

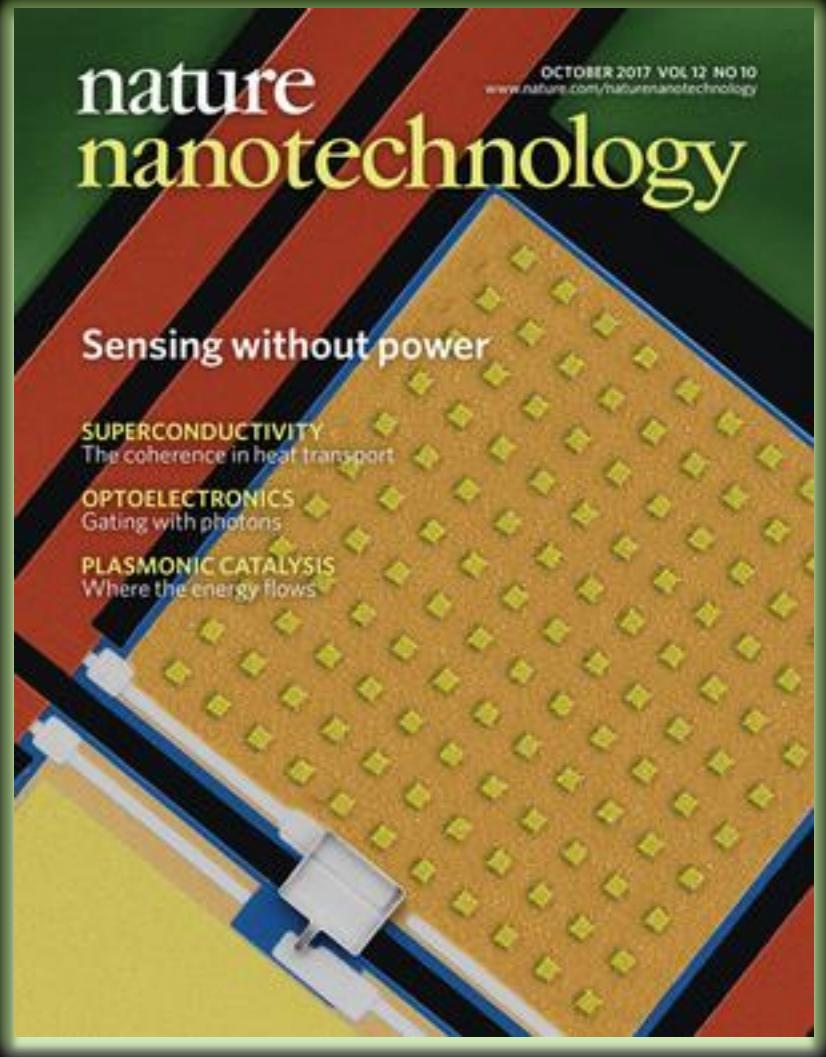
Superconducting circuits: The phase-coherence in thermal transport

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Outline

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



Motivations

- Set the experimental ground for a 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)

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

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 P401](#)

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-Pérez¹ report experiments confirming that this strange phenomenon can actually occur.

In 1982, 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 miraculously jump, or 'tunnel', across the gap without needing an applied electric voltage.

The size of the supercurrent flowing through this 'tunneled barrier' depends on whether the superconductors at either edge of the gap have the same or opposite phases. A property of the quantum-mechanical wavefunction that describes the behaviour of Cooper pairs. In a bulk superconductor, any phase changes in the wavefunction where 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 to be pinned to the circuit loop. 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

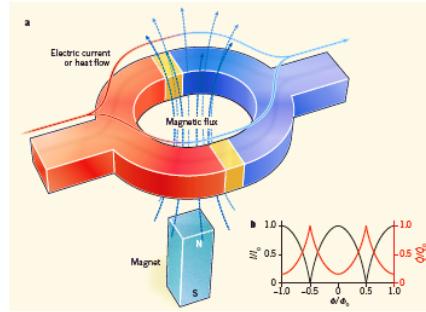


Figure 1 | A direct-current superconducting quantum interference device (d.c.-SQUID). a, In d.c.-SQUIDs, a superconducting loop contains two Josephson junctions — thin insulating barriers (yellow) sandwiched between the two superconductors (red and blue). b, The maximum electrical current (I , black, 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. $I = I_0 \sin(\Phi/\Phi_0)$, where $I_0 = 2.07 \times 10^{-9}$ amperes. Giazotto and Martínez-Pérez have observed an interference effect for heat flow (Q , red, right axis). 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.

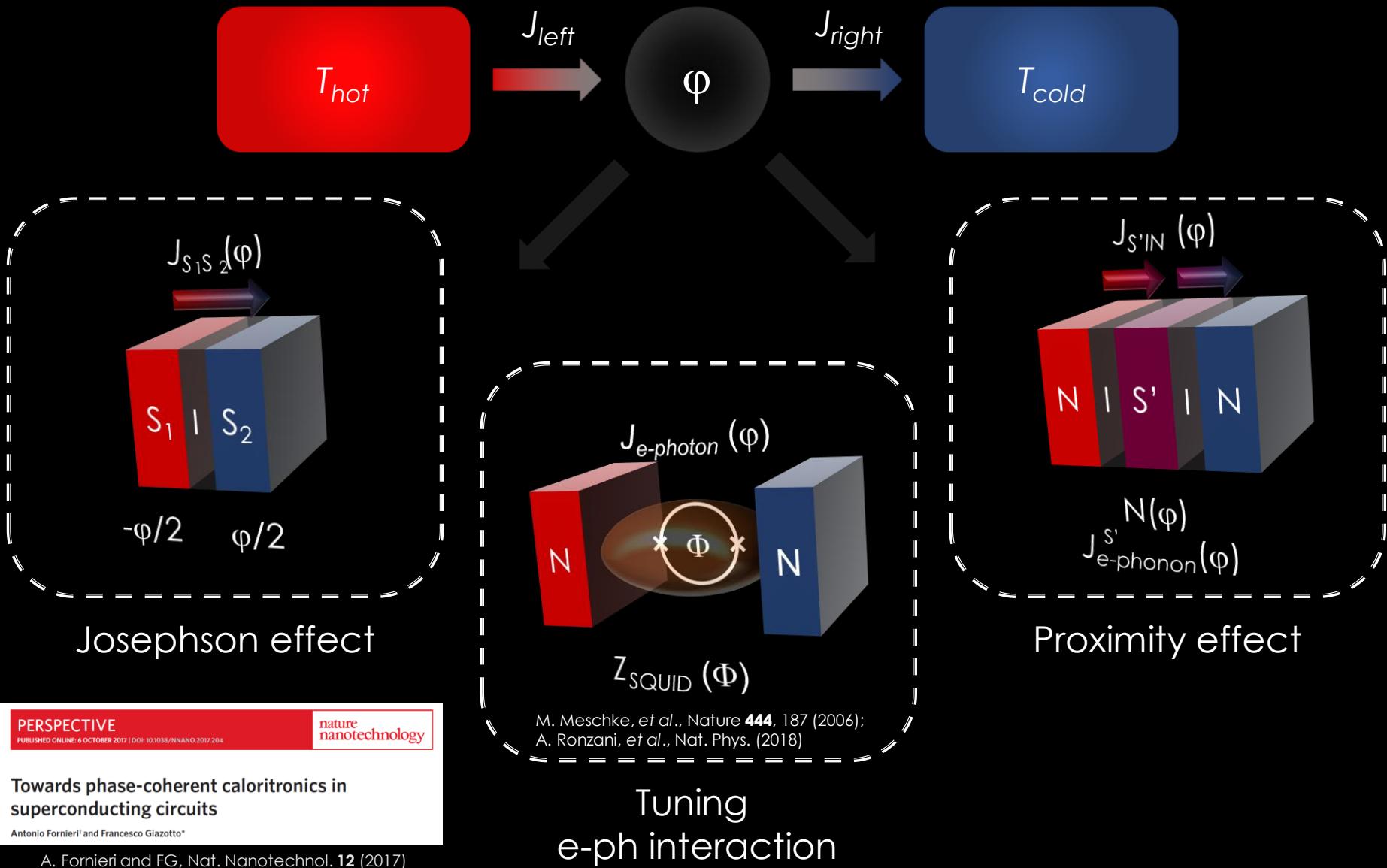
superconducting path with two Josephson junctions can sustain a maximum supercurrent, the amplitude of which can be modulated by the amount of magnetic flux piercing the loop (Fig. 1). Such d.c.-SQUIDs are among the most sensitive detectors of magnetic flux ever created and have found many practical 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 (one-electrons from broken Cooper pairs) of opposite charge through the 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

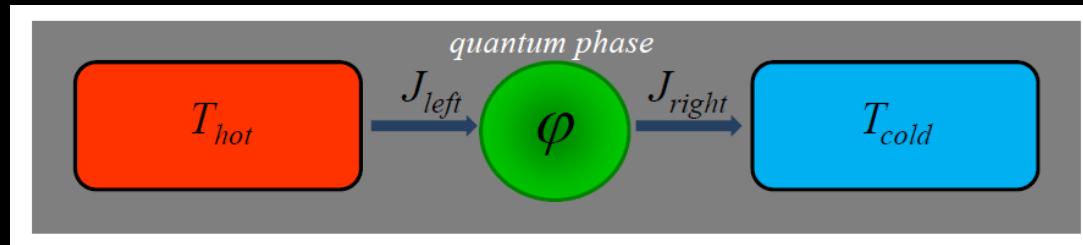
process in which the tunnelling occurred in conjunction with processes for breaking and recombining Cooper pairs. Because Cooper pairs are involved, this current should exhibit interference effects analogous to those seen in d.c.-SQUIDs (in which differences in the wavefunction's accumulated phase along the two paths of a loop create constructive or destructive interference). But electrical experiments that clearly quantify the behavior 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

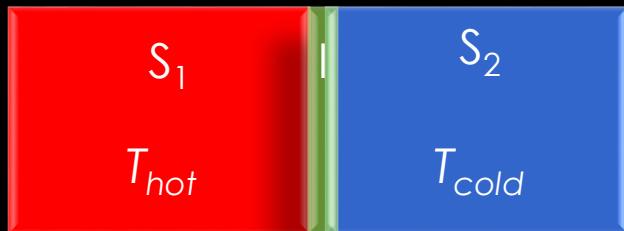
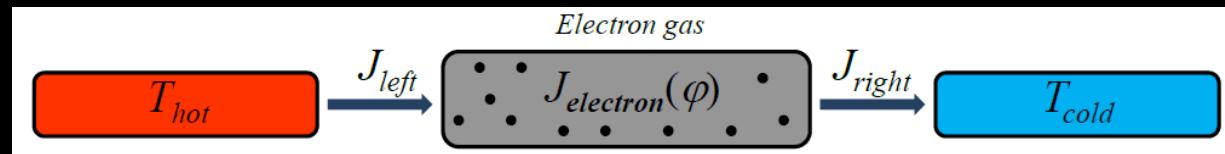
Physical basis of coherent caloritronics



Principle of phase-dependent heat current control



Exploitation of superconducting phase to control heat current flow



Temperature-biased Josephson tunnel junction

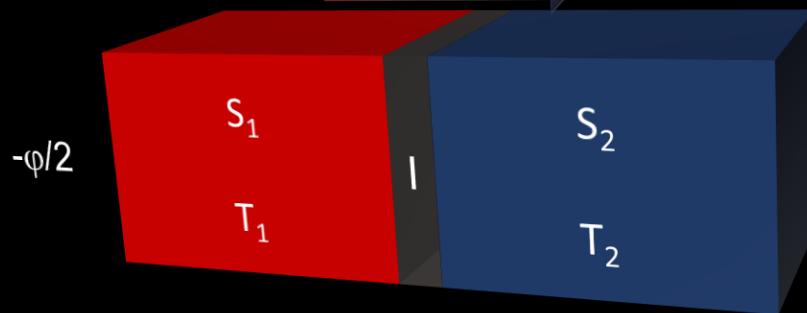


Heat current is predicted to be phase dependent and stationary

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

$$\dot{Q}_{tot}$$



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

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

$$\dot{Q}_{qp}(T_1, T_2) = \frac{2}{e^2 R_T} \int_0^\infty E \mathfrak{N}_1(E, T_1) \mathfrak{N}_2(E, T_2) [f_1(E, T_1) - f_2(E, T_2)] dE \quad \text{quasiparticle}$$

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

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

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

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

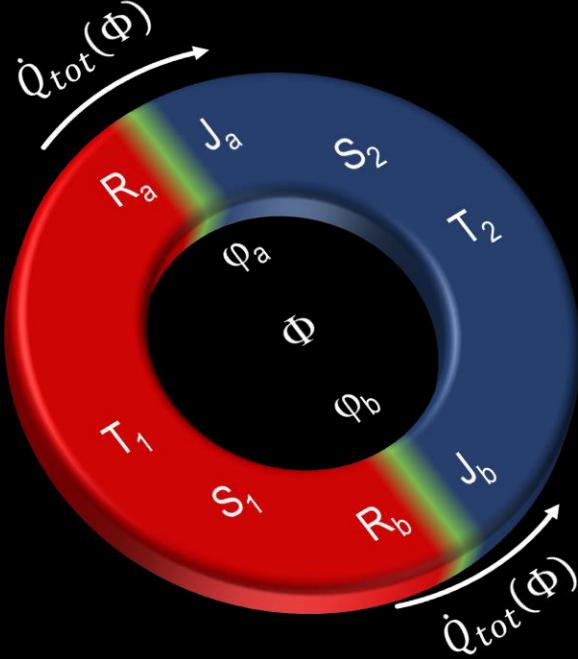
$$\boxed{\begin{array}{ll} \dot{Q}_{qp} = 0 & \text{if } T_1 = T_2 \\ \dot{Q}_{int} = 0 & \text{if } S_1 \text{ or } S_2 \text{ in} \\ \dot{Q}_{int} = 0 & \text{normal state} \end{array}}$$

Temperature-biased DC-SQUID: theory (i)

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

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

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



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

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

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

$$x = \Phi / \Phi_0$$

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

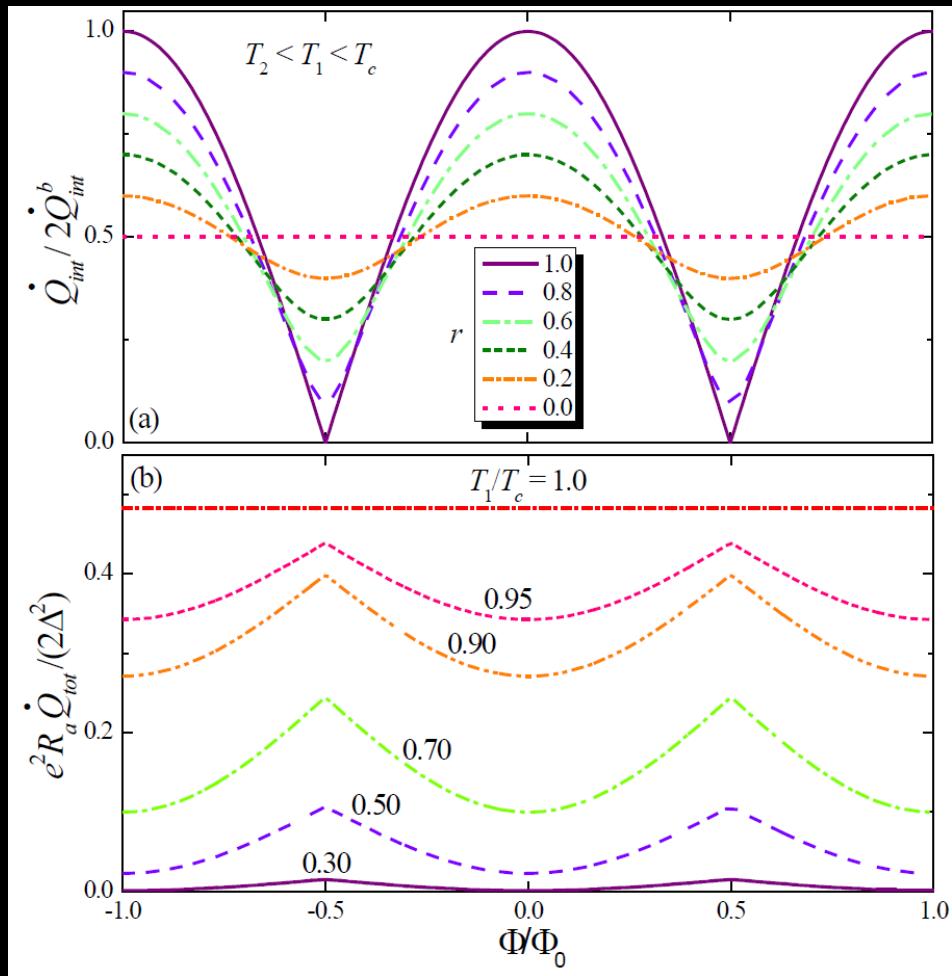
$$r = I_j^a / I_j^b$$

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

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)

$$T_2 = 0.1 T_c$$

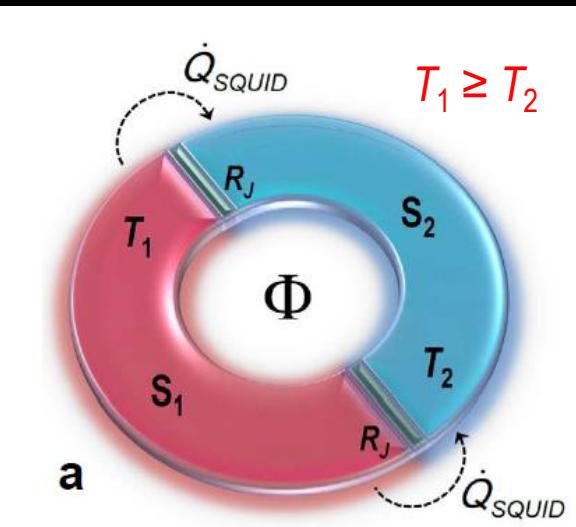
“Josephson heat interferometer”: setup (i)

LETTER

doi:10.1038/nature11702

The Josephson heat interferometer

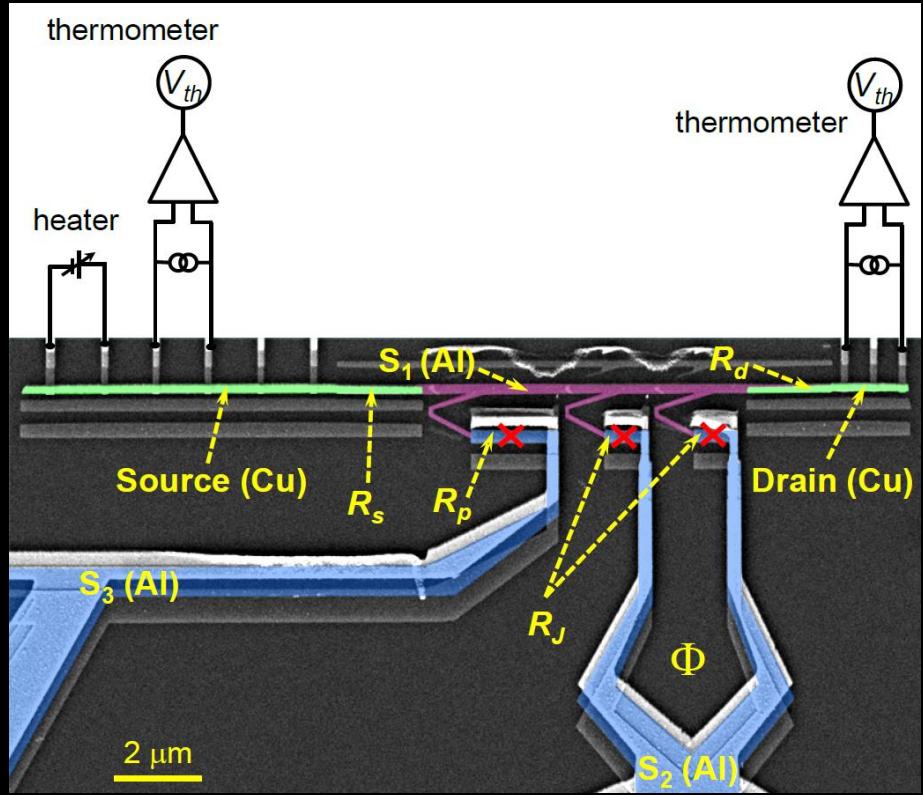
Francesco Gi�otto¹ & Mariano Jos Martinez-Perez¹



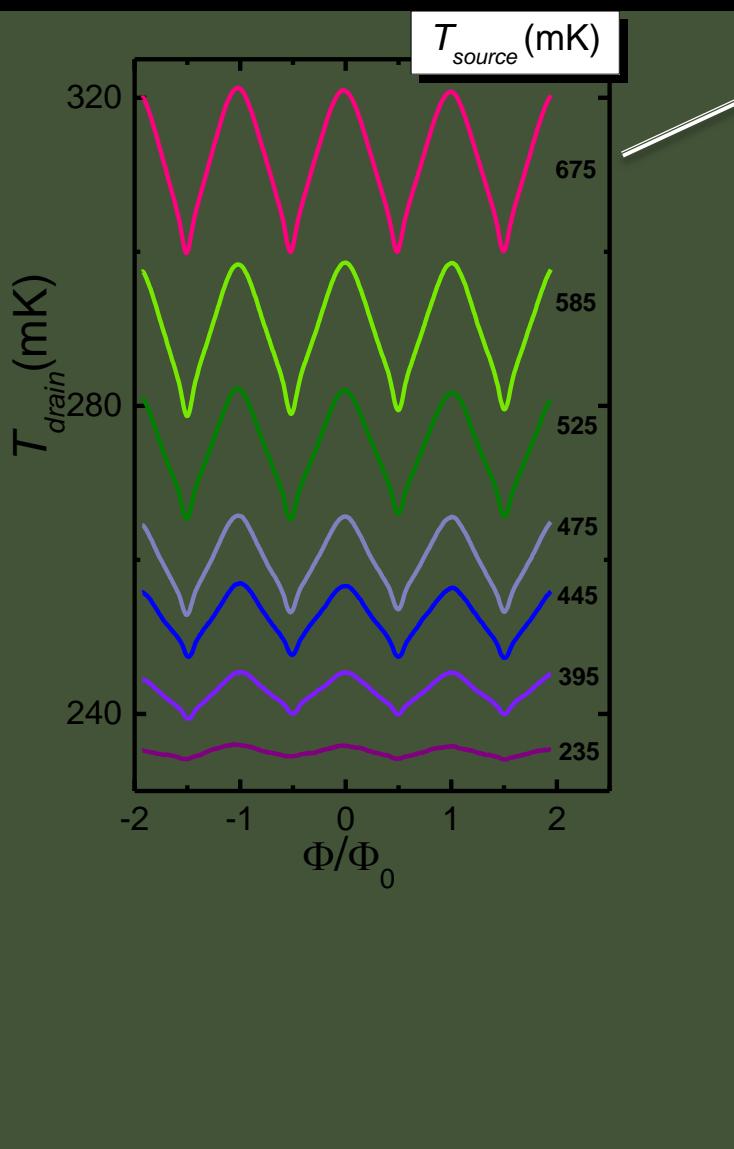
a

Symmetric SQUID ($r = 1$)

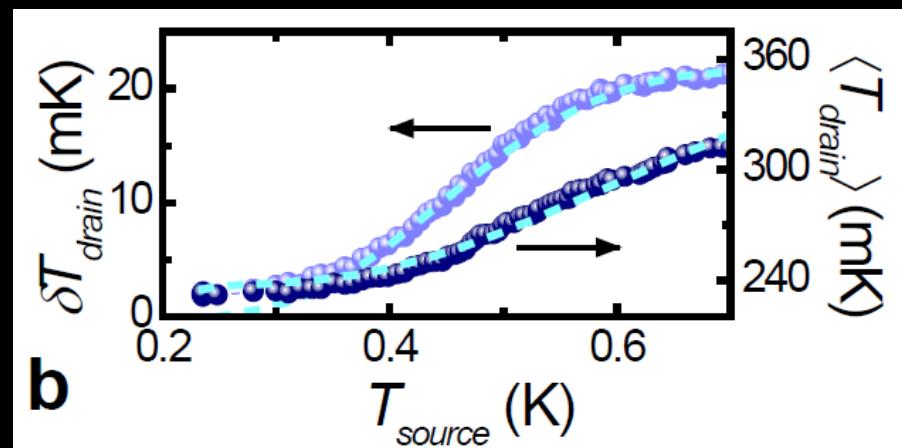
$$\dot{Q}_{\text{SQUID}}(\Phi) = 2\dot{Q}_{qp} - 2\dot{Q}_{int} \left| \cos \left(\frac{\pi\Phi}{\Phi_0} \right) \right|$$



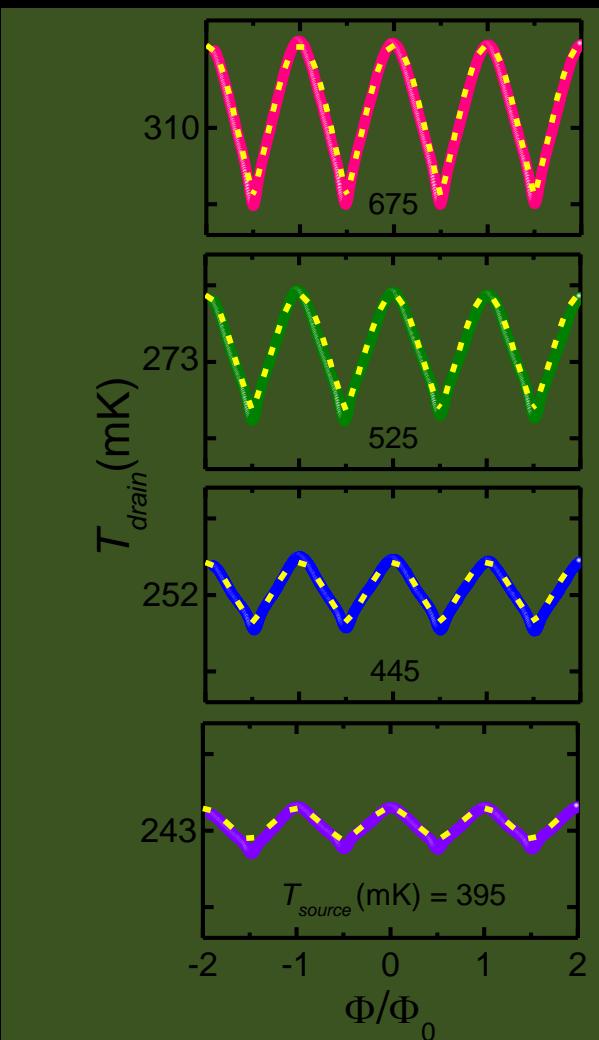
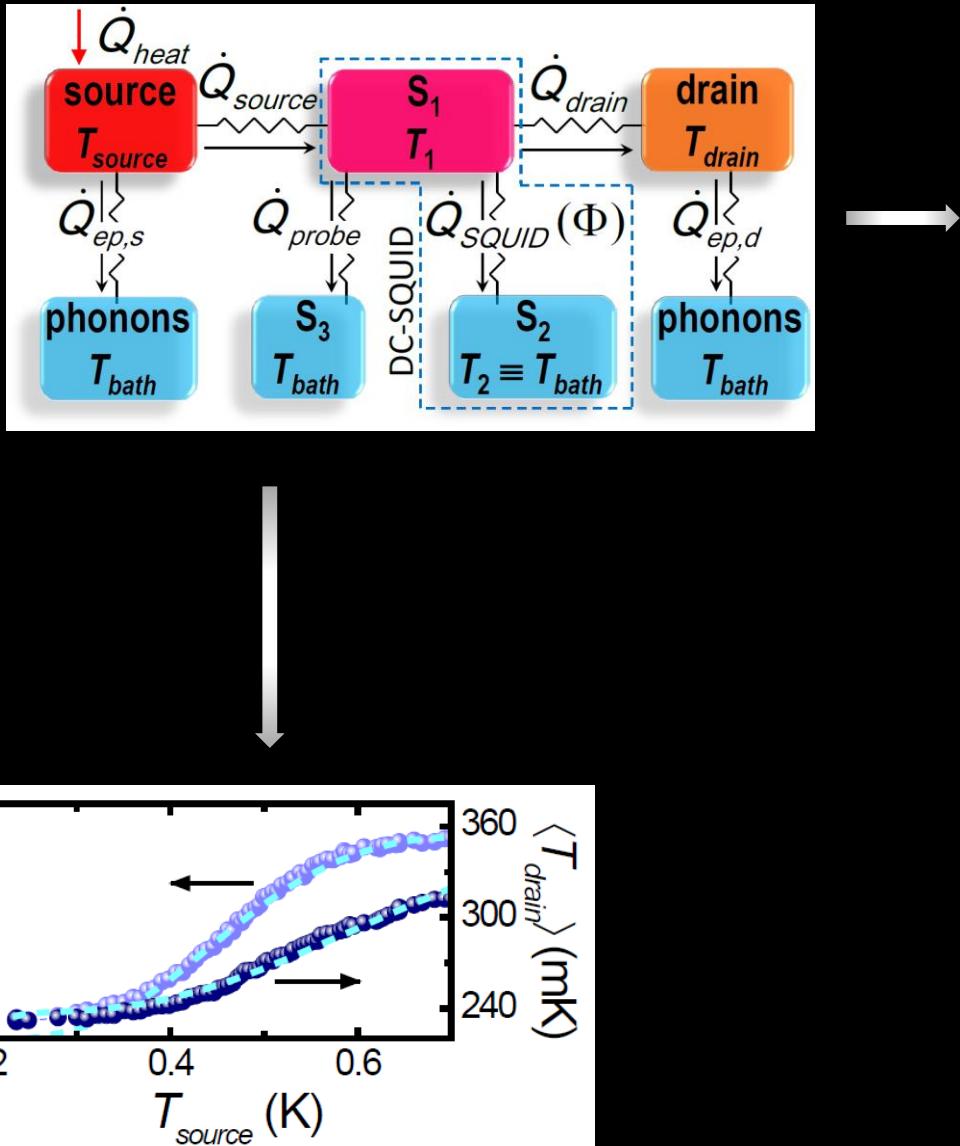
Behavior @ 235 mK (i)



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

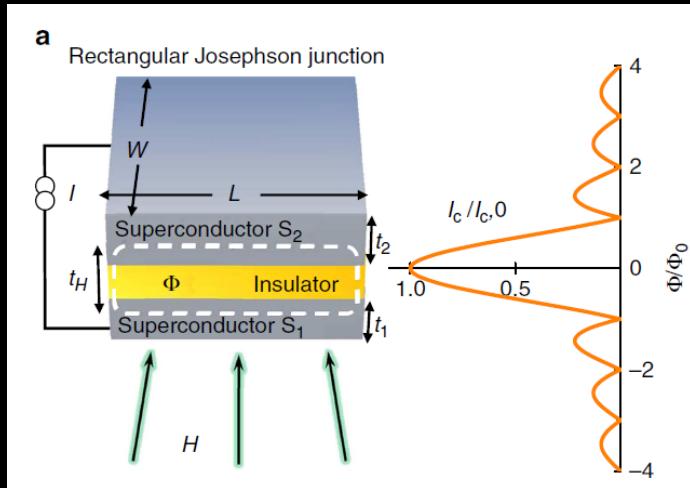


Comparison to theory

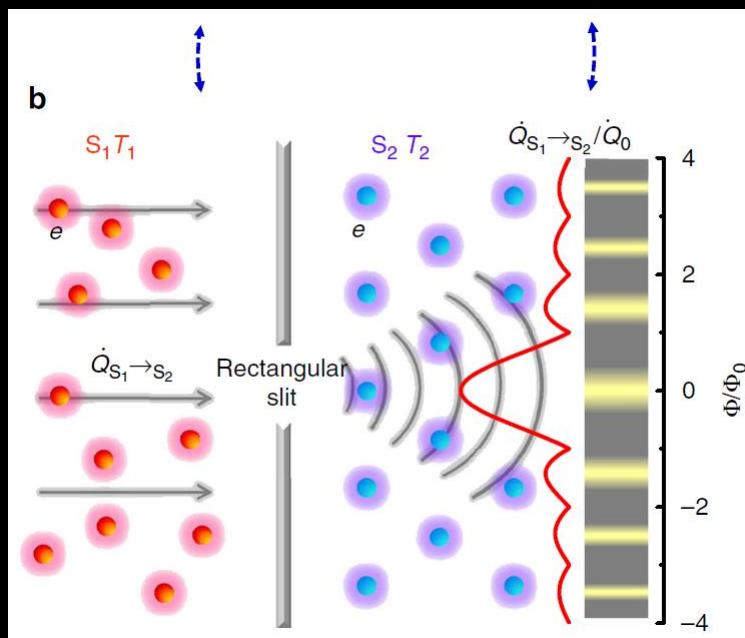


Good agreement with theoretical prediction

Electric vs thermal quantum diffraction

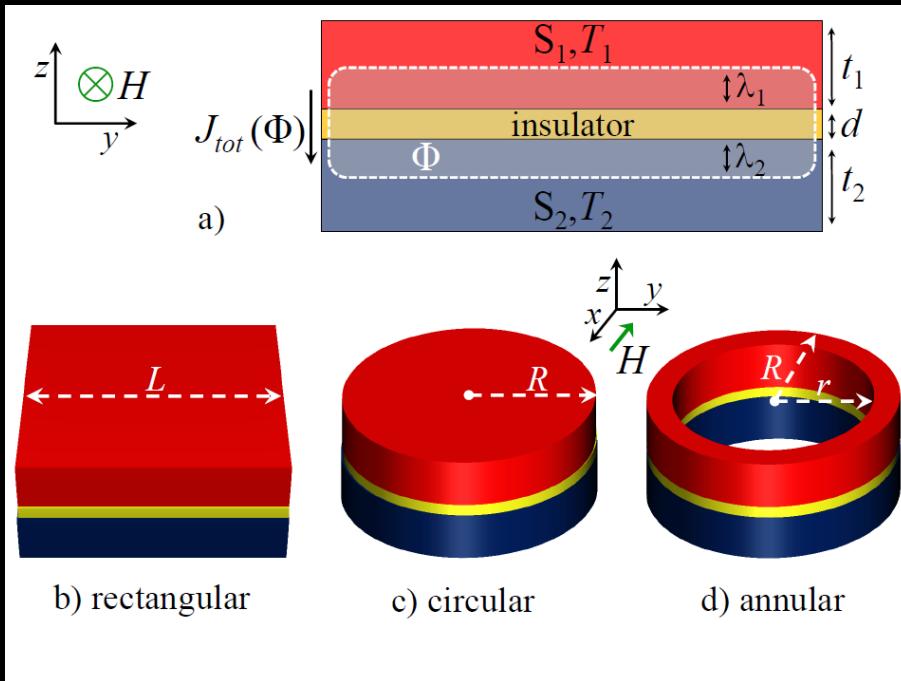


Electric diffraction through
a rectangular slit



Diffraction of heat current
through a rectangular slit

Heat current quantum diffraction in extended short JJs

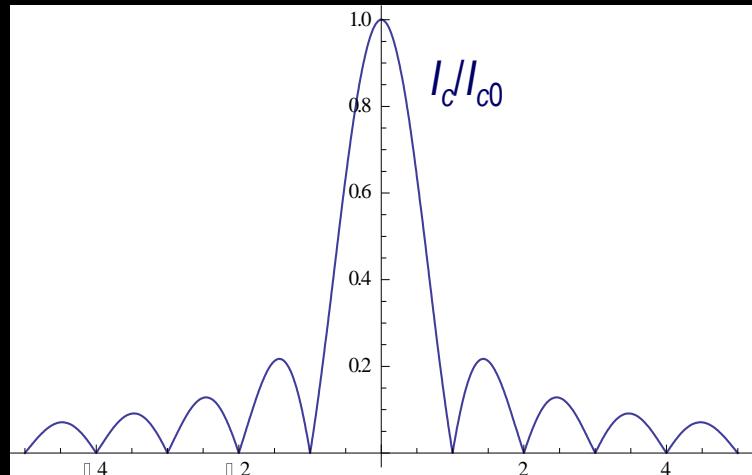


Critical current Fraunhofer pattern for a rectangular JJ

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



$$\Phi/\Phi_0$$



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

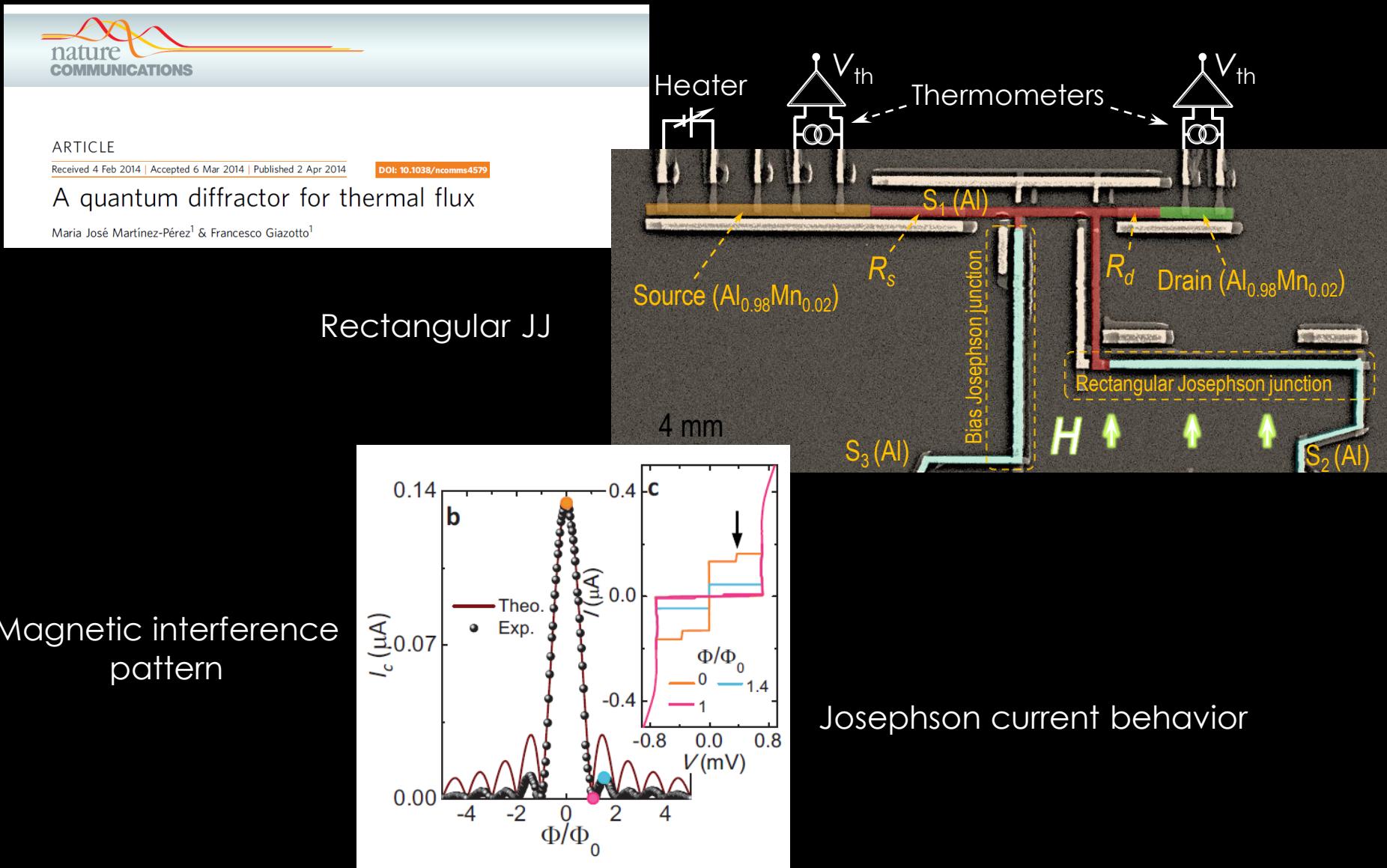
$$\tilde{t} = d + \lambda_1 \tanh \frac{t_1}{2\lambda_1} + \lambda_2 \tanh \frac{t_2}{2\lambda_2}$$

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

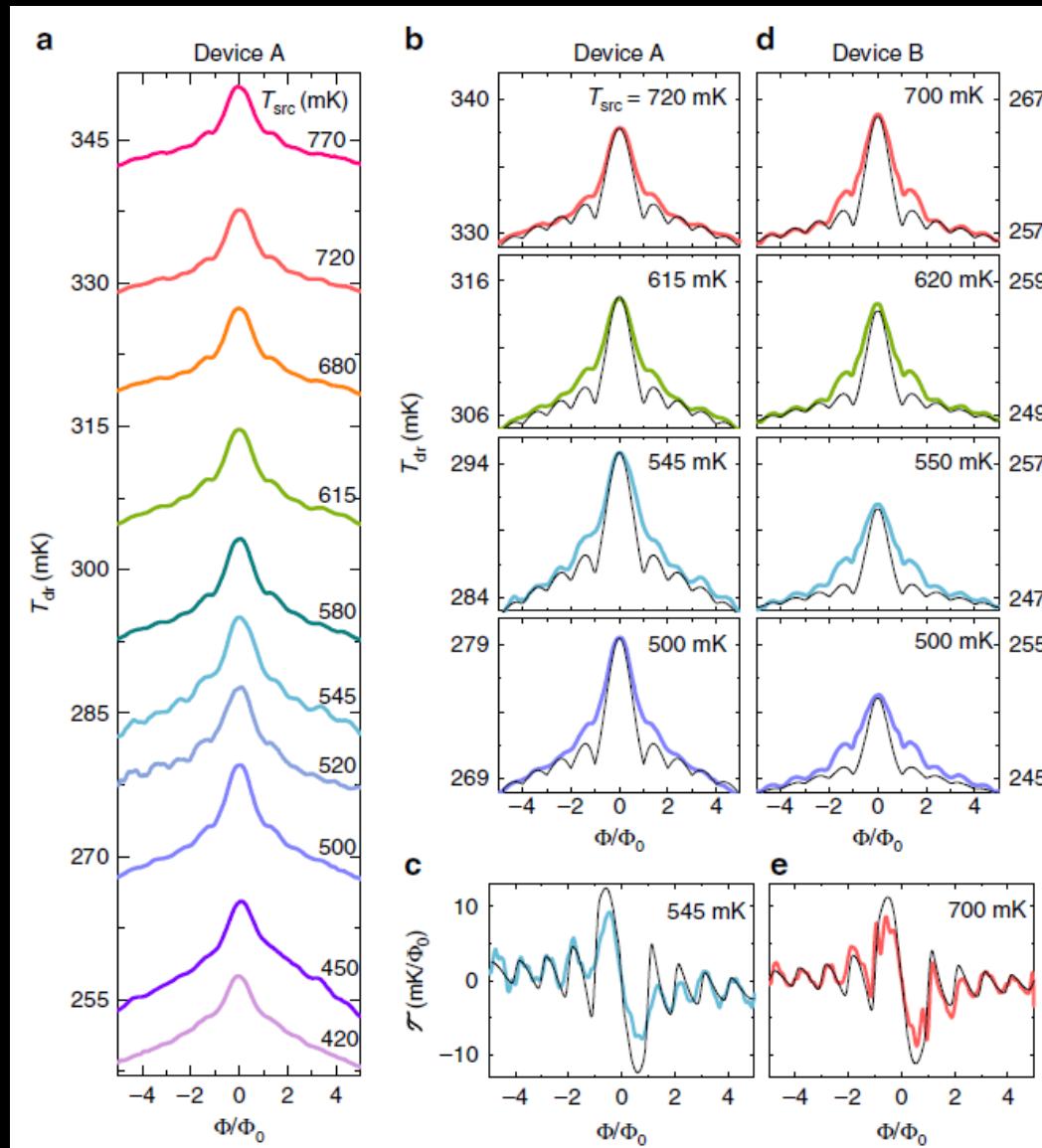
Josephson critical current

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

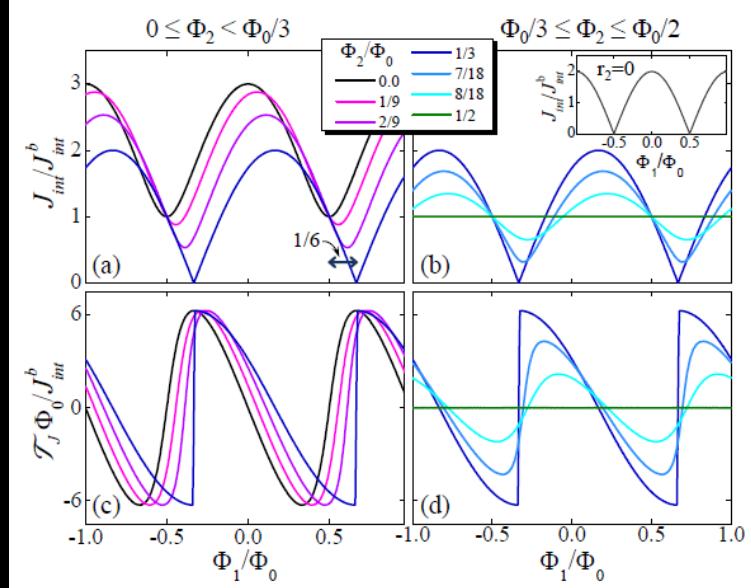
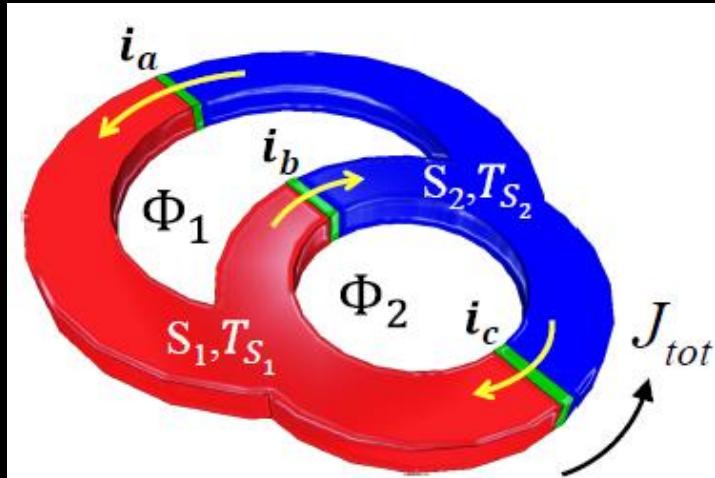
A “quantum diffractor” for thermal flux: experimental setup



Temperature diffraction pattern @ 240 mK

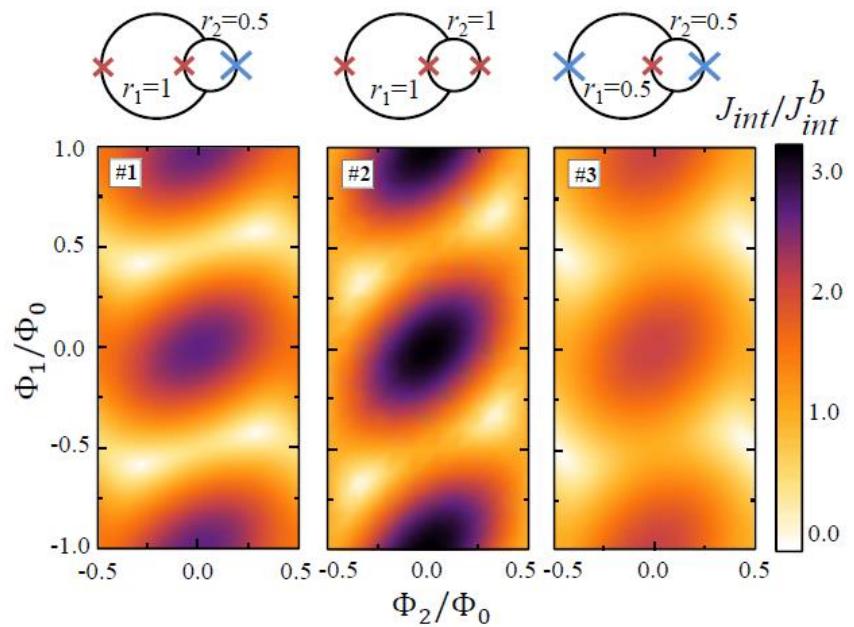


Fully-balanced heat interferometer



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

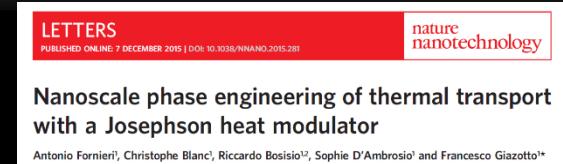
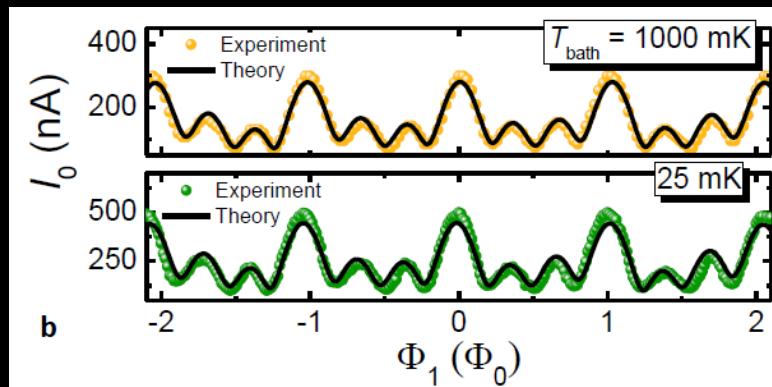
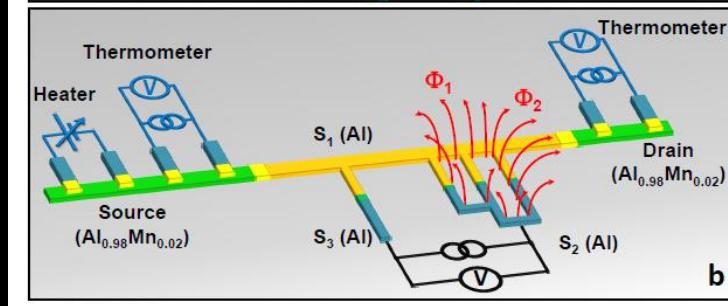
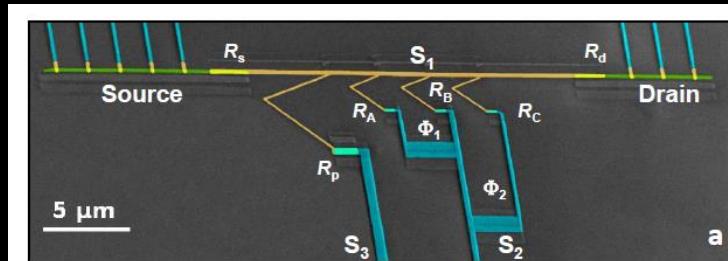
$$i_a - i_c \leq i_b \leq i_a + i_c$$



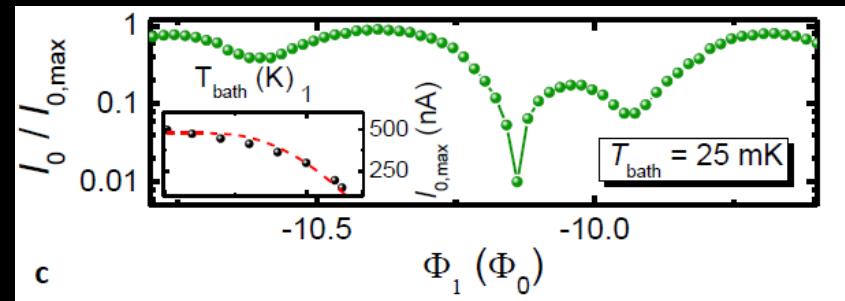
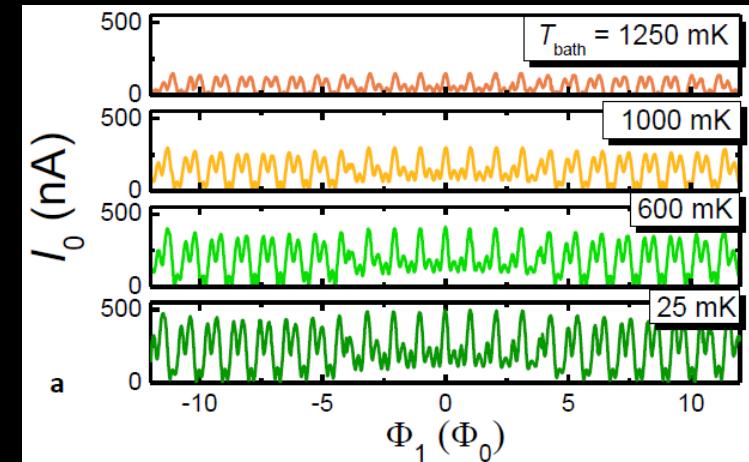
Quantum heat pumping & time-dependent heat engines

Nanoscale phase-engineering of thermal transport

i) Electrical response



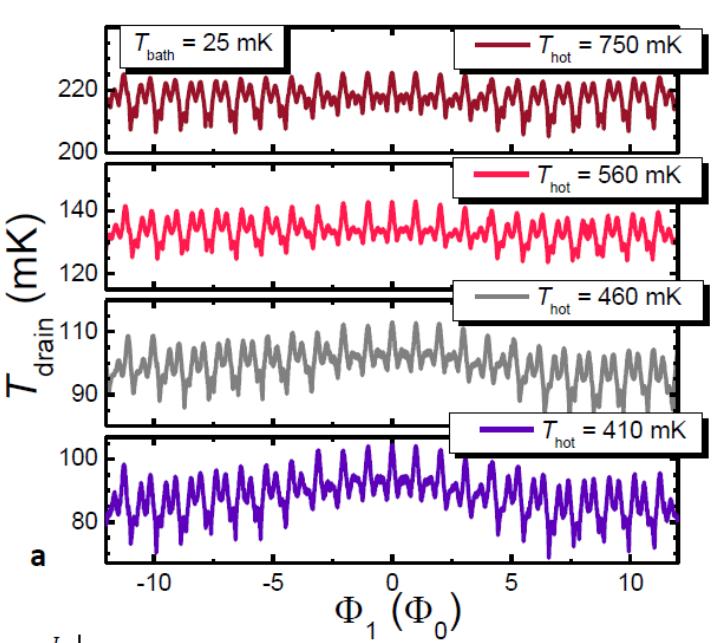
Fully-balanced quantum thermal modulator structure:
full phase-engineering of heat currents



I_C suppression $\sim 99\%$

Nanoscale phase-engineering of thermal transport

ii) Thermal response at base T_{bath}



~ 40mK temperature swing

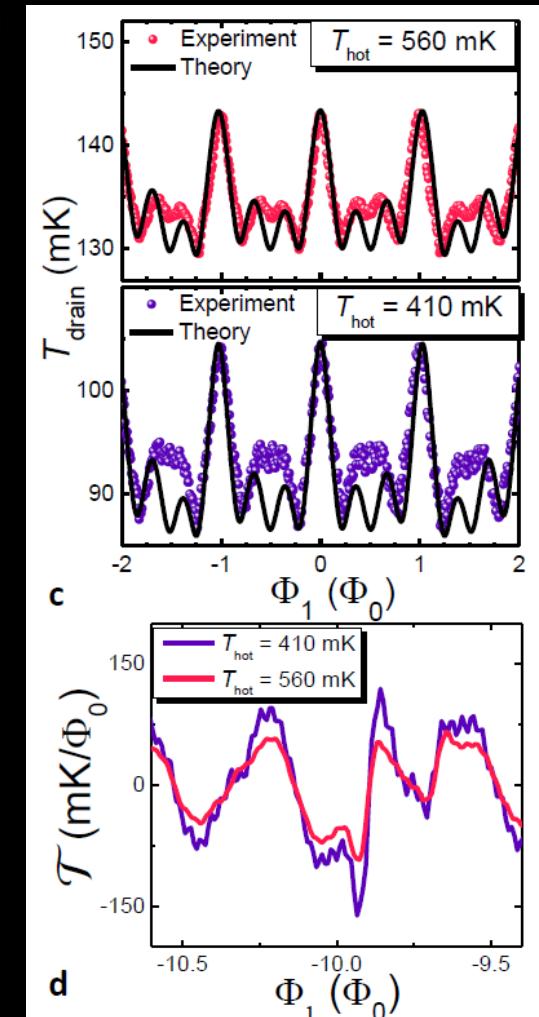
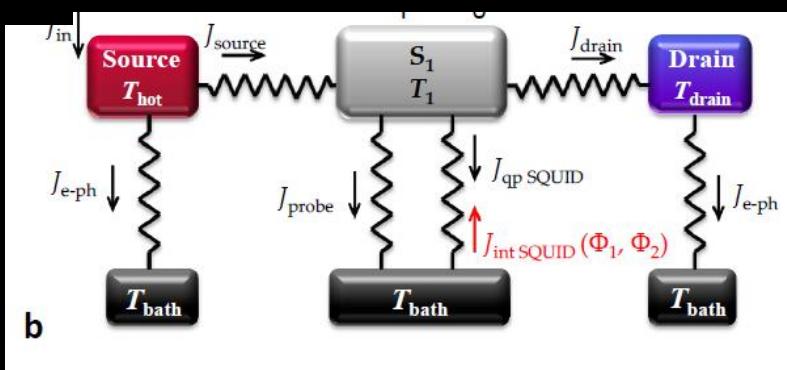
J_{int} suppression ~ 99%

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

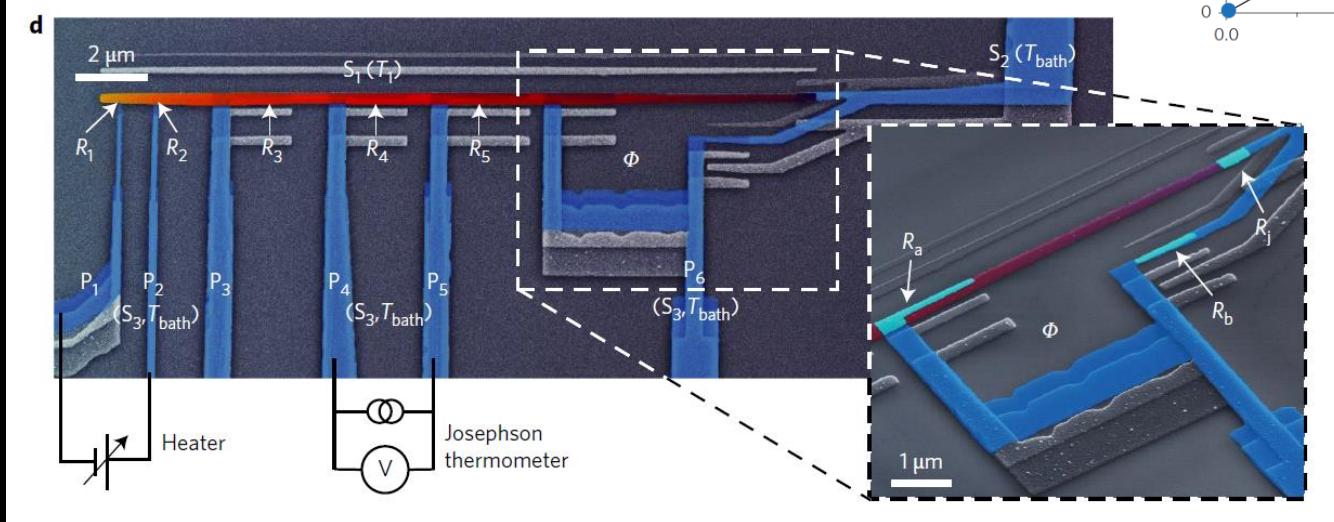
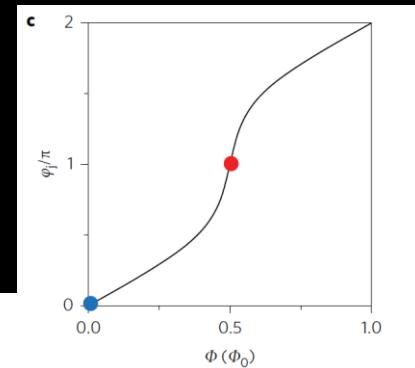
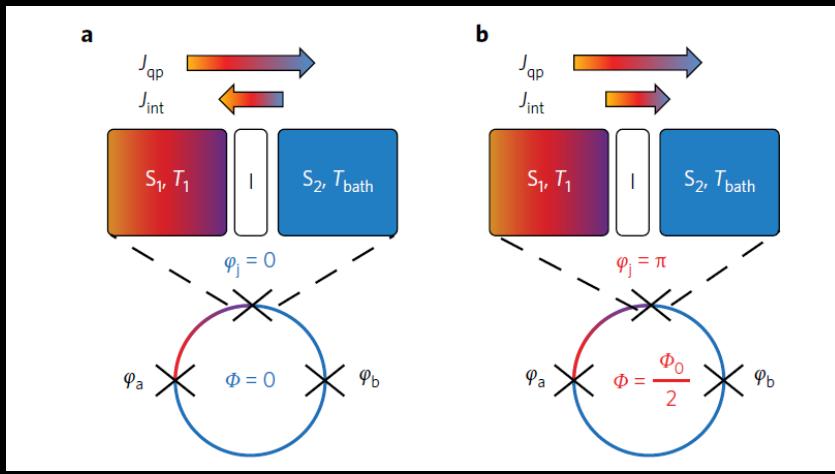


X 3 previous exps

Thermal model

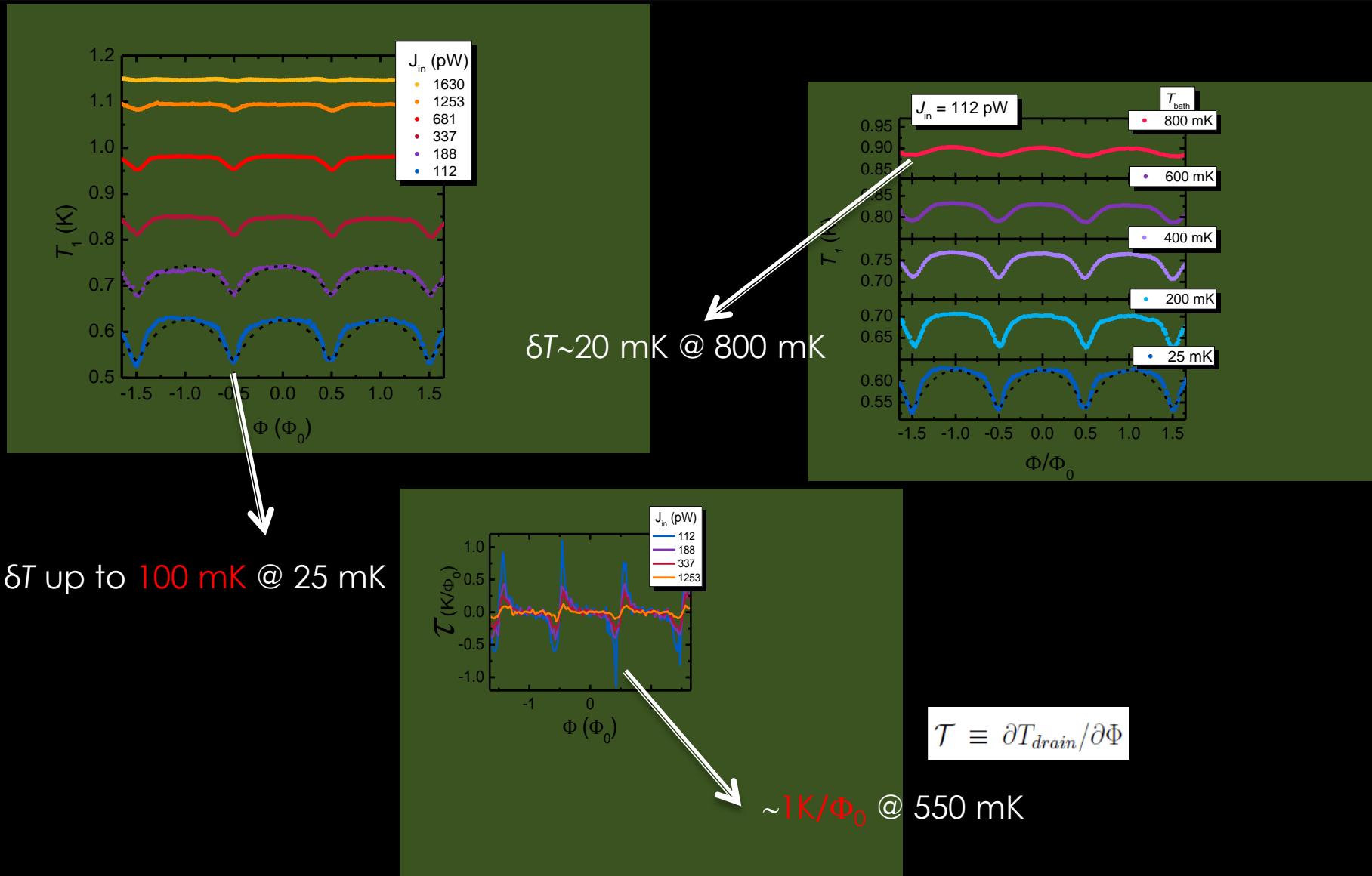


Phase-controllable 0- π thermal Josephson junction



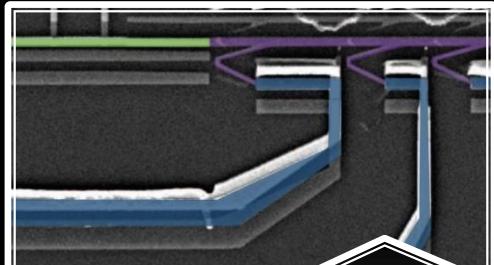
A. Fornieri, G. Timossi, P. Solinas, P. Virtanen, and FG, Nat. Nanotechnol. **12**, 425-429 (2017);
 A. Fornieri, G. Timossi, R. Bosisio, P. Solinas, and FG, Phys. Rev. B **93**, 134508 (2016)

0- π thermal Josephson junction: thermal behavior

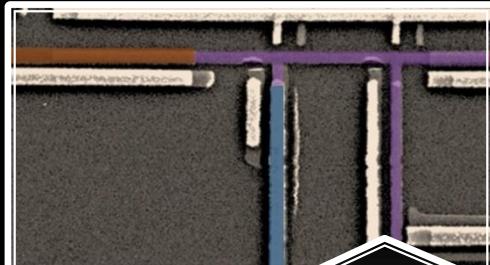


A. Fornieri, G. Timossi, P. Solinas, P. Virtanen, and FG, Nat. Nanotechnol. **12**, 425-429 (2017);
A. Fornieri, G. Timossi, R. Bosisio, P. Solinas, and FG, Phys. Rev. B **93**, 134508 (2016)

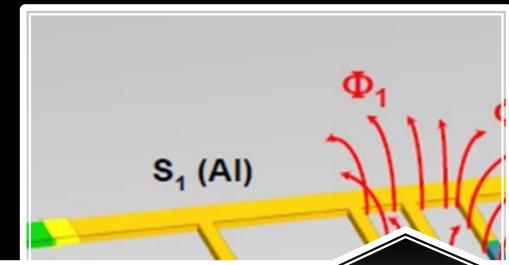
Single output caloritronic devices



The Josephson heat interferometer
Nature **492**, 401 (2012)



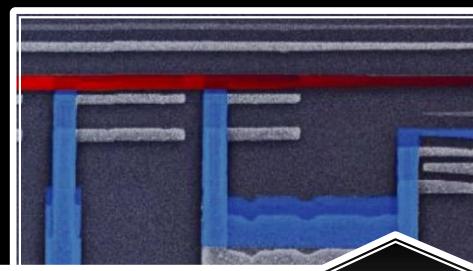
A quantum diffractor for thermal flux
Nat. Commun. **5**, 3579 (2014)



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)



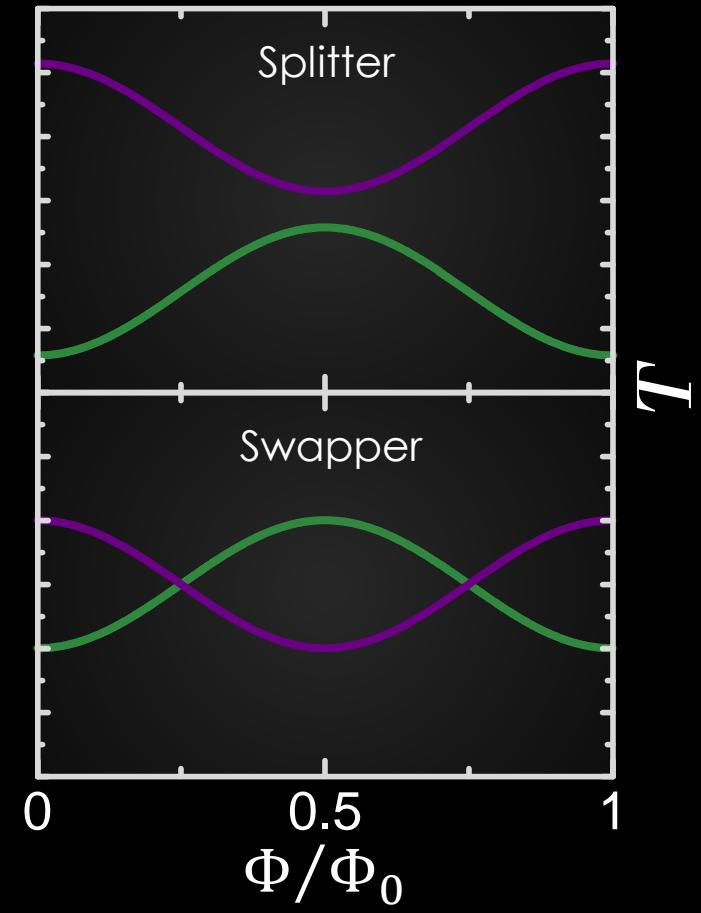
0- π phase-controllable thermal Josephson junction
Nat. Nanotech. **12**, 425 (2017)

Phase-tunable thermal router: General scheme

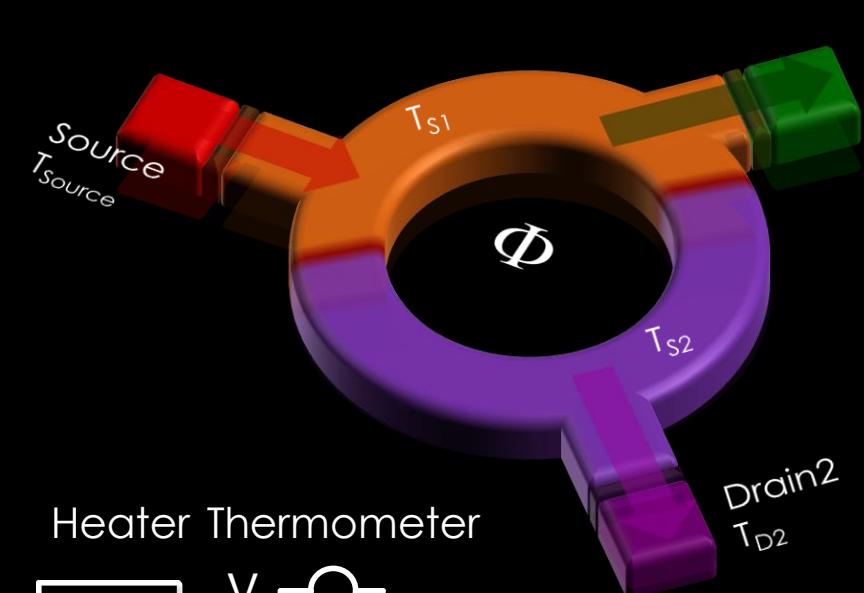
$$\Phi = n\Phi_0$$



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



Phase-tunable thermal router: Device structure



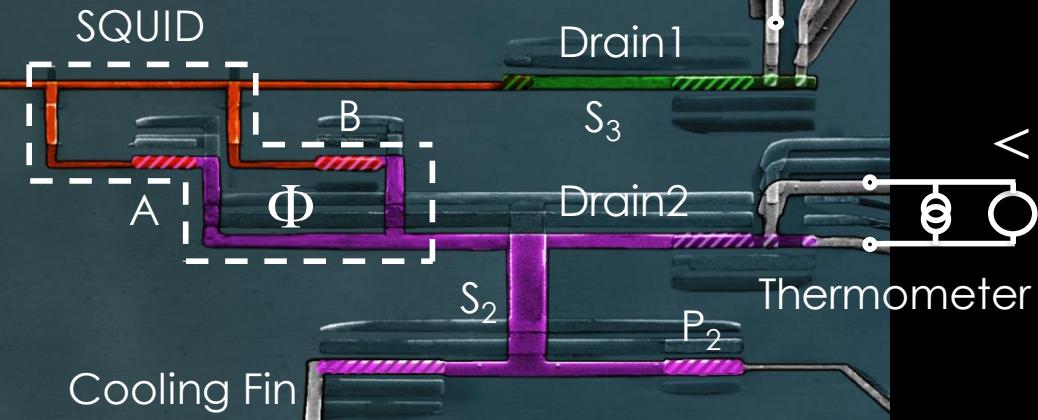
Heater Thermometer



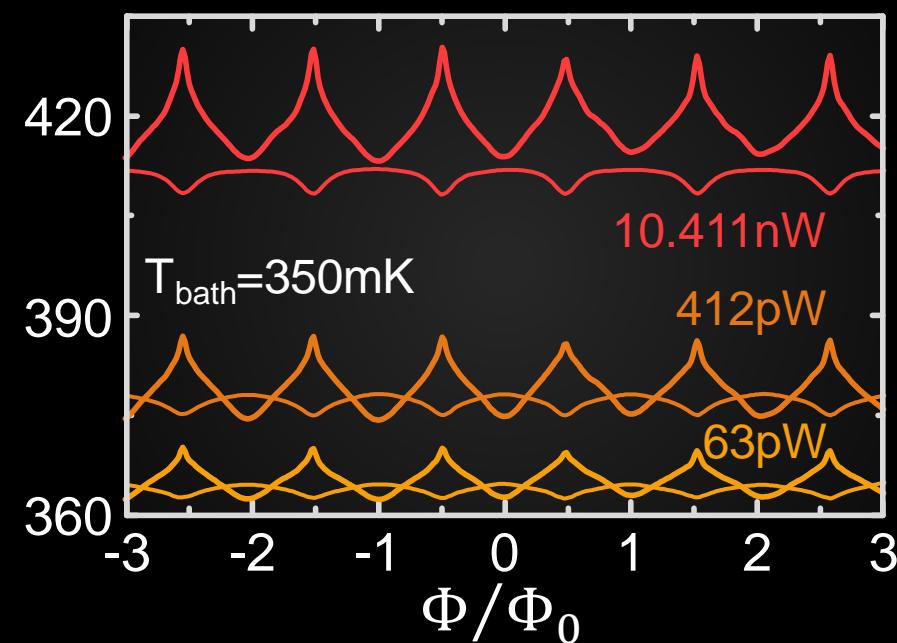
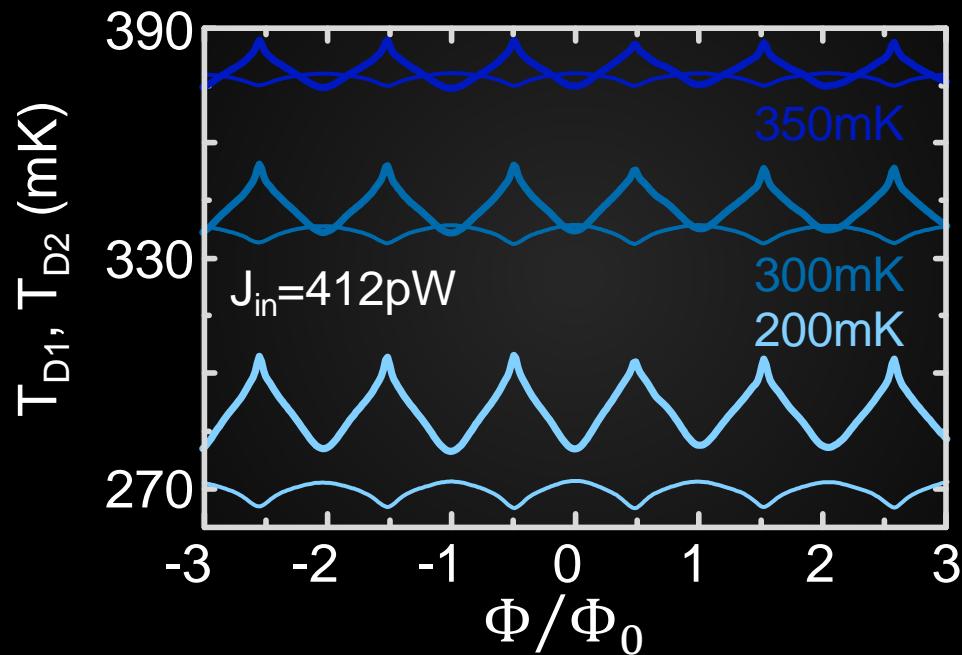
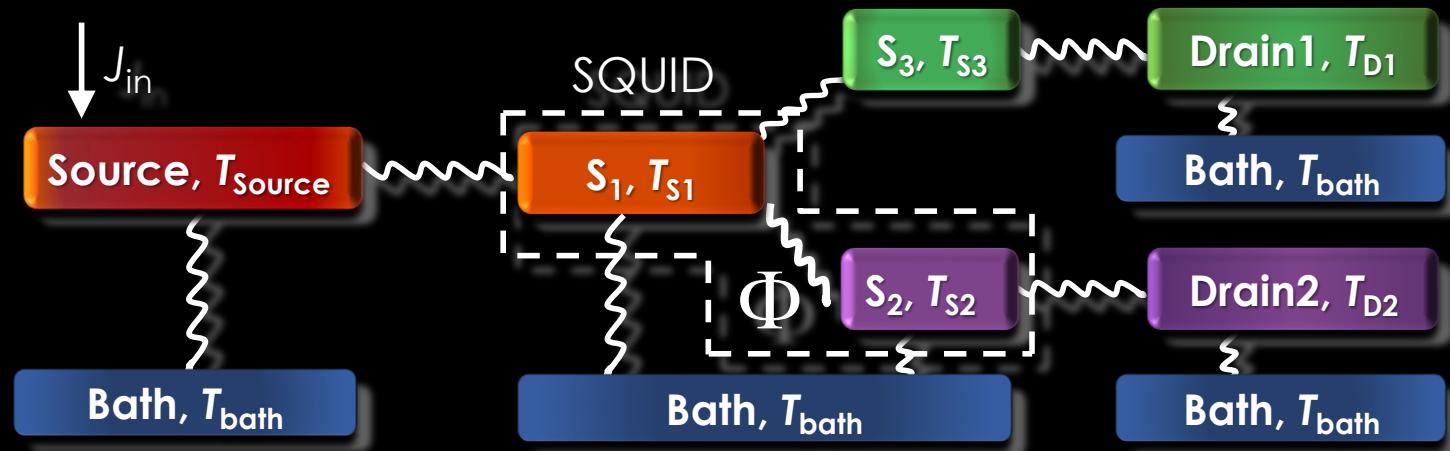
Source

S_1

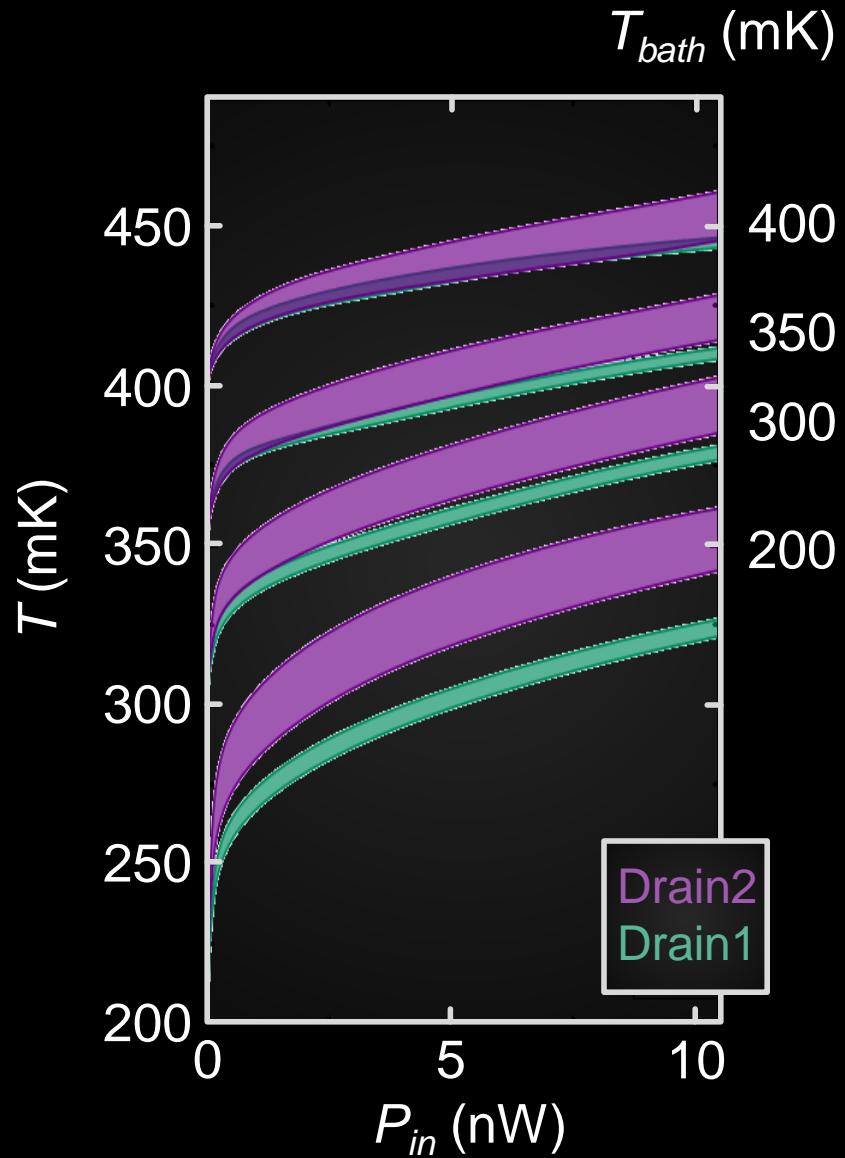
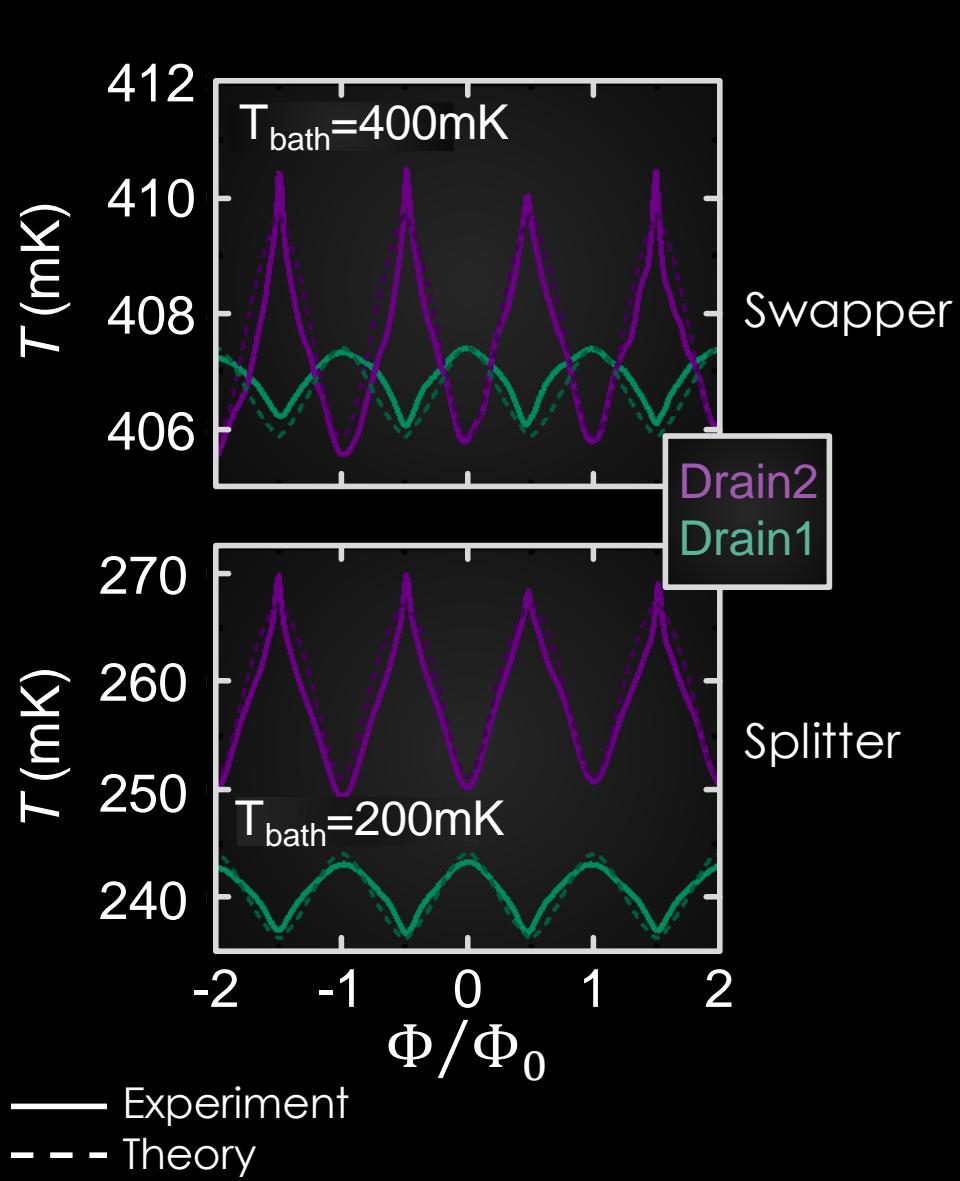
P_1



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: confirmation of the existence, magnitude and sign of the phase-dependent heat current
2. Realization of the first quantum diffractor for thermal flux, complementary proof of the “thermal” Josephson effect
3. Double-loop Josephson thermal modulator: complete phase-engineering of electronic heat current at the nanoscale
4. Realization of the first controllable $0-\pi$ thermal Josephson junction
5. 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
C. Altimiras
P. Virtanen
C. Puglia

MIUR-FIRB2013-Project Coca

FARFAS 2014-Project SCIADRO



ERC consolidator grant No. 615187 - COMANCHE

