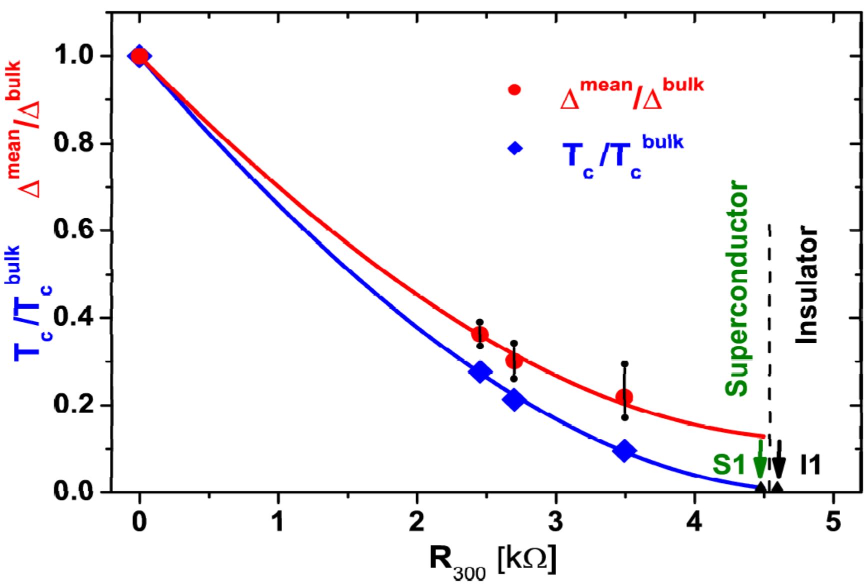
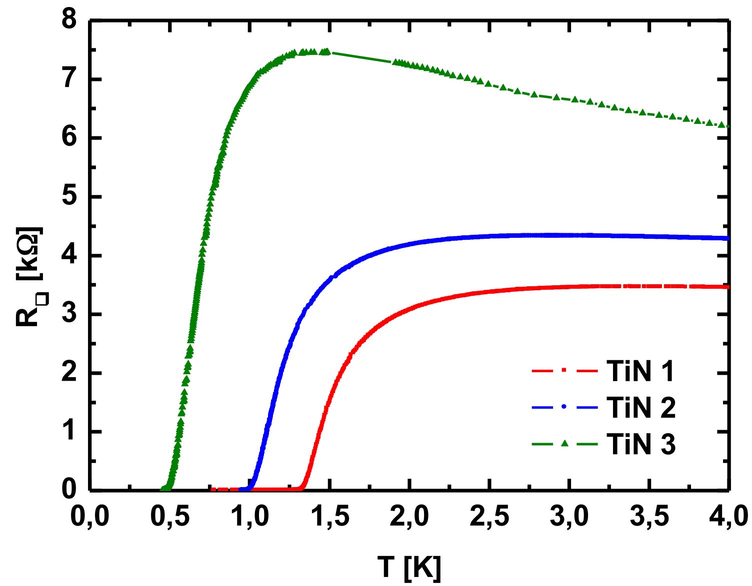
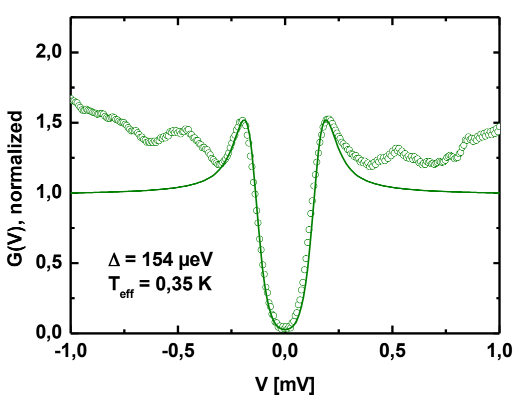
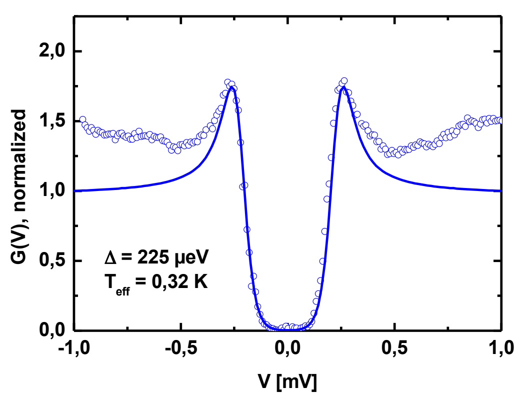
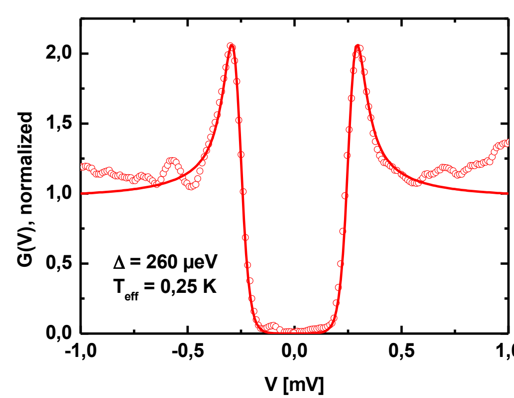
TIN Superconductor-Insulator transition







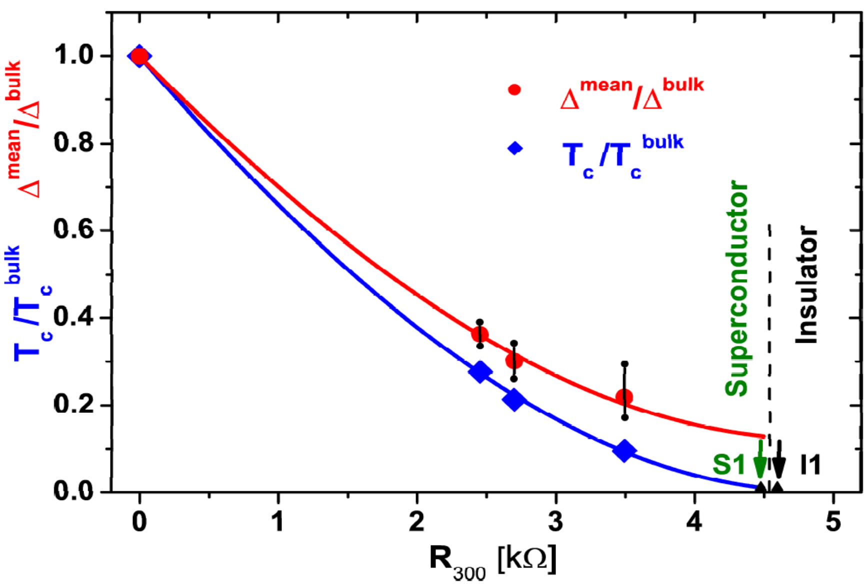


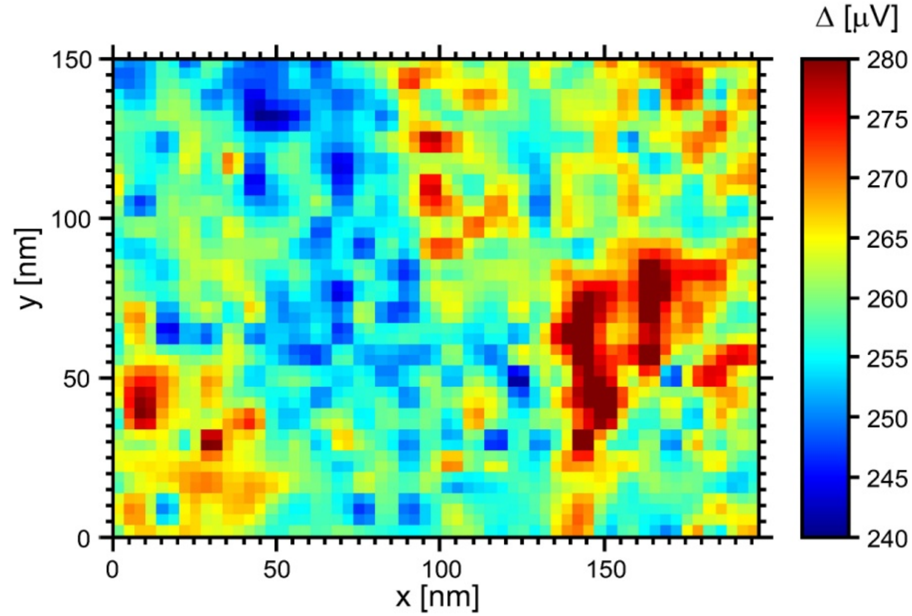


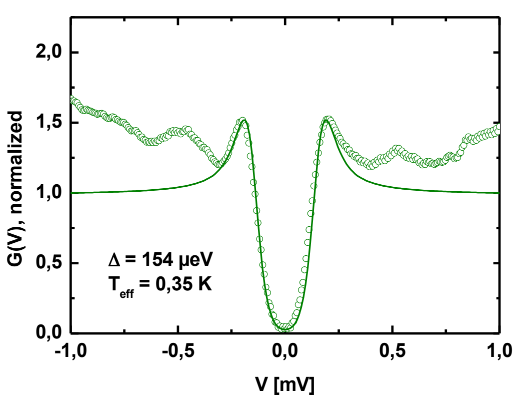
Increasing disorder

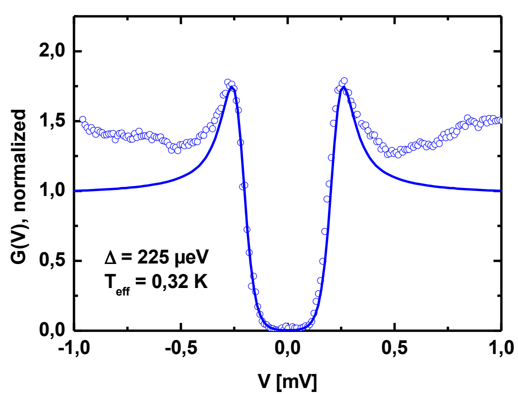
Sacépé et al., *PRL* ***101****, 157006 (2008)*

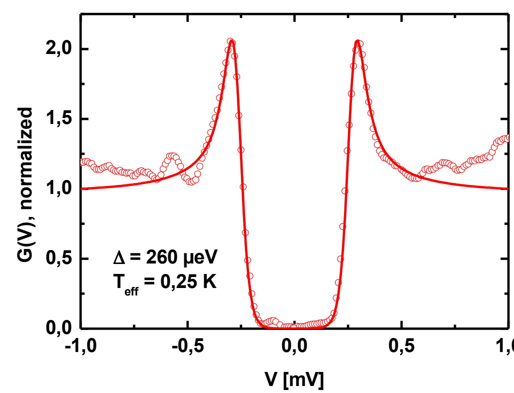
TIN Superconductor-Insulator transition











Increasing disorder

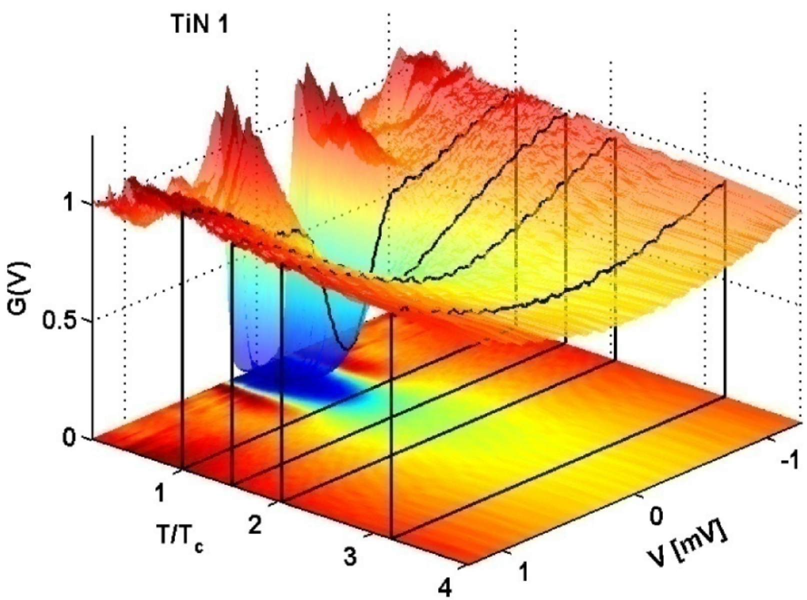
Sacépé et al., *PRL* ***101****, 157006 (2008)*

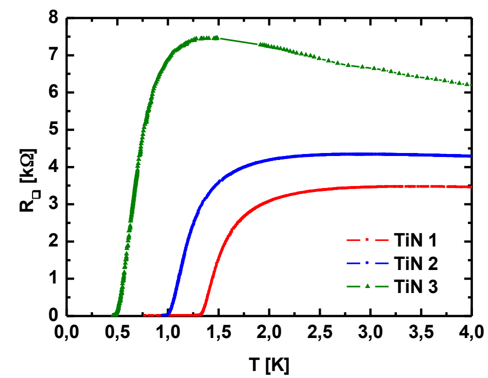
Pseudogap

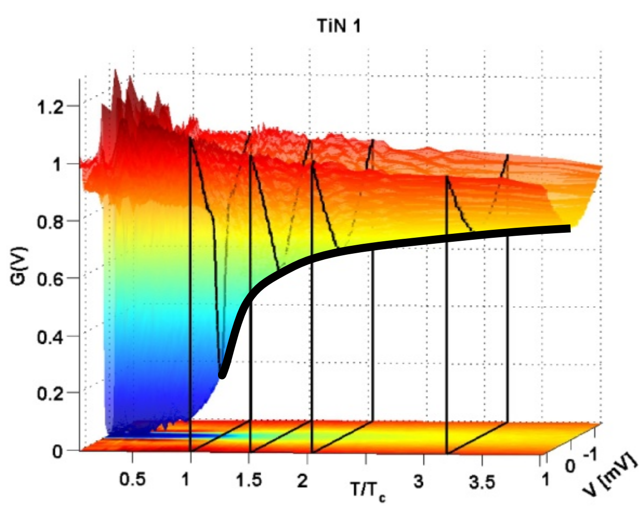
Superconducting fluctuations correction to the DOS

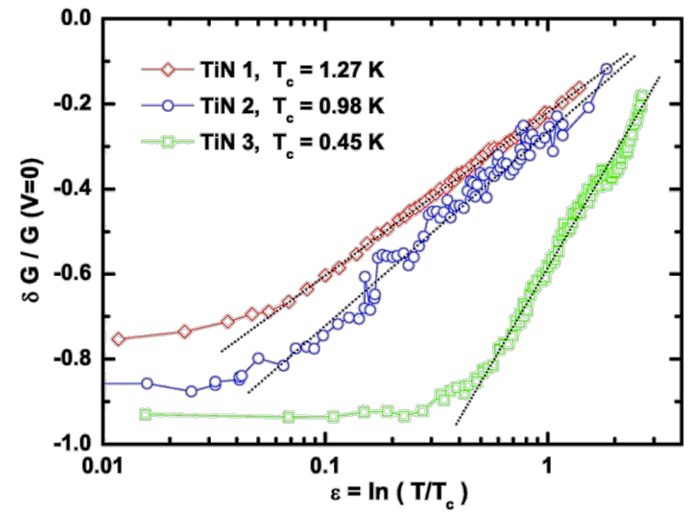
Preformed Cooper pairs above Tc

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









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

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

Localization of preformed Cooper pairs in highly disordered superconducting films

Thomas Dubouchet, Benjamin Sacépé, Marc Sanquer, Claude Chapelier
INAC-SPSMS-LaTEQS, CEA-Grenoble

T. Baturina, *Institute of semiconductor Physics - Novosibirsk*

V. Vinokur, *Material Science Division, Argonne National Laboratory - Argonne*

M. Baklanov, A Satta, *IMEC - Leuven*

Maoz Ovadia, Dan Shahar, *The Weizmann Institute of Science*

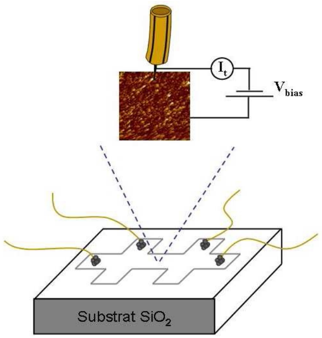
Mikhail Feigel'man, *L. D. Landau Institute for Theoretical Physics*

Lev Ioffe, *Serin Physics laboratory, Rutgers University*

INSTITUT NANOSCIENCES ET CRYOGÉNIE

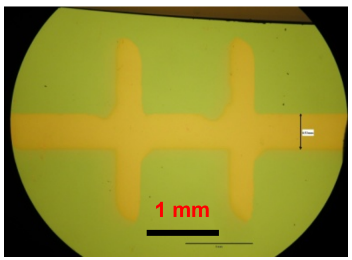
InOx

Amorphous Indium Oxide

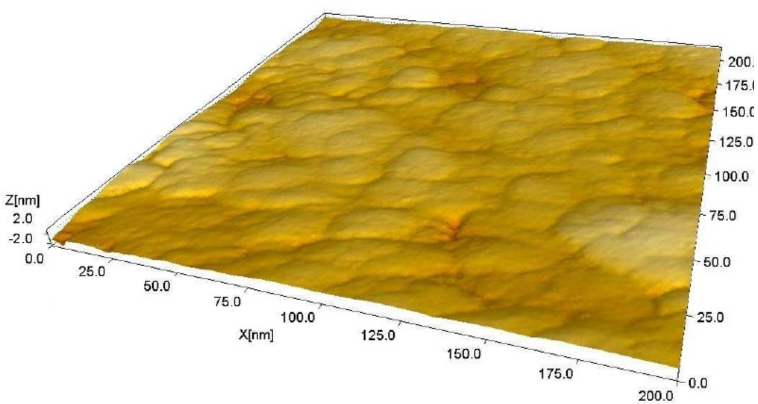


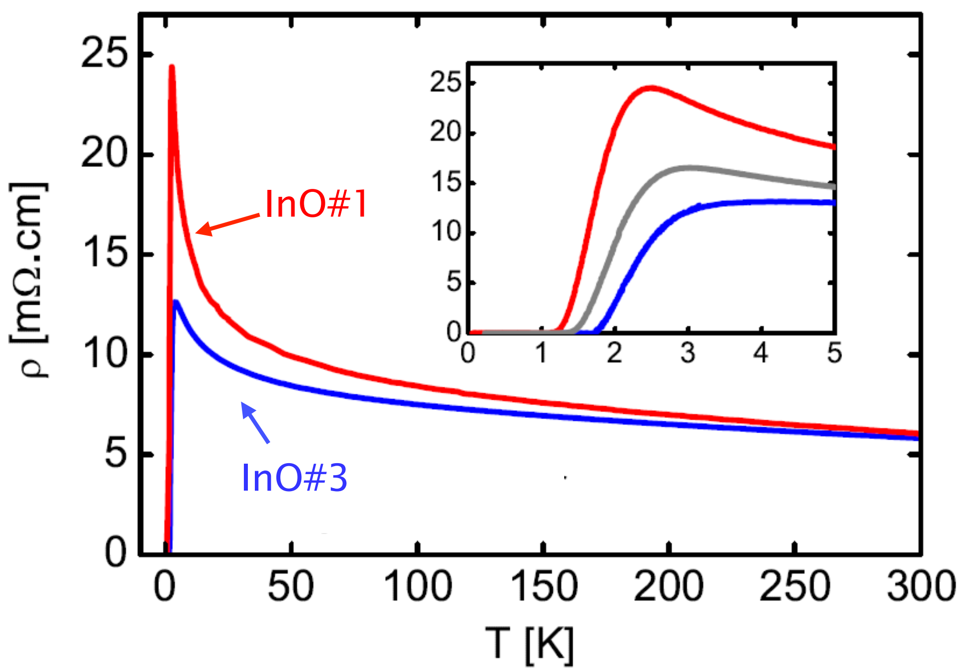
<u>Samples</u>: e-gun evaporation of high purity In_2O_3 onto Si/SiO_2 substrate under O_2 pressure

D. Shahar, Weizmann Institute of Science



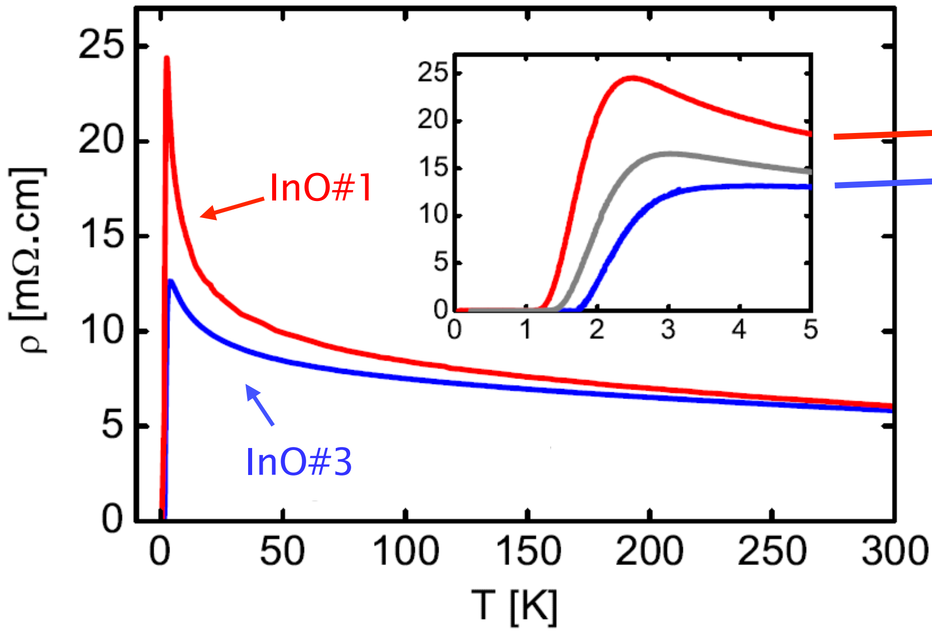
Thickness : 15 nm (red & grey) and 30 nm (blue) – 3D regime

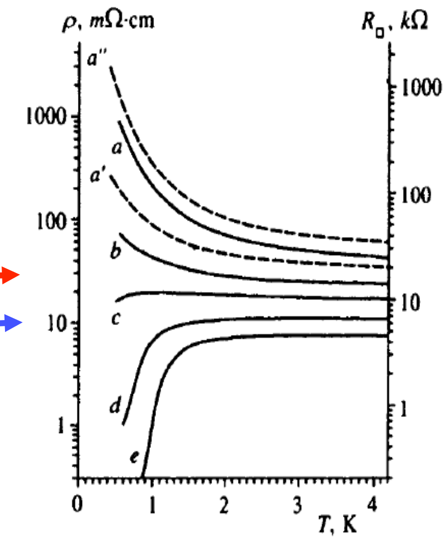




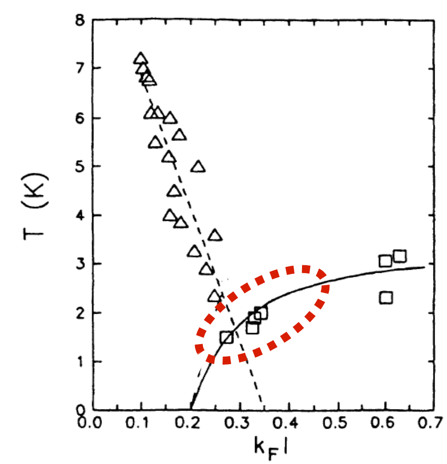
Nearly critical samples

High disorder (red) and low disorder (bleu)





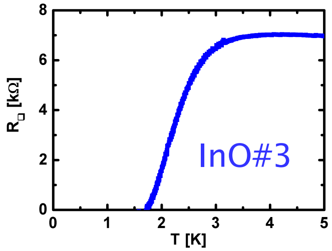
V. F. Gantmakher *et al.*, *JETP* ***82***, 951 (1996)



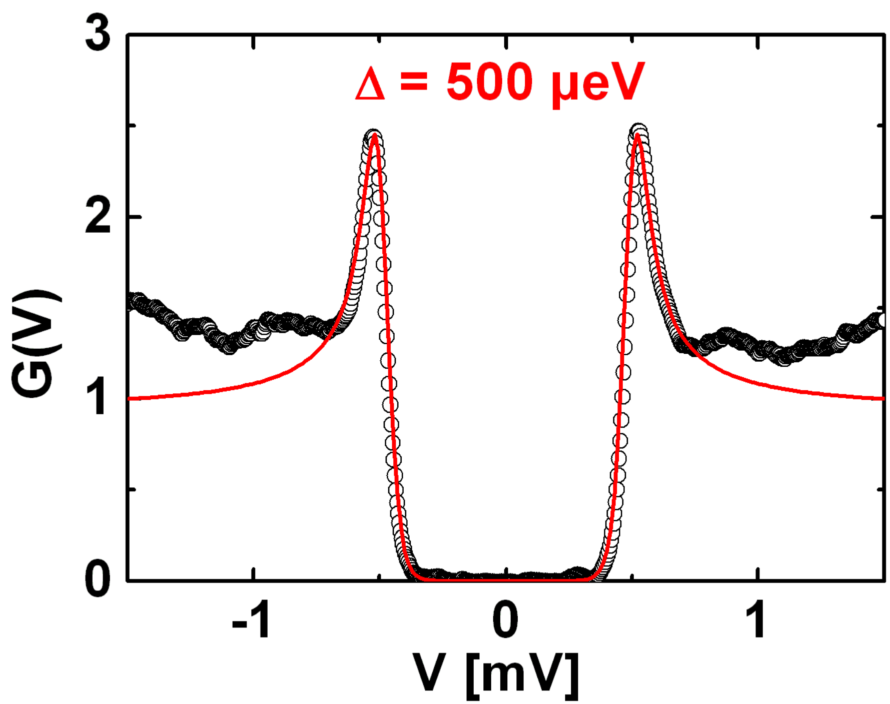
D. Shahar and Z. Ovadyahu, *Phys. Rev. B* ***46***, 10917 (1992)

- **$k_F l_e$ ~ 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}



Typical spectrum measured at 50 mK

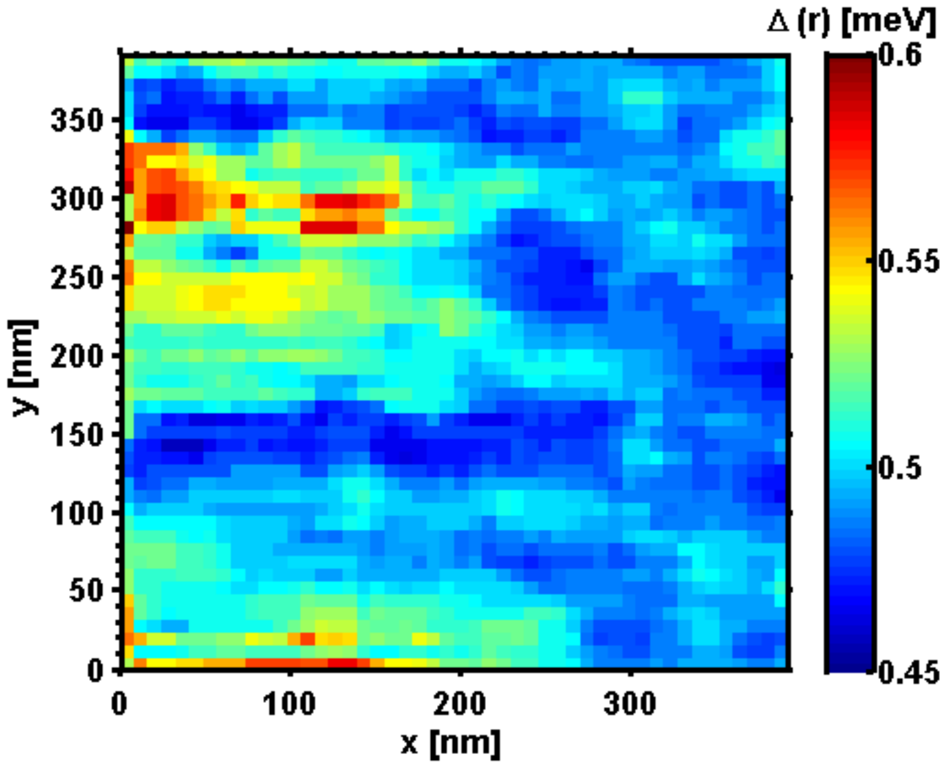


Fit : *s*-wave BCS density of states

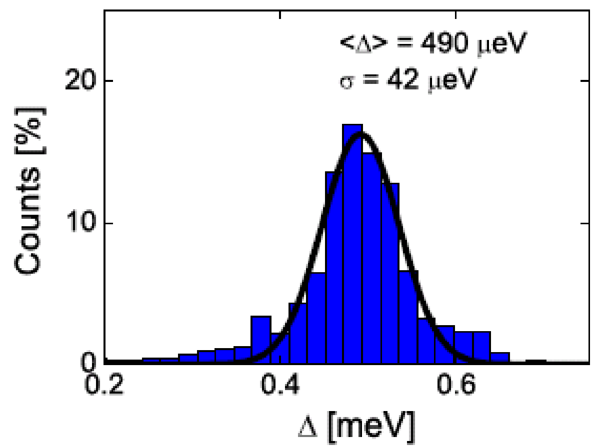
- Absence of quasi-particle excitations at low energies

Spatial fluctuations of the spectral gap Δ(r)

Map of the spectral gap



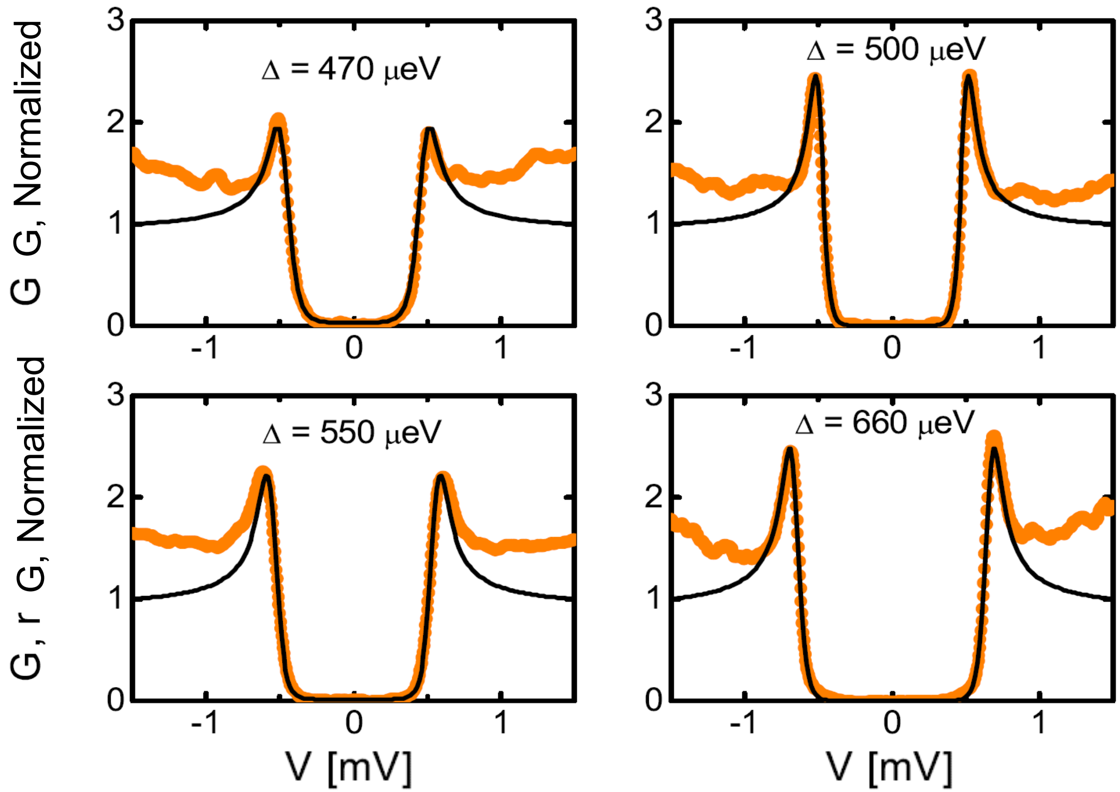
InO#3



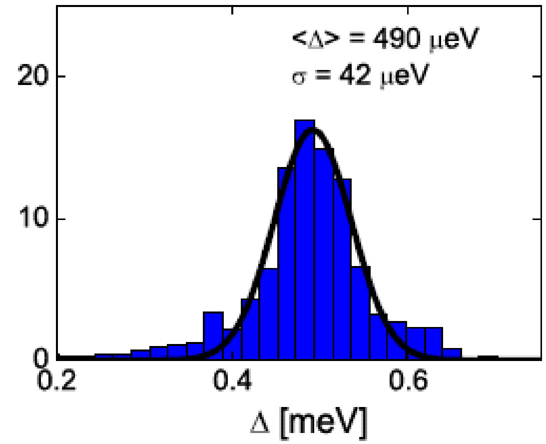
Gaussian distribution

Spatial fluctuations of the spectral gap Δ(r)

Spectra measured at different locations (T=50mK)

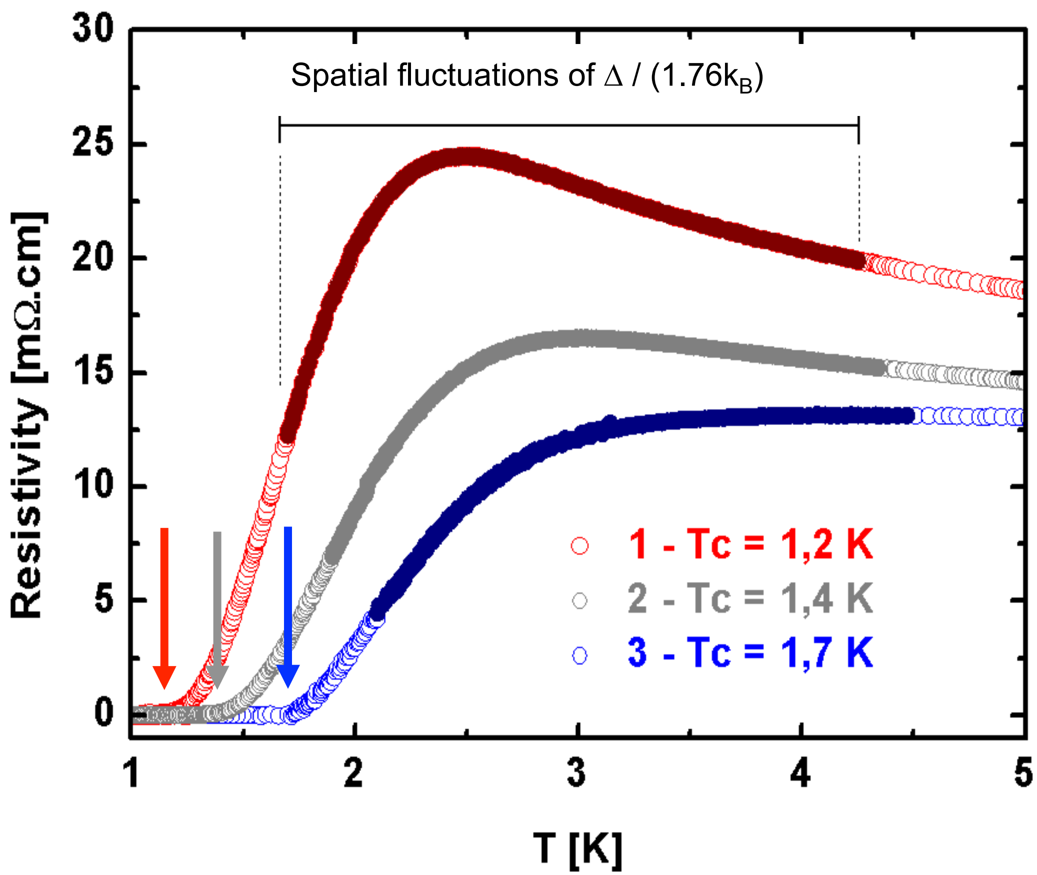


InO#3



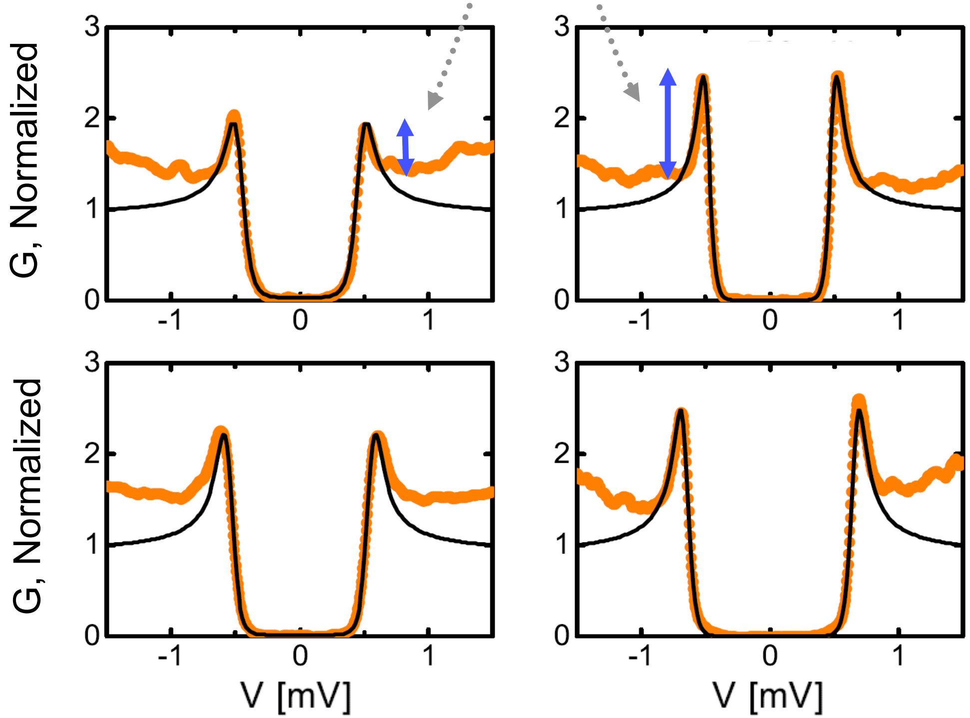
Gaussian distribution

Fluctuations of Δ(r) and superconducting transition

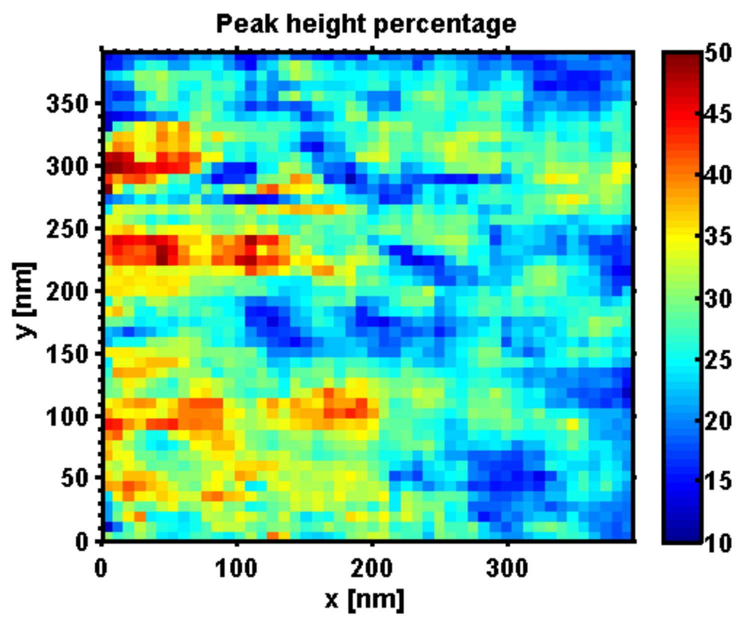


$$3 \leq \frac{\Delta(r)}{k_B T_C} \leq 5.5$$

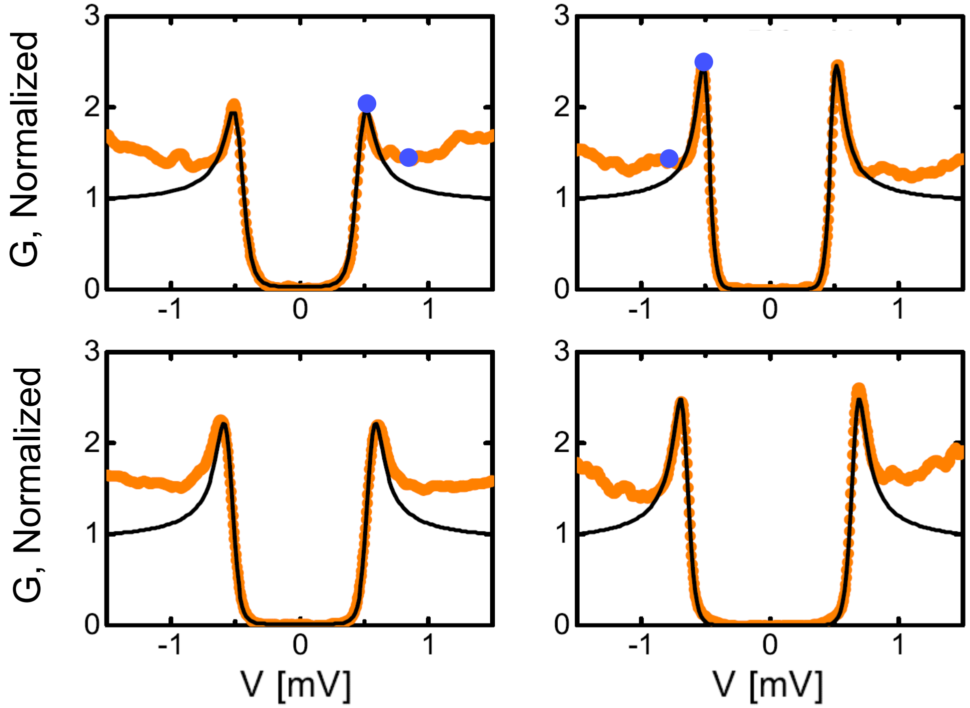
Spatial fluctuations of the coherence peaks height



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

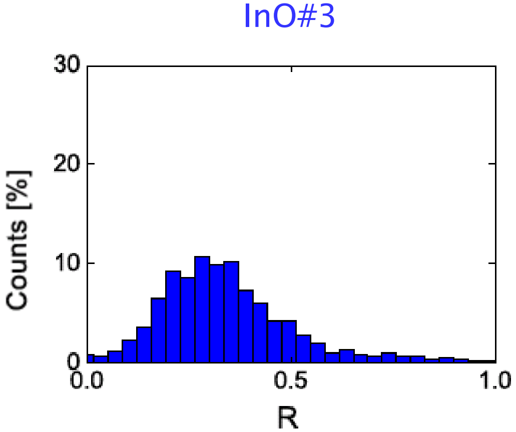


Spatial fluctuations of the coherence peaks height

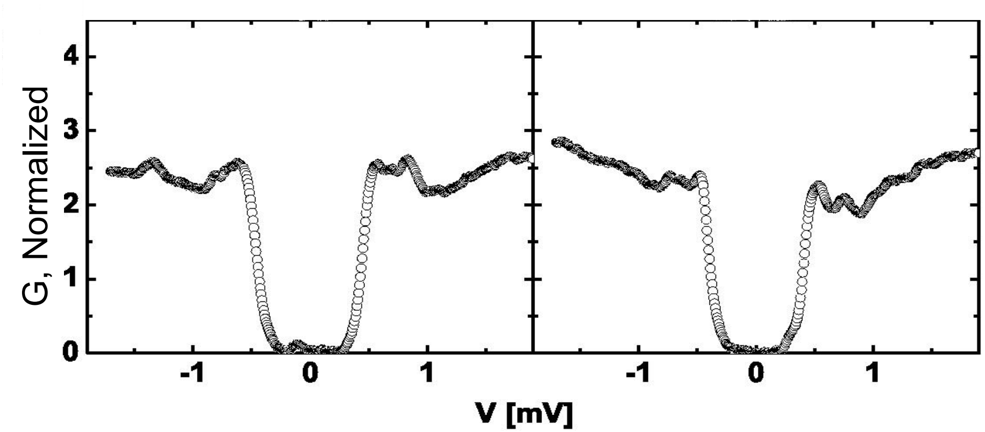


Statistical study

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



Full spectral gap without coherence peaks



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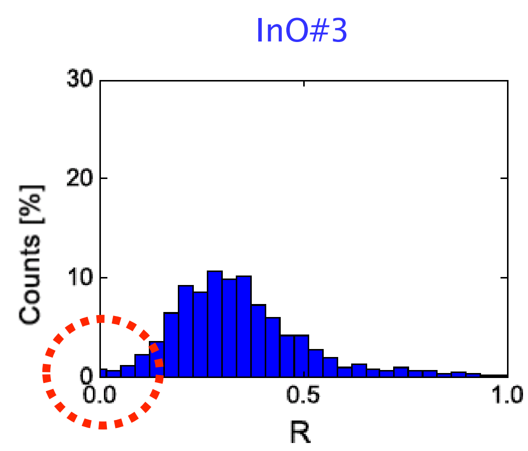

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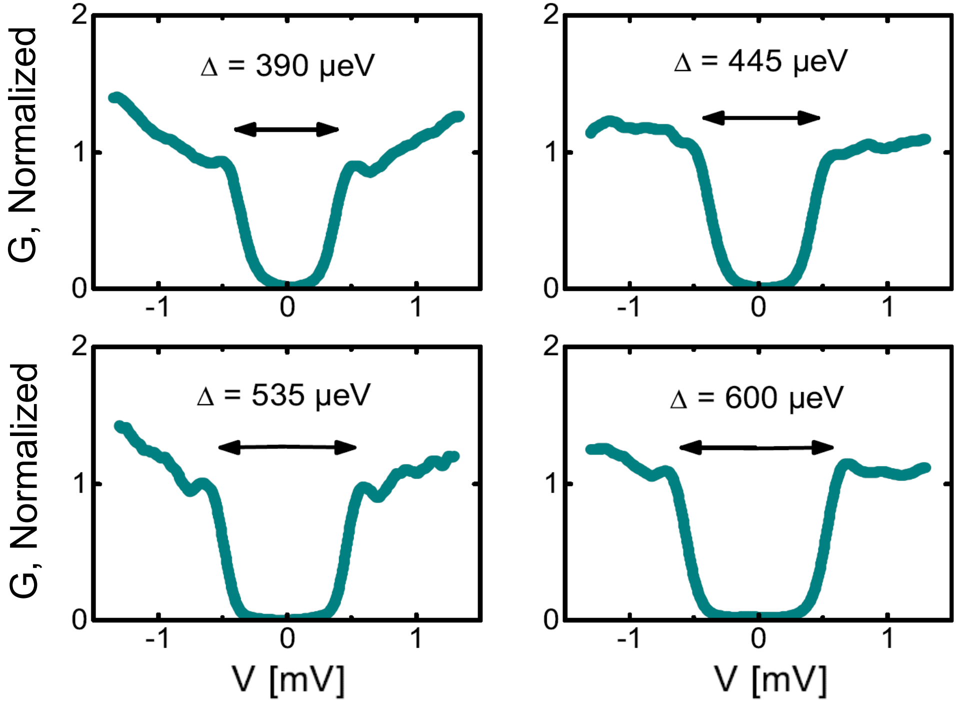

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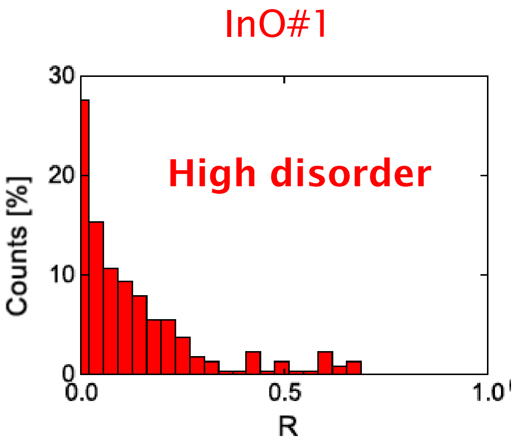
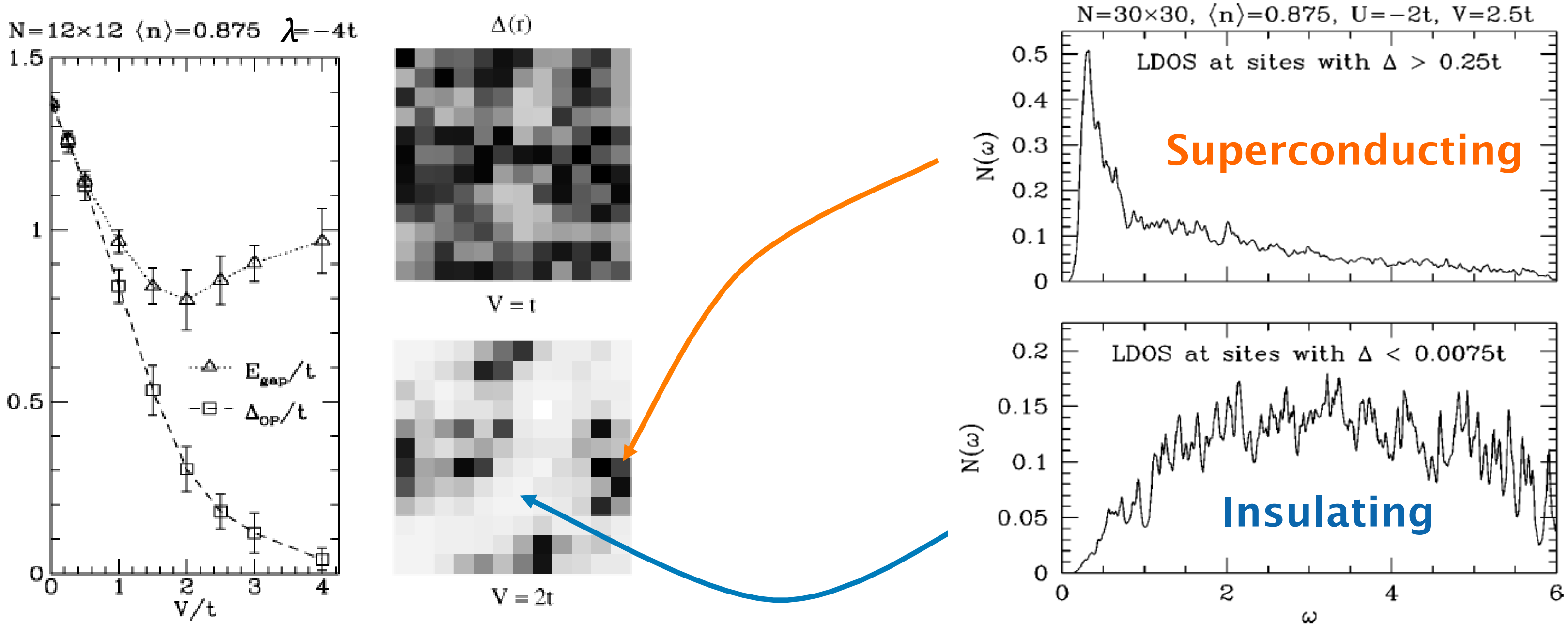


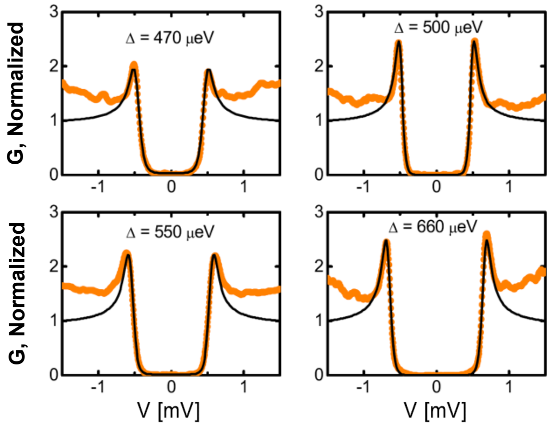
Signature of localized Cooper pairs

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

$$H_0 = -t \sum_{<i,j>,\sigma} \left(c^+_{i\sigma} c_{j\sigma} + h.c.\right) + \sum_{i,\sigma} \left(V_i - \mu\right) n_{i,\sigma} \qquad H_{\text{int}} = -\lambda \sum_i n_{i\uparrow} n_{i\downarrow}$$

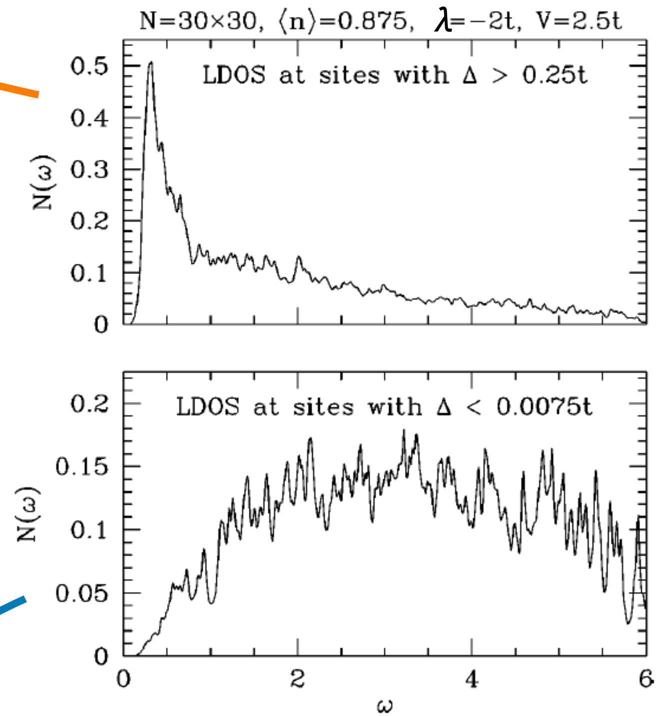


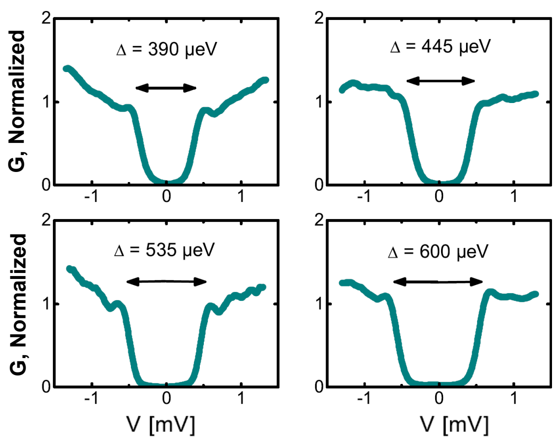
Signature of localized Cooper pairs



Superconducting gap Δ

⇒ delocalized Cooper pairs





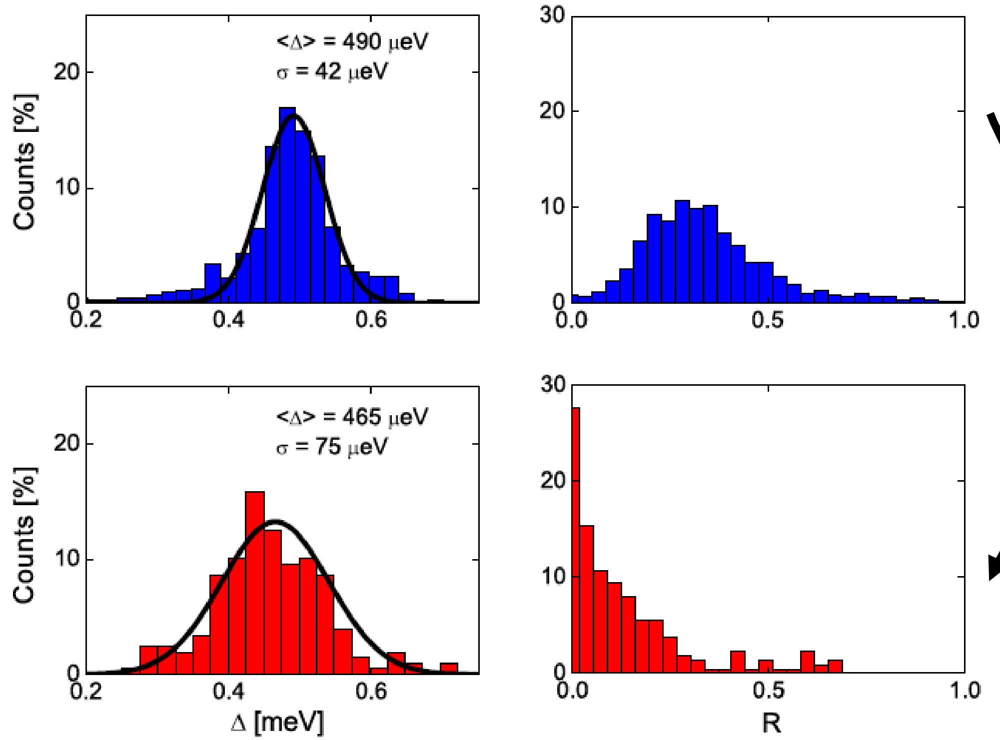
« Insulating » gap E_{gap}

⇒ Localized Cooper pairs

Proliferation of incoherent spectra at the superconductor-insulator transition

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

InO#3
T_c ~ 1.7 K



resistivity × 2

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

InO#1
T_c ~ 1.2 K

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

➢ **Proliferation of spectra without coherence peaks**

Proliferation of incoherent spectra at the superconductor-insulator transition

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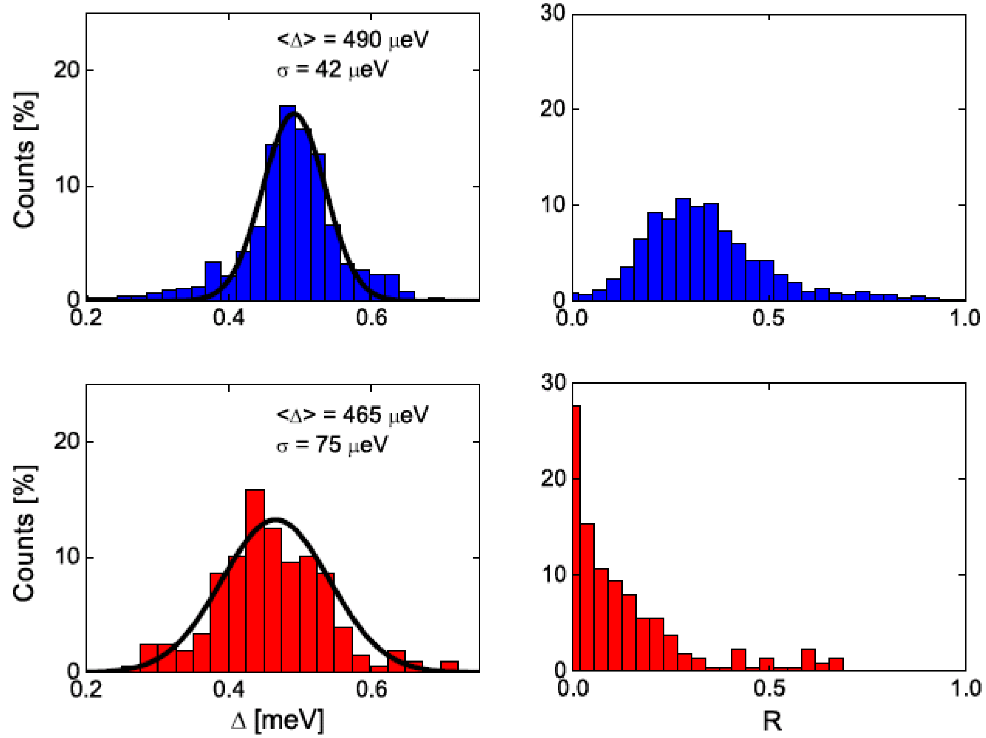

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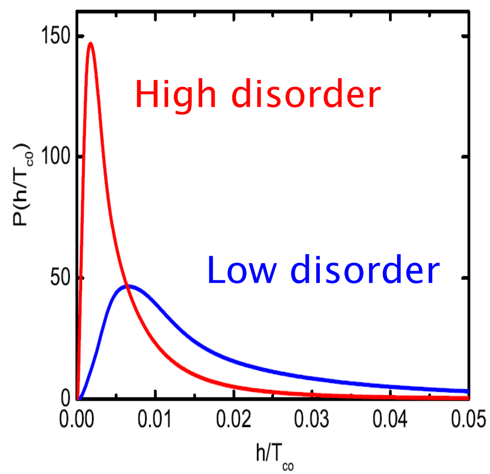
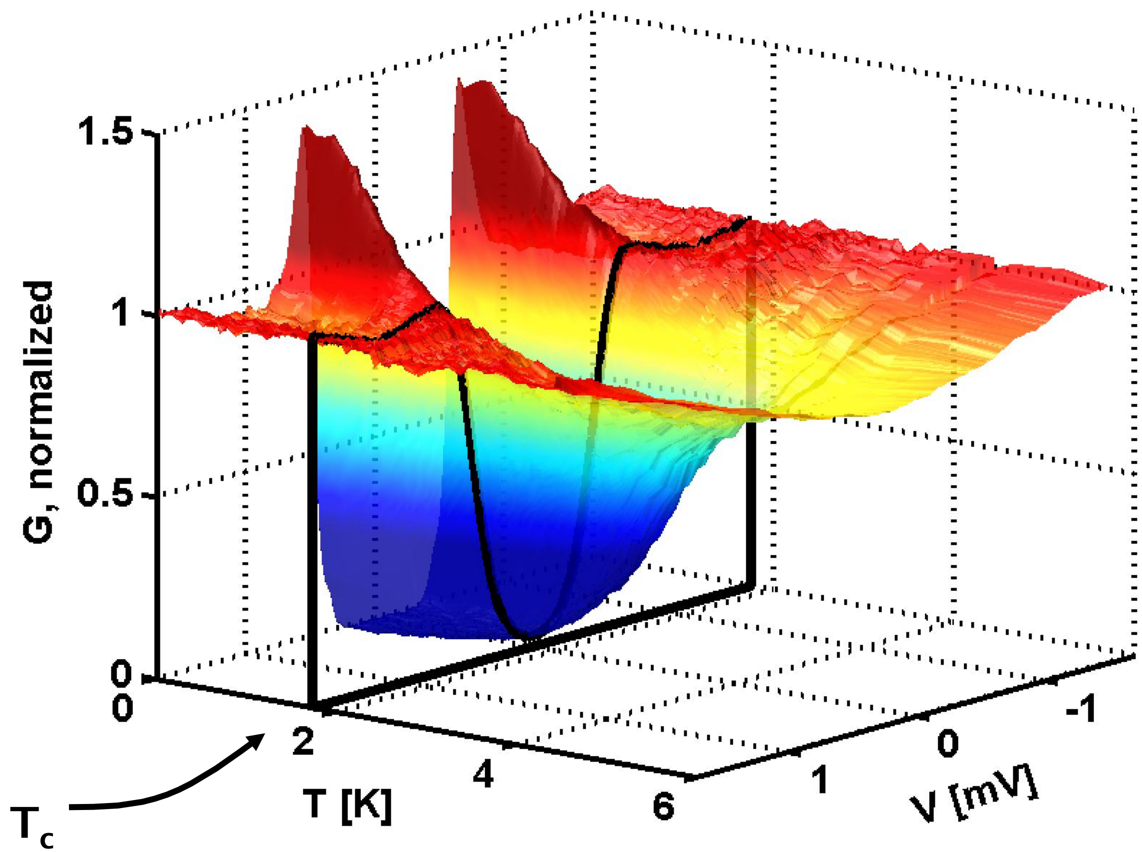
B. Sacépé, et al., *Nature Physics (2011)*

- **Proliferation of spectra without coherence peaks**

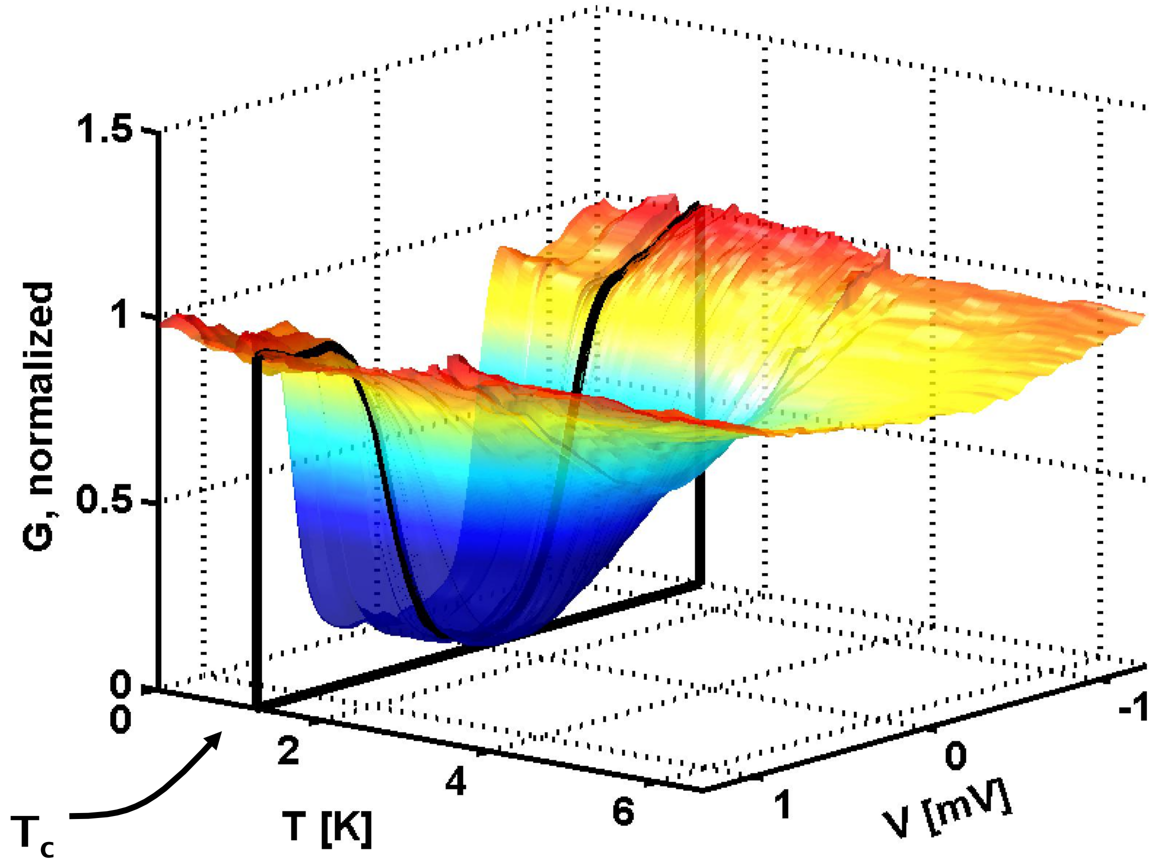


M. Feigel'man *et al.*, *Phys. Rev. Lett.* ***98***, 027001 (2007) ; *Ann.Phys.* **325**, 1390 (2010)

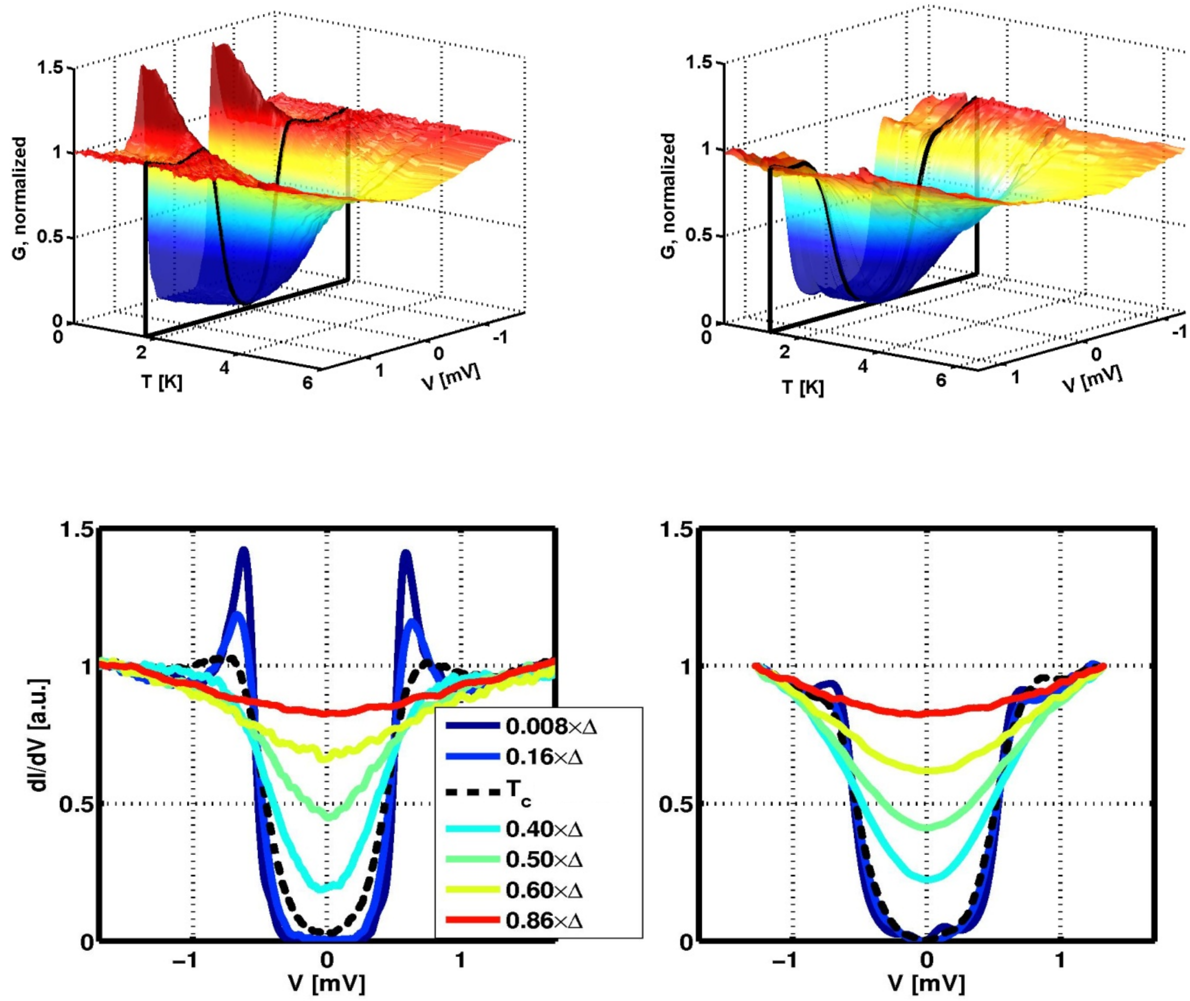
Pseudogap state above Tc

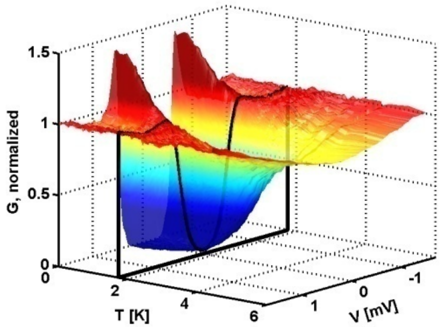


Pseudogap state above Tc

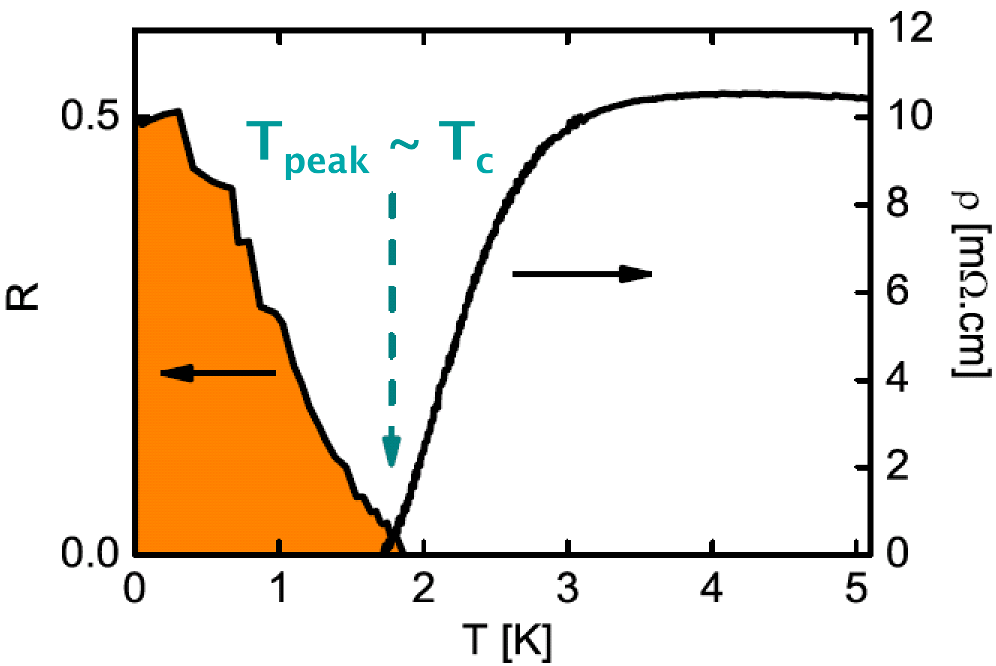


Pseudogap state above Tc

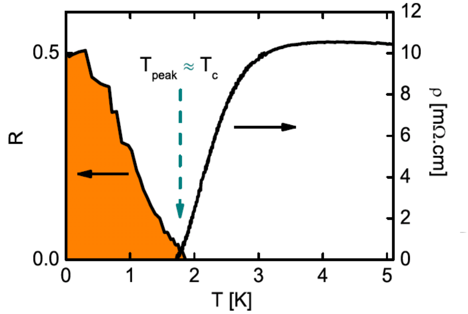




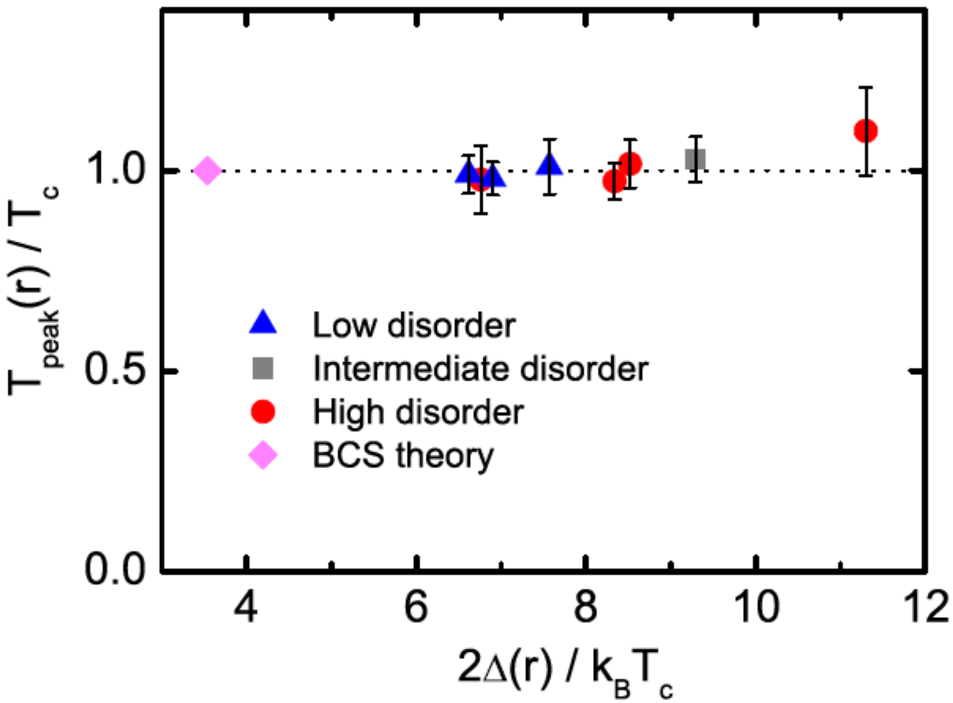
Macroscopic quantum phase coherence probed at a local scale



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



Macroscopic quantum phase coherence probed at a local scale



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

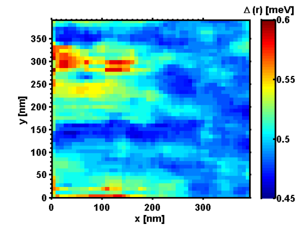
Signatures of the localization of Cooper pairs

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

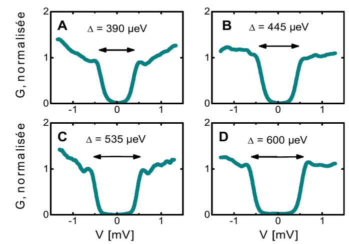
K. Bouadim, Y. L. Loh, M. Randeria, N. Trivedi, *Nature Physics* (2011)

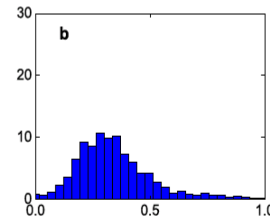
M. Feigel'man *et al.*, *Phys. Rev. Lett.* ***98***, 027001 (2007) ; *Ann.Phys.* **325**, 1390 (2010)

- Spatial fluctuations of the spectral gap

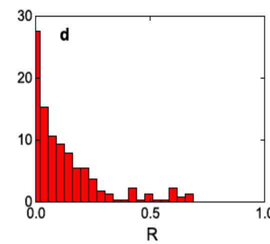


- rectangular-shaped" gap at $T \ll T_c$

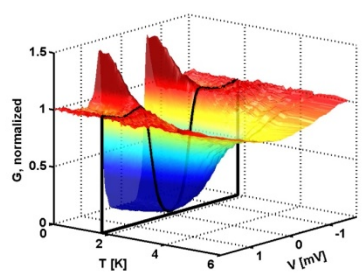


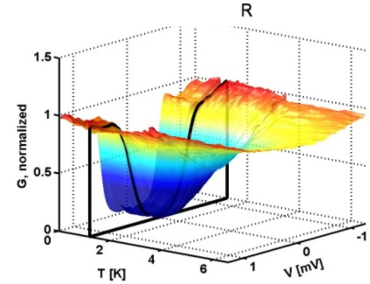


- Statistic distribution of coherence peaks height



- Pseudogap regime above T_c





- Anomalously large spectral gap $6 \leq \dfrac{2E_{gap}(r)}{k_B T_C} \leq 11$

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

⇨ $E_{gap} = \Delta_p + \Delta_{BCS}$

- 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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- 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

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

Δ_{BCS} → "BCS gap"

Δ_p → "parity gap"

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

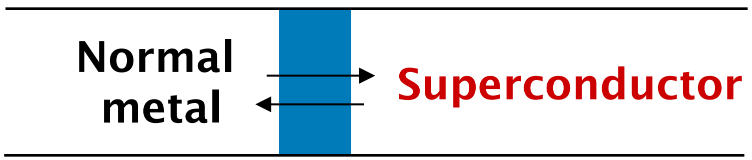
$E_{gap} = \Delta_p + \Delta_{BCS}$ (with Δ_p crossed out)

Δ_{BCS} → "BCS gap"

Conductance of a N/S contact

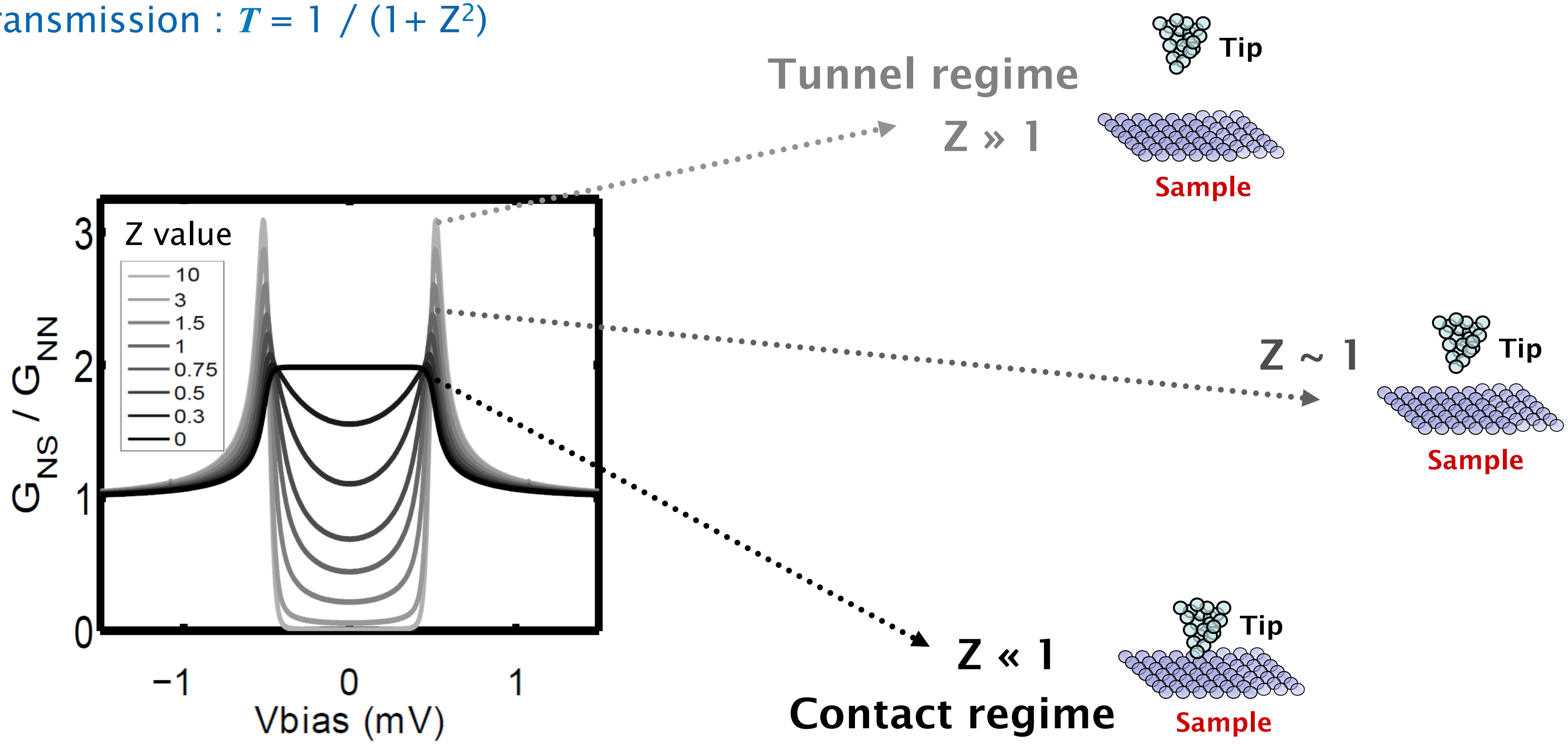
Blonder, G. E., Tinkham, M., and Klapwijk T.M. *Phys. Rev. B* ***25***, 7 4515 (1982)

Barrier : parameter Z

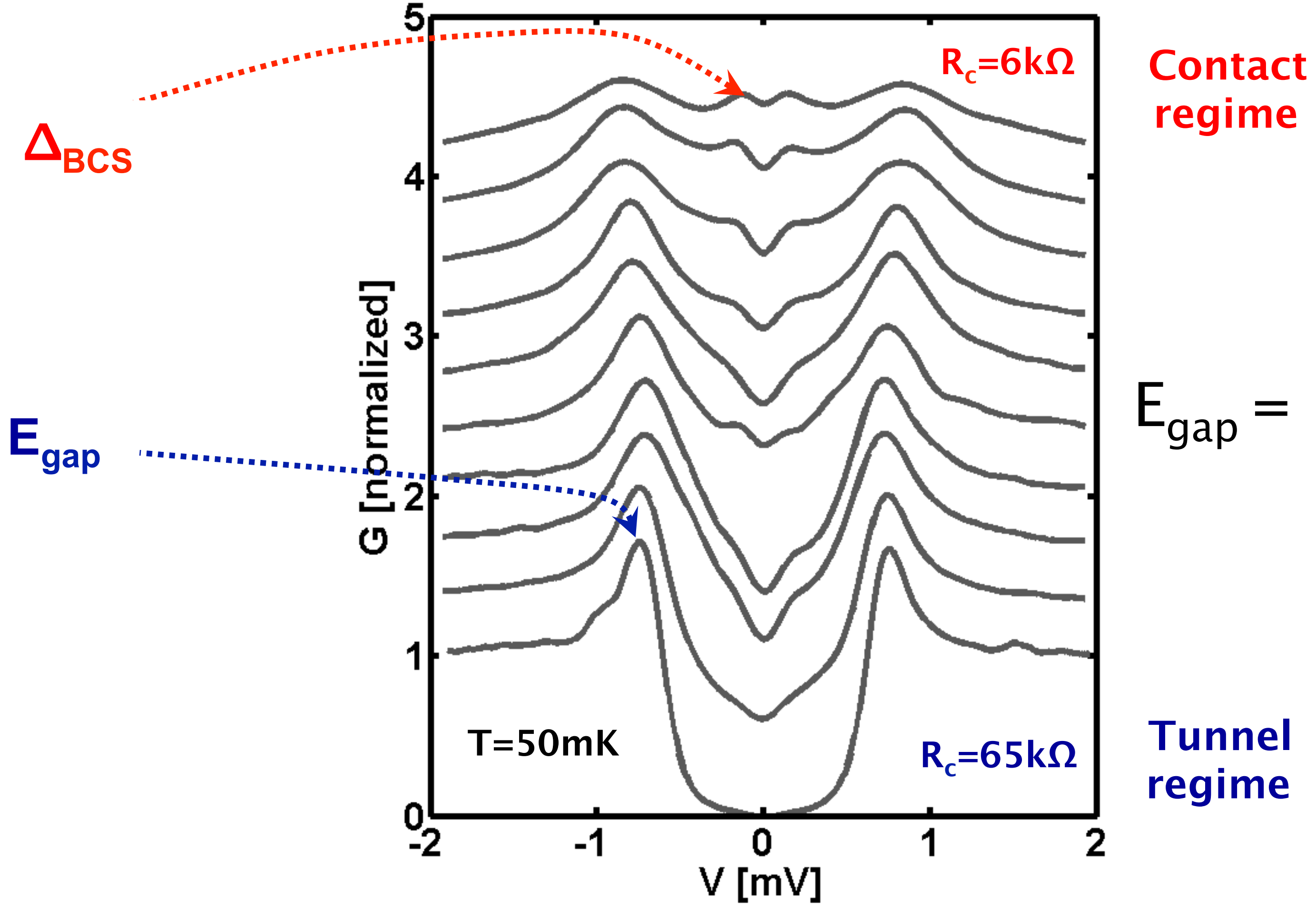


Transmission : $T = 1 / (1 + Z^2)$

- Single-particle transfer $\sim T$
- Two-particles transfer $\sim T^2$

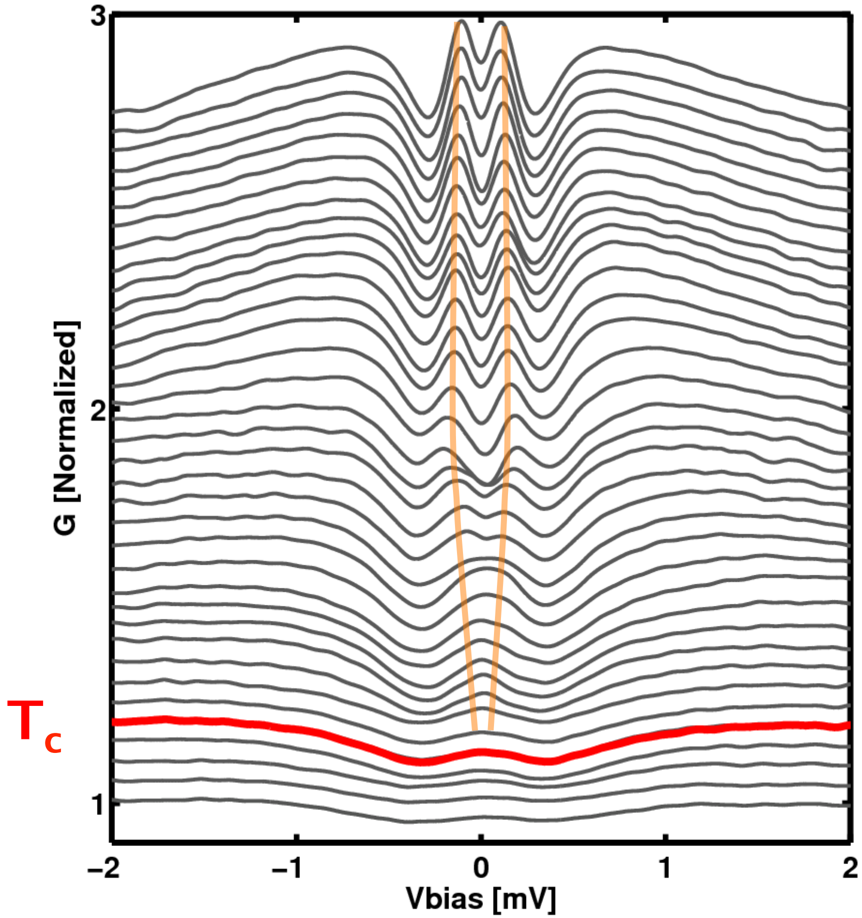


From tunnel to contact in a-InOx



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

T-evolution of Andreev signal



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

. Δ_{BCS} evolves between 0 and ~ T_c

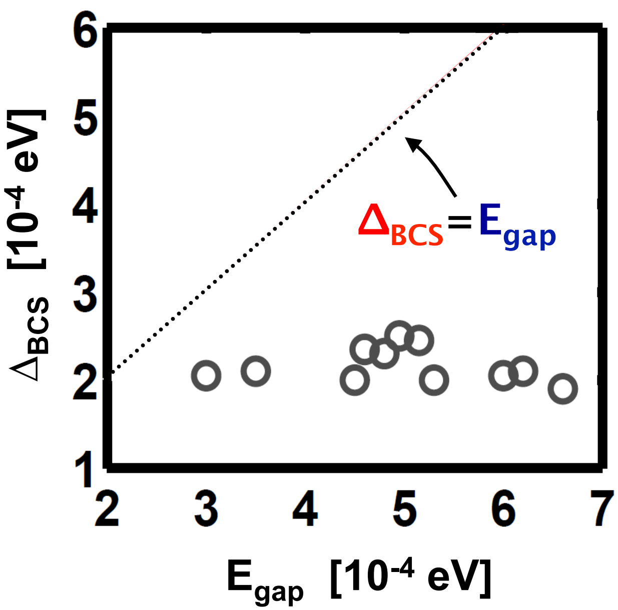
. E_{gap} evolves between 0 and ~3-4T_c

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

Two distinct energy scales in a-InOx

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

11 evolutions on 3 samples

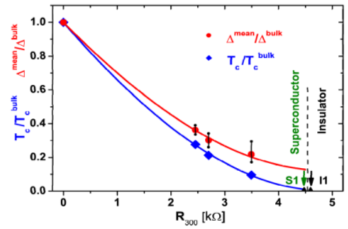


- Δ_{BCS} probed by AR remains uniform
- E_{gap} probed by STS fluctuates

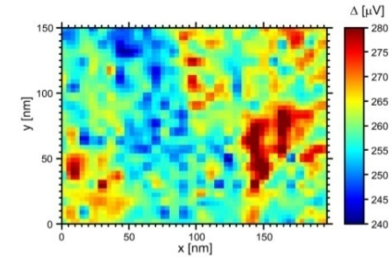
➢ **Distinct energy scales for pairing and coherence in disordered a-InO_x**

Conclusion : Fluctuation and localization of preformed Cooper pairs

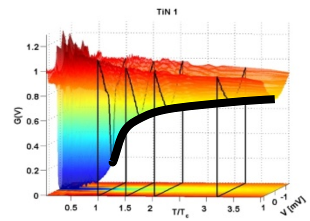
- Homogeneously disordered system with a continuous decrease of Tc

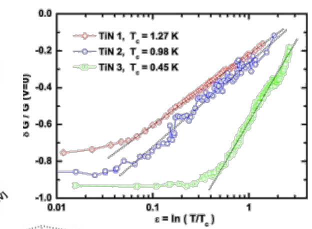


- But inhomogeneous superconducting state at T<Tc

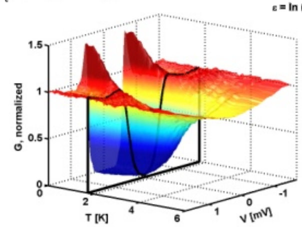


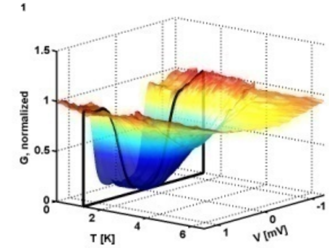
- Fluctuating Cooper-Pairs above Tc



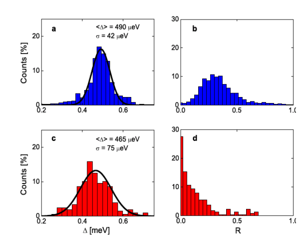


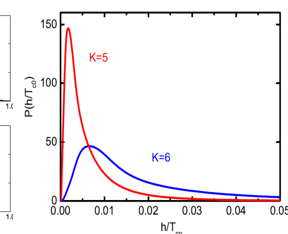
- “Partial” condensation of these preformed pairs below Tc





- SIT occurs through the localization of Cooper-pairs





- Distinct energy scales for pairing and coherence