Collective energy gap of preformed Cooper-pairs

Thomas Dubouchet, Marc Sanquer, Claude Chapelier *INAC, CEA-Grenoble*

Benjamin Sacépé, Johanna Seidemann *Néel Institute, CNRS Grenoble*

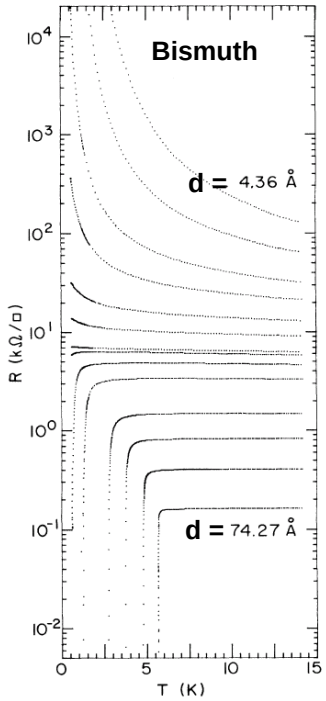
Dan Shahar, *The Weizmann Institute of Science*

INSTITUT NANOSCIENCES ET CRYOGÉNIE

UNIVERSITÉ Grenoble Alpes

Superconductor to insulator quantum phase transition (SIT)

Amorphous films

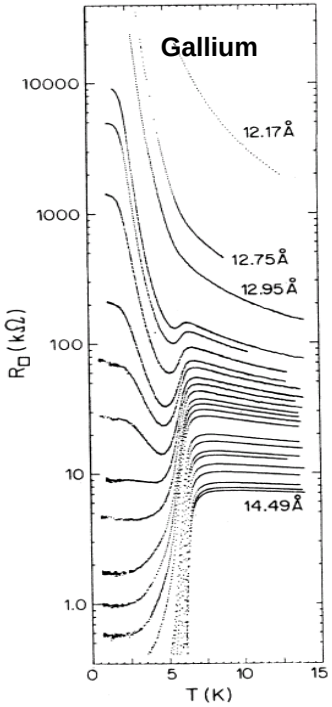


$$\psi = |\psi| e^{i\varphi}$$

Bosonic

Fermionic

Granular films



D.B. Haviland, Y. Lui, A.M. Goldman, *PRL* ***62***, 2180 (1989)

H. M. Jaeger, et al. Phys.Rev.B 34, 4920 (1986)

- Continuous decrease of T_c

- Inhomogeneous superconducting state

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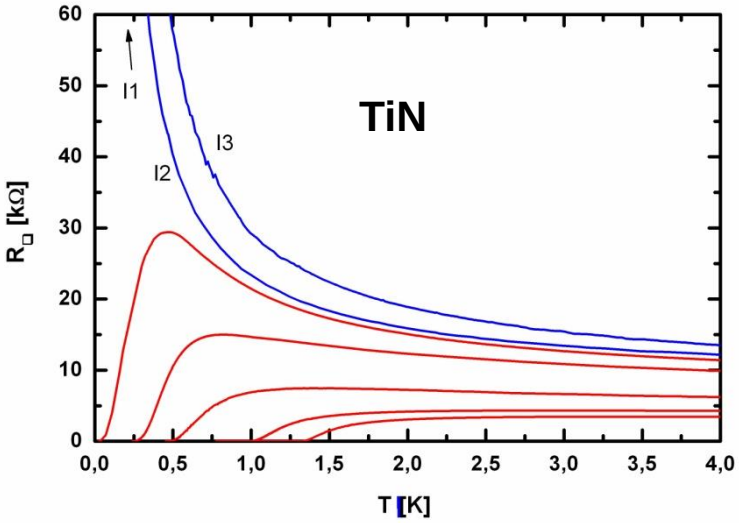

T. I. Baturina, et al.PRL ***99,*** *257003 (2007)*

Bosonic

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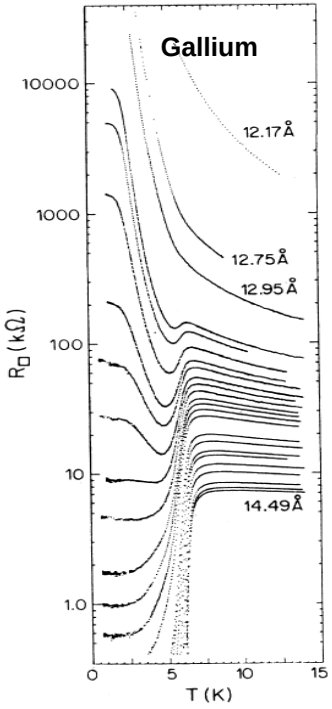
Granular films



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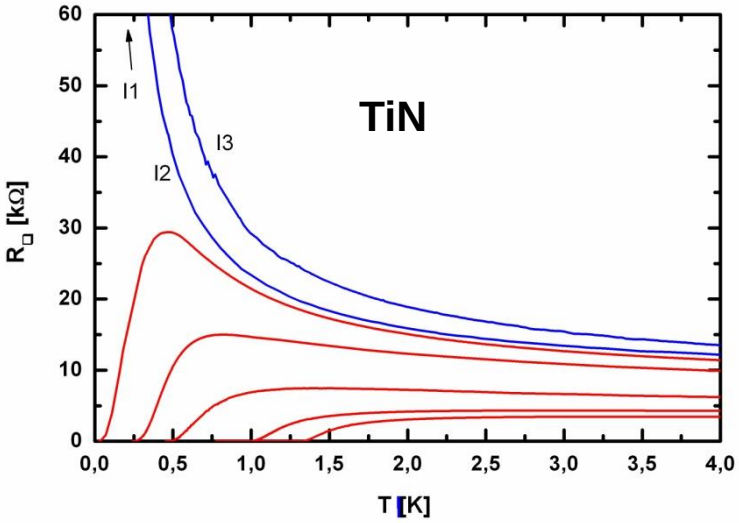

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Bosc

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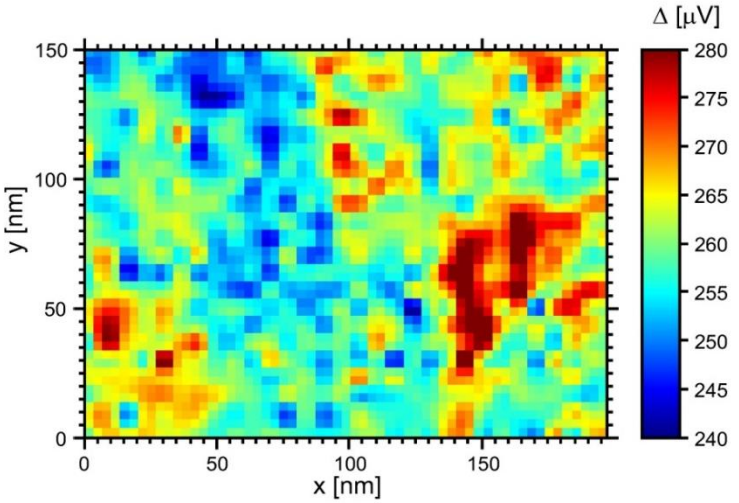

Sacépé et al., *PRL* ***101****, 157006 (2008)*

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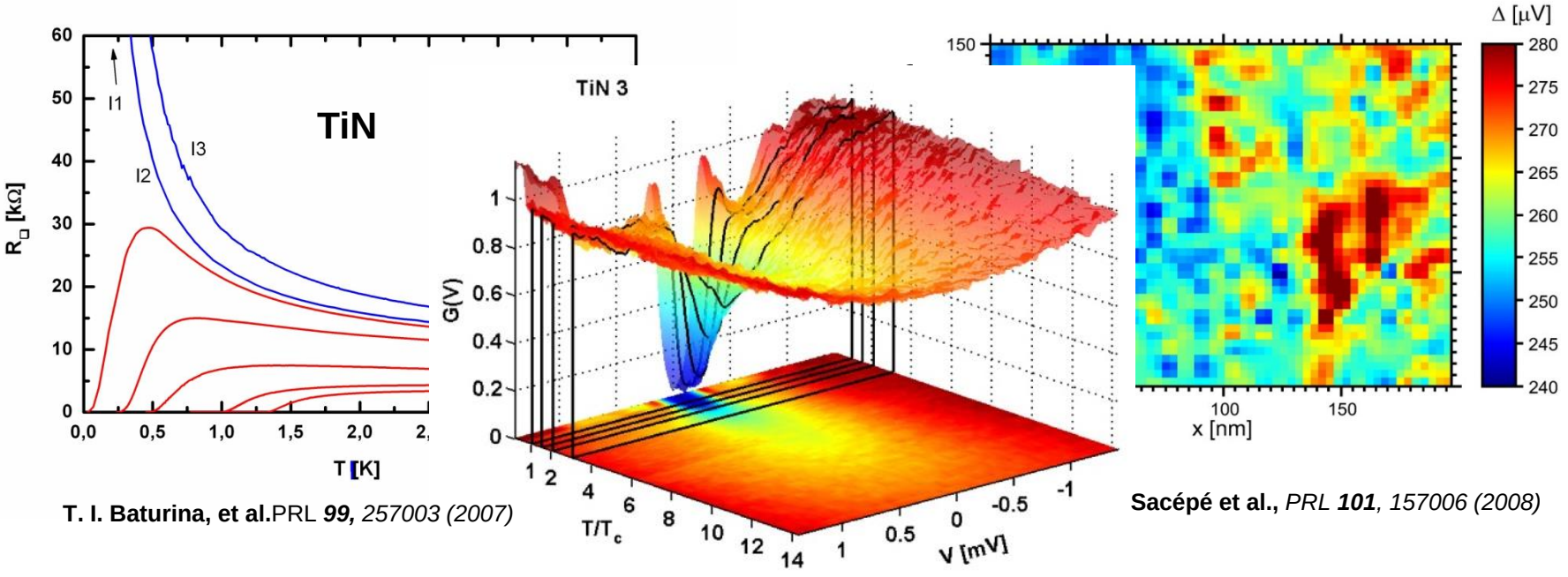

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B. Sacépé, et al., *Nature Physics (2011)*

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- Continuous decrease of T_c
- Pseudogap
- Large Eg/Tc
- Inhomogeneous superconducting state

Superconductor to insulator quantum phase transition (SIT)

Preformed Cooper pairs

- Pseudogap
- Large Eg/Tc

BCS transition

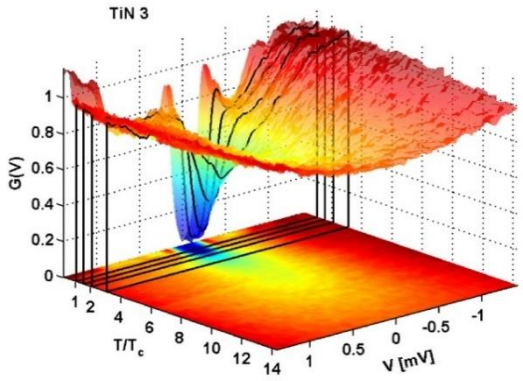
- No Pseudogap
- Eg/Tc ≈ 2

Superconductor to insulator quantum phase transition (SIT)

Preformed Cooper pairs

BCS transition

TiN



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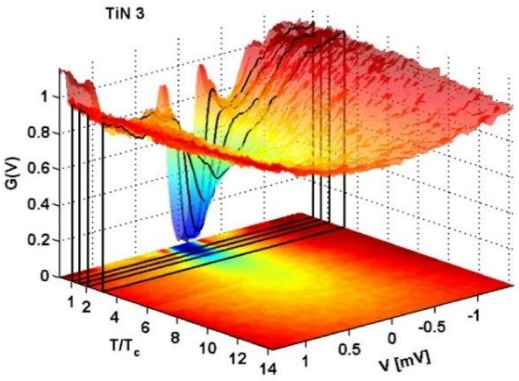

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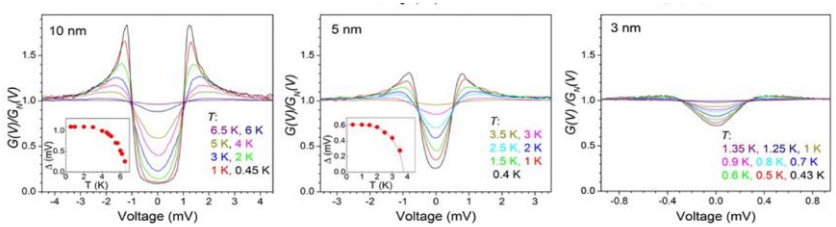
BCS transition

MoC



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Szabo et al., *PRB **93**, 014505 (2016)*

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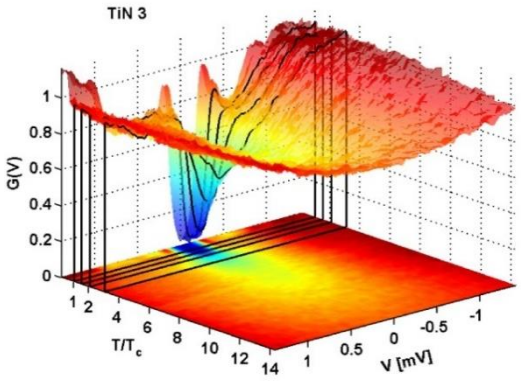

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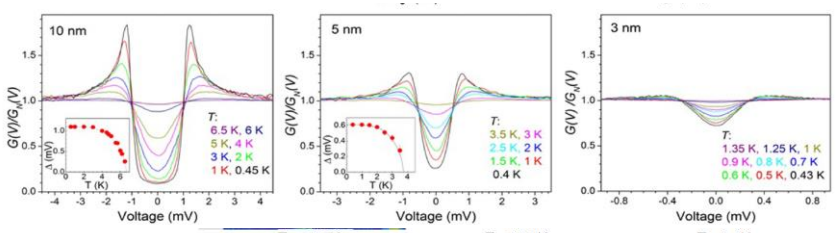
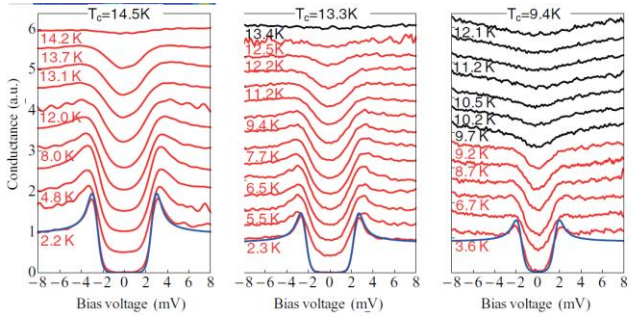


NbN



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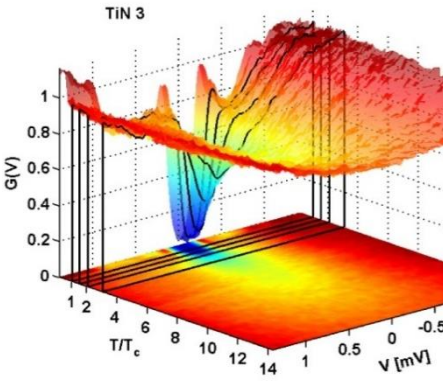

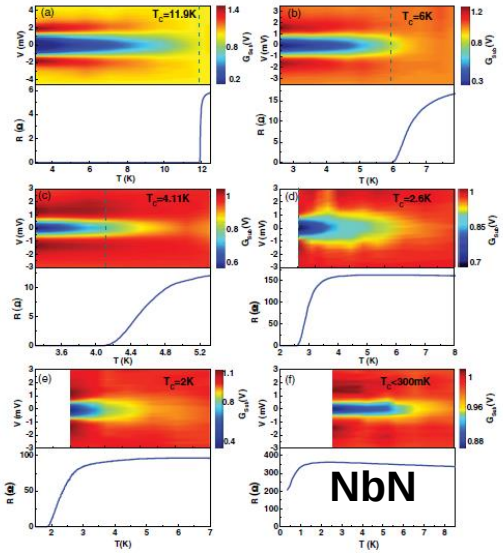

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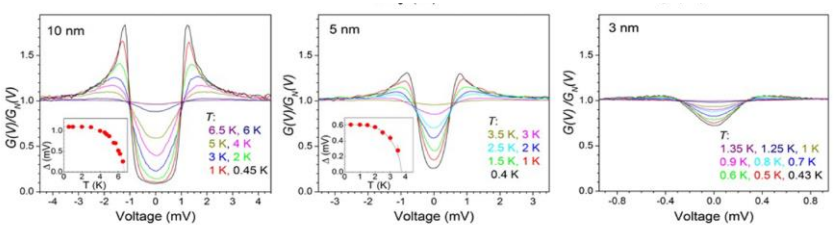
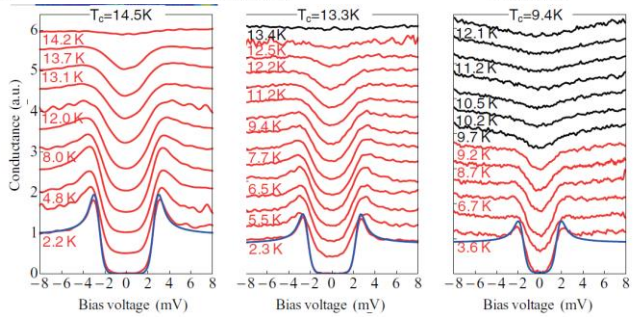
Madhavi Chand et al., *Phys. Rev. B* ***85****, 014508*, (2012)

BCS transition

MoC



NbN



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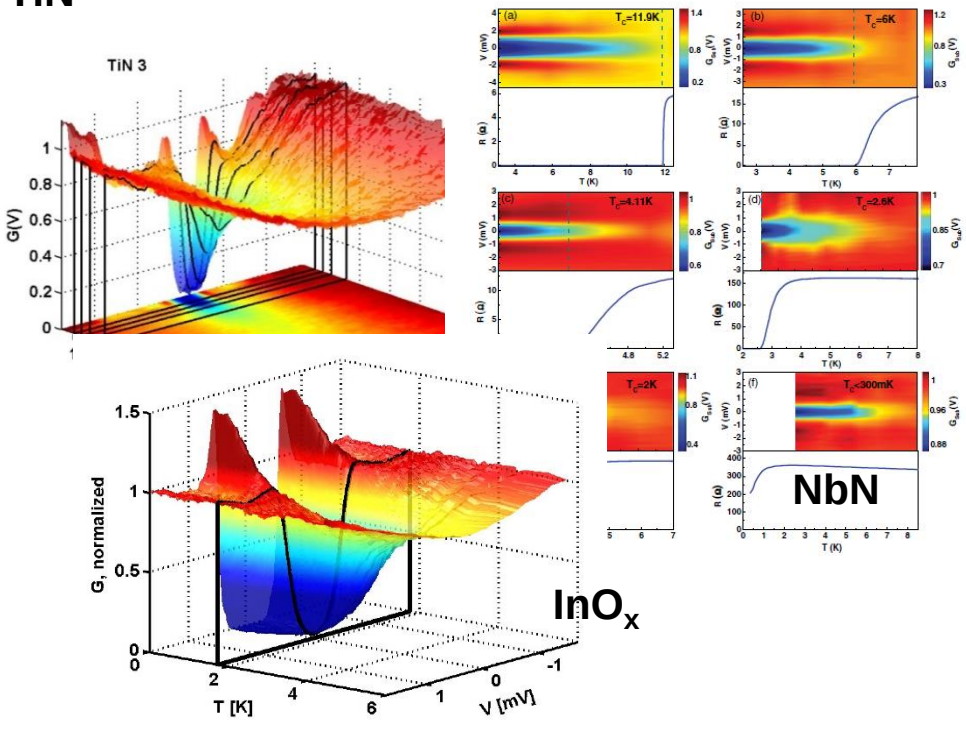

InO_x

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B. Sacépé, et al., *Nature Communications (2010)*

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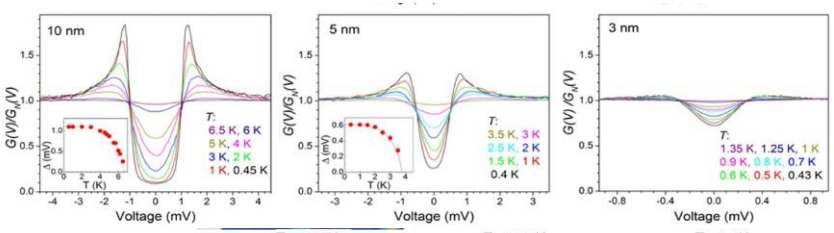
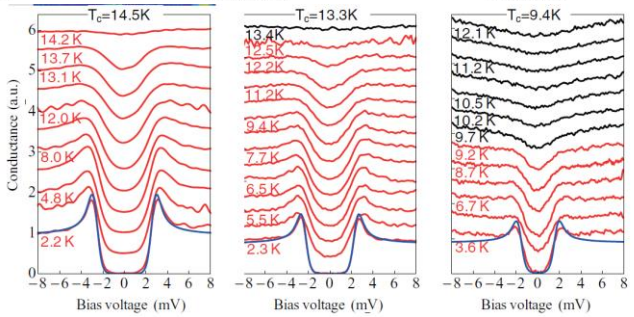


NbN



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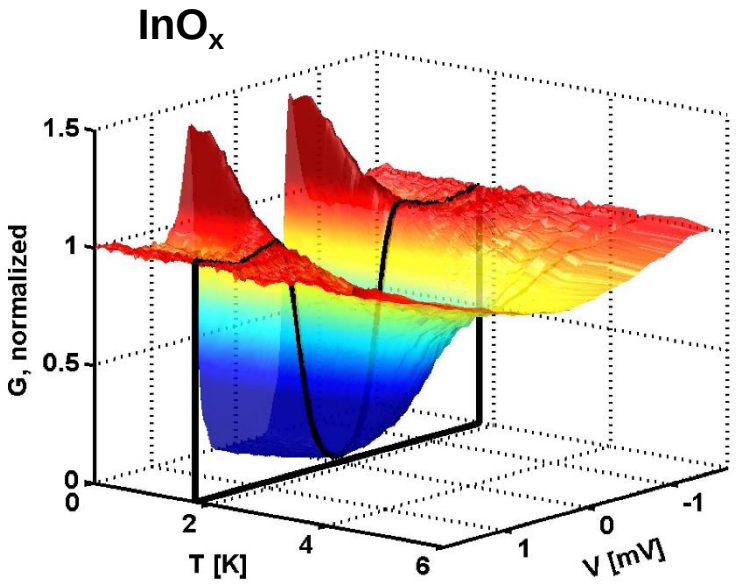

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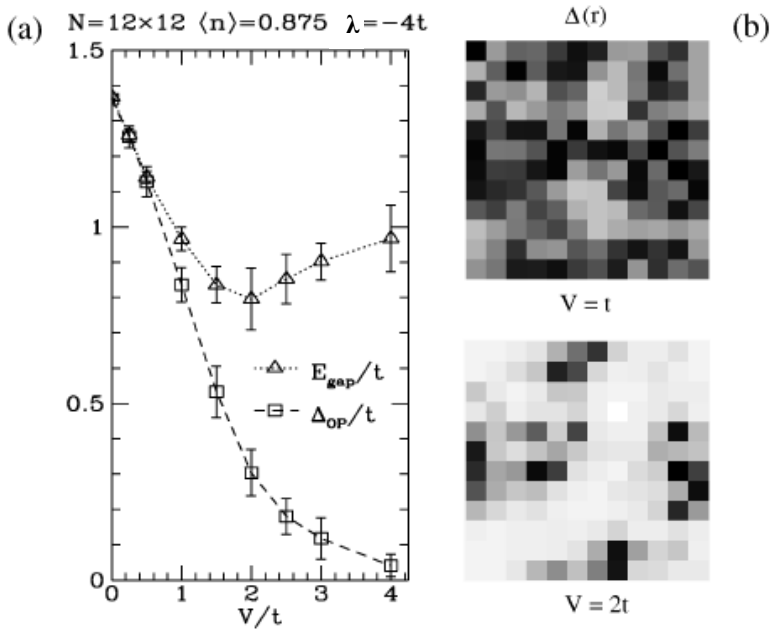
OUTLINE

Two energy scales : theoretical background
Andreev Spectroscopy vs Tunneling Spectroscopy

Two energy scales : theoretical background

A. Ghosal, M. Randeria, N. Trivedi, *PRL* ***81***, 3940, (1998) & *PRB* ***65***, 014501 (2001)



Anderson model :

$$H_0 = -t \sum_{<i,j>,\sigma} \left(c^{+}_{i\sigma} c_{j\sigma} + h.c. \right) + \sum_{i,\sigma} \left(V_i - \mu \right) n_{i,\sigma}$$

Hopping parameter : t

On-site disorder : V_i

Attractive interaction λ :

$$H_{\text{int}} = -\lambda \sum_i n_{i\uparrow} n_{i\downarrow}$$

With increasing disorder:

- Superconductivity becomes **« *granular-like* »**
- Spectral gap is **not** the SC order parameter

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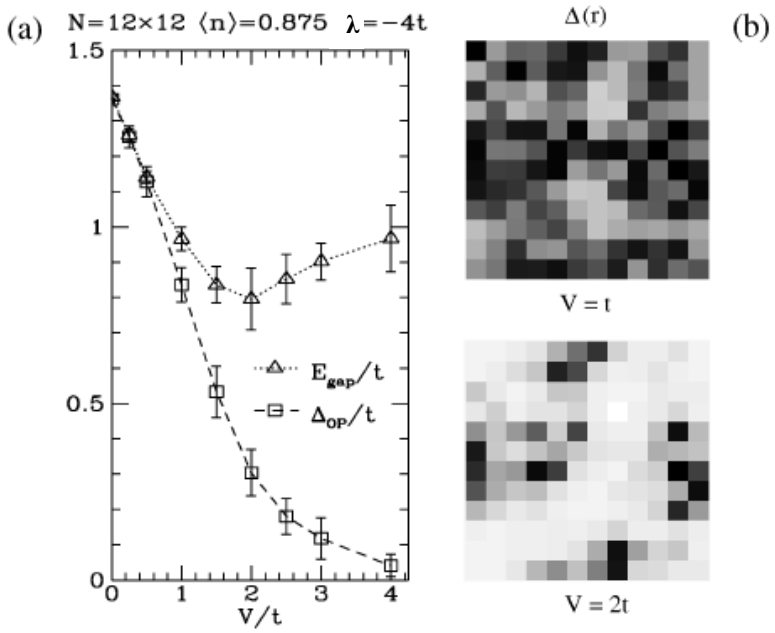

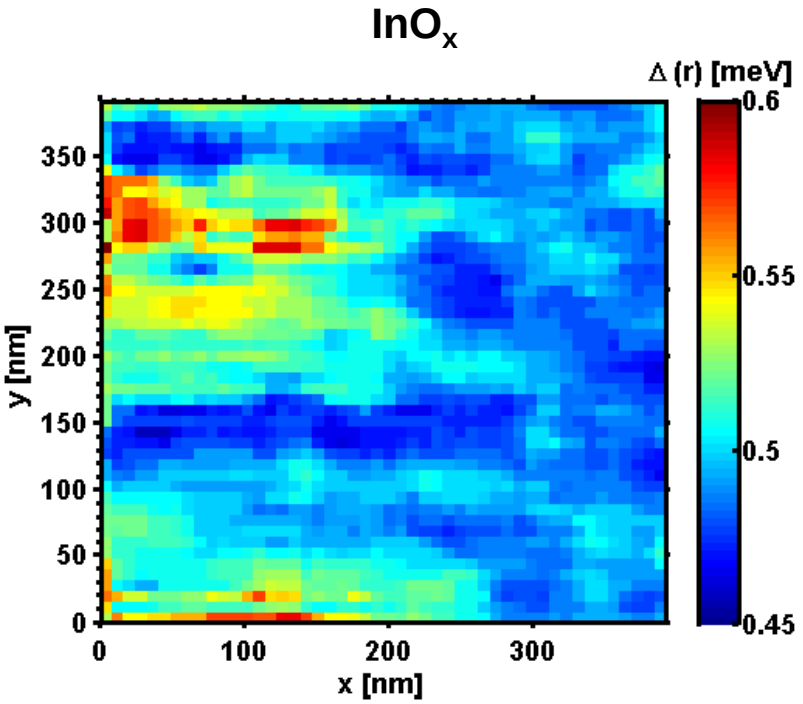

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M. Feigel'man, et al., *Phys. Rev. Lett.* ***98***, 027001, (2007)

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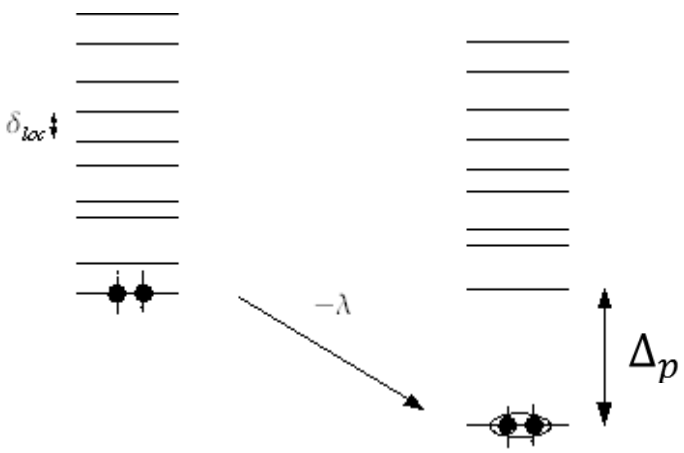

BCS Hamiltonian built on
eigenstates of the Anderson problem

$$H = \sum_{j\sigma} \epsilon_j \, c^\dagger_{j\sigma} c_{j\sigma} \; - \frac{\lambda}{\nu} \sum_{jk} M_{jk} \, c^\dagger_{j\uparrow} c^\dagger_{j\downarrow} c_{k\uparrow} c_{k\downarrow}$$

with $\quad M_{jk} = \int dr \, \psi_j^2(r) \, \psi_k^2(r)$

In the high-disorder regime : $\quad \delta_{loc} = \frac{1}{\nu L_{loc}^3} > \Delta_c$

$$M_{jk} \approx \delta_{jk} \int dr \, \psi_j^4(r) \approx \delta_{jk} \frac{1}{L_{loc}^3}$$

$$\Delta_p = \frac{\lambda}{2} E_0 \left(\frac{L_0}{L_{loc}} \right)^D \qquad E_0 = \frac{1}{\nu L_0^3} \quad D = 1.3$$

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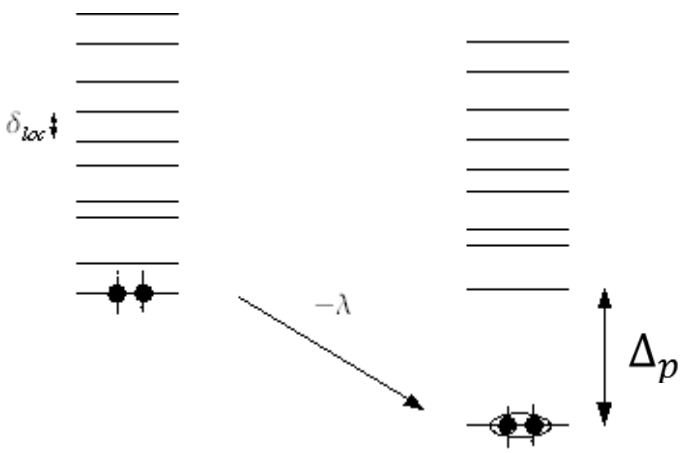

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$$E_g = \Delta_p + \Delta_c$$

- Δ_p "parity gap": pairing of 2 electrons in localized wave functions
- Δ_c "BCS gap": long-range SC order between localized pairs

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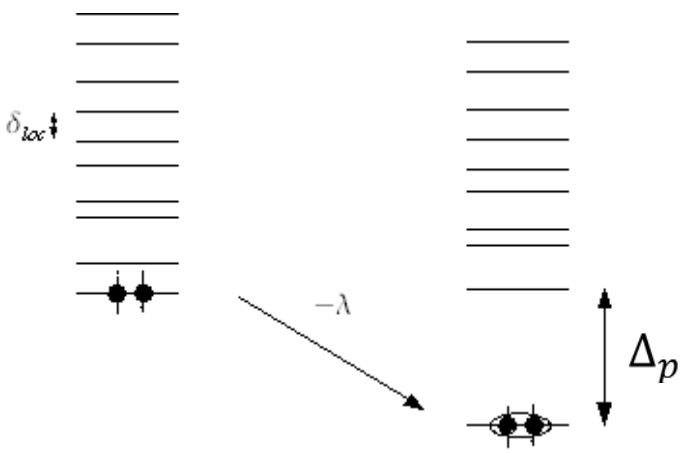

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- Tunneling spectroscopy

(single-particle DOS)

Tunnel barrier

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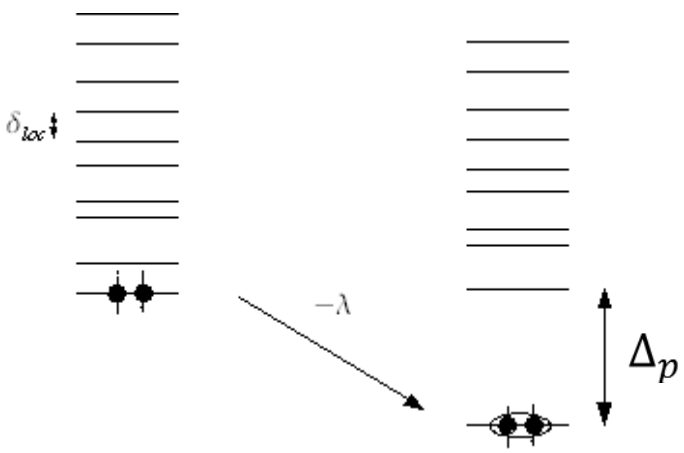

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$$E_g = \Delta_p + \Delta_c$$

- Tunneling spectroscopy

(single-particle DOS)

Tunnel barrier

$$E_A = \Delta_c$$

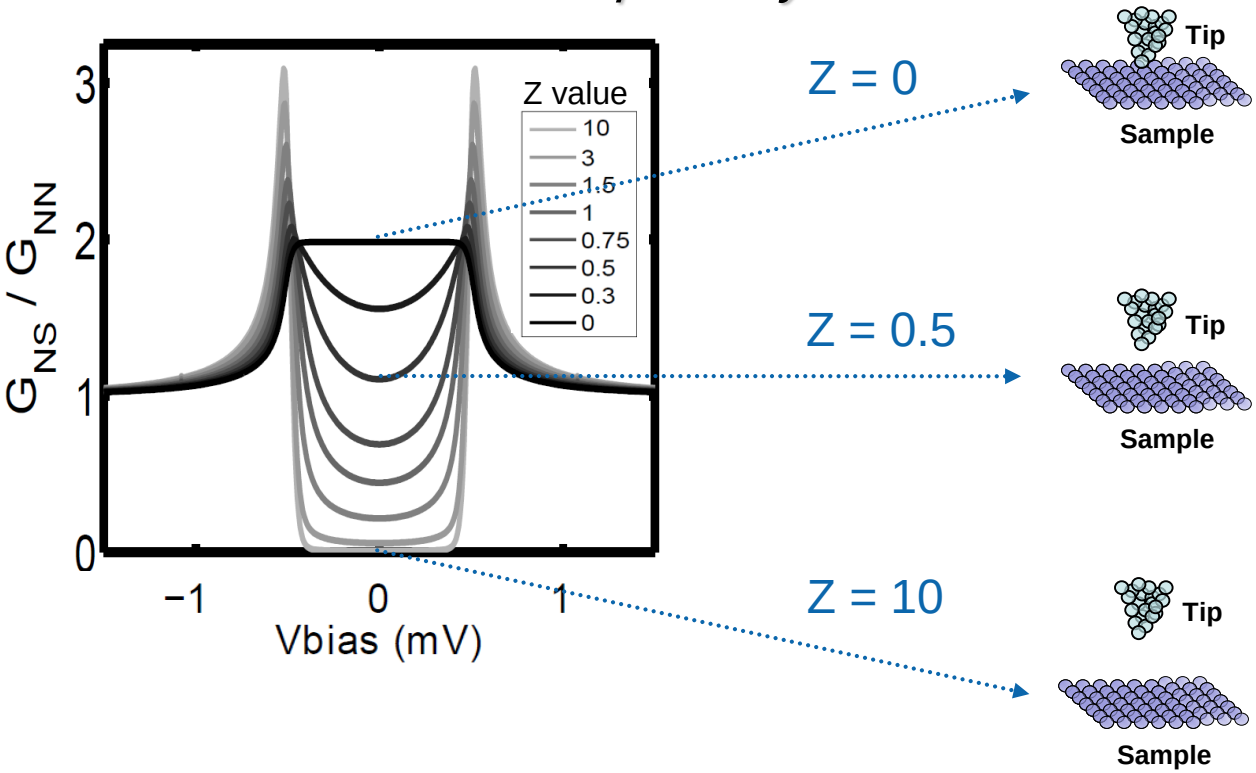
- Point-contact spectroscopy

(Andreev reflection = transfer of pairs)

Transparent interface

Andreev Spectroscopy vs Tunneling Spectroscopy

Conductance of a N/S contact
for different barrier transparency



Blonder, G.E. *et al.*, *Phys. Rev. B* **25**, 4515 (1982)

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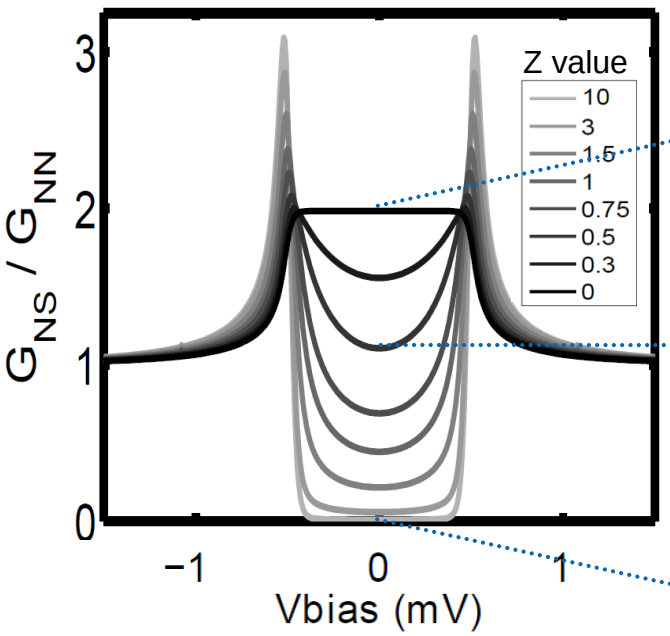
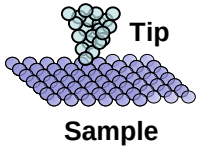
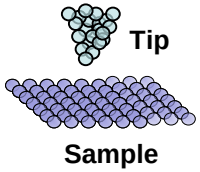
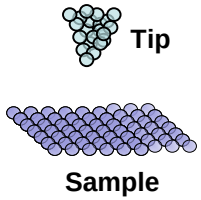
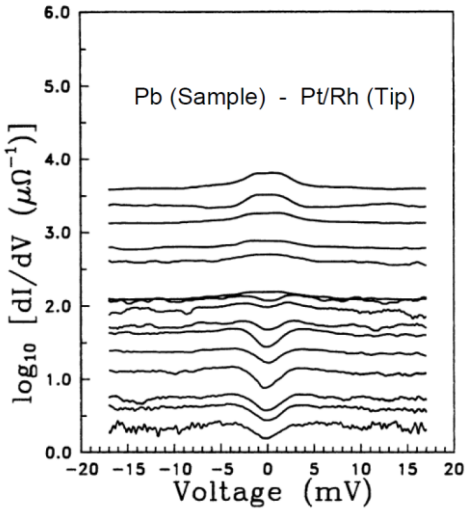








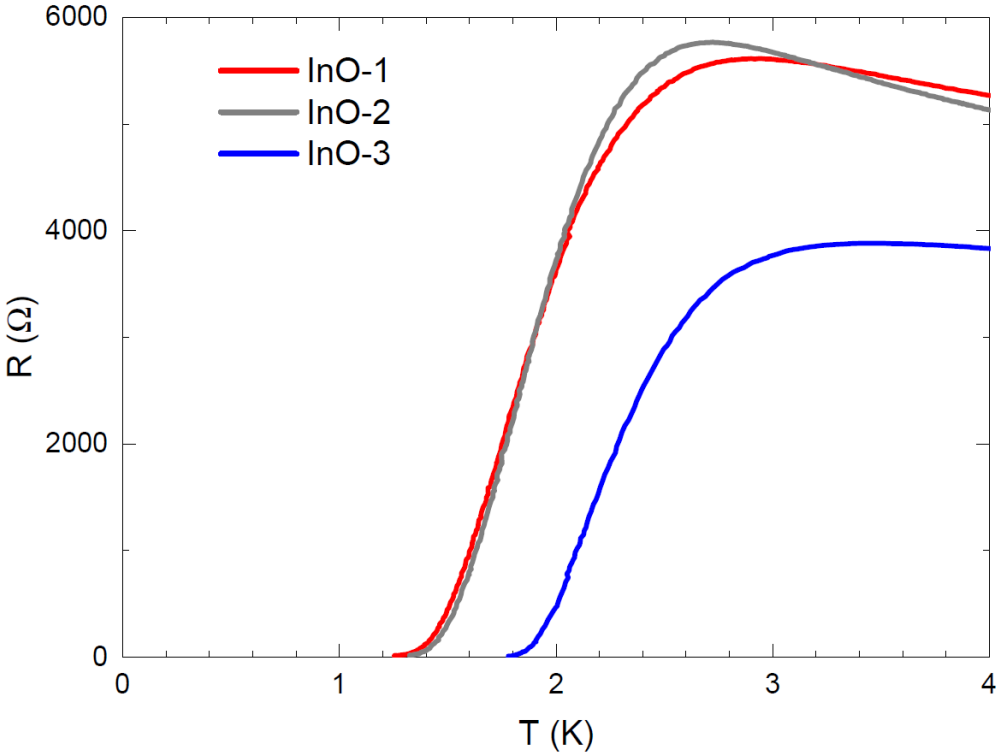


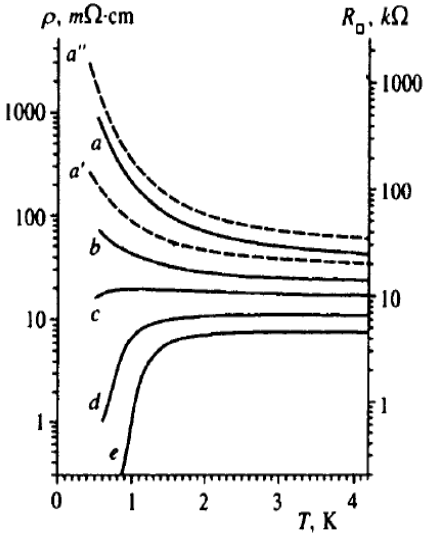
Blonder, G.E. *et al.*, *Phys. Rev. B* **25**, 4515 (1982)

Agrait, N. *et al.*, *Phys. Rev. B* **46**, 9 5814 (1992)

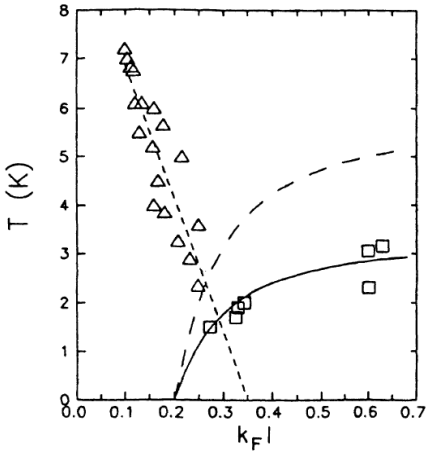
Andreev Spectroscopy vs Tunneling Spectroscopy

Amorphous Indium Oxide



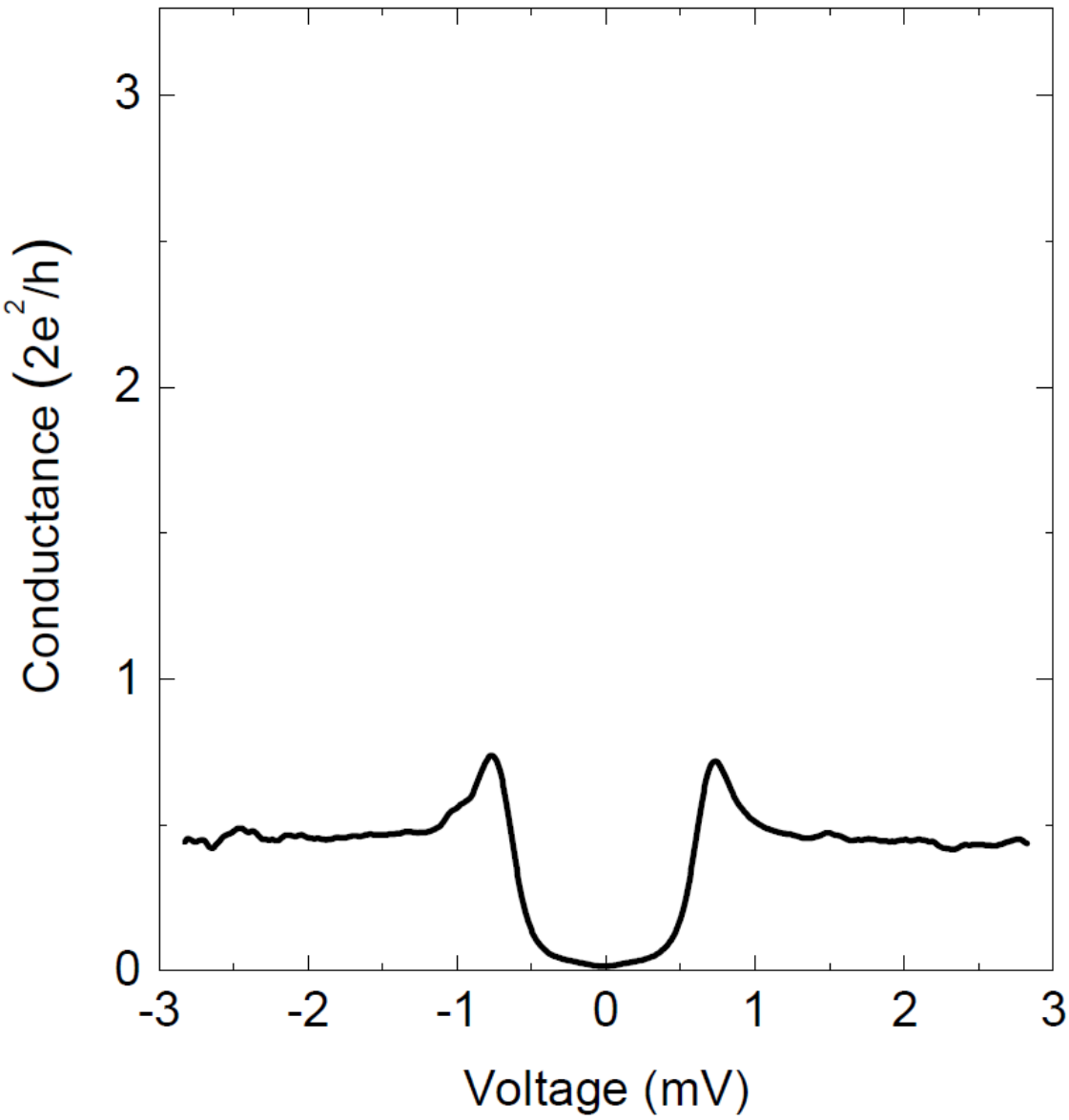


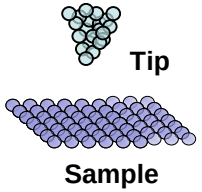
V. F. Gantmakher *et al.*, *JETP* ***82***, 951 (1996)



D. Shahar and Z. Ovadyahu, *Phys. Rev. B* ***46***, 10917 (1992)

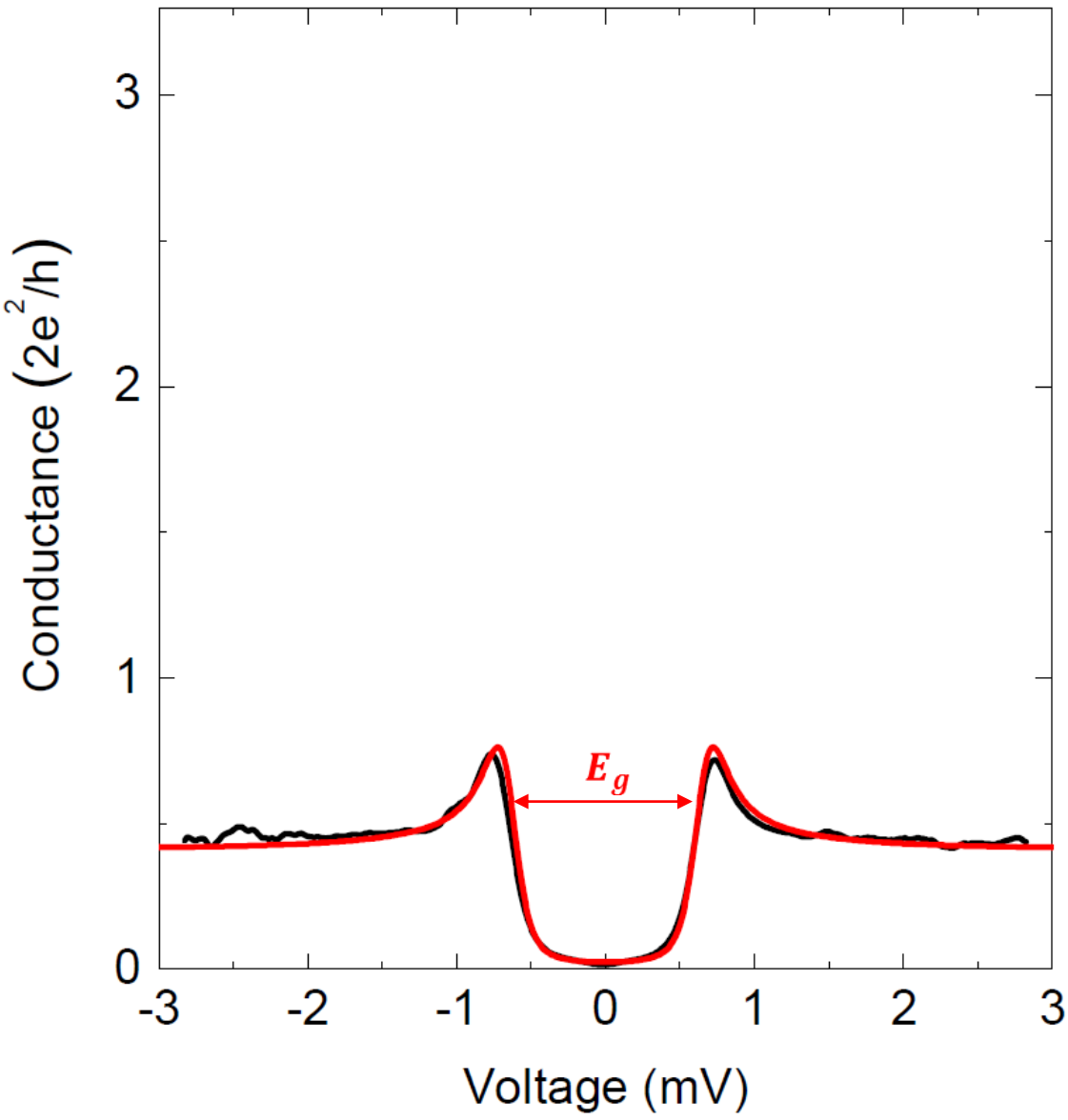
Andreev Spectroscopy vs Tunneling Spectroscopy

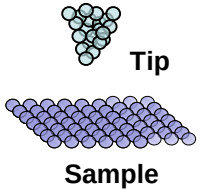




T = 50 mK

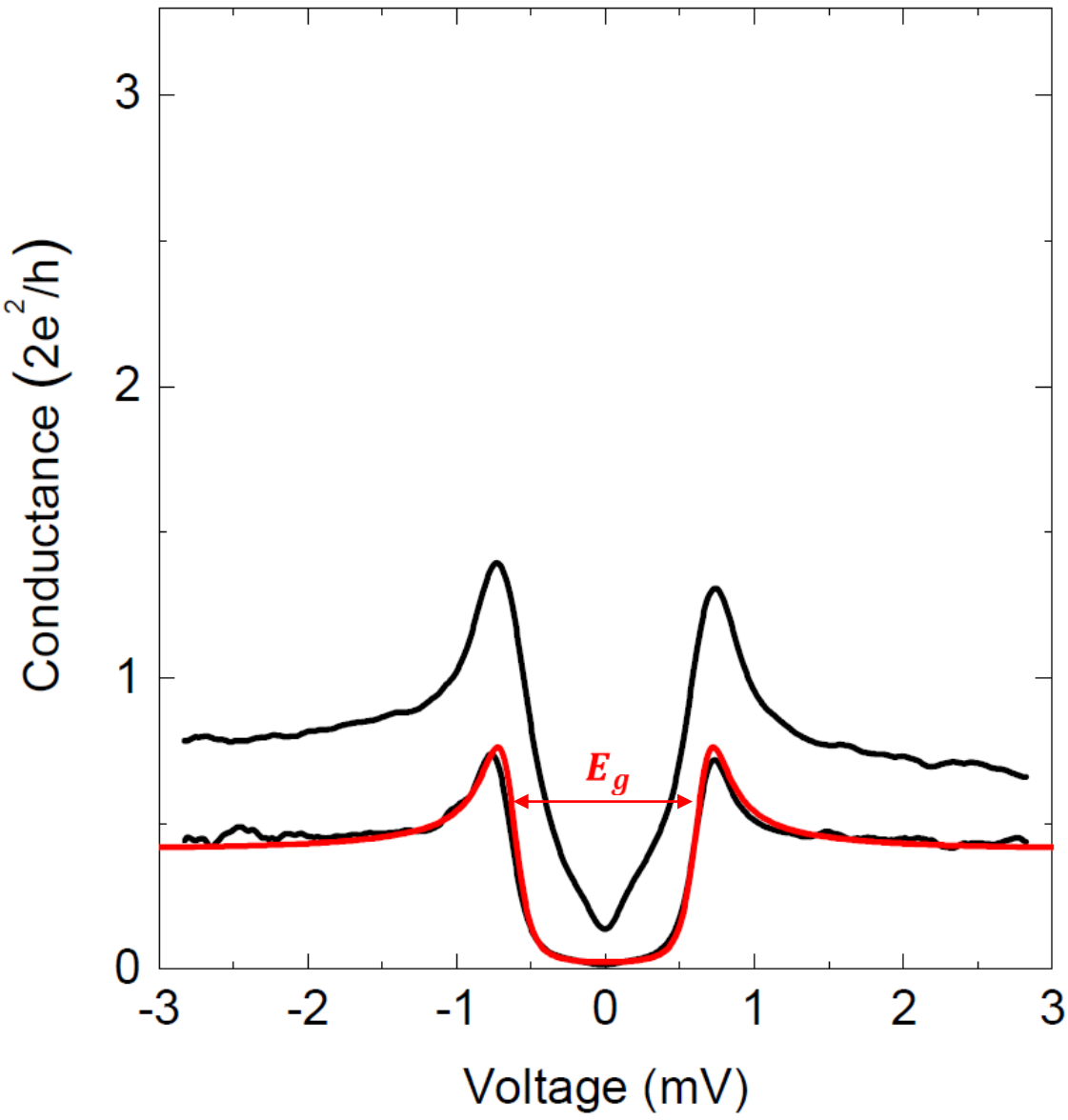
Andreev Spectroscopy vs Tunneling Spectroscopy

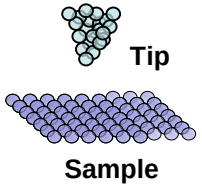




T = 50 mK

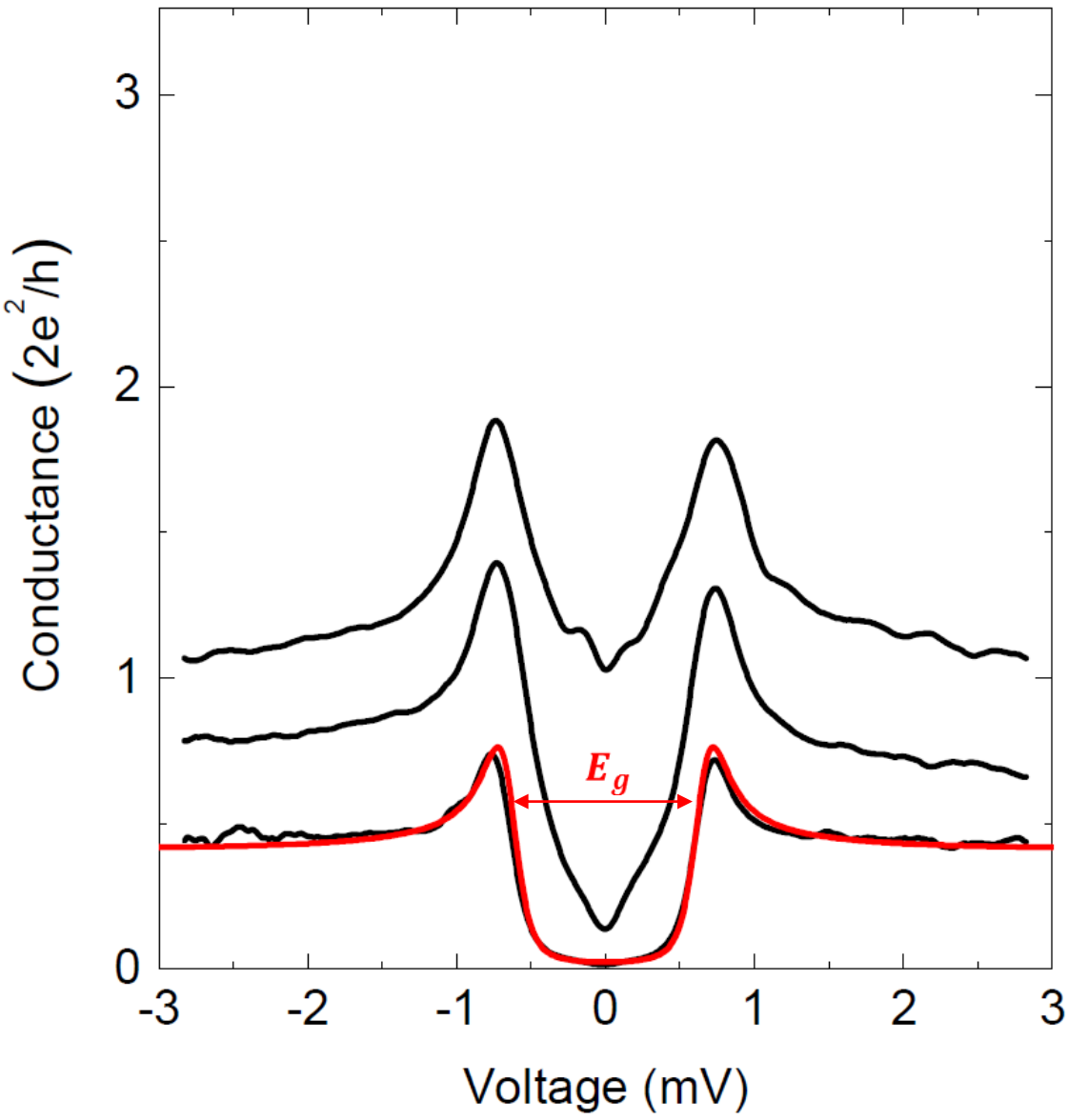
Andreev Spectroscopy vs Tunneling Spectroscopy

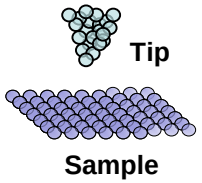




T = 50 mK

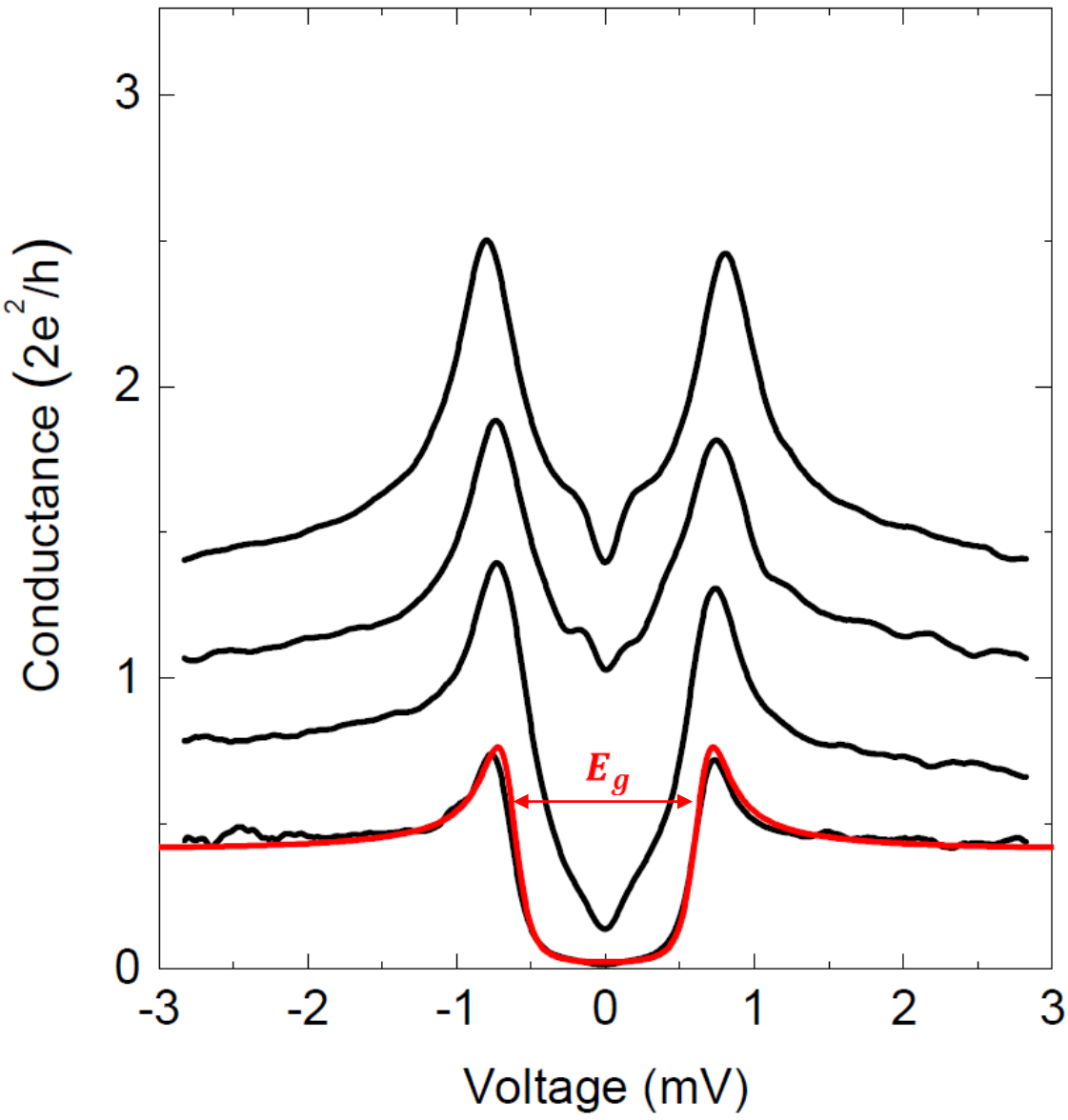
Andreev Spectroscopy vs Tunneling Spectroscopy

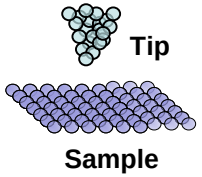




T = 50 mK

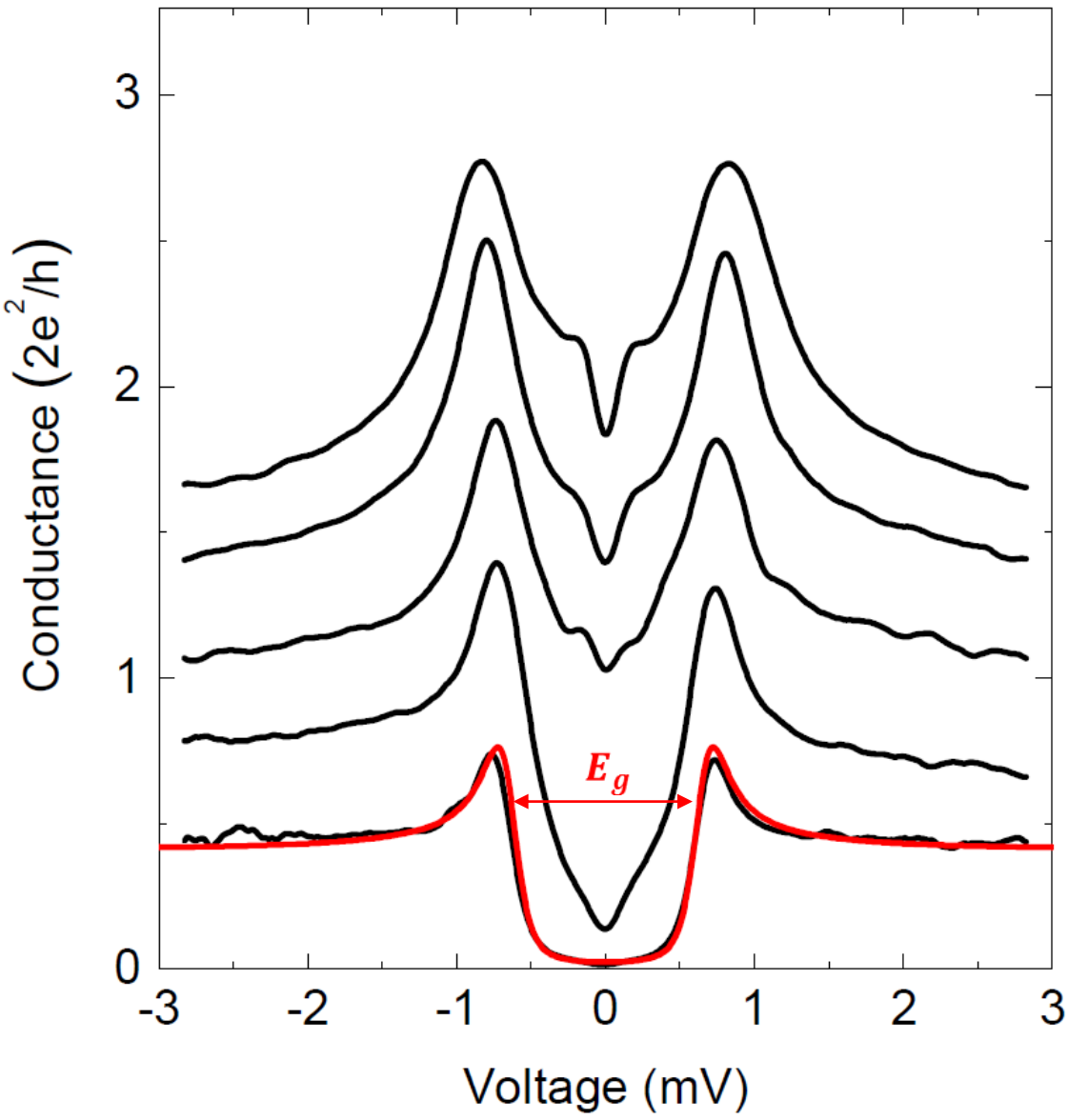
Andreev Spectroscopy vs Tunneling Spectroscopy

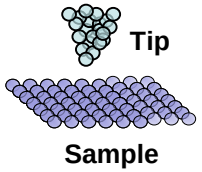




T = 50 mK

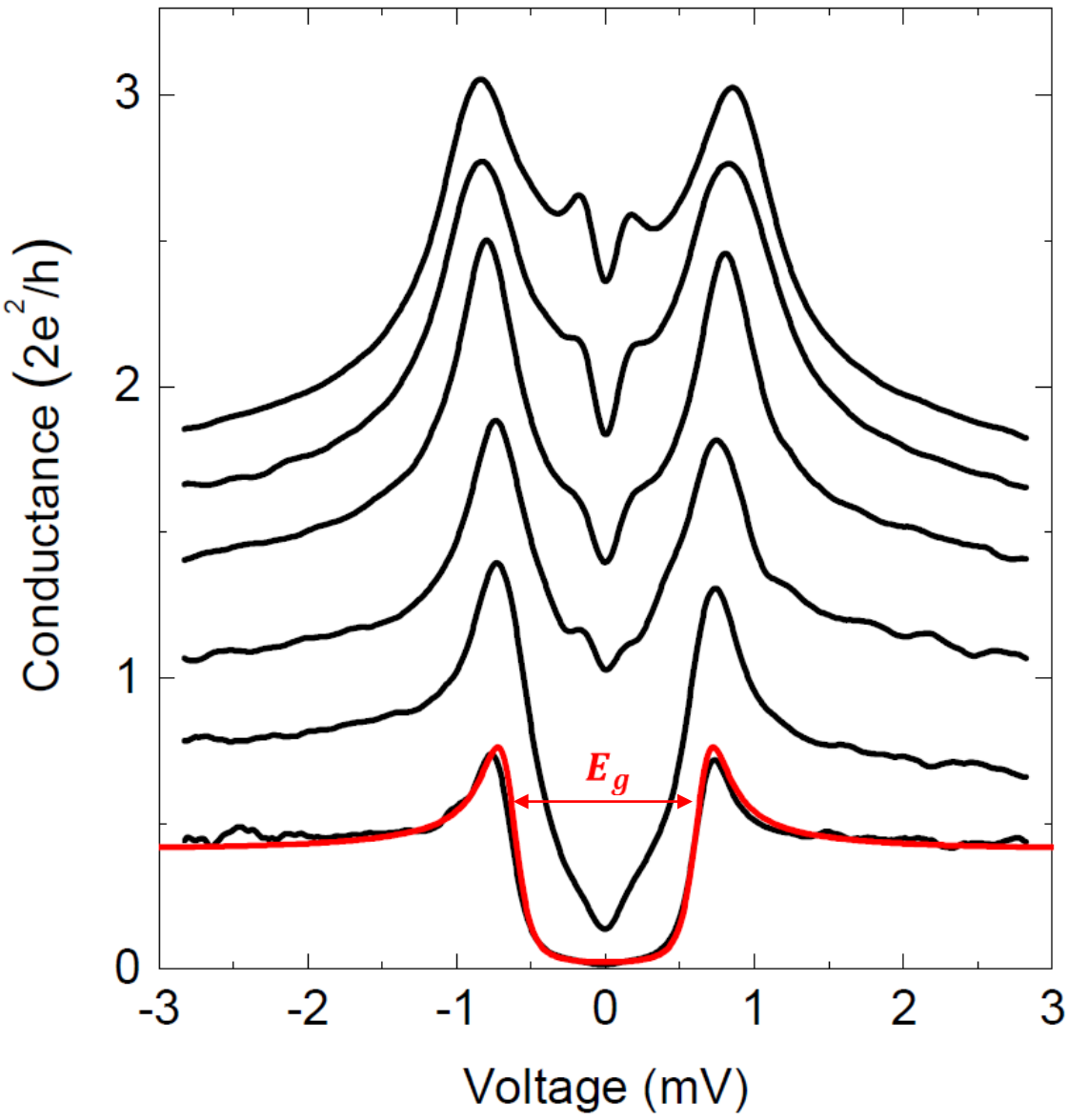
Andreev Spectroscopy vs Tunneling Spectroscopy

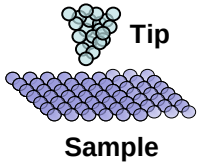




T = 50 mK

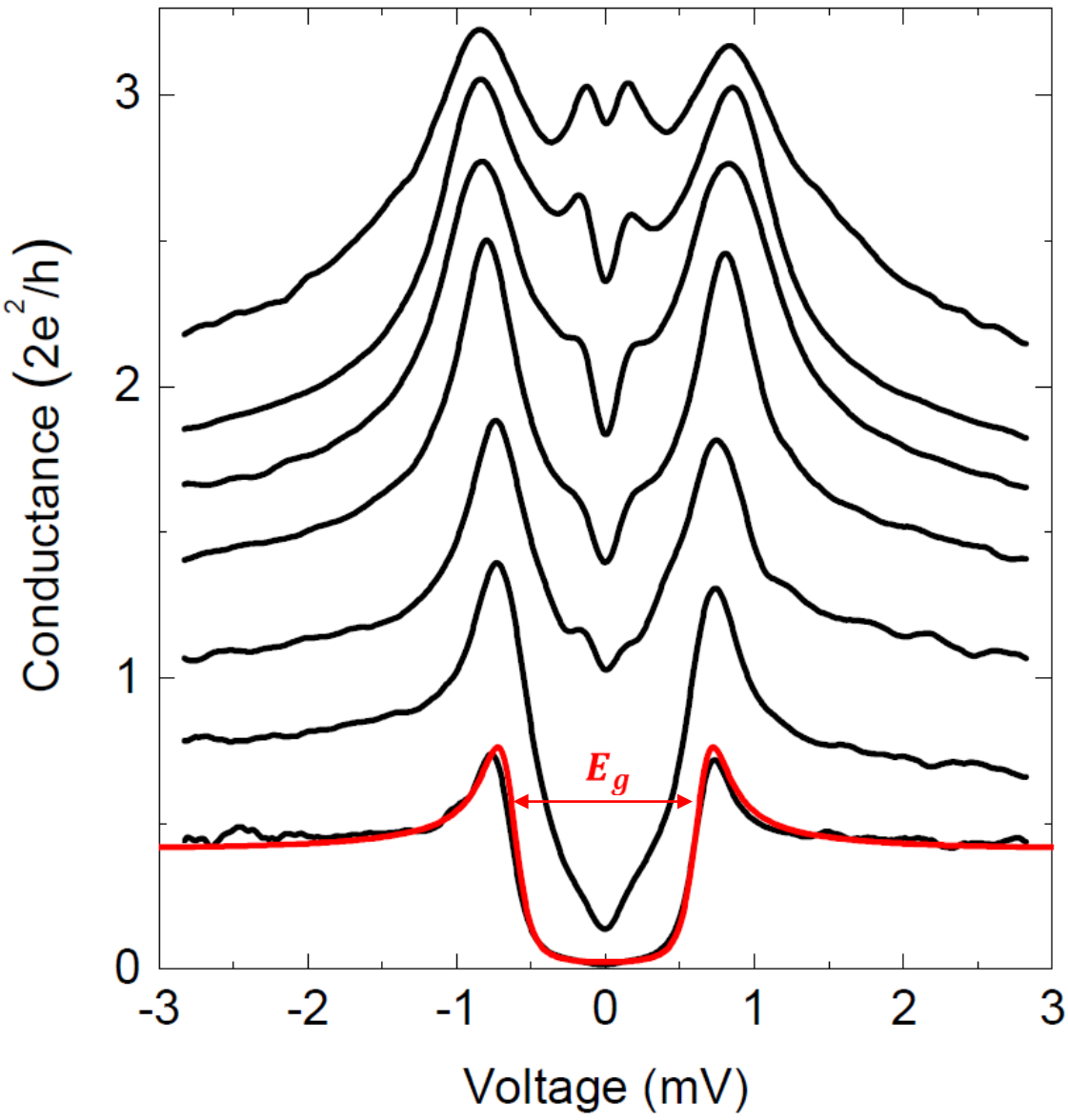
Andreev Spectroscopy vs Tunneling Spectroscopy

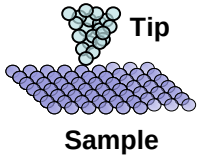




T = 50 mK

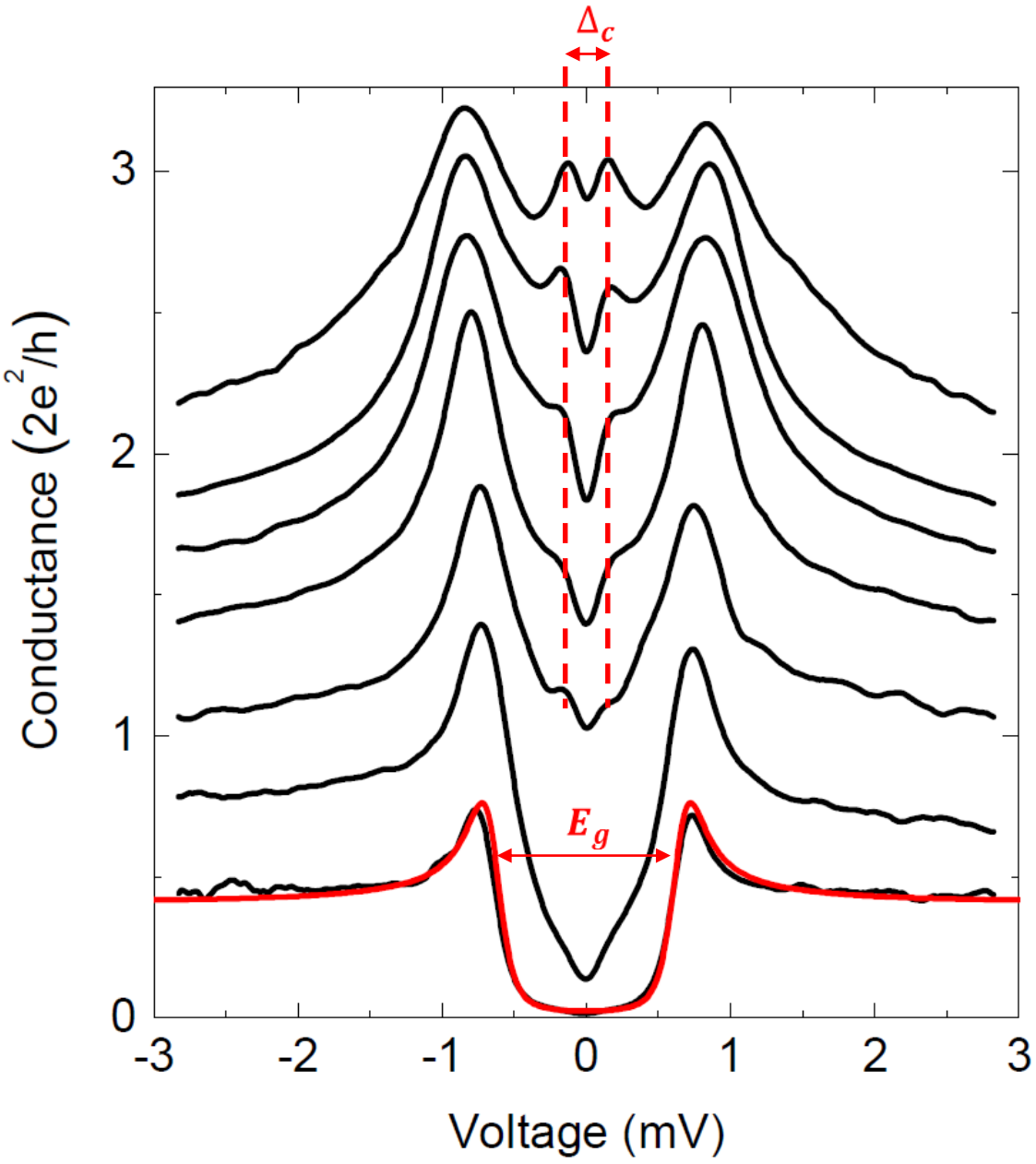
Andreev Spectroscopy vs Tunneling Spectroscopy

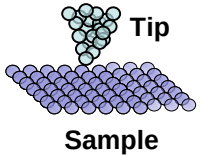




T = 50 mK

Andreev Spectroscopy vs Tunneling Spectroscopy

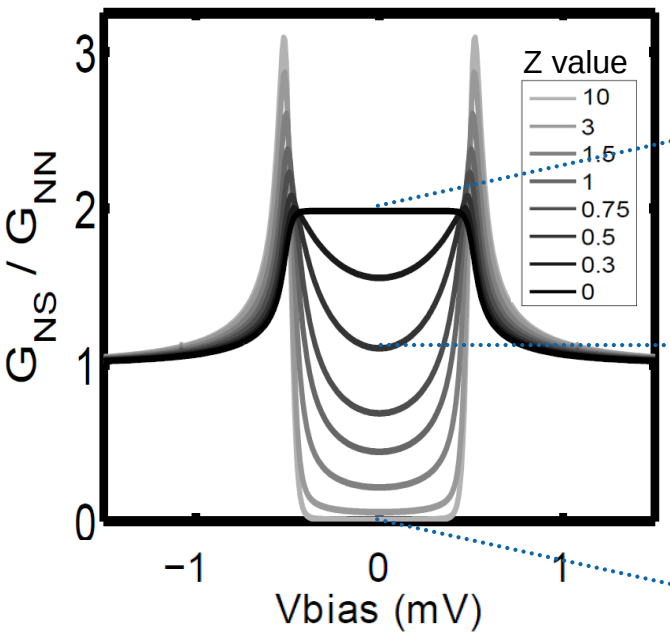




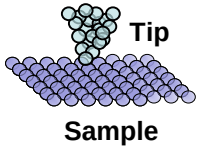
T = 50 mK

Andreev Spectroscopy vs Tunneling Spectroscopy

Conductance of a N/S contact for different barrier transparency



Z = 0



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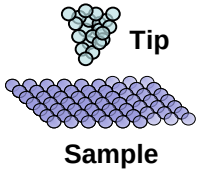

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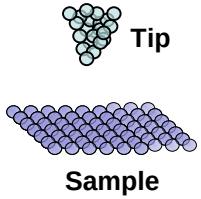
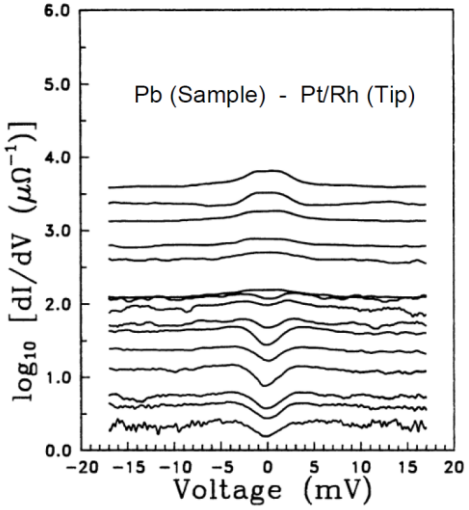
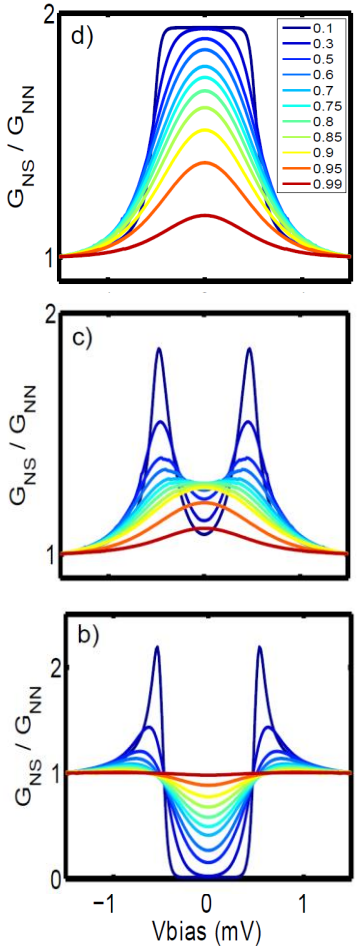




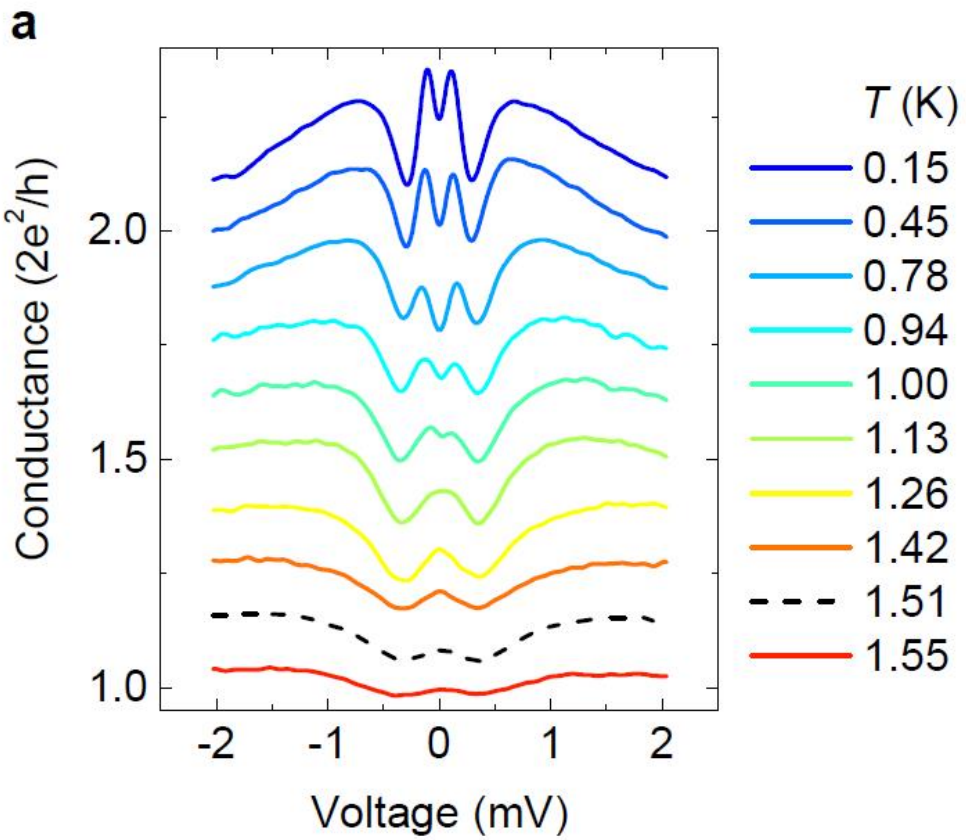
Agrait, N. *et al.*, *Phys. Rev. B* **46**, 9 5814 (1992)

Finite temperature effects

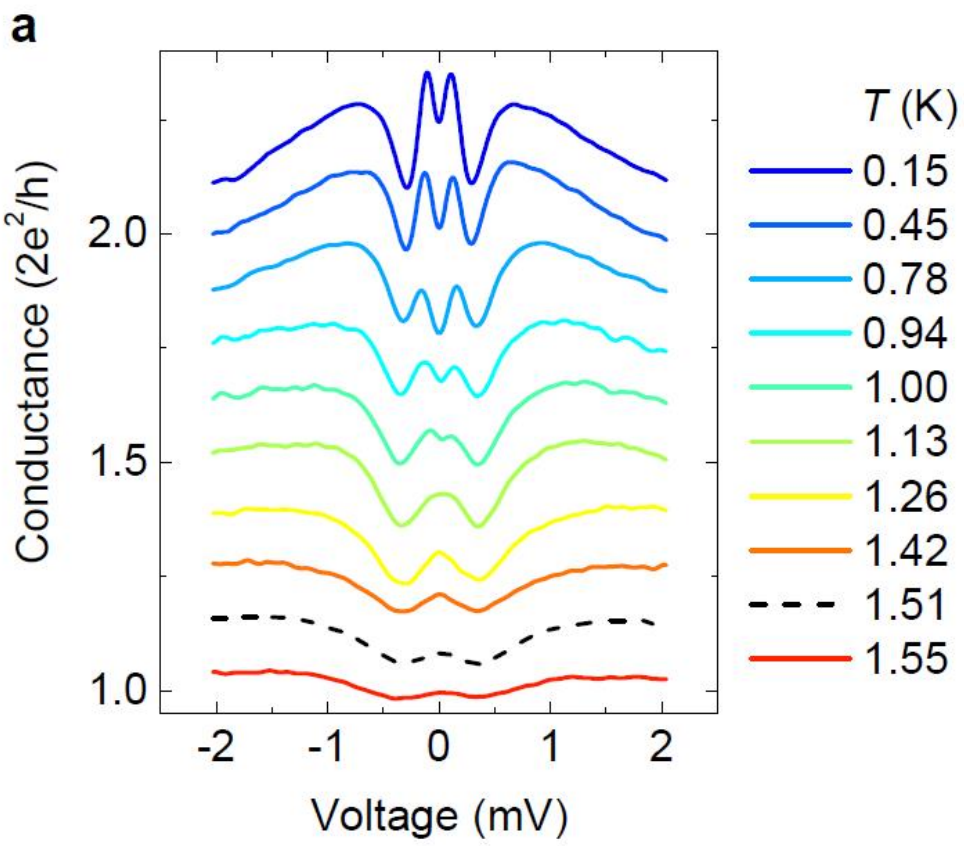


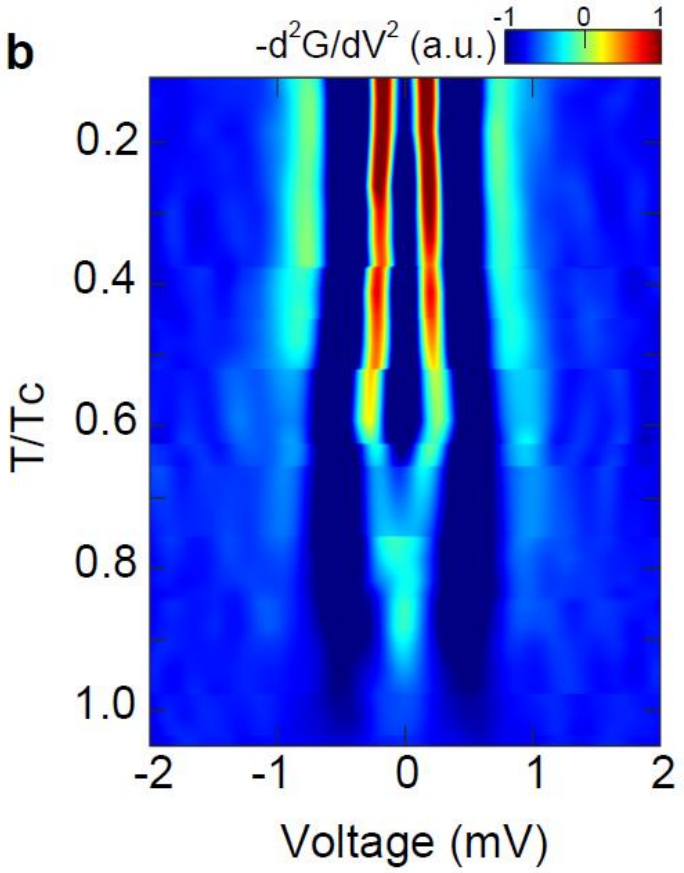
Blonder, G.E. *et al.*, *Phys. Rev. B* **25**, 4515 (1982)

Thermal evolution of an Andreev spectrum



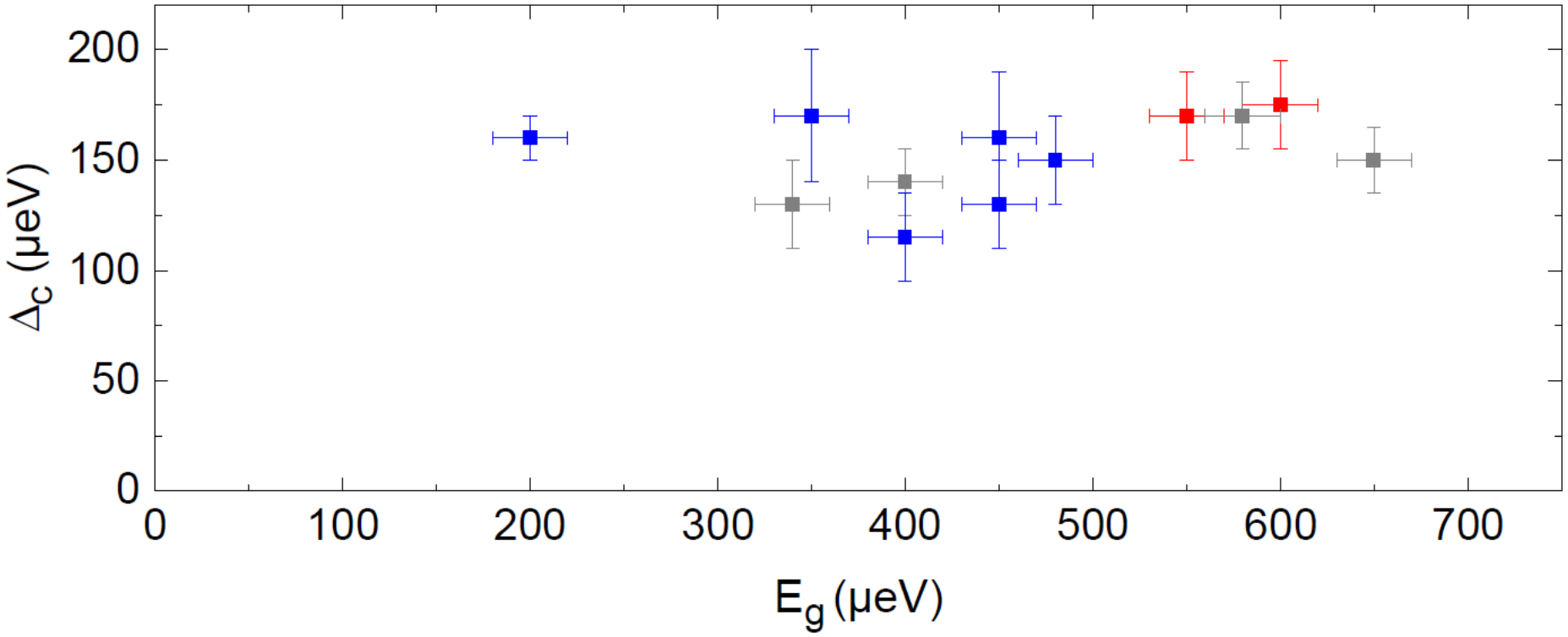
Thermal evolution of an Andreev spectrum





Andreev Spectroscopy vs Tunneling Spectroscopy

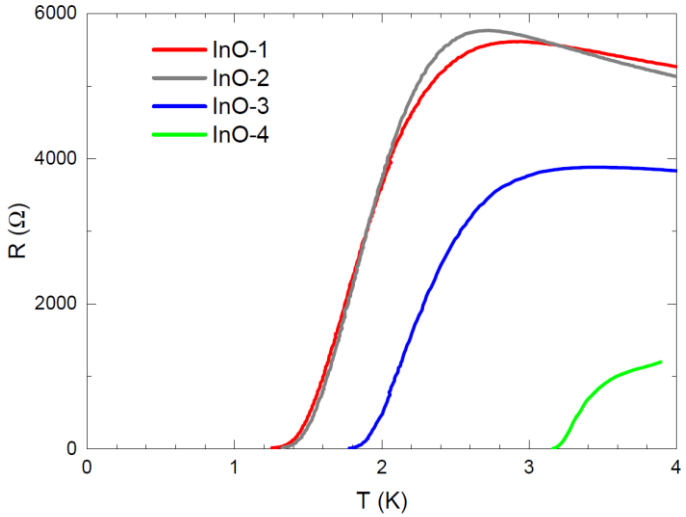
Collective gap versus spectral gap



$$\Delta_c \simeq 150\,\mu eV \sim T_c$$

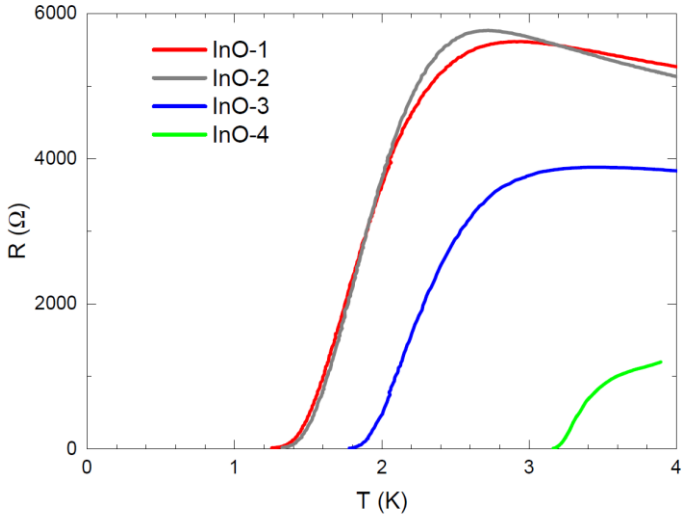
Andreev Spectroscopy vs Tunneling Spectroscopy

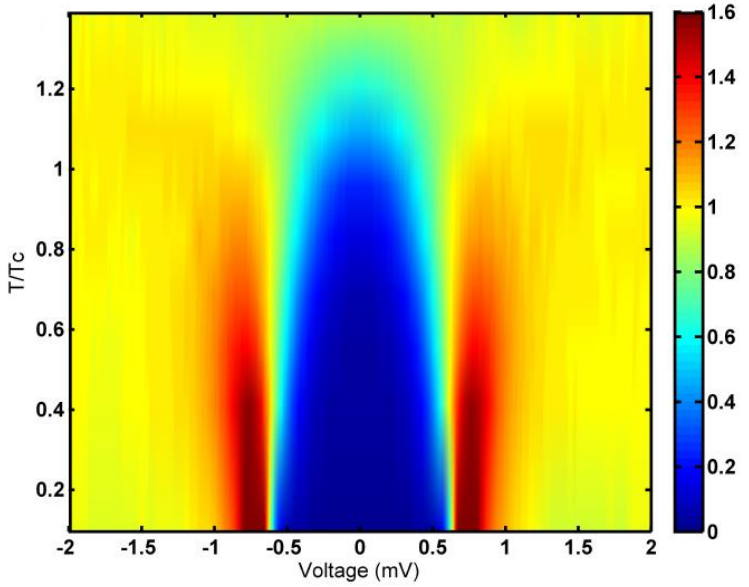
Low disorder film



Andreev Spectroscopy vs Tunneling Spectroscopy

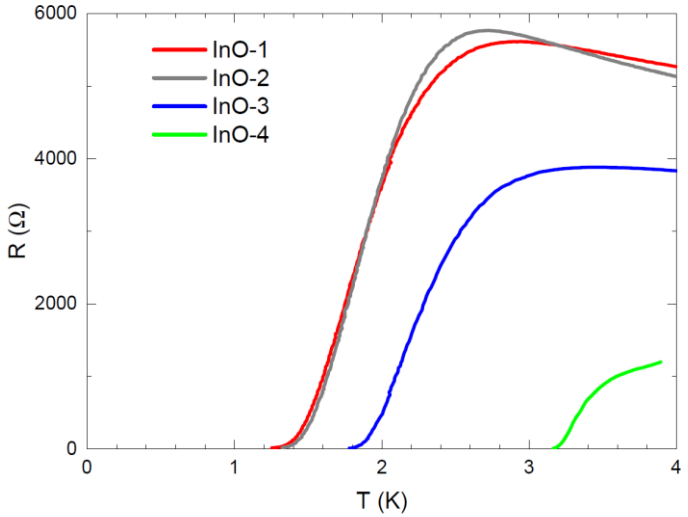
Low disorder film

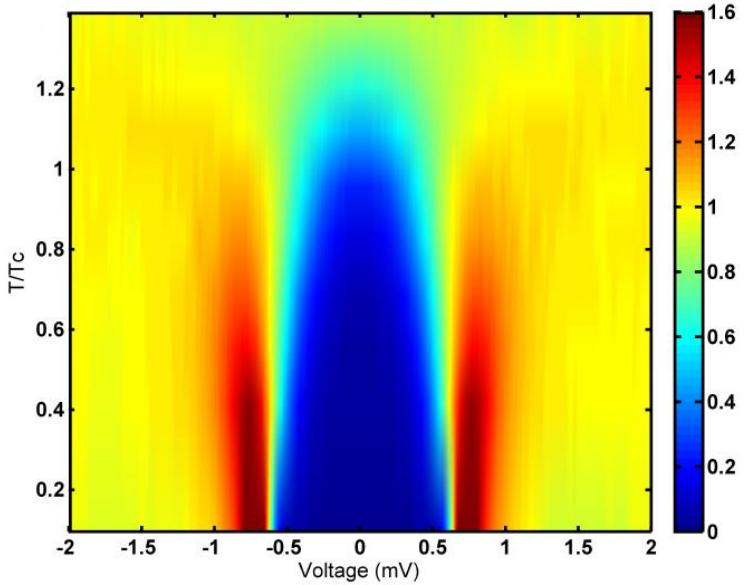


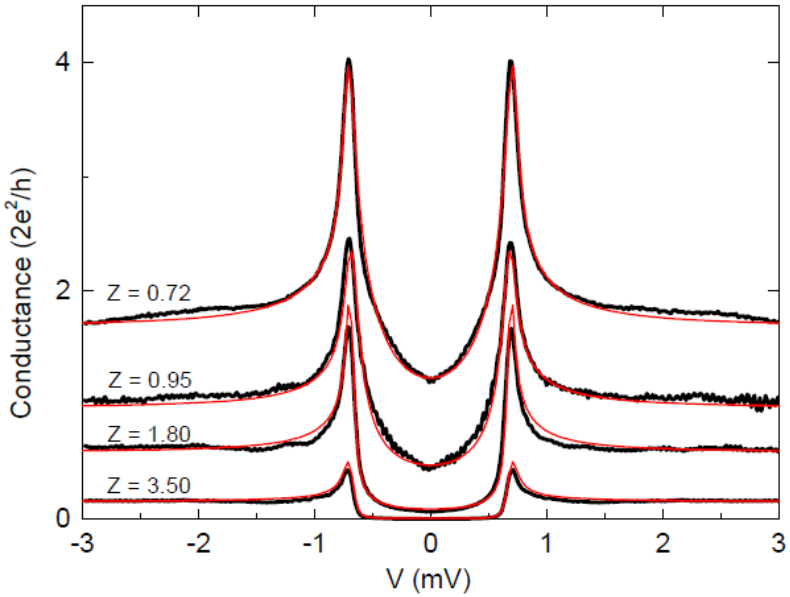


Andreev Spectroscopy vs Tunneling Spectroscopy

Low disorder film

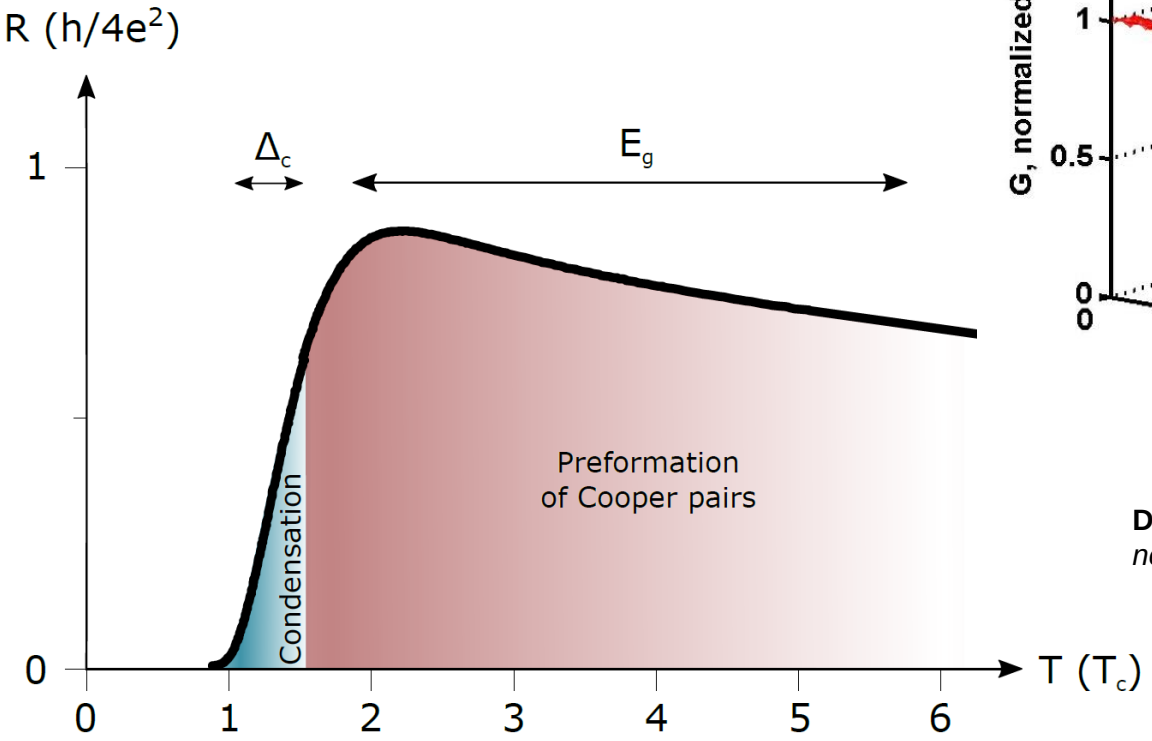


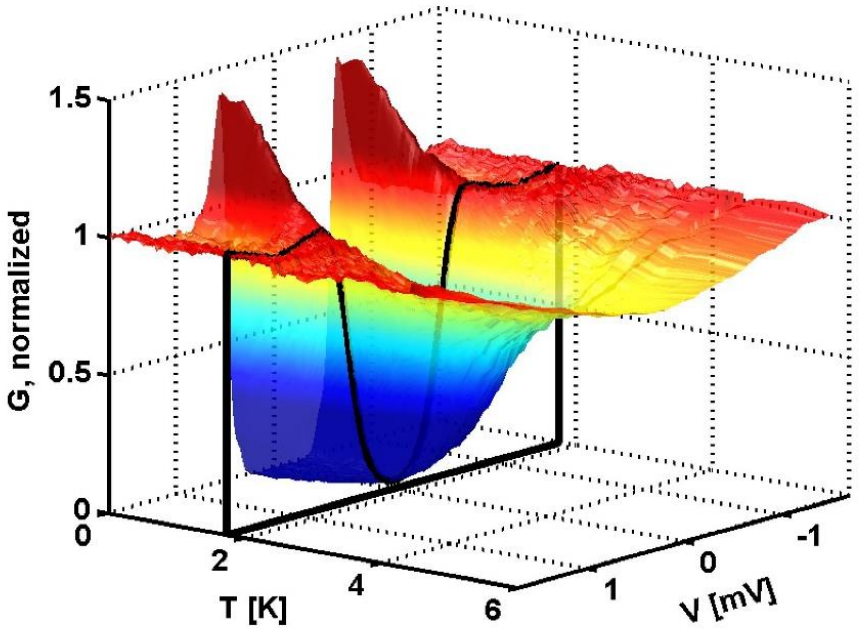




Andreev Spectroscopy vs Tunneling Spectroscopy

Two energy scales for a two-step superconducting transition in highly disordered superconductors close to an insulating state

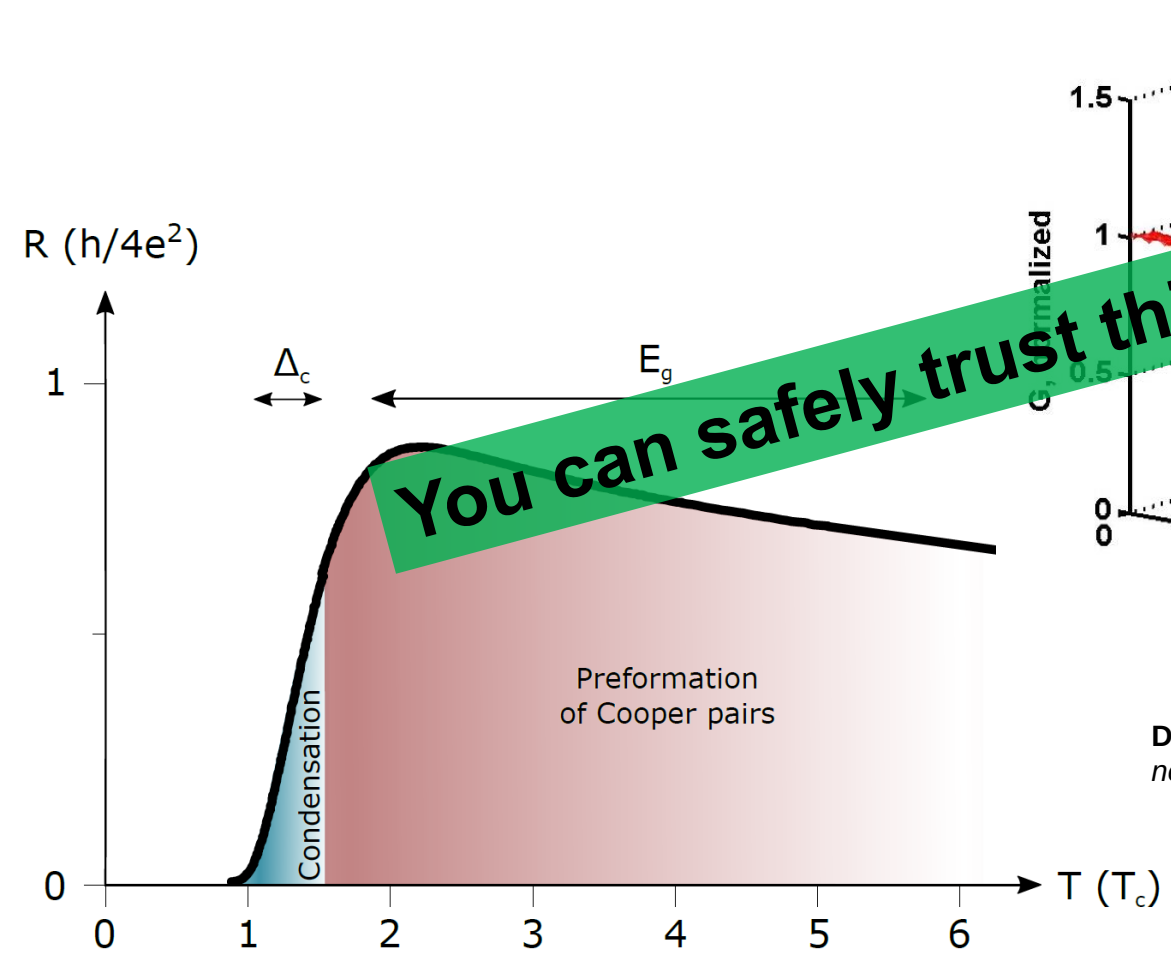




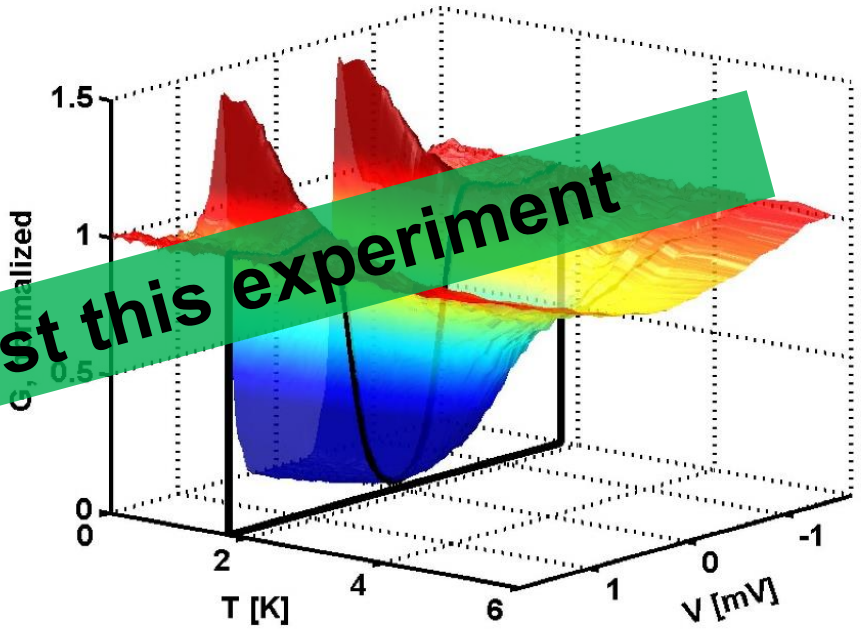
Dubouchet, T. *et al.*, *arXiv:1806.00323, nearly accepted in Nat. Phys.*

Andreev Spectroscopy vs Tunneling Spectroscopy

Two energy scales for a two-step superconducting transition in highly disordered superconductors close to an insulating state



You can safely trust this experiment



Dubouchet, T. *et al.*, *arXiv:1806.00323, nearly accepted in Nat. Phys.*