2583-16

Workshop on Coherent Phenomena in Disordered Optical Systems

26 - 30 May 2014

Tunneling Spectroscopy of Fluctuating and Localized Preformed Coopers Pairs in Highly Disordered Superconducting Films

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France

Tunneling spectroscopy of fluctuating and localized preformed Coopers pairs in highly disordered superconducting films

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V. Vinokur, *Material Science Division, Argonne National Laboratory - Argonne*
M. Baklanov, A Satta, *IMEC - Leuven*
Maoz Ovadia, Dan Shahar, *The Weizmann Institute of Science*
Mikhail Feigel'man, *L. D. Landau Institute for Theoretical Physics*
Lev Ioffe, *Serin Physics laboratory, Rutgers University*

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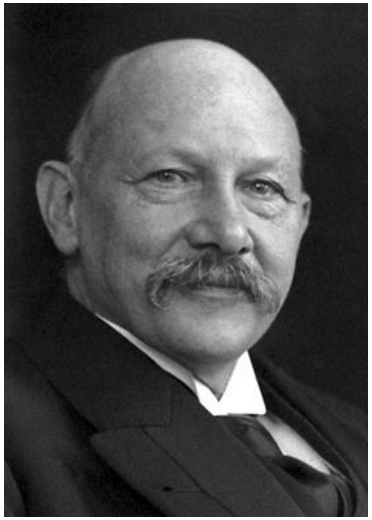
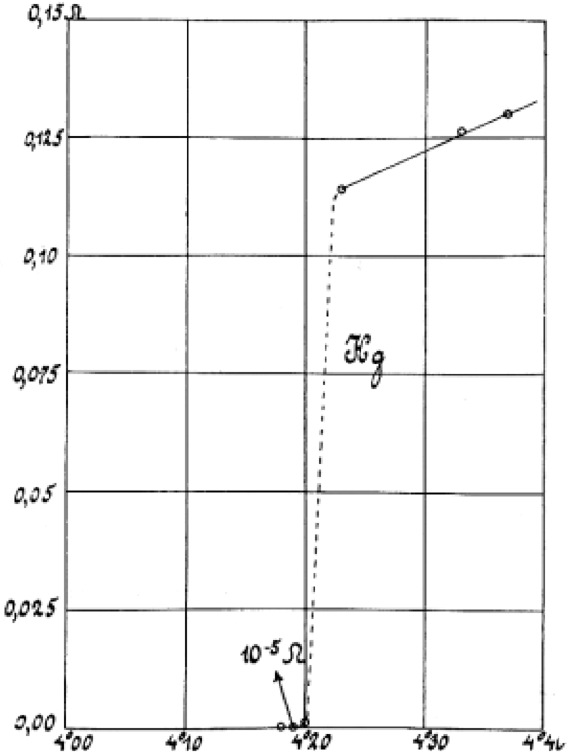
Superconductivity in pure metals *and alloys …*





Kamerlingh Onnes, H., "Further experiments with liquid helium. C. On the change of electric resistance of pure metals at very low temperatures, etc. IV. The resistance of pure mercury at helium temperatures." *Comm. Phys. Lab. Univ. Leiden*; No. 120b, 1911.

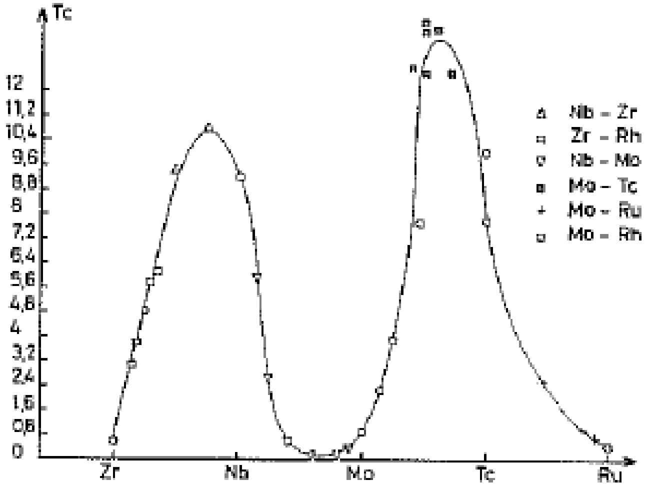
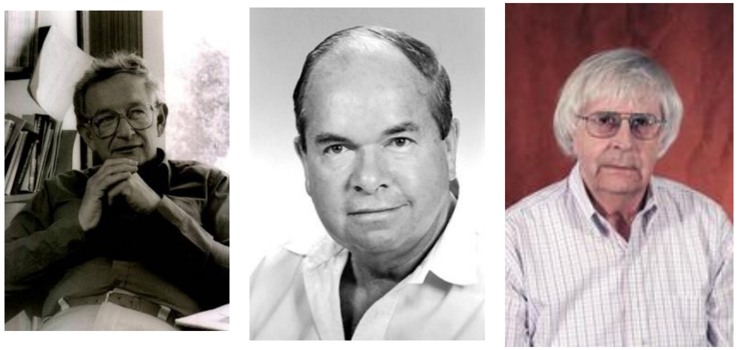


FIG. 1.11. — *Variation de T_c dans les alliages à base de* Zr, Nb, Mo, Tc *et* Ru (voir ROBERTS).

J.P. Burger
la supraconductivité des métaux, des alliages et des films minces (Ed.Masson)

Superconductivity and disorder



P.W. Anderson, *J. Phys. Chem. Solids.* ***11***, 26, (1959)

A.A. Abrikosov & I.P. Gorkov, *Sov. Phys. JETP* ***8***, 1090, (1959)

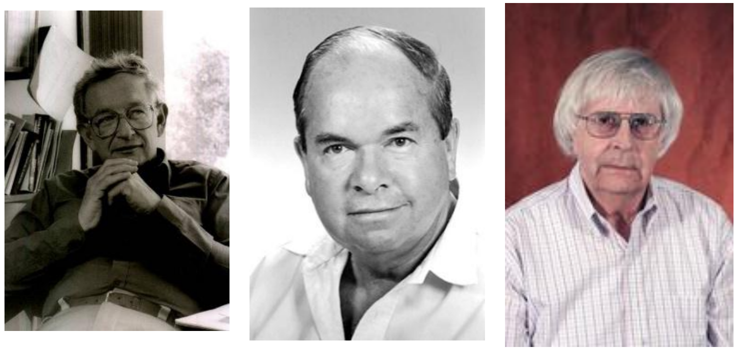
- Weak disorder : Anderson’s theorem

BCS superconductivity can be built on pairing of exact time reversal symmetric egenstates

$$k_F l_e > 1$$

⟶ T_c and Δ insensitive to weak disorder

Superconductivity and disorder



P.W. Anderson, *J. Phys. Chem. Solids.* ***11***, 26, (1959)

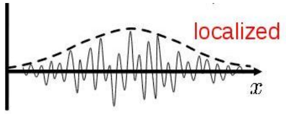
A.A. Abrikosov & I.P. Gorkov, *Sov. Phys. JETP* ***8***, 1090, (1959)

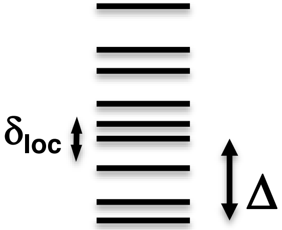
- Weak disorder : Anderson's theorem

BCS superconductivity can be built on pairing of exact time reversal symmetric egenstates as long as :

$$k_F l_e > 1$$

→ T_c and Δ insensitive to weak disorder





- Strong disorder $k_F l_e \leq 1$

BCS state can survive even if single particles are localized as long as mean level spacing δ_{loc} is smaller than SC gap Δ:

$$1 = U \int_{\varepsilon < \omega_D} \frac{1}{\sqrt{\varepsilon^2 + \Delta^2}} \nu(\varepsilon)\, d\varepsilon \longrightarrow \delta = \frac{1}{\nu \xi^d_{loc}} < \Delta$$

Density-of-states

Localization volume

Kapitulnik, Kotliar, *PRL* (1985), PRB (1986)

Ma & Lee, *PRB* (1985)

Sadowskii, *Phys. Rep.* (1997)

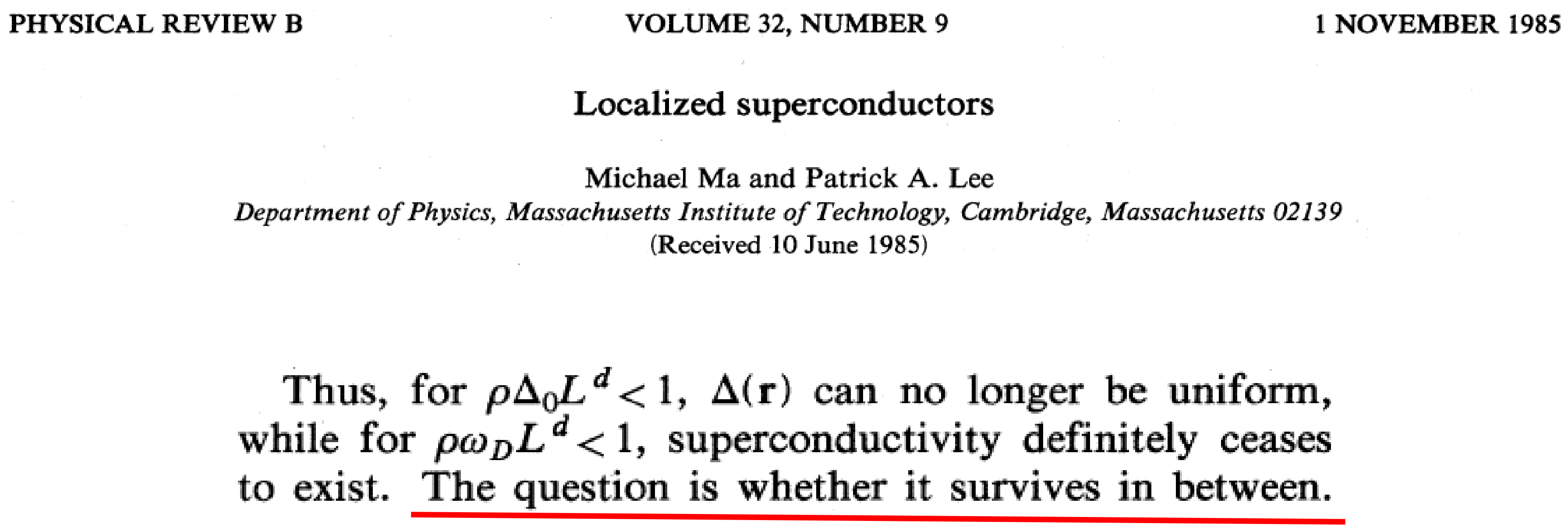
Ghosal *et al.*, PRL (1998) ; PRB (2001)

Feigel'man *et al.*, *PRL* (2007) ; *Ann.Phys.* (2010)

Porkrovsky, Falco, Natterman *PRL* (2010)

Bouadim et al. *Nature Physics* (2011)

Superconductivity and disorder



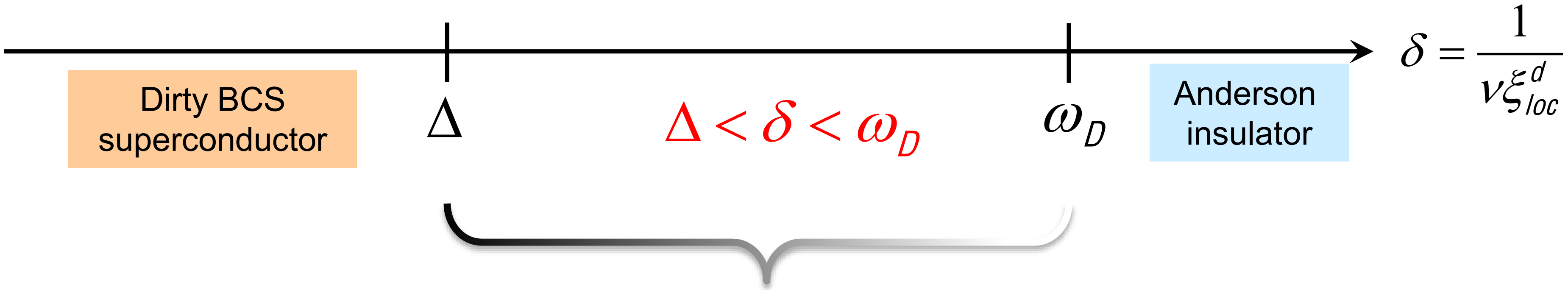
PHYSICAL REVIEW B VOLUME 32, NUMBER 9 1 NOVEMBER 1985

Localized superconductors

Michael Ma and Patrick A. Lee
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 10 June 1985)

Thus, for $\rho\Delta_0 L^d < 1$, $\Delta(\mathbf{r})$ can no longer be uniform, while for $\rho\omega_D L^d < 1$, superconductivity definitely ceases to exist. The question is whether it survives in between.



Dirty BCS superconductor

Δ

$\Delta < \delta < \omega_D$

ω_D

Anderson insulator

$$\delta = \frac{1}{\nu \xi_{loc}^d}$$

Q1: Do Cooper pairs vanish with Tc or get localized ?

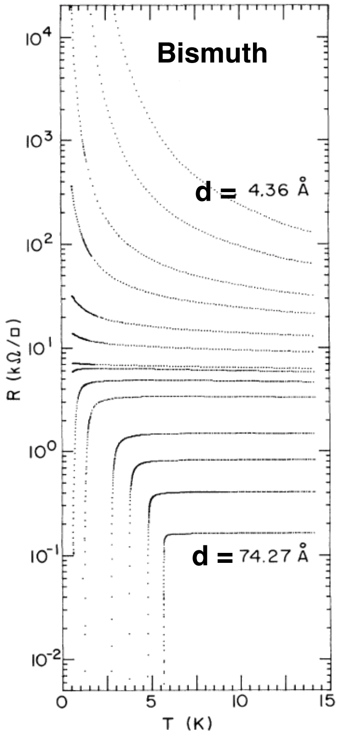
Q2: Nature of the ensuing insulating state ?

Superconductor-insulator transition (SIT) in thin films

Measure of disorder: sheet resistance

$$R = \frac{\rho}{d}$$

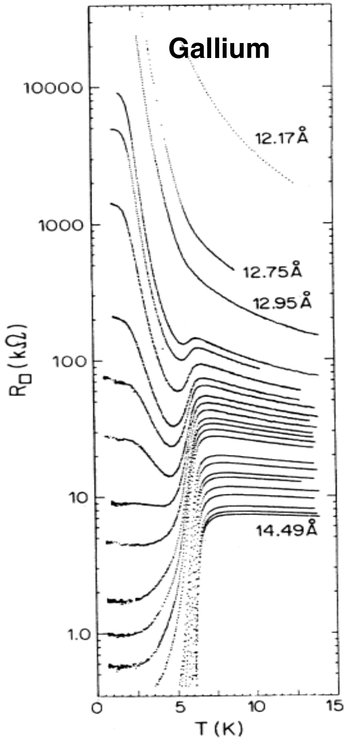
Amorphous films



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

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

Granular films



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

- ➢ SIT due to phase fluctuations
- ➢ Cooper pairs localized in grains

Superconductor-insulator transition (SIT) in thin films

Measure of disorder: sheet resistance

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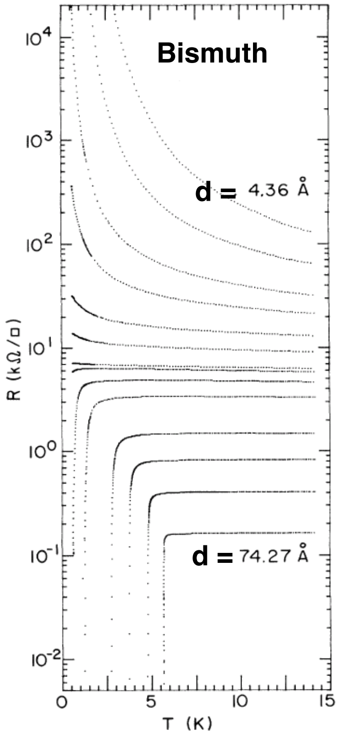
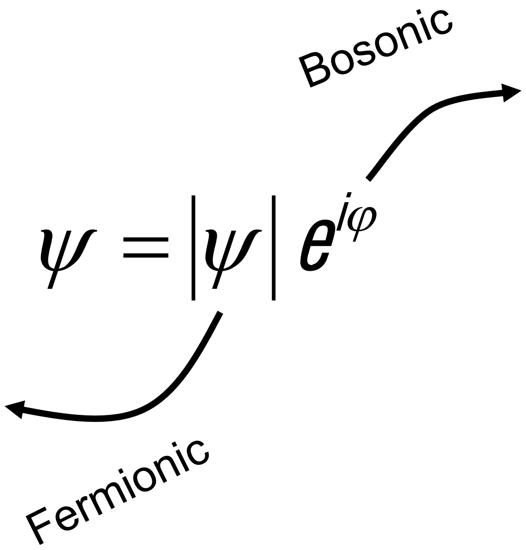
Amorphous films



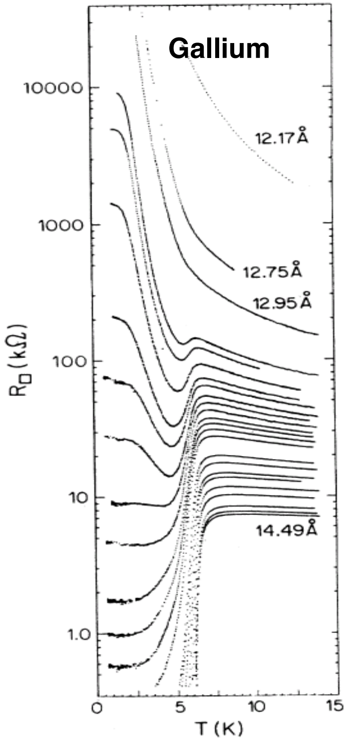


Bosonic

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

Fermionic

Granular films



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- ➢ Cooper pairing suppressed at the SIT

- ➢ SIT due to phase fluctuations
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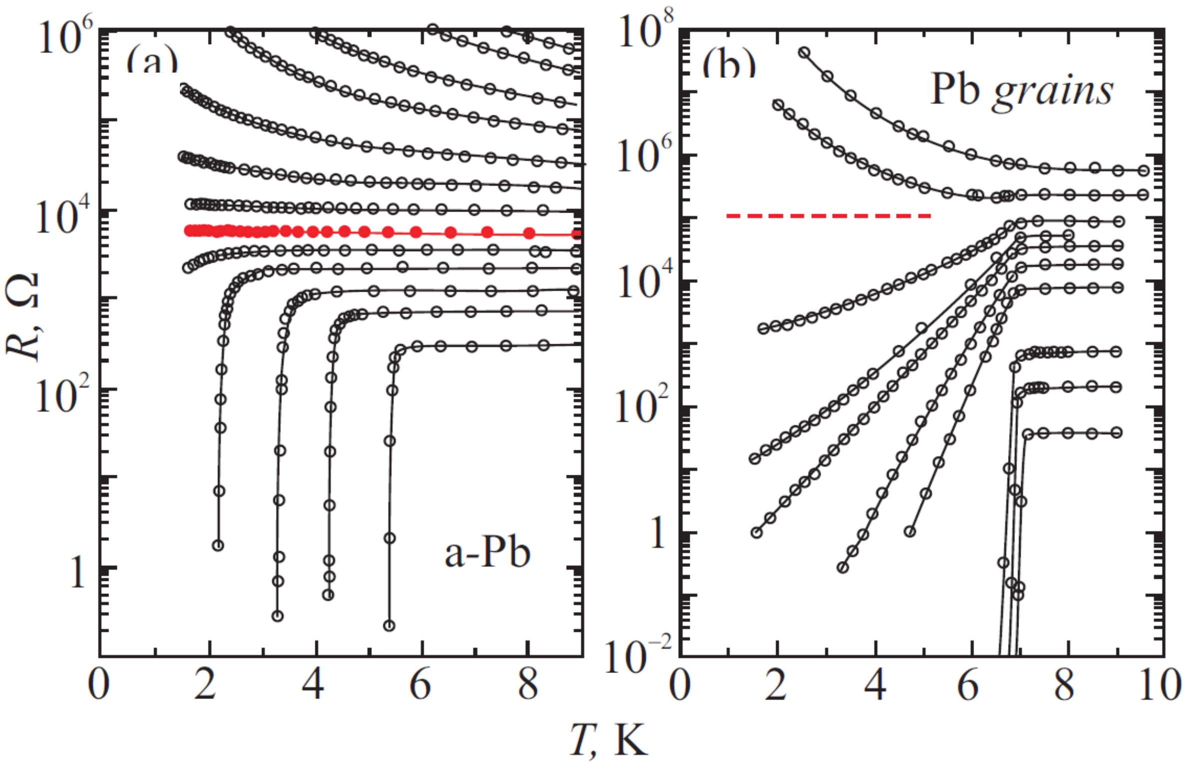
Superconductor-insulator transition (SIT) in thin films

Uniform system

Granular system



Frydman, A., *Physica C : Superconductivity* ***391***, 189 (2003)

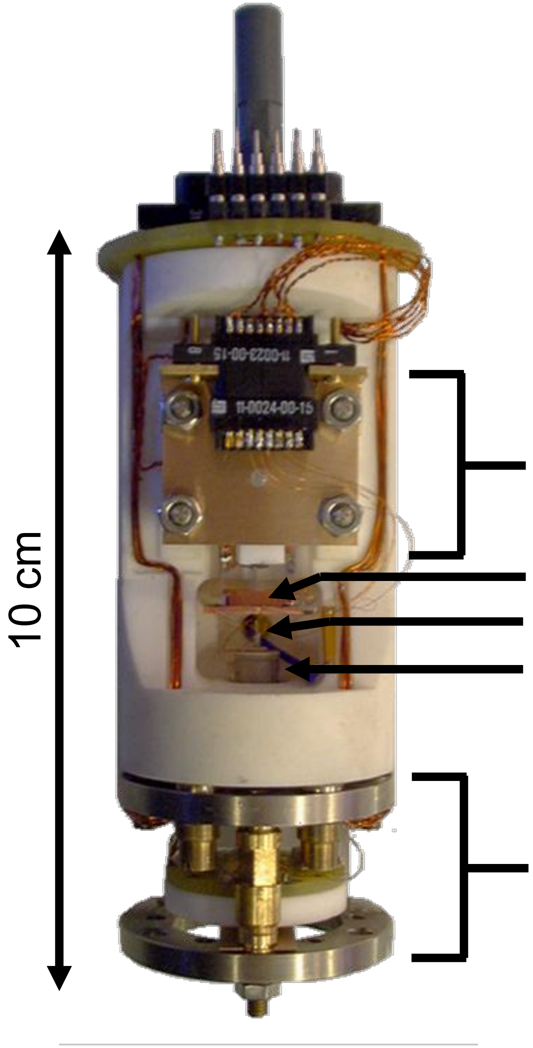
Hsu, S.-Y., and Valles, J. M. *Phys. Rev. B* ***48***, 4164 (1993)

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

- SIT due to phase fluctuations
- Cooper pairs localized in grains

Continuous decrease of T_c → Homogeneously disordered films

Scanning Tunneling Microscopy : experimental set-up



10 cm

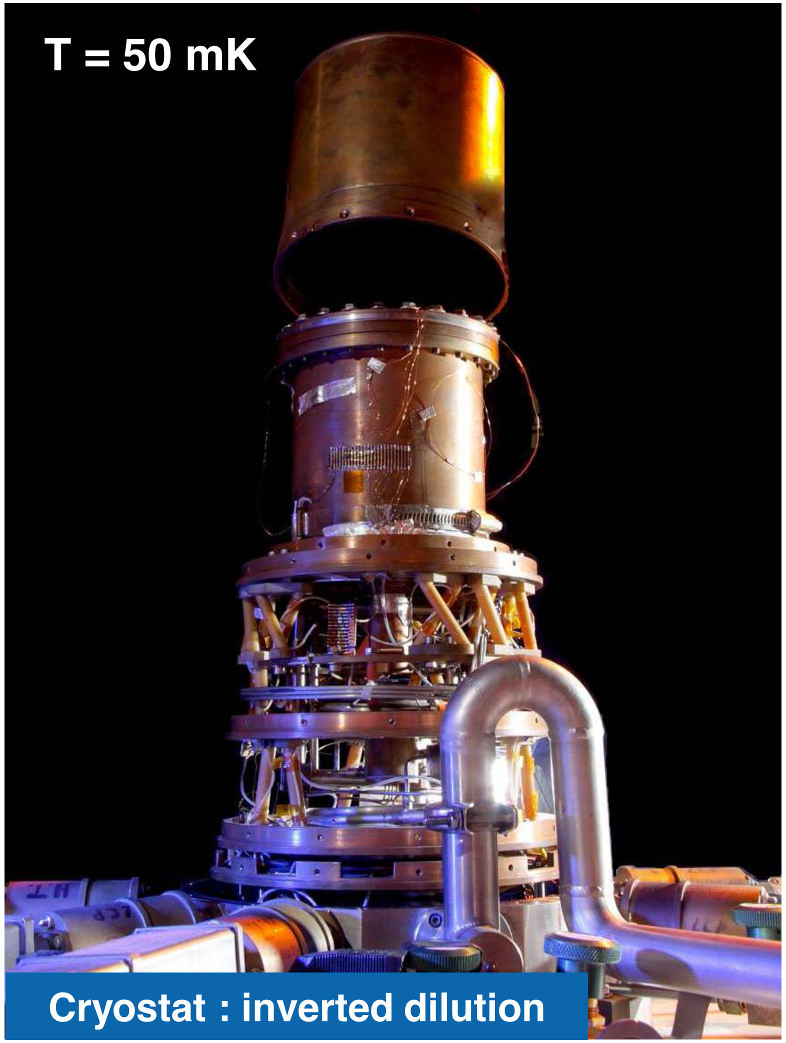
Coarse approach motor

Sample holder

Tip

Piezo tube

Coarse positioning X-Y table



T = 50 mK

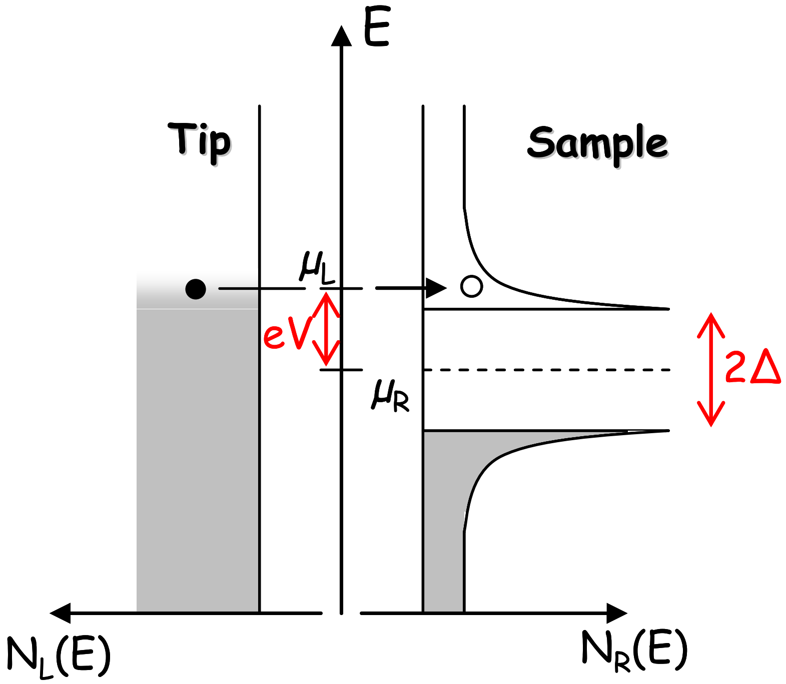
Cryostat : inverted dilution

- Combined transport & spectroscopy measurements

Scanning 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

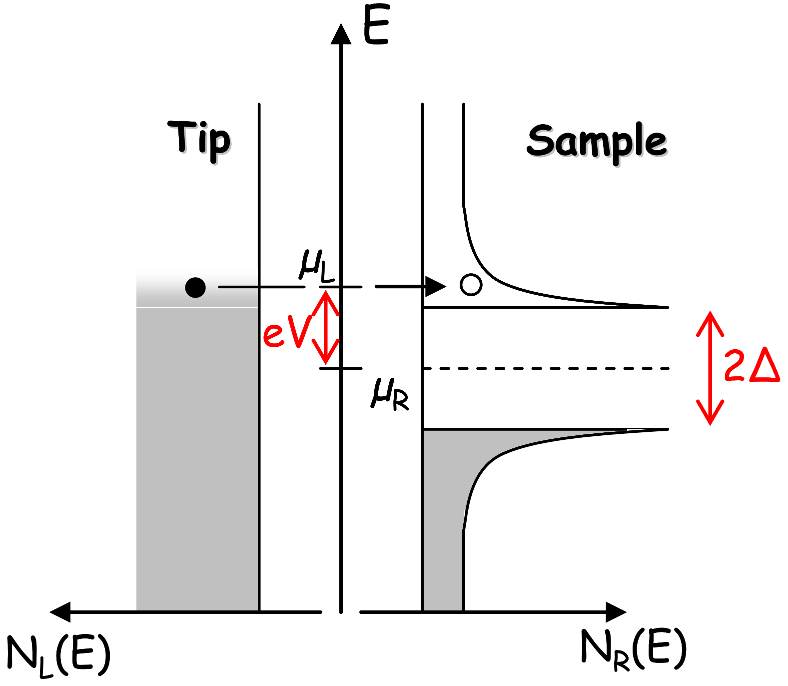
$f_T(\varepsilon)$: Fermi-Dirac distribution

$\Delta(T)$: superconducting gap

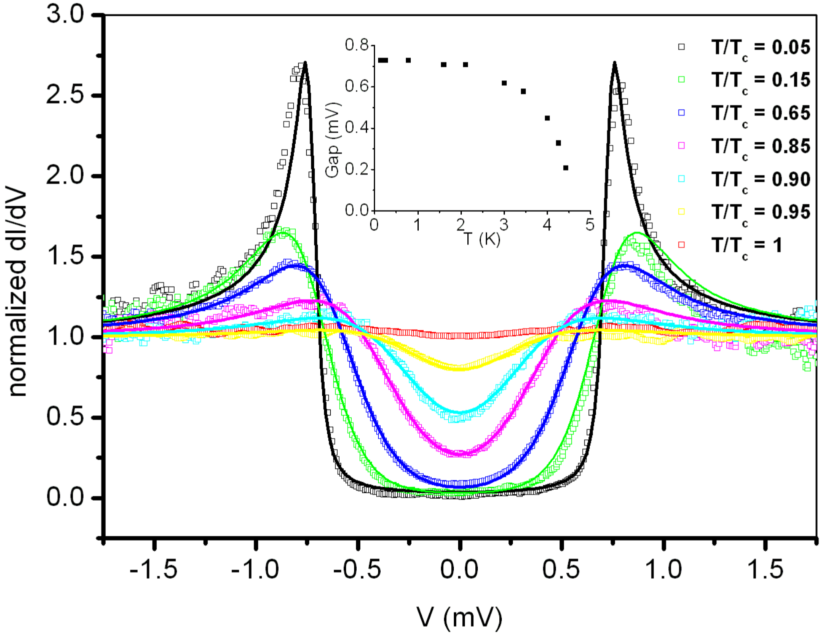
Scanning Tunneling Spectroscopy

Measurement of the Density-Of-States (DOS)

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



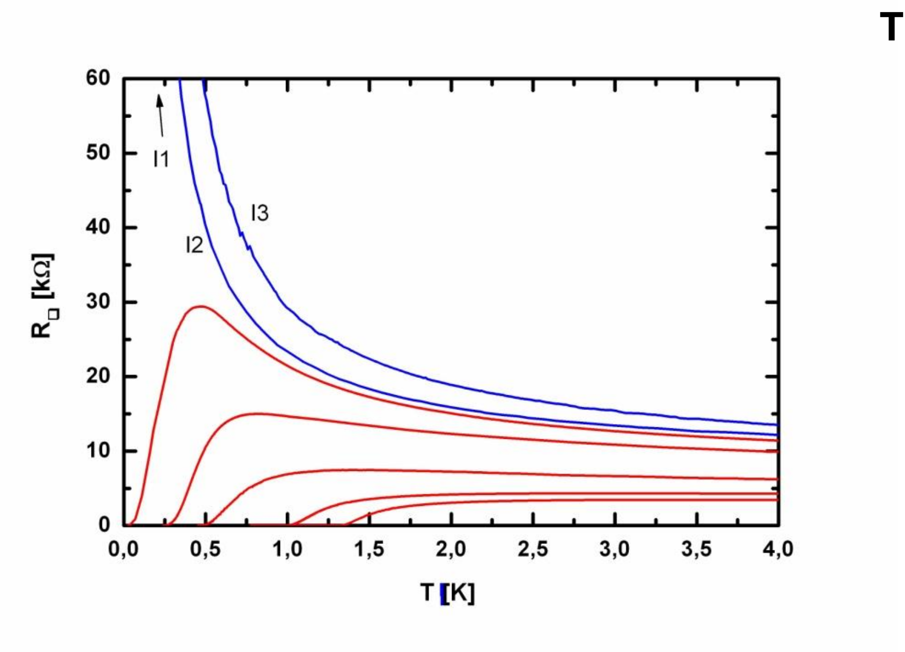
TiN 100 nm thick film



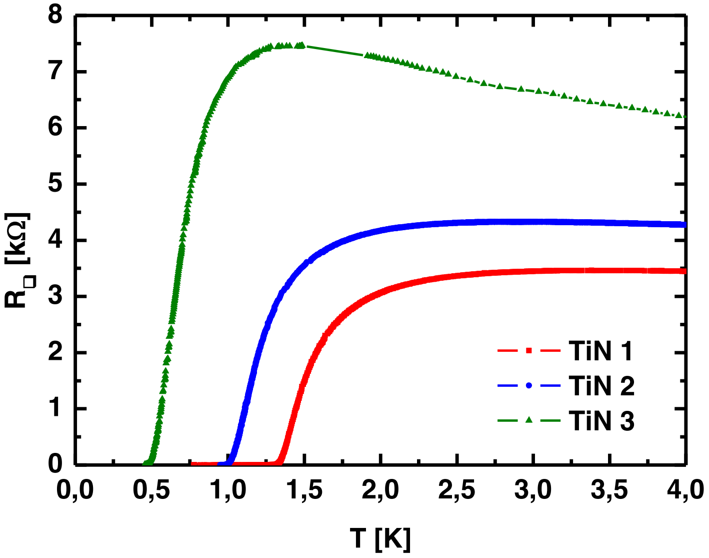
W. Escoffier, et al., *PRL **93**, 217005, (2004)*

TIN Superconductor-Insulator transition

TiN 1 : 3.6 nm, grown at 400 ° C
TiN 2 : 5.0 nm, grown at 350 ° C
TiN 3 : 5.0 nm, grown at 350 ° C + plasma etching



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



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

TIN Superconductor-Insulator transition

Fermionic scenario

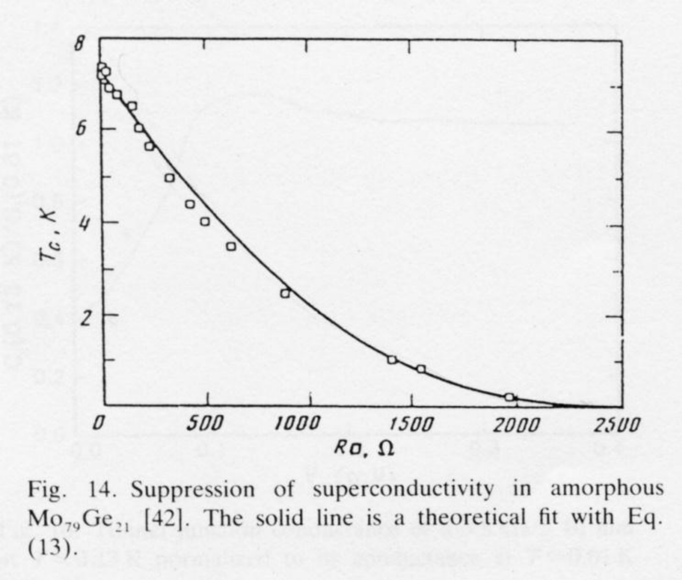
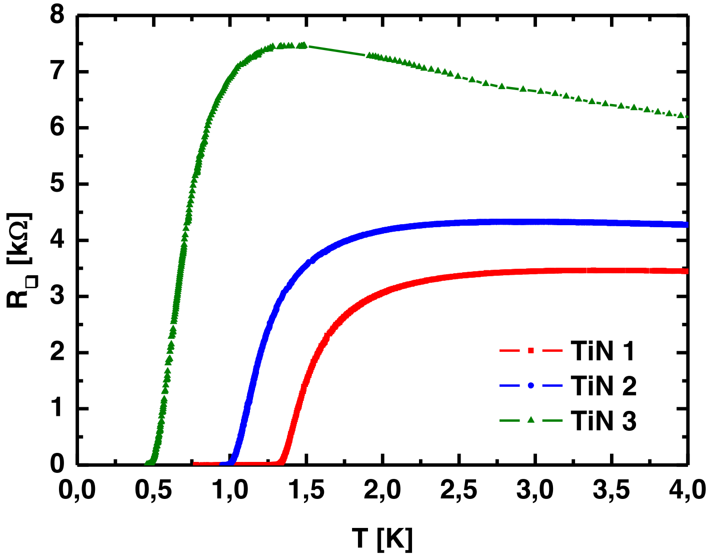


Fig. 14. Suppression of superconductivity in amorphous $Mo_{79}Ge_{21}$ [42]. The solid line is a theoretical fit with Eq. (13).

$$\frac{T_c}{T_c^{bulk}} = e^{\gamma}\left(\frac{1/\gamma - \sqrt{r/2} + r/4}{1/\gamma + \sqrt{r/2} + r/4}\right)^{1/\sqrt{2r}}$$

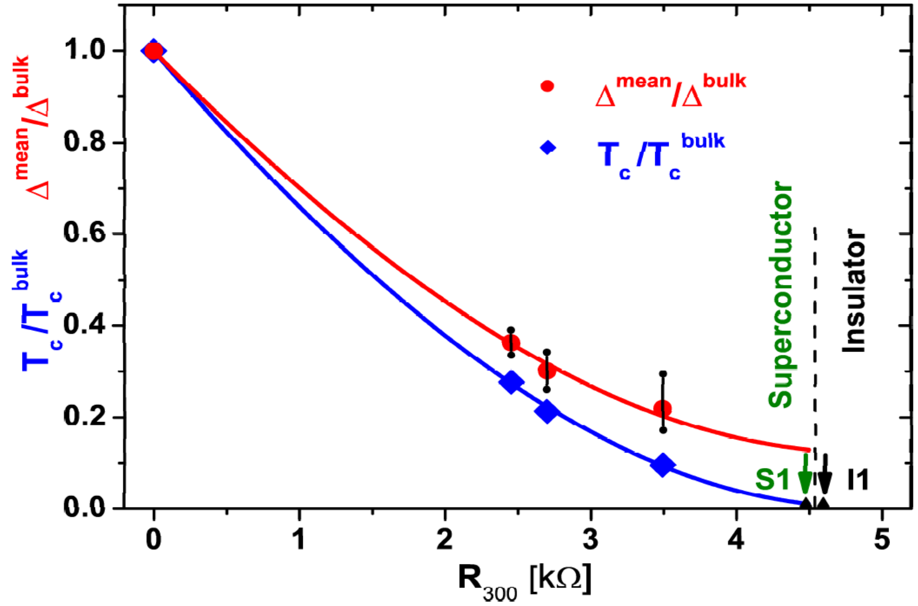
$$r = \frac{R_\square e^2}{\pi h} \qquad \gamma = 6.2$$

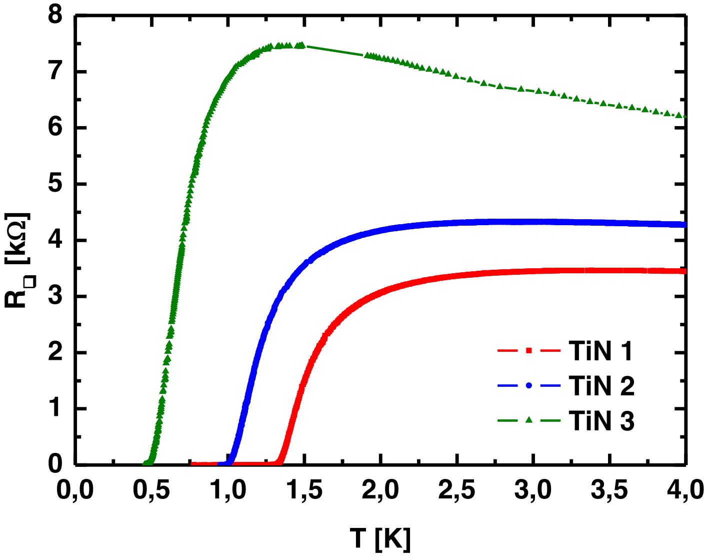
A. M. Finkel'stein, *Physica B* ***197***, 636, (1994)



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

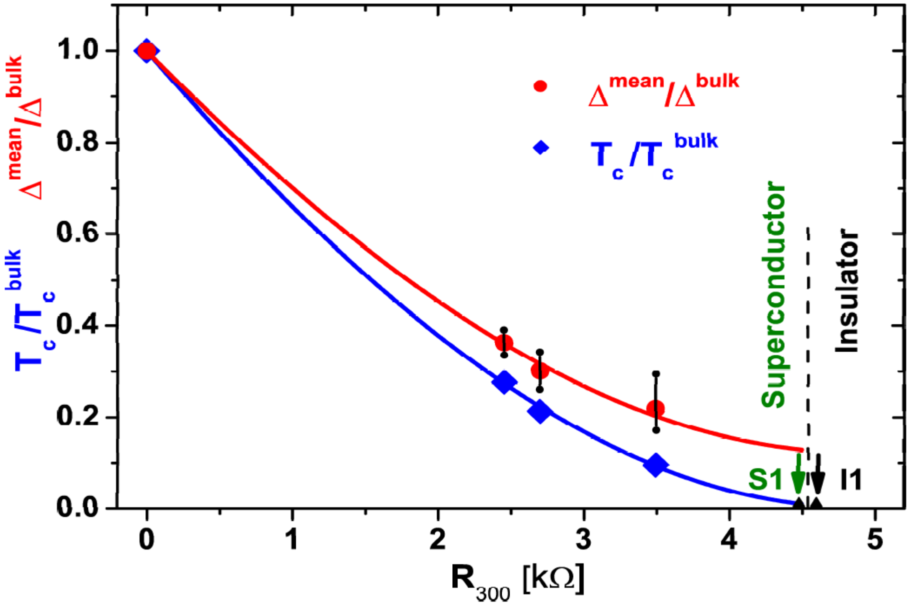
TIN Superconductor-Insulator transition

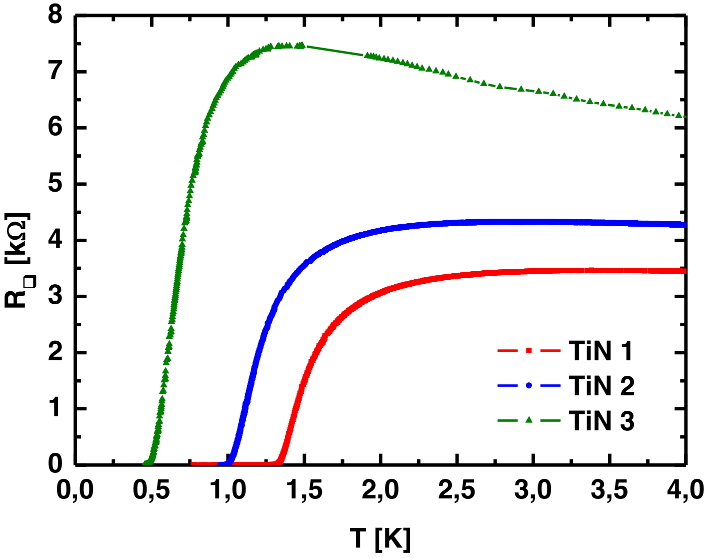


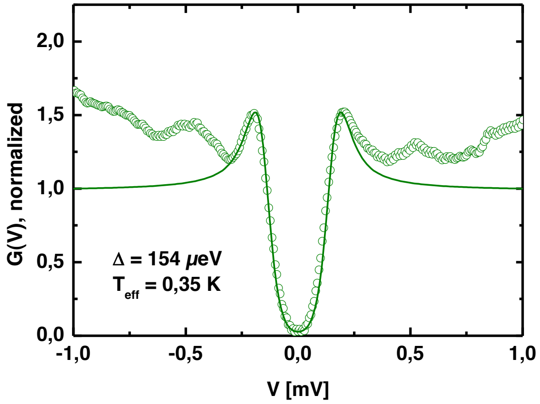


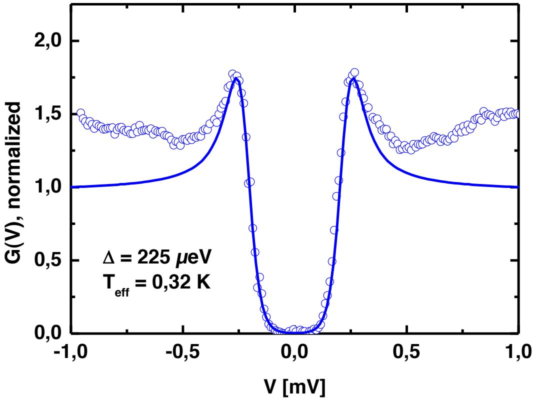
Sacépé et al., *PRL **101**, 157006 (2008)*

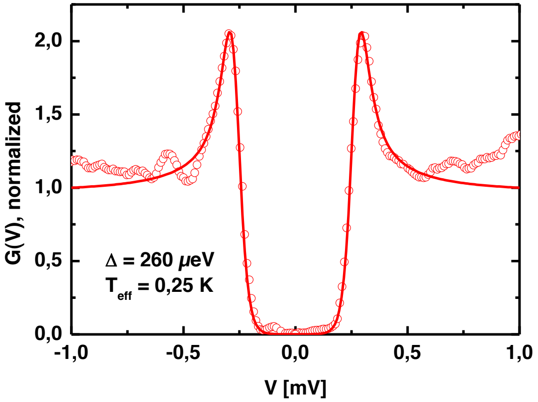
TIN Superconductor-Insulator transition







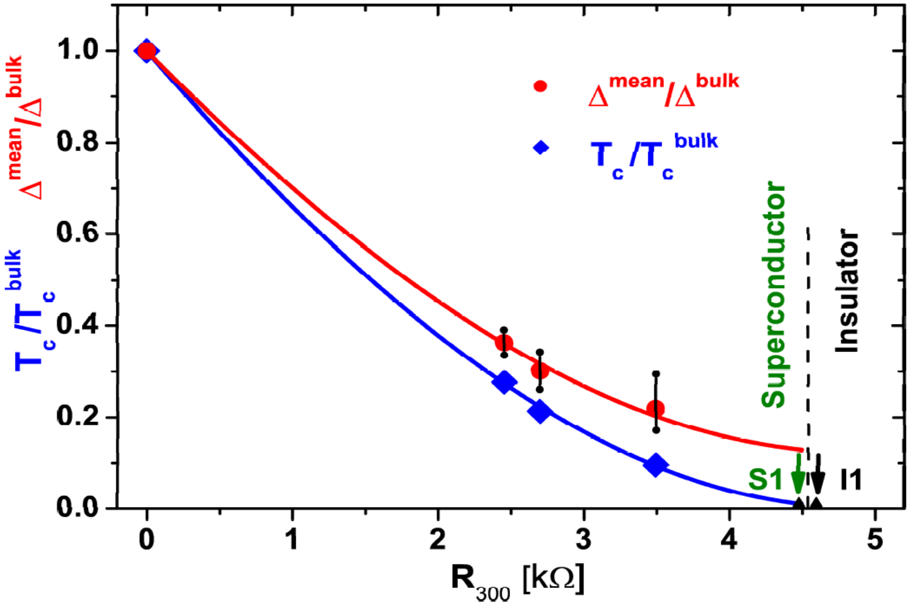




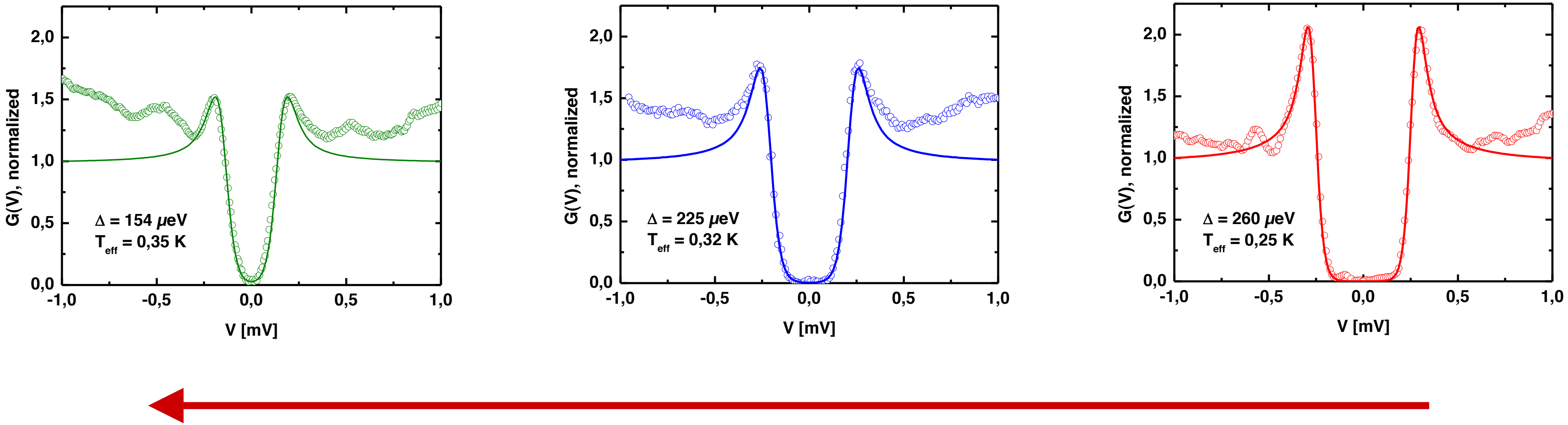
Increasing disorder

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

TIN Superconductor-Insulator transition



T_c [K]	Δ/T_c
4.7	1.8
1.3	2.3
1	2.6
0.45	4

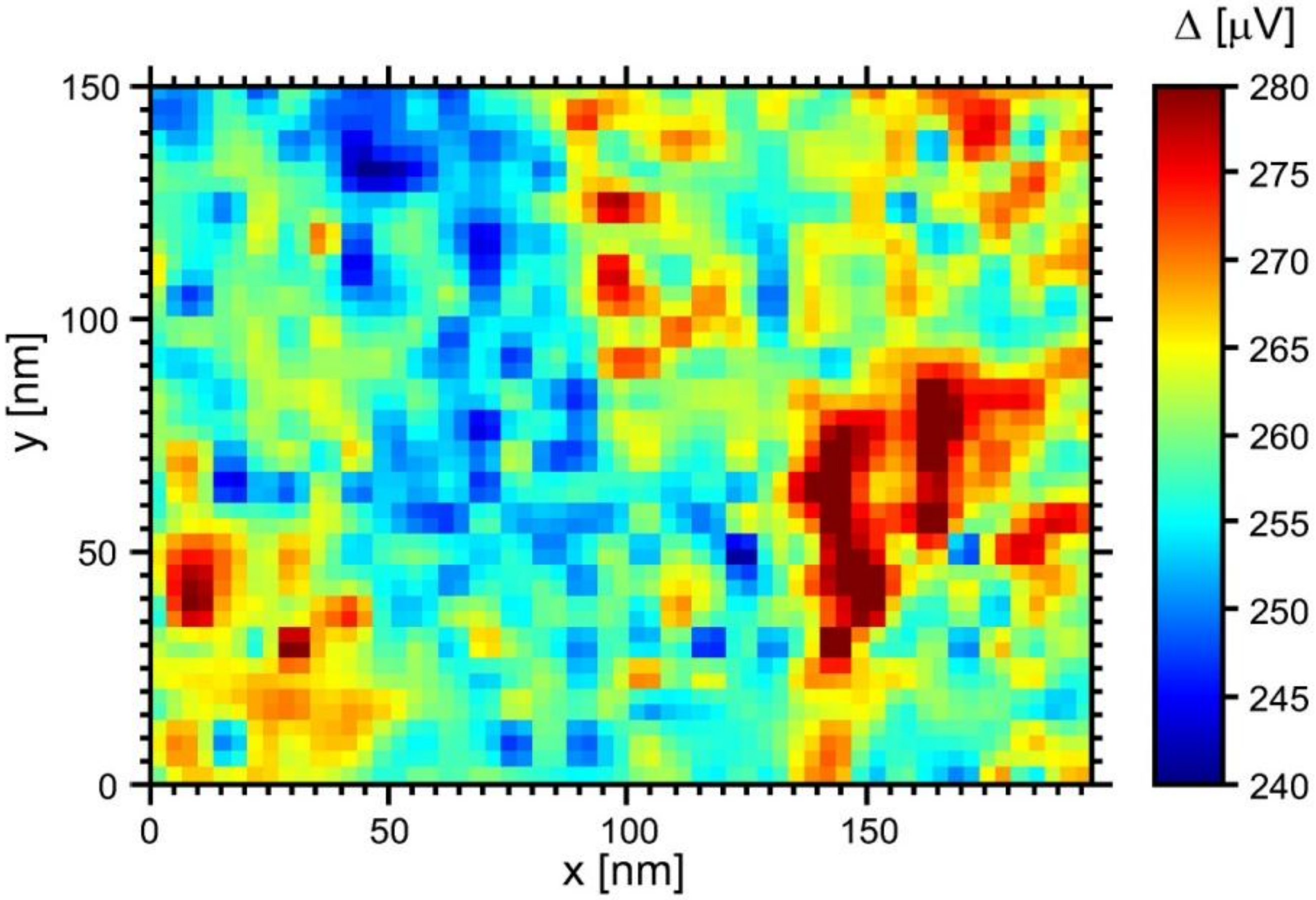


Increasing disorder

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

TIN Inhomogeneus superconducting state

TiN 1 **(T_c = 1.3 K)**

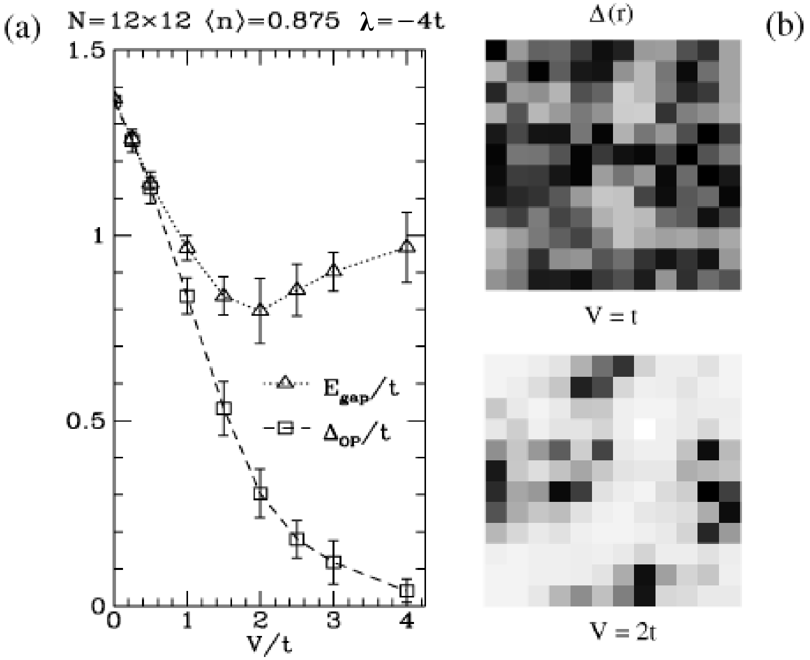


Sacépé et al., *PRL* ***101****, 157006 (2008)*

Bosonic scenario : Inhomogeneus superconducting state

Anderson localization and superconducting pairing

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 :

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

Bosonic scenario : Inhomogeneus superconducting state

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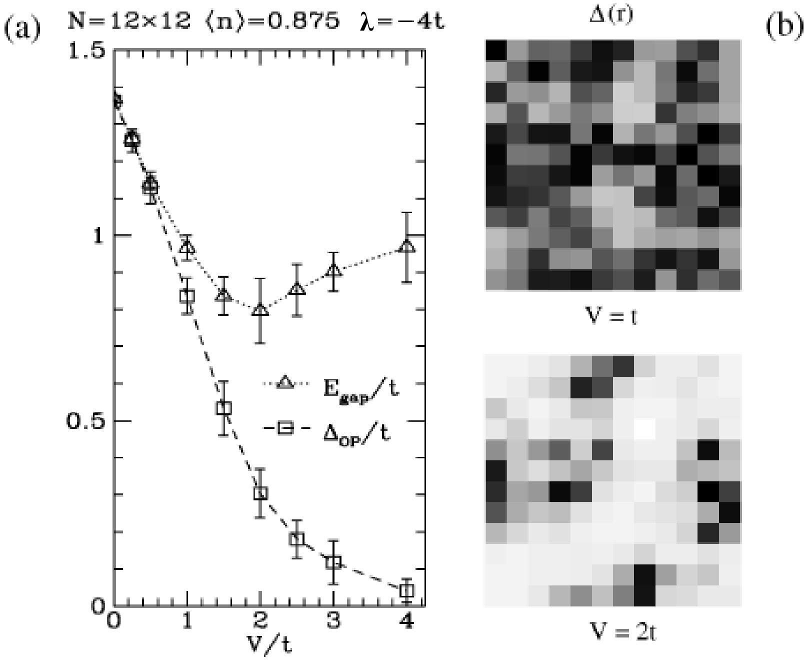
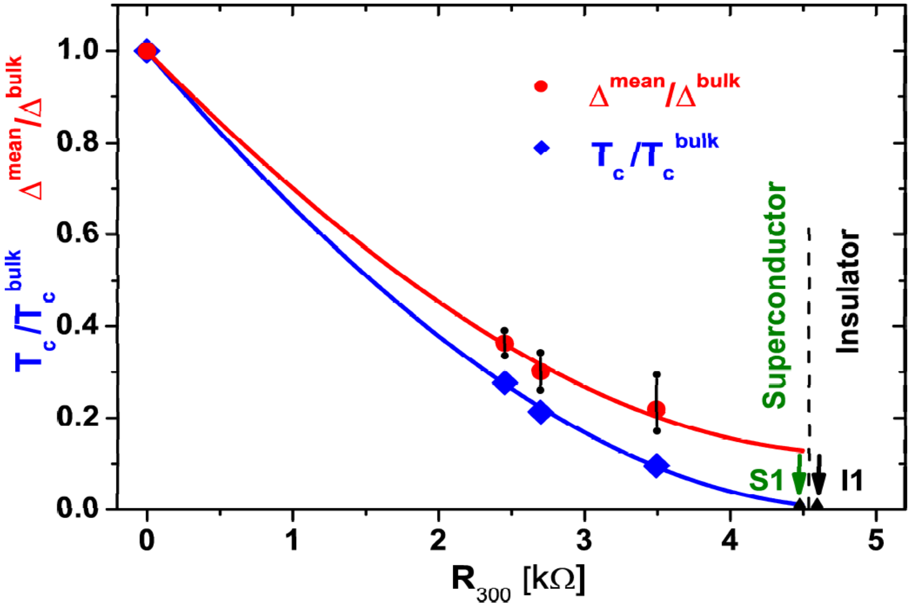
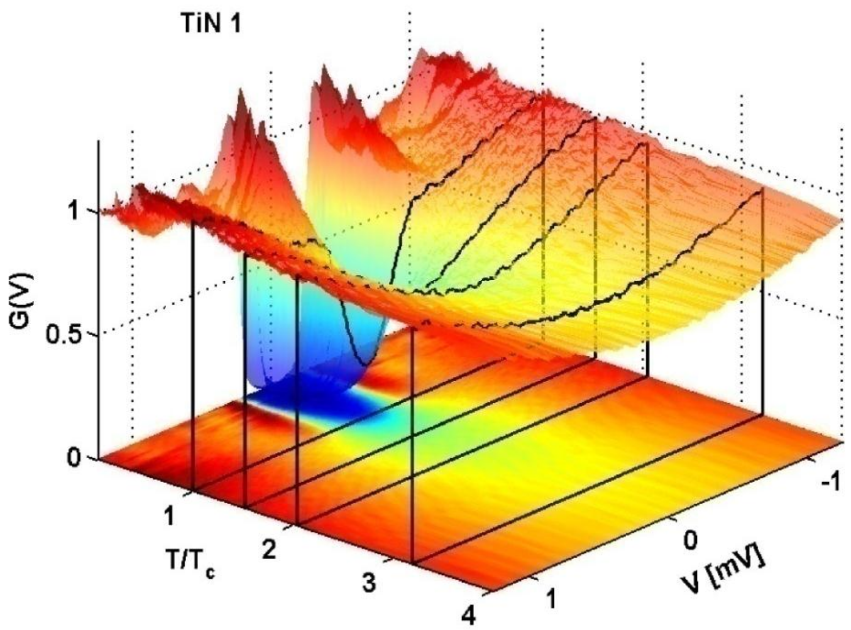
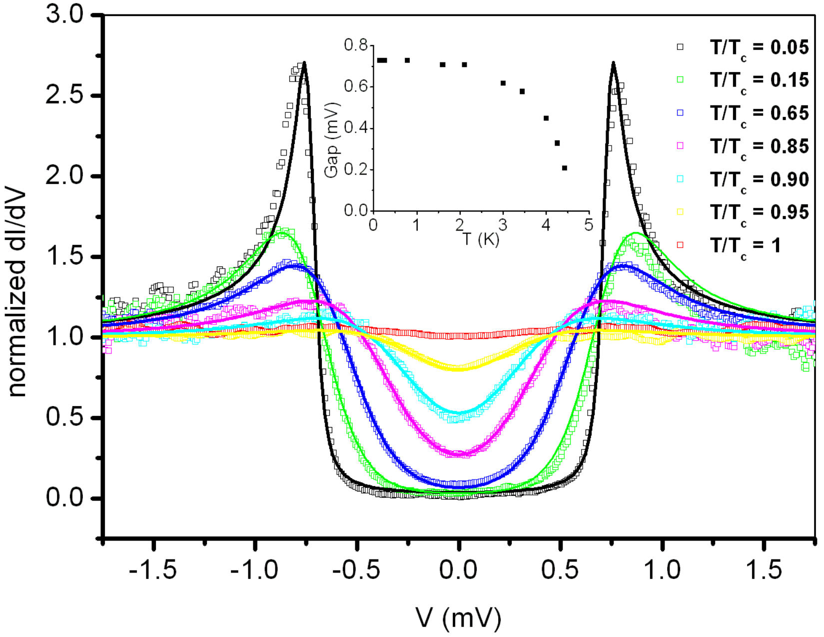




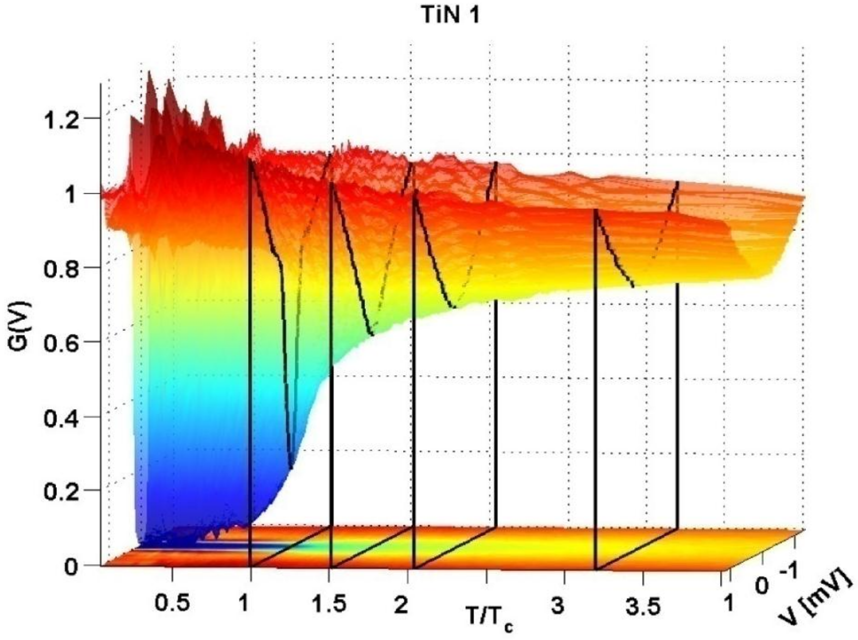
T_c [K]	Δ/T_c
4.7	1.8
1.3	2.3
1	2.6
0.45	4

Thermal evolution of the superconducting gap





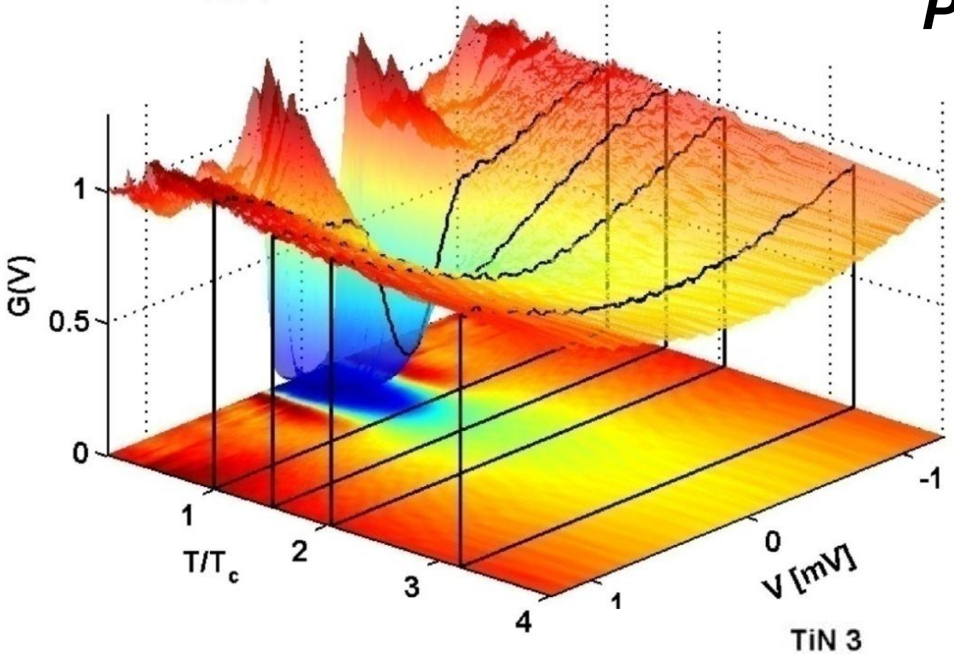
W. Escoffier, et al., *PRL* ***93****, 217005, (2004)*



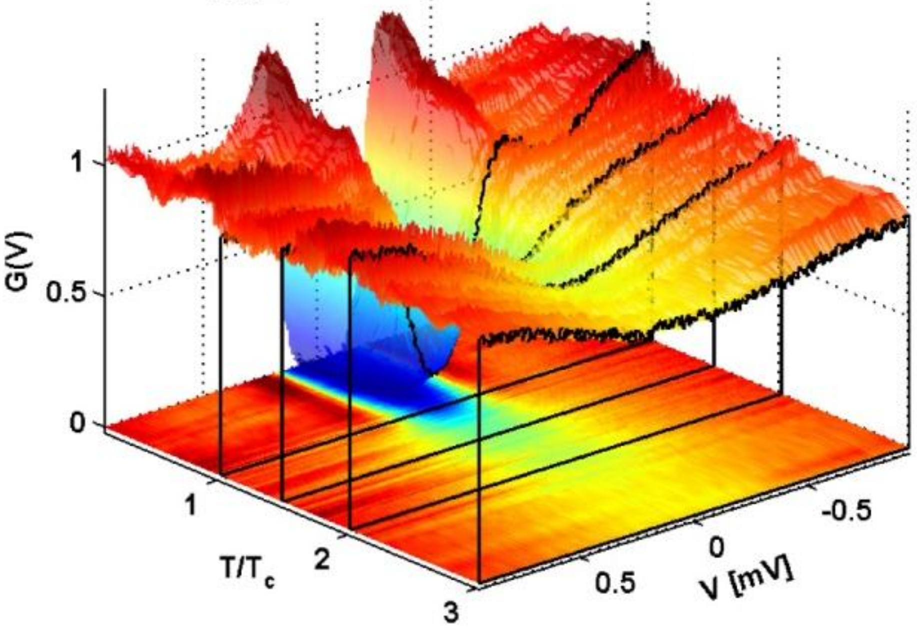
B. Sacépé, et al., *Nature Communications (2010)*

Thermal evolution of the superconducting gap

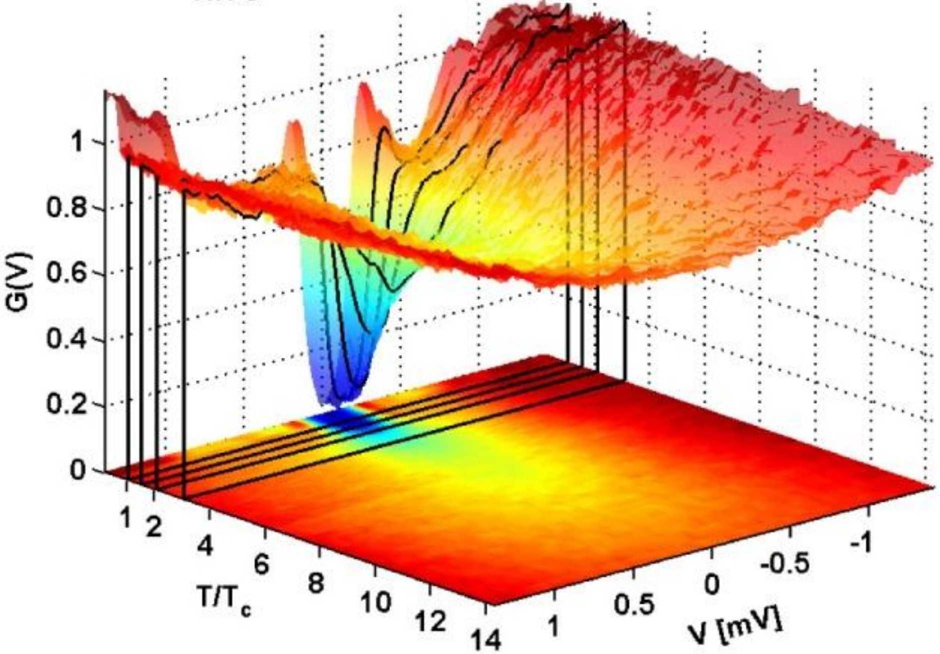
Pseudogap above Tc



TiN 1



TiN 2



TiN 3

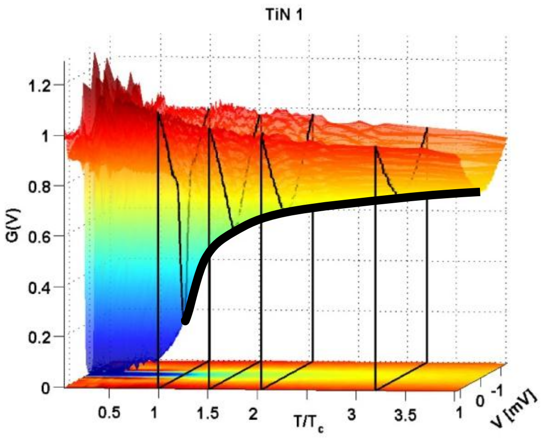
Pseudogap

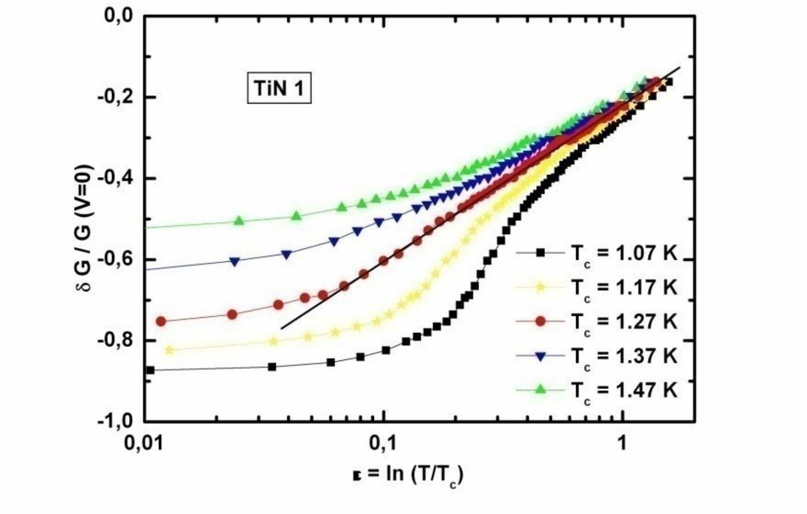
Superconducting fluctuations correction to the DOS

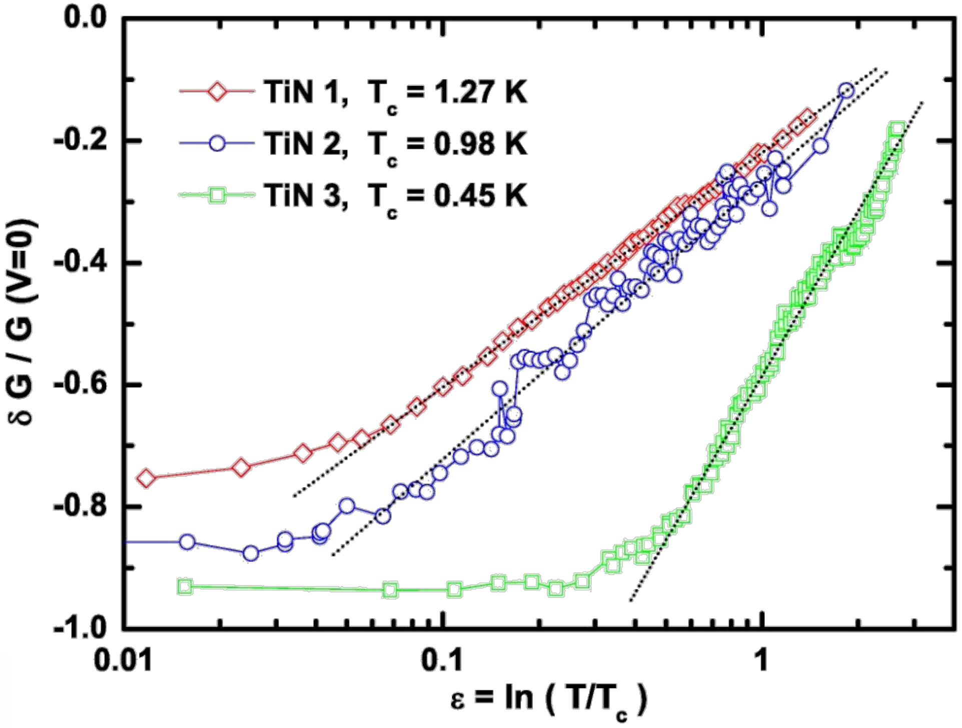
A. Varlamov and V. Dorin, *Sov. Phys. JETP* ***57****, 1089, (1983)*

$$\frac{\delta G}{G}(eV=0) = -2Gi\,\ln(\ln\frac{T}{T_c})$$

$$Gi = \frac{\hbar}{16e^2}R_\square$$







Slopes increase with $G_i \sim R_\square$

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

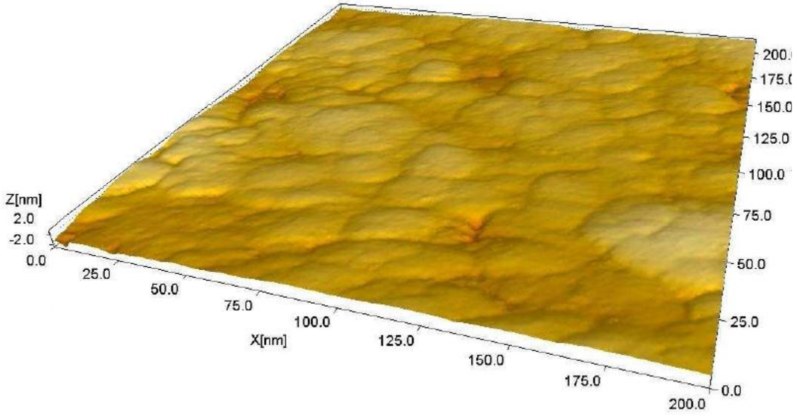
InOx Superconductor-Insulator transition

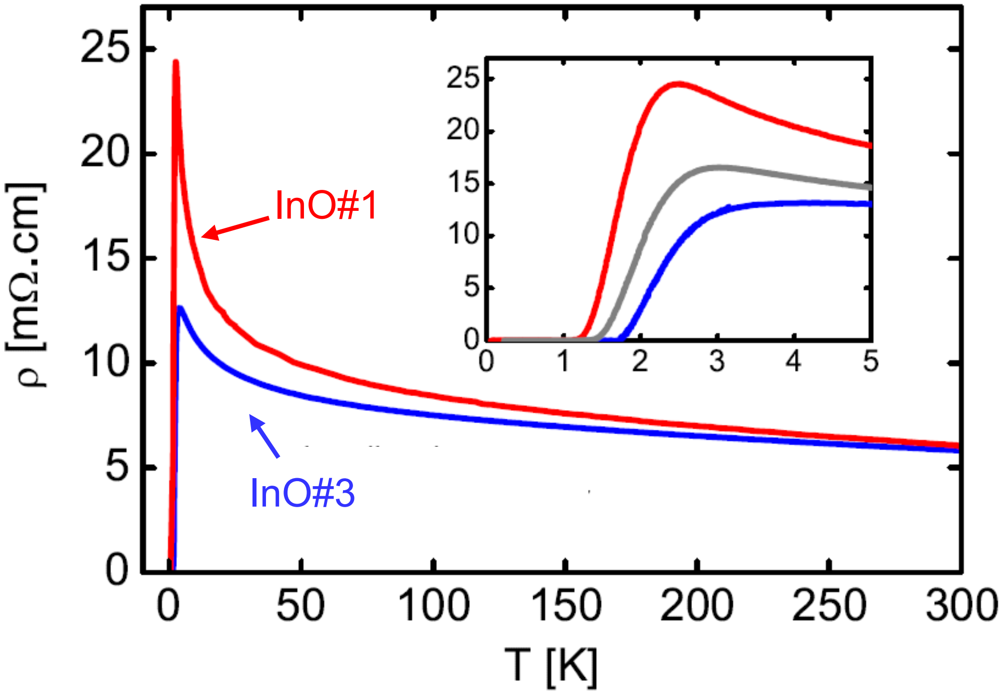
Amorphous Indium Oxide

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

D. Shahar, Weizmann Institute of Science

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

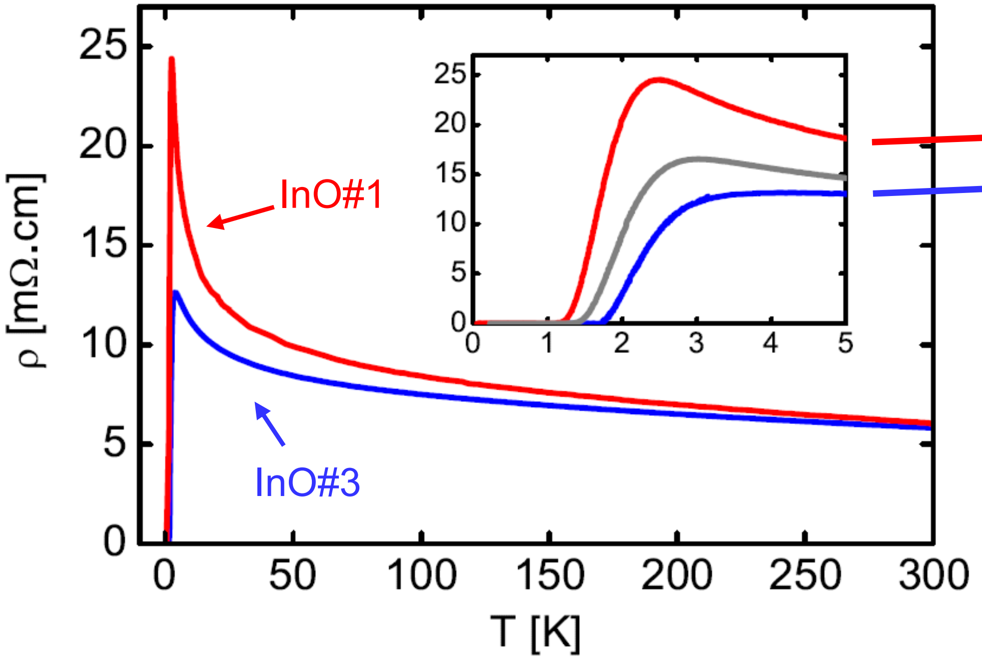


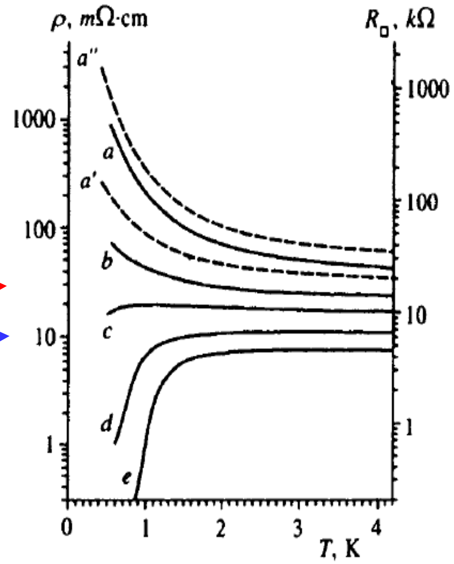


InOx

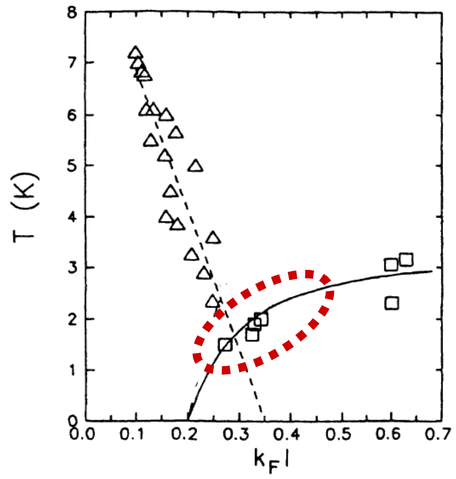
Nearly critical samples

High disorder (red) and low disorder (bleu)





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

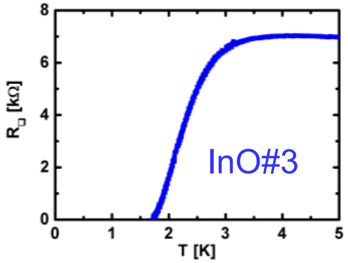


D. Shahar and Z. Ovadyahu, *Phys. Rev. B* ***46***, 10917 (1992)

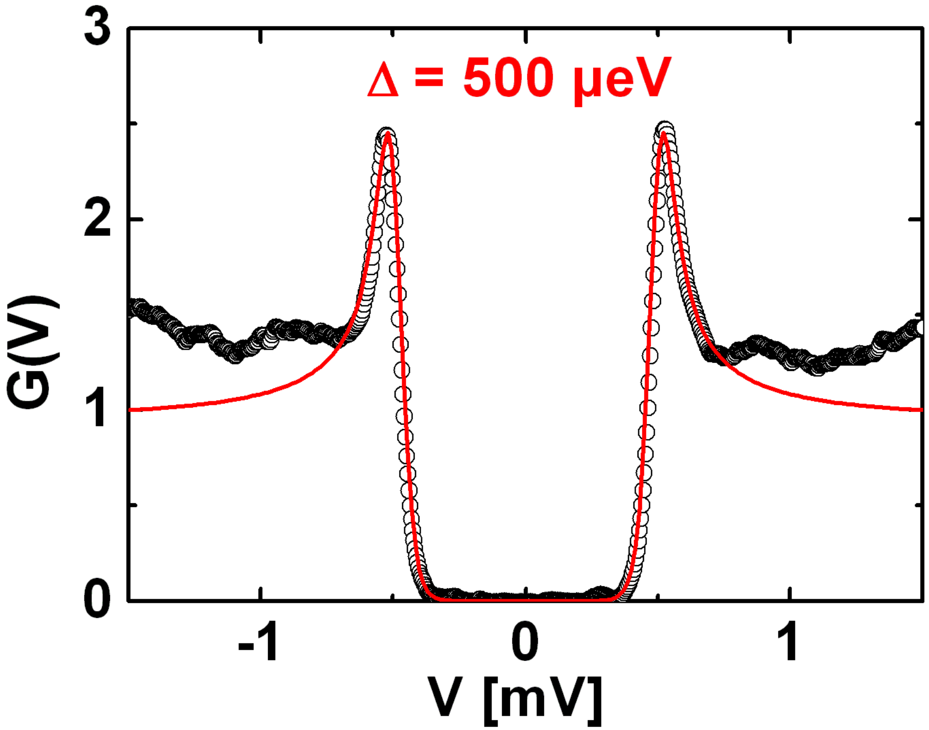
- **$k_F l_e$ ~ 0.4-0.5<1 → localized regime (Ioffe-Regel criterion)**
- **T_c comprised between 1K and 2K**

- Carrier density : N = 3.5 x 10^{21} cm^{-3}

STM and transport measurements



Typical spectrum measured at 50 mK

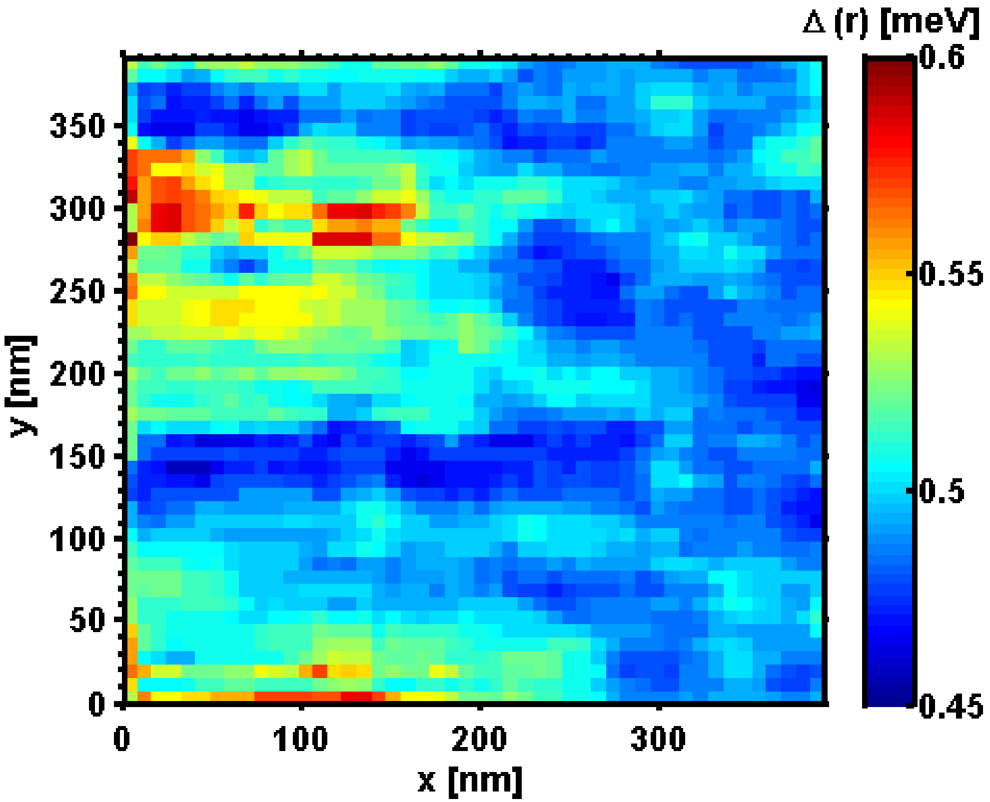


Fit : *s*-wave BCS density of states

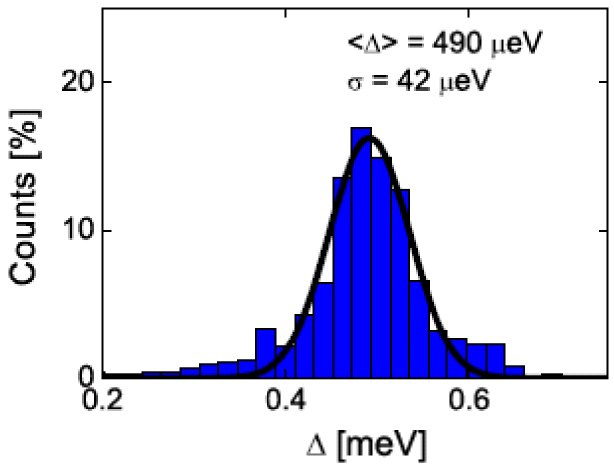
- Absence of quasi-particle excitations at low energies

Spatial fluctuations of the spectral gap Δ(r)

Map of the spectral gap



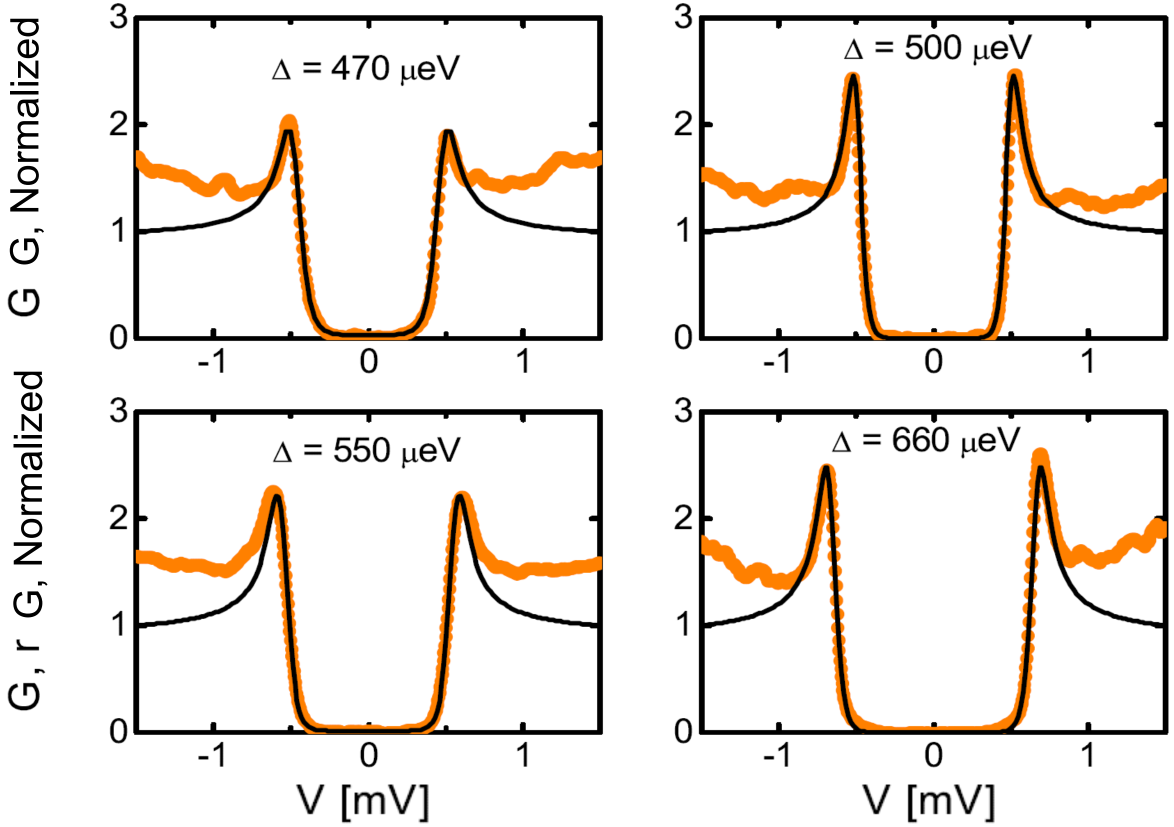
InO#3

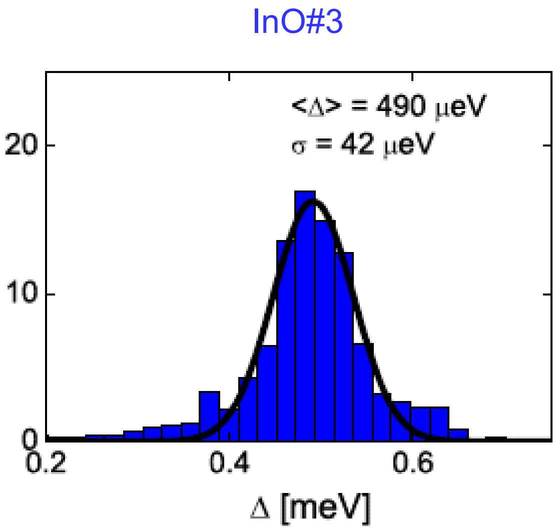


Gaussian distribution

Spatial fluctuations of the spectral gap Δ(r)

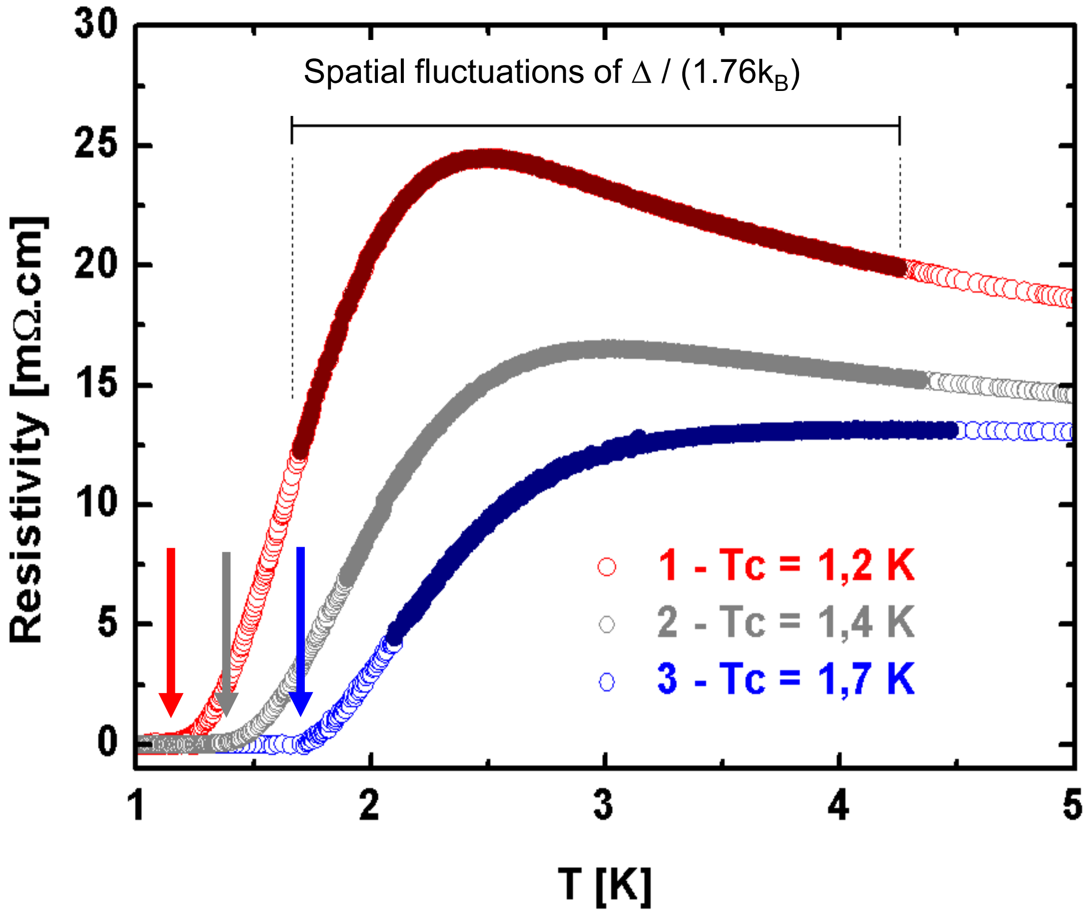
Spectra measured at different locations (T=50mK)





Gaussian distribution

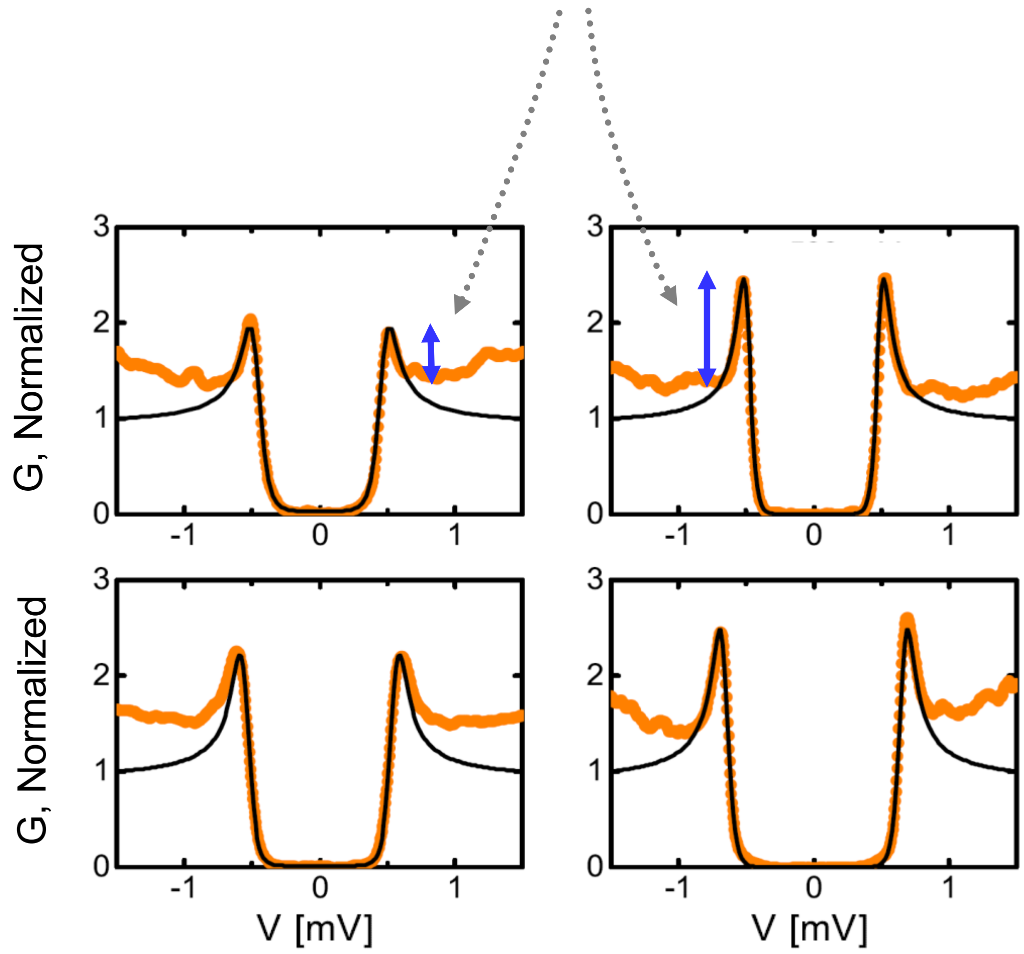
Fluctuations of Δ(r) and superconducting transition



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

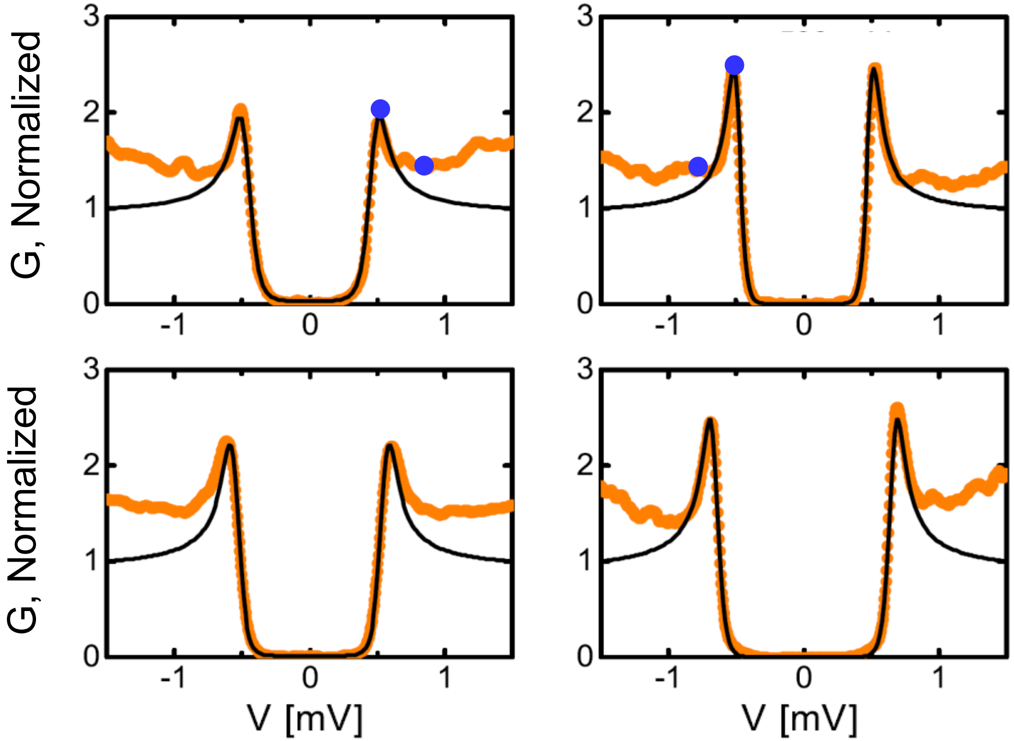
Coherence peaks

Spatial fluctuations of the coherence peaks height



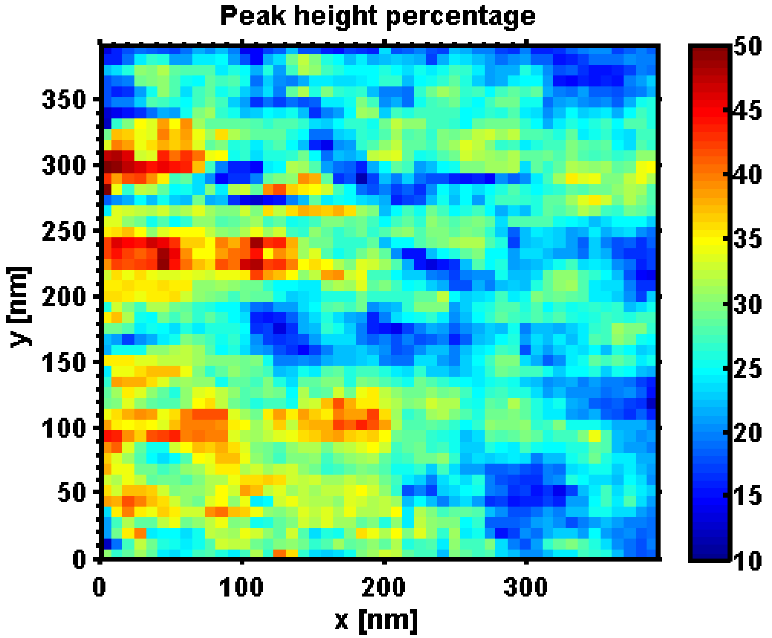
Coherence peaks

Spatial fluctuations of the coherence peaks height



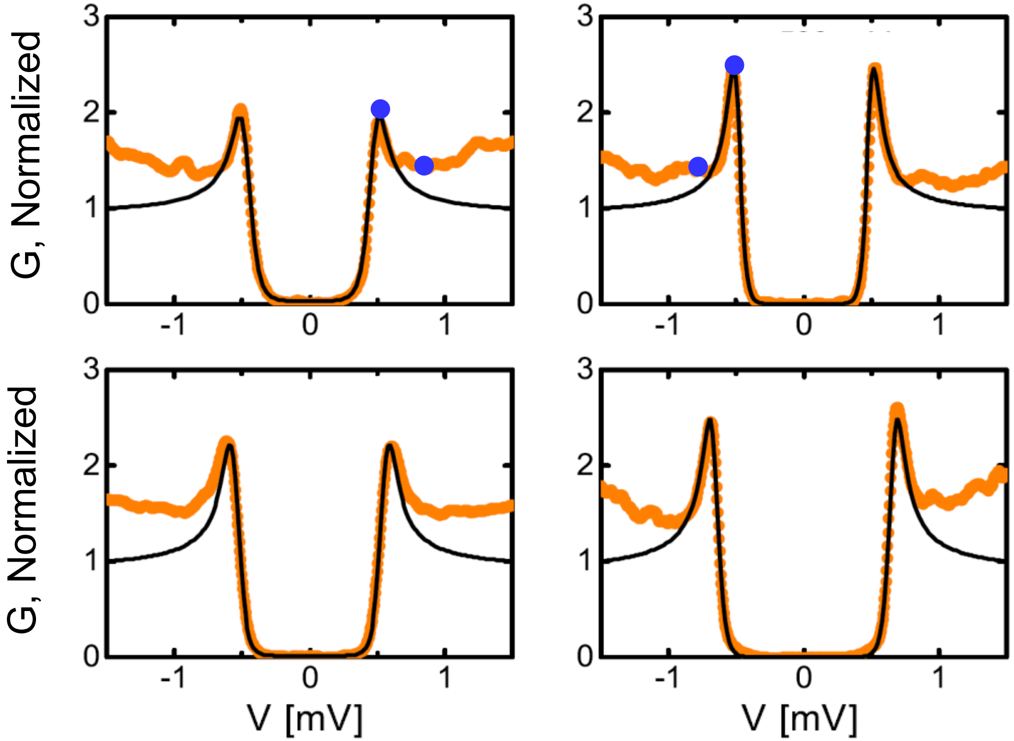
Statistical study

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



Coherence peaks

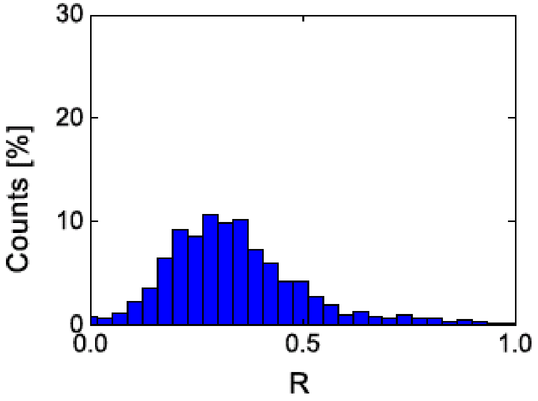
Spatial fluctuations of the coherence peaks height



Statistical study

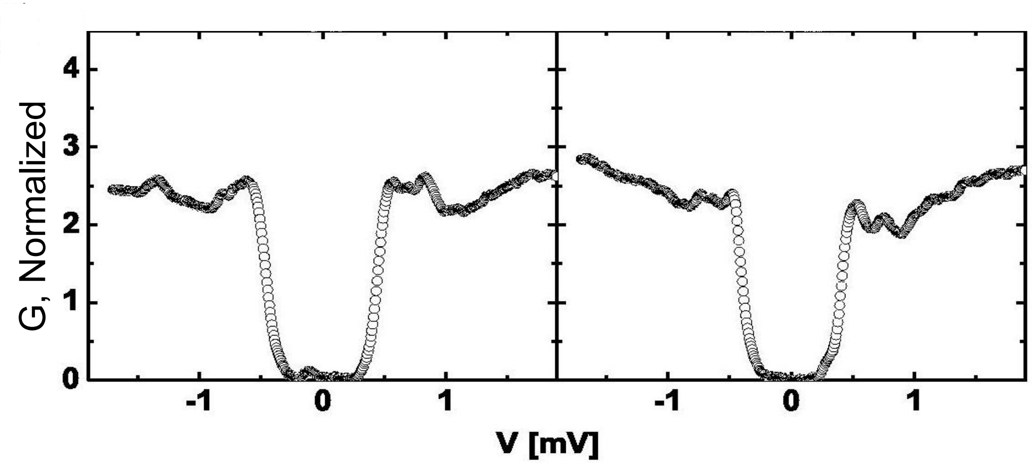
$$R = \frac{G(\Delta) - G(eV > \Delta)}{G(eV > \Delta)}$$

InO#3



Incoherent spectra

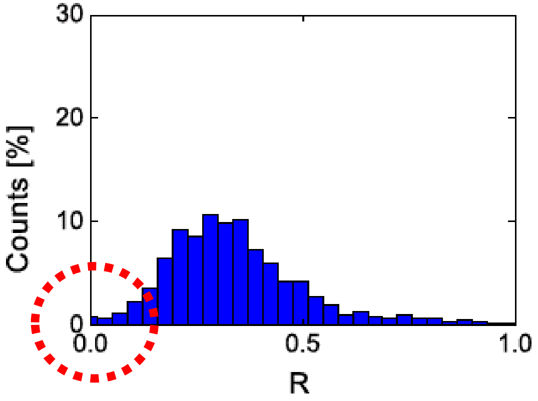
Full spectral gap without coherence peaks



Statistical study

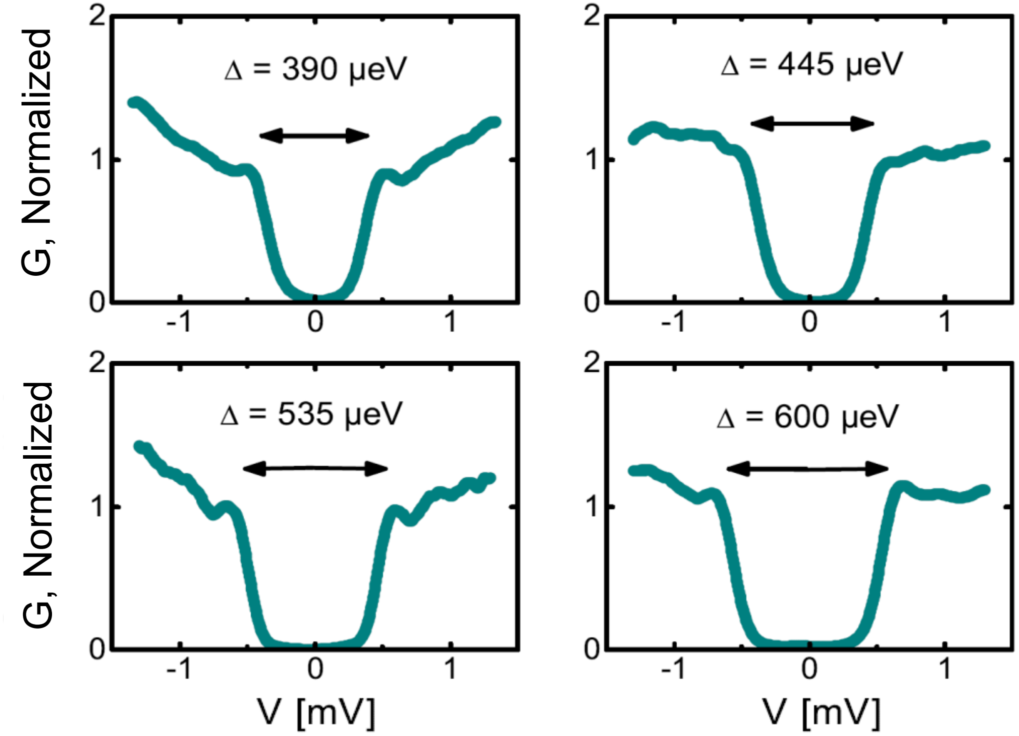
$$R = \frac{G(\Delta) - G(eV > \Delta)}{G(eV > \Delta)}$$

InO#3



Incoherent spectra

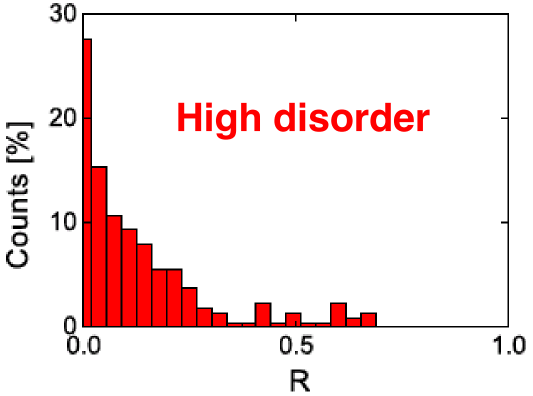
Full spectral gap without coherence peaks



Statistical study

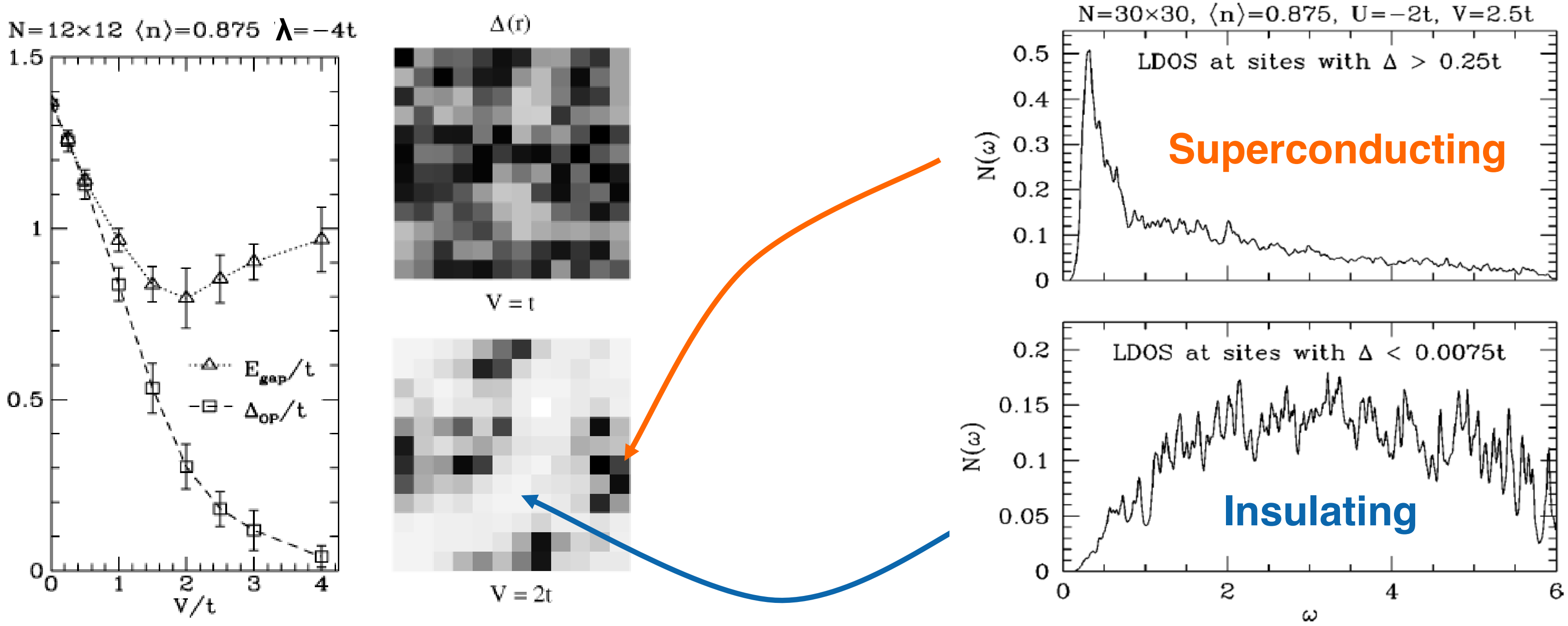
$$R = \frac{G(\Delta) - G(eV > \Delta)}{G(eV > \Delta)}$$

InO#1

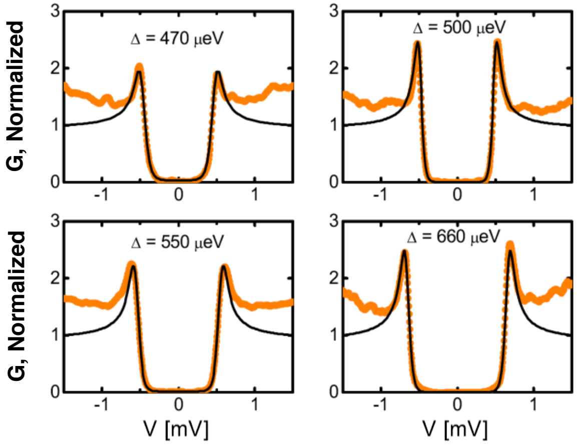


Signature of localized Cooper pairs

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

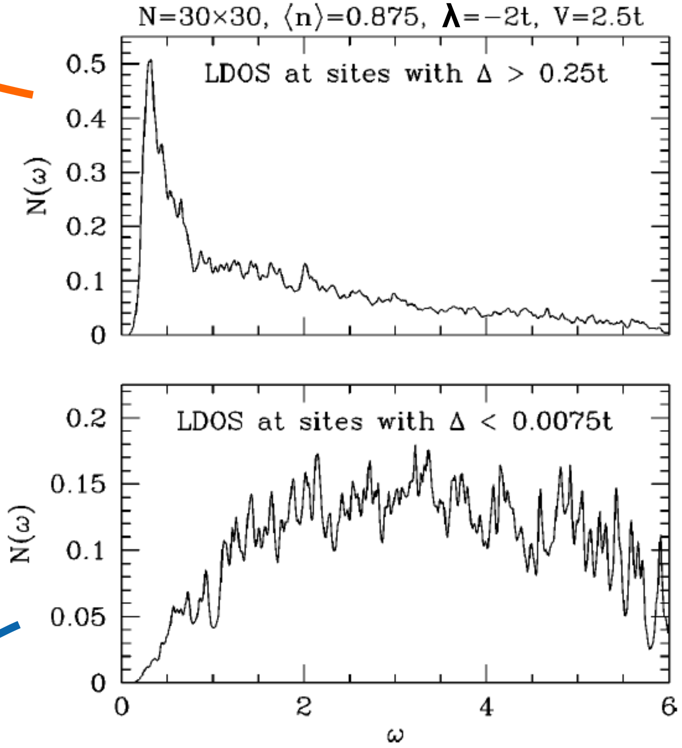


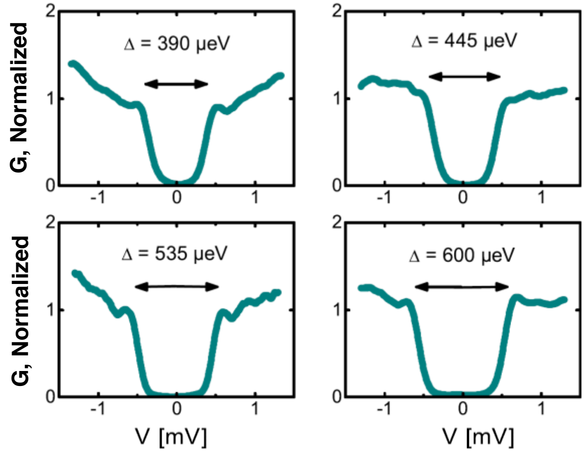
Signature of localized Cooper pairs



Superconducting gap Δ

⇒ delocalized Cooper pairs



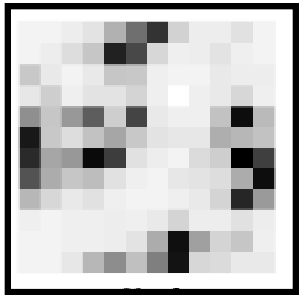


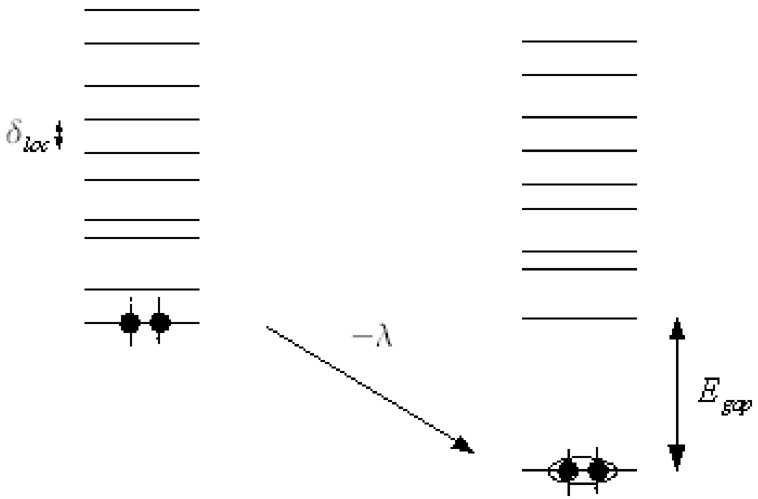
« Insulating » gap E_{gap}

⇒ Localized Cooper pairs

Insulating gap due to Cooper pairing

P. W. Anderson, *J. Phys. (Paris) Colloq.* 37, C4-339 (1976)
M. Ma, and P. A. Lee, *PRB 32*, 5658, (1985)
K. A. Matveev and A. Larkin, *PRL. 78*, 3749, (1997)
A. Ghosal, et al. *PRL 81*, 3940, (1998) and *PRB 65*, 014501 (2001)
M. Feigel'man, et al. *PRL 98*, 027001, (2007)
M. Feigel'man, et al. *Ann. Phys.* 325, 1390 (2010)
M. Feigel'man, et al. *PRB* 82, 184534 (2010)





Reduced BCS Hamiltonian built on eigenstates of the Anderson problem

$$H = \sum_{j\sigma} \epsilon_j c^\dagger_{j\sigma} c_{j\sigma} - \frac{\lambda}{\nu_0} \sum_{j,k} M_{jk} c^\dagger_{j\uparrow} c^\dagger_{j\downarrow} c_{k\uparrow} c_{k\downarrow},$$

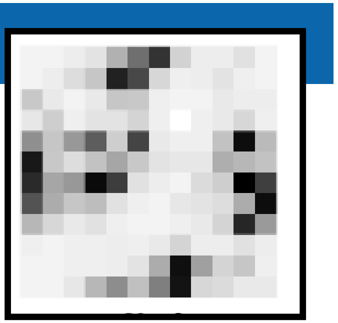
$$M_{jk} = \int d\mathbf{r} \psi_j^2(\mathbf{r}) \psi_k^2(\mathbf{r}),$$

In the high-disorder regime when $\delta_{loc} > \Delta$

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

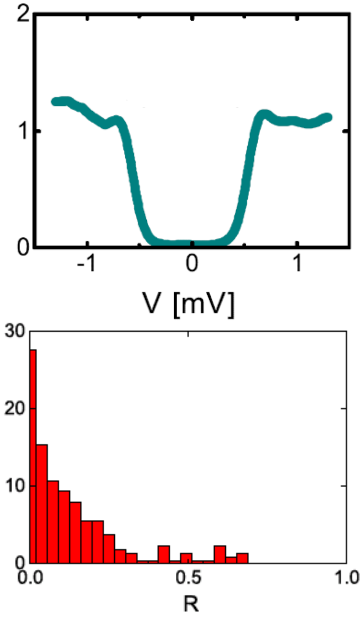
In the lowest order: $E_{gap} \sim \lambda \, \delta_{loc} \square \frac{\lambda}{\nu \xi_{loc}^3}$

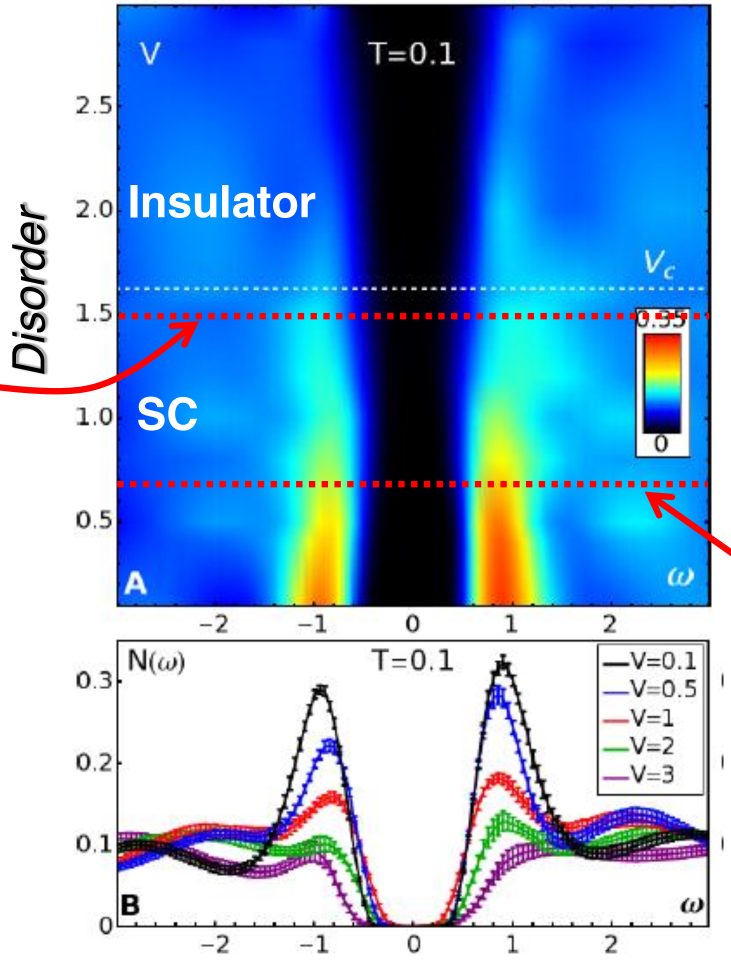
Insulating gap due to Cooper pairing

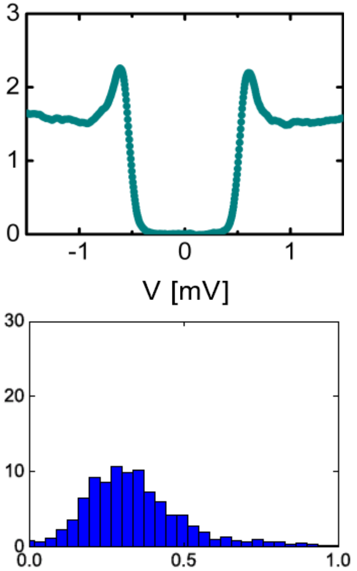


BdG + Quantum Monte Carlo simulations

K. Bouadim, Y. Loh, M. Randeria, N. Trivedi, *Nature Physics* (2011)



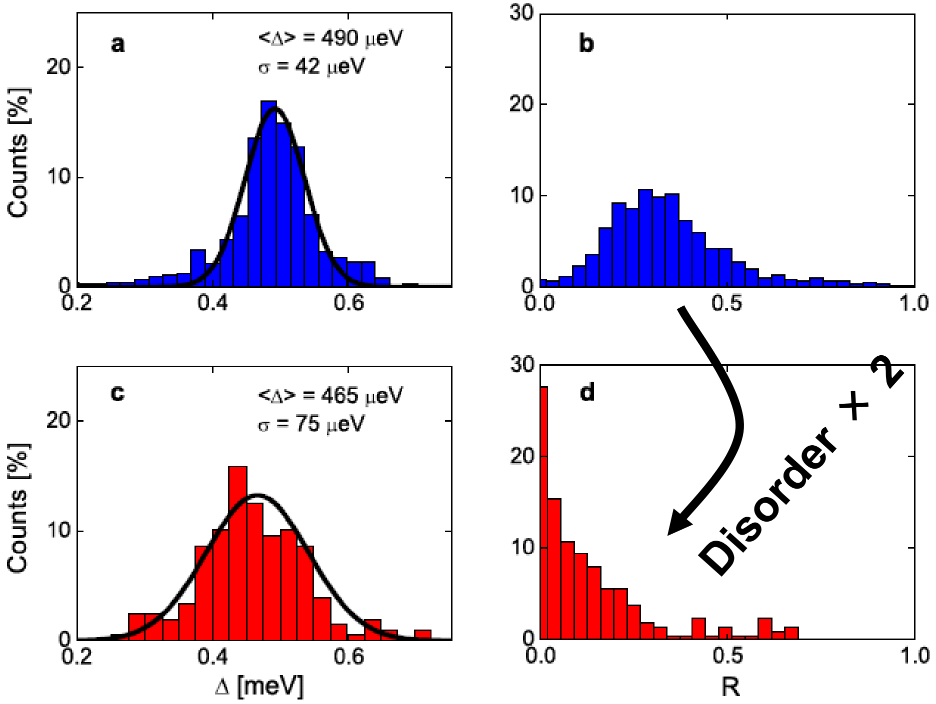




Proliferation of incoherent spectra at the superconductor-insulator transition

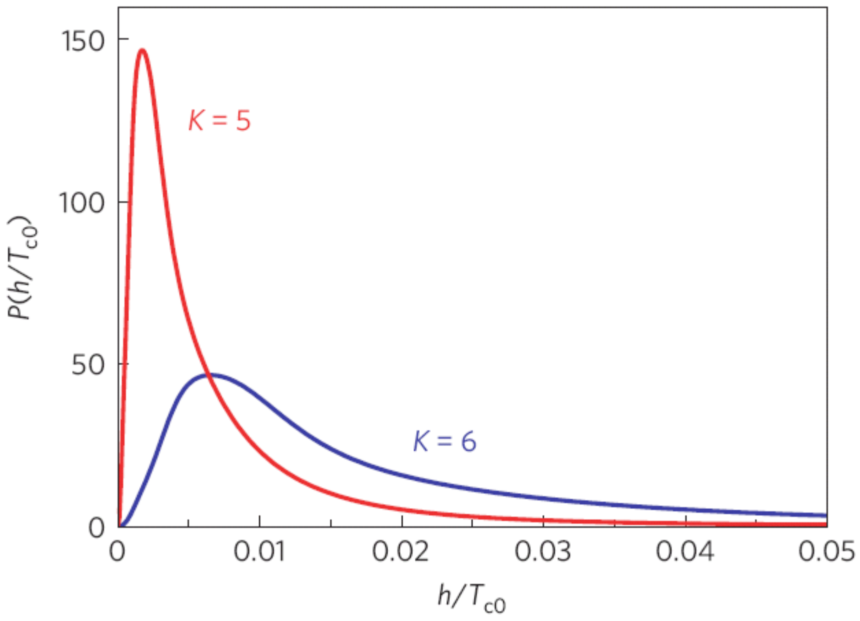
Superconductivity near the mobility edge

M. Feigel’man, et al., *PRL* (‘07)
M. Feigel’man, et al, *Ann. Phys.* (‘10)
M. Feigel’man, et al, *PRB* (‘10)



Simulations on the Bethe lattice

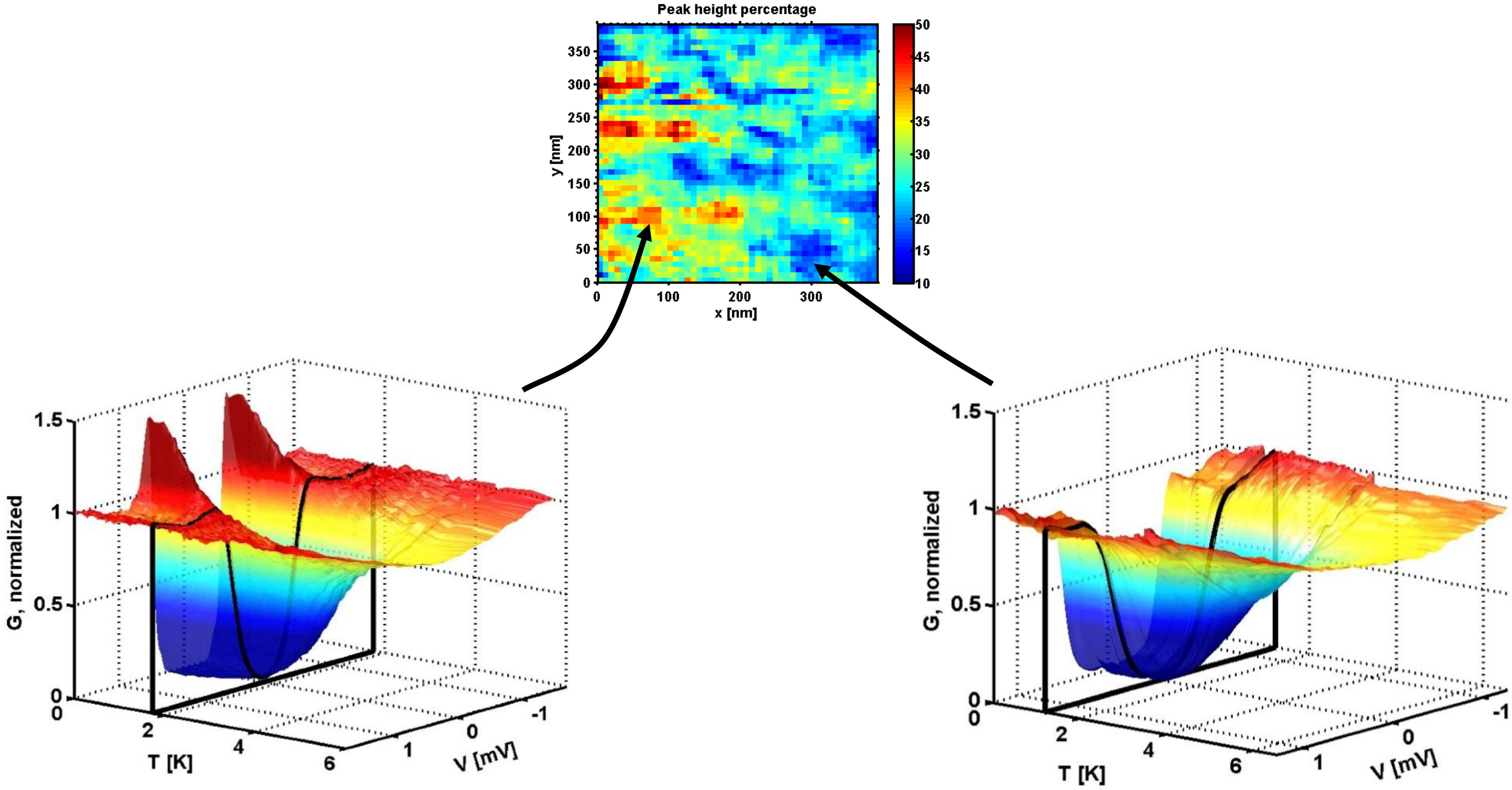
Lev Ioffe, Misha Feigel’man



- ***Proliferation of localized « Cooper »-pairs when approaching the SIT***

Pseudogap state above Tc

Self-induced inhomogeneities

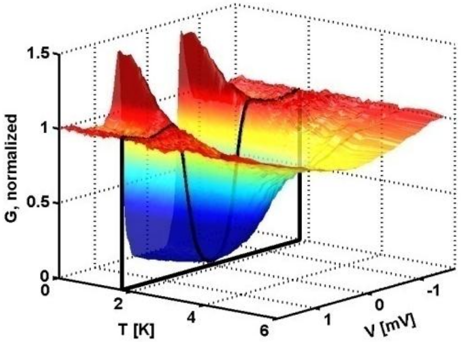


Condensation of preformed Cooper-pairs

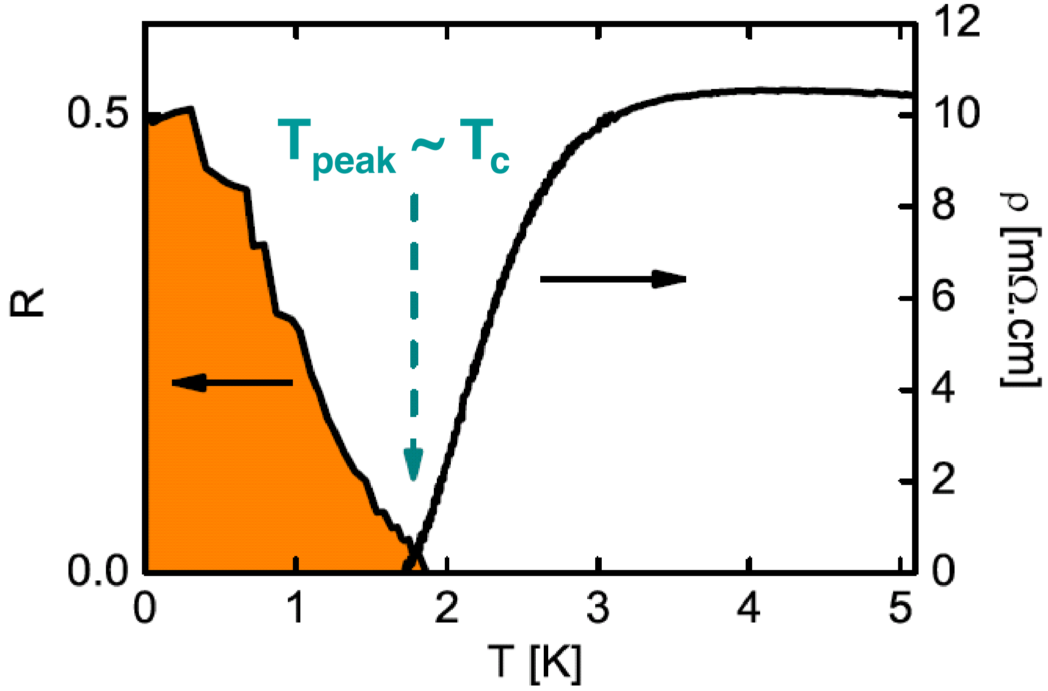
Localization of preformed Cooper-pairs

B. Sacépé, et al. *Nature Phys. 7, 239 (2011)*

Definition of Tc

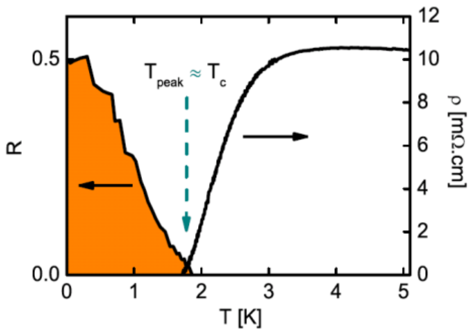


Macroscopic quantum phase coherence probed at a local scale



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

Definition of Tc



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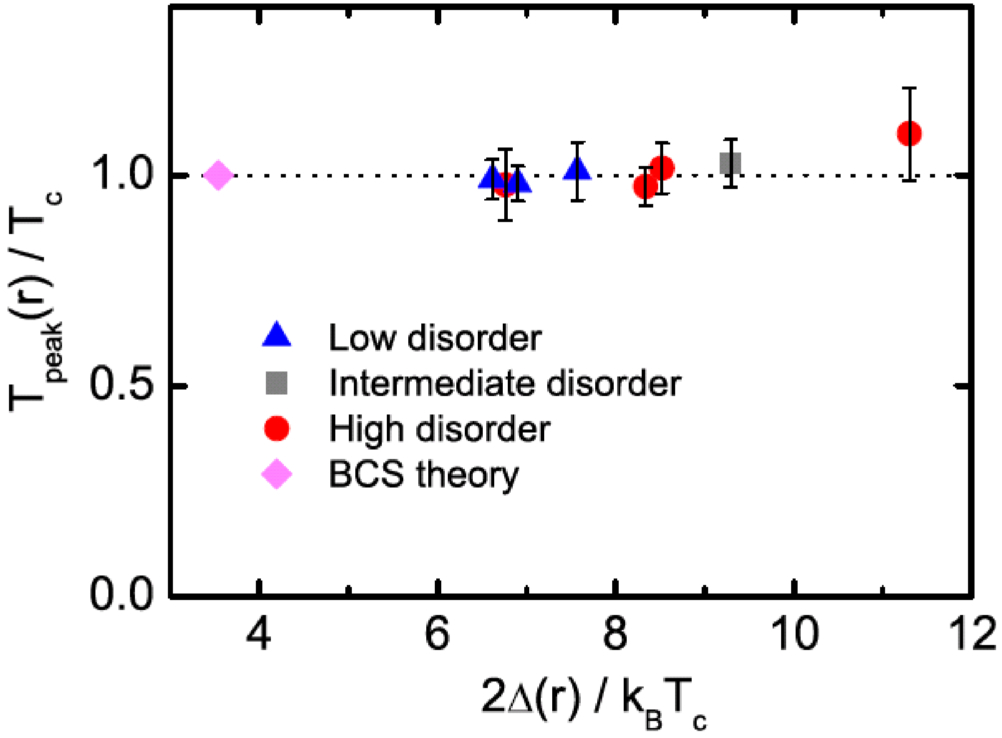


- **BCS peaks appear along with superconducting phase coherence**

Two contributions to the spectral gap

Superconductivity beyond the mobility edge

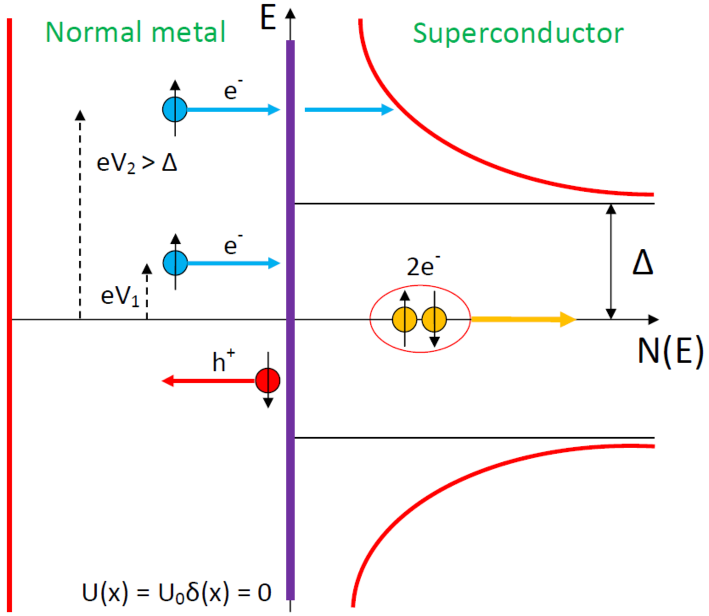
M. Feigel'man *et al.*, *Phys. Rev. Lett.* ***98***, 027001, (2007)
M. Feigel'man *et al.*, *Ann. Phys.* **325,** 1390 (2010)

BCS model built on fractal eigenfunctions of the Anderson problem

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

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

How to measure the SC order parameter ?



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⇨ $E_{gap} = \Delta_p + \Delta_{BCS}$

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

How to measure the SC order parameter ?

- Tunneling spectroscopy
  (single-particle DOS)
  Tunnel barrier

"BCS gap"

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

"parity gap"

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

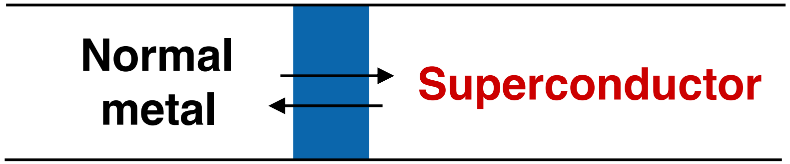
"BCS gap"

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

Conductance of a N/S contact

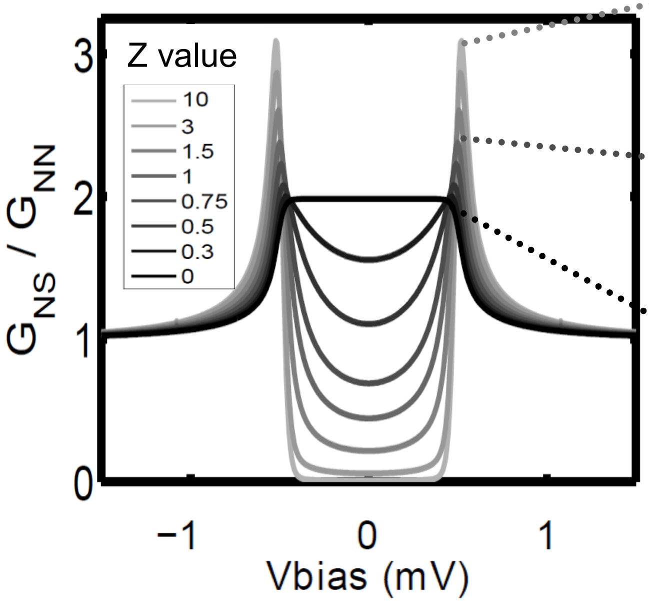
Blonder, G. E., Tinkham, M., and Klapwijk T.M. *Phys. Rev. B* ***25***, 7 4515 (1982)

Barrier : parameter Z



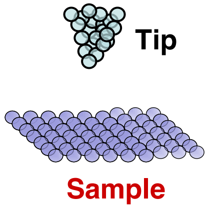
Transmission : $\mathcal{T} = 1 / (1 + Z^2)$

- Single-particle transfer ~ $\mathcal{T}$
- Two-particles transfer ~ $\mathcal{T}^2$

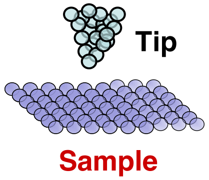


Tunnel regime

Z » 1

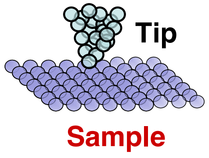


Z ~ 1



Z « 1

Contact regime



Conductance of a N/S contact

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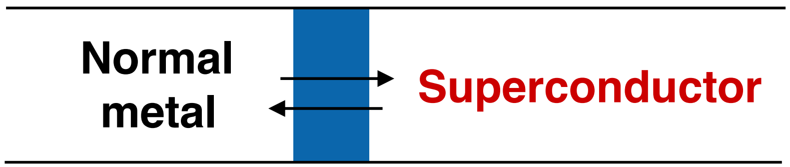


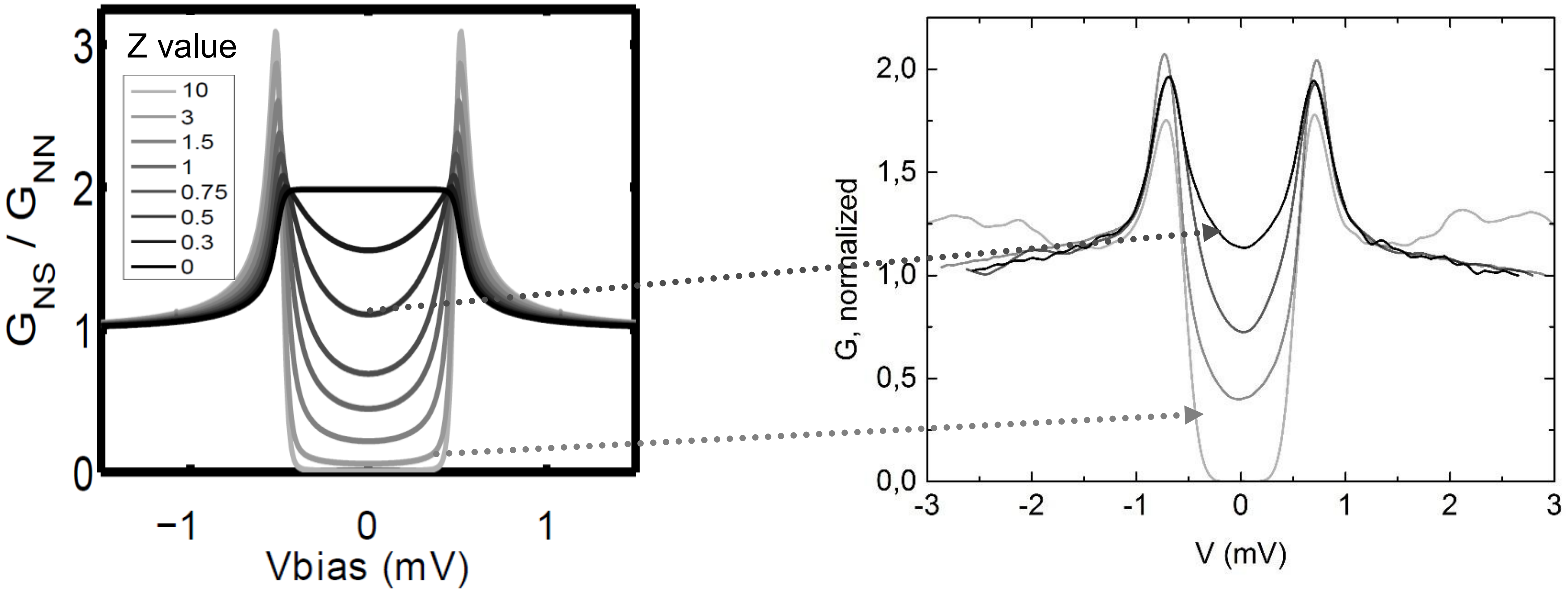
Normal metal

Superconductor

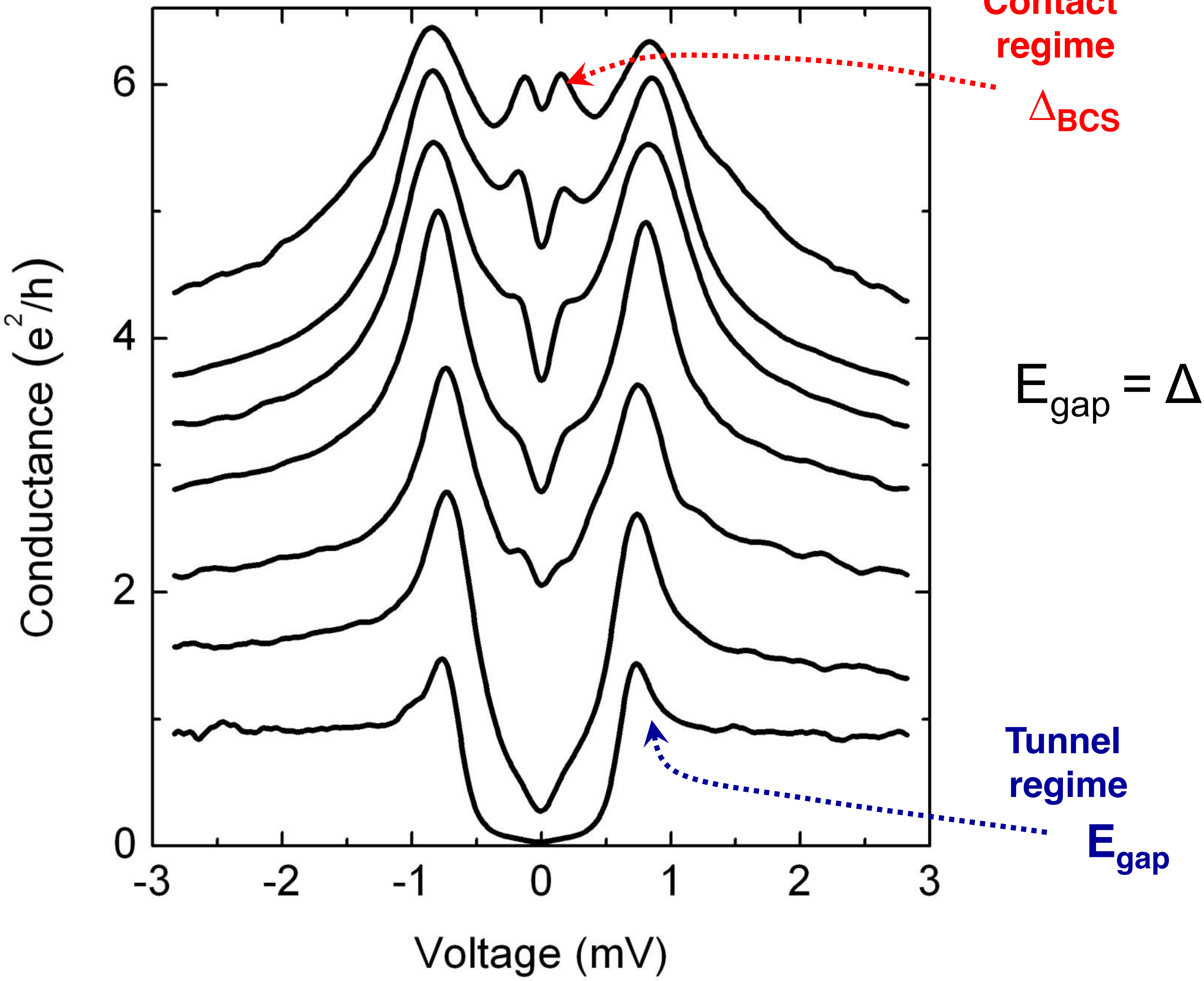
Transmission : $T = 1 / (1+ Z^2)$

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

Point contact spectroscopy on InOx
Far from SIT (R = 600Ω, Tc = 3K)



From tunnel to contact in a-InOx



Contact regime

Δ_{BCS}

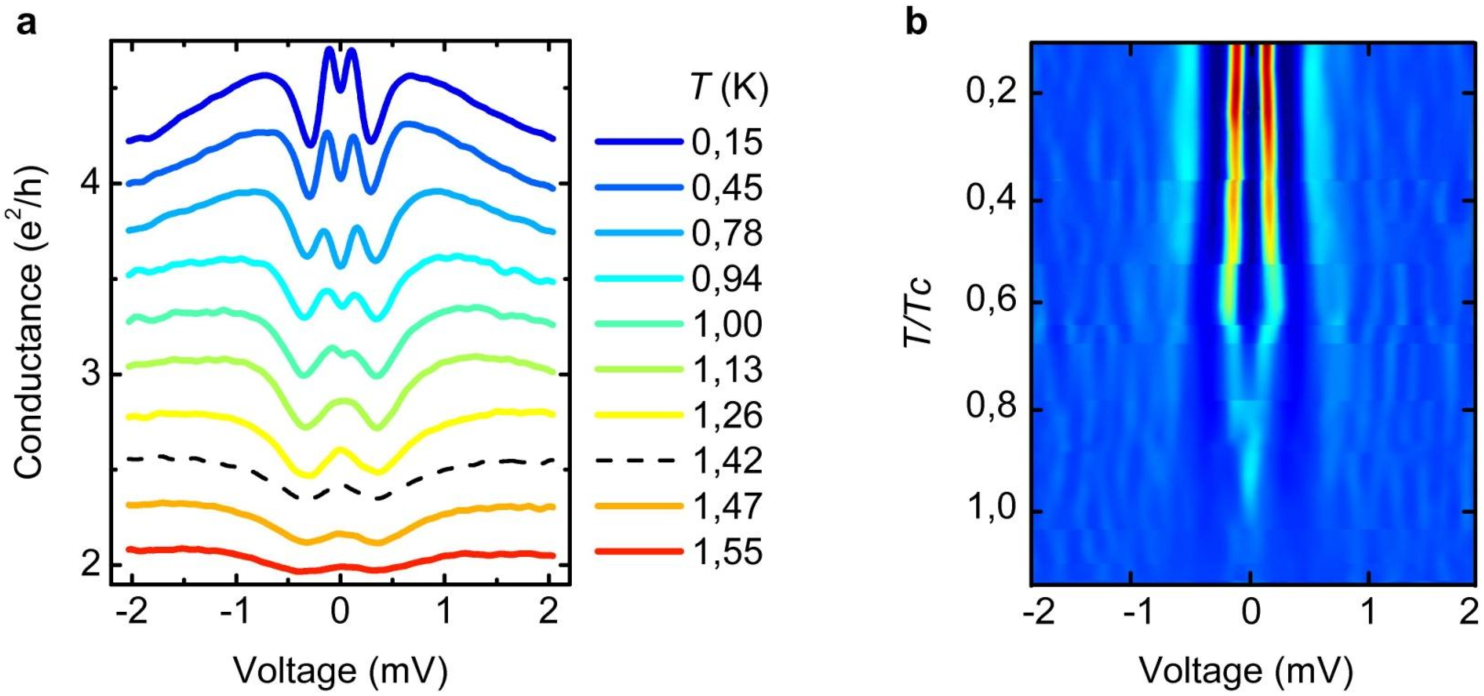
$$E_{gap} = \Delta_p + \Delta_{BCS}$$

Tunnel regime

E_{gap}

Andreev signal : evolution with *T*

T-evolution of Andreev signal



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

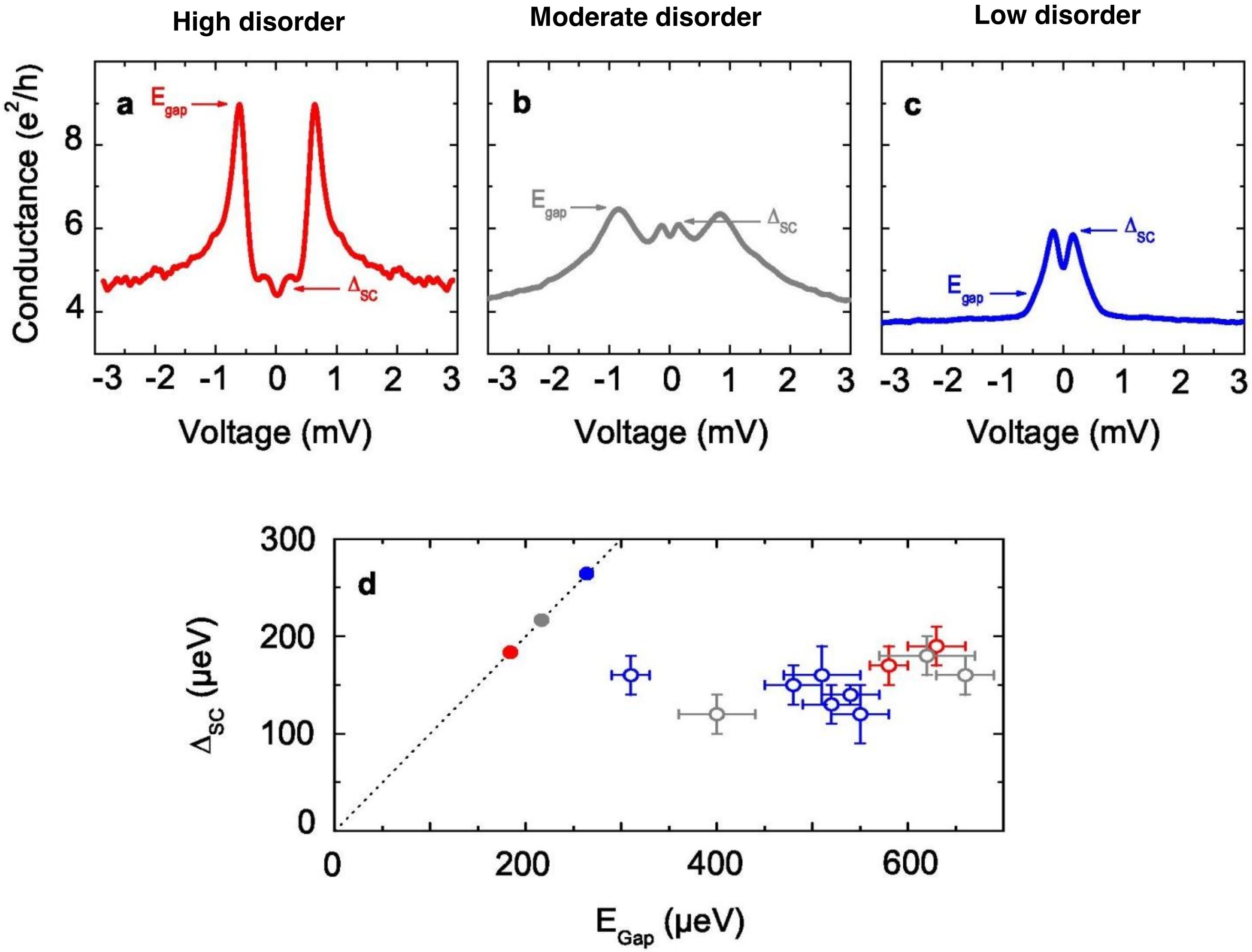
. E_{gap} evolves between 0 and ~3-4T_c

. Δ_{BCS} evolves between 0 and ~ T_c

- ➢ **E_{gap} and Δ_{BCS} evolve on distinct temperature range**
- ➢ **Δ_{BCS} : local signature of SC phase coherence**

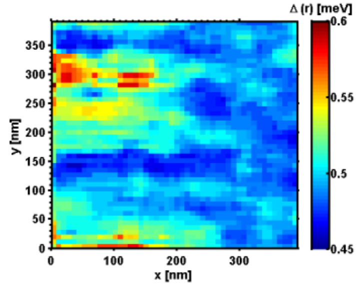
Distinct energy scales for pairing and coherence

Disorder-dependence of Andreev signal

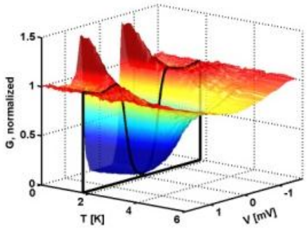


Conclusion : Fluctuation and localization of preformed Cooper pairs in InO$_x$

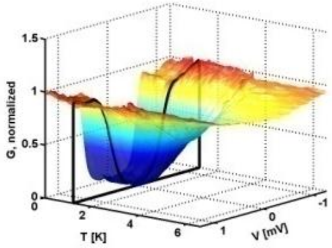
- **Inhomogeneous superconducting state at T<Tc**



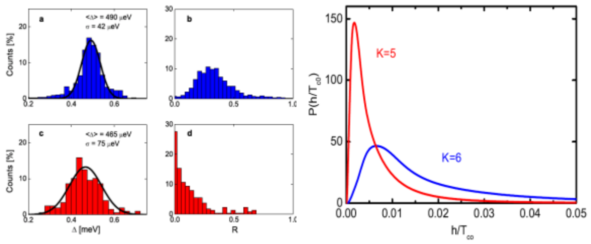
- **Preformed Cooper-Pairs above Tc**



- **The lack of coherence peaks at T<< Tc is the signature of localization**



- **SIT occurs through the localization of Cooper-pairs**



- **Distinct energy scales for pairing and coherence**