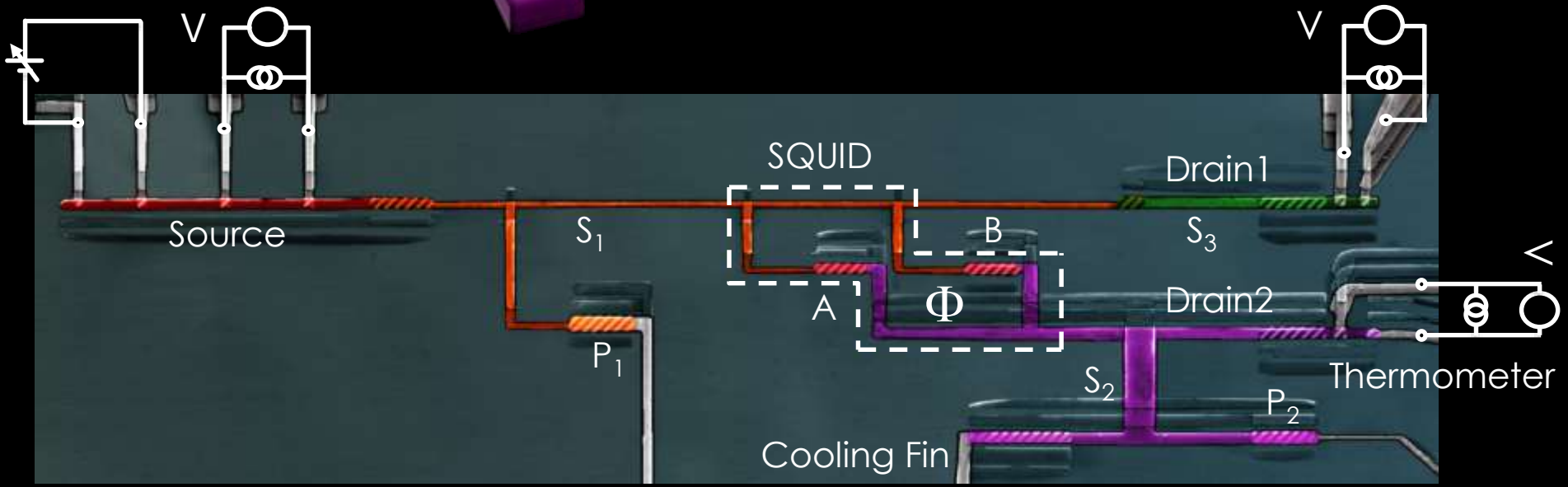
Phase-tunable thermal router: Device structure



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

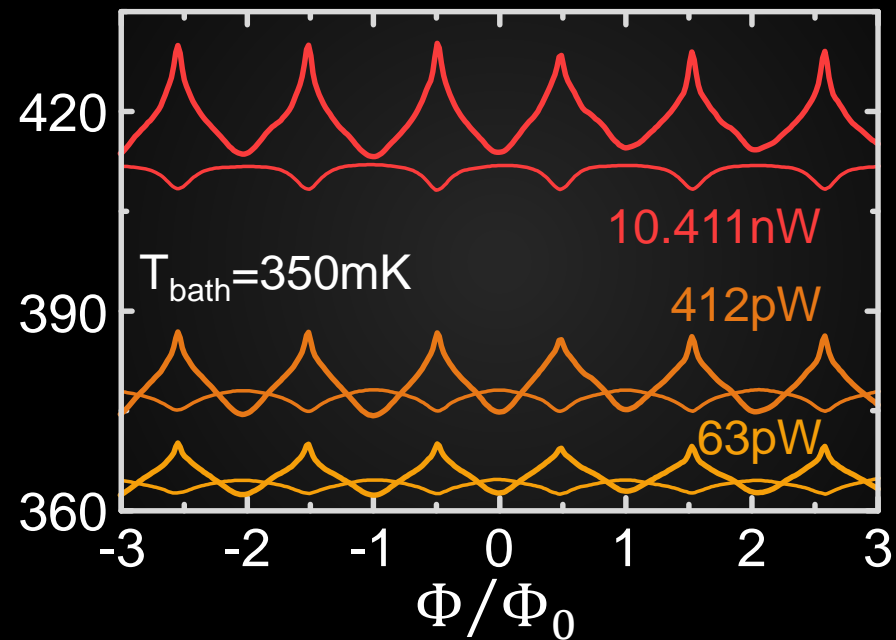
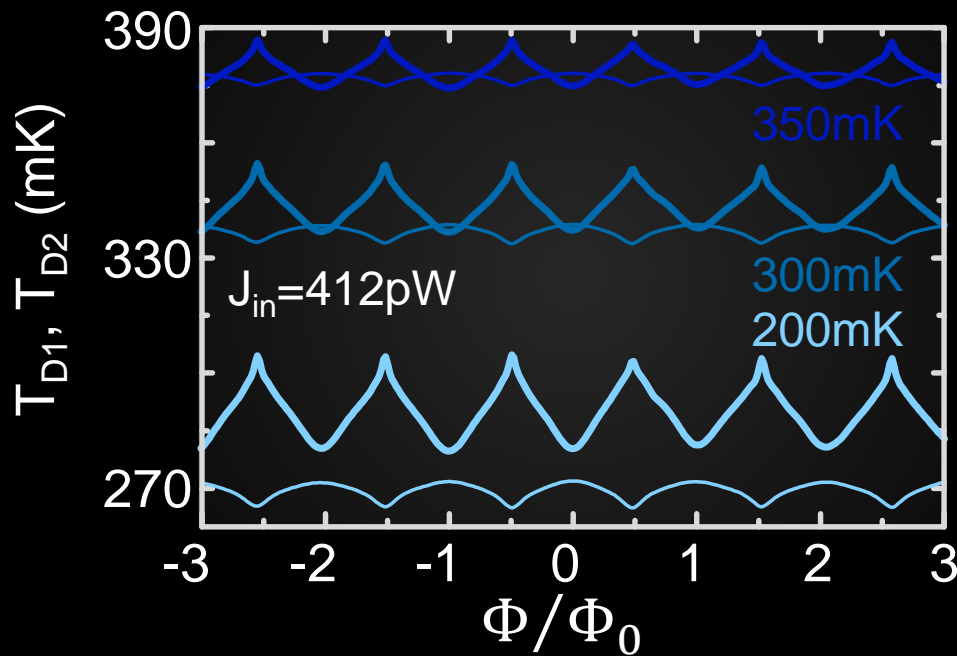
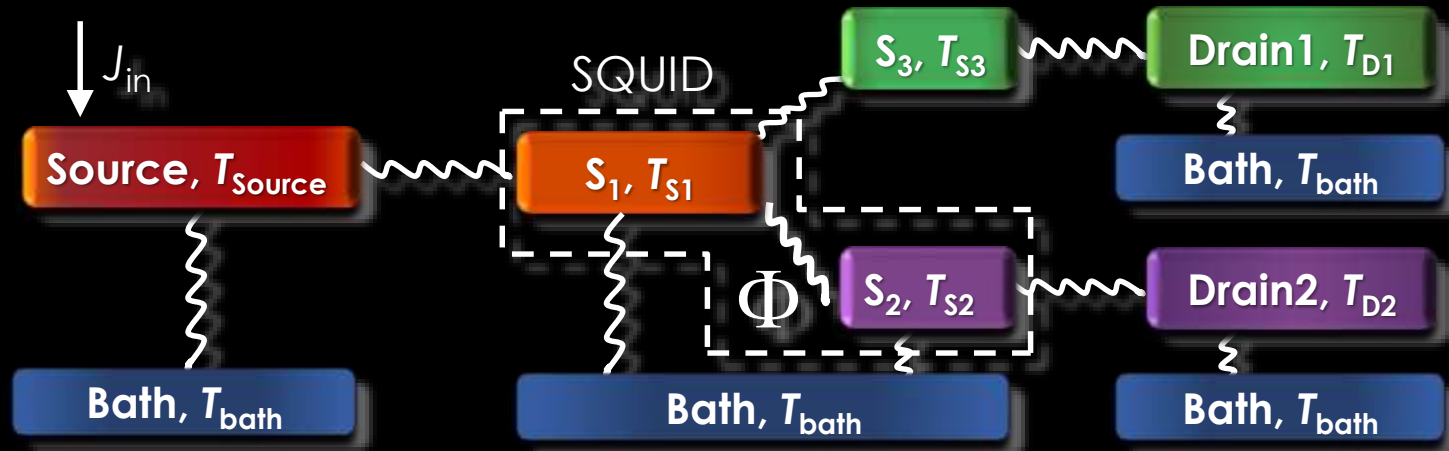
Heater Thermometer

Thermometer

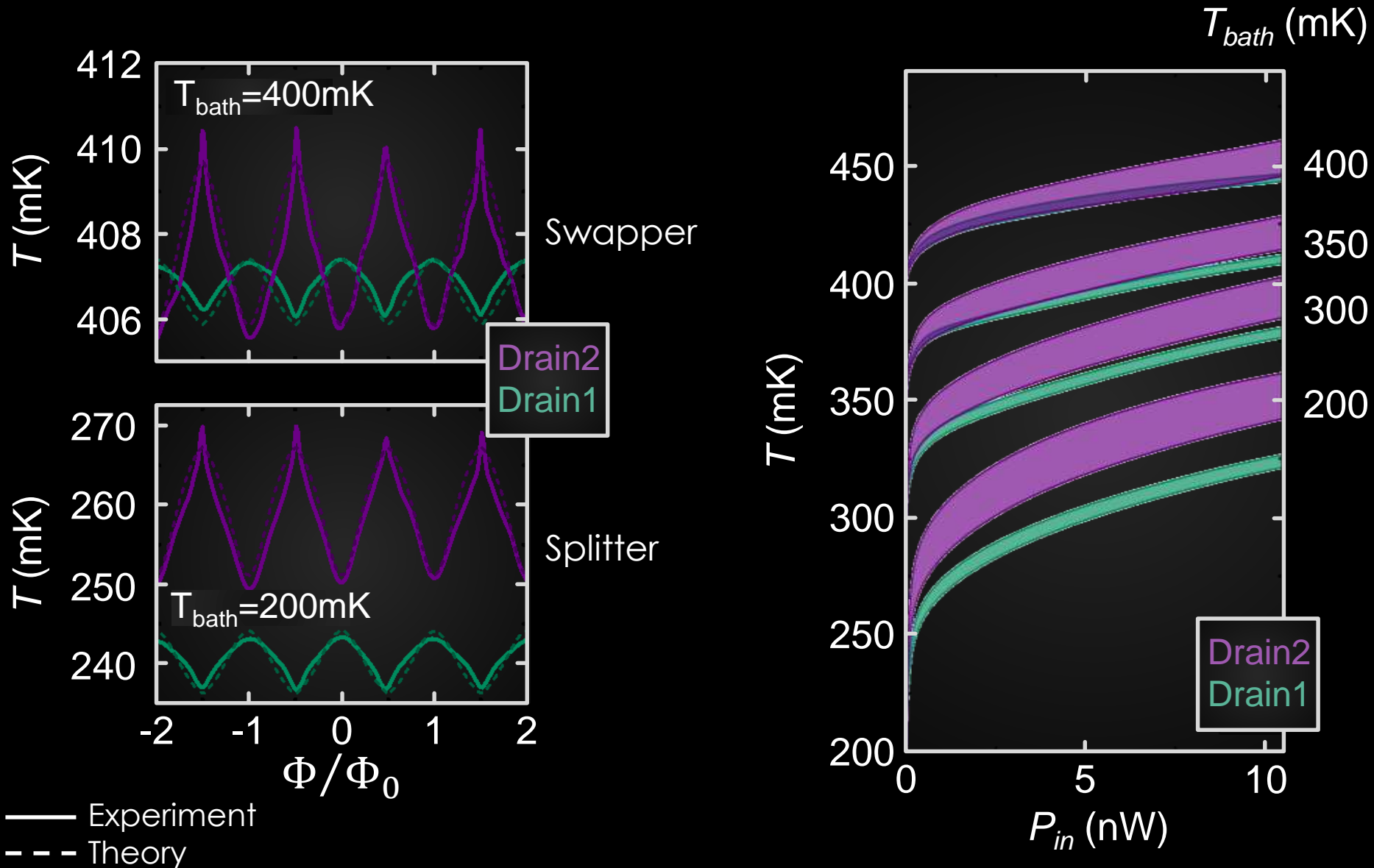


G. Timossi, A. Fornieri, F. Paolucci, C. Puglia, and FG, Nano Lett. **18**, 1764 (2018)

Phase-tunable thermal router: Experiment



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 $0-\pi$ 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”

Acknowledgments

A. Fornieri
M. J. Martinez-Perez
P. Solinas
F. Paolucci
G. Timossi
R. Bosisio
S. D'Ambrosio
C. Blanc
A. Altimiras
P. Virtanen
C. Puglia

MIUR-FIRB2013-Project Coca

FARFAS 2014-Project SCIADRO



ERC consolidator grant No. 615187 - COMANCHE

