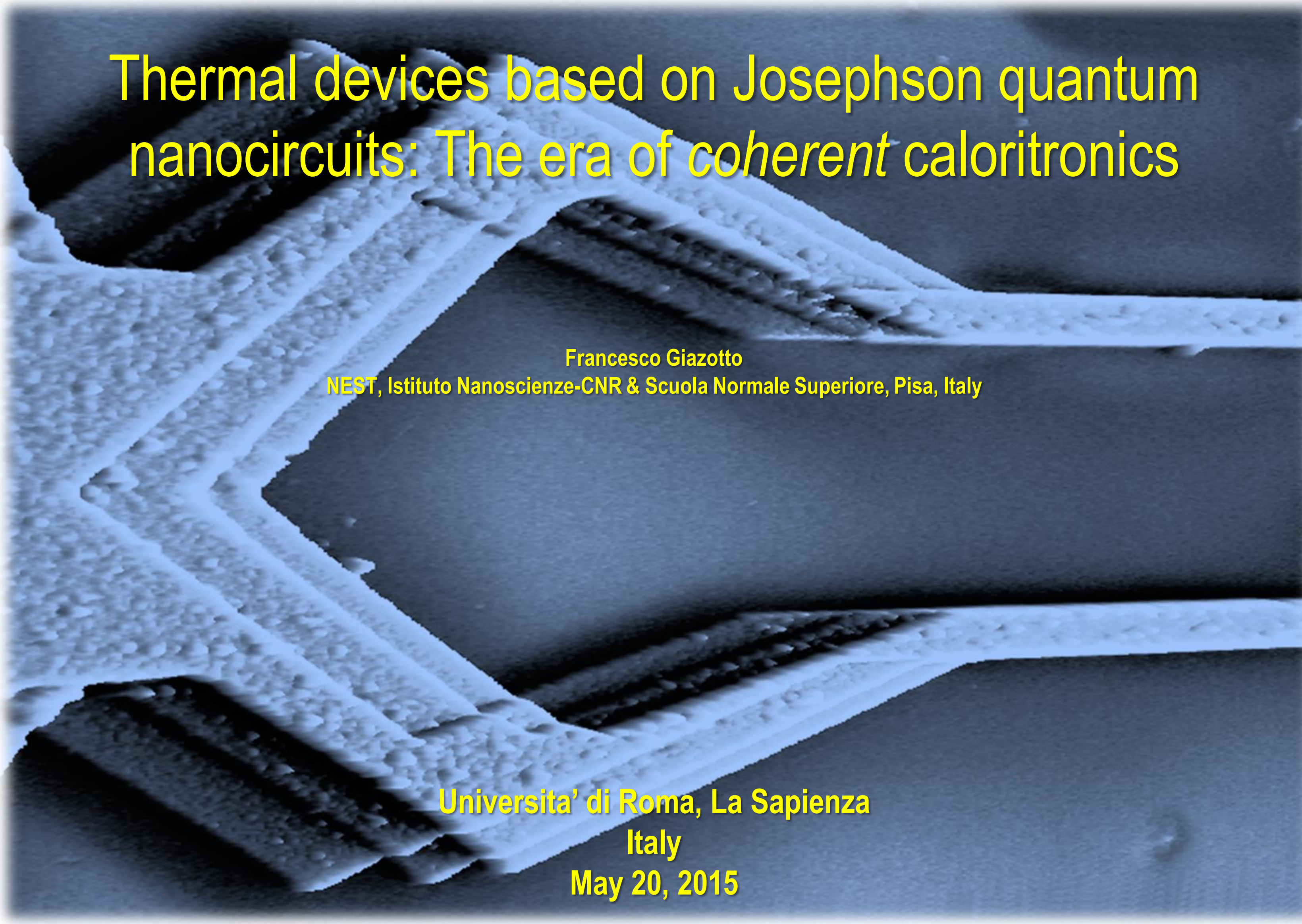

Thermal devices based on Josephson quantum nanocircuits: The era of *coherent* caloritronics

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Outline

1. Motivations & mission
2. Principle of phase-coherent heat flux control
3. Behavior of a temperature-biased Josephson tunnel junction
4. Josephson heat interferometer
5. Quantum diffractor for thermal flux
6. An ultraefficient thermal rectifier
7. Perspectives

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].

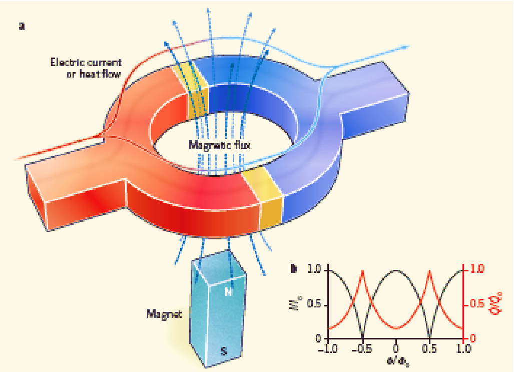

Figure 1 | A direct-current superconducting quantum interference device (d.c.-SQUID). a, In d.c.-SQUIDs, a superconducting loop contains two Josephson junctions — thin insulating barriers (yellow) sandwiched between the two superconductors (red and blue). b, The maximum electrical current (I, black, 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.

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

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Motivations & mission

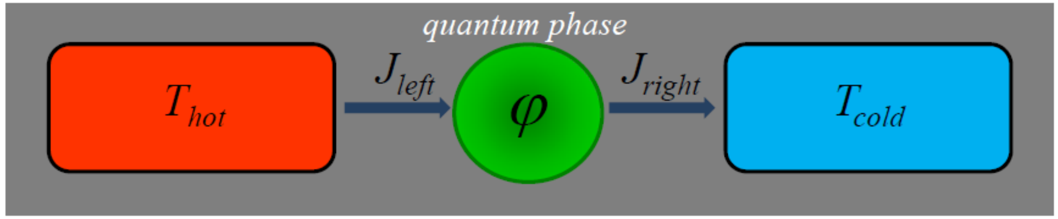
- Set the experimental ground for a challenging new branch of science: the *coherent caloritronics,* i.e., the complementary of coherent electronics

- Phase-manipulate & master heat transfer in a solid-state environment

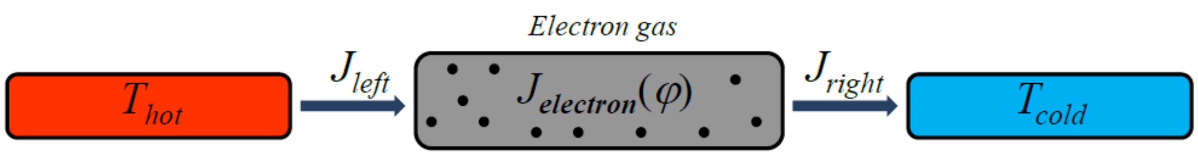
- Provide original & novel approaches to realize thermal devices (heat transistors, splitters, diodes, refrigerators, exotic quantum circuits)

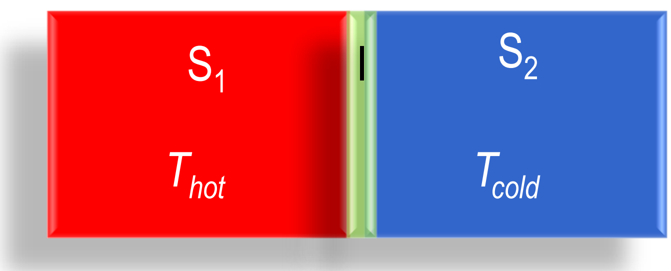
- Address & understand fundamental energy- and heat-related phenomena at nanoscale (coherent dynamics, heat interference, time-dependent effects, thermodynamics, decoherence)

Principle of phase-dependent heat current control



Exploitation of quantum phase to control heat current flow



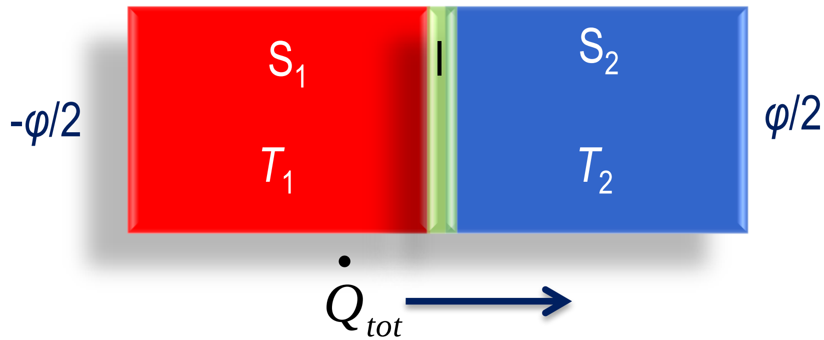


Temperature-biased Josephson tunnel junction

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 T-biased Josephson tunnel junctions: theory (i)



$T_1 \geq T_2$

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

$$\dot{Q}_{qp}(T_1,T_2) = \frac{2}{e^2R_J}\int_0^\infty d\varepsilon\varepsilon\mathcal{N}_1(\varepsilon,T_1)\mathcal{N}_2(\varepsilon,T_2)[f_1(\varepsilon,T_1) - f_2(\varepsilon,T_2)]$$ Quasiparticles heat current

$$\dot{Q}_{int}(T_1,T_2) = \frac{2}{e^2R_J}\int_0^\infty d\varepsilon\varepsilon\mathcal{M}_1(\varepsilon,T_1)\mathcal{M}_2(\varepsilon,T_2)[f_1(\varepsilon,T_1) - f_2(\varepsilon,T_2)]$$ Interference heat current

$$\mathcal{N}_{1(2)}(\varepsilon,T) = |\varepsilon|/\sqrt{\varepsilon^2 - \Delta_{1(2)}(T)^2}\Theta[\varepsilon^2 - \Delta_{1(2)}(T)^2]$$

$$\mathcal{M}_{1(2)}(\varepsilon,T) = \Delta_{1(2)}(T)/\sqrt{\varepsilon^2 - \Delta_{1(2)}(T)^2}\Theta[\varepsilon^2 - \Delta_{1(2)}(T)^2]$$

$$f_i(\varepsilon,T_i) = [1 + \exp(\varepsilon/k_BT_i)]^{-1}$$

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

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

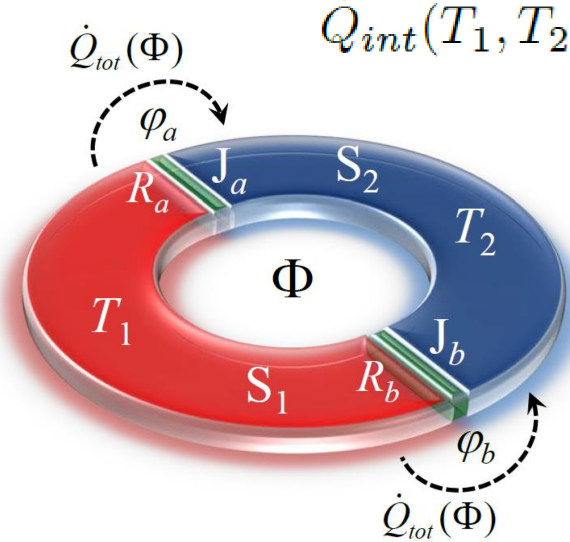
Maki and Griffin, PRL **15**, 921 (1965);
Guttman *et al.*, PRB **55**, 12691 (1997);
Zhao *et al.*, PRL **91**, 077003 (2003)

Temperature-biased DC-SQUID: theory (i)

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

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

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



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

$$I^a_J \sin\varphi_a = I^b_J \sin\varphi_b$$

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

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

$$x = \Phi/\Phi_0$$
$$r = I^a_J/I^b_J$$
(with $0 \le r \le 1$)

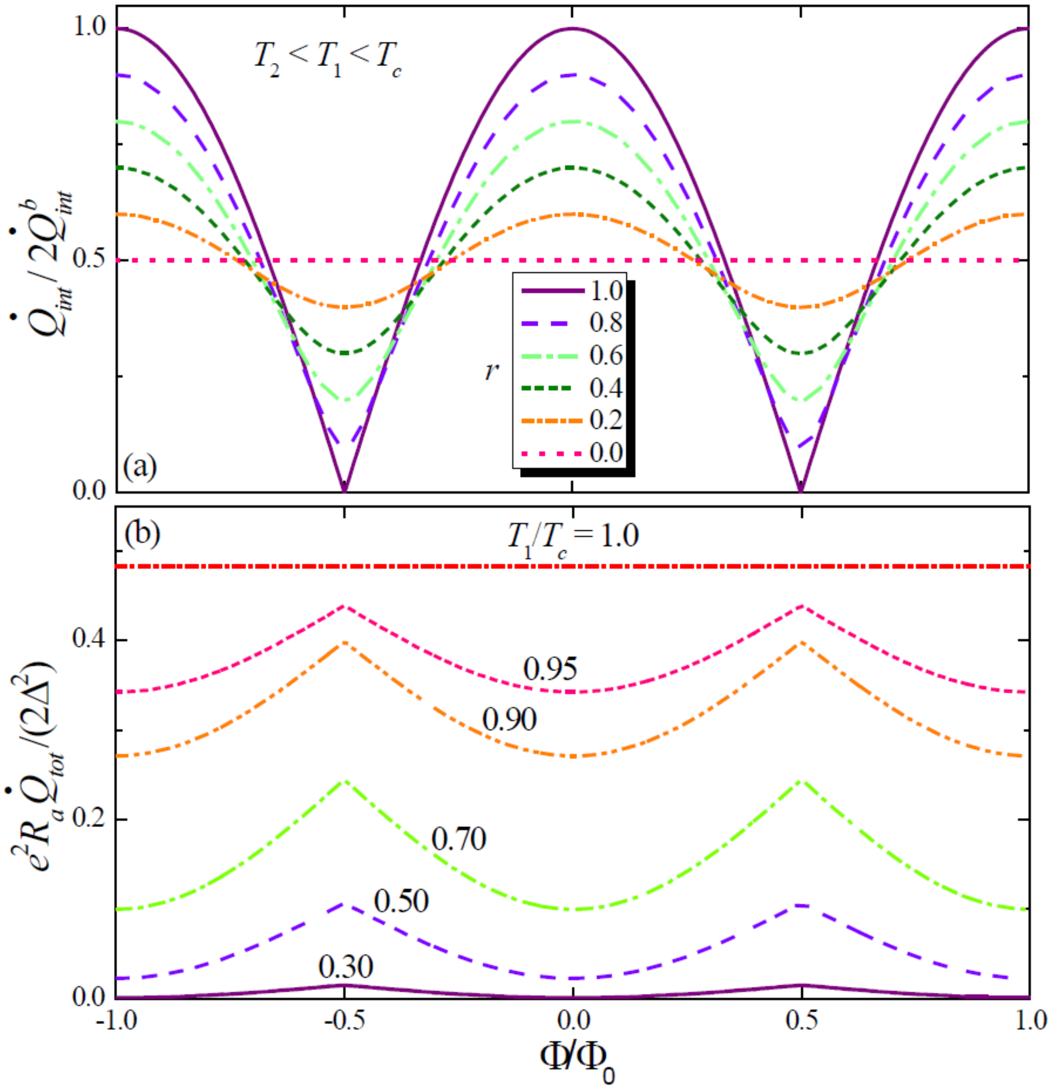
$$\dot{Q}_{int} = \dot{Q}^b_{int}(T_1, T_2)\sqrt{1 + r^2 + 2r\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)}$$

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)
$T_2 = 0.1 T_c$

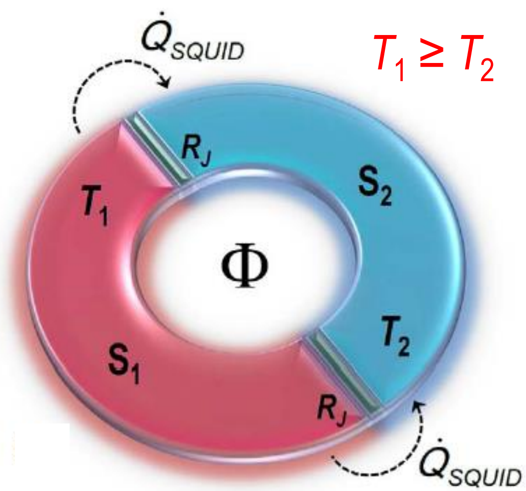
FG and M. J. Martinez-Perez, APL **101**, 102601 (2012)

“Josephson heat interferometer”: setup (i)

LETTER

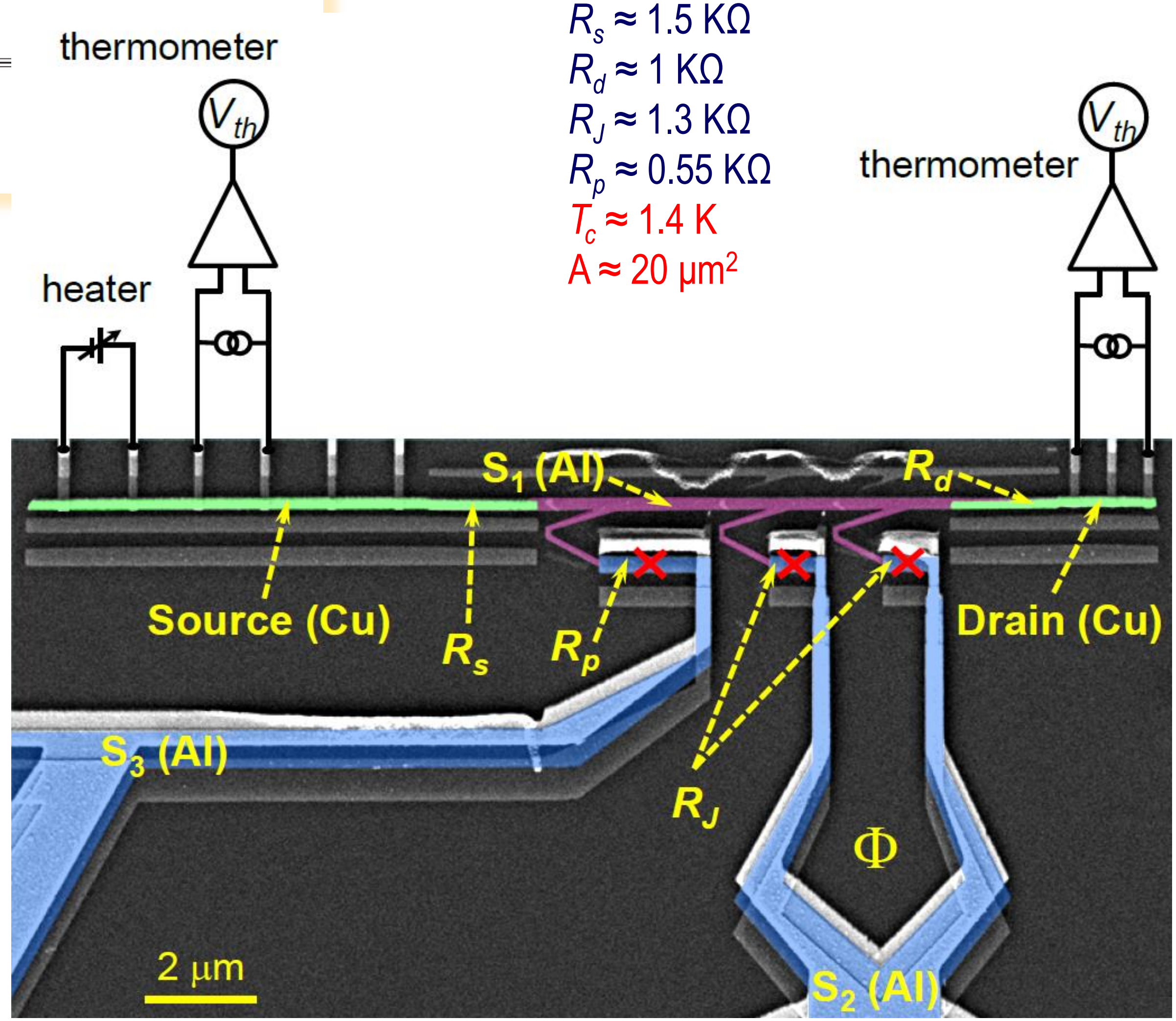
The Josephson heat interferometer

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



Symmetric SQUID (r = 1)

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



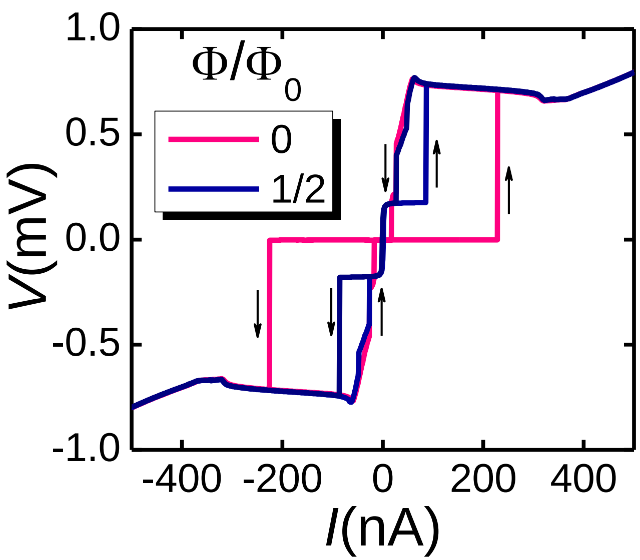
Main parameters:

- $R_s \approx 1.5$ KΩ
- $R_d \approx 1$ KΩ
- $R_J \approx 1.3$ KΩ
- $R_p \approx 0.55$ KΩ
- $T_c \approx 1.4$ K
- A ≈ 20 µm²

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

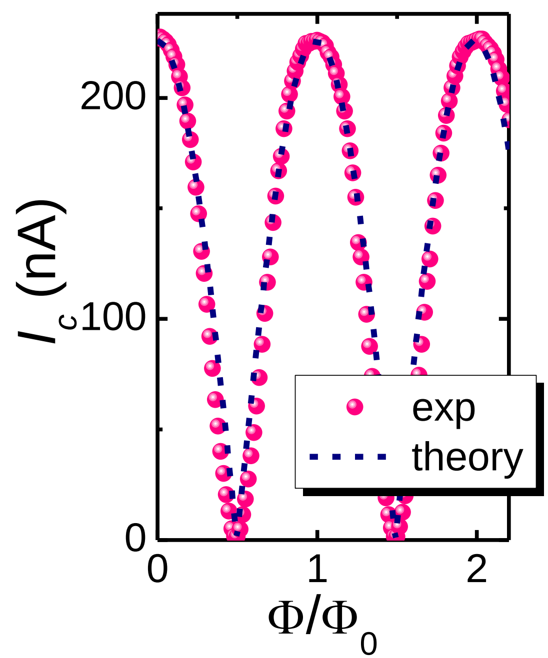
"Josephson heat interferometer": setup (ii)

V vs *I* chars @ 240 mK



$I_c \approx 226$ nA

Magnetic interference pattern



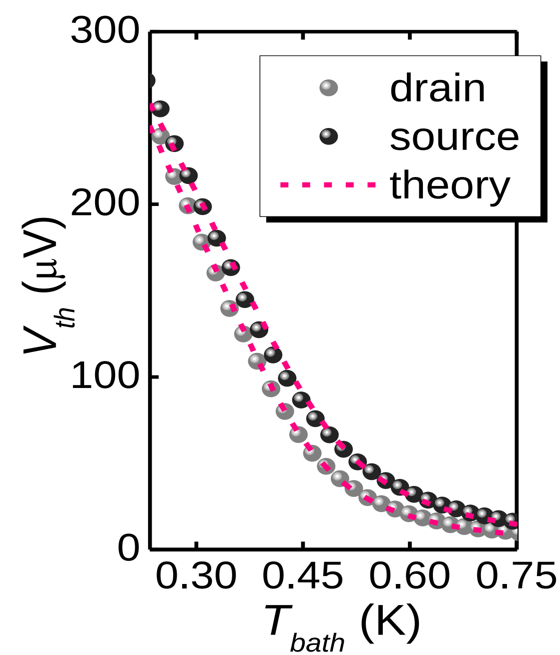
$\alpha \sim 0.3\%$

$\beta_L \sim 1.6\text{x}10^{-3} << 1$

$L \sim 15$ pH

SINIS thermometers

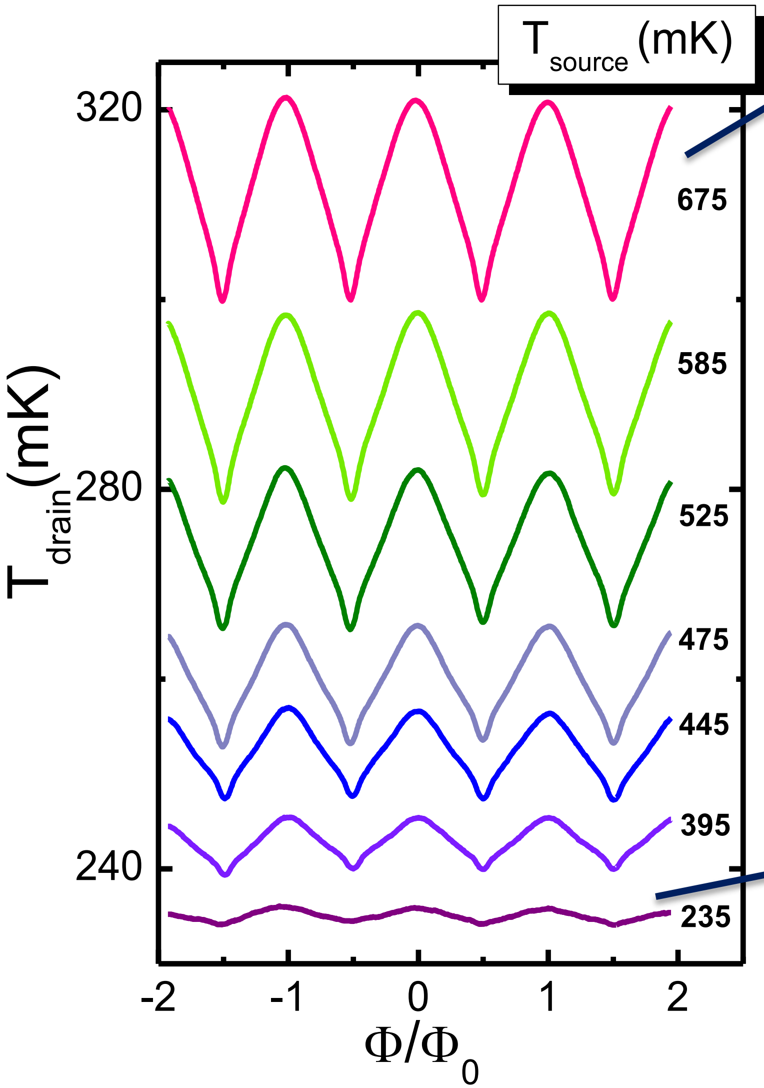
$R_{thermo} \approx 25$ KΩ



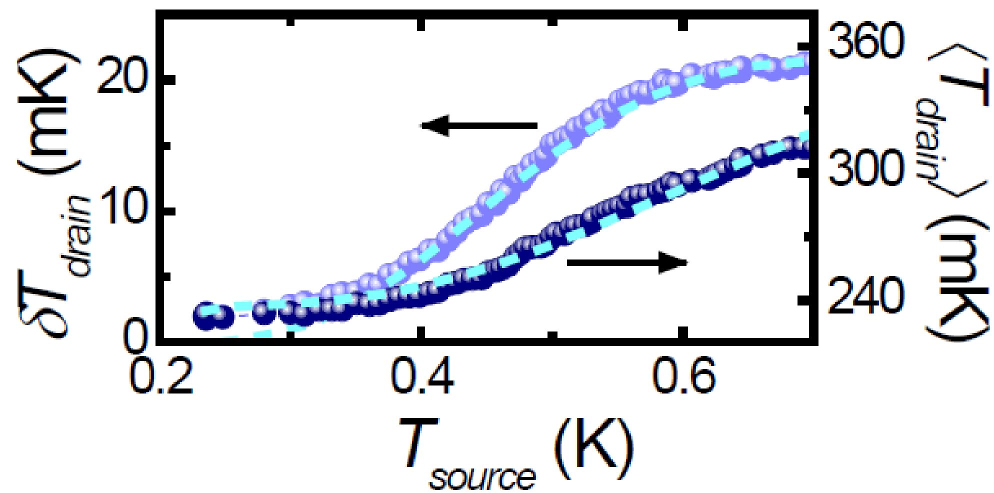
$I_{bias} \sim 40\text{-}70$ pA

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

Behavior @ 235 mK (i)



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

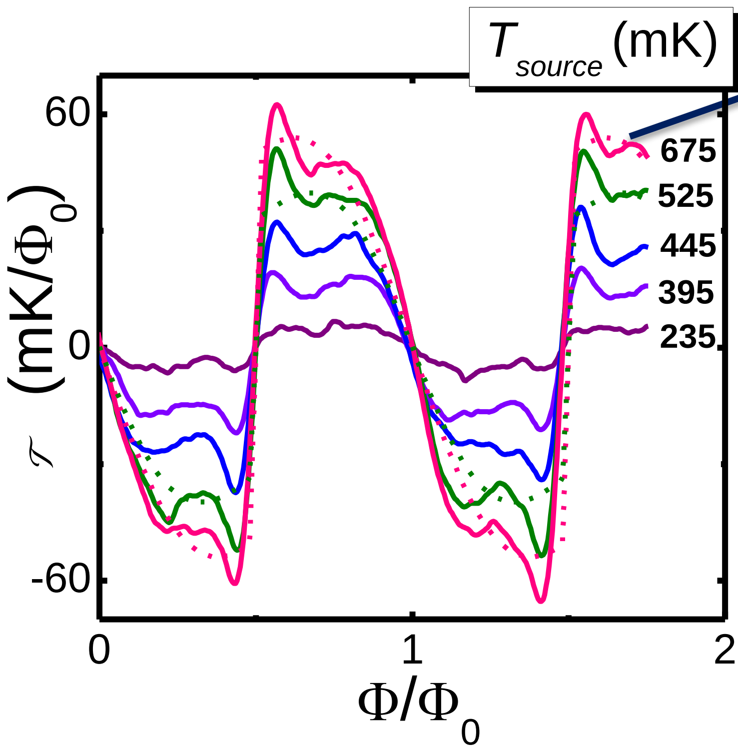


δT_{drain} ~ 1.5-2 mK
parasitic power input
(~1-5 fW)

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

Behavior @ 235 mK (ii)

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

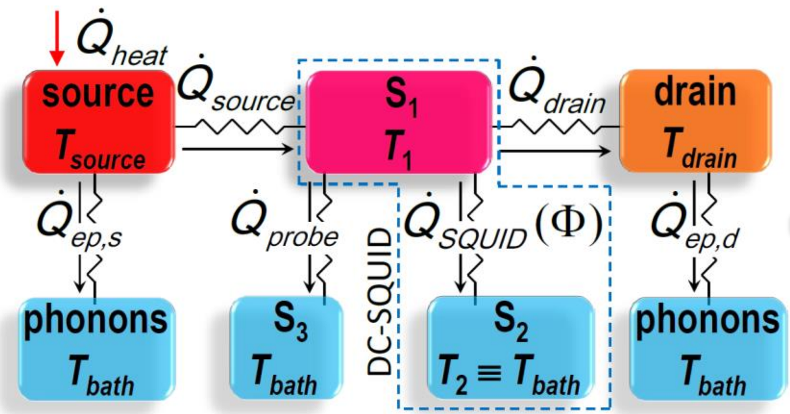


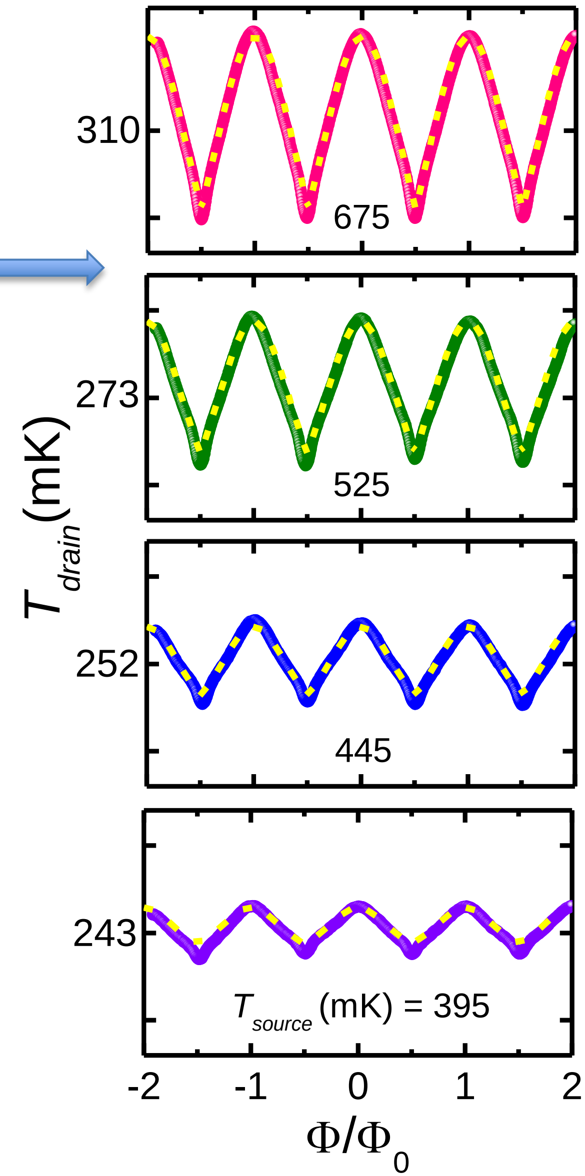
Flux-to-temperature transfer function up to ~ 60 mK/Φ_0 @ 675 mK

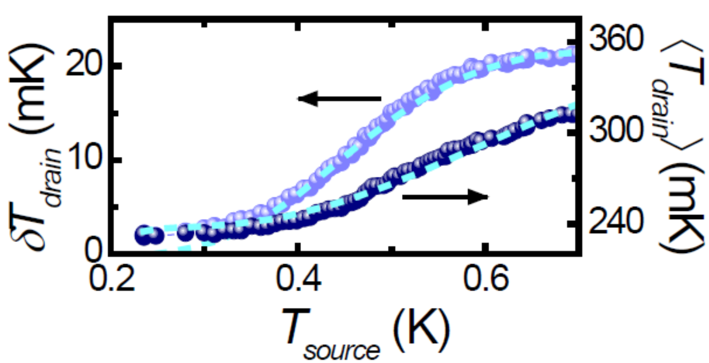
Heat interference ↔ T bias

$$\cos(\varphi_0 + 2eV_{SQUID} t / \hbar) \leftrightarrow \nu = V_{SQUID} / \Phi_0$$

Comparison to theory



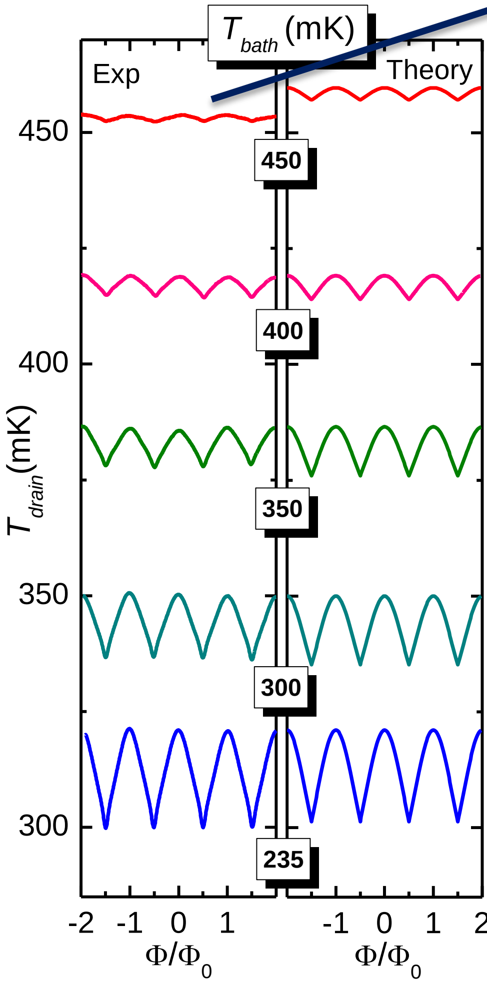




Good agreement with theoretical prediction

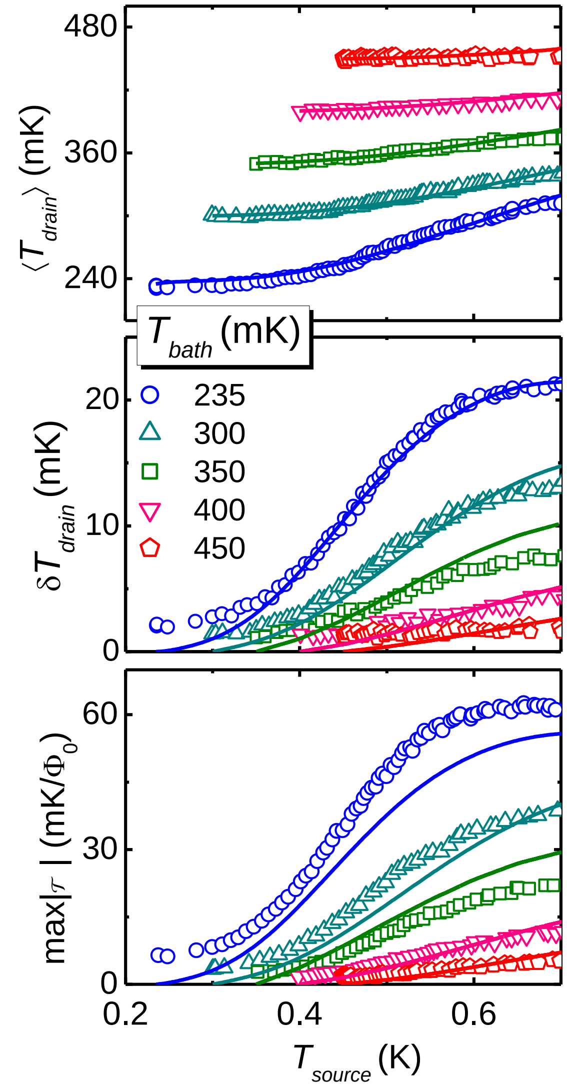
FG and M. J. Martinez-Perez, Nature **492**, 401 (2012)

Heat interferometer: bath temperature dependence



δT_{drain} ~ 2.5 mK

Suppression of δT_{drain}
&
Smearing of T_{drain}

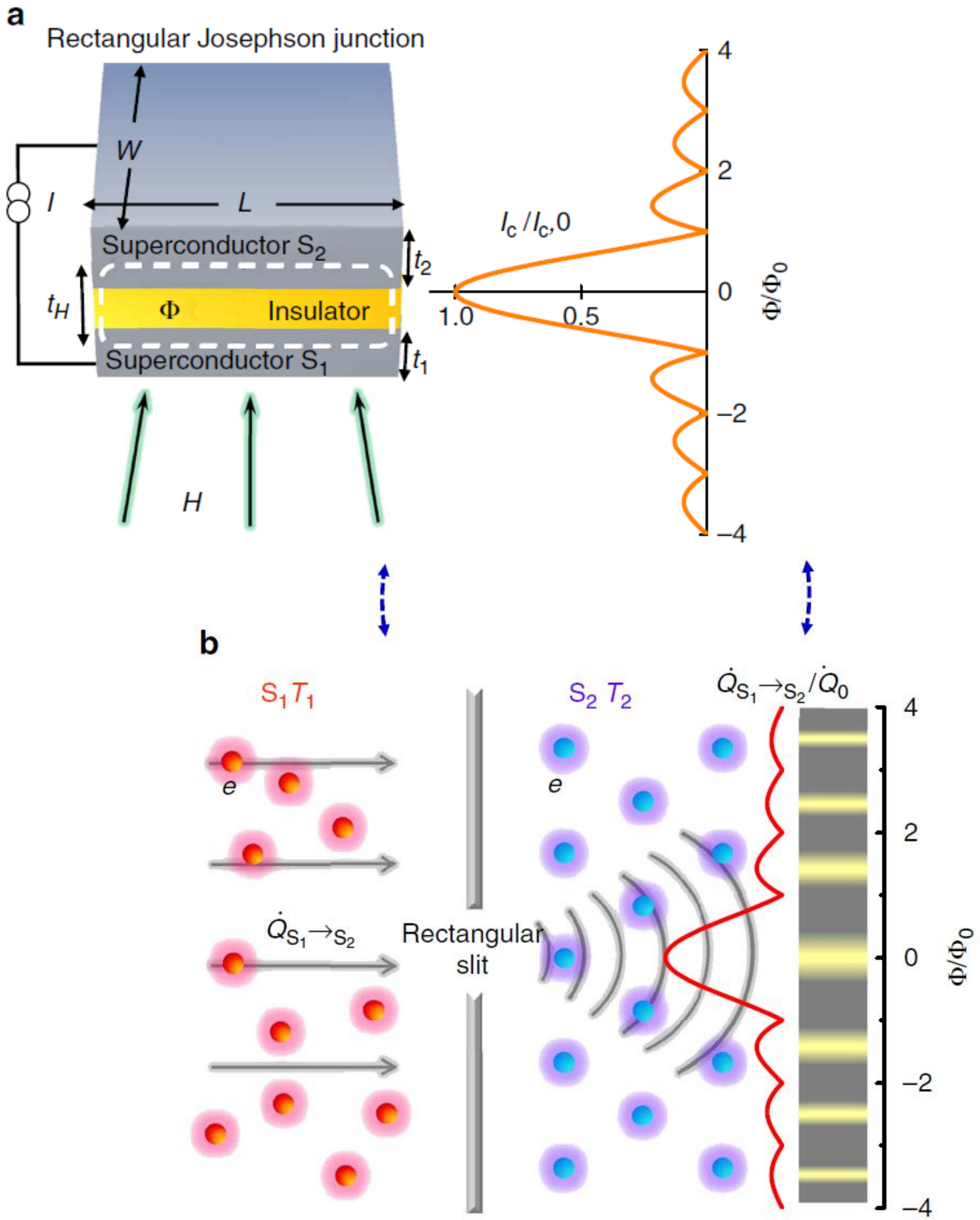


T_{source} ~ 700 mK

Heat interference disappears at ~ 500 mK

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

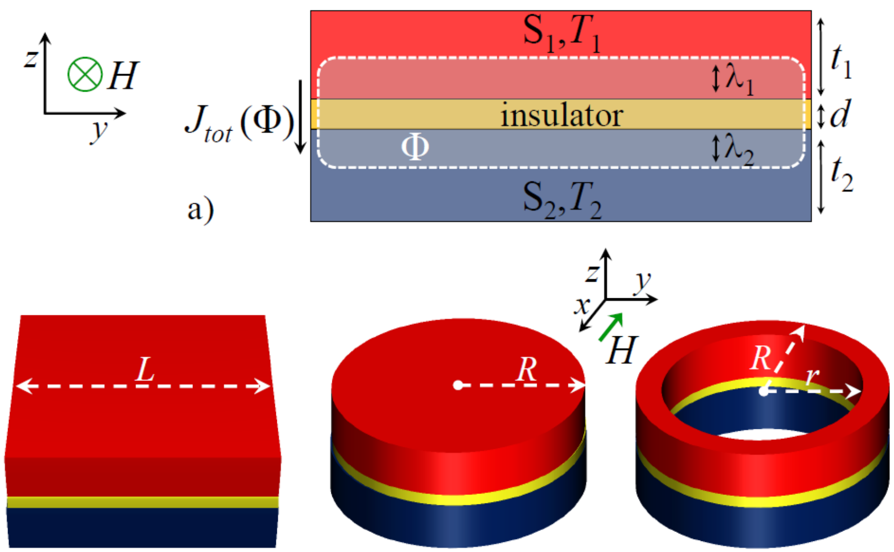
Electric vs thermal quantum diffraction



Electric diffraction through a rectangular slit

Diffraction of heat current through a rectangular slit

Heat current quantum diffraction in extended short JJs



b) rectangular c) circular d) annular

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

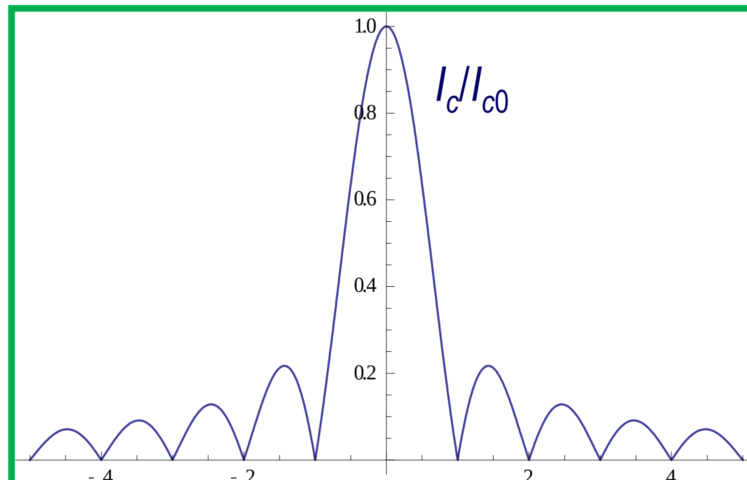
$$L \ll \lambda_J \equiv \sqrt{\frac{\Phi_0 W L}{2\mu_0 I_c \tilde{t}}}$$

Josephson critical current

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

Critical current Fraunhofer pattern for a rectangular JJ

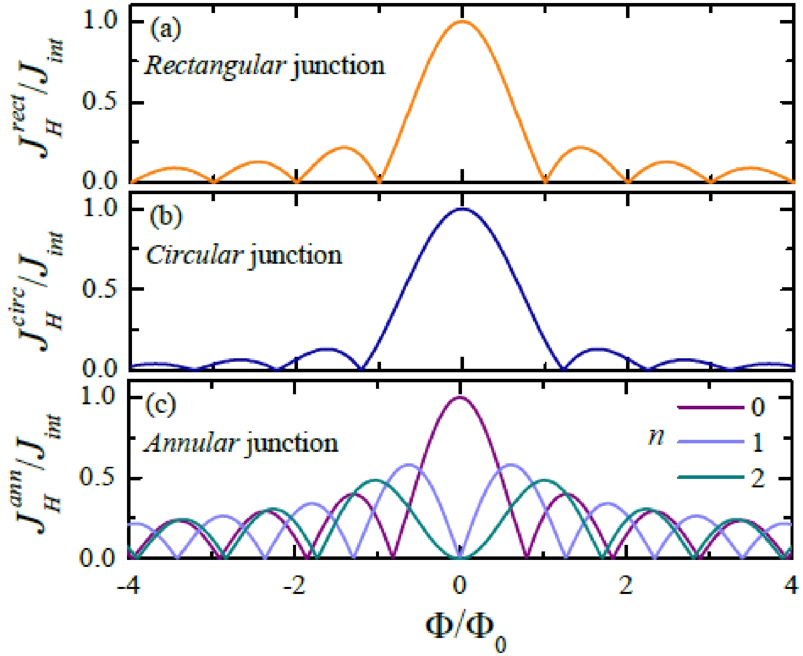
$$\frac{I_c}{I_{c0}} = |\sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)|$$



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

Heat current quantum diffraction in short JJs

$$J_{int}(\Phi) \propto |J_0 \int_{-\infty}^{\infty} g(y) \cos\left(\frac{2\pi\Phi}{\Phi_0}\frac{y}{L}\right) dy \,|$$



Interference component of thermal current

$$I_H(T_1, T_2, H) = \mathrm{Im}\left\{e^{i\varphi_0}\int_{-\infty}^{\infty} dy \mathfrak{J}(y, T_1, T_2) e^{i\kappa y}\right\} = \sin\varphi_0 \int_{-\infty}^{\infty} dy \mathfrak{J}(y) \cos\kappa y,$$

Nulling of the supercurrent

$$E_J(T_1, T_2, H) = E_{J,0} - \frac{\Phi_0}{2\pi}\mathrm{Re}\left\{e^{i\varphi_0}\int_{-\infty}^{\infty} dy \mathfrak{J}(y, T_1, T_2) e^{i\kappa y}\right\} = E_{J,0} - \frac{\Phi_0}{2\pi}\cos\varphi_0 \int_{-\infty}^{\infty} dy \mathfrak{J}(y) \cos\kappa y$$

$$E_{J,0} = \Phi_0 I_c / 2\pi$$

Minimization of Josephson coupling energy

$\varphi_0 = m\pi$, with $m = 0, \pm1, \pm2 \ldots$

φ_0 will undergo a π *slip*

S. V. Kuplevakhsky and A. M. Glukhov, Phys. Rev. B **73**, 024513 (2006)

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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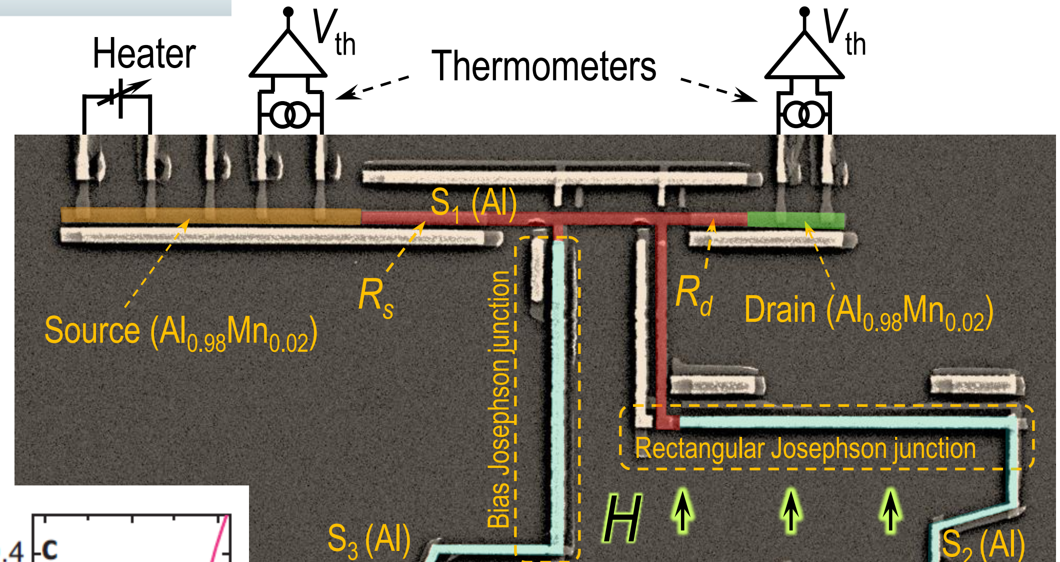
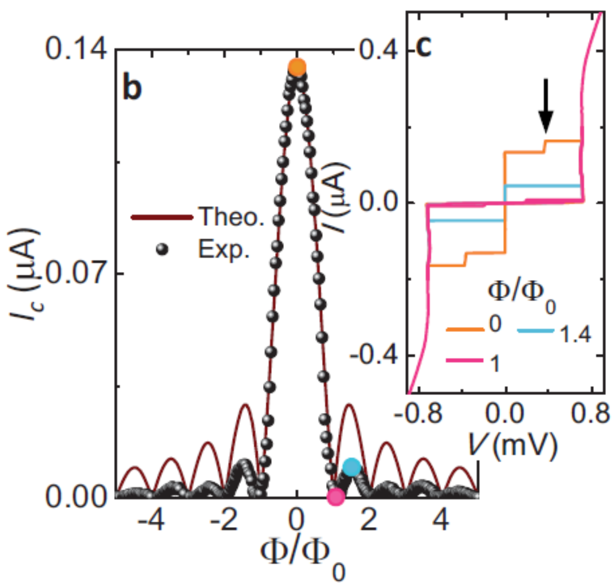
A quantum diffractor for thermal flux

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



Rectangular JJ

Magnetic interference pattern

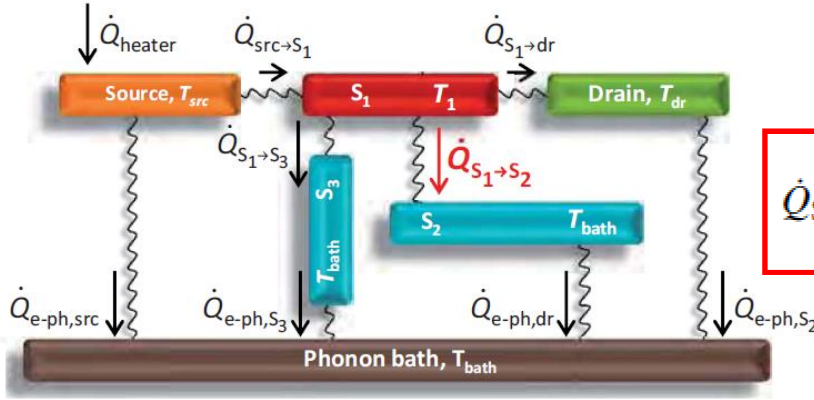


I vs V chars @ 240 mK

$I_{c,max} \approx 140$ nA

Josephson current behavior

Thermal model & expected behavior

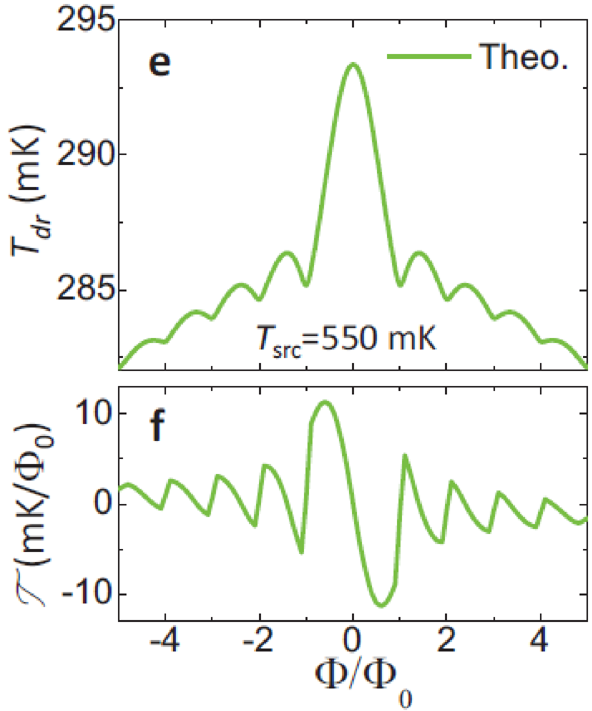


$$\dot{Q}_{S_1\rightarrow S_2} = \dot{Q}_{qp} - \dot{Q}_{int}\left|\frac{\sin(\pi\Phi/\Phi_0)}{(\pi\Phi/\Phi_0)}\right|$$

Negligible Kapitza Resistance

$T_{phonon} = T_{bath}$

The model neglects
- electron-photon coupling
- phonon heat current

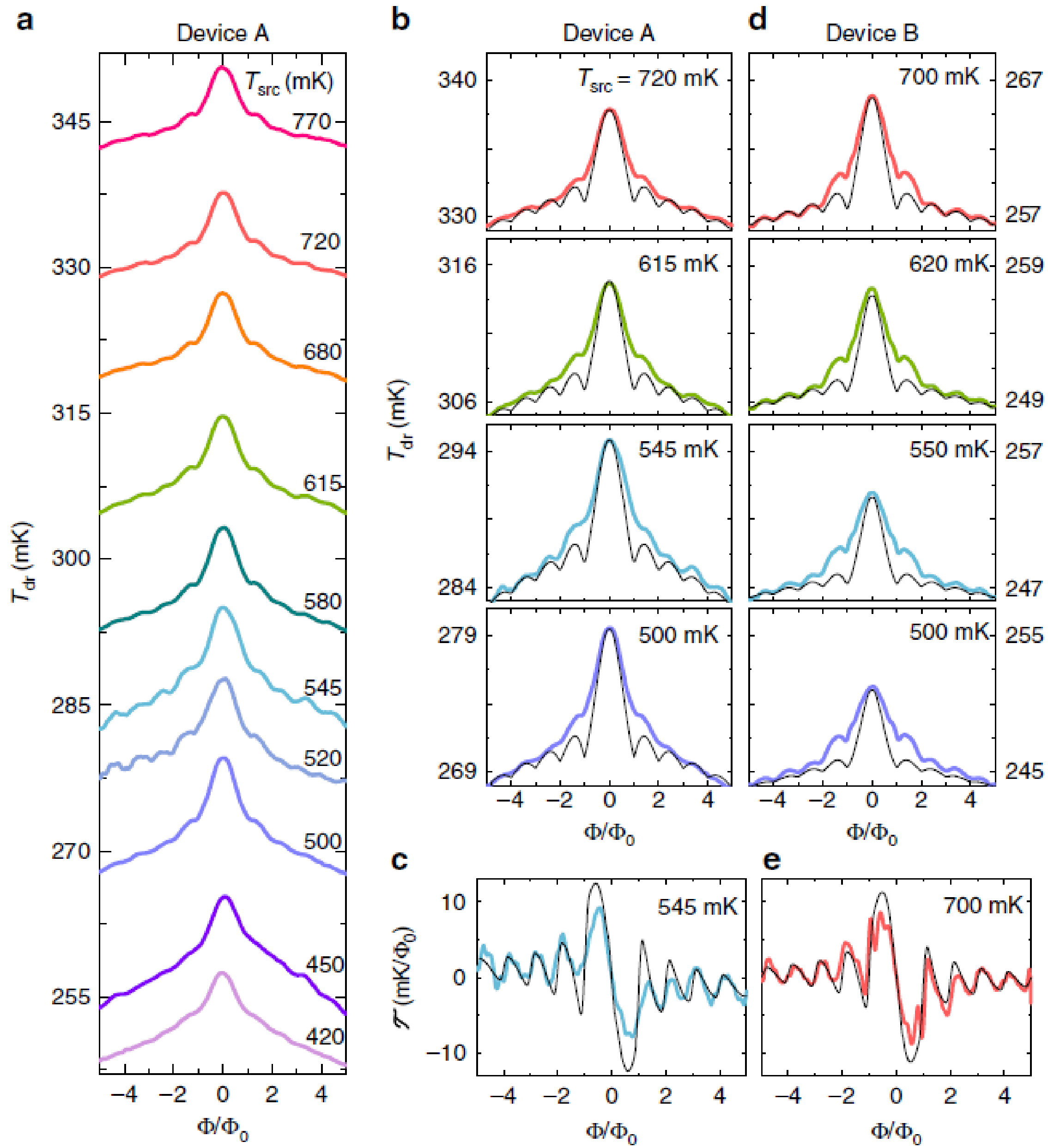


Drain temperature diffraction pattern

Flux-to-drain temperature transfer function

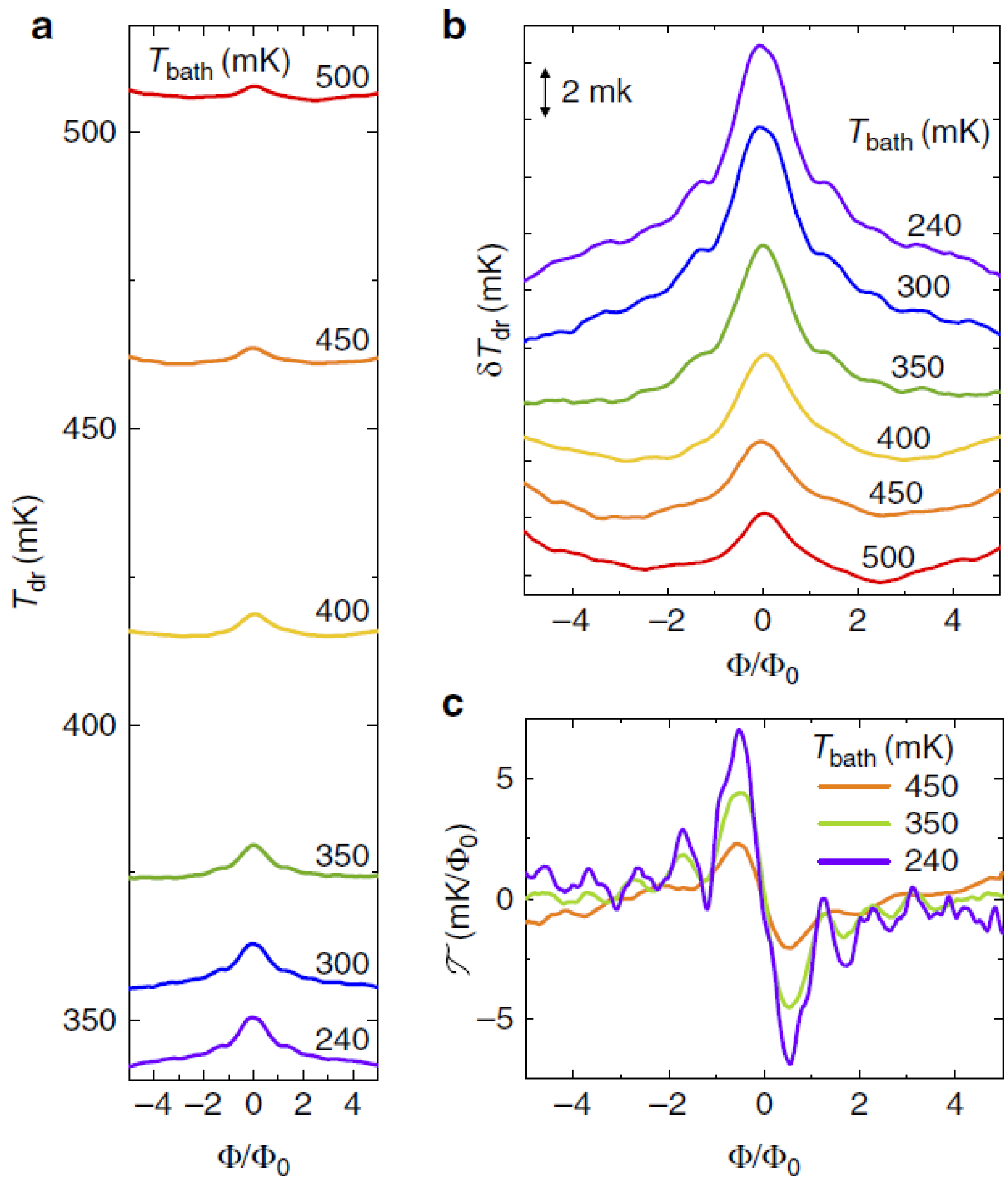
T_{bath} = 240 mK

Temperature diffraction pattern @ 240 mK



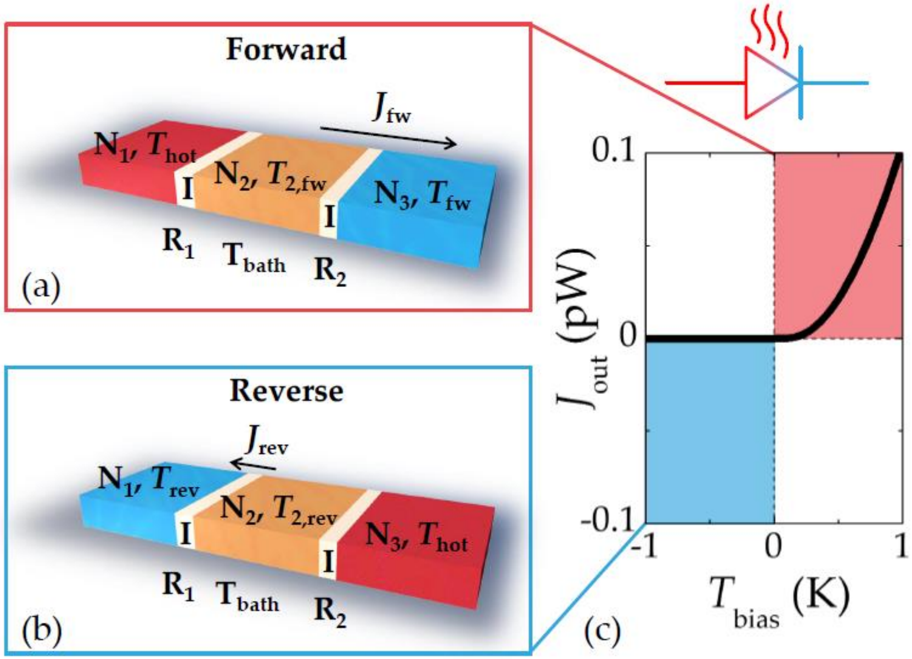
M. J. Martinez-Perez and FG, Nat. Commun. **5**, 3579 (2014)

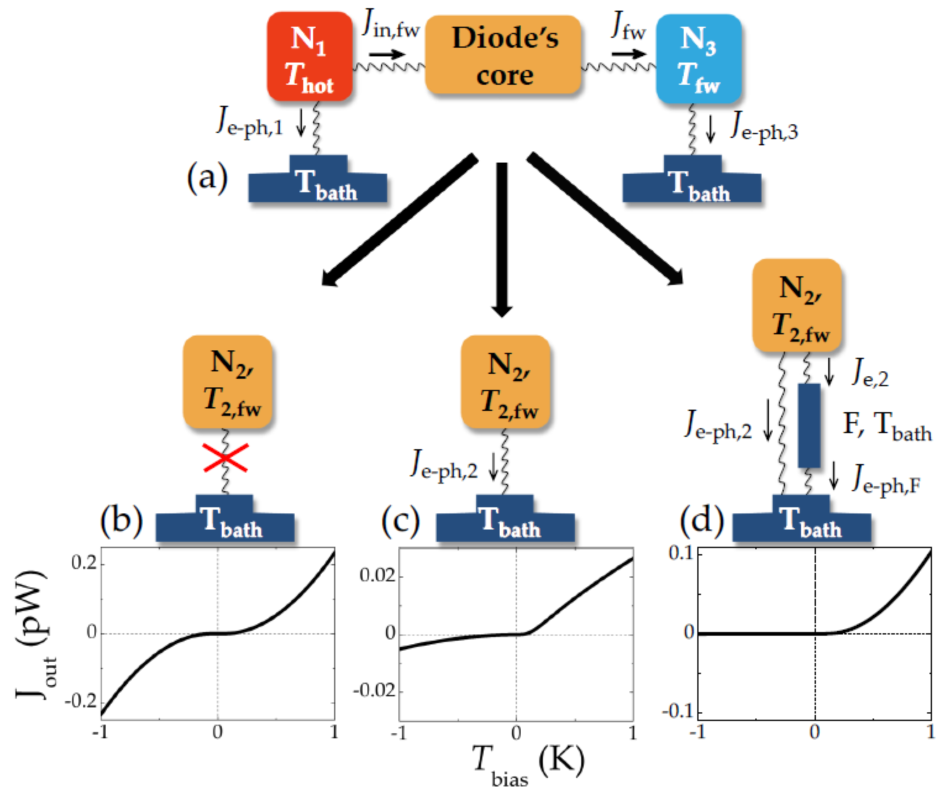
Heat diffraction: Bath temperature dependence



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

Thermal rectification with N tunnel junctions: principle





Conditions for thermal rectification:

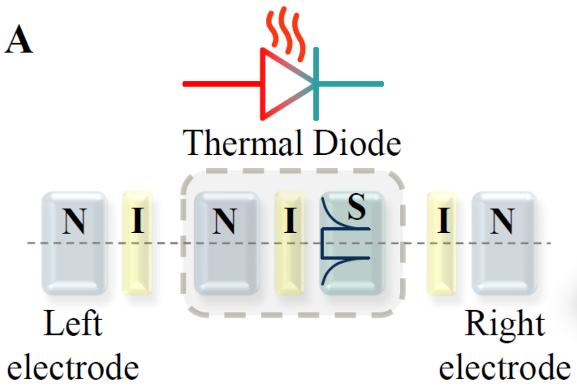
i) large tunnel resistance mismatch

ii) N_2 must be coupled to phonon bath

$$R = \frac{J_{fw}}{J_{rev}} \sim 10^3$$

A. Fornieri, M. J. Martinez-Perez and FG, APL **104**, 183108 (2014)

An ultraefficient hybrid thermal rectifier



Hybrid heat diode concept

nature nanotechnology LETTERS
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Rectification of electronic heat current by a hybrid thermal diode

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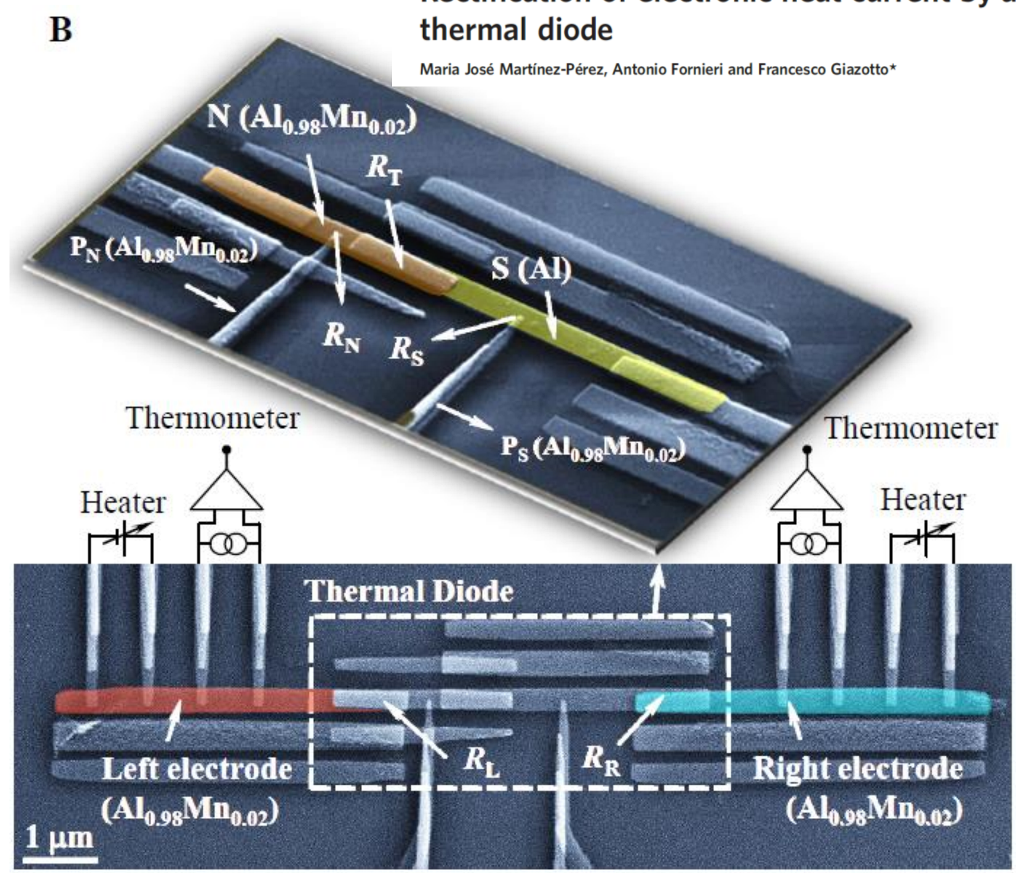
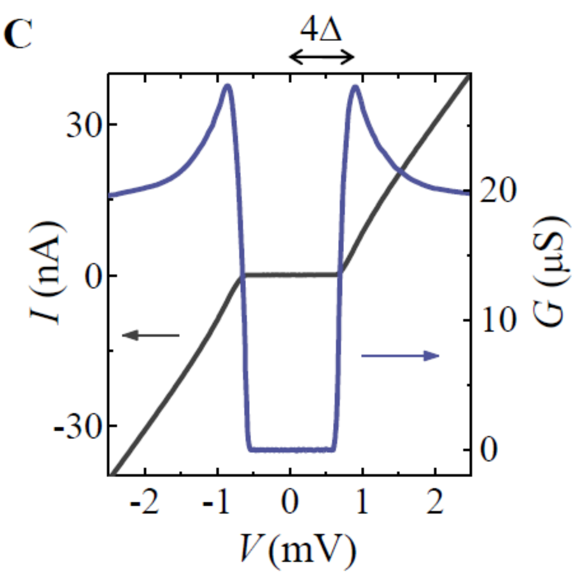


Experimental structure



G vs V char @ 50 mK

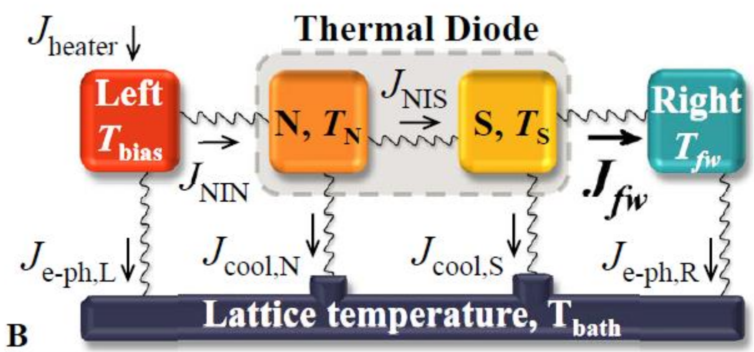
Full symmetry from the electrical point of view

M. J. Martinez-Perez, A. Fornieri, and FG, Nat. Nanotechnol. **10**, 303 (2015);
FG and F. S. Bergeret, APL **103**, 242602 (2013); M. J. Martinez-Perez and FG, APL **102**, 182602 (2013).

Asymmetrical thermal transport

Directional thermal current mismatch

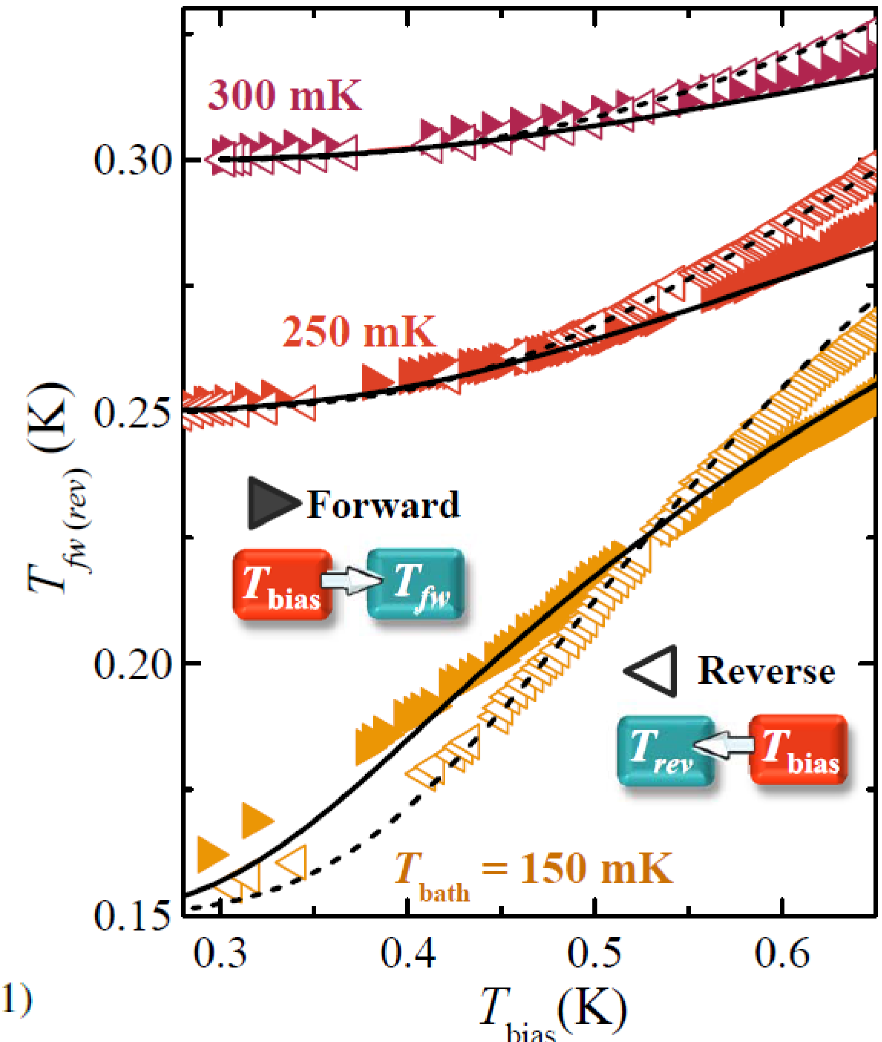
Thermal model



$$J_{\text{NIN}}(T_{\text{bias}}, T_{\text{N}}) - J_{\text{cool,N}}(T_{\text{N}}, T_{\text{bath}}) - J_{\text{NIS}}(T_{\text{N}}, T_{\text{S}}) = 0, \quad (1)$$

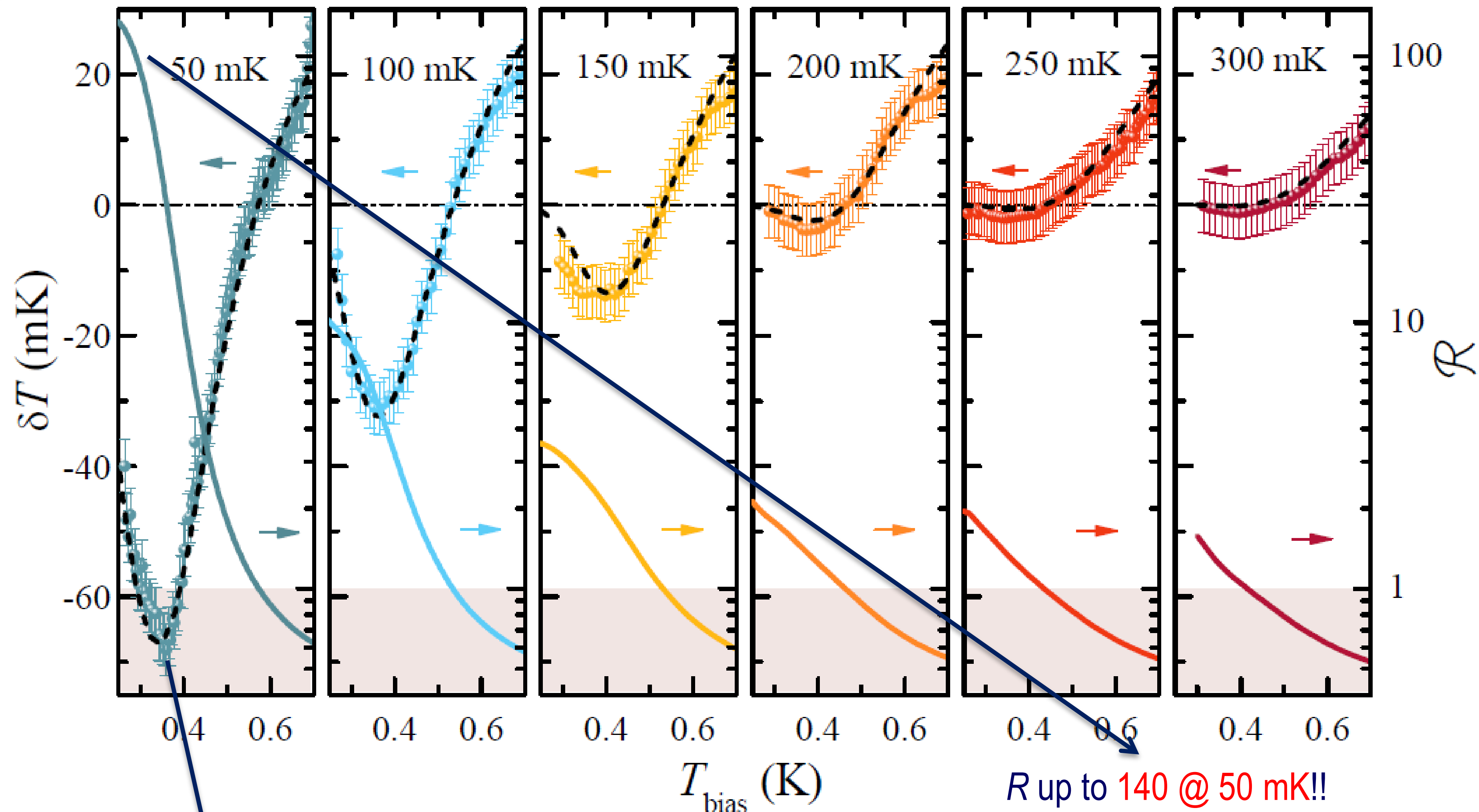
$$J_{\text{NIS}}(T_{\text{N}}, T_{\text{S}}) - J_{\text{cool,S}}(T_{\text{S}}, T_{\text{bath}}) - J_{fw}(T_{\text{S}}, T_{fw}) = 0, \quad (2)$$

$$J_{fw}(T_{\text{S}}, T_{fw}) - J_{\text{e-ph,R}}(T_{fw}, T_{\text{bath}}) = 0. \quad (3)$$



M. J. Martinez-Perez, A. Fornieri, and FG, Nat. Nanotechnol. **10**, 303 (2015)

Ultra-efficient thermal rectification



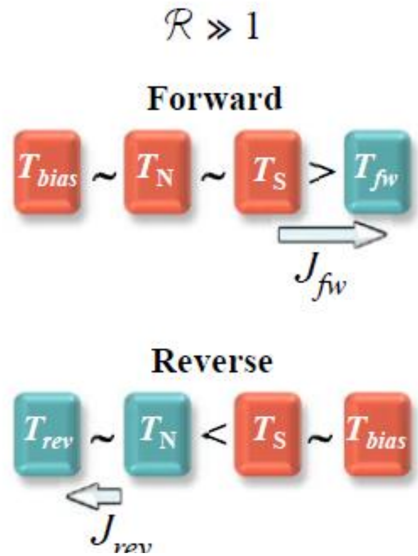
R up to 140 @ 50 mK!!

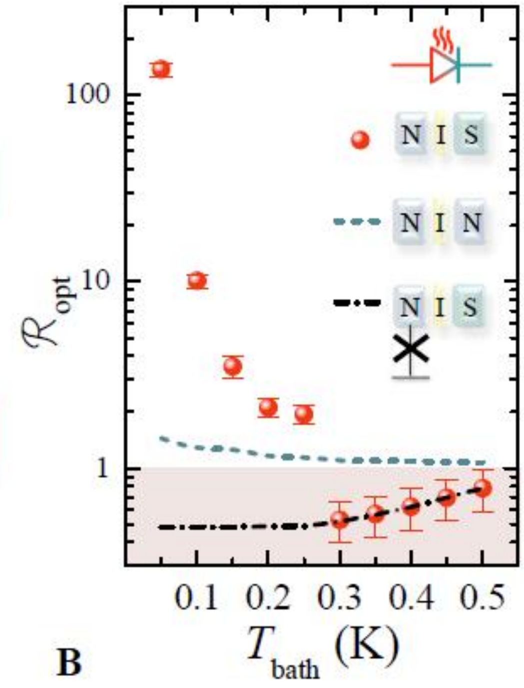
δT up to 60 mK @ T_{bath} = 50 mK

(to be compared to *R* ~ 1)

M. J. Martinez-Perez, A. Fornieri, and FG, Nat. Nanotechnol. **10**, 303 (2015)

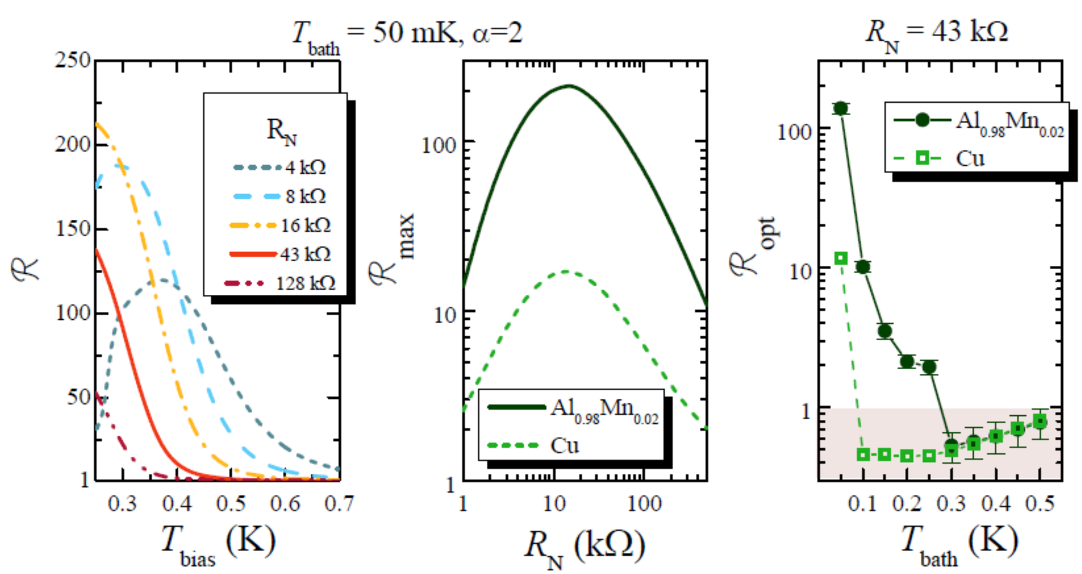
Ultra-efficient thermal rectification: comparison





Mechanism & role of

different structure elements



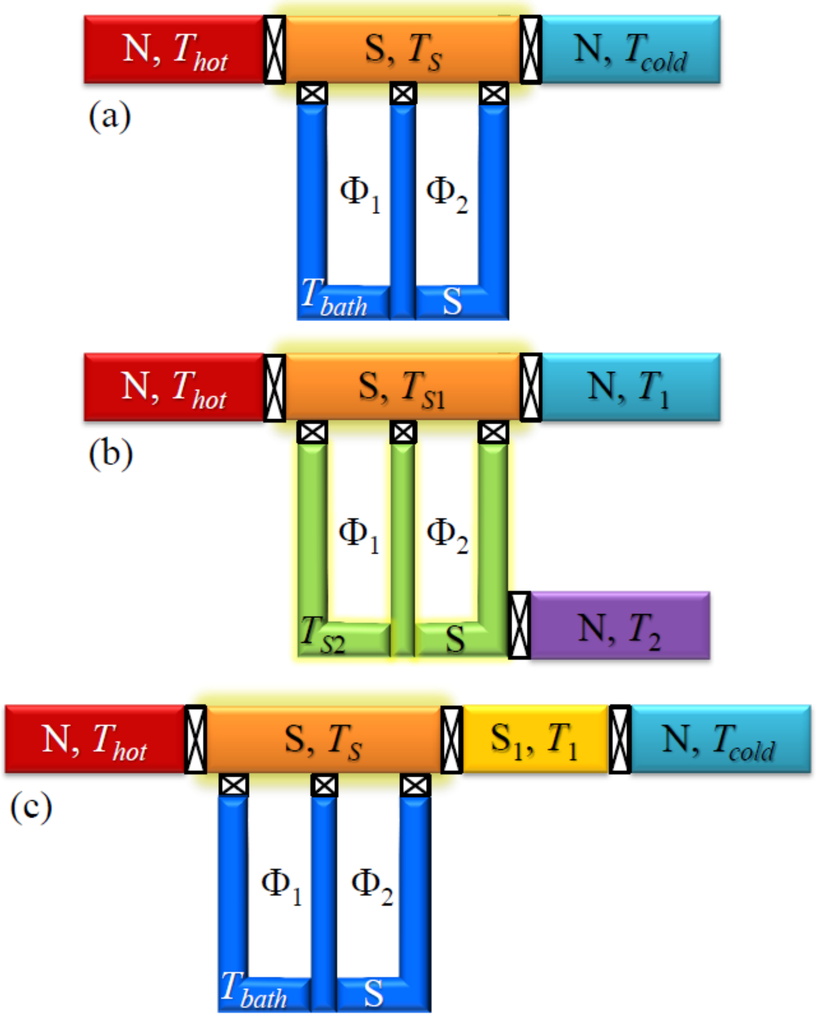
Role of probe & N material type

M. J. Martinez-Perez, A. Fornieri, and FG, Nat. Nanotechnol. **10**, 303 (2015)

Conclusions

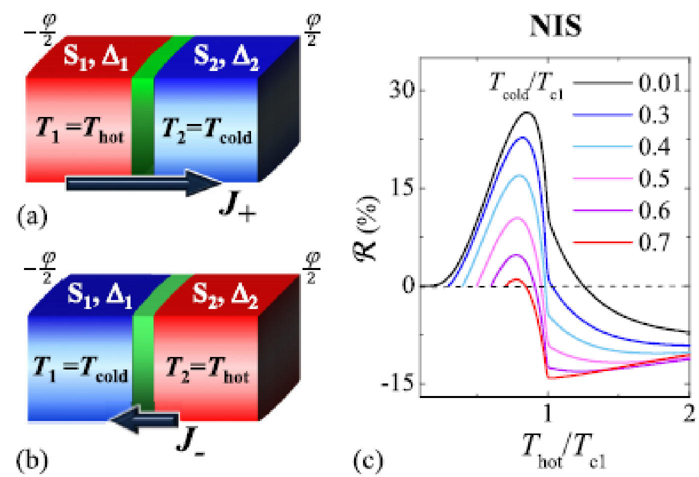
1. Realization of a heat interferometer
2. Confirmation of the existence, magnitude and sign of the phase-dependent heat current
3. Realization of a quantum diffractor for thermal flux
4. Complementary proof of the “thermal” Josephson effect
5. Realization of an ultraeficient low-temperature hybrid thermal rectifier (with very large $R \sim 140$)
6. Novel “coherent caloritronic” devices

Perspective for "coherent caloritronic" devices



Heat transistors or
phase-tunable electron coolers

Heat splitters



Heat rectifiers (diodes)

M. J. Martinez-Perez and FG, APL **102**, 182602 (2013); FG and F. S. Bergeret, APL **103**, 242602 (2013);
A. Fornieri, M. J. Martinez-Perez and FG, APL **104**, 183108 (2014)