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PHYSIQUE STATISTIQUE, MAGNETISME ET SUPRACONDUCTIVITE

Local spectroscopy at low temperature of disordered superconducting systems

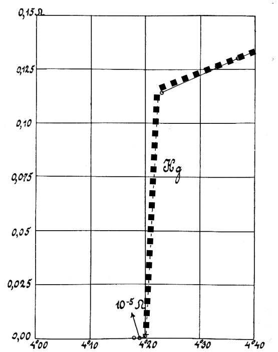
Thomas DUBOUCHET

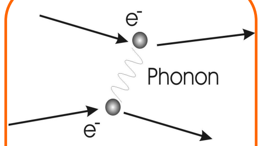
October 11th 2010

Advisors : Claude Chapelier & Marc Sanquer

Quantum Electronic Transport and Superconductivity Laboratory

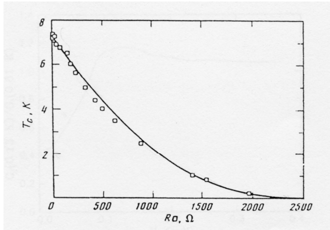
Disorder & superconductivity : milestones

Superconductivity


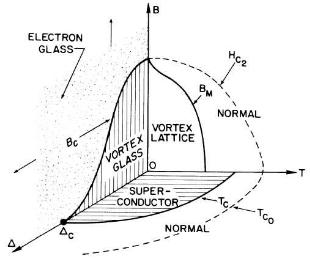
BCS theory


Anderson theorem

Anderson localization

Fermionic scenario


A.M. Finkel'stein
JETP Lett. ***45***, 46 (1987)

Bosonic scenario


M.P.A. Fisher, *PRL* **65**, 923 (1990)

Localization vs. Superconductivity

Time

1911 — 1957 — 1958 - 1959 — 1987 — 1990 — 2000 - 2010

A. Kapitulnik, G. Kotliar, *Phys. Rev. Lett.* ***54***, 473, (1985)

M. Ma, P.A. Lee, *Phys. Rev. B* ***32***, 5658, (1985)

G. Kotliar, A. Kapitulnik, *Phys. Rev. B* ***33***, 3146 (1986)

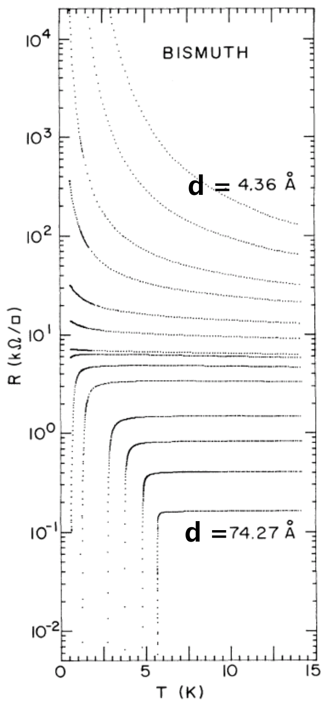
M.V. Sadowskii, *Phys. Rep.*, ***282***, 225 (1997)

A. Ghosal *et al*., PRL ***81***, 3940 (1998) ; PRB ***65***, 014501 (2001)

M. Feigel'man *et al*., *Phys. Rev. Lett.* ***98***, 027001 (2007) ; *Ann.Phys.* **325**, 1390 (2010)

Superconductor to insulator quantum phase transition (SIT)

Amorphous films



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

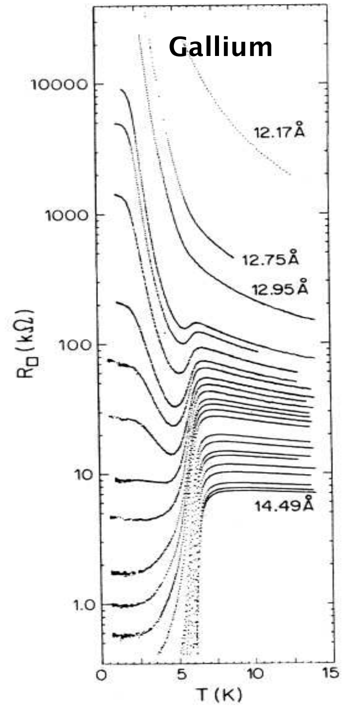
- Continuous decrease of T_c
- Cooper pairing suppressed at the SIT

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

Bosonic

Fermionic

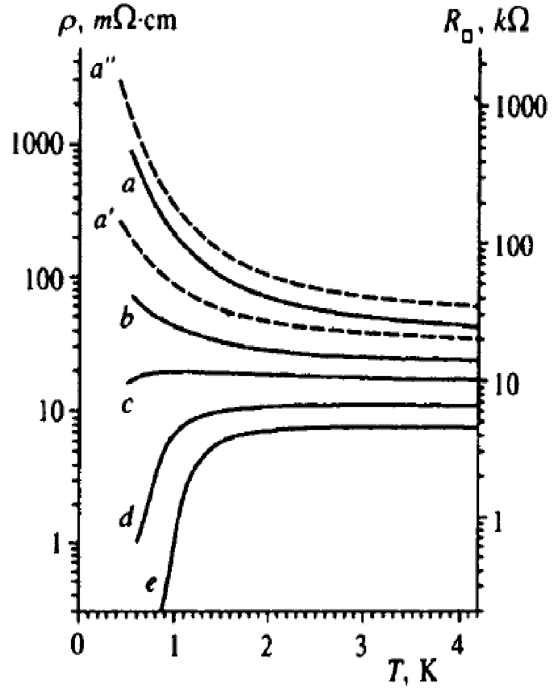
Granular films



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

- Competition between E_C and E_J
- Cooper pairs localized in grains

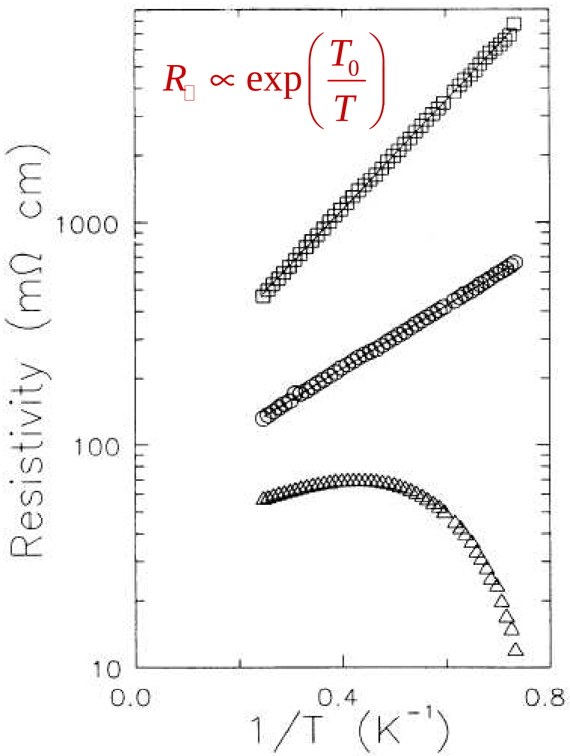
Disorder-tuned SIT in Amorphous Indium Oxide films (InO_x)

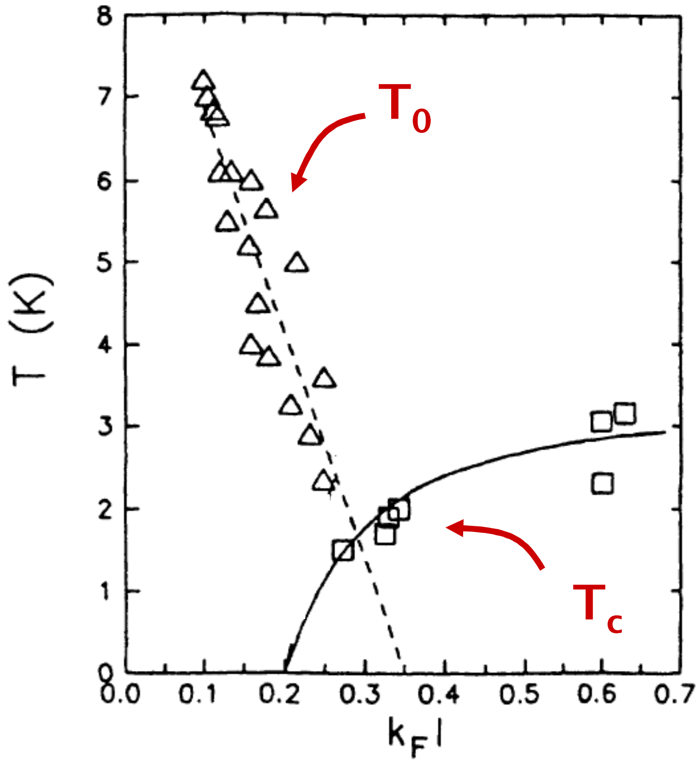


V. F. Gantmakher *et al.*, *JETP* ***82***, 951 (1996)

➢ Homogeneously disordered a-InO_x → progressive reduction of T_c

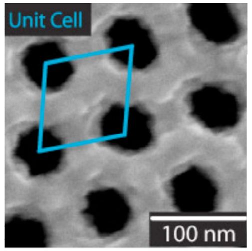
Activated behavior and localized superconductivity



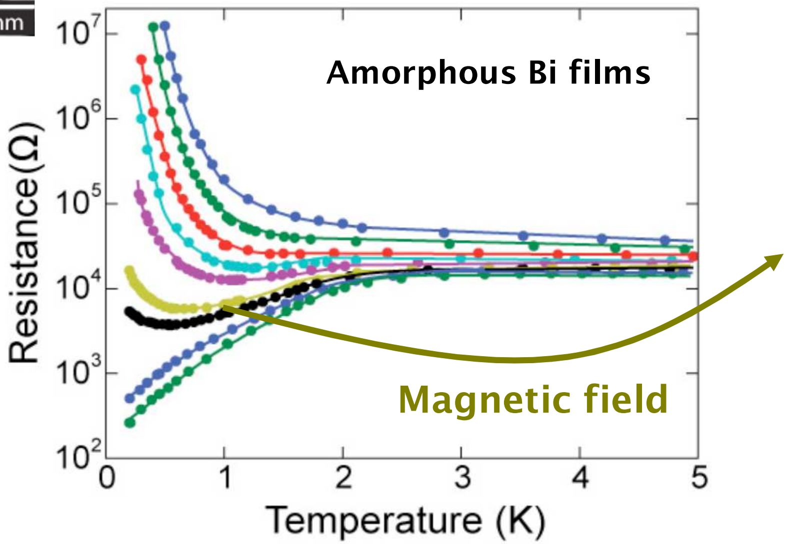


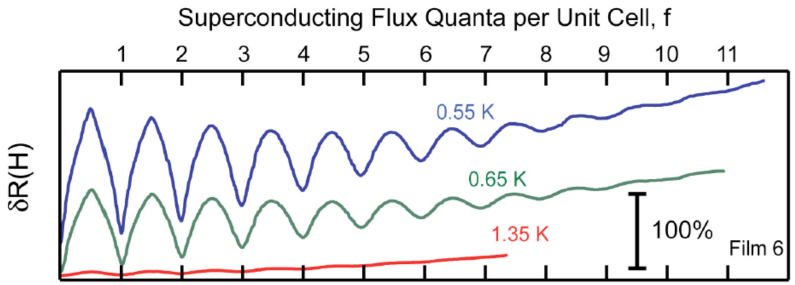
D. Shahar and Z. Ovadyahu, *Phys. Rev. B* ***46***, 10917 (1992)

- Superconductivity survives in the localized regime
- T_0: gapped insulator? Superconductivity related?
- Continuity between T_0 and T_c



Magneto-resistance oscillations with half-flux periodicity





Period: H_M = h/2eS → 2e charge carriers
(S = unit cell area)

Stewart, Jr., M. D., Yin, A., Xu, J. M., Valles, Jr., J. M., *Science* **318**, 1273, (2007)

➢ Transport measurements give only indirect evidence for the existence of localized Cooper-pairs...

Transport measurements & theories
suggest the possible
Quantum localization of Cooper-pairs

A need to probe electronic properties
at a local scale

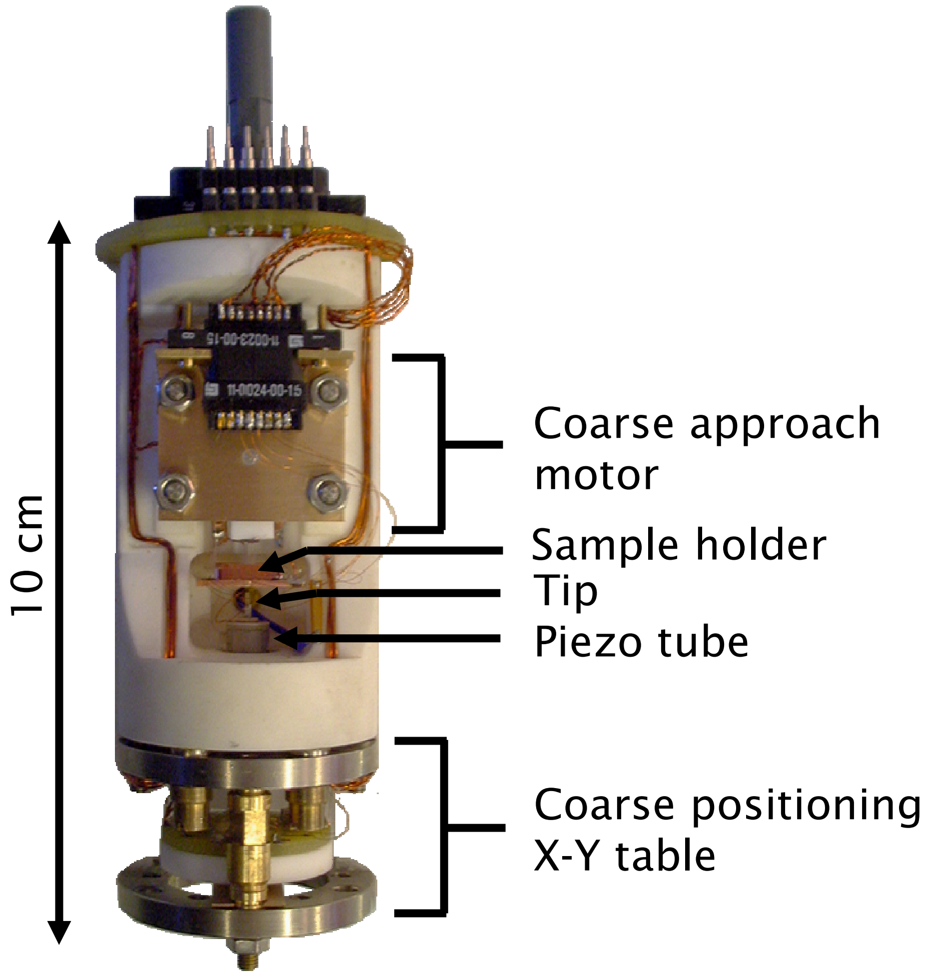
⇨ *Scanning Tunneling Spectroscopy*

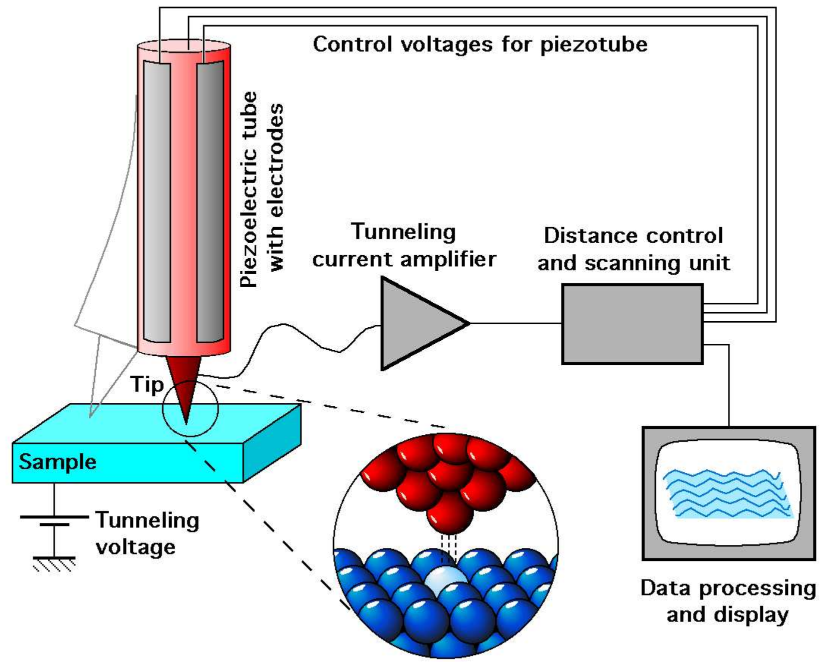
I. Experimental techniques

II. Localized Cooper pairs in a-InO_x

III. Coherence energy in a-InO_x

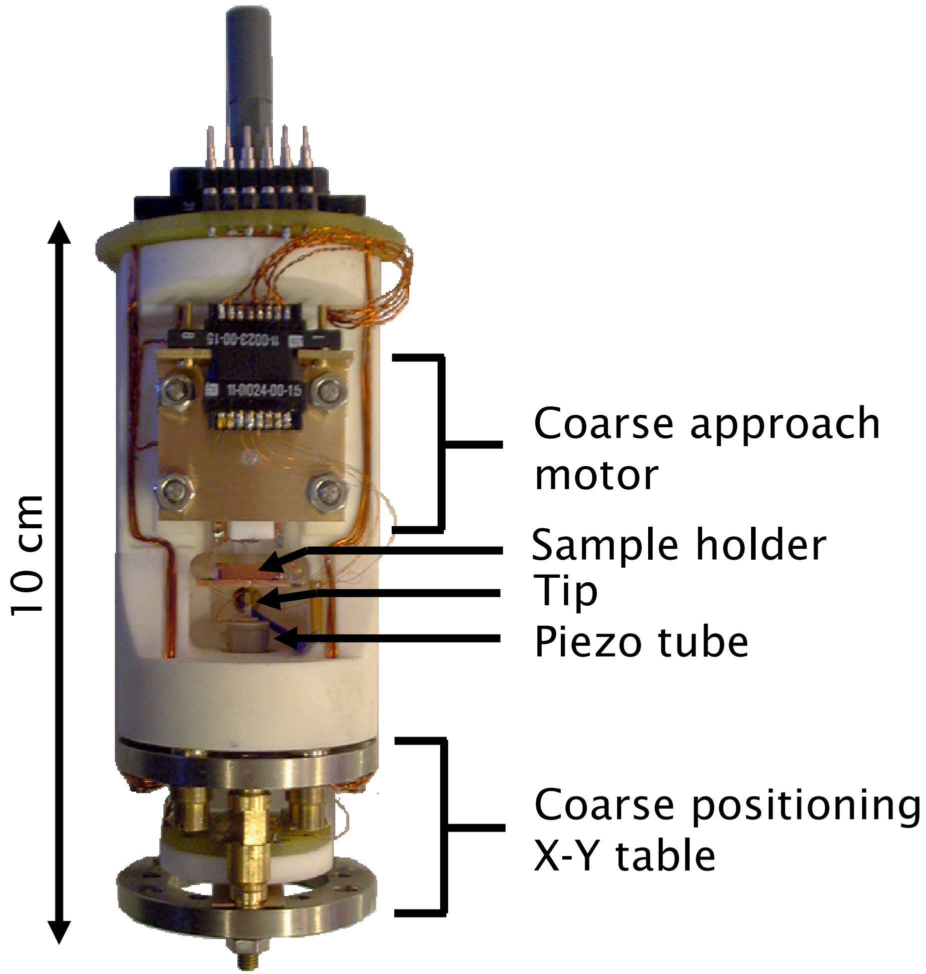
Very-low temperature Scanning Tunneling Microscope

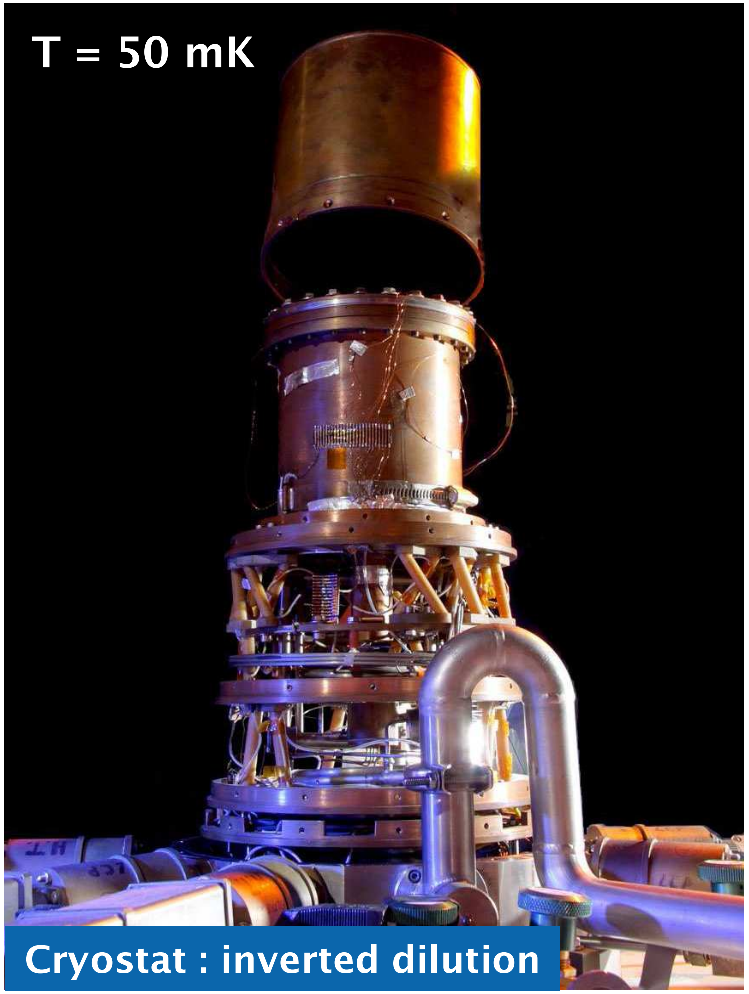




- Combined transport & spectroscopy measurements

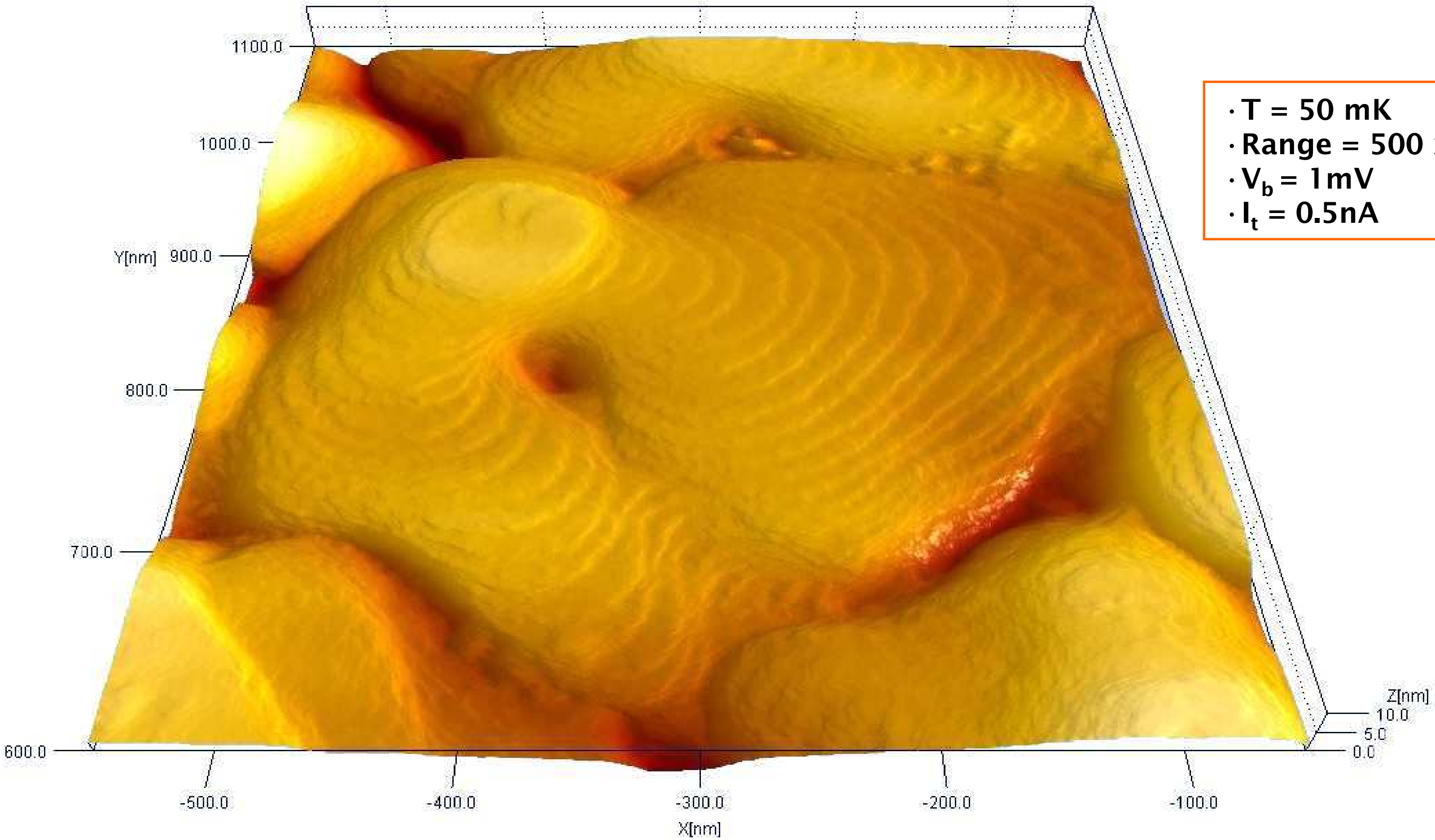
Very-low temperature Scanning Tunneling Microscope





- Combined transport & spectroscopy measurements

Topographic image of epitaxial Rhenium



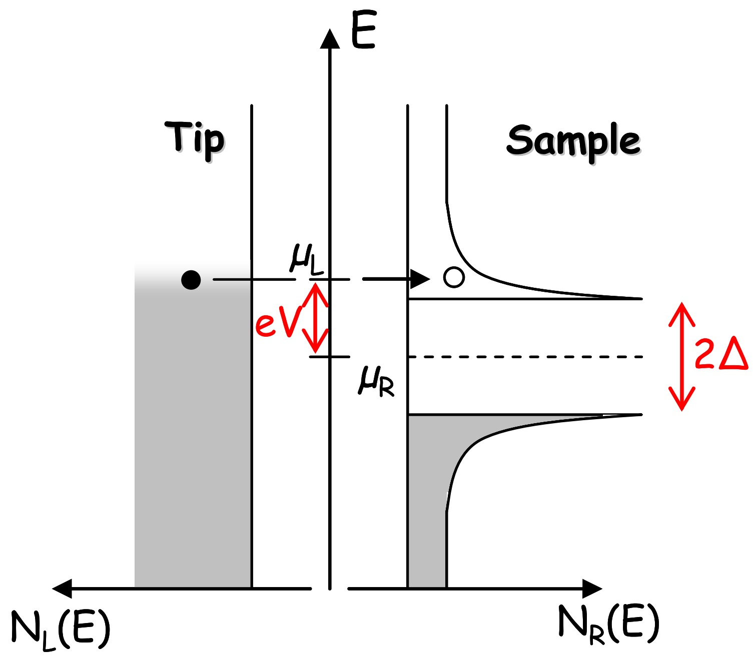
- T = 50 mK
- Range = 500 x 500 nm²
- V_b = 1mV
- I_t = 0.5nA

Scanning range : 30×30 μm² (T=300K) --- 3×3 μm² (T=50mK)

Tunneling spectroscopy

Measurement of the Density-Of-States (DOS)

$$G(V)=\frac{dI}{dV}\propto\int d\varepsilon N_S(\varepsilon)\left(-\frac{\partial f_T(\varepsilon+eV)}{\partial V}\right)$$



$N_S(\varepsilon)$: density of states of the sample

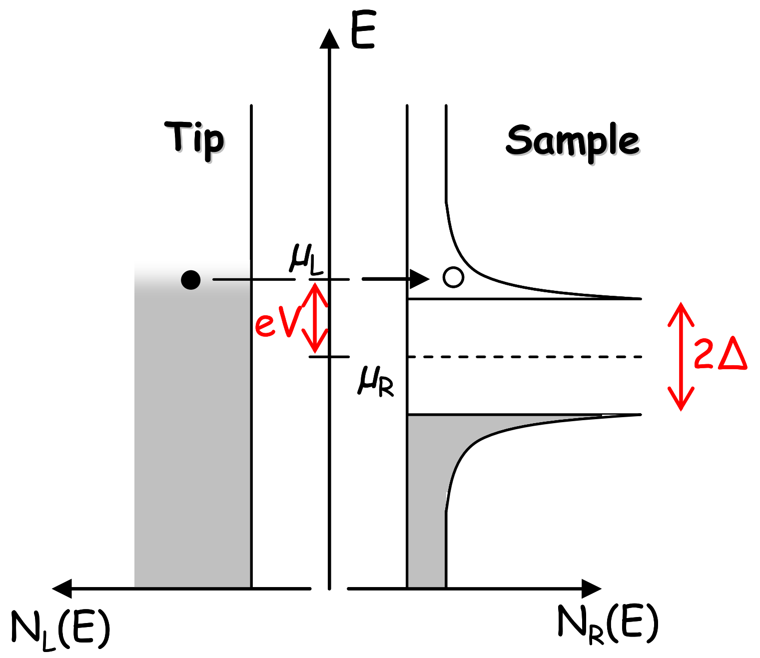
$f_T(\varepsilon)$: Fermi-Dirac distribution

$\Delta(T)$: superconducting gap

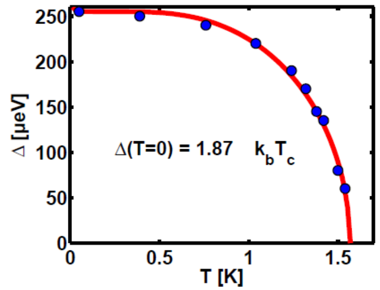
Tunneling spectroscopy

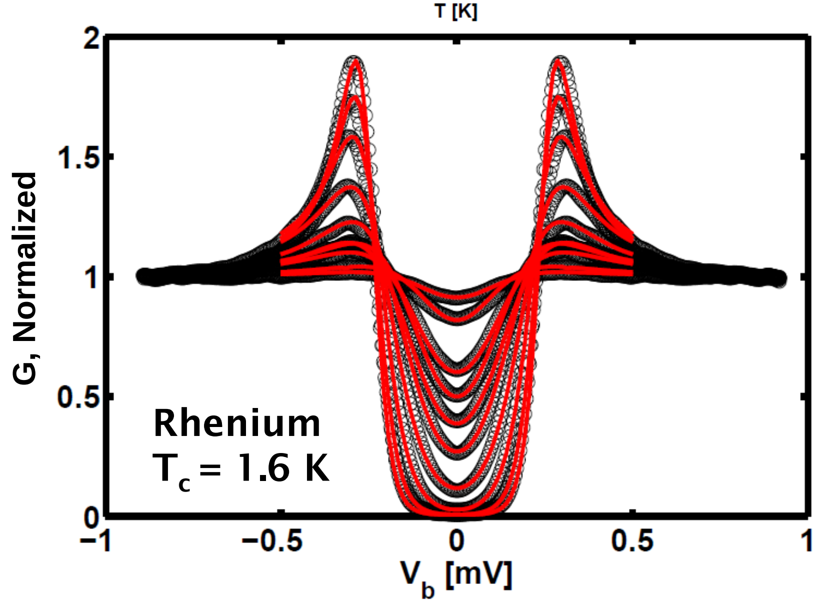
Measurement of the Density-Of-States (DOS)

$$G(V)=\frac{dI}{dV}\propto\int d\varepsilon N_S(\varepsilon)\left(-\frac{\partial f_T(\varepsilon+eV)}{\partial V}\right)$$



Resolution ≈ 70 - 90 μeV

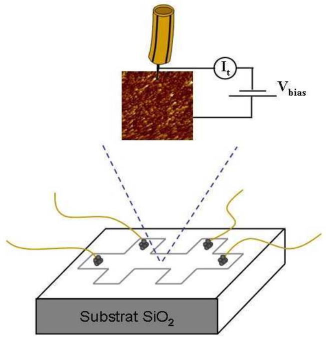




I. Experimental techniques

II. Localized Cooper pairs in a-InO_x

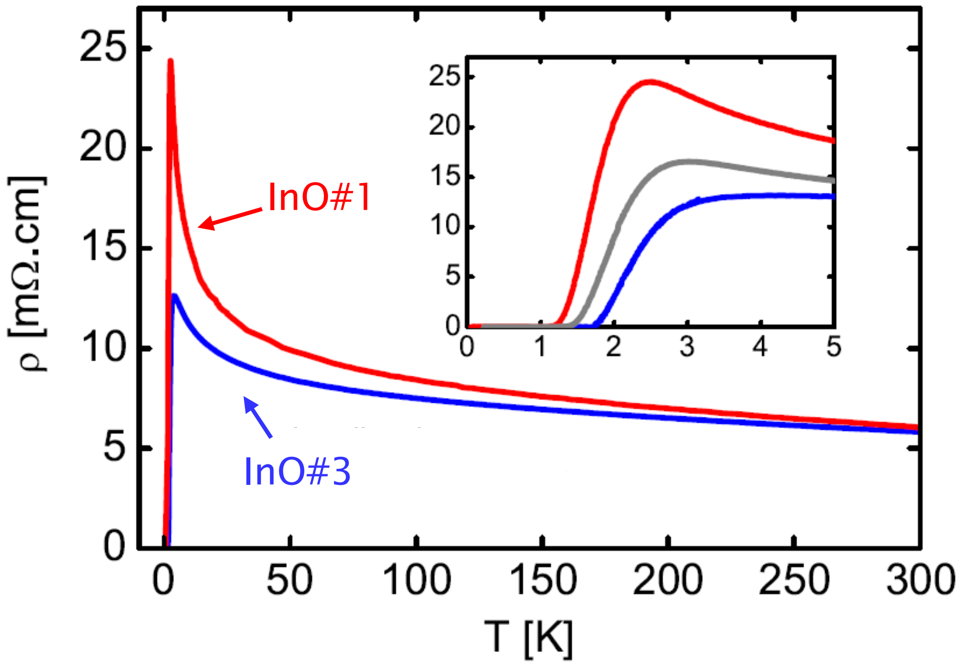
III. Coherence energy in a-InO_x



Amorphous Indium Oxide

Transport Measurements

Thickness : 15 nm (red & grey) and 30 nm (bleu) – 3D regime

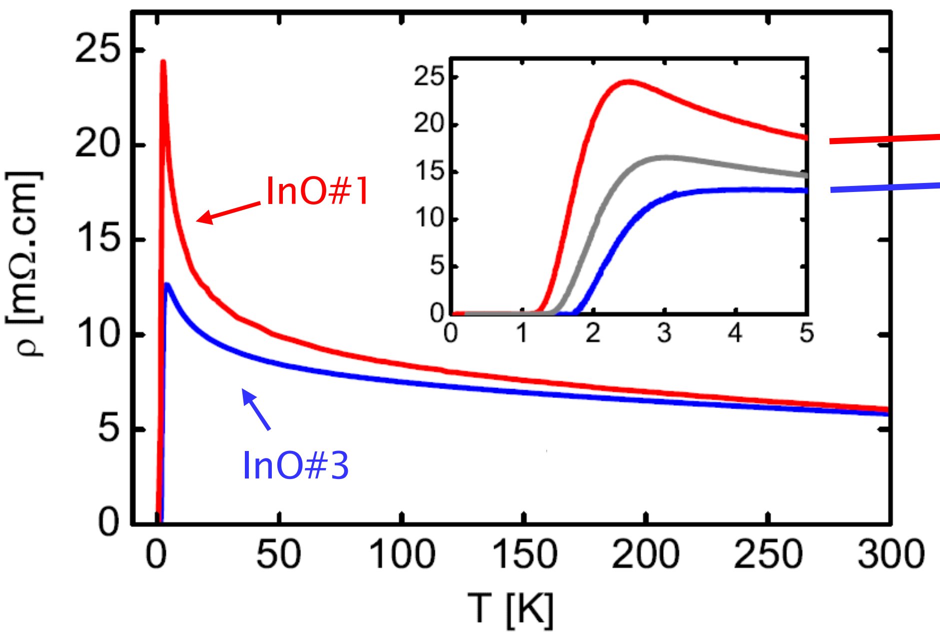


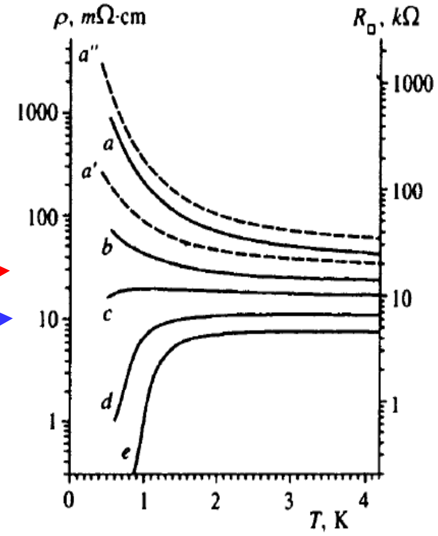
Samples: e-gun evaporation of high purity In_2O_3 onto Si/SiO_2 substrate under O_2 pressure

D. Shahar, Weizmann Institute of Science

Nearly critical samples

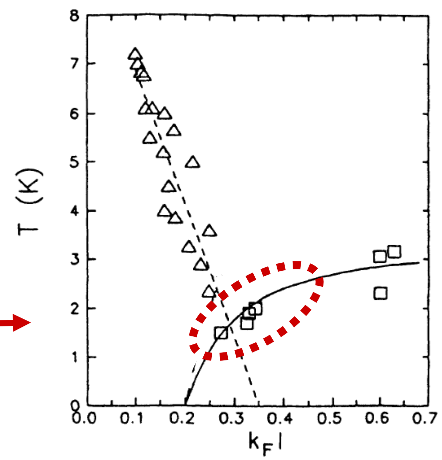
High disorder (red) and low disorder (bleu)

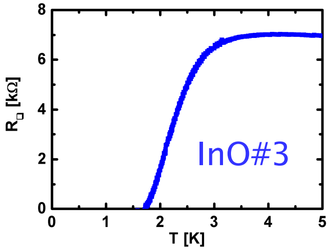




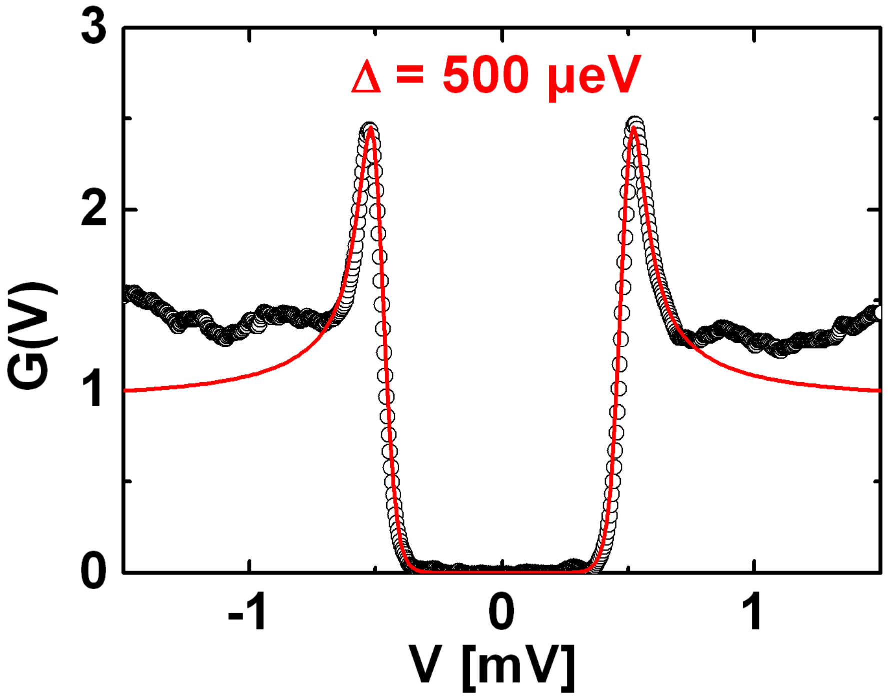
- $k_F l_e \sim 0.4\text{-}0.5 < 1$ → **localized regime (Ioffe-Regel criterion)**
- **T_c comprised between 1K and 2K**

- Carrier density : $N = 3.5 \times 10^{21}$ cm^{-3}
- Fermi vector k_F ; Elastic mean free path l_e





Typical spectrum measured at 50 mK

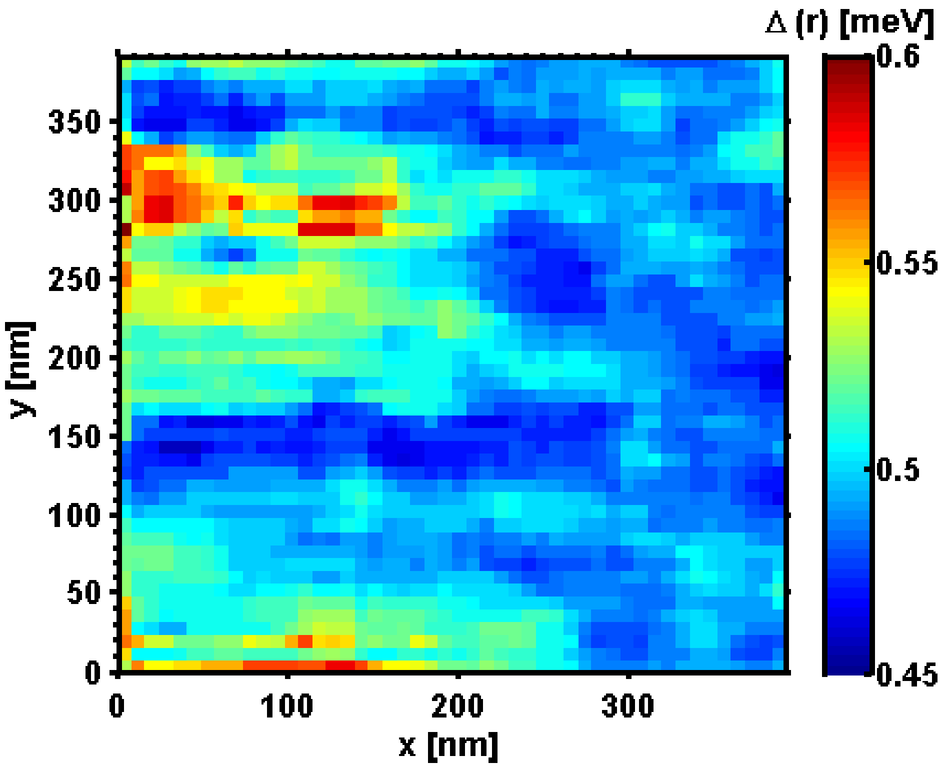


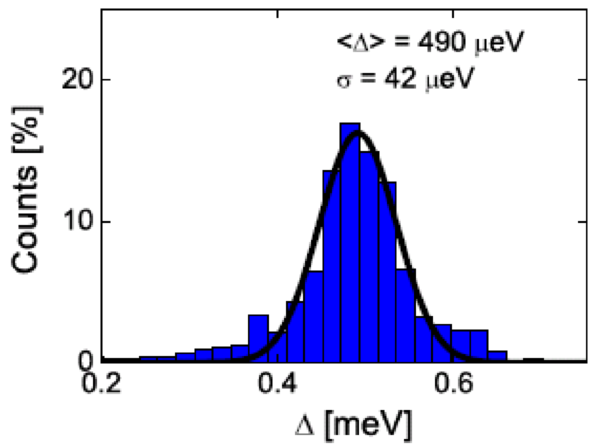
Fit : *s*-wave BCS density of states

➢ Absence of quasi-particle excitations at low energies

Spatial fluctuations of the spectral gap Δ(r)

Map of the spectral gap

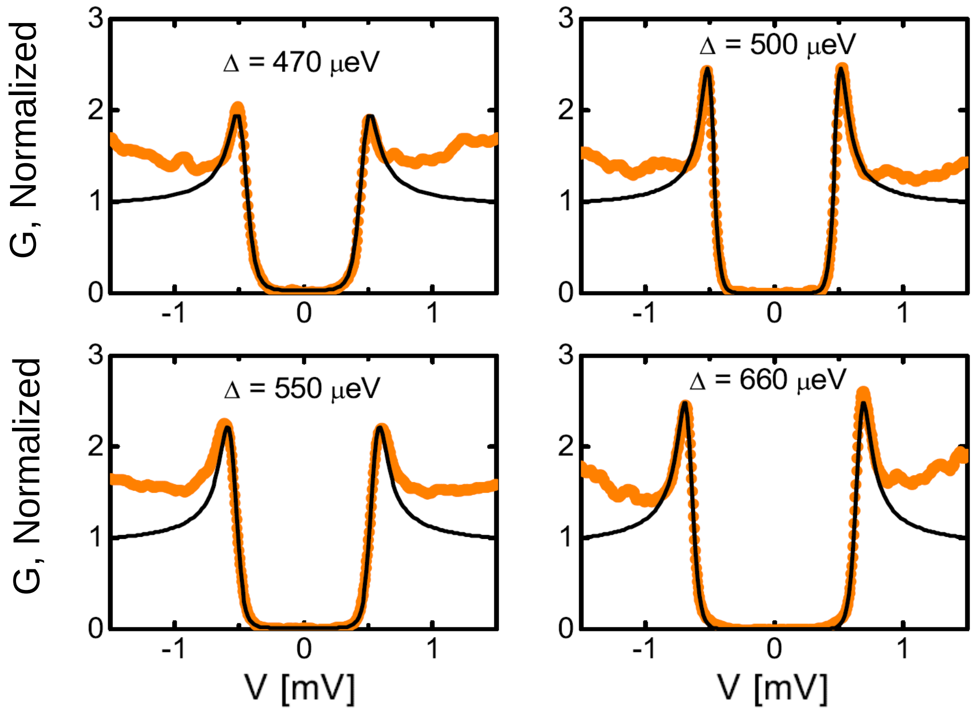


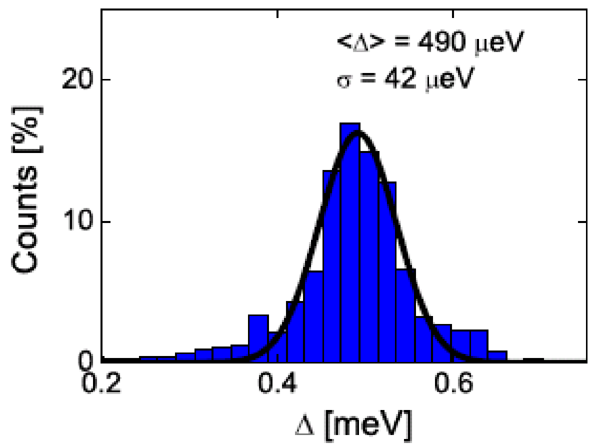


Gaussian distribution

Spatial fluctuations of the spectral gap Δ(r)

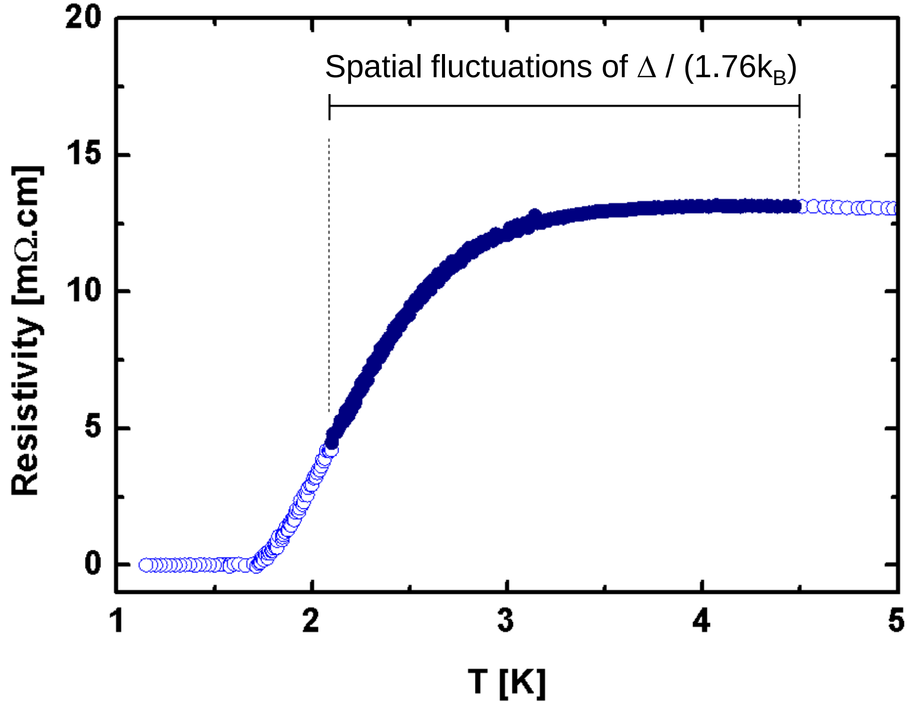
Spectra measured at different locations (T=50mK)





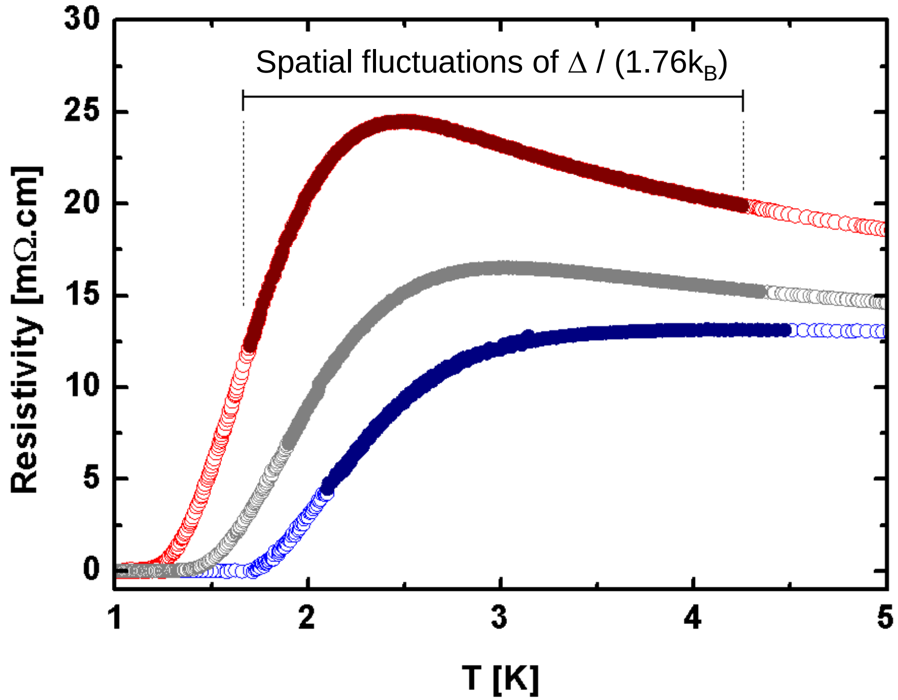
Gaussian distribution

Fluctuations of Δ(r) and superconducting transition



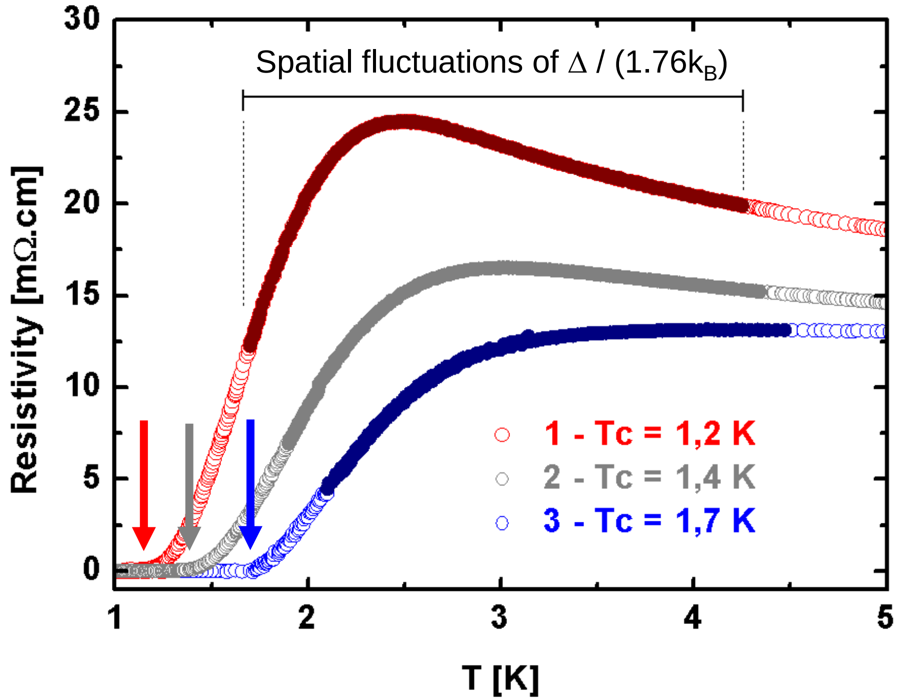
➢ Unusual relation between transport & spectroscopy ?

Fluctuations of Δ(r) and superconducting transition



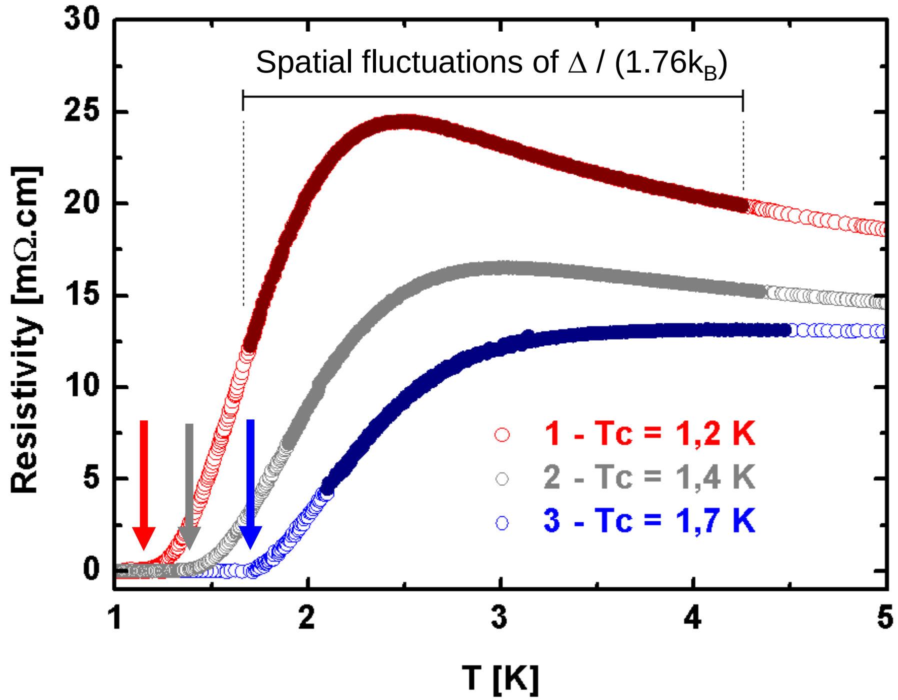
➢ Unusual relation between transport & spectroscopy ?

Fluctuations of Δ(r) and superconducting transition



- Unusual relation between transport & spectroscopy ?
- Definition of T_c : zero-resistance state (macroscopic coherence)

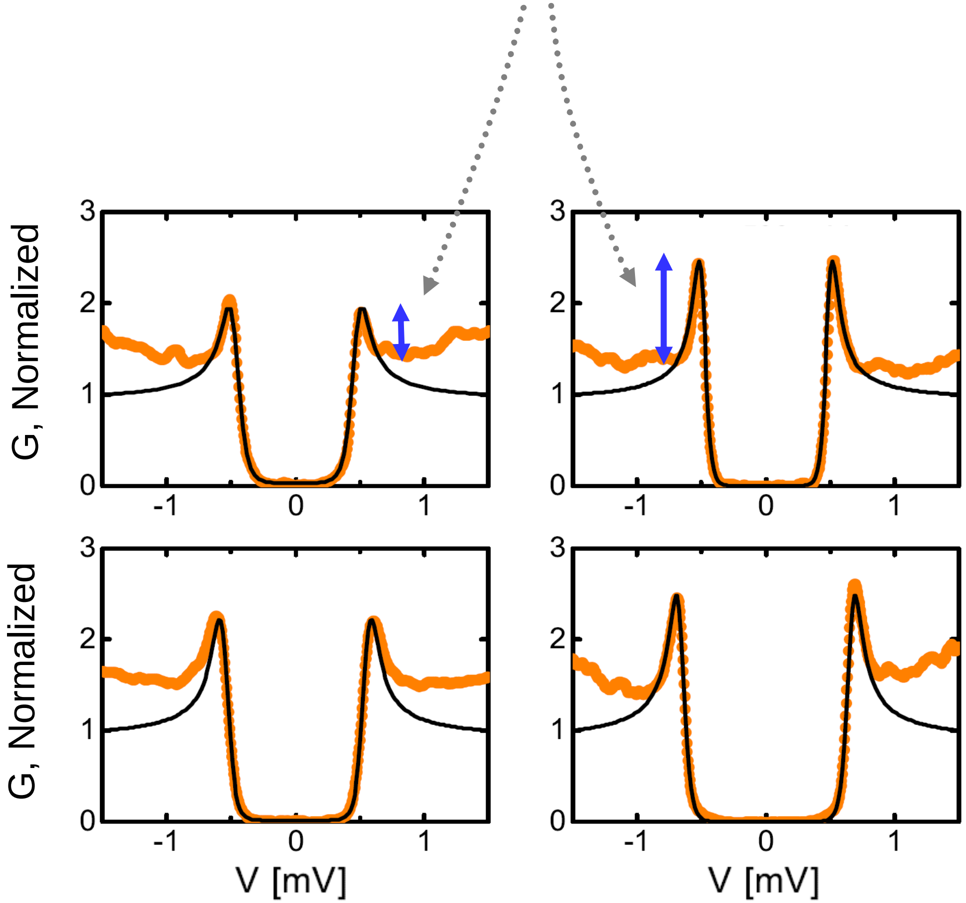
Fluctuations of Δ(r) and superconducting transition



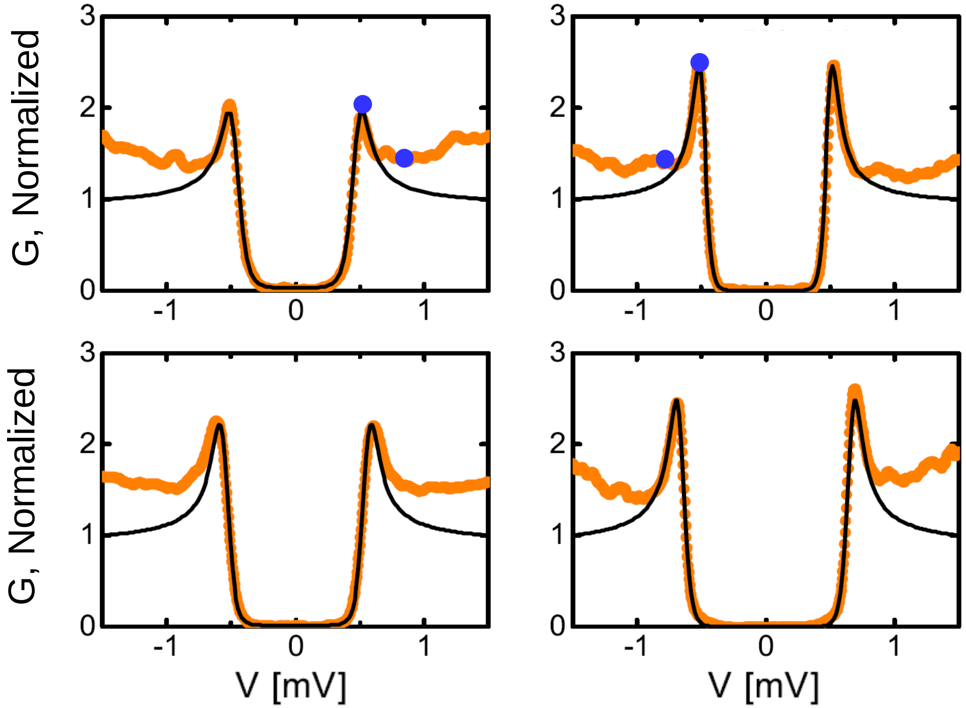
$$3 \leq \frac{\Delta(r)}{k_B T_C} \leq 5.5$$

- ➢ Unusual relation between transport & spectroscopy ?
- ➢ Definition of T_c : zero-resistance state (macroscopic coherence)
- ➢ Anomalously large spectral gap

Spatial fluctuations of the coherence peaks height

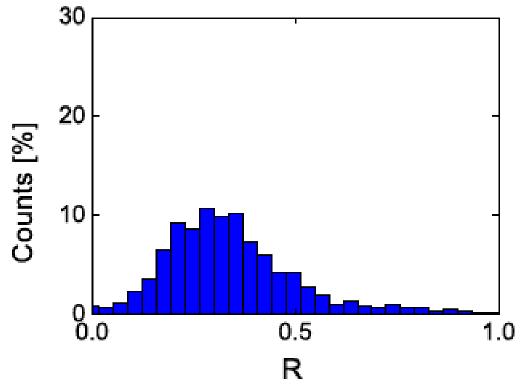


Spatial fluctuations of the coherence peaks height

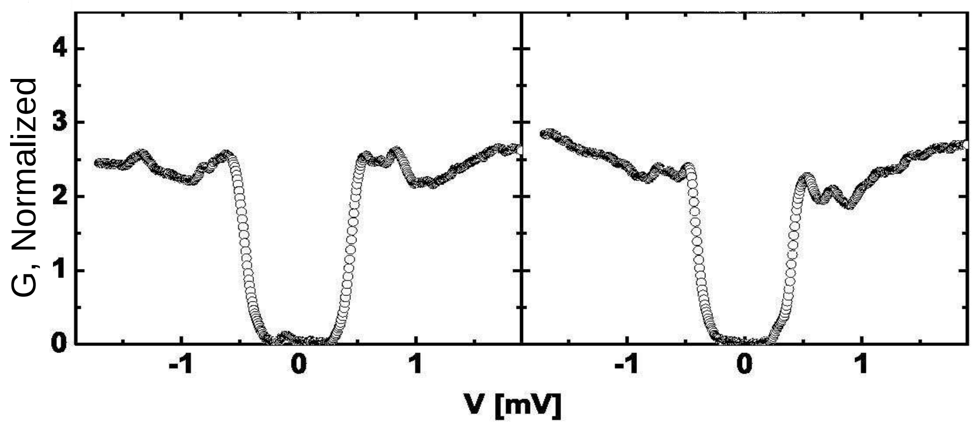


Statistical study

$$R = \frac{G(\Delta) - G(eV > \Delta)}{G(eV > \Delta)}$$



Full spectral gap
without coherence peaks



Statistical study

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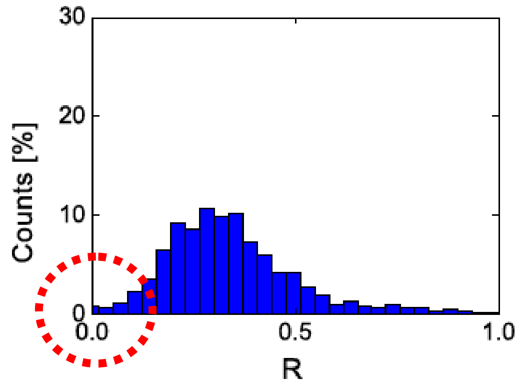
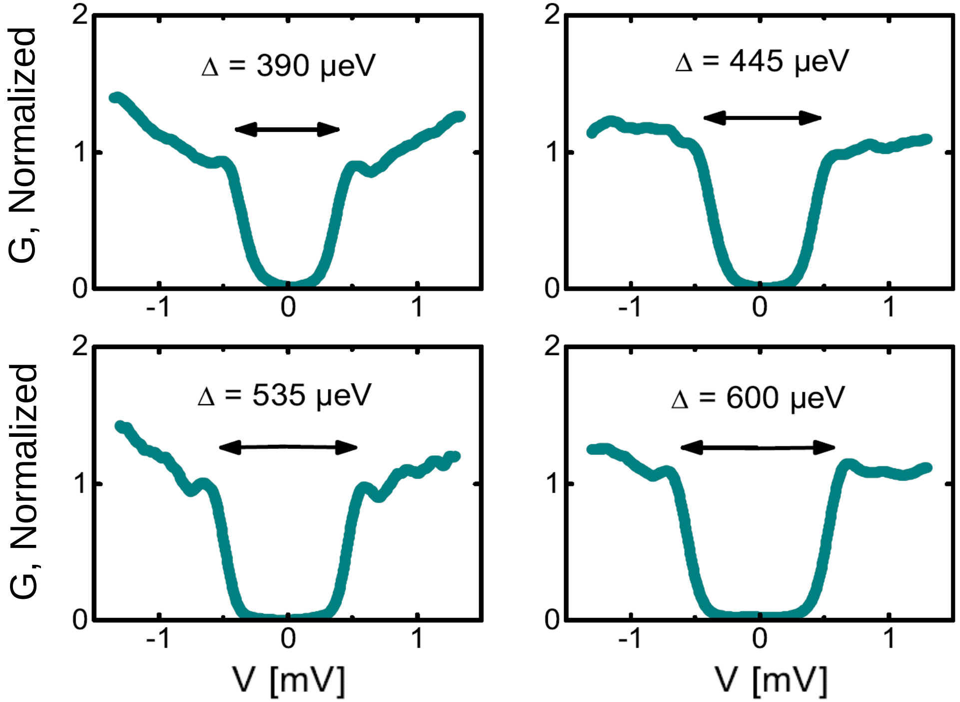


Full spectral gap without coherence peaks



Statistical study

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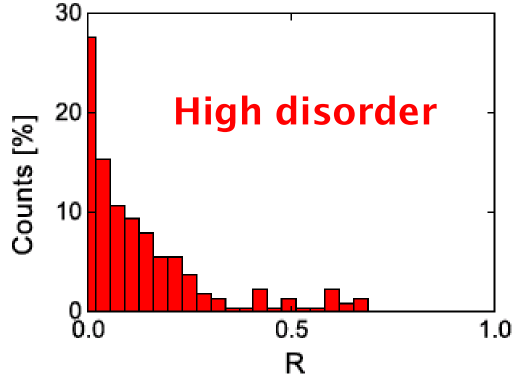
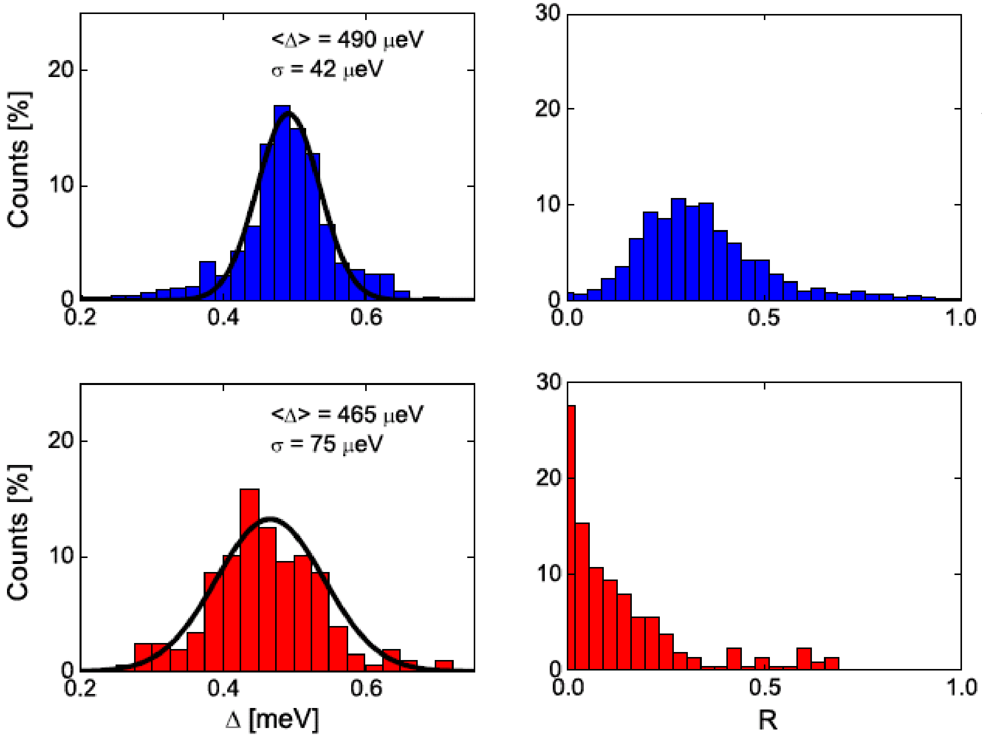


Increase of disorder

$\frac{\sigma}{\langle \Delta \rangle} \sim 8\%$



InO#3 $T_c \sim 1.7$ K

resistivity × 2

$\frac{\sigma}{\langle \Delta \rangle} \sim 16\%$

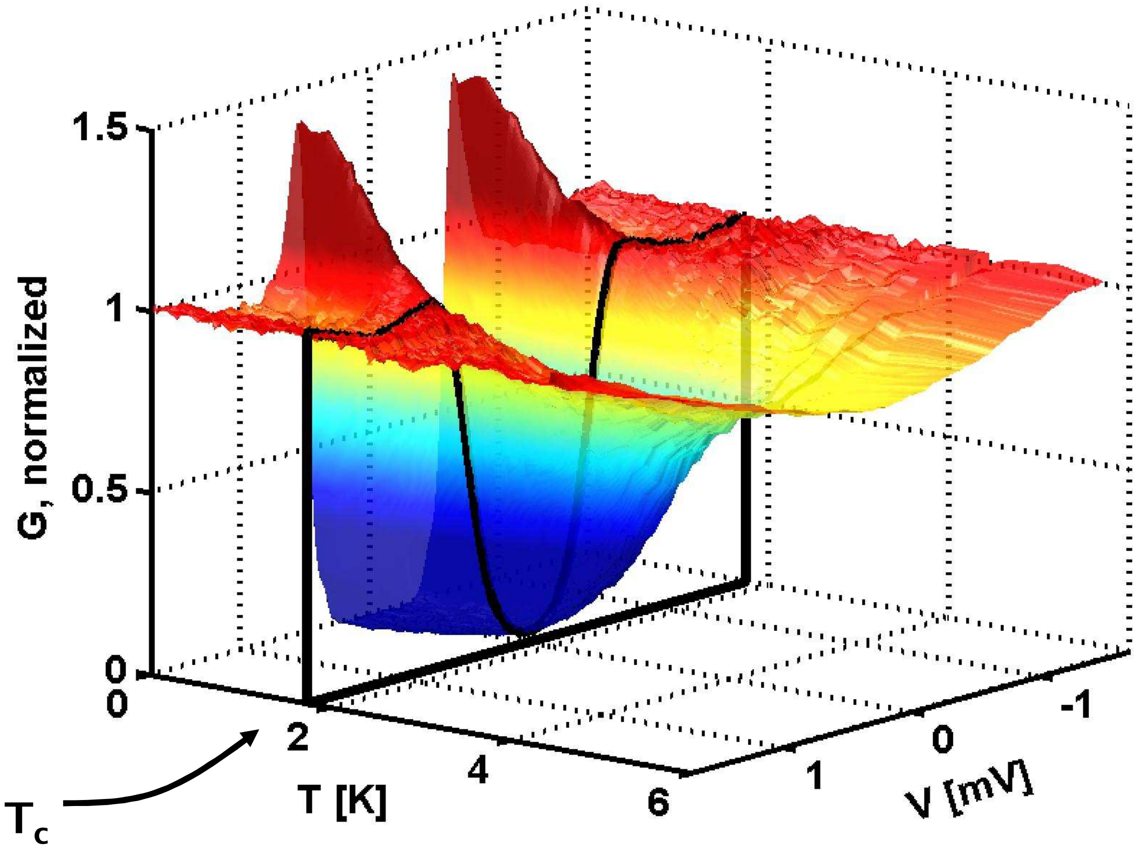
InO#1 $T_c \sim 1.2$ K

➢ **Proliferation of spectra without coherence peaks**

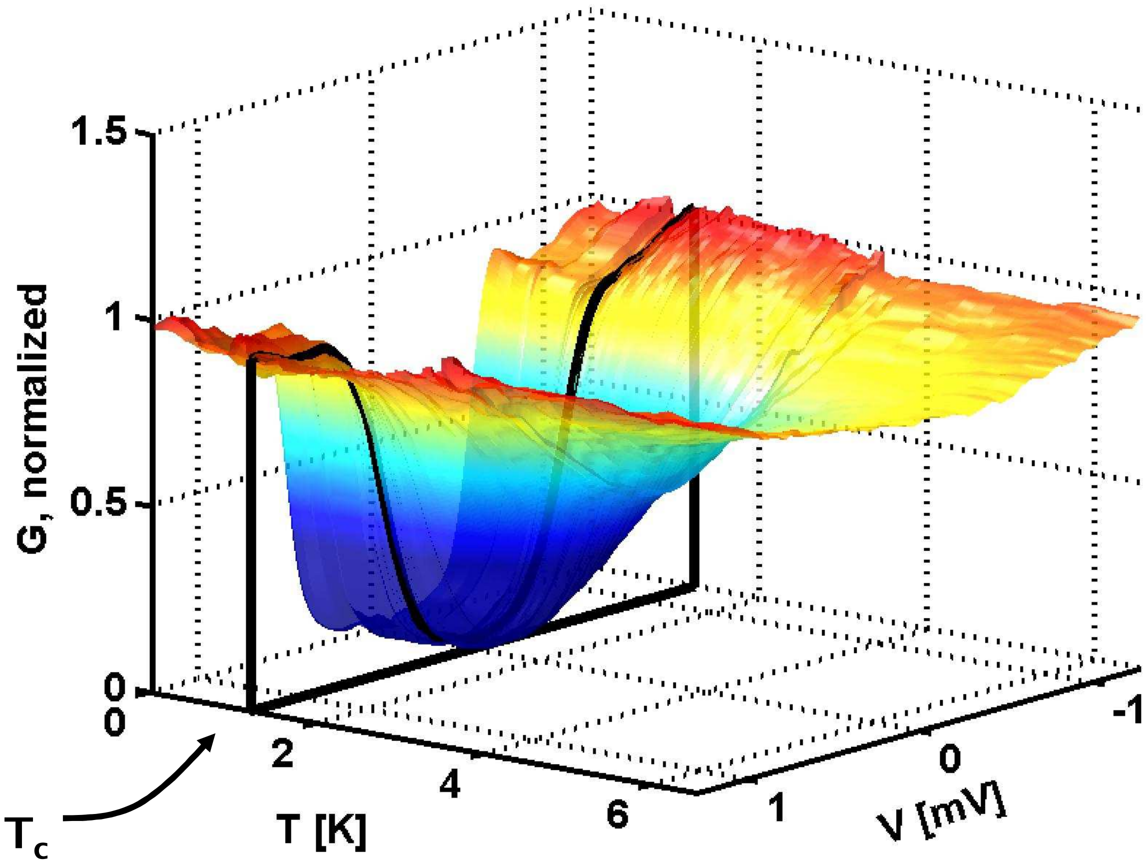
Question :

How are the BCS singularities related to the superconducting phase coherence ?

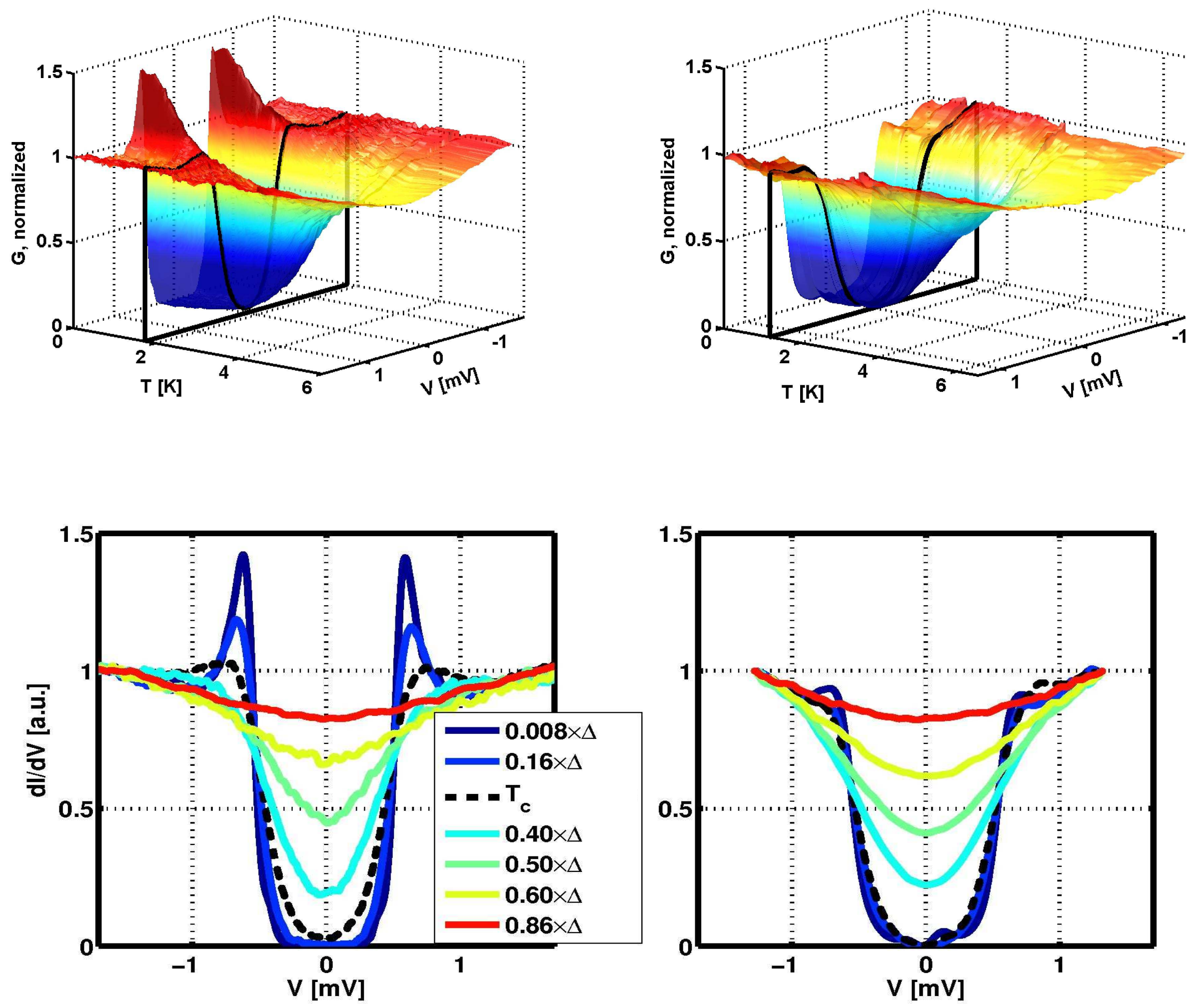
II.2 Pseudogap state above Tc

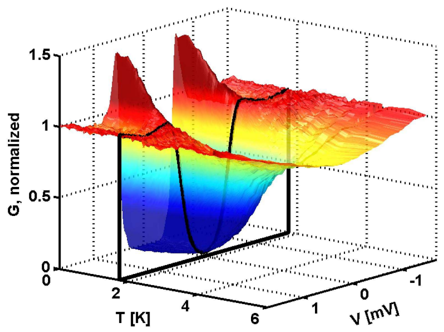


II.2 Pseudogap state above Tc

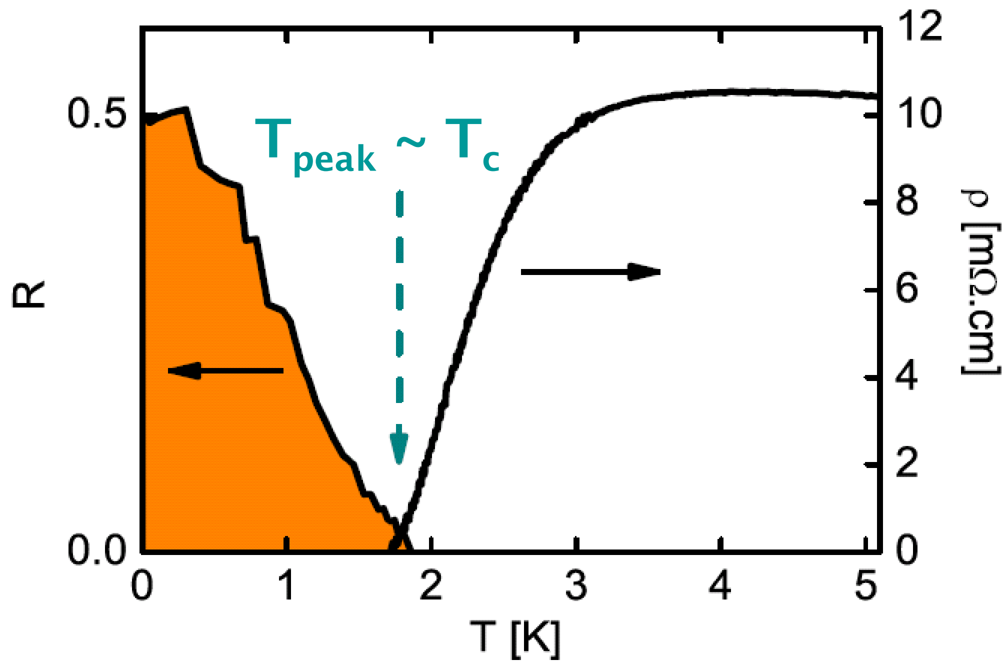


II.2 Pseudogap state above Tc

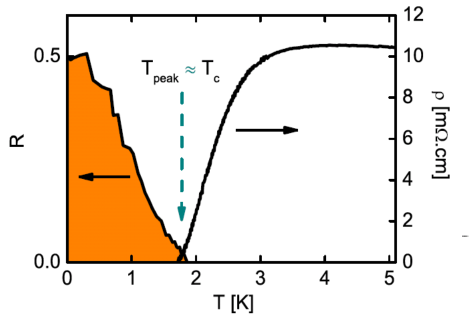




Macroscopic quantum phase coherence probed at a local scale



➢ **BCS peaks appear along with superconducting phase coherence**



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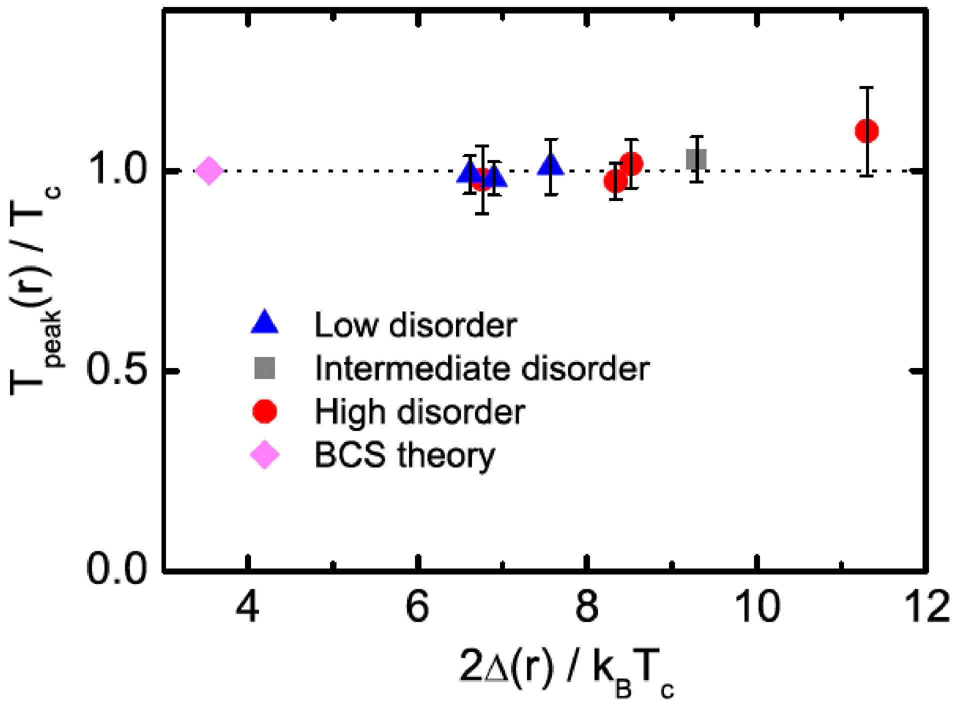
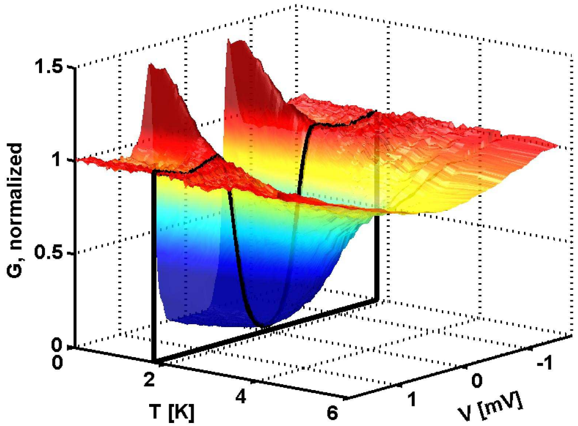


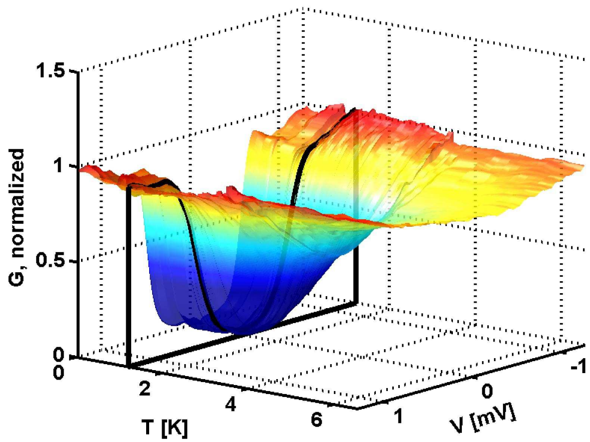
- **Phase coherence signaled at T_c independently of $\Delta(r)$**
- **Justification of T_c**



- **Formation of a pseudogap without BCS peaks at $T>T_c$**

  ⇒ Local pairing without phase coherence at $T > T_c$

  ⇒ Phase coherence is locked at $T=T_c$



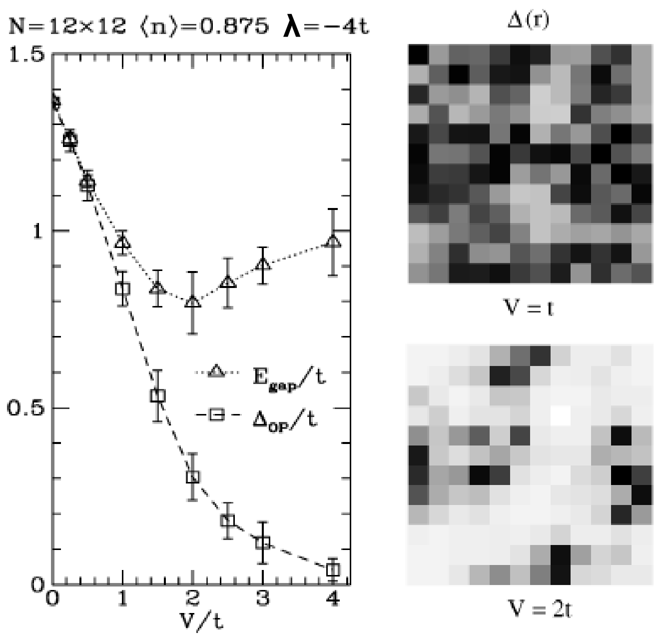
- **"Incoherent" gap at 50 mK**

  ⇒ Local pairing without phase coherence

→ Spectral signature of localized Cooper pairs

Numerical calculations : superconductivity with disorder

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



<u>Anderson model :</u>

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

Hopping parameter : ***t***
On-site disorder : V_i

<u>Attractive interaction λ :</u>

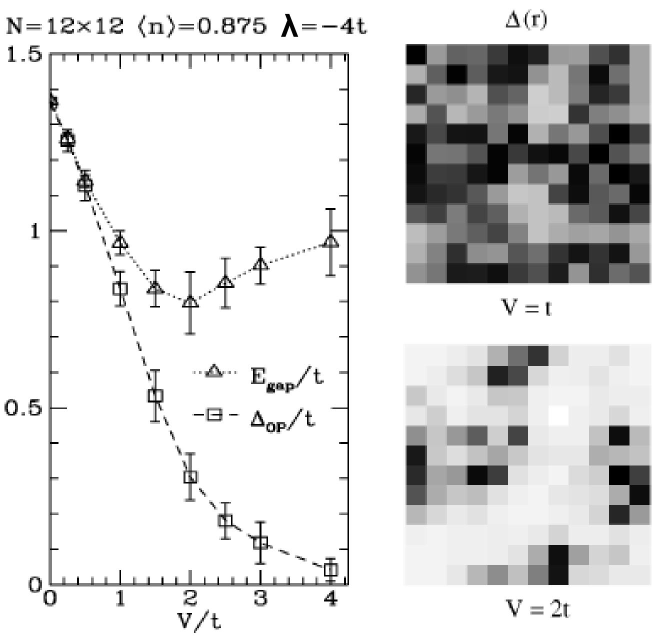
$$H_{\text{int}} = -\lambda \sum_i n_{i\uparrow} n_{i\downarrow}$$

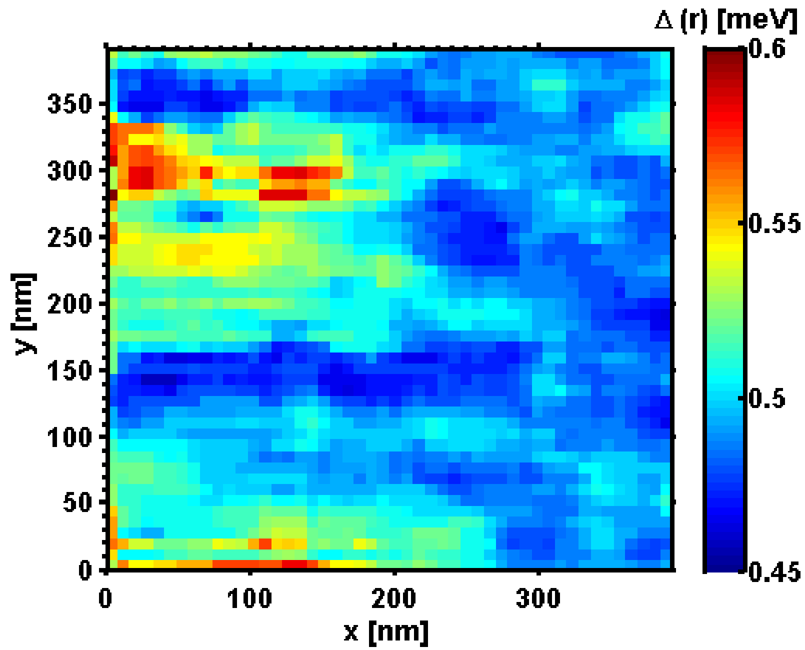
<u>*With increasing disorder:*</u>

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

Numerical calculations : superconductivity with disorder

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



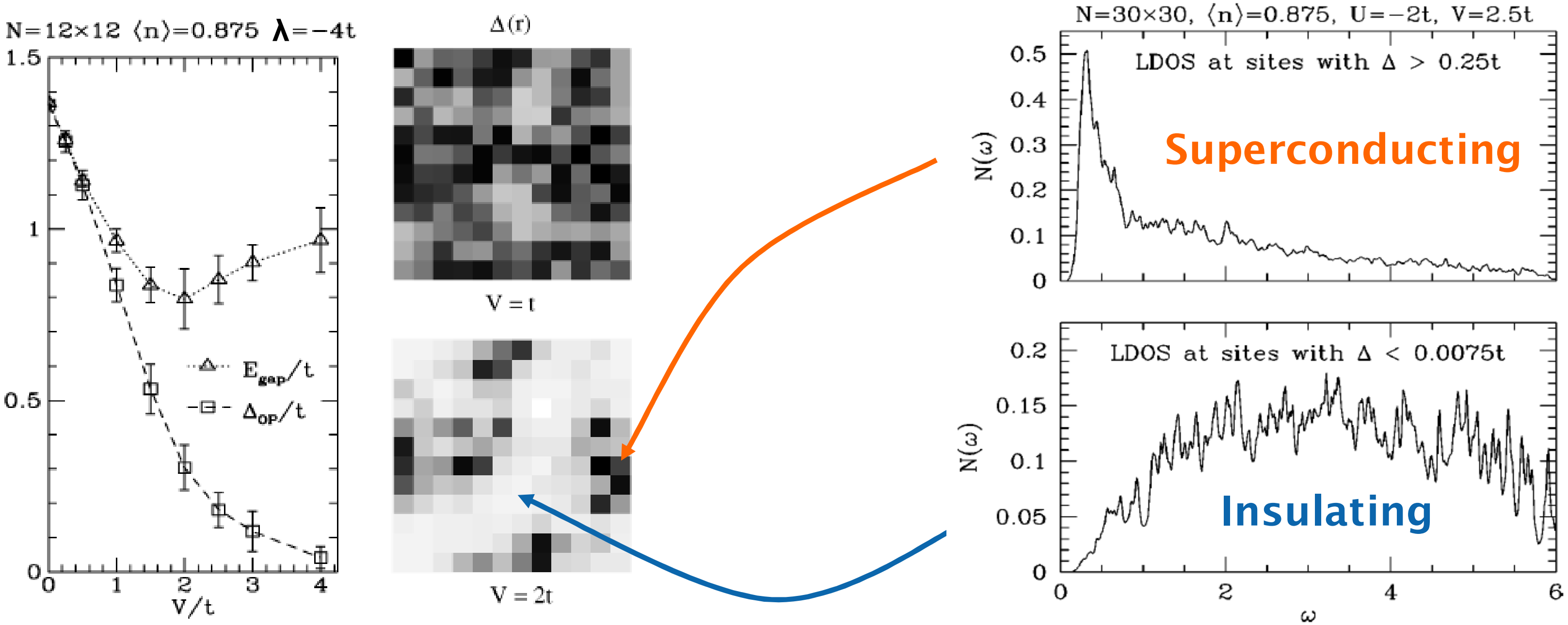


<u>With increasing disorder:</u>

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

Numerical calculations : superconductivity with disorder

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



With increasing disorder:

- Superconductivity becomes « ***granular-like*** »
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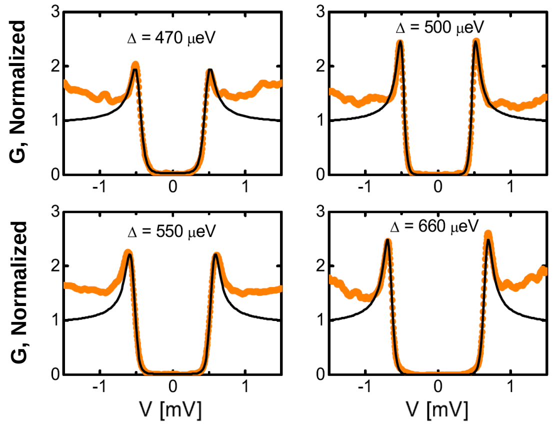
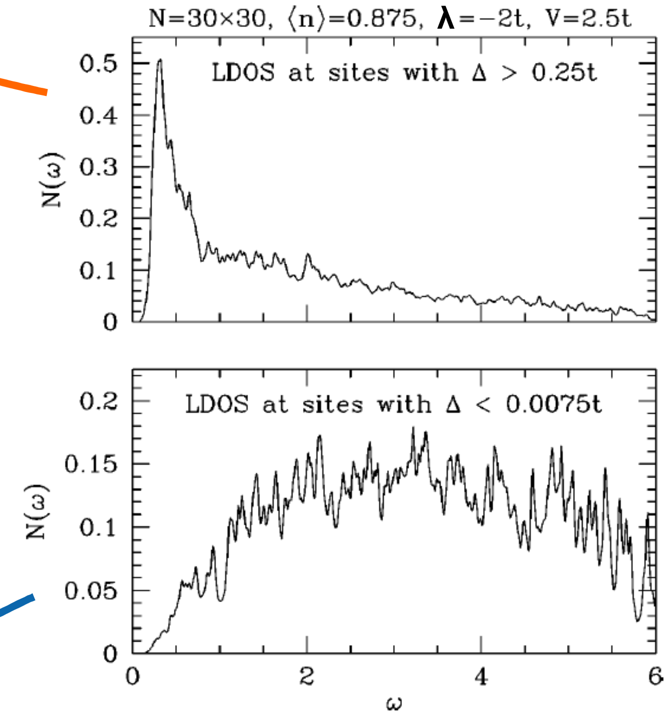
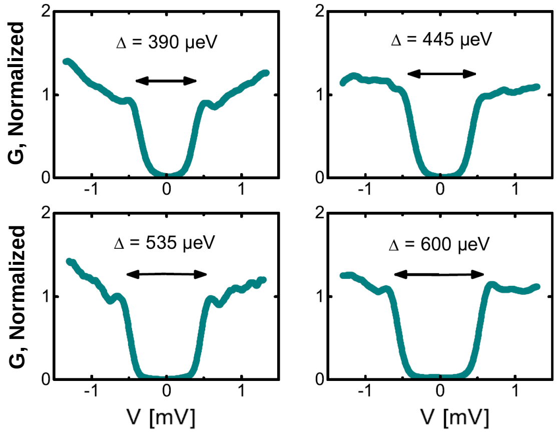
II.3 Proliferation of localized Cooper pairs

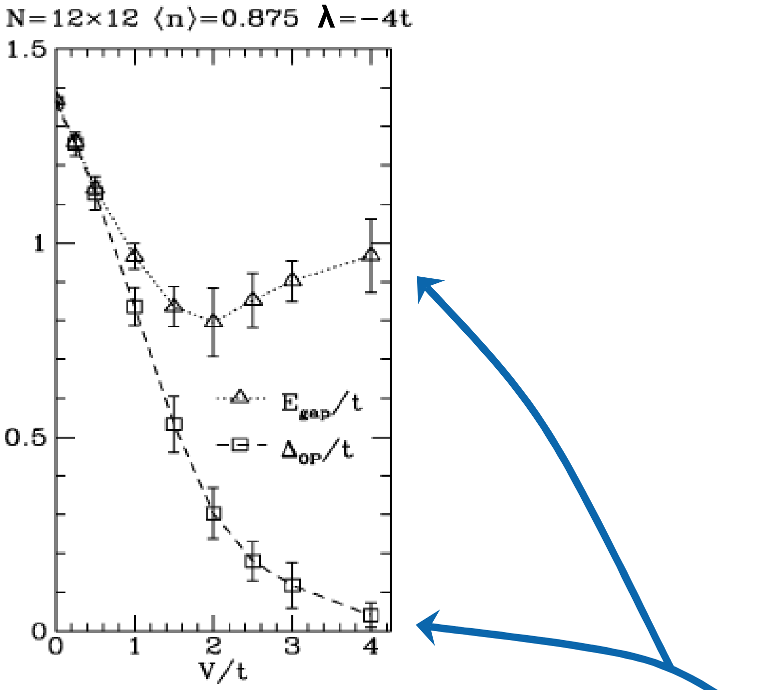


Superconducting gap Δ
⇒ delocalized Cooper pairs



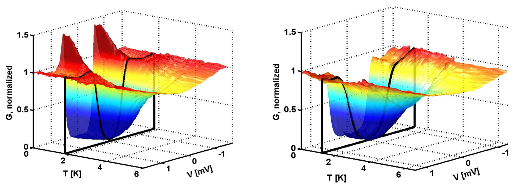


« Insulating » gap E_{gap}
⇒ Localized Cooper pairs



- Why spectral gap & SC order parameter are <u>different</u> ?

- How to explain pseudogap regime ?



I. Experimental techniques

II. Localized Cooper pairs in a-InO_x

III. Coherence energy in a-InO_x

Fractal Superconductivity near Anderson transition

M. Feigel'man *et al.*, *Phys. Rev. Lett.* ***98***, 027001, (2007)
M. Feigel'man *et al.*, *Ann. Phys.* **325,** 1390 (2010)

BCS model built on fractal eigenfunctions of the Anderson problem

⇨ $E_{gap} = \Delta_p + \Delta_{BCS}$

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

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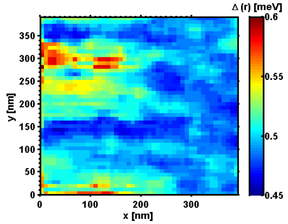
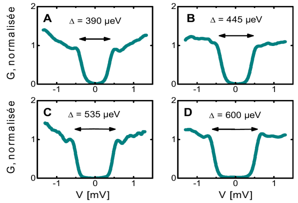
Predictions :

- Spatial fluctuations of Δ_p



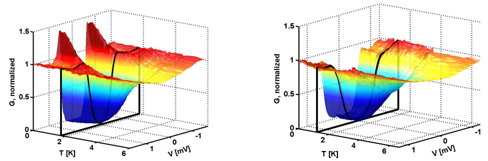
- Δ_p: "rectangular-shaped" gap at $T \ll T_c$



- Δ_p: anomalously large spectral gap

$$6 \leq \frac{2E_{gap}(r)}{k_B T_C} \leq 11$$

- **Δ_p: pseudogap regime above T_c**



How to measure the SC order parameter ?

- Tunneling spectroscopy
  (single-particle DOS)
  Tunnel barrier

$$E_{gap} = \Delta_p + \Delta_{BCS}$$

"parity gap" ← Δ_p ; Δ_{BCS} → "BCS gap"

- Point-contact spectroscopy
  (Andreev reflection = transfer of pairs)
  Transparent interface

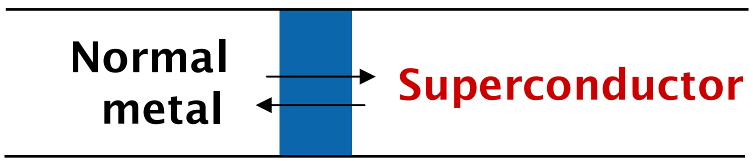
$$E_{gap} = \cancel{\Delta_p} + \Delta_{BCS}$$

Δ_{BCS} → "BCS gap"

Conductance of a N/S contact

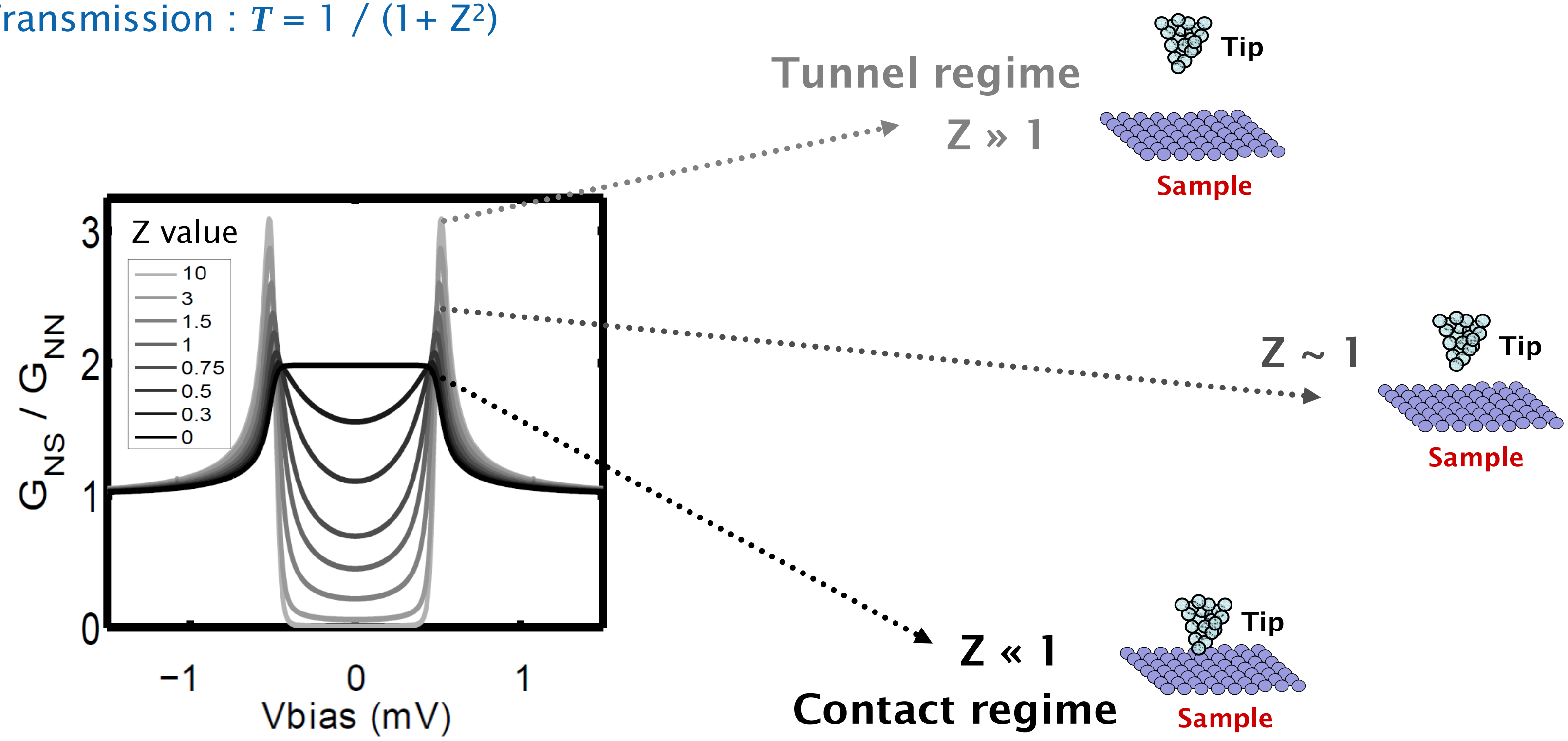
Blonder, G. E., Tinkham, M., and Klapwijk T.M. *Phys. Rev. B* ***25***, 7 4515 (1982)

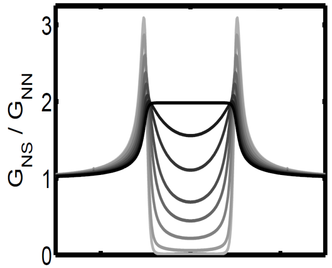
Barrier : parameter Z



Transmission : $T = 1 / (1 + Z^2)$

- Single-particle transfers ~ T
- Two-particles transfers ~ T^2

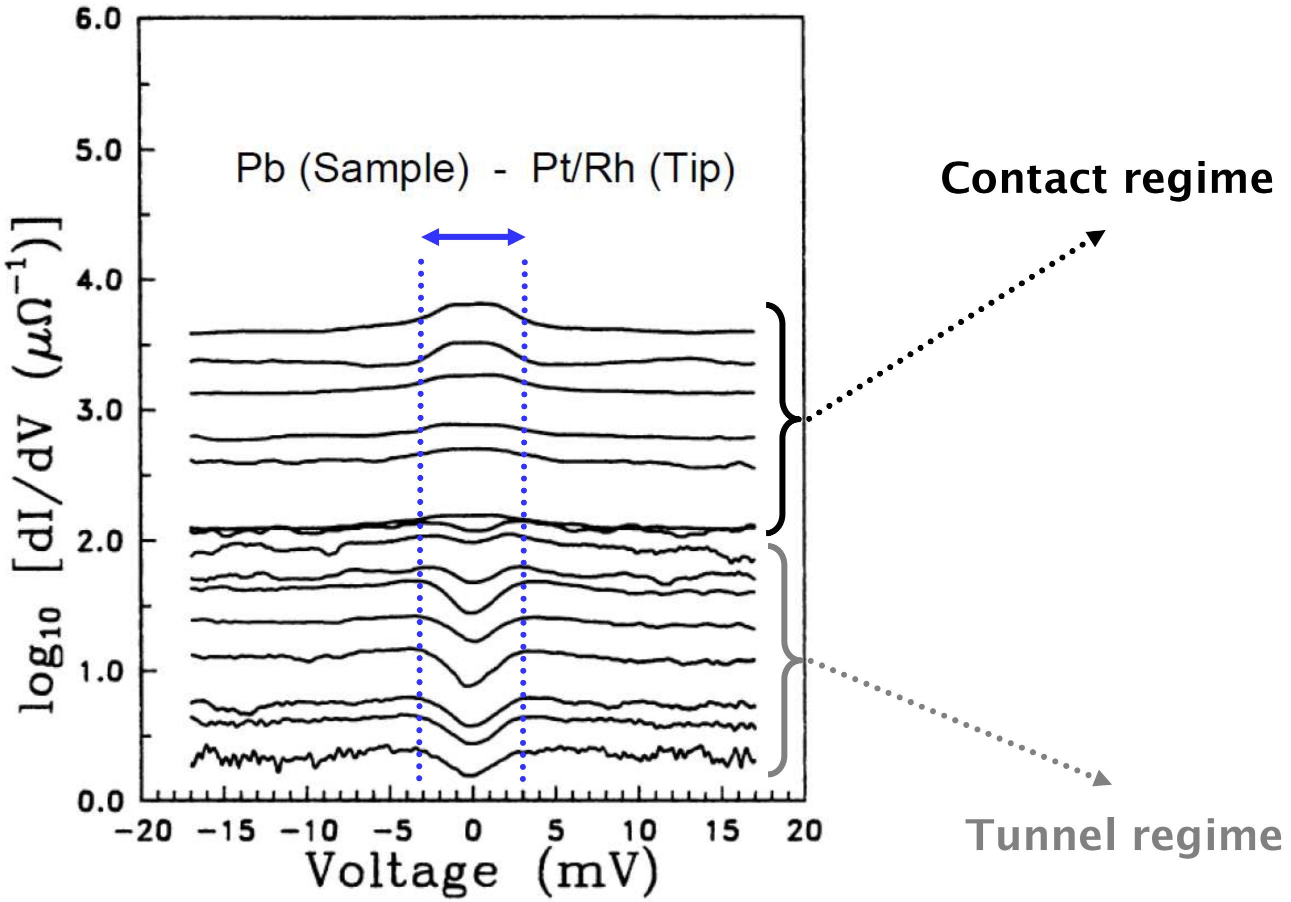




From tunnel to contact regime

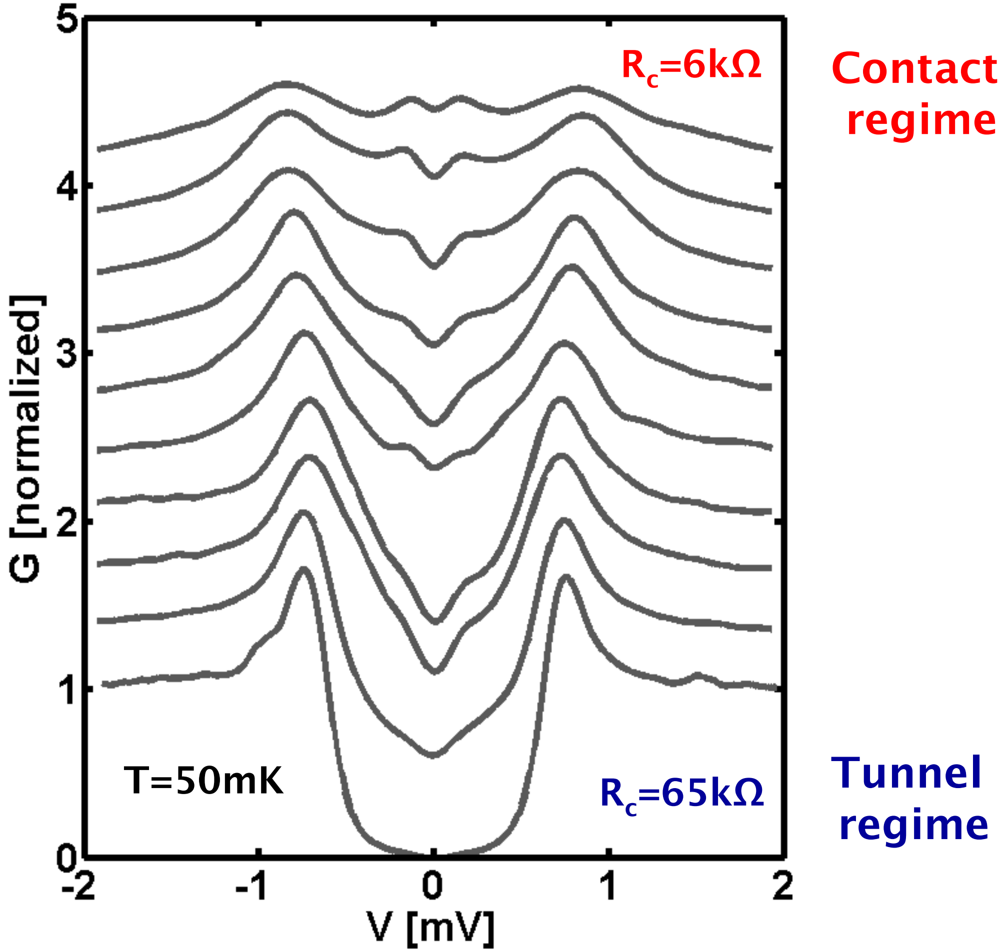
Control parameter:

Contact resistance
$R_c = V_{Bias} / I_t$

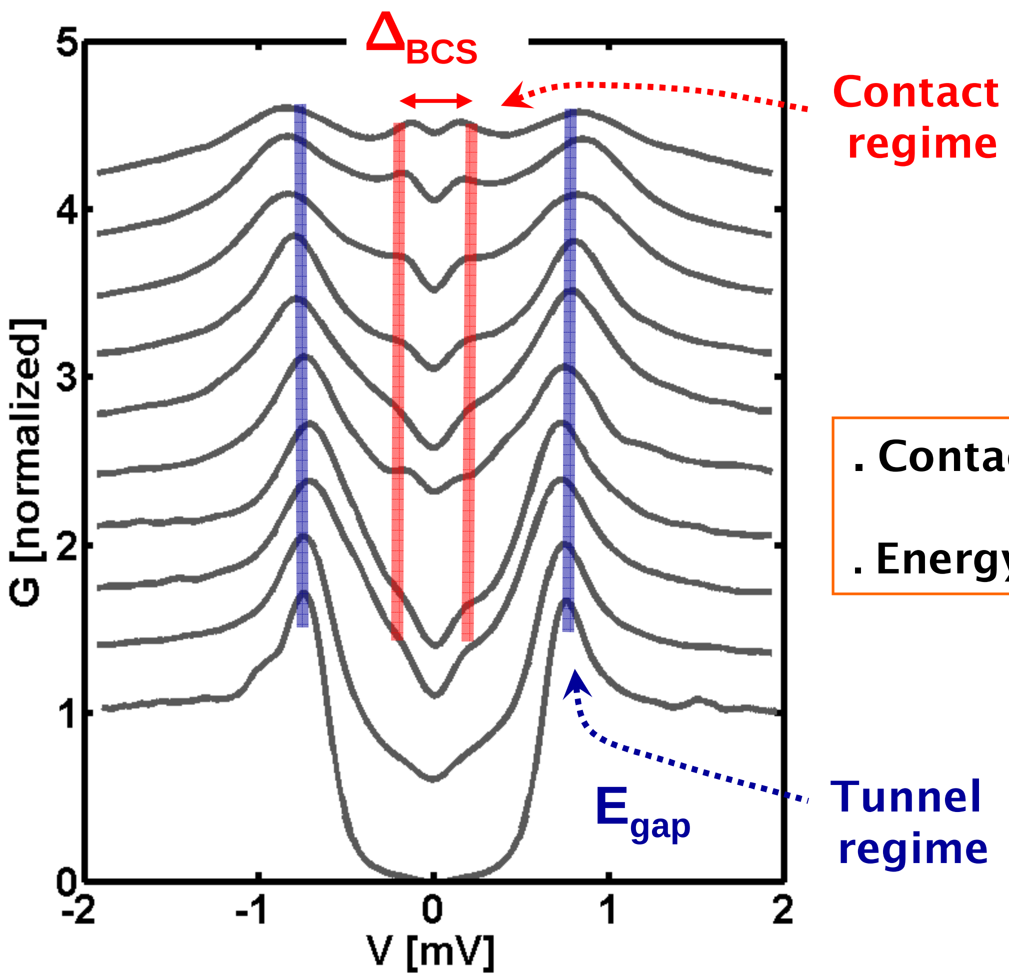


Agrait, N. *et al.*, *Phys. Rev. B* **46**, 9 5814 (1992)

From tunnel to contact in a-InOx



From tunnel to contact in a-InOx

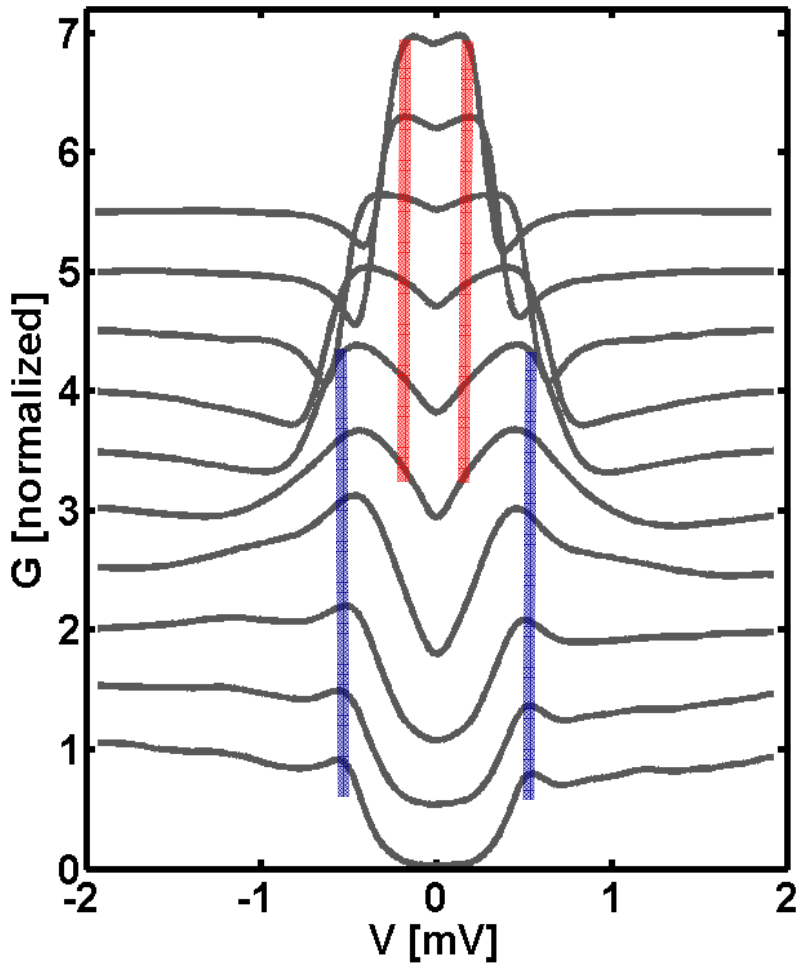


$$E_{gap} = \Delta_p + \Delta_{BCS}$$

. **Contact: additional peaks at eV ≈ ± 200 μeV**

. **Energy scale Δ_{BCS} independent of R_c**

From tunnel to contact in a-InOx



Contact regime

Tunnel regime

$$E_{gap} = \Delta_p + \Delta_{BCS}$$

2-particles signal at $eV=\Delta_{BCS}$

mixed with

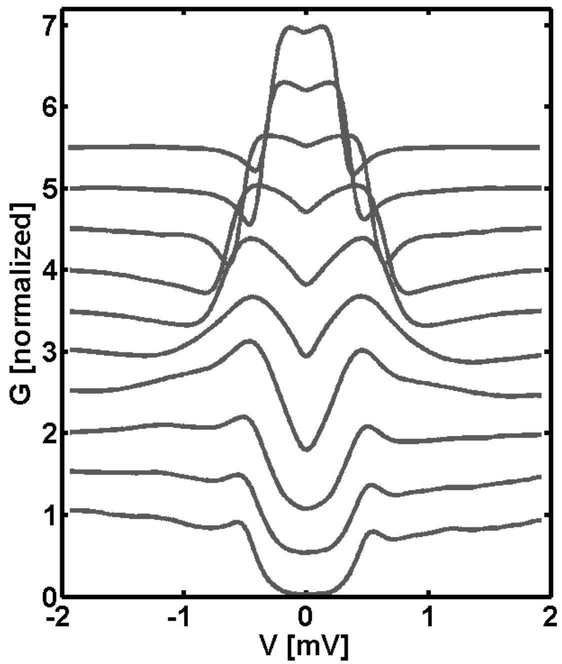
1-particle signal at $eV=E_{gap}$

⇨ V-shaped G(V) curves

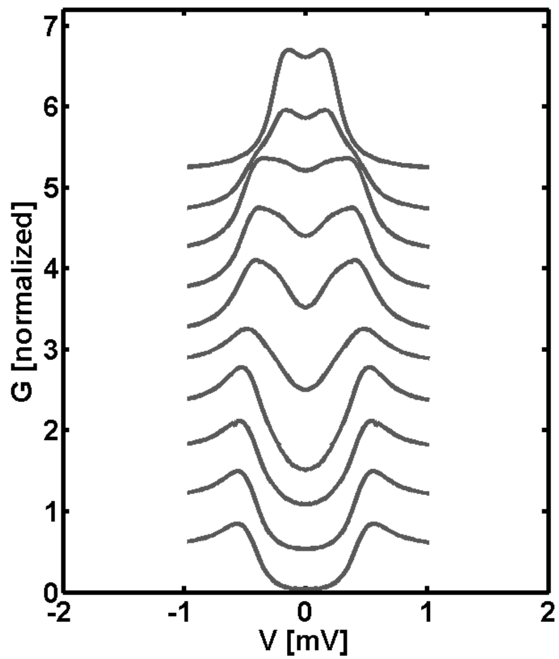
From tunnel to contact in a-InOx

- BTK-model with 2 contributions : E_{gap} & Δ_{BCS}
- With decreasing R_c : relative weight shifted from E_{gap} to Δ_{BCS}

Experiments



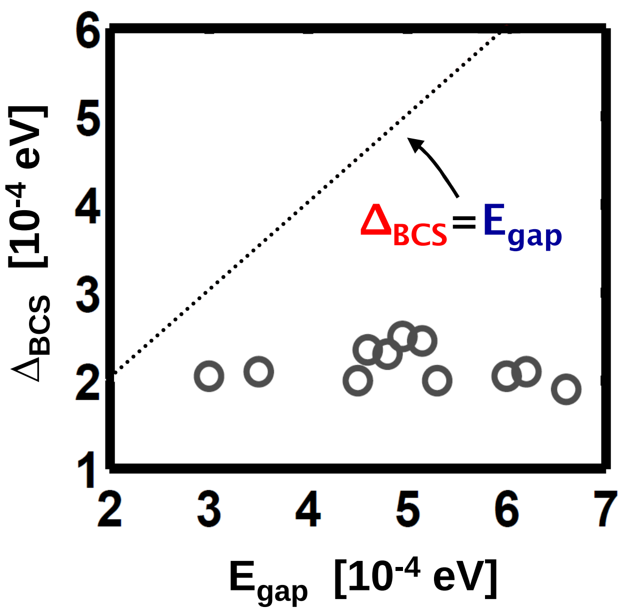
Simulation



Two distinct energy scales in a-InOx

$$E_{gap}(\mathbf{r}) = \Delta_p(\mathbf{r}) + \Delta_{BCS}$$

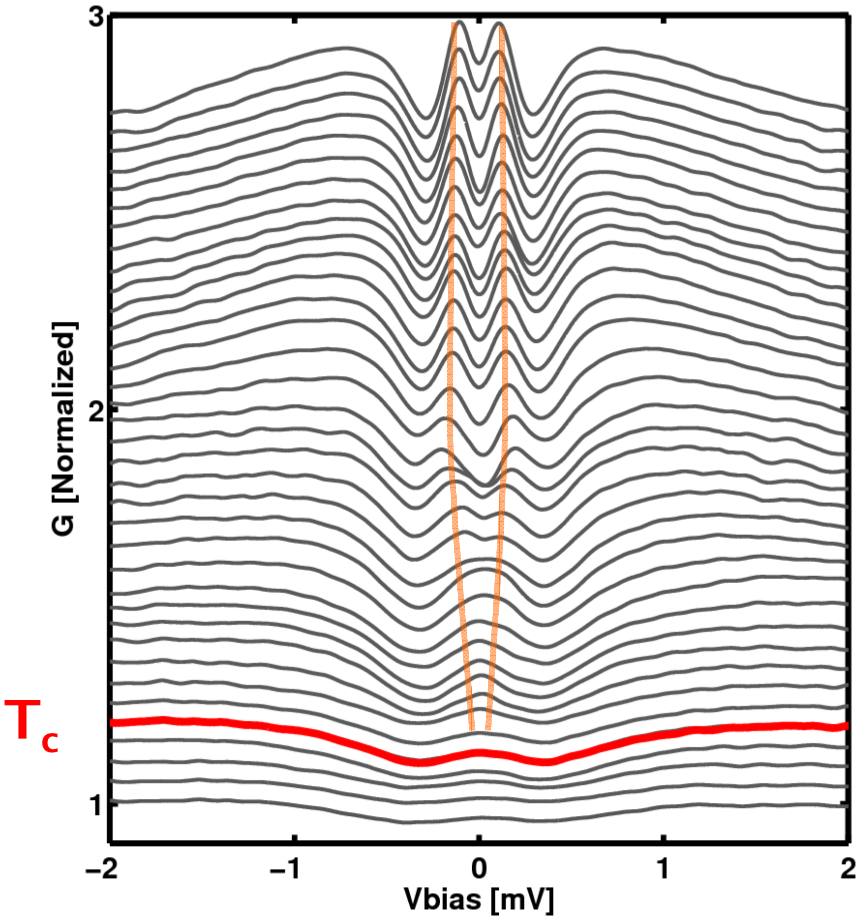
11 evolutions on 3 samples



- Δ_{BCS} probed by AR remains uniform
- E_{gap} probed by STS fluctuates

➢ **Distinct energy scales for pairing and coherence in disordered a-InO_x**

T-evolution of Andreev signal

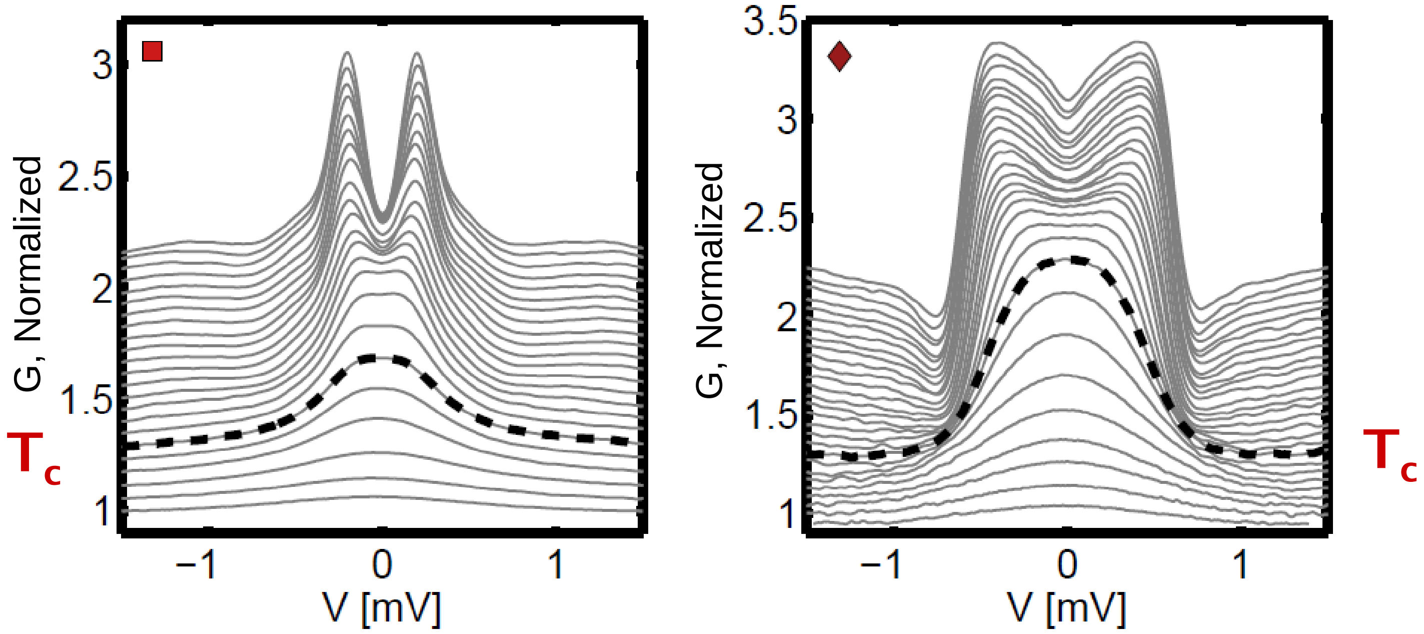


$$E_{gap}(T) = \Delta_p + \Delta_{BCS}(T)$$

- Δ_{BCS} evolves between 0 and ~ T_c
- E_{gap} evolves between 0 and ~3-4T_c

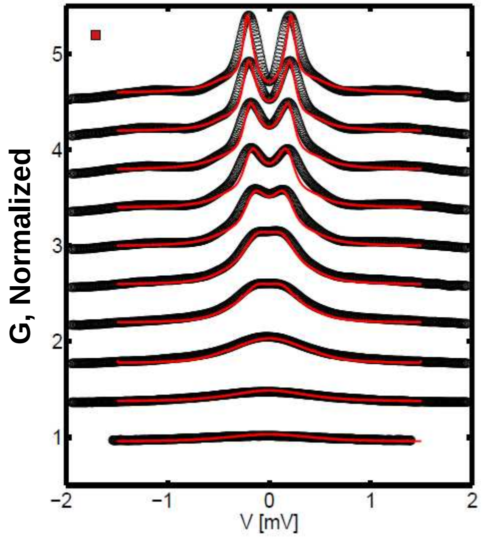
➢ **Δ_{BCS}: local signature of SC phase coherence**

T-evolution of Andreev signal



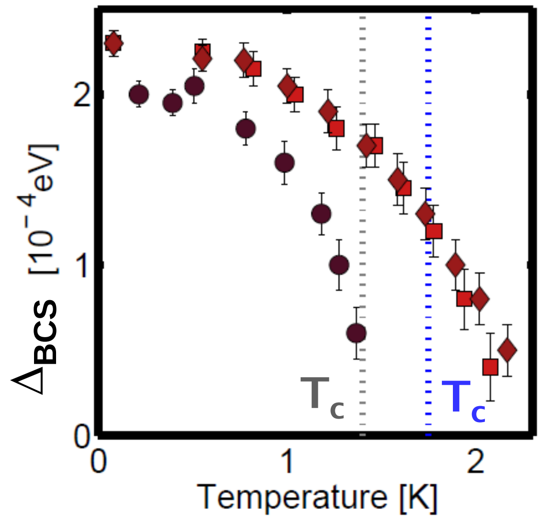
➢ Locally: Andreev signal detected between T_c and ~1.3T_c

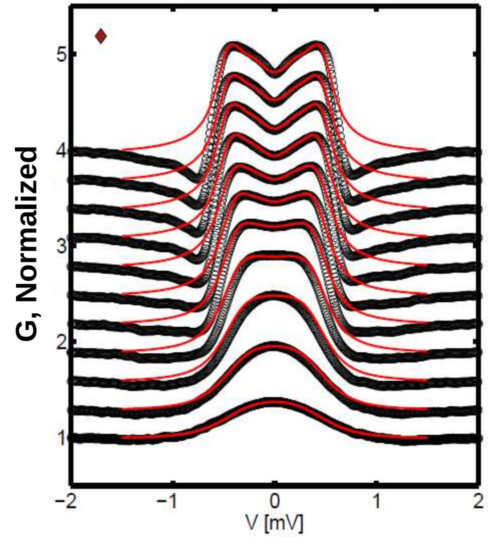
T-evolution of Andreev signal



BTK-model with :

$E_{gap}(T) = \Delta_p + \Delta_{BCS}(T)$





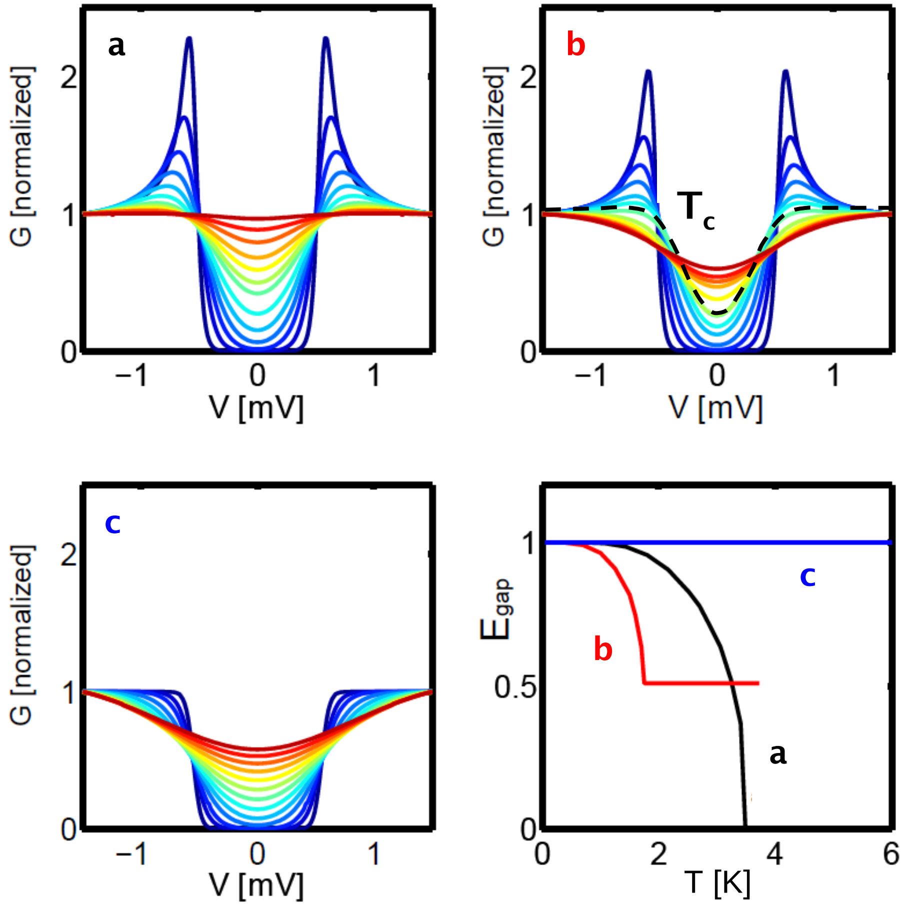
➢ Δ_{BCS} remains finite between T_c and ~1.3T_c (preformed pairs)

Link between tunnel & contact measurements

Simulations of tunneling conductance with : $E_{gap}(T) = \Delta_p + \Delta_{BCS}(T)$

E_{gap} = 550 µeV
Δ_p = 0 µeV
Δ_{BCS} = 550 µeV

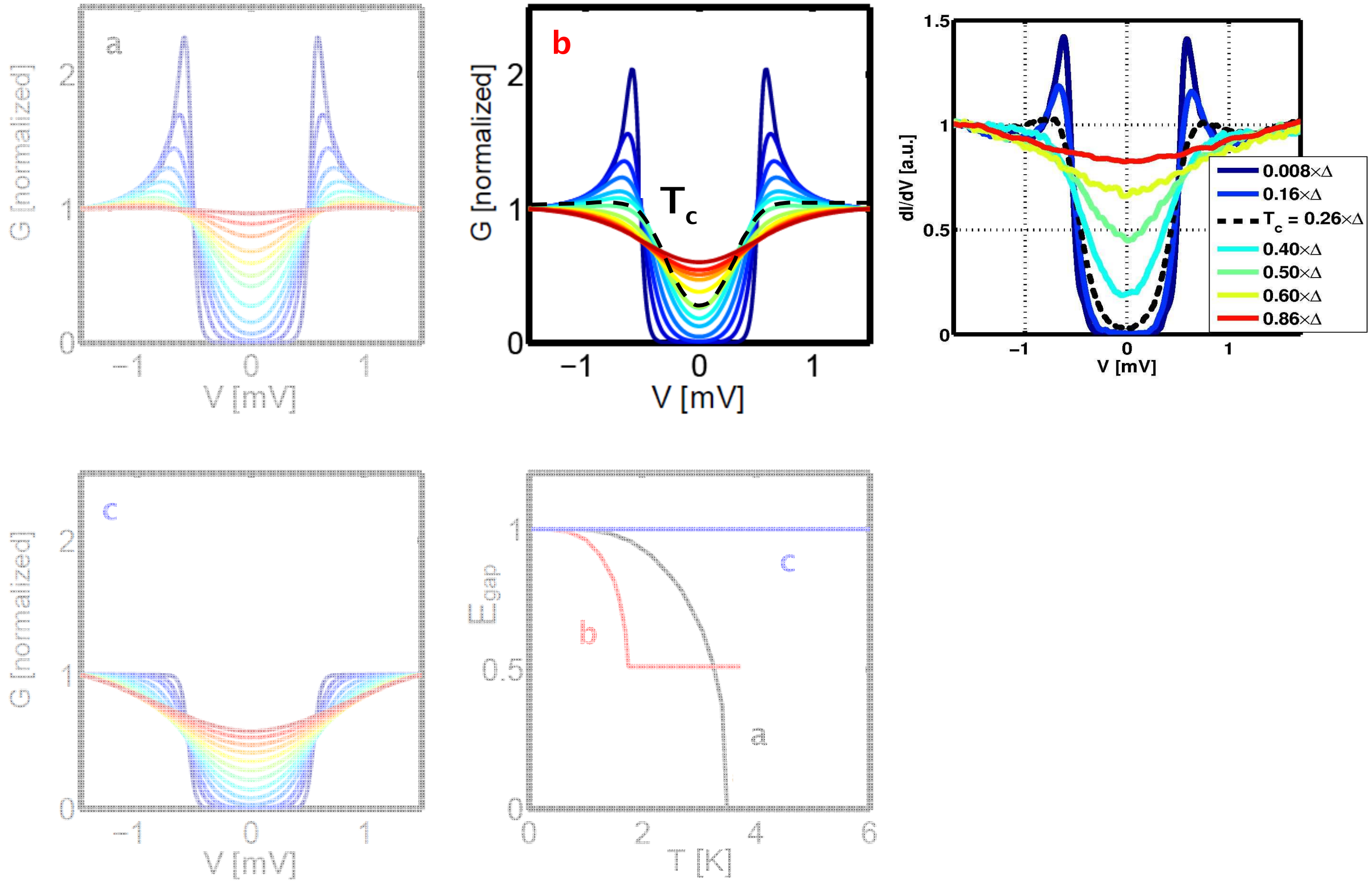
E_{gap} = 550 µeV
Δ_p = 280 µeV
Δ_{BCS} = 270 µeV



E_{gap} = 550 µeV
Δ_p = 550 µeV
Δ_{BCS} = 0 µeV

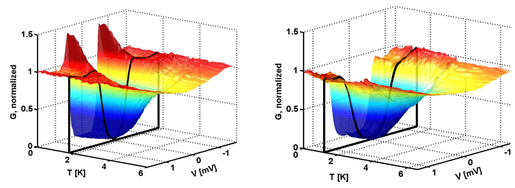
Link between tunnel & contact measurements

Simulations of tunneling conductance with : $E_{gap}(T) = \Delta_p + \Delta_{BCS}(T)$

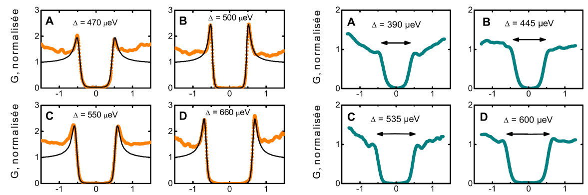


Localization of Cooper pairs

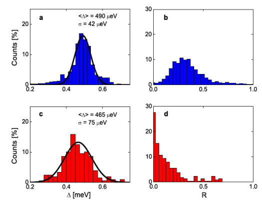
- **Preformed Cooper-Pairs above Tc**
  Pseudogap in the DOS between Tc and ~ 3-4 Tc



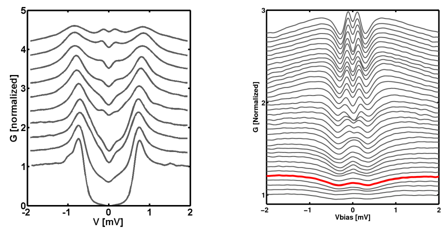
- **“Partial” condensation of pairs below Tc**
  Rectangular spectra at 50mK = localized Cooper pairs



- **SIT occurs through the localization of Cooper-pairs**
  Gap in the DOS remains & coherence peaks disappear



- **Distinct energy scales for pairing and coherence**
  STS measures E_{gap} and Andreev reflection measures Δ_{BCS}



Thank you for your attention !