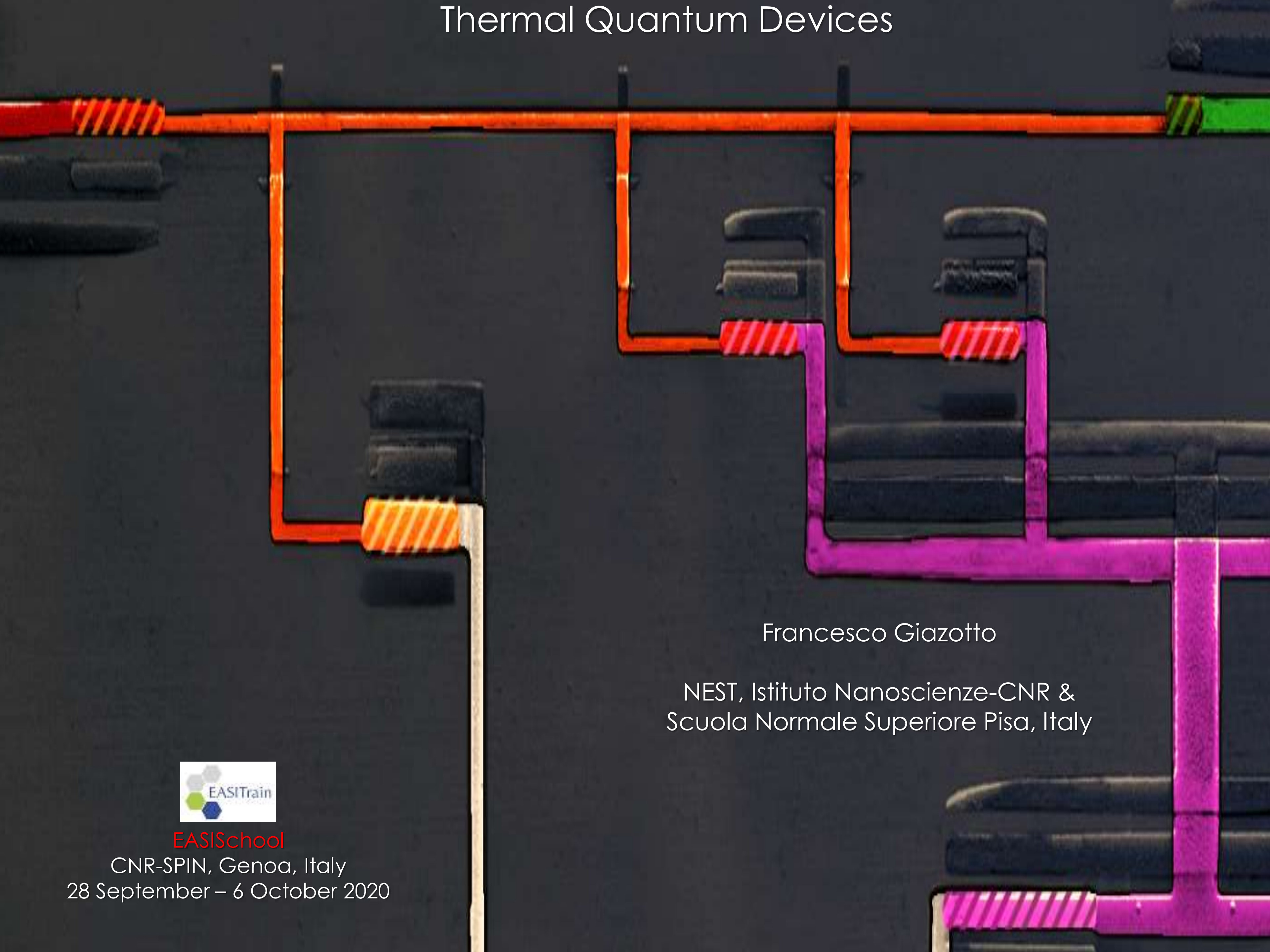

Thermal Quantum Devices

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EASITrain

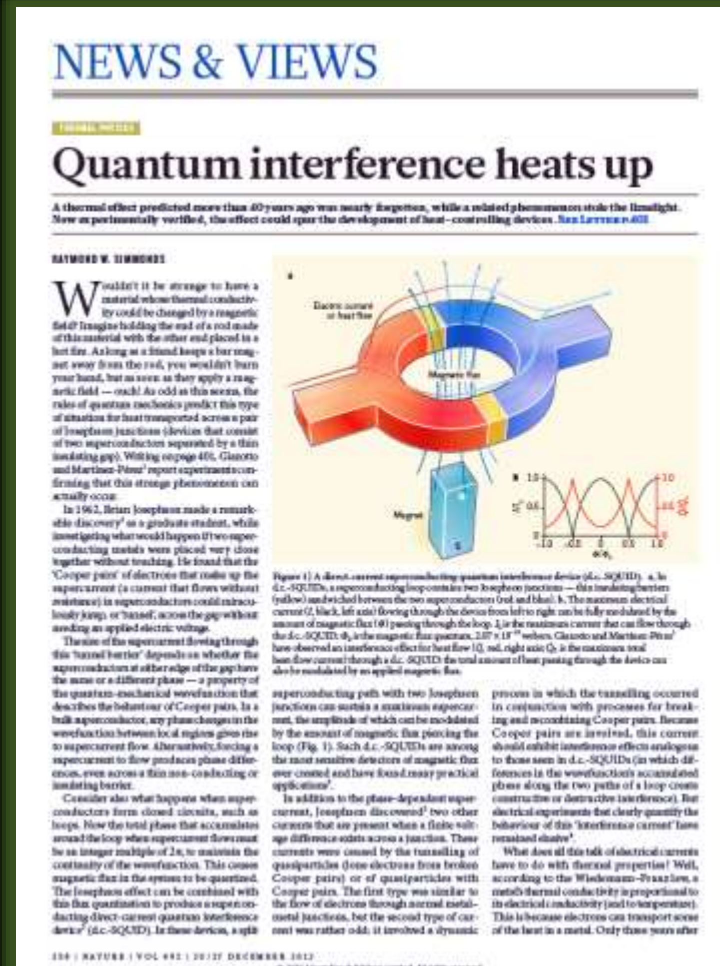
EASISchool
CNR-SPIN, Genoa, Italy
28 September – 6 October 2020

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

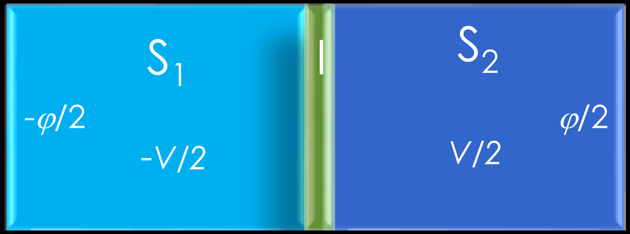
- Set the experimental ground for a challenging young branch of science: the *coherent caloritronics*, i.e., the complementary of coherent electronics
- *Phase*-manipulate & master heat transfer in a solid-state environment
- Provide original & novel approaches to realize *thermal devices* (heat transistors, 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

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

Electric Josephson effect: tunnel junction

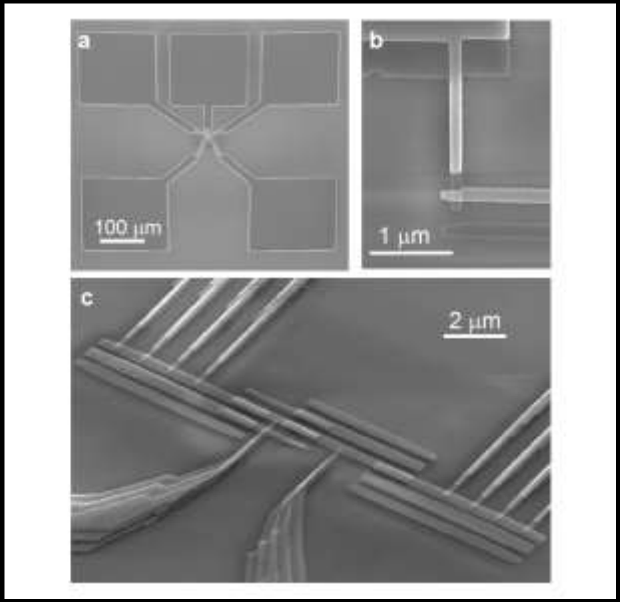


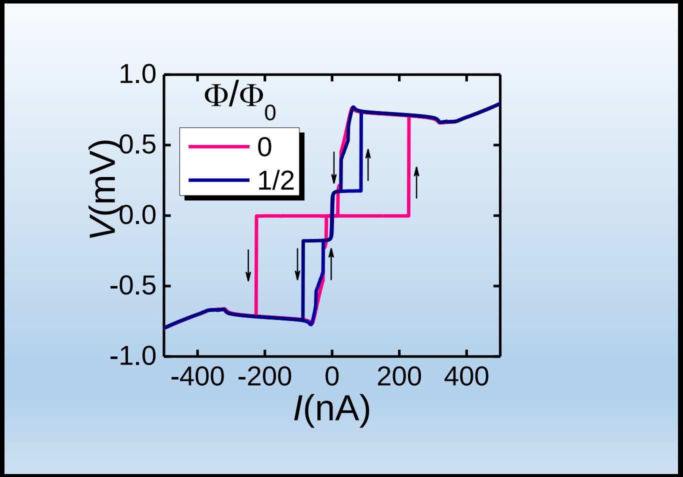
Josephson tunnel junction

$I_c = I_0 \sin\varphi$ where $I_0 = (\pi\Delta/2eR_T)\tanh(\Delta/2kT)$ — 1st Josephson equation

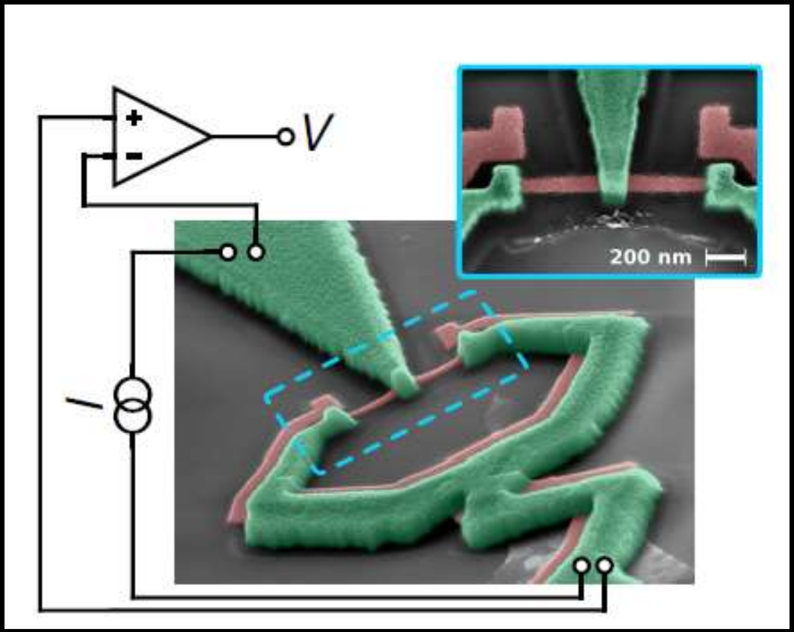
$V = (\Phi_0/2\pi)\, d\varphi/dt$ where $\Phi_0 = h/2e$ — 2nd Josephson equation

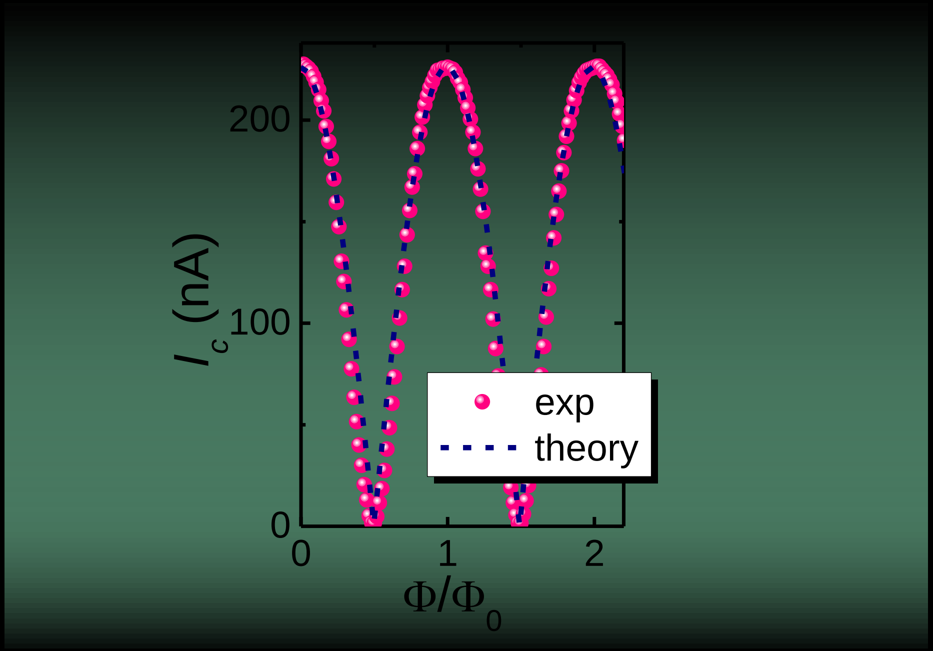
$\upsilon_J = V/\Phi_0$ Josephson frequency — $\upsilon_J \sim 484$ GHz/mV





Electric Josephson effect: SQUIDs



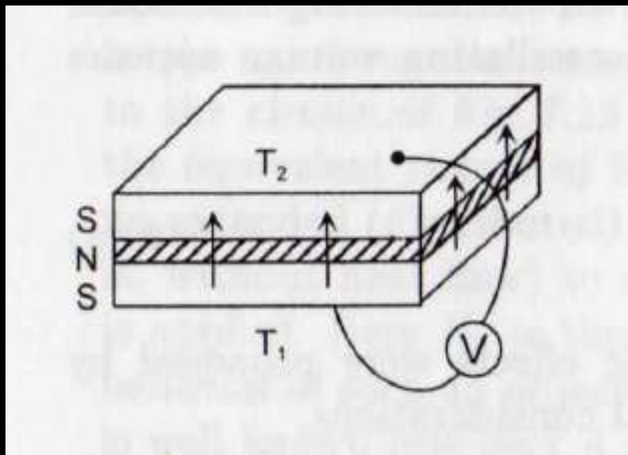


$$I_c = I_1 \sqrt{1 + r^2 + 2r \cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$

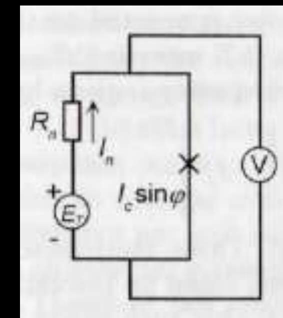
$$I_c = 2I_0 \left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|$$

Thermoelectric effects in Josephson junctions

dc & ac thermoelectric response



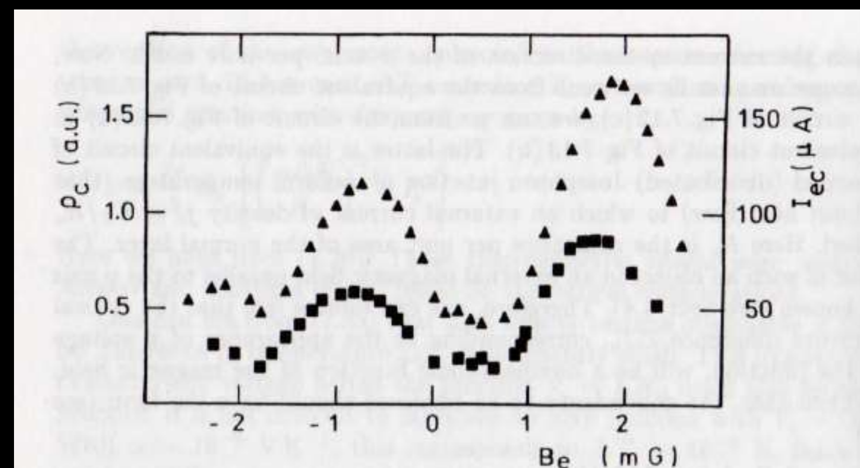
SNS-like Josephson junction



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

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

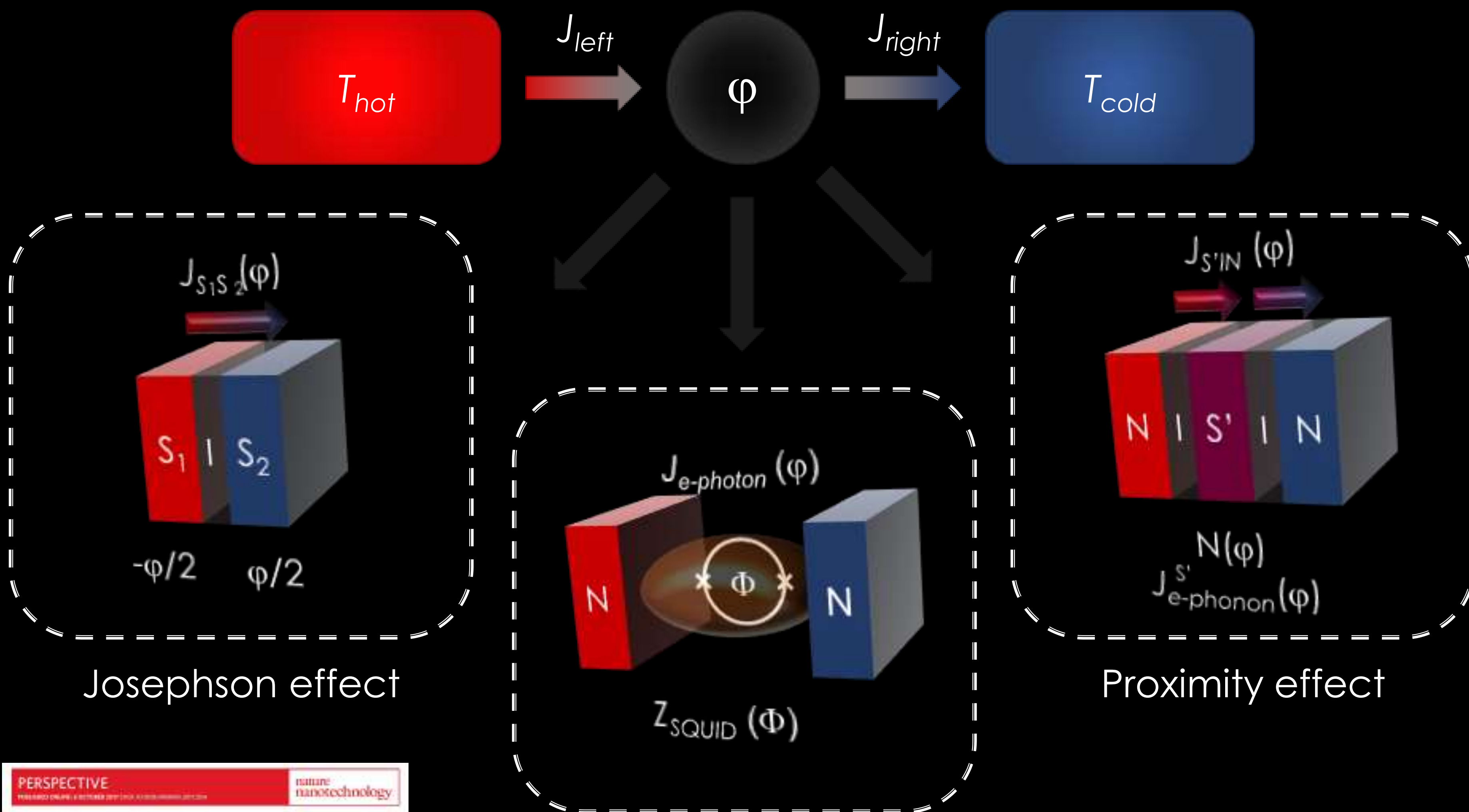
Presence of a magnetic field



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



PERSPECTIVE

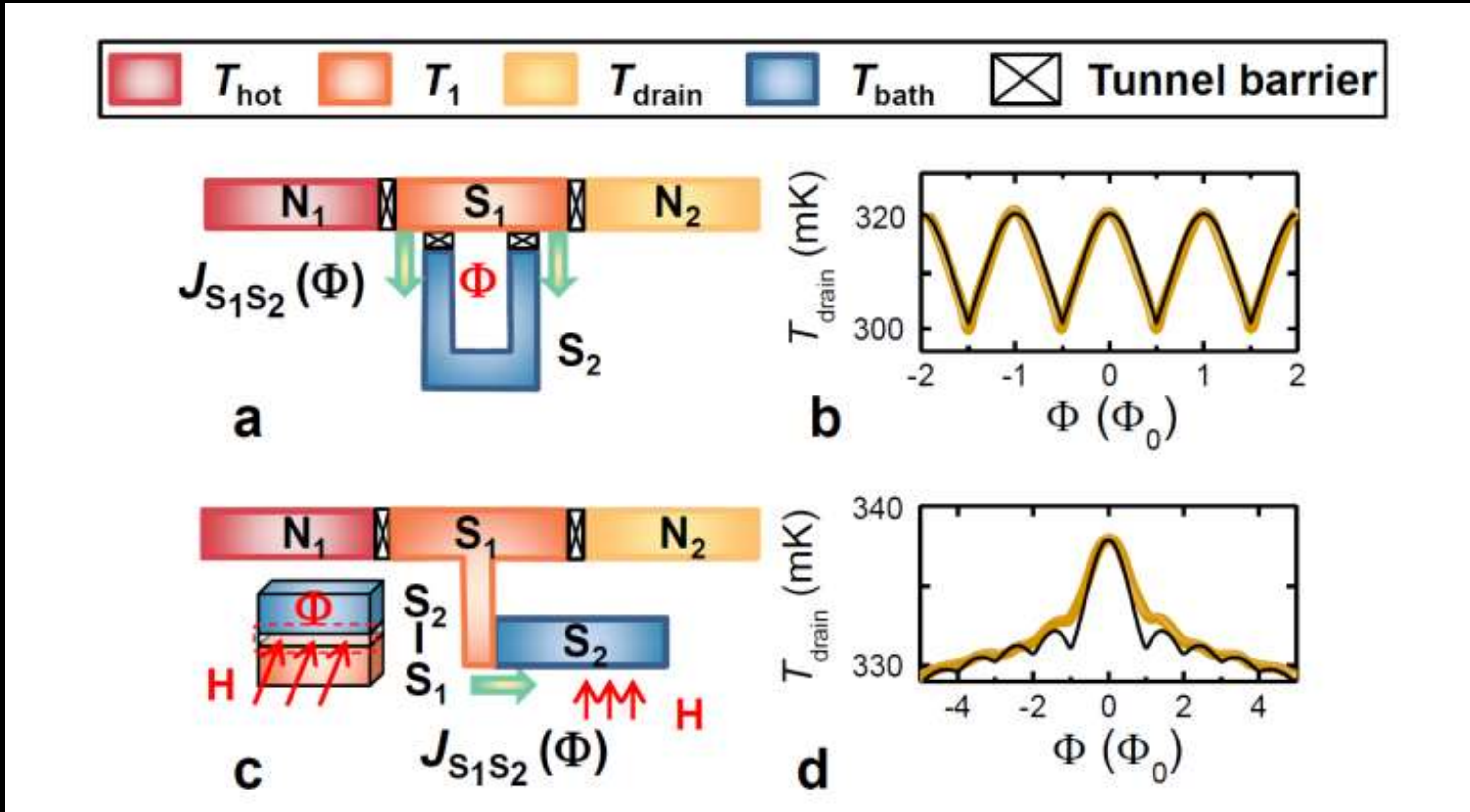
nature nanotechnology

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

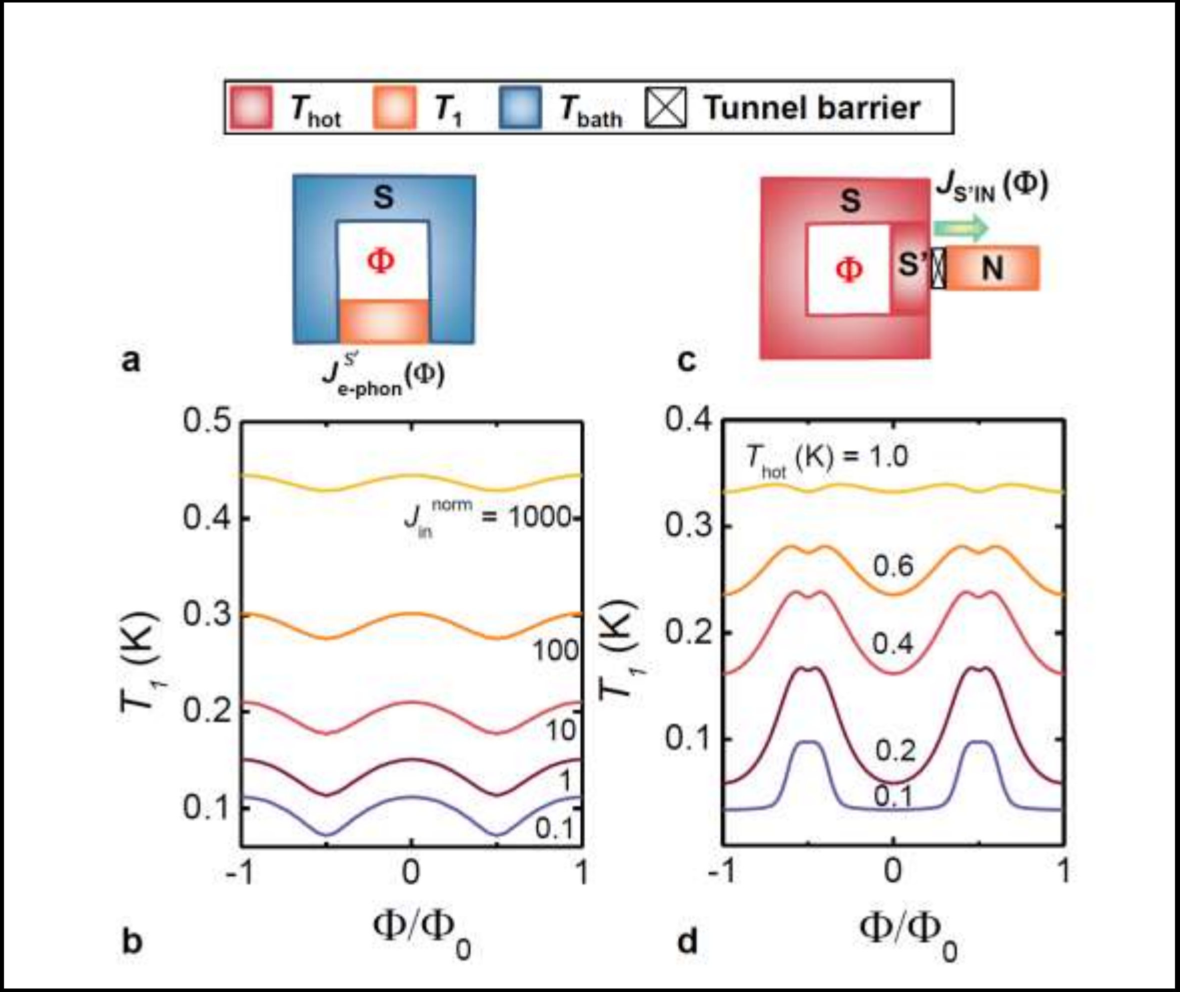
$$J_{\text{SQUID}}(T_1, T_{\text{bath}}, \Phi) = 2J_{\text{qp}}(T_1, T_{\text{bath}}) - 2J_{\text{int}}(T_1, T_{\text{bath}}) \left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|$$

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)

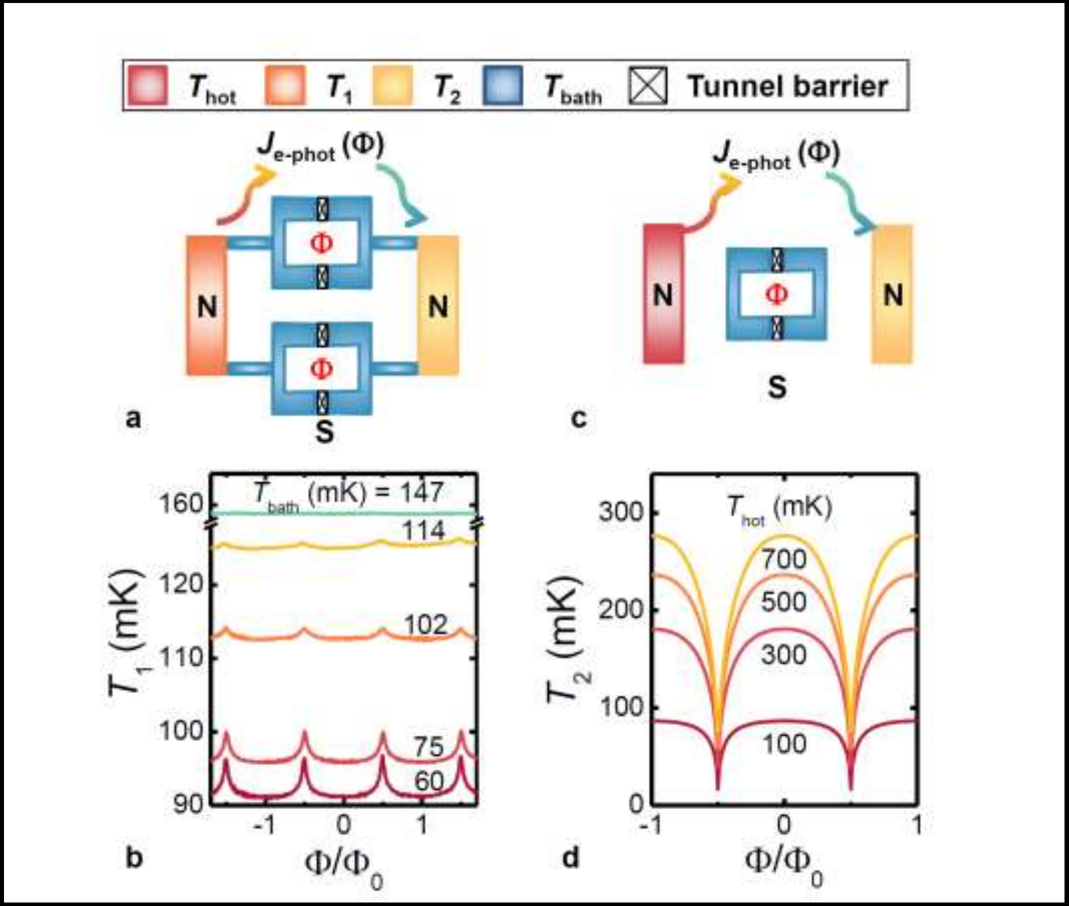
Superconducting proximity structures



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

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

Photonic heat transistors



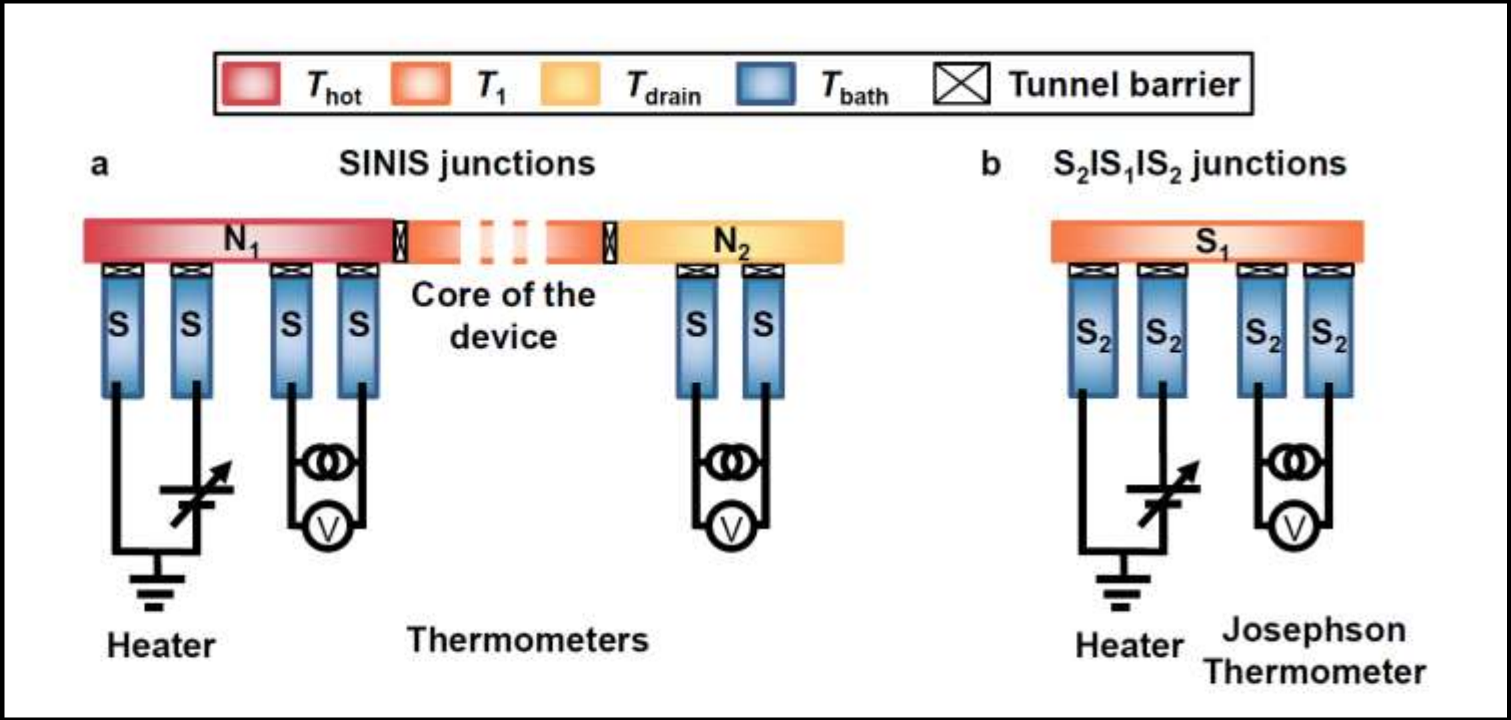
a – First demonstration of phase-dependent photonic heat conduction

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

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

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



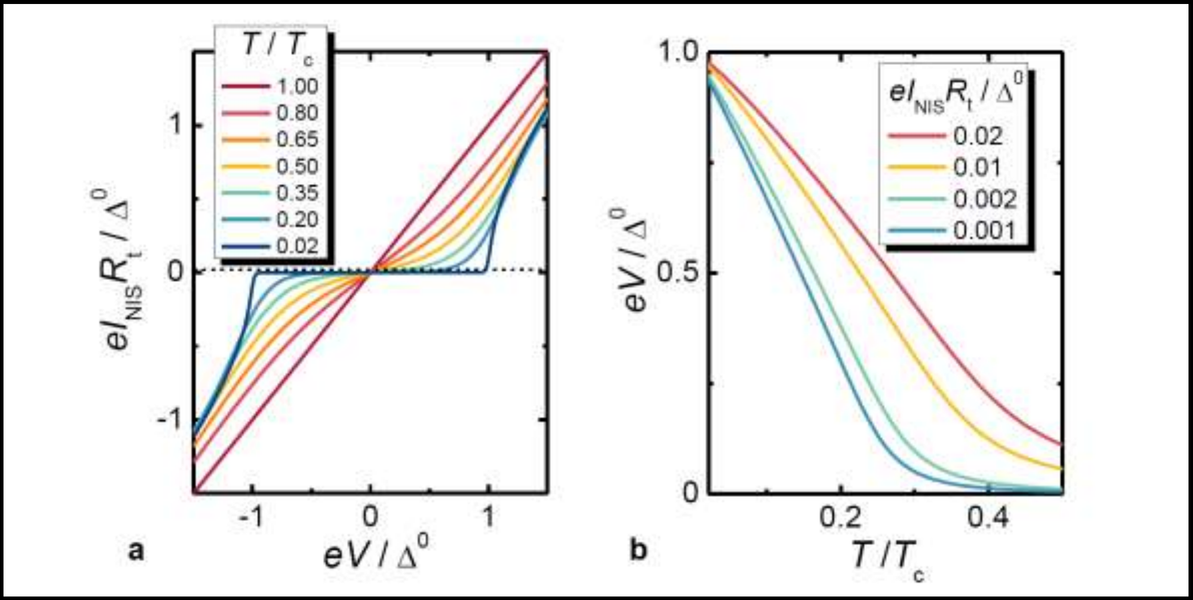
a – DC & RF electron thermometry through SINIS tunnel junctions

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

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)



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

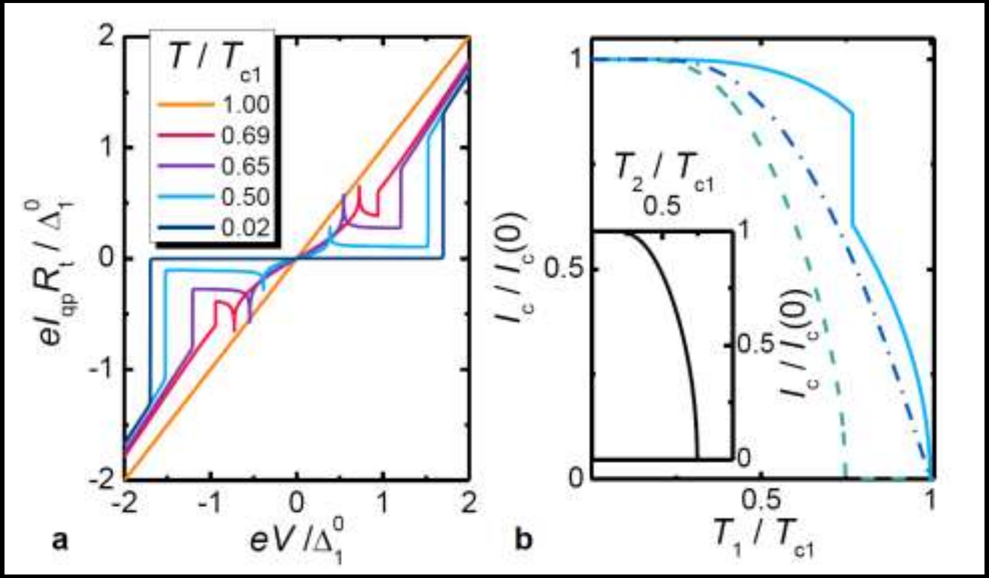
a – *I/V* characteristics of a NIS junction

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)



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

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

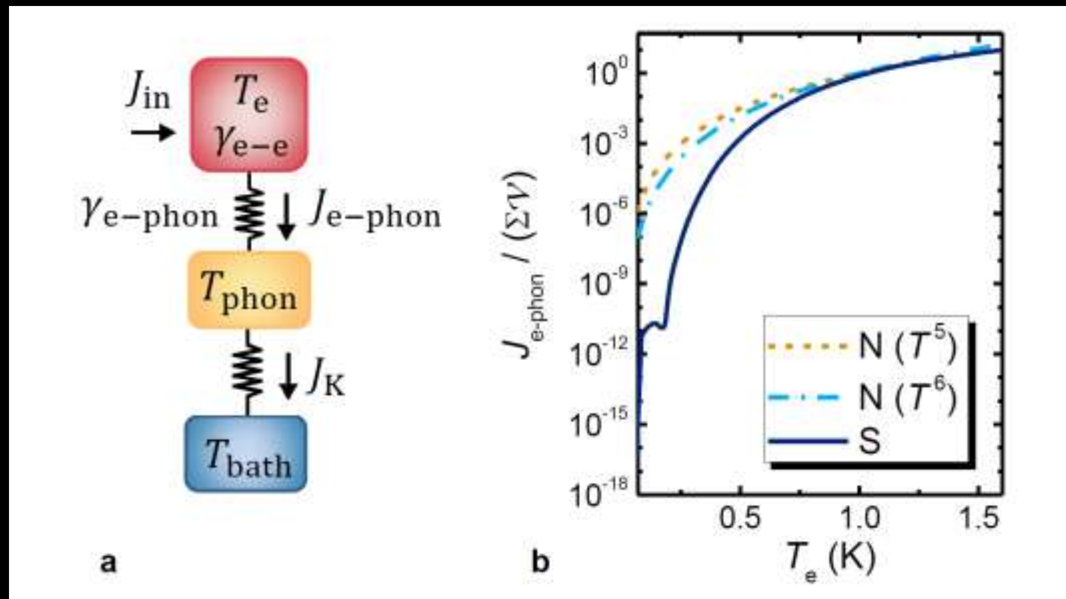
a – *I/V* quasiparticle characteristics of a SIS junction: more complicated thermometry

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



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

clean metal

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

disordered metal

a – Scheme of N or S film on a substrate

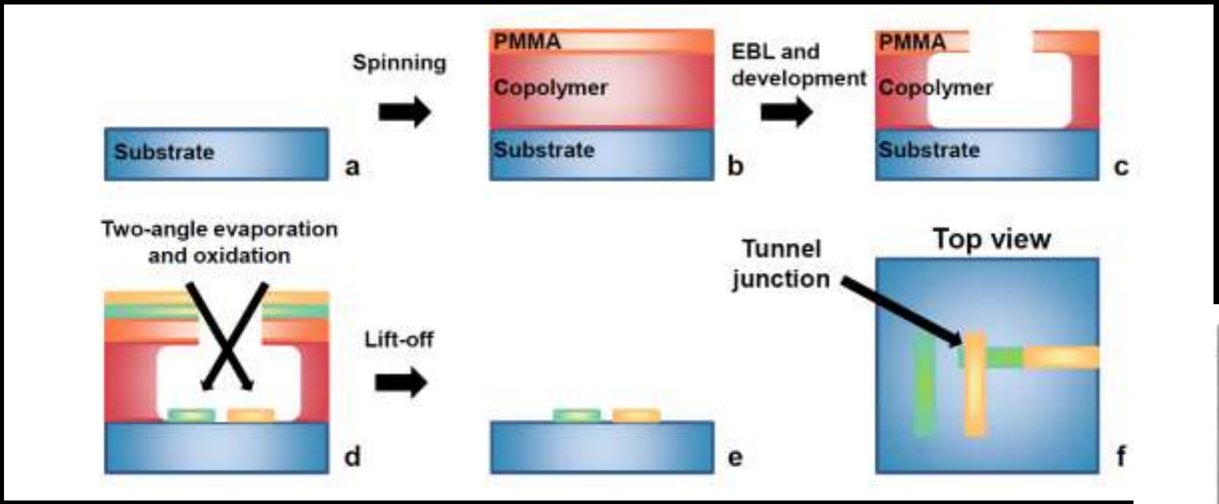
b – Electron-phonon coupling in N and S

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

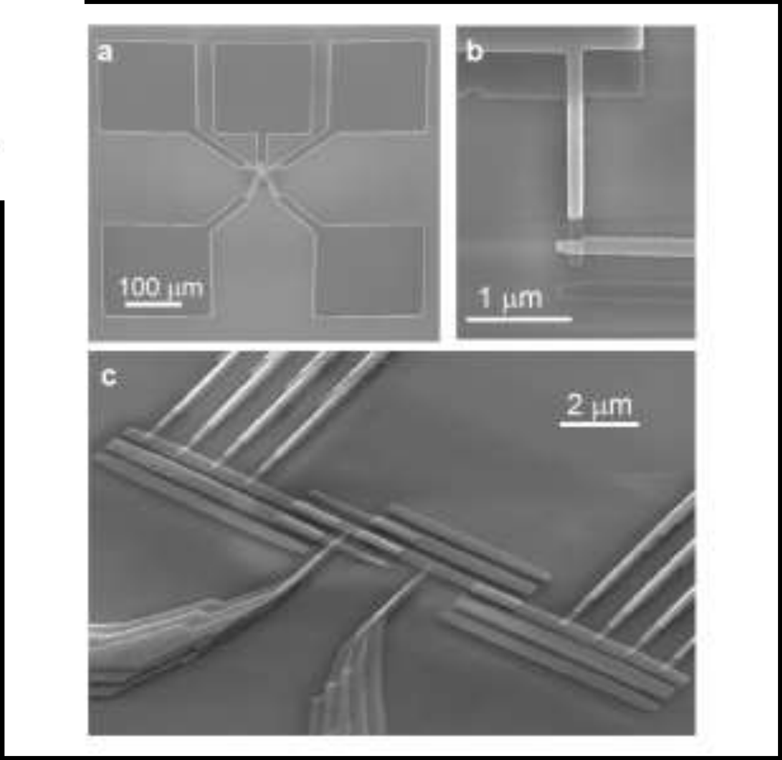
superconductor

FG, T. T. 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

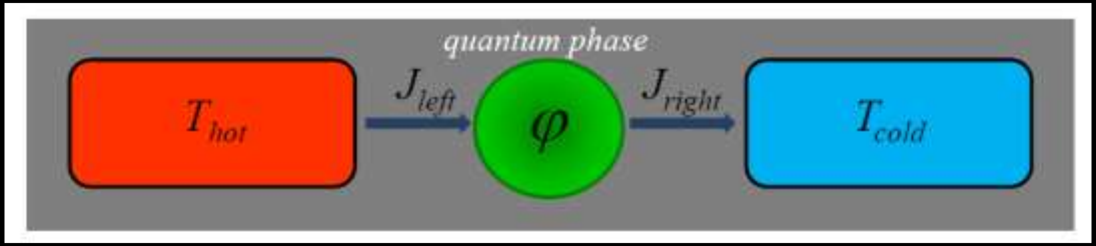


Angle evaporation and *in-situ* oxidation

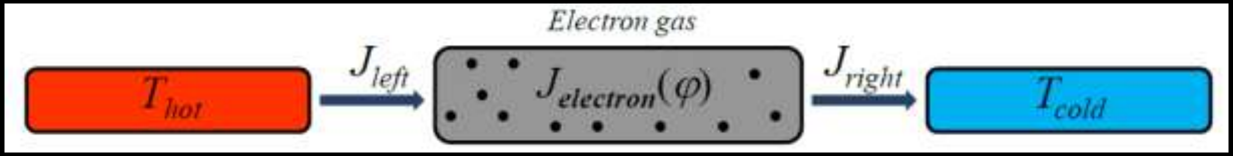


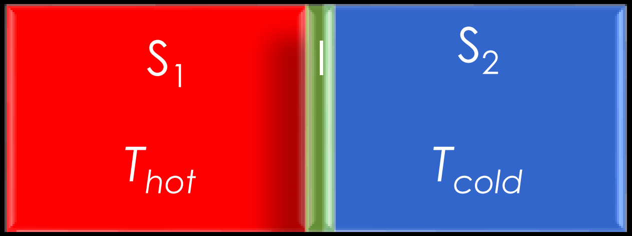
Typical shadow-mask evaporated structures

Principle of phase-dependent heat current control



Exploitation of superconducting phase to control heat current flow



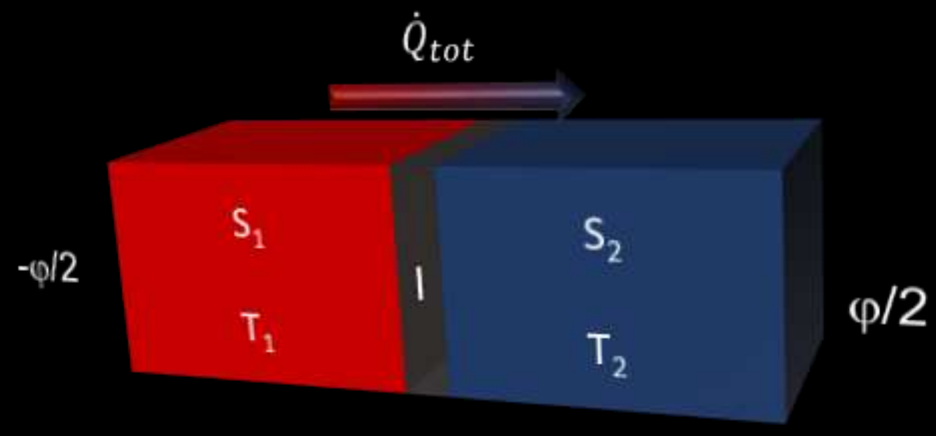


Temperature-biased Josephson tunnel junction

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

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

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

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

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

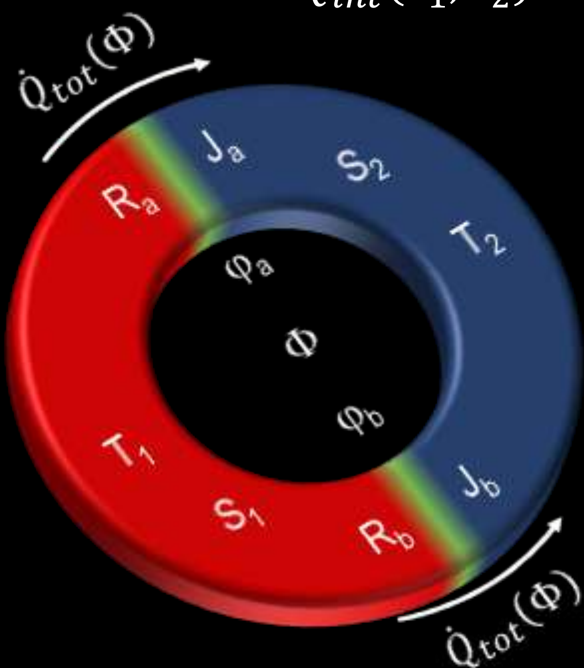
$$\dot{Q}_{int} = 0 \quad if\ S_1\ or\ S_2\ in\ normal\ state$$

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

$I_j^a \sin\varphi_a = I_j^a \sin\varphi_b$ Circulating charge current conservation

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

$$\cos\varphi_b = \frac{1 + \cos(2\pi x)}{\sqrt{1 + r^2 2r\cos(2\pi x)}} \qquad \text{r} = I_j^a/I_j^b$$

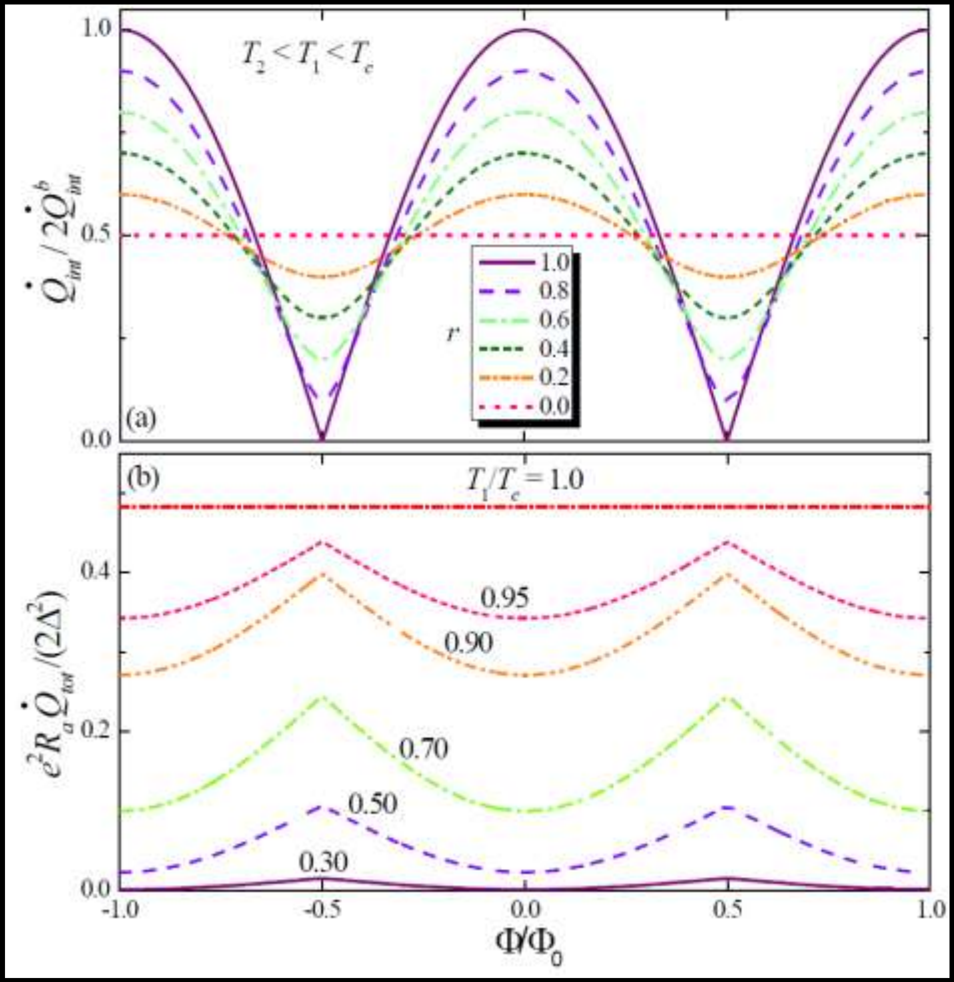
$$\dot{Q}_{int} = \dot{Q}^b_{int}(T_1,T_2)\sqrt{1 + r^2 + 2r\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$

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)

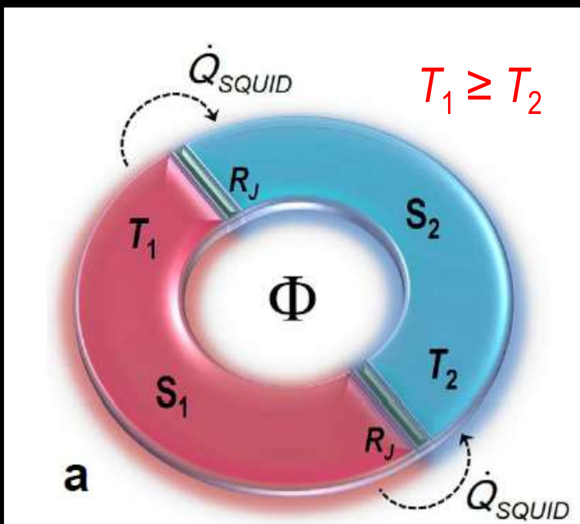
$T_2 = 0.1T_c$

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

"Josephson heat interferometer": setup (i)

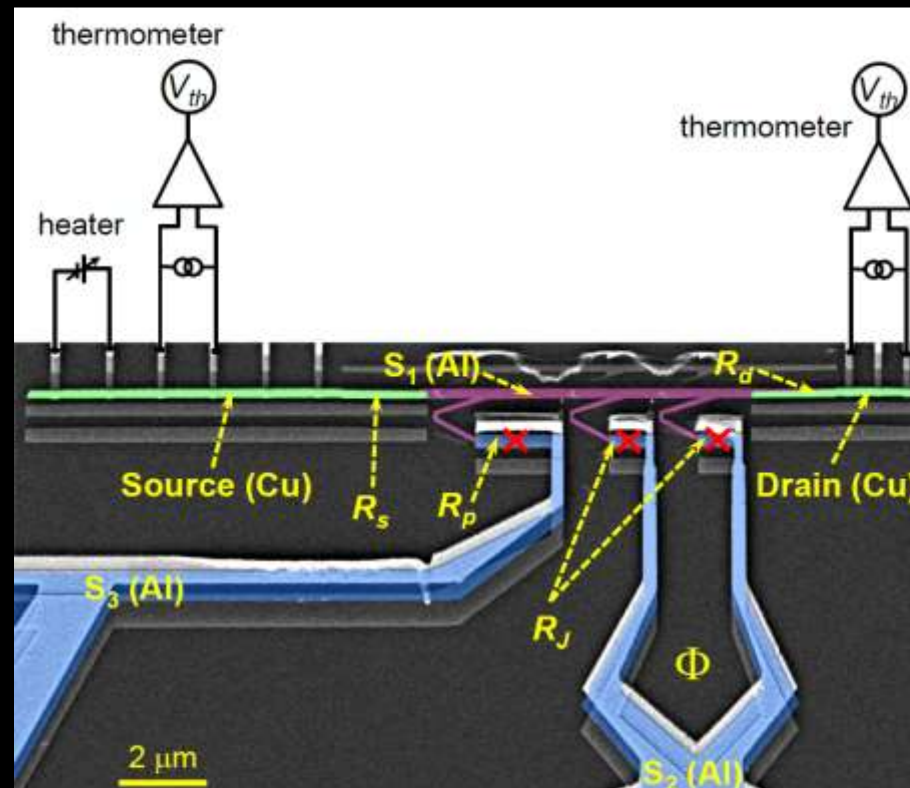

LETTER

The Josephson heat interferometer



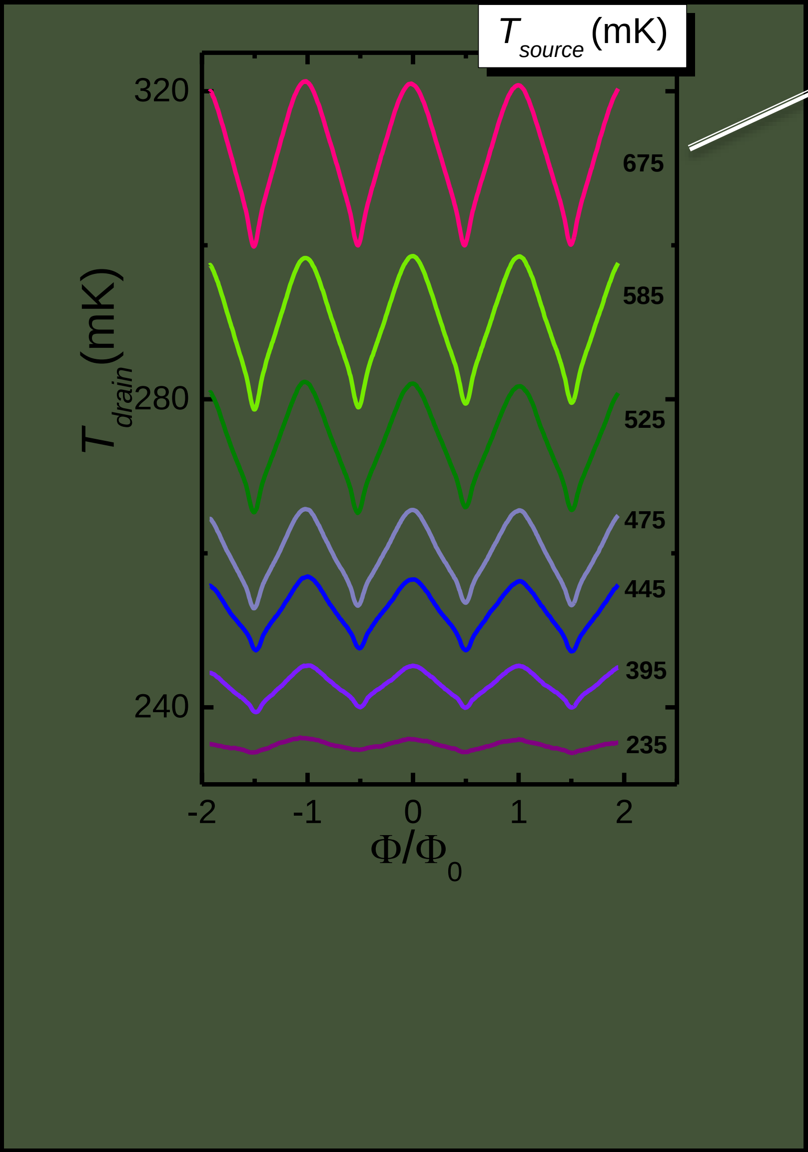
Symmetric SQUID (r = 1)

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

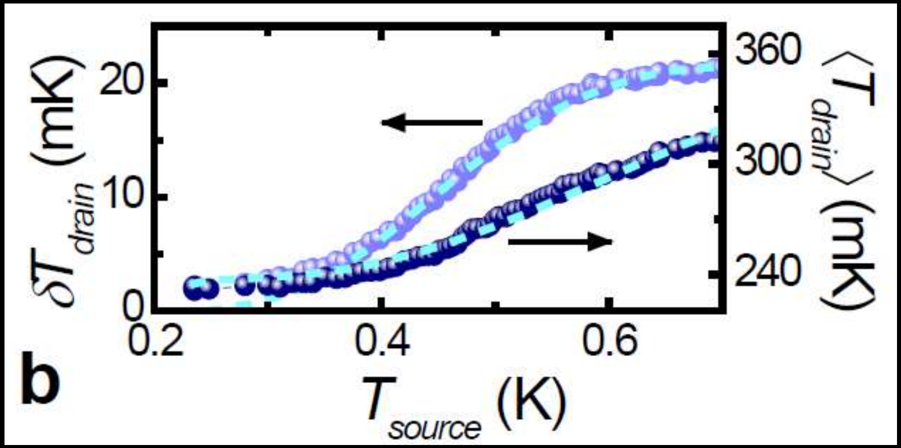


FG and M. J. Martinez-Perez, Nature **492**, 401 (2012)

Behavior @ 235 mK (i)

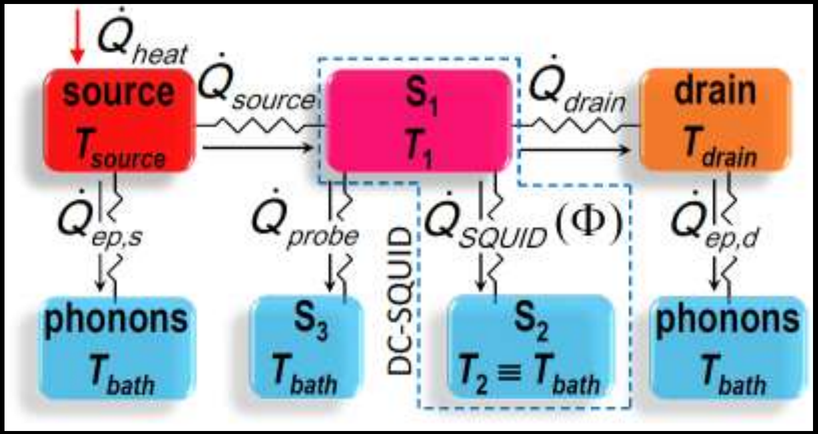


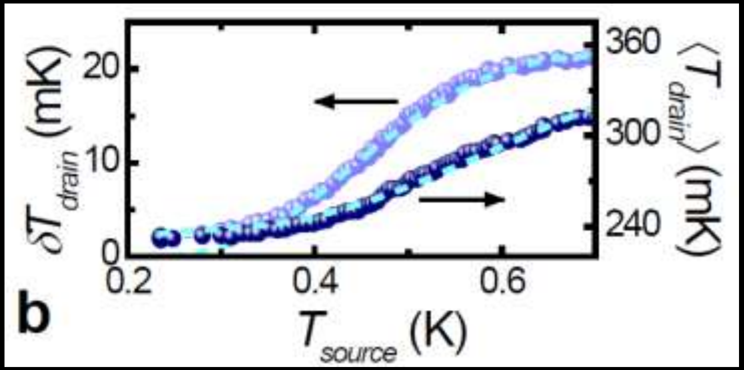
δT_{drain} ~ 21 mK
9% relative
modulation amplitude

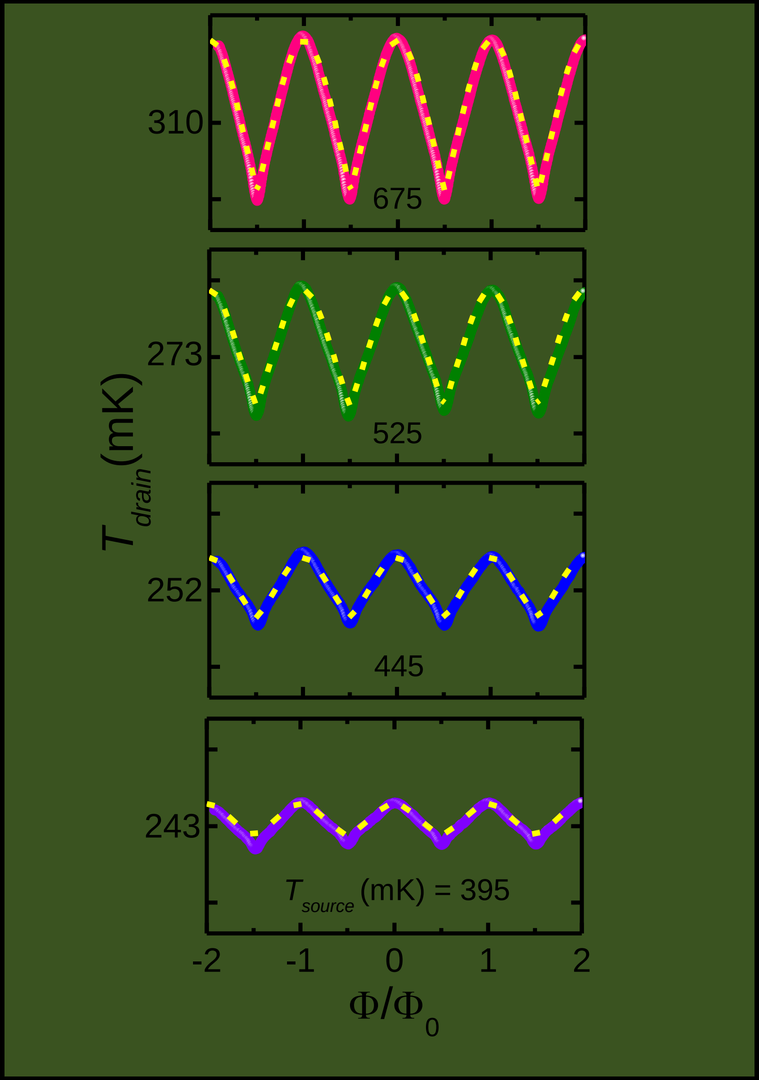


FG and M. J. Martinez-Perez, Nature **492**, 401 (2012)

Comparison to theory

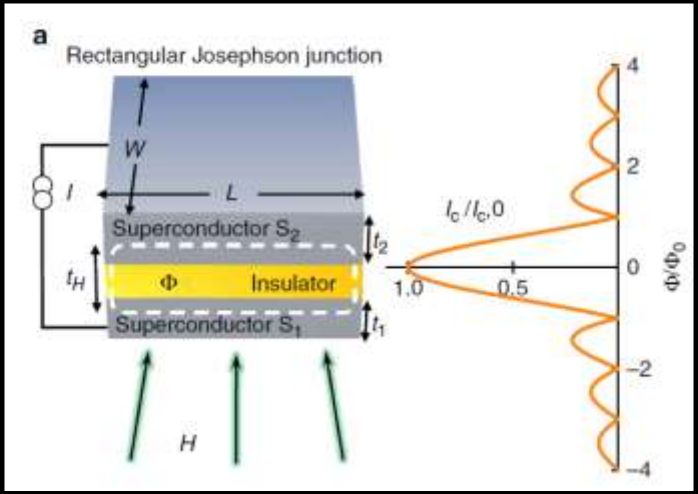




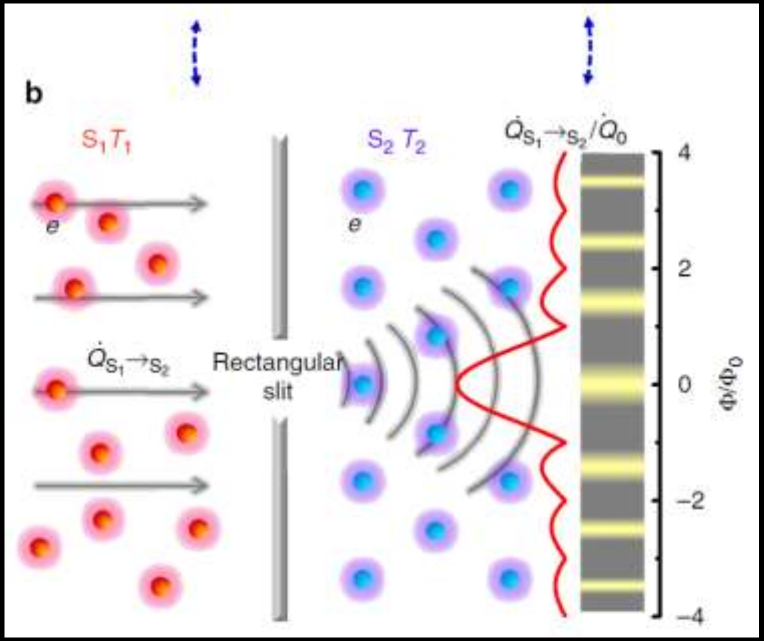


Good agreement with theoretical prediction

Electric vs thermal quantum diffraction

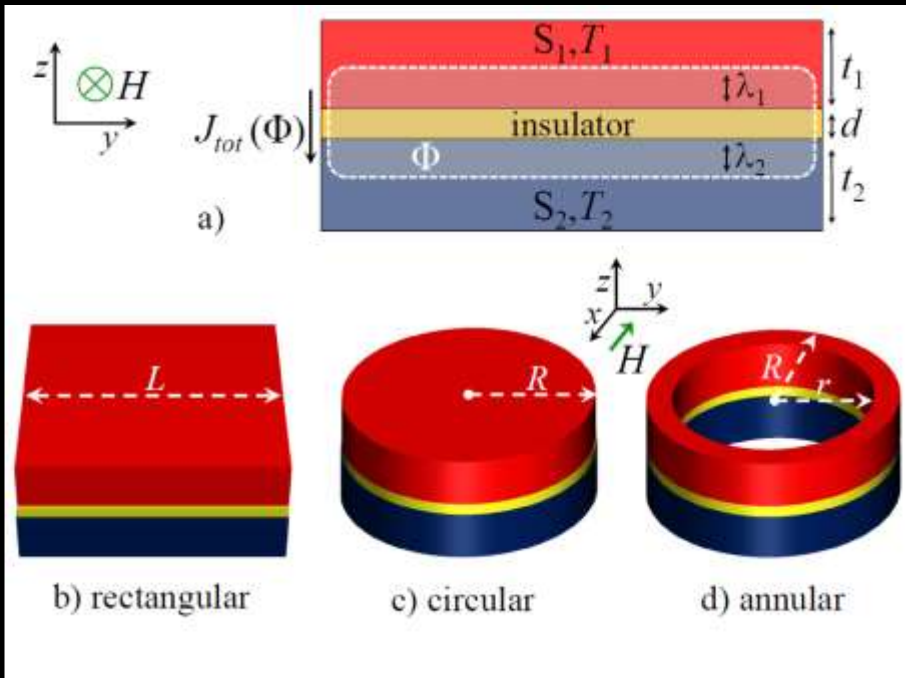


Electric diffraction through a rectangular slit



Diffraction of heat current through a rectangular slit

Heat current quantum diffraction in extended short JJs



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

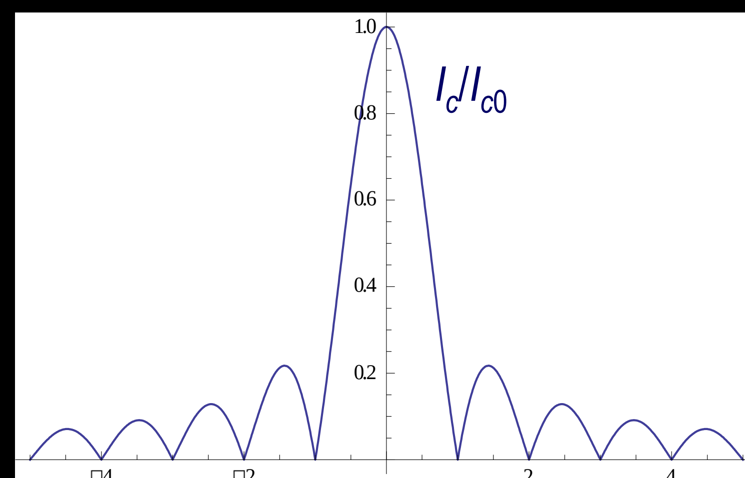
$$L, W \ll \lambda_J \equiv \sqrt{\frac{\Phi_0 W L}{2\mu_0 I_c \tilde{t}}}$$

Josephson critical current

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

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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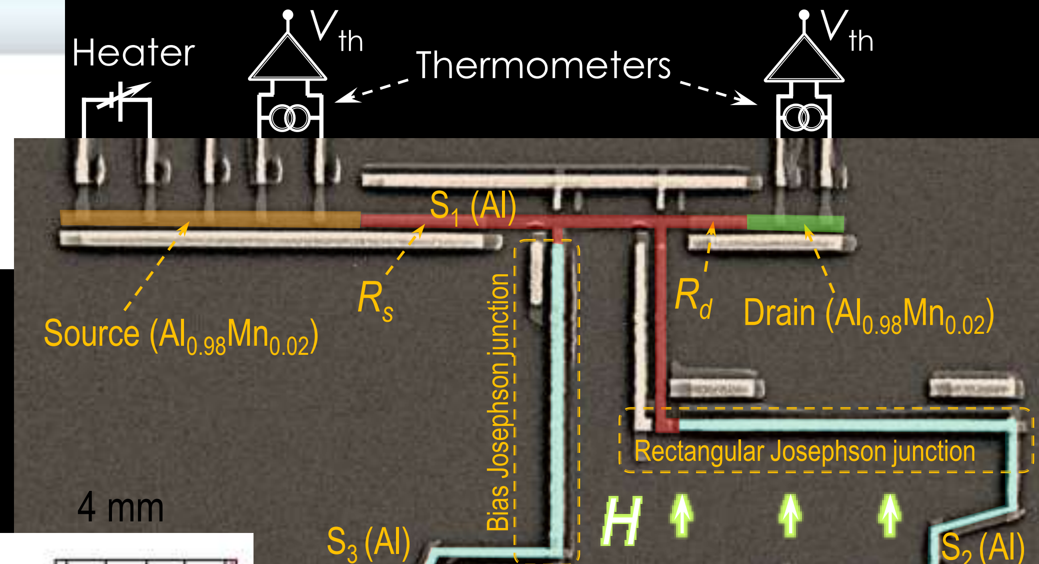
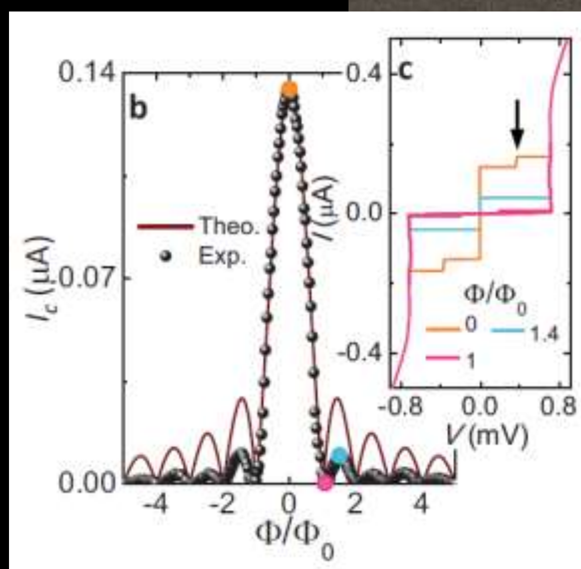
A quantum diffractor for thermal flux

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

Rectangular JJ

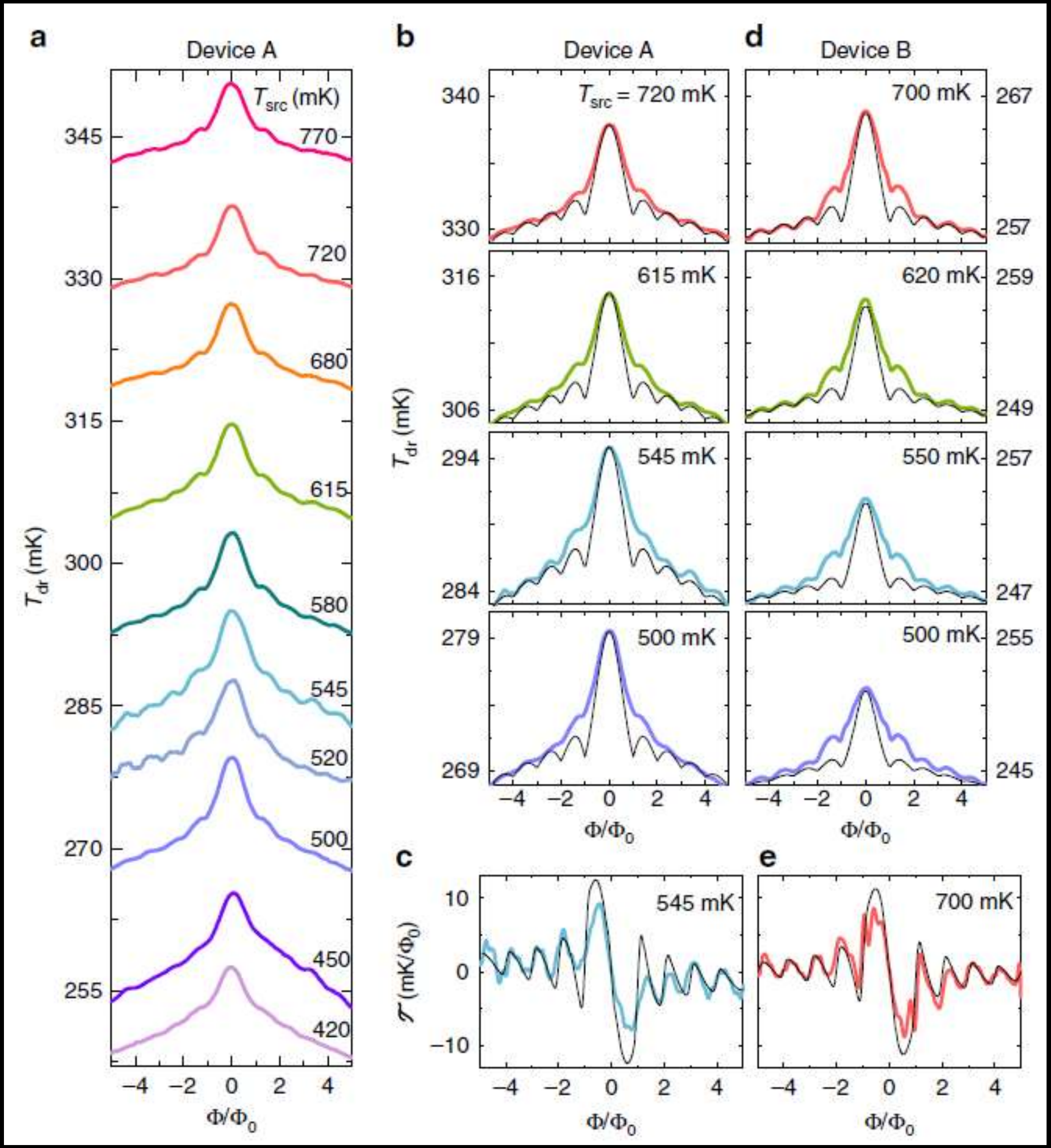


Magnetic interference pattern



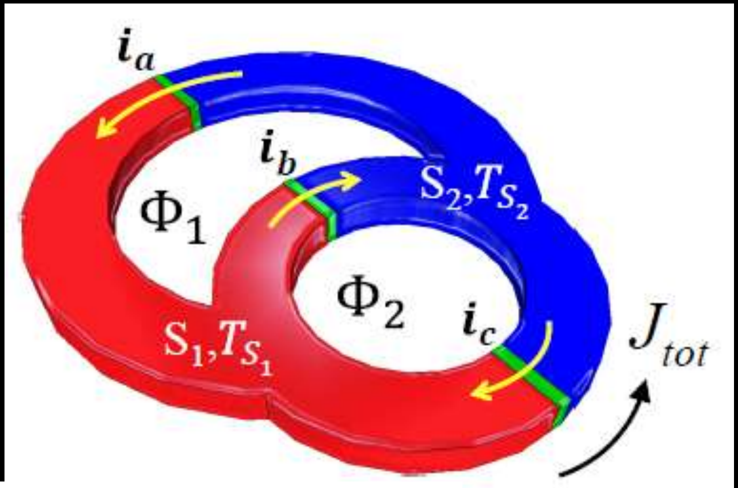
Josephson current behavior

Temperature diffraction pattern @ 240 mK



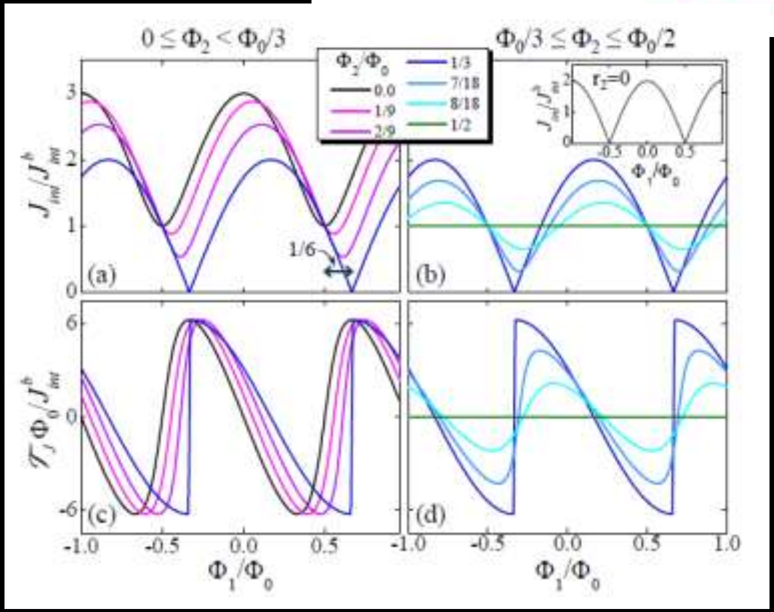
M. J. Martinez-Perez and FG, Nat. Commun. **5**, 3579 (2014)

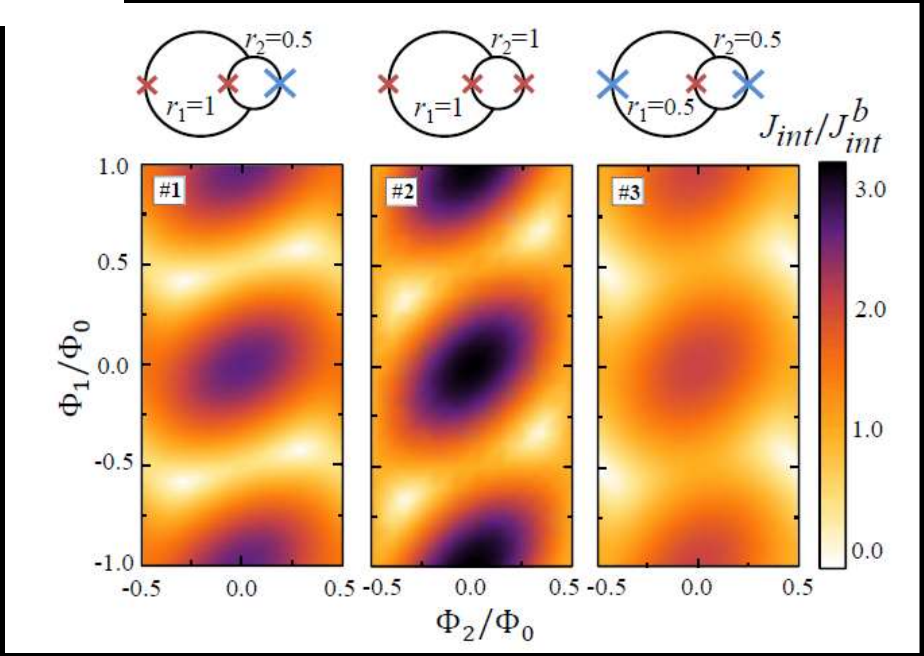
Fully-balanced heat interferometer



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

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

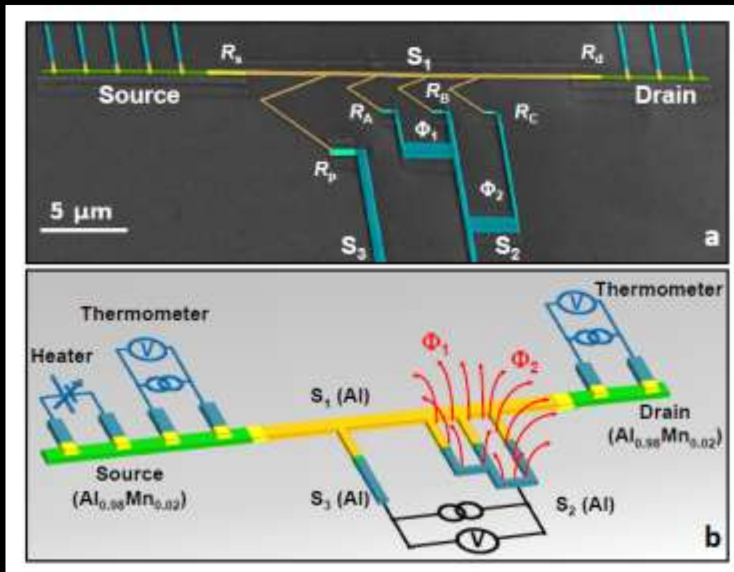




M. J. Martinez-Perez and FG, APL **102**, 401 (2013)

Quantum heat pumping & time-dependent heat engines

Nanoscale phase-engineering of thermal transport
i) Electrical response



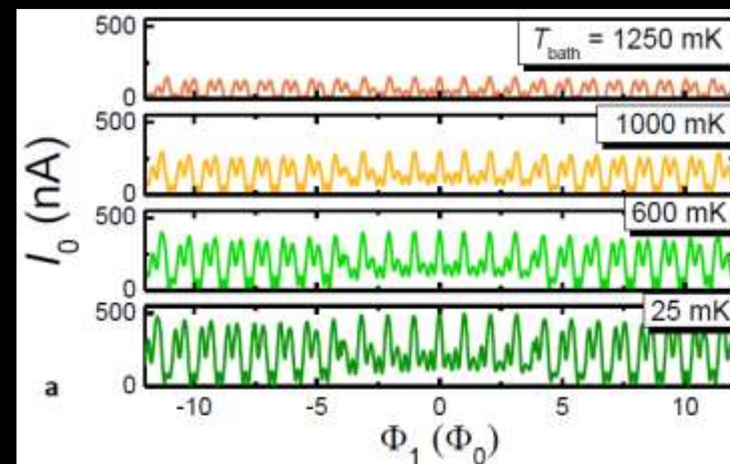

LETTERS

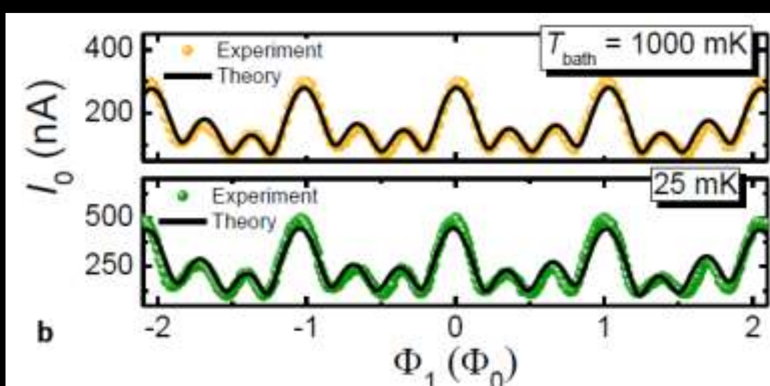
nature nanotechnology

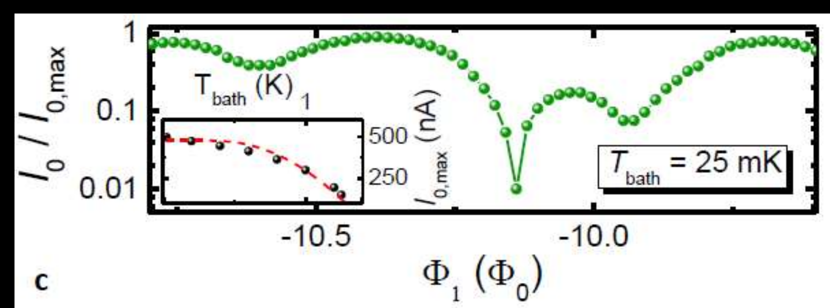
Nanoscale phase engineering of thermal transport with a Josephson heat modulator

Antonio Fornieri, Christophe Blanc, Riccardo Bosisio, Sophie D'Ambrosio and Francesco Giazotto

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

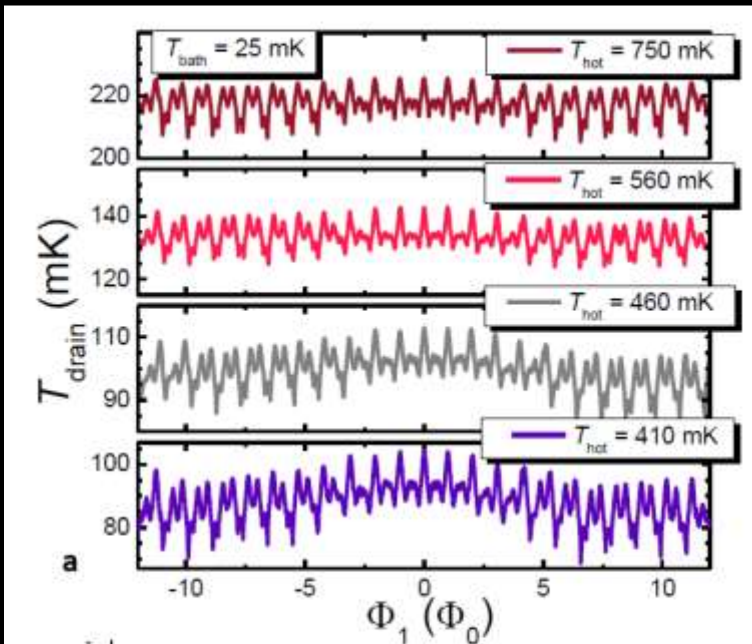






I_c suppression ~ 99%

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

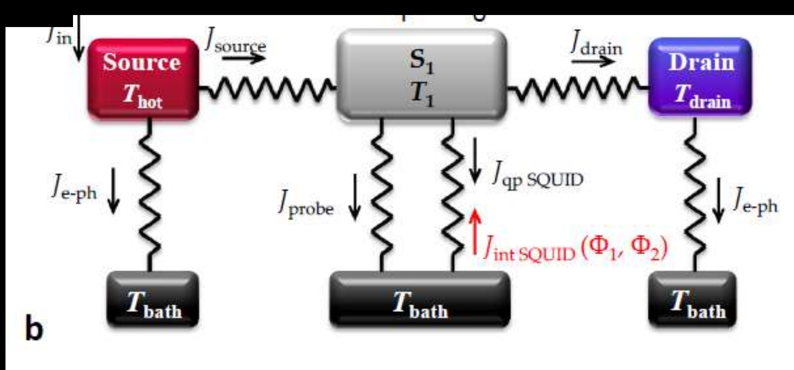


~ 40mK temperature swing

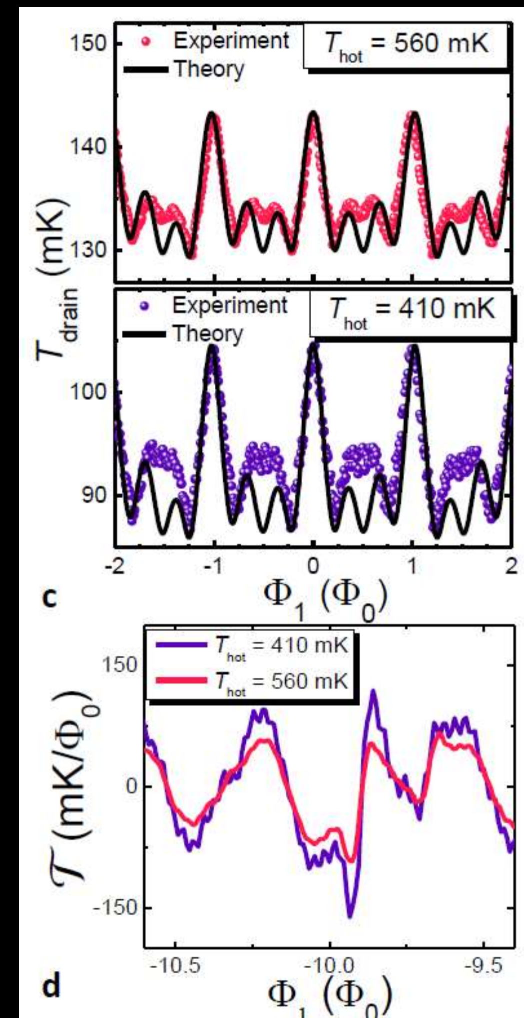
J_{int} suppression ~ 99%

$\tau \sim$ 200mK/Φ_0 @ 25mK

X 3 previous exps

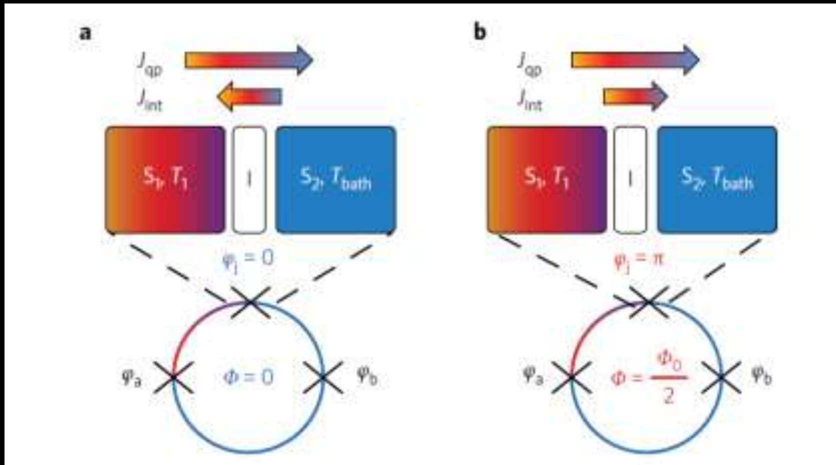


Thermal model



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
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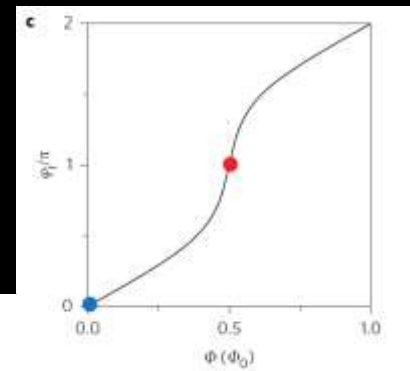
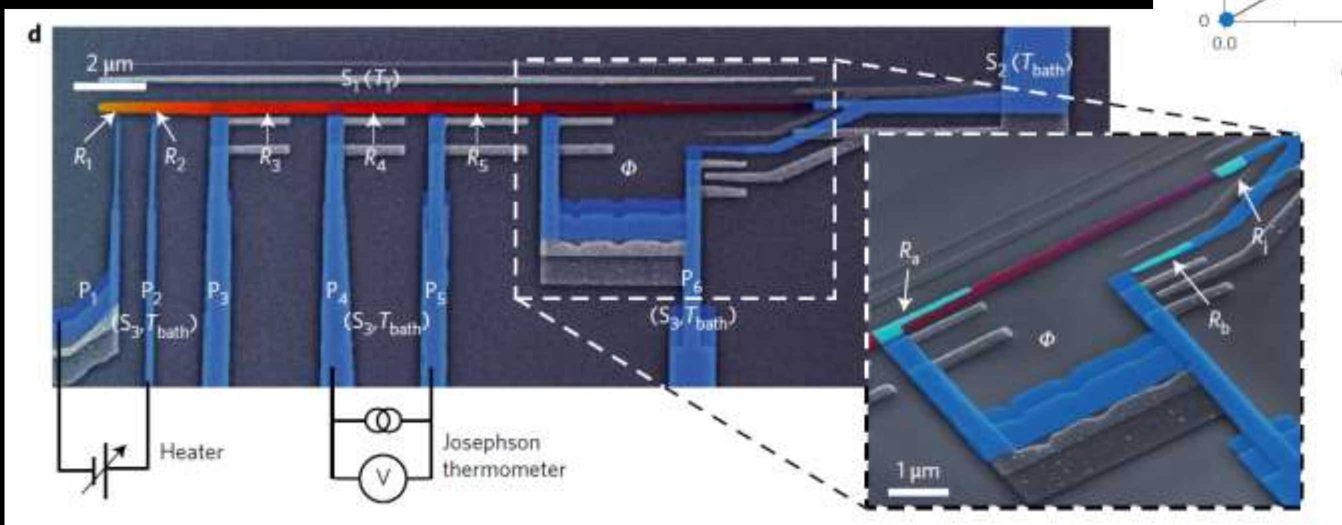
0-π phase-controllable thermal Josephson junction

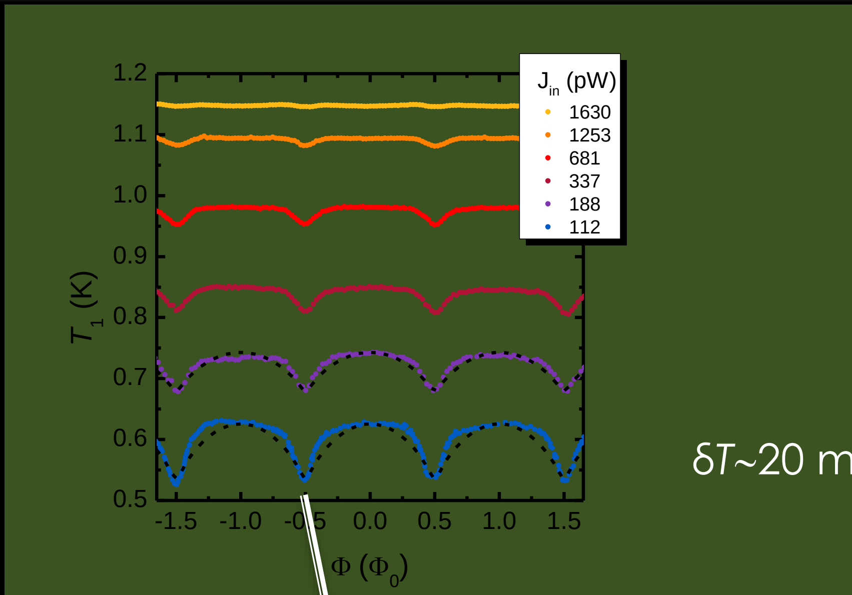
Antonio Fornieri[1], Giuliano Timossi[1], Pauli Virtanen[1], Paolo Solinas[2] and Francesco Giazotto[1]*

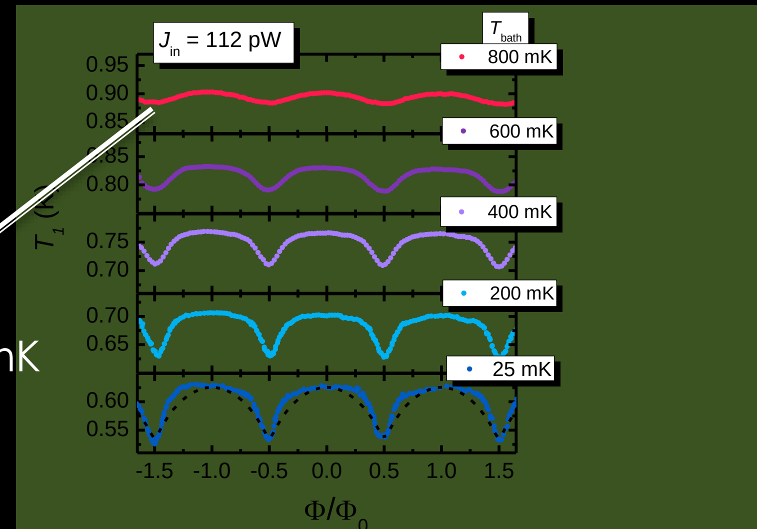




A. Fornieri, G. Timossi, P. Solinas, P. Virtanen, and FG, Nat. Nanotechnol. **12**, 425-429 (2017);
A. Fornieri, G. Timossi, R. Bosisio, P. Solinas, and FG, Phys. Rev. B **93**, 134508 (2016)

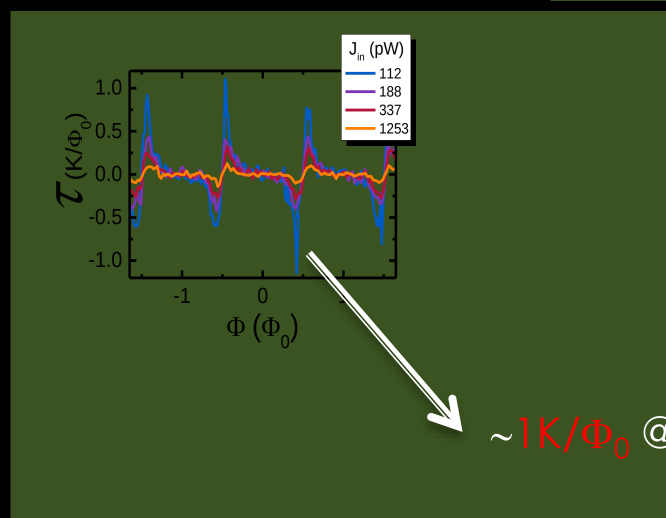
0-π *thermal* Josephson junction: thermal behavior





δT~20 mK @ 800 mK

δT up to 100 mK @ 25 mK



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

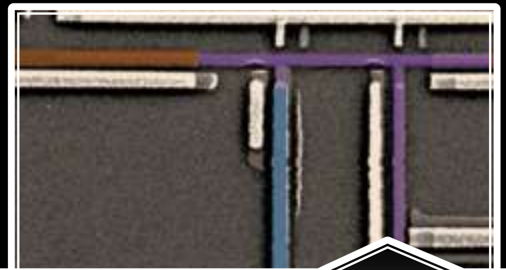
~1K/Φ$_0$ @ 550 mK

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

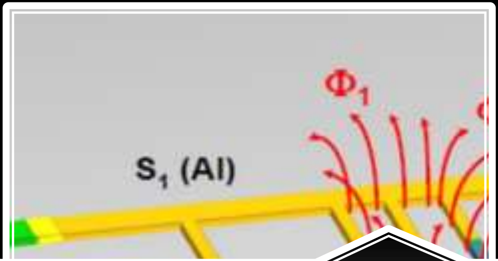
The Josephson heat interferometer

Nature **492**, 401 (2012)



A quantum diffractor for thermal flux

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

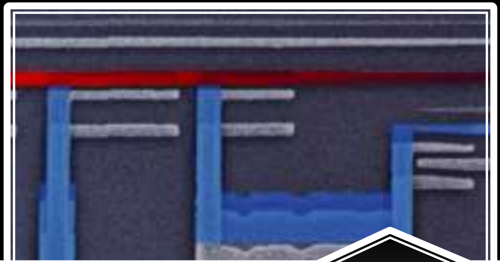


Nanoscale phase engineering of thermal transport with a Josephson heat modulator

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

Rectification of electronic heat current by a hybrid thermal diode

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



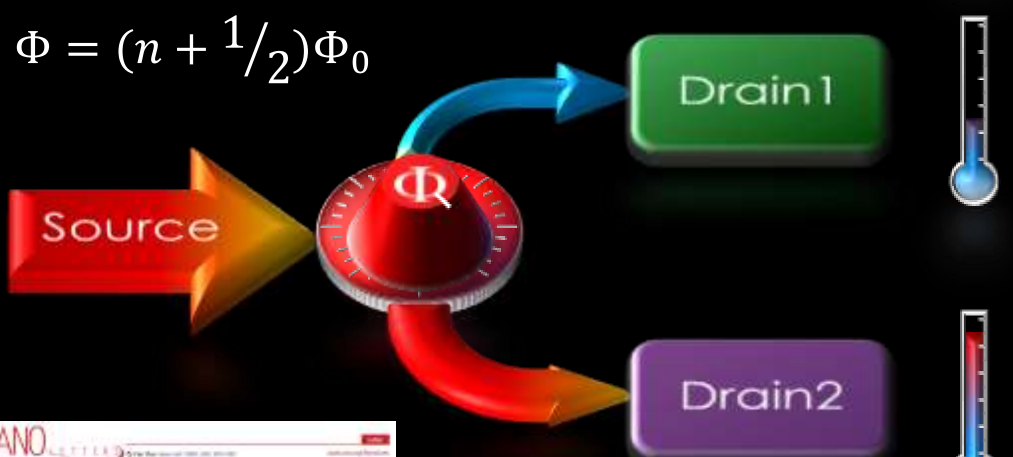
0-π phase-controllable thermal Josephson junction

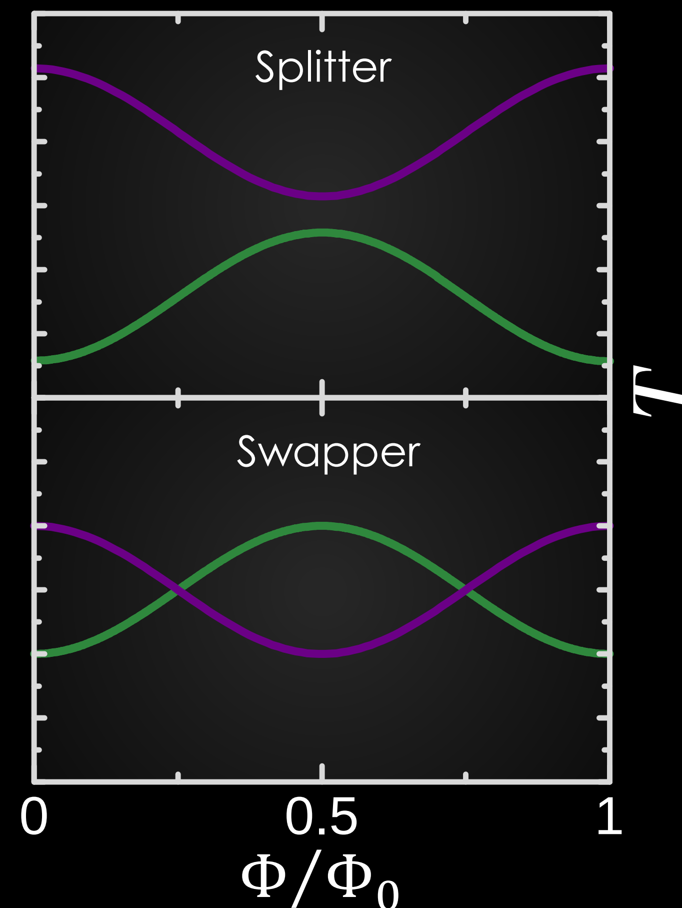
Nat. Nanotech. **12**, 425 (2017)

Phase-tunable thermal router: General scheme

$\Phi = n\Phi_0$

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



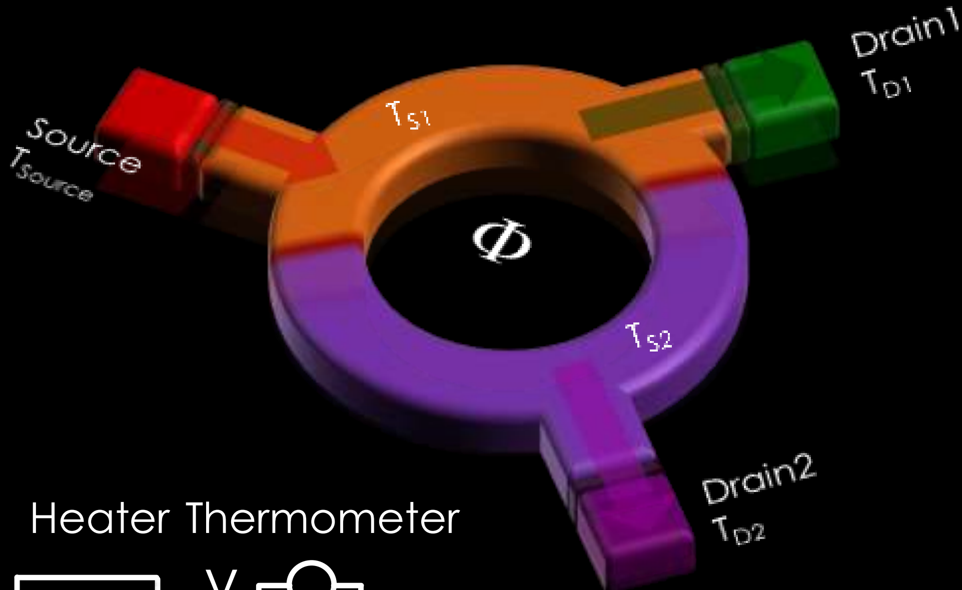



NANO LETTERS

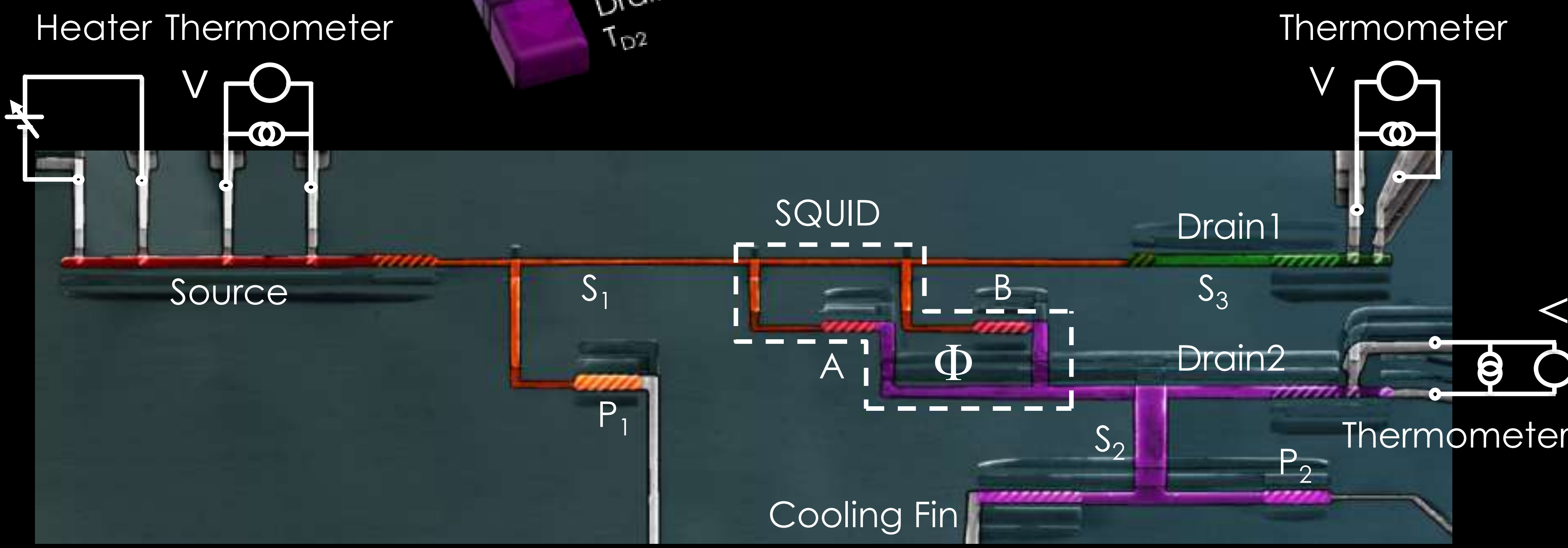
Phase-Tunable Josephson Thermal Router

DOI: 10.1021/acs.nanolett.7b04906

Phase-tunable thermal router: Device structure

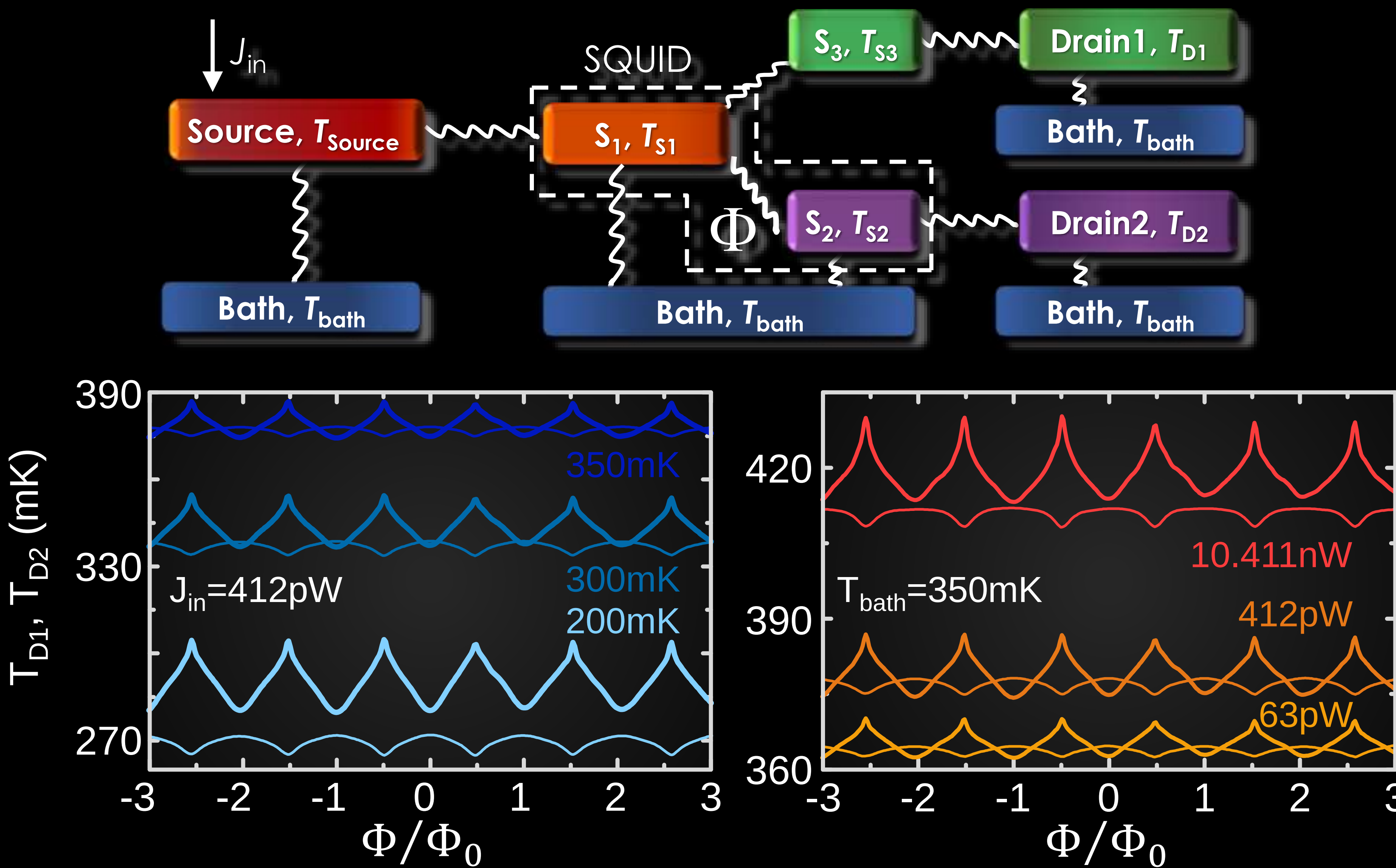


$$\dot{Q}_{int} = \dot{Q}^{A}_{int}(T_{S1}, T_{S2}) \sqrt{1 + r^2 + 2r\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$



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

Phase-tunable thermal router: Experiment



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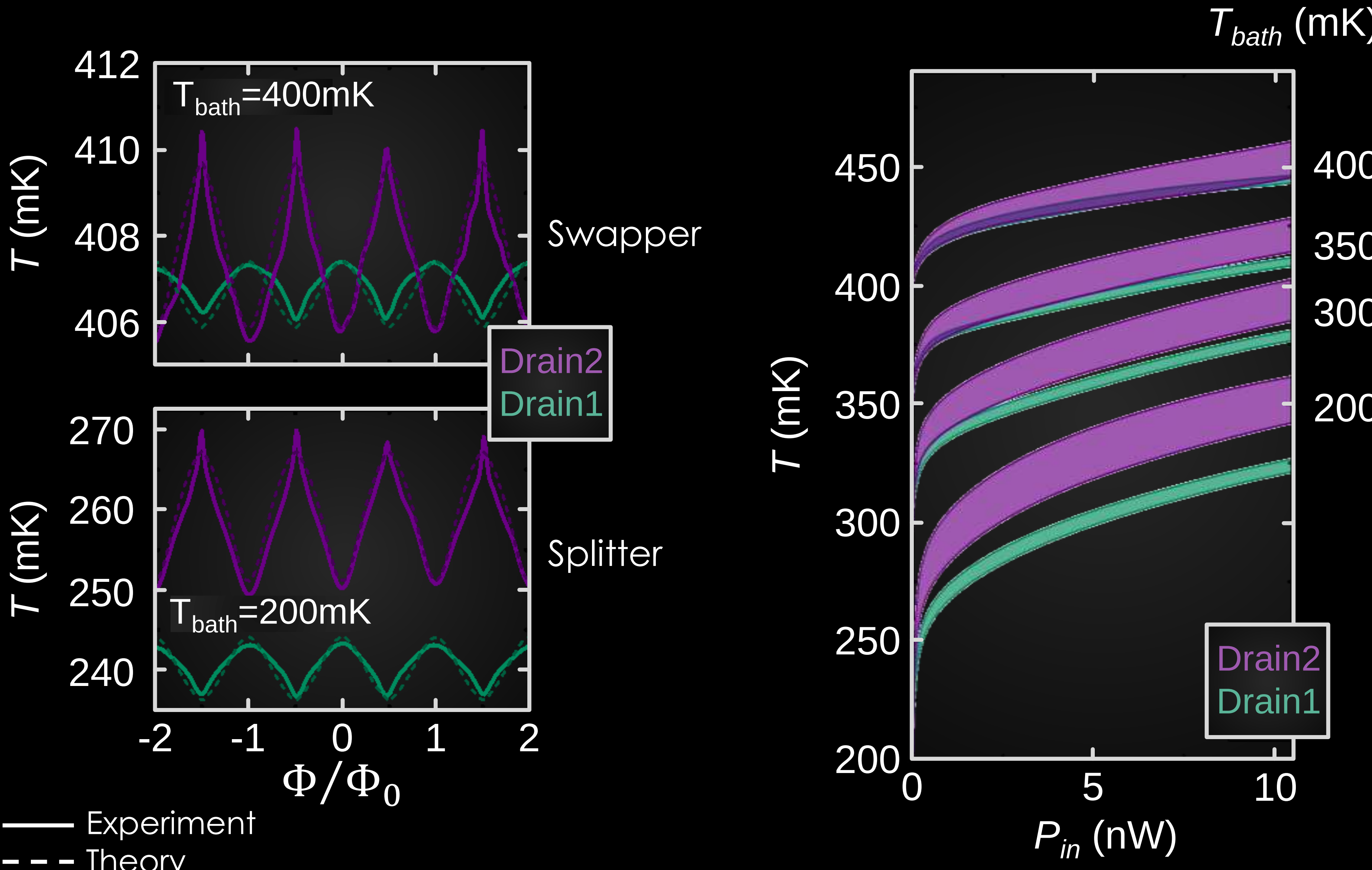

G. Timossi, A. Fornieri, F. Paolucci, C. Puglia, and FG, Nano Lett. **18**, 1764 (2018)

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”

Acknowledgments

A. Fornieri
M. J. Martinez-Perez
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C. Puglia

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FARFAS 2014-Project SCIADRO

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