אוניברסיטת בן-גוריון בנגב
Ben-Gurion University of the Negev

Yaakov Kleeorin

Yigal Meir

Yonatan Dubi

Ben Gurion University of the Negev,
Beer Sheva, Israel

F .Giazotto (Scoula Normale Superiore di Pisa)

O. Entin-Wohlman (Ben Gurion University)

Large Tunable Thermo-phase in SC-QD-SC Junction

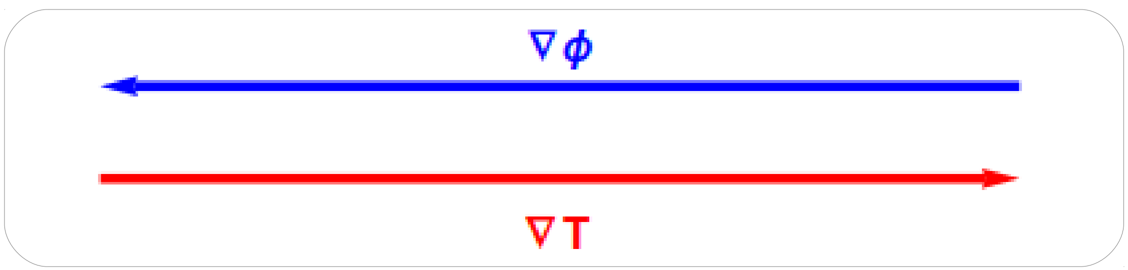
Thermoelectricity

The electric response due to thermal gradients

- An emerging player in energy conversion and **production**
- A powerful tool in **probing** strongly correlated effects

Thermoelectricity in Superconductors

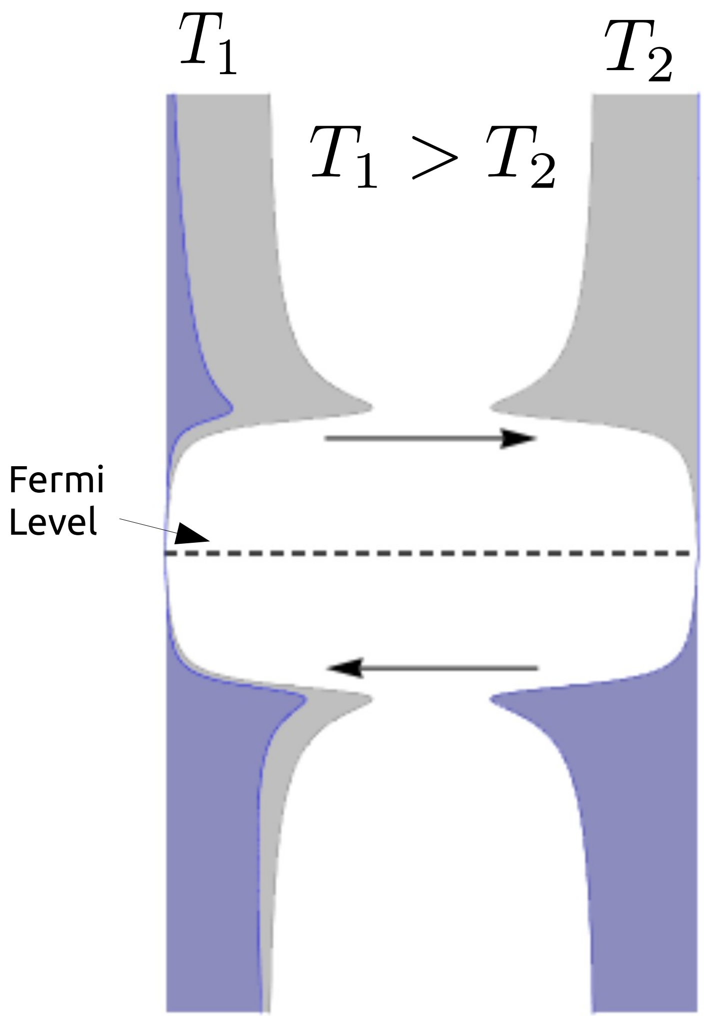
- Thermoelectricity in SC was long considered **absent**:
  - The SC induces **thermo-phase** instead of thermoelectricity under temperature gradients



$$J_c \sin(\Delta\phi)$$
$$L_T \Delta T$$

  - The SC in inherently **particle-hole symmetric**
  - Theory ~40's   Experiment ~ 70's

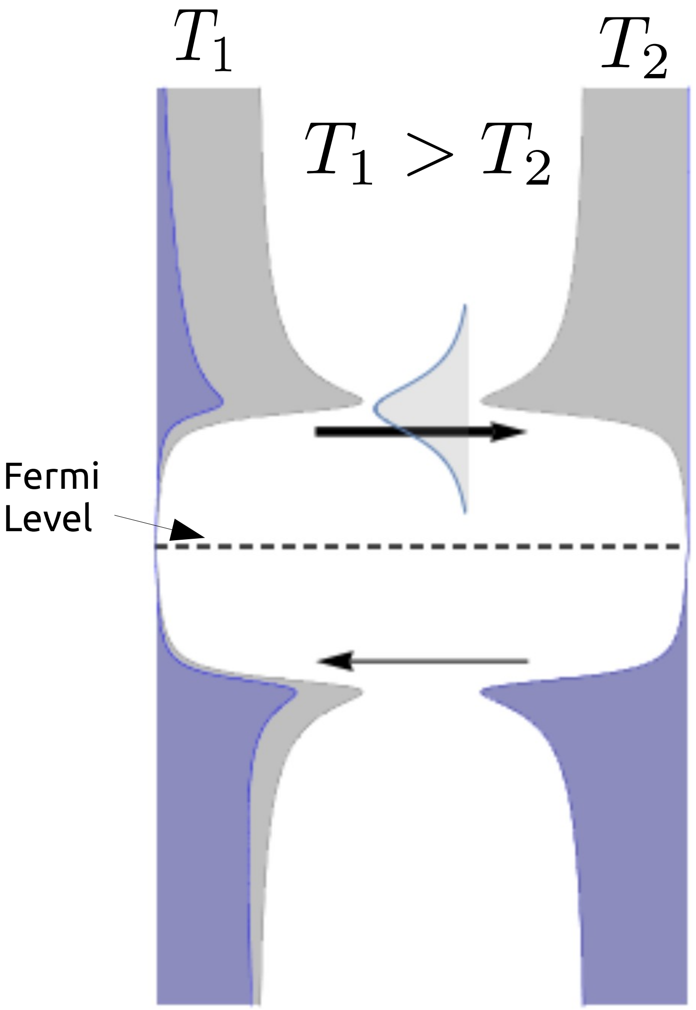
The SC-I-SC Junction



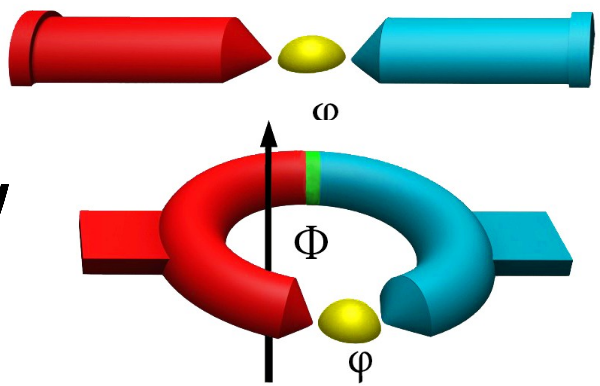
- p-h symmetric
- Any assymetry would come from impurities
- Rather well studied (The,Exp)

Small thermal response, mainly around the transition temperature

The SC-QD-SC Junction

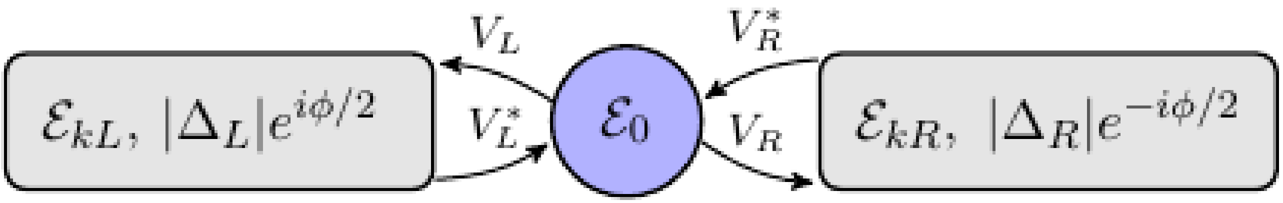


- Offering tunable p-h symmetry breaking
- Offering substantial thermal response
- Experimentally relevant [1,2]



  - [1] Giazotto et al, Nat Nano 11, 258–262 (2016)
  - [2] De Franceschi et al, Nat Nano 5, 703–711 (2010)

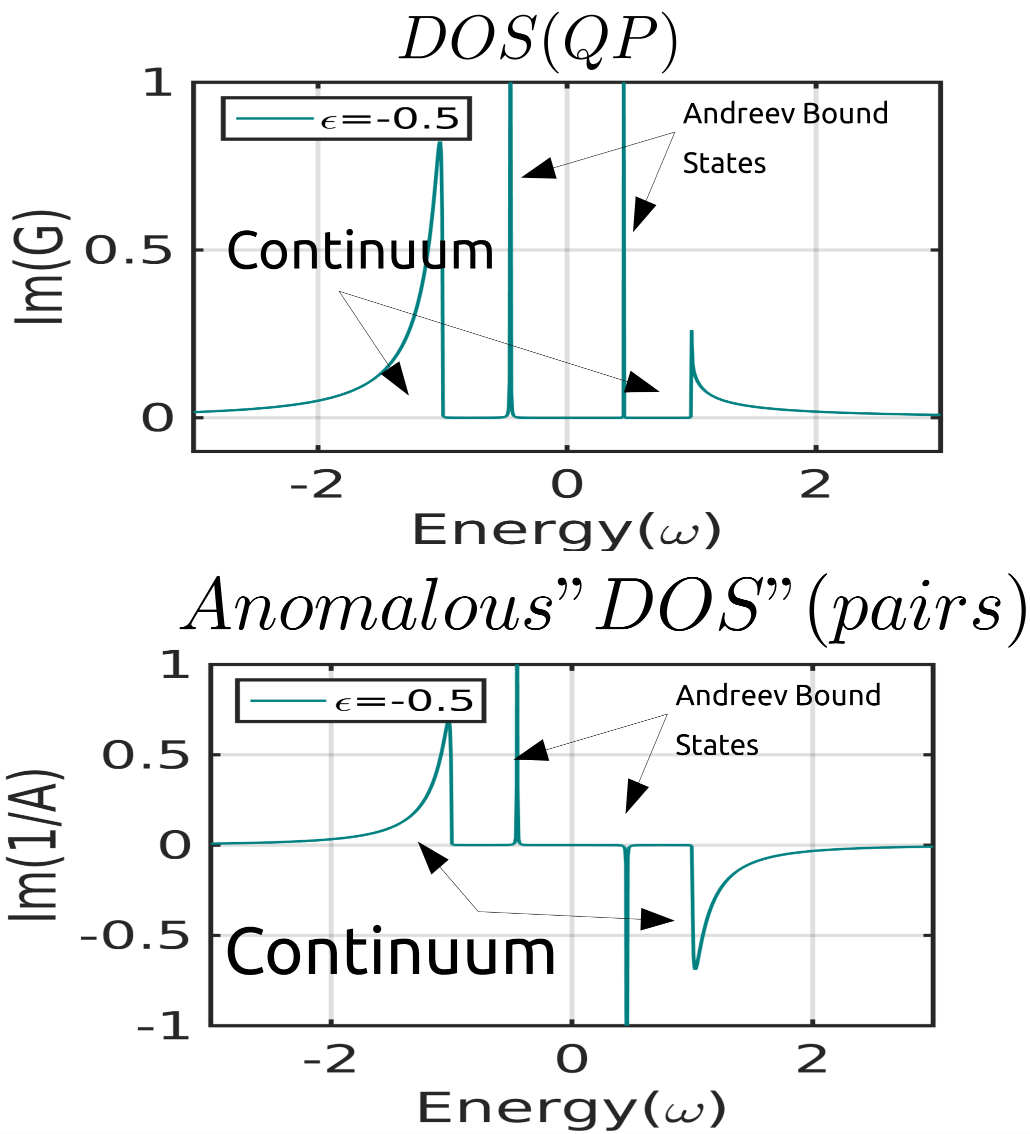
Model and Methods



- An energy level between two SC reservoirs
- We apply a temperature gradient
- Using the Keldysh non-eq Greens Function we calculate the thermal response
- We get: $I(\phi,\ \Delta T,\ T_{av},\ \epsilon)$

Phase — ϕ; Temperature difference — ΔT; Average Temperature — T_{av}; Level energy — ϵ

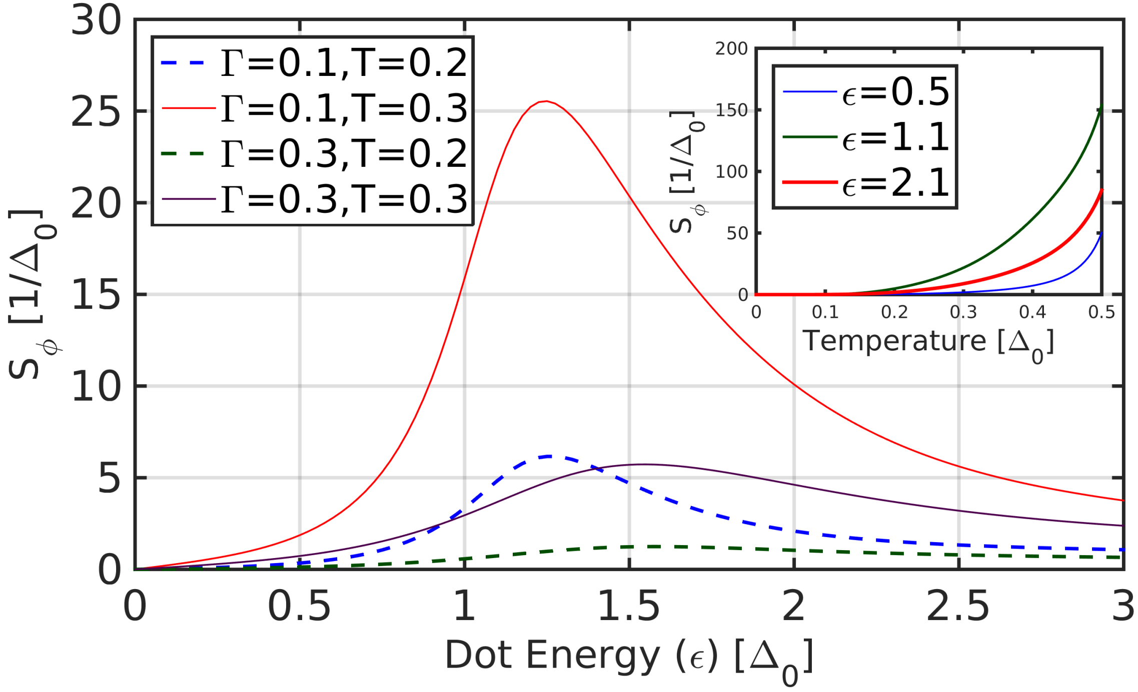
Transmission

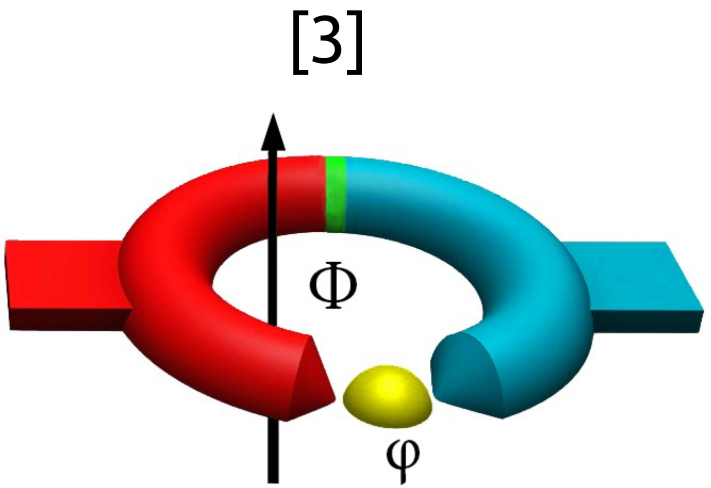


- Quasiparticle current travels through the **continuum**(ΔT)
- Supercurrent travels through the **ABS** and the **continuum**(ϕ)
- Pair->QP tranmission is p-h symmetric, no contribution

Thermo-Phase Seebeck Coefficient

$$S_\phi = -\left(\frac{dI/dT}{dI/d\phi}\right)_{I=0}, \quad \phi_{th} = S_\phi \Delta T$$



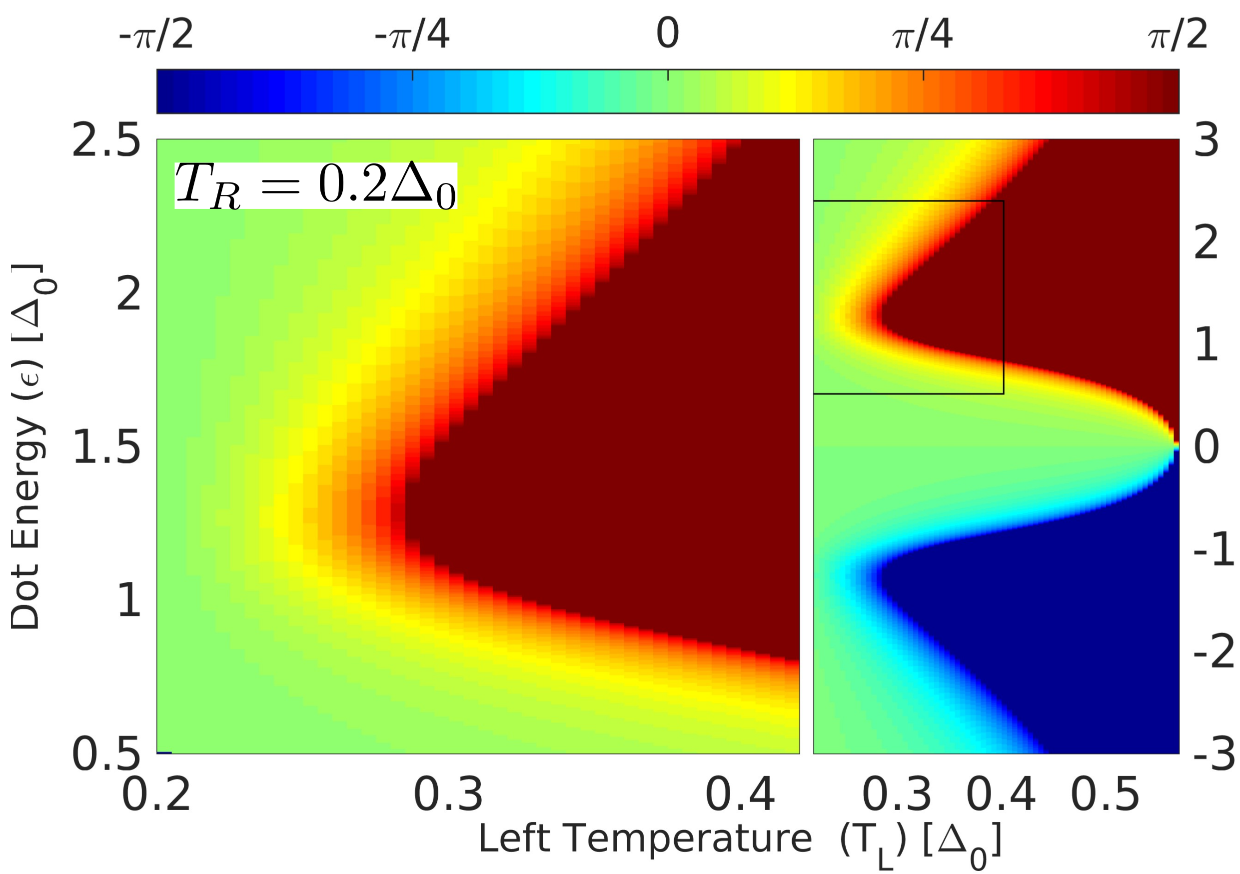


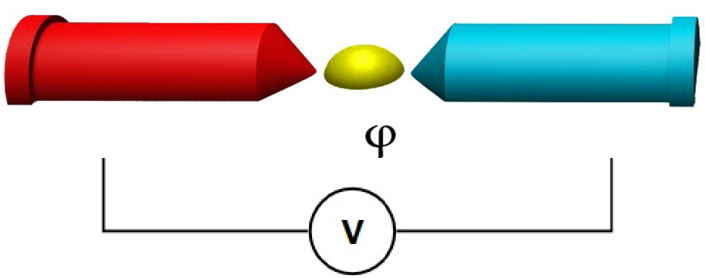
$$\phi_{th} = 2\pi(n + \Phi/\Phi_0)$$

- [3] Garland et al, Physics letters A, 47 423 (1974)

Beyond Linear Response

$$I(\phi_{th}, \Delta T, T, \epsilon) = 0$$



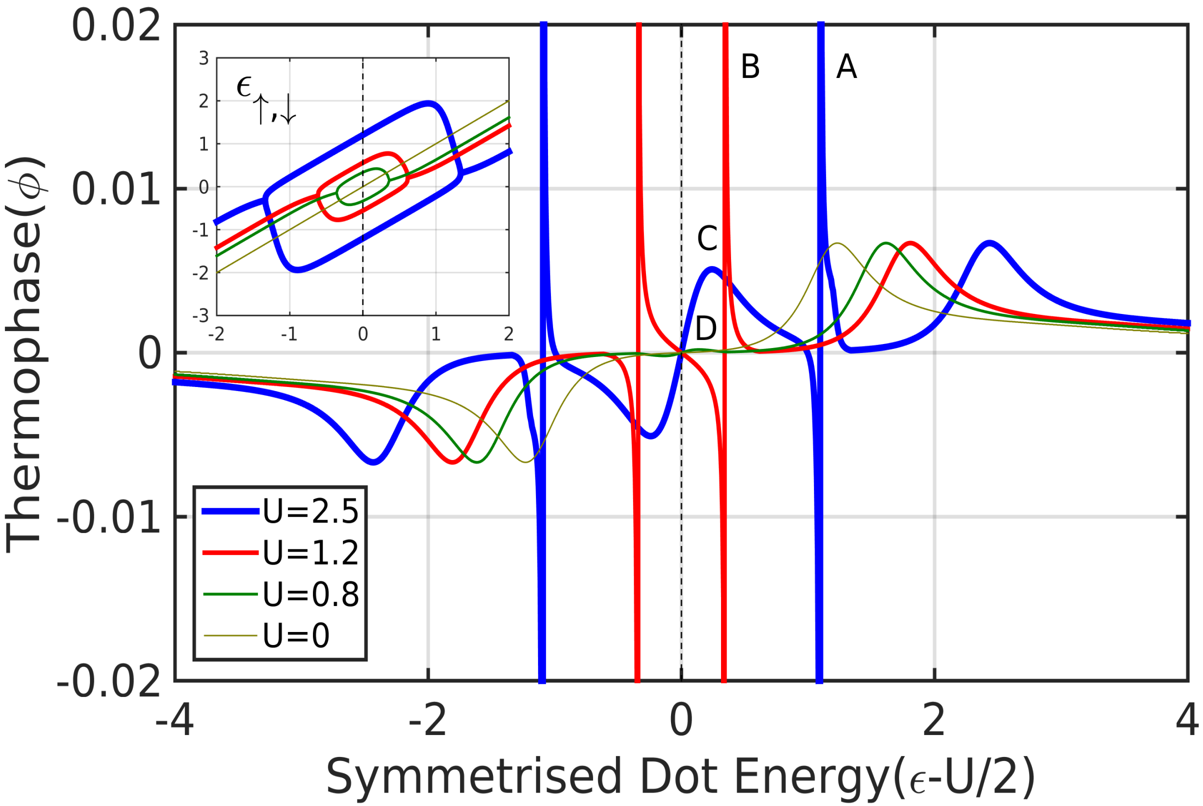


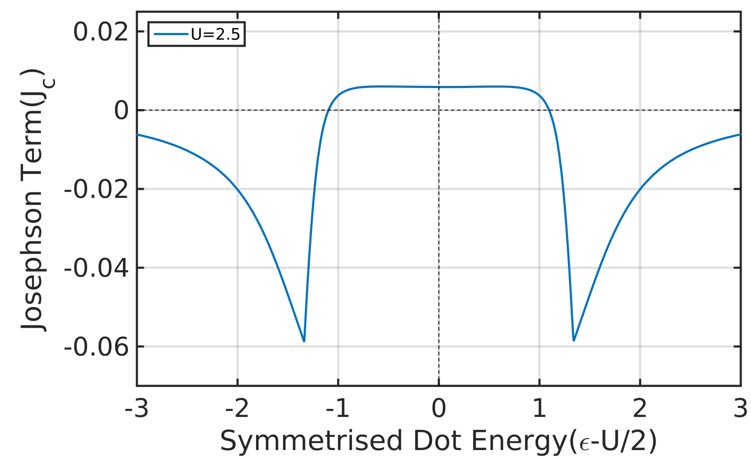
Capri Spring School,
18/04/16

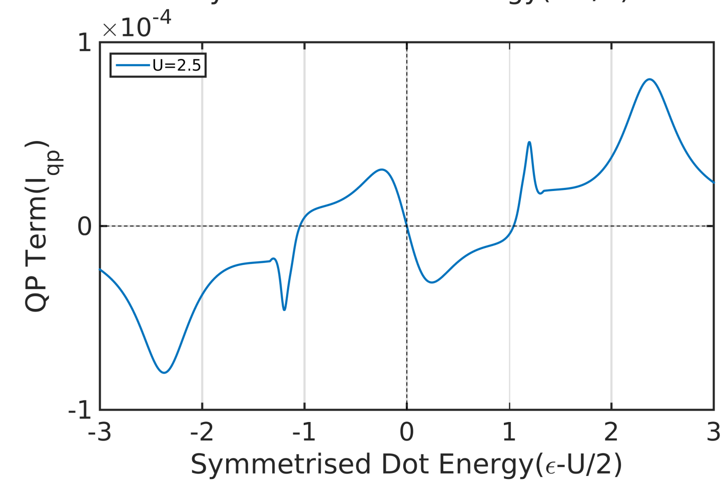
Thermo-phase with Coulomb Interaction

$$H_{int} = U n_\uparrow n_\downarrow$$

$$\epsilon_\sigma = \epsilon_0 + \langle n_{-\sigma} \rangle U$$

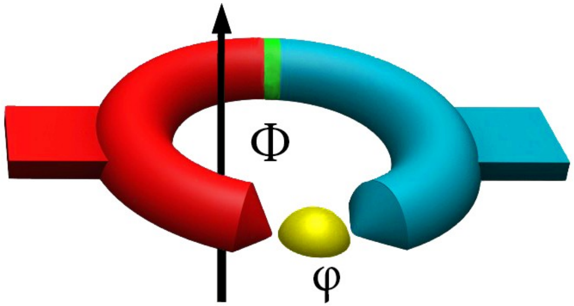


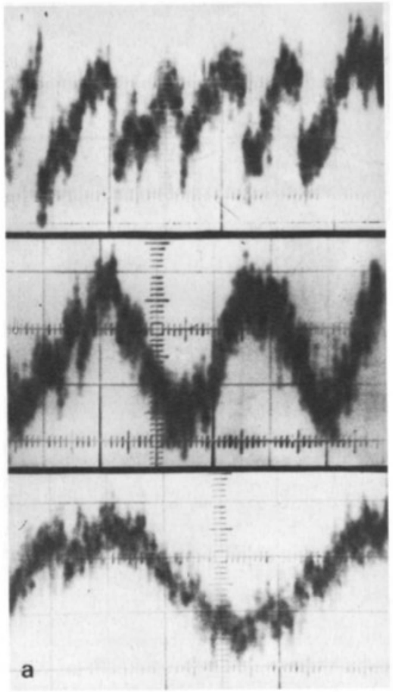




Summary

We suggest and investigate a realizable setup for controlling and measuring substantial thermal response in SC





We lay the grounds and set the tools for a study of the AC thermal Josephson effect

[4] Panaitov et al, Phys lett A, 100, 301 (1984)

Appendix

$$H_S = \epsilon_{ks} \sum_{s,k,\sigma} c^{\dagger}_{sk\sigma} c_{sk\sigma} + \sum_{s,k,\sigma} \Delta_s c^{\dagger}_{sk\sigma} c^{\dagger}_{s-k-\sigma} + H.c$$

$$H_{QD} = \sum_{\sigma} \epsilon_{\sigma} d^{\dagger}_{\sigma} d_{\sigma}$$

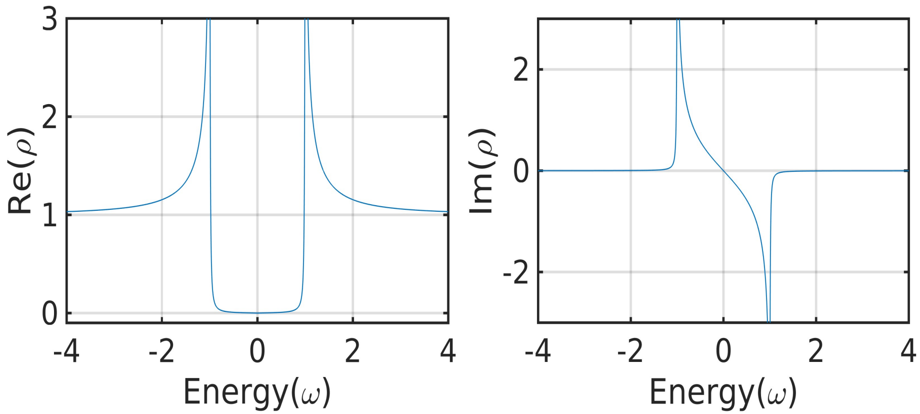
$$H_V = \sum_{s,k,\sigma} V_{ks} c^{\dagger}_{sk\sigma} d_{\sigma} + H.c$$

$$H_{int} = U n_{\uparrow} n_{\downarrow}$$

Appendix

$$\hat{G}^r_\sigma(t) = -i\theta(t)\langle\{\mathbf{\Psi(t)}, \mathbf{\Psi}^\dagger(0)\}\rangle, \qquad \Psi^\dagger = \begin{pmatrix} d^\dagger_\sigma \\ d_{\overline{\sigma}} \end{pmatrix}$$

$$\hat{\Sigma}^r_s(\omega) = -\frac{i}{2}\Gamma_s\rho_s(\omega)\begin{pmatrix} 1 & -\frac{\Delta}{\omega}e^{i\phi_s} \\ -\frac{\Delta}{\omega}e^{-i\phi_s} & 1 \end{pmatrix}$$

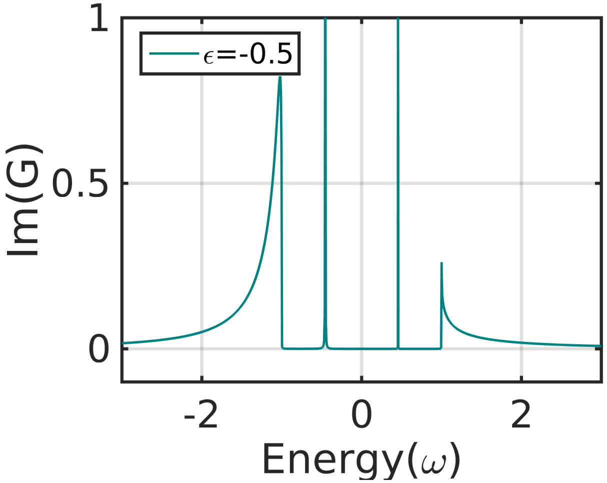


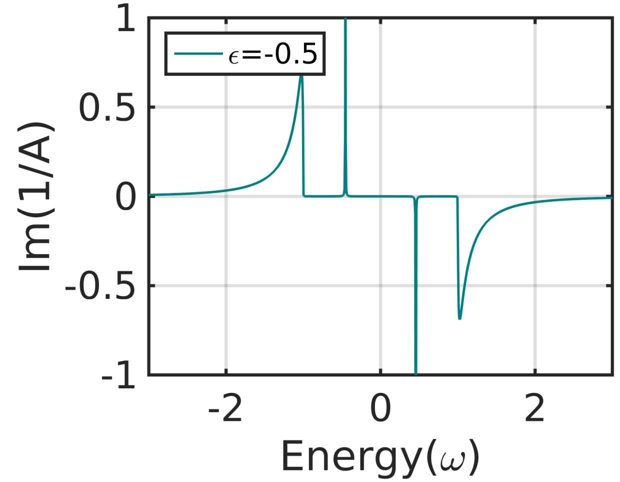
$$\rho_s(\omega) = \begin{cases} \frac{|\omega|}{\sqrt{(\omega)^2 - \Delta_s^2}} & |\omega| > \Delta_s \\ \frac{\omega}{i\sqrt{\Delta_s^2 - (\omega)^2}} & |\omega| < \Delta_s \end{cases}$$

Appendix

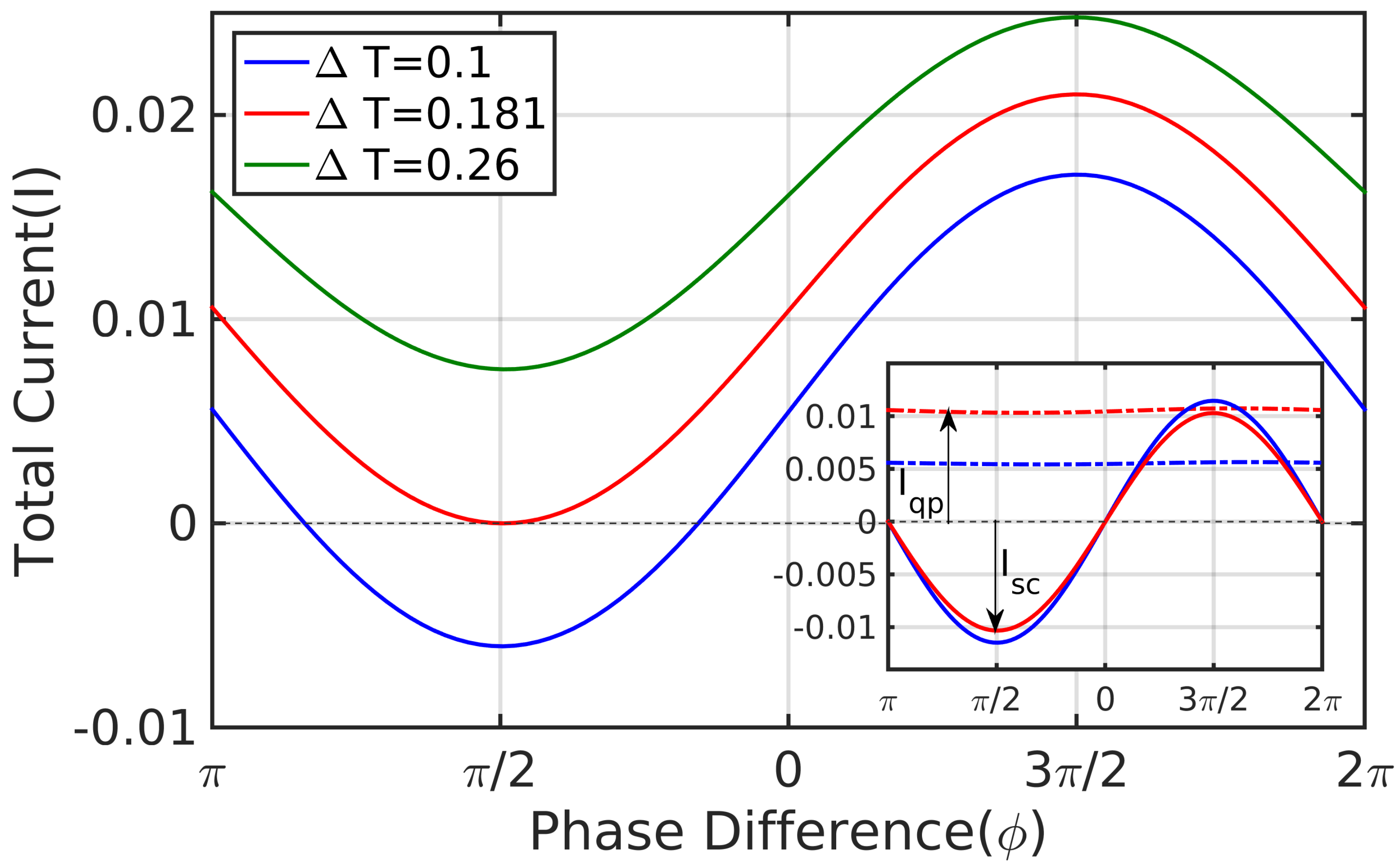
$$I_{qp} = \frac{e}{h} \sum_{\sigma} \int_{-\infty}^{\infty} d\omega \frac{f(\omega)}{dT} \Gamma \ \mathrm{Re}[\rho(\omega)] \ \mathrm{Im}[-G^{r}_{11}(\omega)] \Delta T$$

$$I_{sc} = \frac{e}{h} \sum_{\sigma} \int_{-\infty}^{\infty} d\omega f(\omega) \frac{\Delta^2 \Gamma^2}{\omega^2 - \Delta^2} \ \mathrm{Im}[1/A(\omega)] \sin(\phi)$$





Appendix


Δ T=0.1
Δ T=0.181
Δ T=0.26
0.02
0.01
0
-0.01
Total Current(I)
π
π/2
0
3π/2
2π
Phase Difference(ϕ)
0.01
0.005
0
-0.005
-0.01
I_qp
I_sc
π
π/2
0
3π/2
2π