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Phase-dependent heat transport with unconventional superconductors

Alexander Bauer and Björn Sothmann ▪ 09.05.2019

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Capri Spring School on Transport 2019

Phase-coherent transport at the nanoscale

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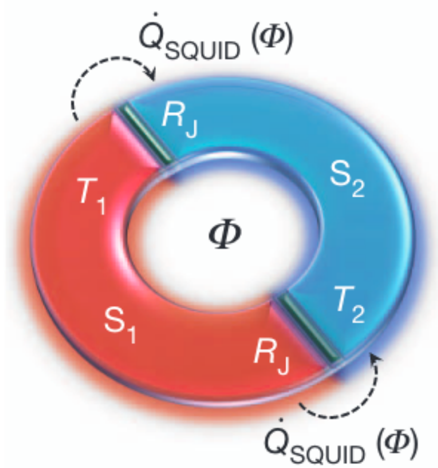


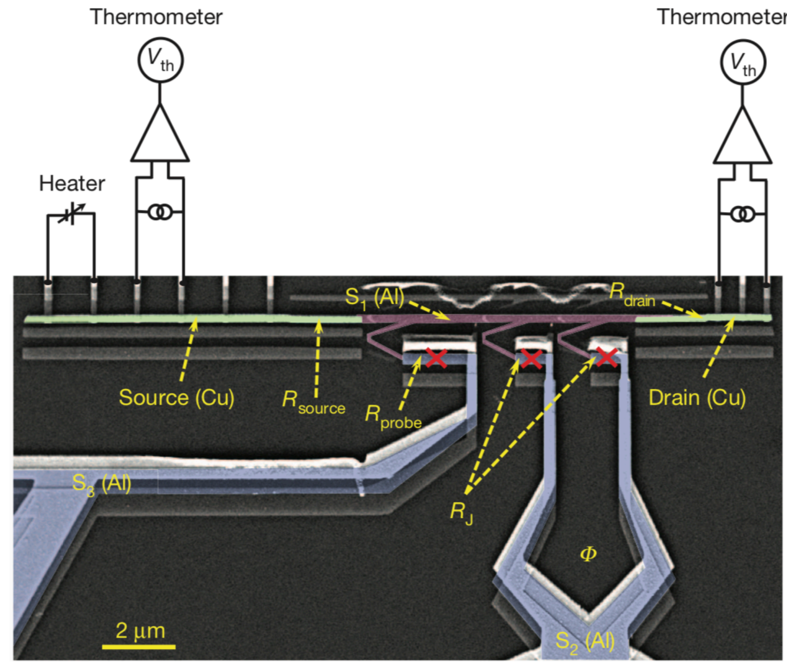
- Heat current in thermally biased Josephson Junction [1]

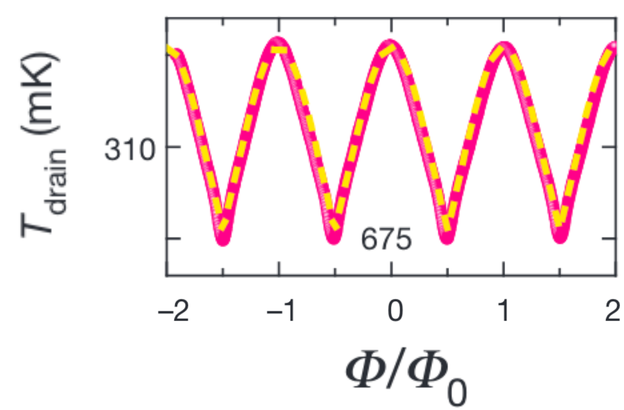
$$I_h = I_0 + I_1 \cos(\phi)$$

I_0 : conv. quasiparticle transport

I_1 : Andreev like transport

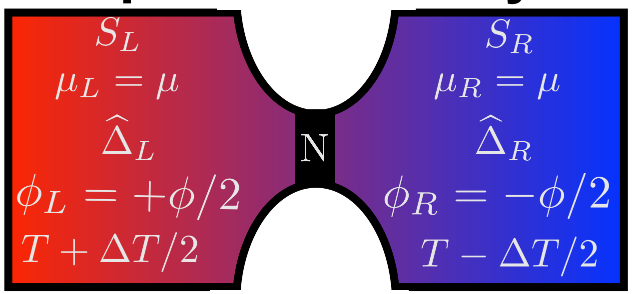
- Experimentally verified by Giazotto et. Al [2]
- Of interest for caloritronic applications





[1] K. Maki and A. Griffin, Phys. Rev. Lett. 16 , 258 (1966).
[2] F. Giazotto and M. J. Martínez-Pérez, Nature 492 , 401 (2012).

Using phase-coherent to probe unconventional superconductivity ?



Short S-N-S junction

Description of p-wave pairing

$$\Delta(\mathbf{k}) = -\Delta(-\mathbf{k}) = \begin{pmatrix} \Delta_{\uparrow,\uparrow}(\mathbf{k}) & \Delta_{\uparrow,\downarrow}(\mathbf{k}) \\ \Delta_{\downarrow,\uparrow}(\mathbf{k}) & \Delta_{\downarrow,\downarrow}(\mathbf{k}) \end{pmatrix}$$

Balian Werthammer vector

$$\Delta(\mathbf{k}) = \mathbf{d}(\mathbf{k}) \cdot \boldsymbol{\sigma} i\sigma_y = \begin{pmatrix} -d_x(\mathbf{k}) + i\, d_y(\mathbf{k}) & d_z(\mathbf{k}) \\ d_z(\mathbf{k}) & d_x(\mathbf{k}) + i\, d_y(\mathbf{k}) \end{pmatrix}$$

$$H_{\mathrm{BdG}}(\mathbf{k}) = \begin{pmatrix} \sigma_0 \otimes \left[\frac{\hbar^2 \mathbf{k}^2}{2m} - \mu\right] & \Delta(\mathbf{k}) \\ -\Delta^\star(-\mathbf{k}) & \sigma_0 \otimes \left[-\frac{\hbar^2 \mathbf{k}^2}{2m} + \mu\right] \end{pmatrix}$$

↓

Scattering states

↓

Matching→Transmissionfunction $\mathcal{T}$

↓

Thermal conductance in linear response

↓

$$\kappa = \frac{\partial Q}{\partial t} / \Delta T = \frac{1}{h} \int_{|\Delta_0|}^{+\infty} \epsilon\, \mathcal{T}(\phi, \epsilon) \frac{df}{dT}\, d\epsilon$$

Helical pairing (e.g. He^3 B-phase)

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Helical p-wave pairing

$$\mathbf{d}(\mathbf{k}) = -\mathbf{d}(-\mathbf{k}) = \Delta_0/k_F\,(k_x, k_y, k_z)^T$$

$$\hat{\Delta}(\mathbf{k}) = \Delta_0/k_F \begin{pmatrix} -k_x + ik_y & k_z \\ k_z & k_x + ik_y \end{pmatrix}$$

TR invariant

$$TH(\mathbf{k})T^{-1} = H(-\mathbf{k})$$

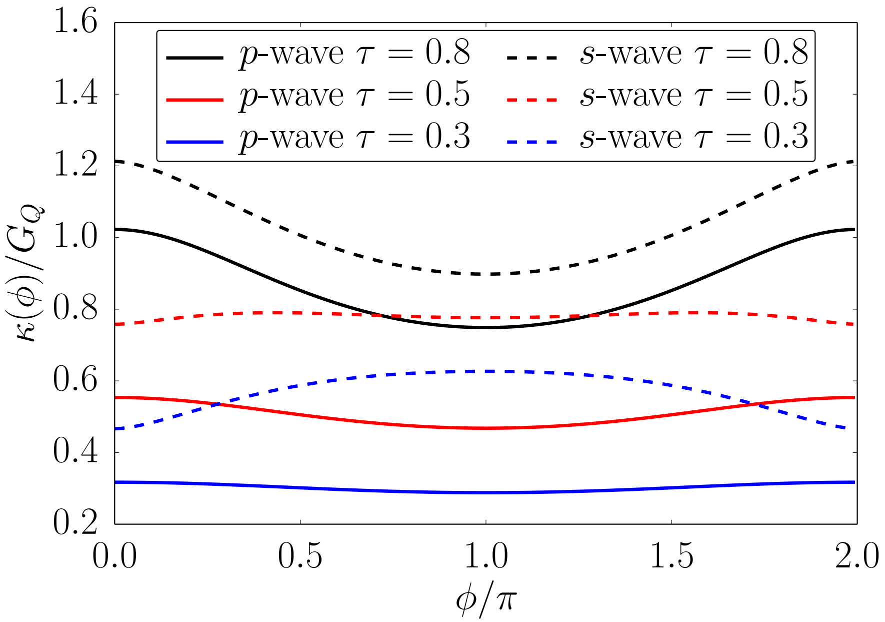
isotropic in k-space

$$\mathrm{Tr}(\Delta(\mathbf{k})^\dagger \Delta(\mathbf{k})) = |\Delta_0|^2$$

1D transport : helical p-wave vs s-wave pairing for var. transmission

Thermal conductance

$$\kappa(\phi) = \int_{|\Delta_0|}^{+\infty} d\epsilon\, \epsilon\, \mathcal{T}(\phi,\epsilon)\, \frac{df}{dT}$$



Helical pairing (e.g. He^3 B-phase)

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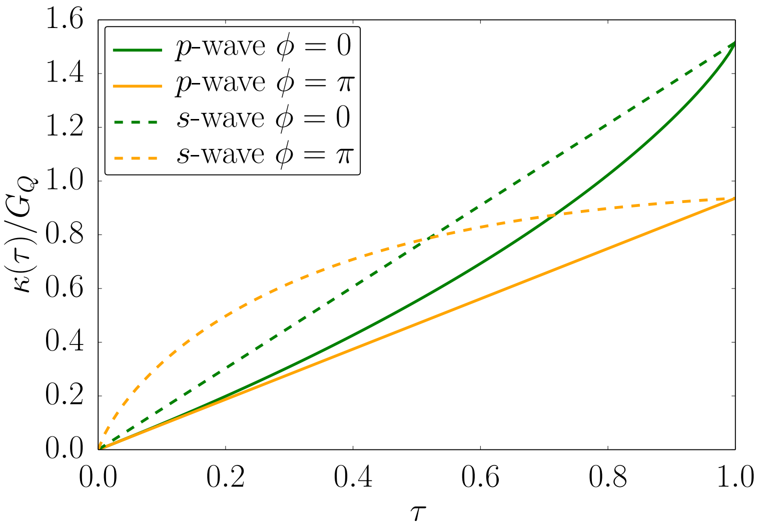
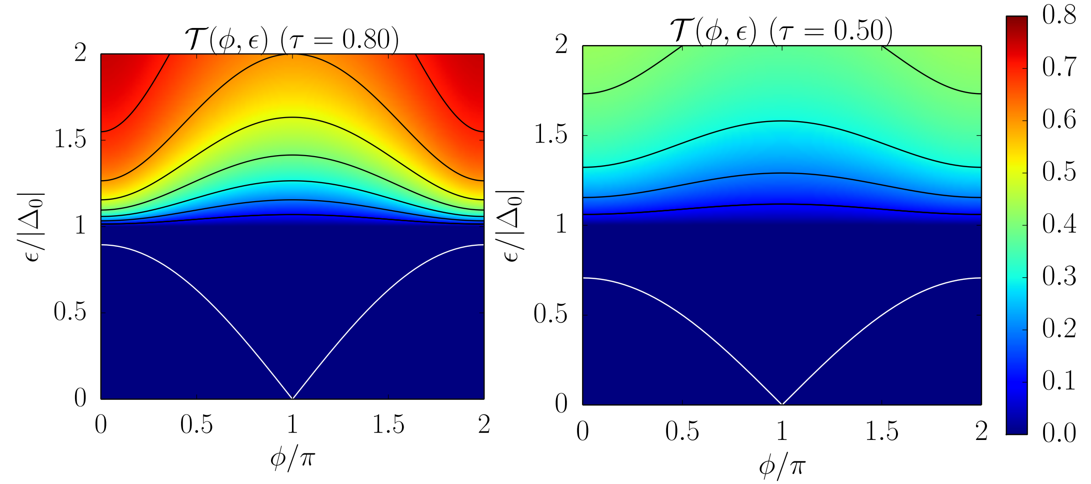
$$\kappa(\phi) = \int_{|\Delta_0|}^{+\infty} d\epsilon \; \epsilon \, \mathcal{T}(\phi, \epsilon) \; \frac{df}{dT}$$

$$\mathcal{T}_{p-wave} = \frac{\epsilon^2 - |\Delta_0|^2}{\epsilon^2/\tau - |\Delta_0|^2 \cos^2(\phi/2)}$$

varying transmission τ of the normal state





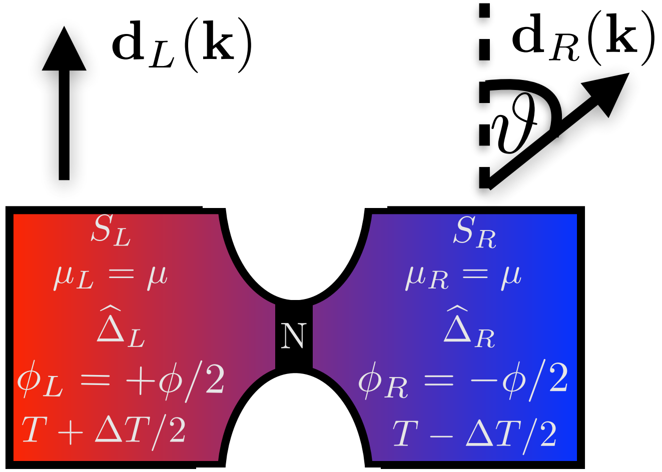
Majorana modes below the gap are related to minimum of $\mathcal{T}$

$$E^{ABS}_{p-wave} = \pm|\Delta_0|\sqrt{\tau}\cos(\phi/2)$$

s-wave: crossover of minima and maxima

p-wave: always minimum $\phi = \pi$

Chiral pairing (e.g. He^3 A-phase,Sr_2RuO_4)



Chiral p-wave pairing

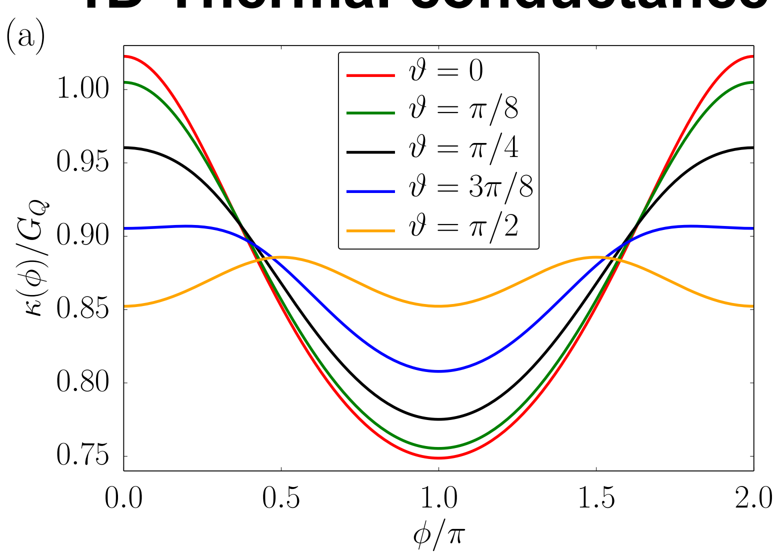
$$\mathbf{d}(\mathbf{k}) = -\mathbf{d}(-\mathbf{k}) = \Delta_0/k_F\ (k_x + i\,k_y)\mathbf{e}_i$$

No TR invariance

$$TH(\mathbf{k})T^{-1} \neq H(-\mathbf{k})$$

anisotropic in k-space

1D Thermal conductance

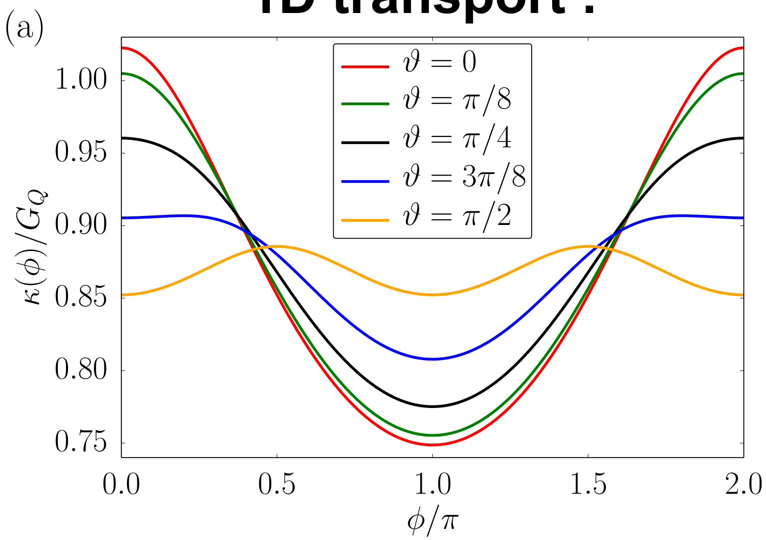


-Relative orientation of d-vector has impact on transport properties

-Possibility to interchange from 2π to π periodicity

Chiral pairing (e.g. He^3 A-phase, Sr_2RuO_4)

1D transport :



$$\hat{\Delta}(\vec{k}) = \begin{pmatrix} \Delta_{\uparrow,\uparrow}(\vec{k}) & \Delta_{\uparrow,\downarrow}(\vec{k}) \\ \Delta_{\downarrow,\uparrow}(\vec{k}) & \Delta_{\downarrow,\downarrow}(\vec{k}) \end{pmatrix}$$

$$\vartheta = 0 \rightarrow \mathbf{d}_L(\mathbf{k}) = \mathbf{d}_R(\mathbf{k})$$

$$\hat{\Delta}_L(\mathbf{k}) = \hat{\Delta}_R(\mathbf{k}) = \begin{pmatrix} 0 & k_x + ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

2π-periodic single Cooper pair transport

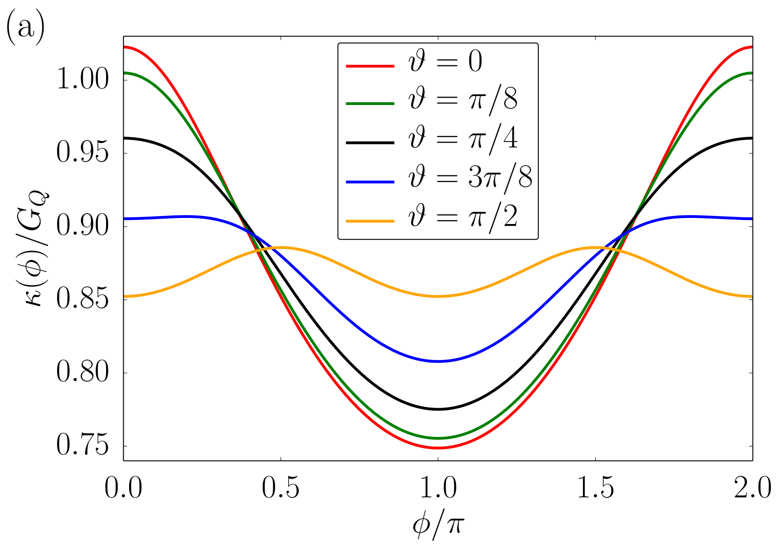
$$\vartheta = \pi/2$$

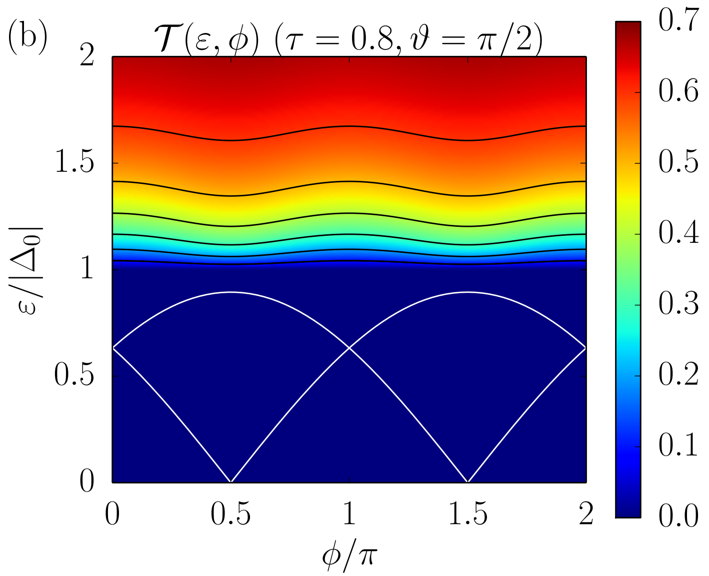
$$\hat{\Delta}_L(\mathbf{k}) = \begin{pmatrix} 0 & k_x + ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

$$\hat{\Delta}_R(\mathbf{k}) = \begin{pmatrix} -(k_x + ik_y) & 0 \\ 0 & k_x + ik_y \end{pmatrix}$$

π-periodic double Cooper pair transport

Alternatively understanding by the ABS structure





$$\vartheta = \pi/2$$

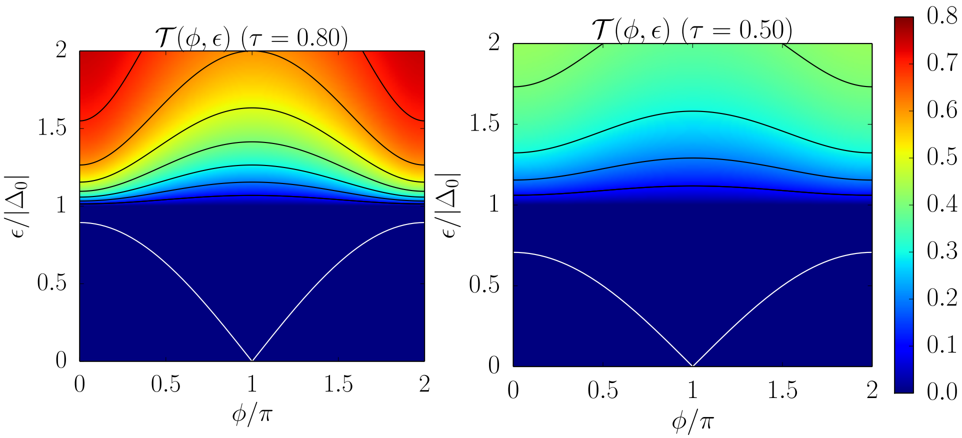
$$\hat{\Delta}_L(\mathbf{k}) = \begin{pmatrix} 0 & k_x + ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

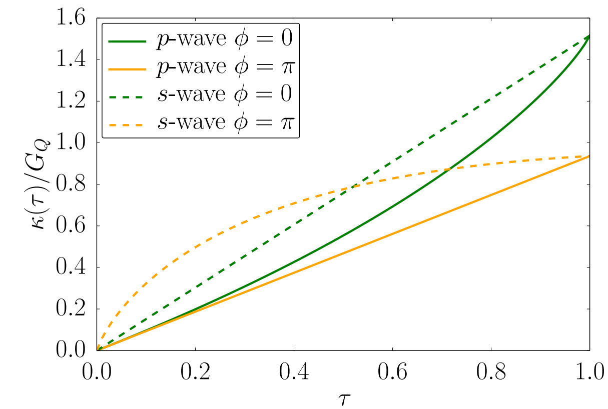
$$\hat{\Delta}_R(\mathbf{k}) = \begin{pmatrix} -(k_x + ik_y) & 0 \\ 0 & k_x + ik_y \end{pmatrix}$$

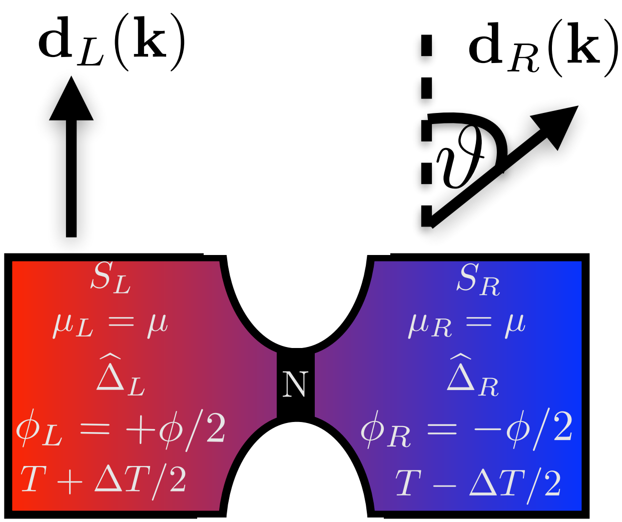
$$E^{\mathrm{ABS}} = \pm|\Delta_0|\sqrt{\tau}\cos(\phi/2 + \pi/4)$$
$$E^{\mathrm{ABS}} = \pm|\Delta_0|\sqrt{\tau}\cos(\phi/2 - \pi/4)$$

Conclusion

Presence of Majorana bound states affect thermal transport signatures







Possibility to distinguish different types of unconventional pairing symmetries from each other