Spectroscopies and transport measurements in highly disordered superconductors

Claude Chapelier, ***INAC, CEA - Université Grenoble Alpes***
…/…

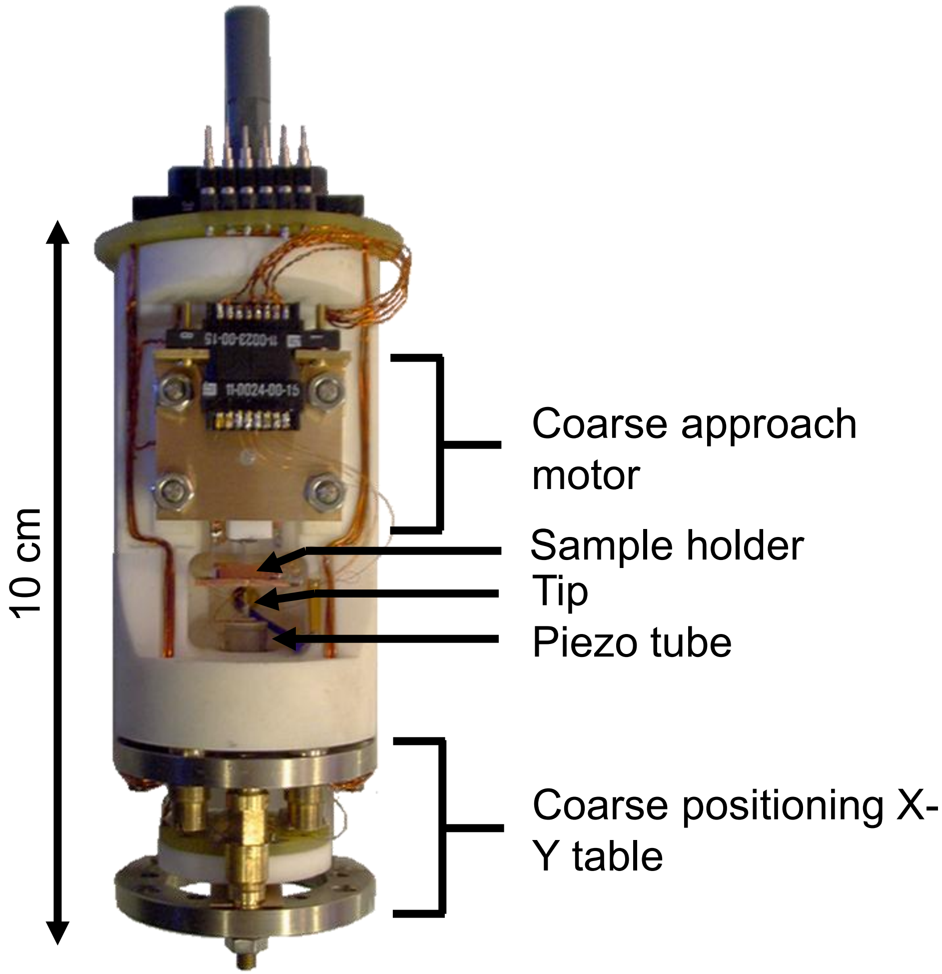
Outline

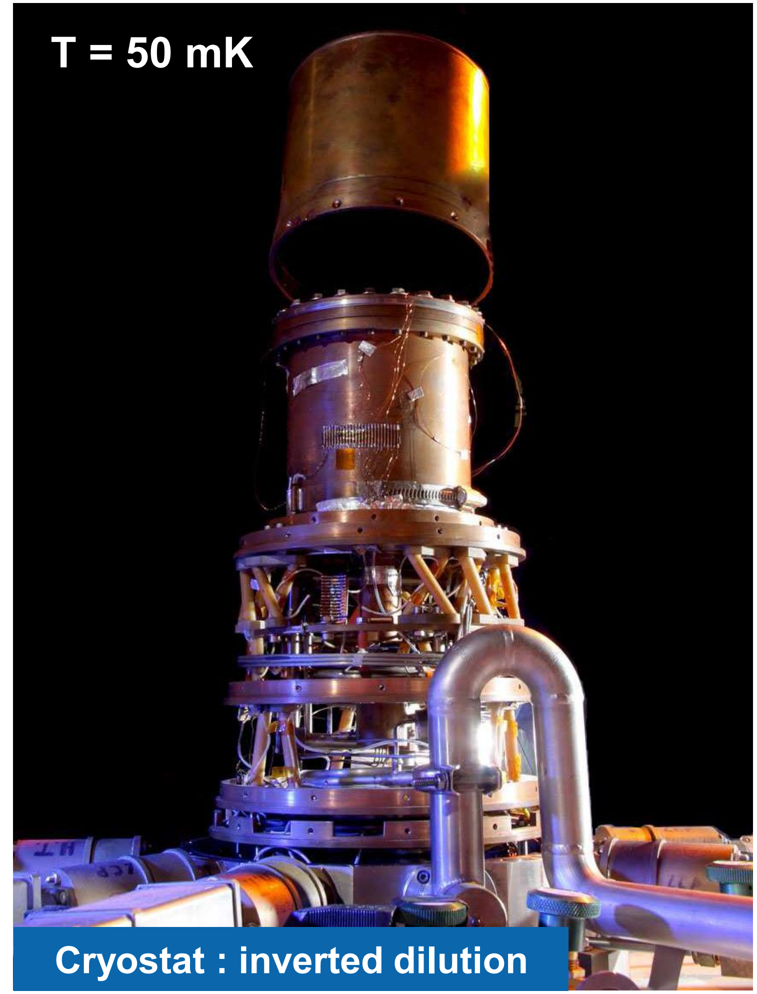
Localization, Interaction, Superconductivity

Université Joseph Fourier GRENOBLE
INSTITUT NANOSCIENCES ET CRYOGÉNIE

Experimental setup

Very-low temperature Scanning Tunneling Microscope



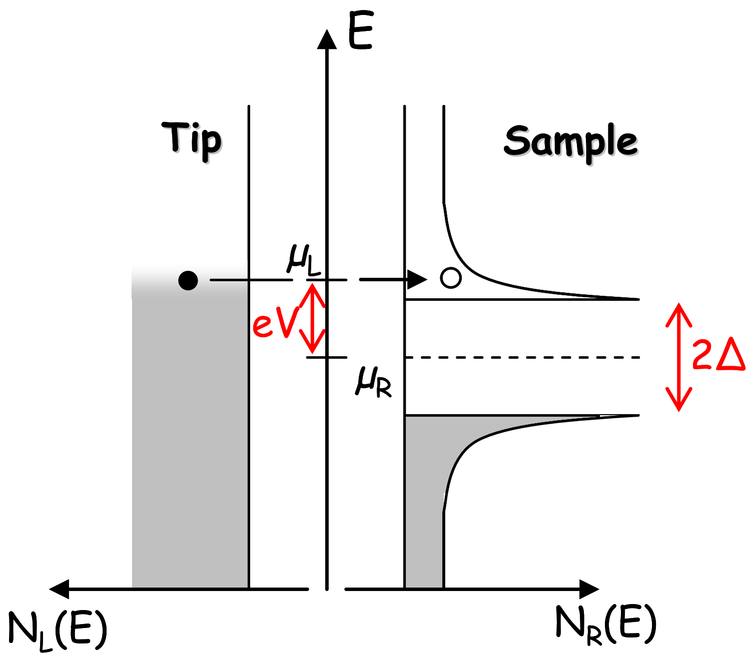


- Combined transport & spectroscopy measurements

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

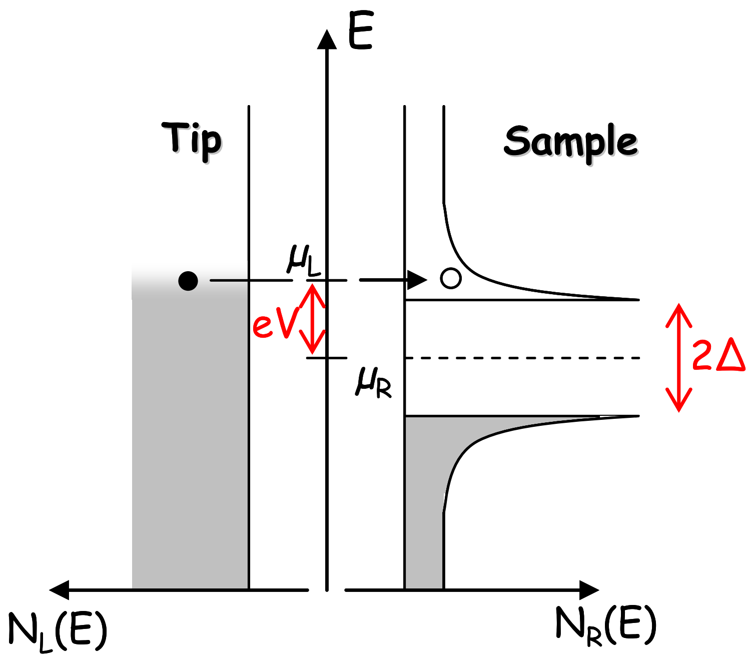
$f_T(\varepsilon)$: Fermi-Dirac distribution

$\Delta(T)$: superconducting gap

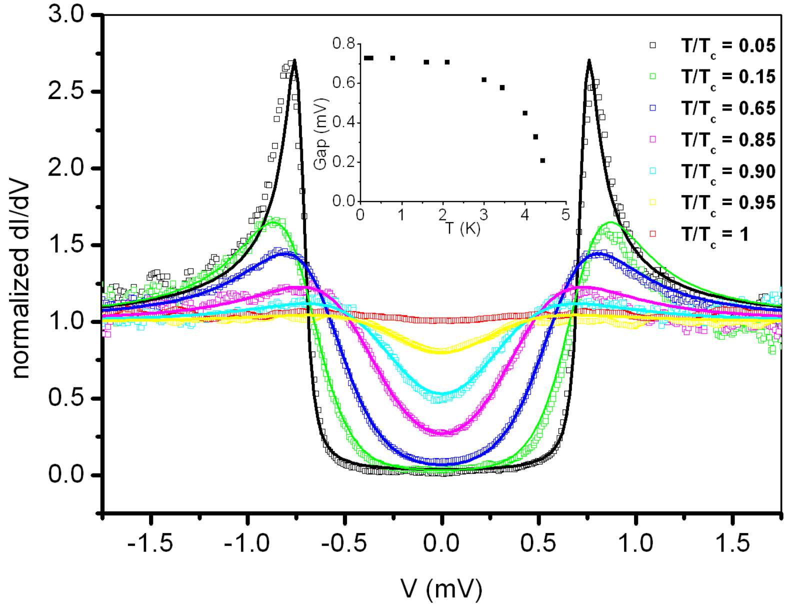
Tunneling spectroscopy

Measurement of the Density-Of-States (DOS)

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



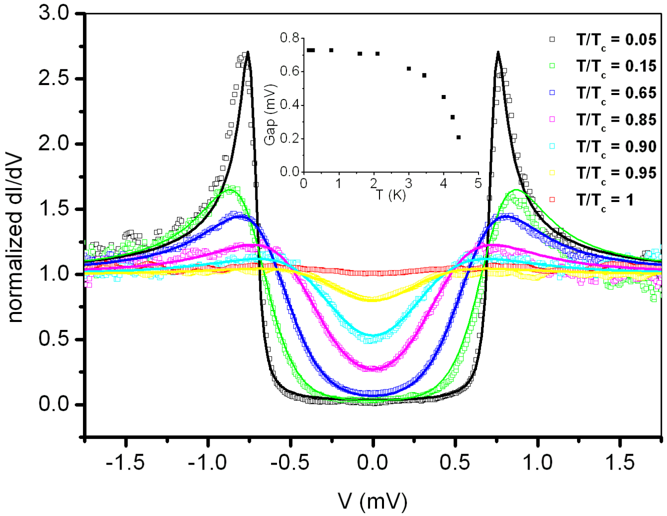
Resolution ≈ 80 µeV



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

Superconductivity and Coulomb interaction

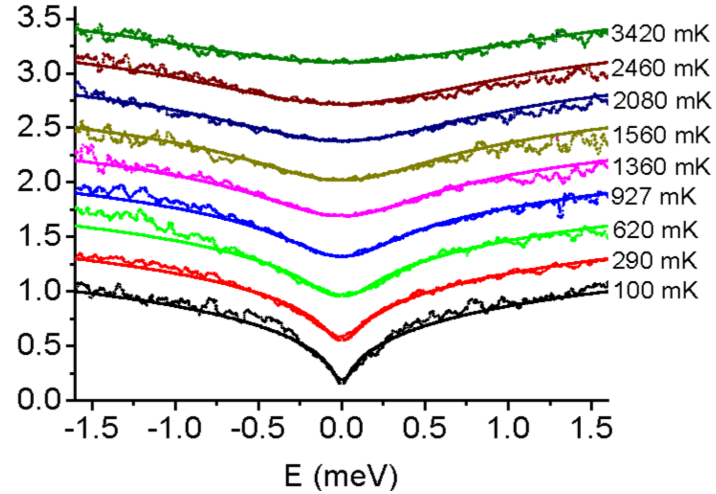
Superconducting film



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

$$T_c = 1.13\,\omega_D\,exp\left[-\frac{1}{N(0)(\lambda-\mu^{*})}\right]$$

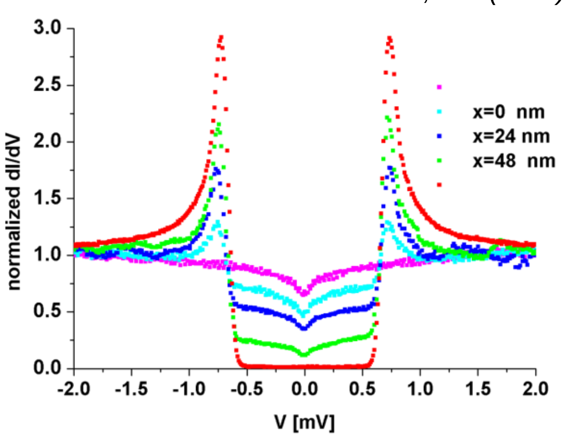
Bad metal film

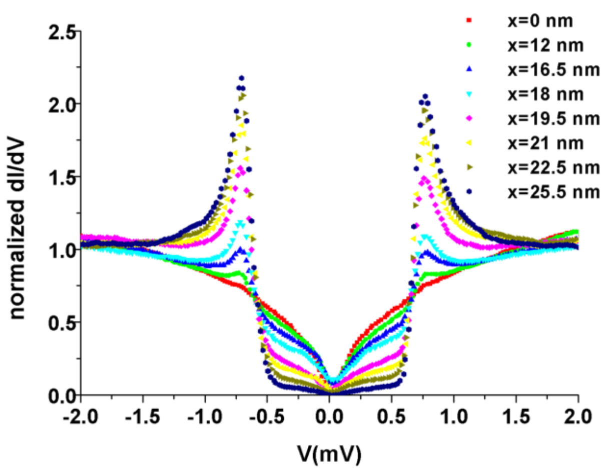


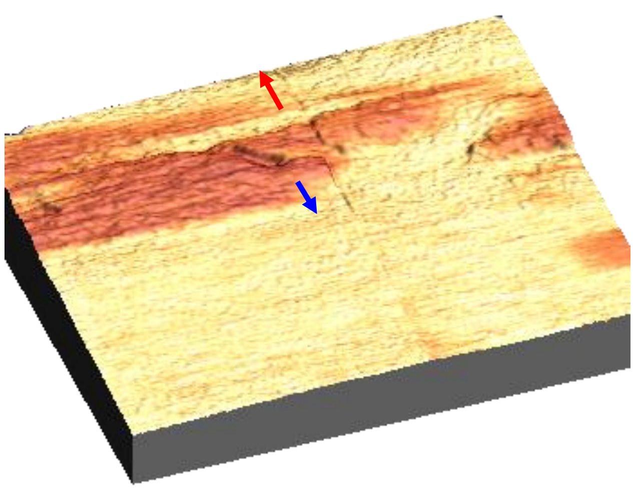
W. Escoffier (unpublished)

B. Altshuler *et al., Phys. Rev. Lett.* ***44****, 1288 (1980)*
A. M. Finkelstein, *Zh. Eskp. Theor. Fiz.* ***84****, 168 (1983)*
A. Kamenev and **A. Andreev,** *Phys. Rev. B* ***60****, 2218 (1999)*
L. Bartosh and **P. Kopietz,** Eur. Phys. J. B. **28**, 29 (2002)

C. Chapelier *et al.*, 24th Conf. on Low Temp. Phys.
AIP Conf. Proc. ***850****, 975 (2006)*

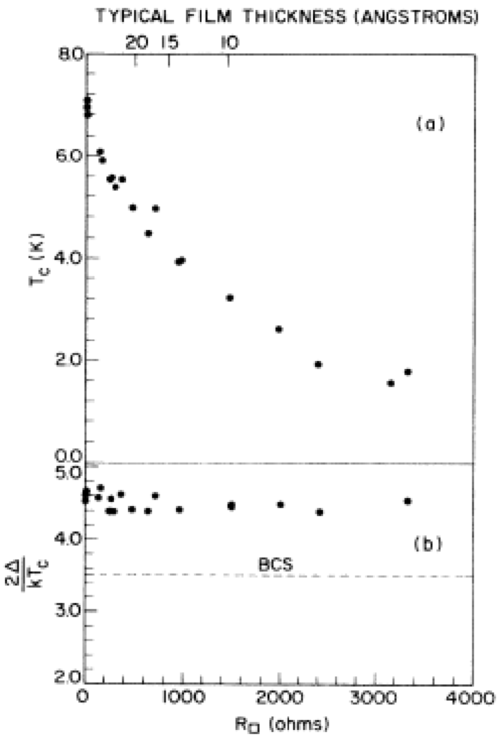


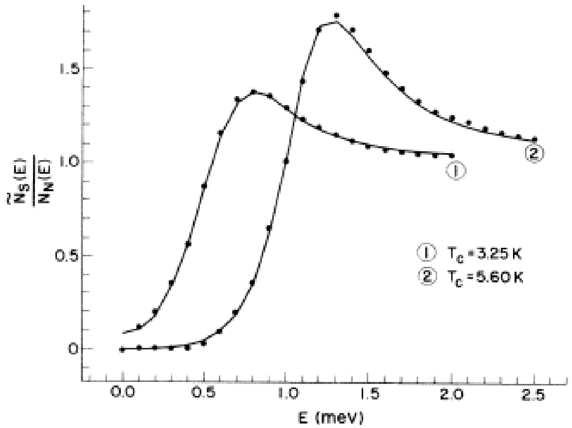




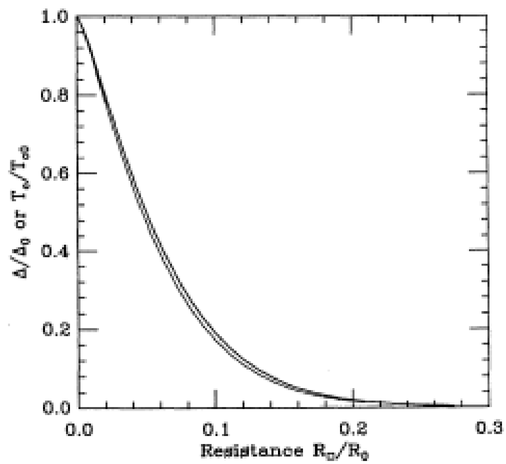
Superconductivity and Coulomb interaction

Pb



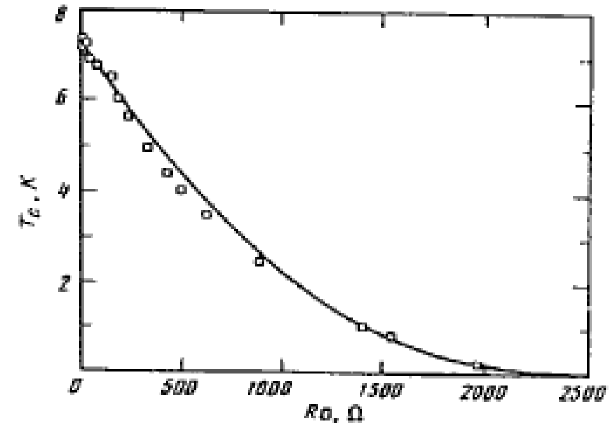


R.C. Dynes, A. E. White,J.M. Graybeal , and **J.P. Garno**
Phys. Rev. Lett. ***57***, 2195 (1986)



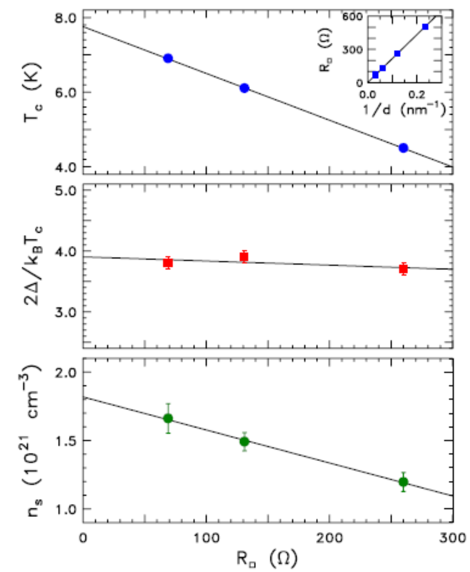
R. A. Smith, M.Y. Reizer, and J. W. WIlkins
Phys. Rev. B **51**, 6470(1995**)**

MoGe



J.M. Graybeal ,
Physica, **135B**, 113 (1985**)**

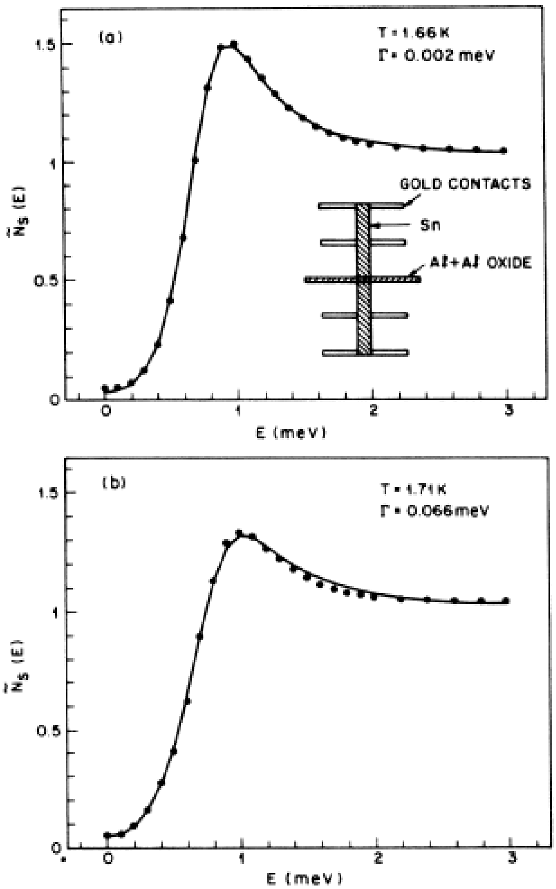
A.M Finkelstein
Pis'sma Zh. Esk. Theor. Fiz., **45**, 46 (1987**)**

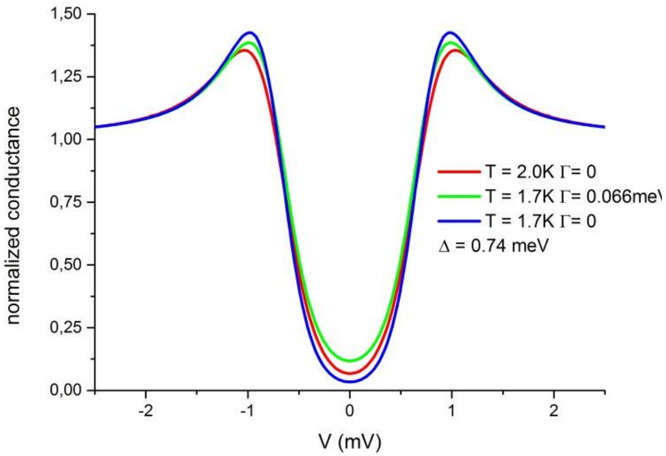


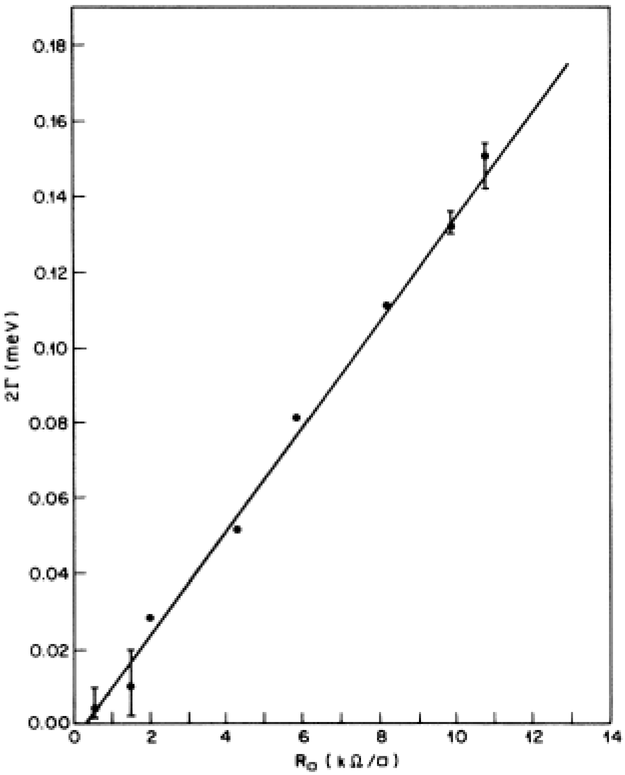
H. Tashiro, J.M. Graybeal *et al.,*
Phys. Rev. B., **78**, 014509 (2008**)**

Sn

$$N(E,\Gamma) = \mathrm{Re}\left[\frac{E}{\sqrt{E^2-\Delta^2}}\right], \quad E = E' - i\Gamma \ .$$





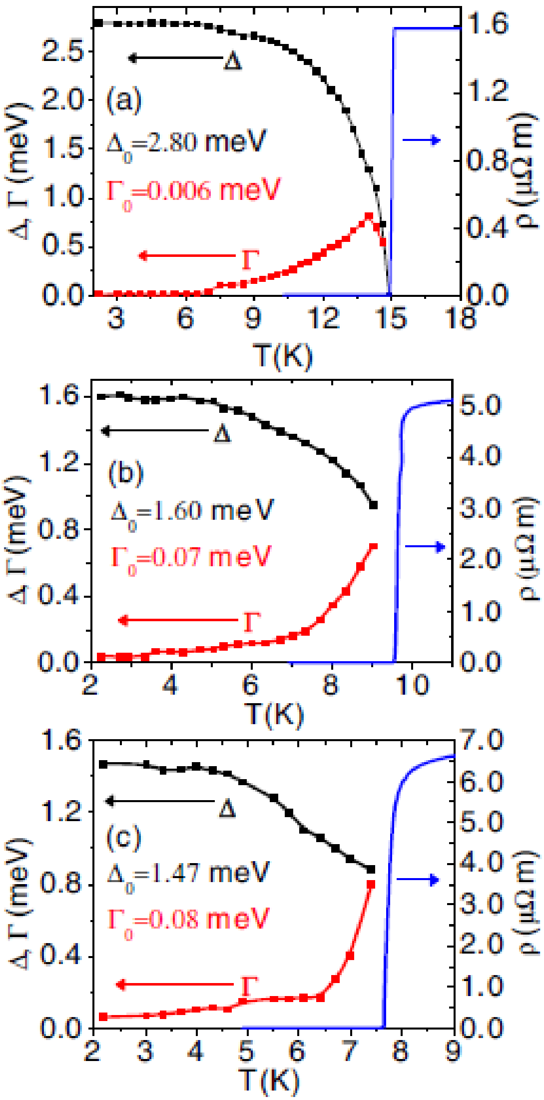


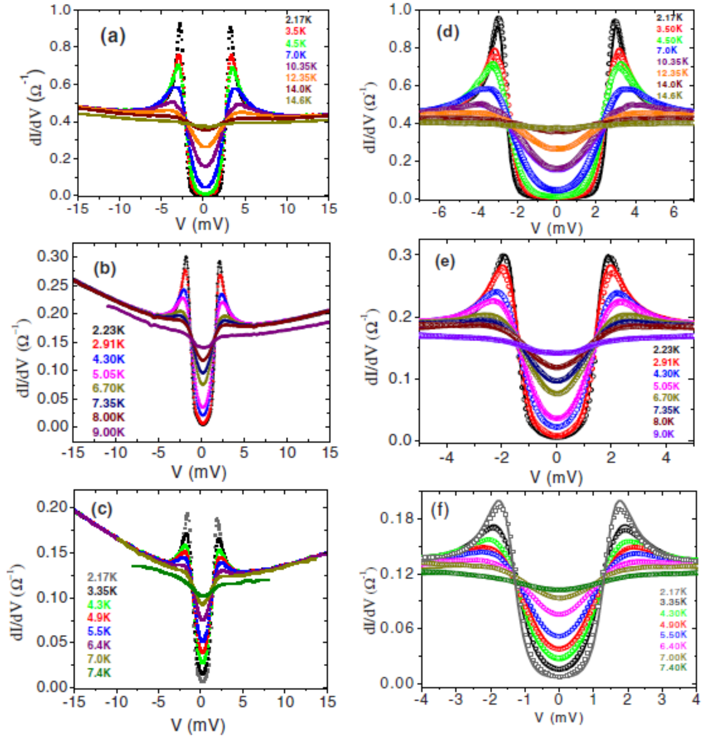
variation of Γ. Although the results are not yet complete, we find that Γ increases substantially with increasing T up to T_c, where we can no longer measure it using this technique.

Alice E. White, R.C. Dynes, and J.P. Garno
Phys. Rev. B ***33***, (R) 3549 (1986)

Superconductivity and Coulomb interaction

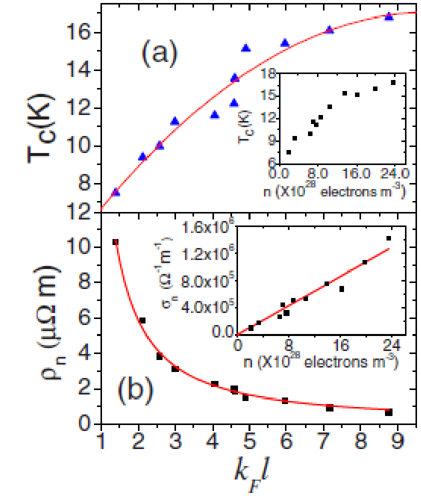
NbN

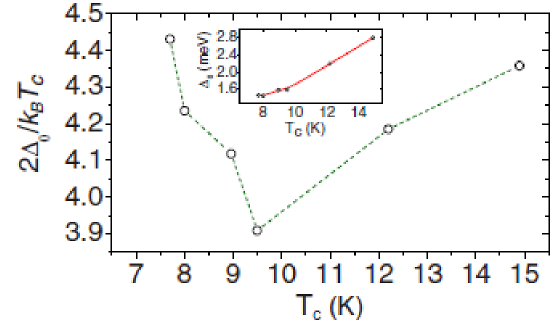


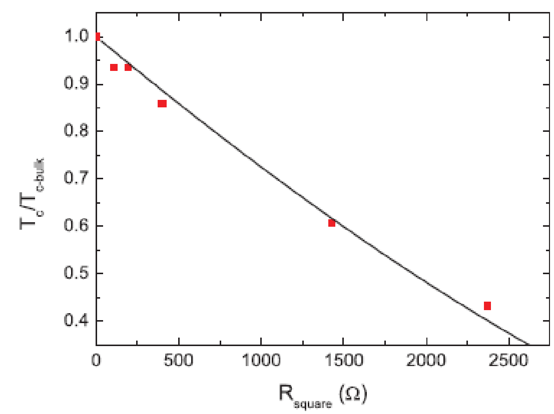


S.P. Chockalingam *et al.*, *Phys. Rev. B* ***79**, 094509 (2009)*

d (nm)	15	8	4	2.33	2.16
T_C(K)	15.0	14.5	13.3	9.4	6.7
Δ_{BCS}	2.85	2.7	2.4	1.7	1.3
$\delta\Delta_{BCS}$	<0.03	0.03	0.08	0.2	...
Γ_{Dynes}	<0.01	0.01	0.01	0.05	0.1
$2\Delta_{BCS}/k_B T_C$	4.4	4.3	4.2	4.2	4.0



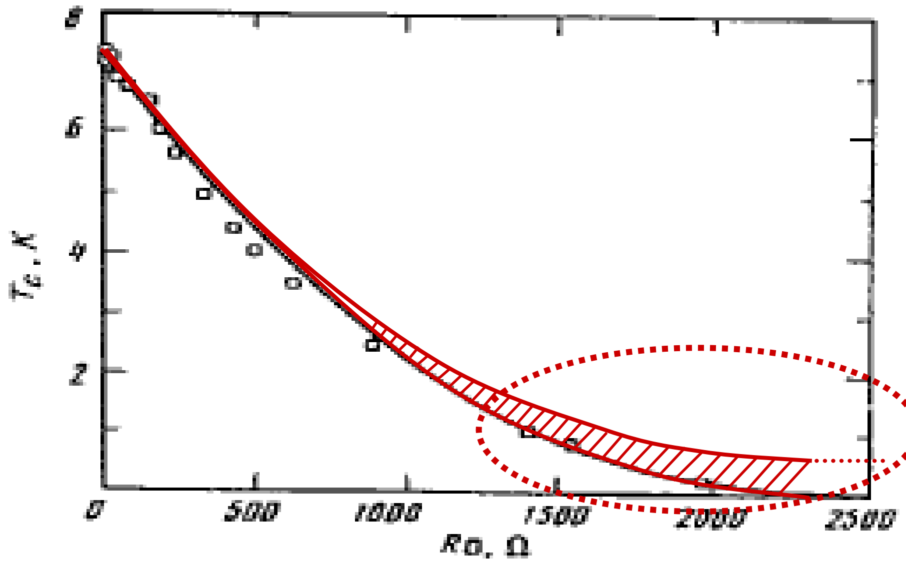




Y. Noat *et al.*, *Phys. Rev. B* ***88**, 014503 (2013)*

Superconductivity and Coulomb interaction

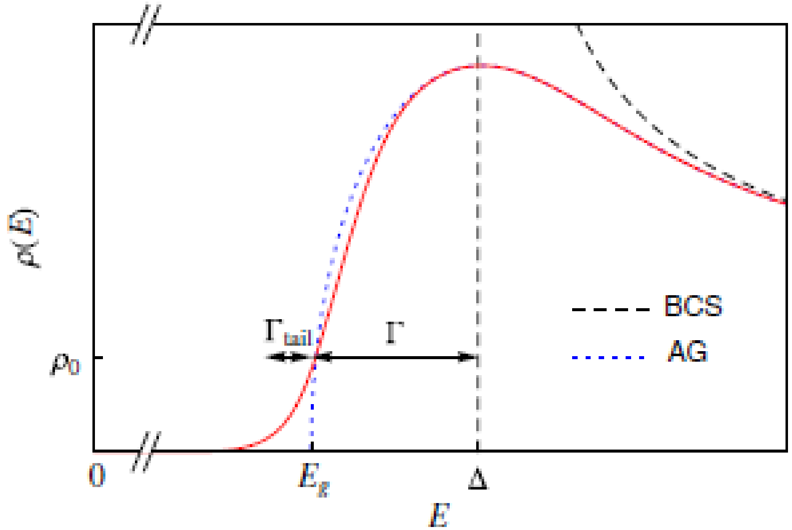
M. A. Skvortsov and M. V. Feigel'man, *Phys. Rev. Lett.* ***95****, 057002, (2005)*



$$\lambda = \lambda_0 - \frac{1}{24\pi g}\log(\frac{1}{\epsilon\tau})$$

$$T_c \;\alpha\; \omega_D e^{-\frac{1}{\lambda N(E_F)}} \Rightarrow \frac{\delta T_c}{T_c} = \frac{\delta\lambda}{\lambda^2}$$

Spatial fluctuations of Tc

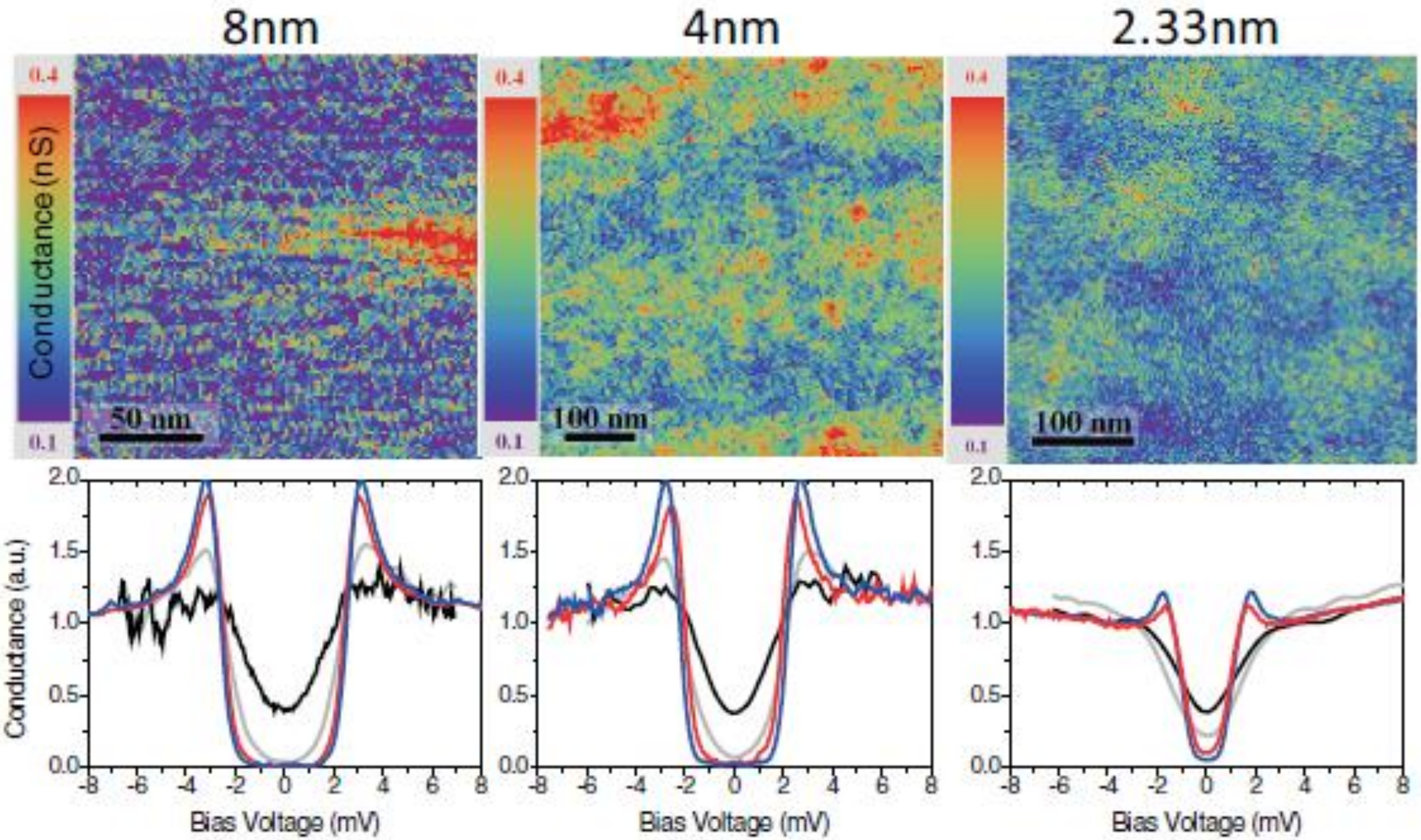


$$\frac{D}{2}\nabla^2\theta + iE\sin\theta + \Delta(\mathbf{r})\cos\theta - \Delta_0\,\eta\cos\theta\sin\theta = 0,$$

M.V. Feigelman and M.A. Skvortsov, *Phys. Rev. Lett.* ***109***, 147002 (2012)

A.I. Larkin and Yu. N. Ovchinnikov, Sov. JETP **34**, 1144 (1972)

NbN

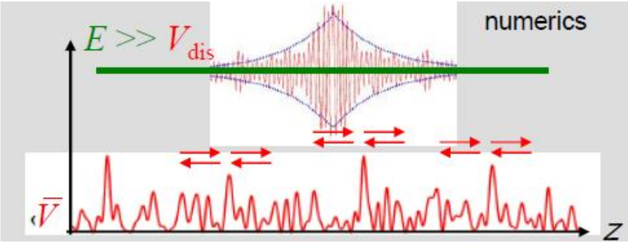


Y. Noat *et al.*, *Phys. Rev. B* ***88****, 014503 (2013)*

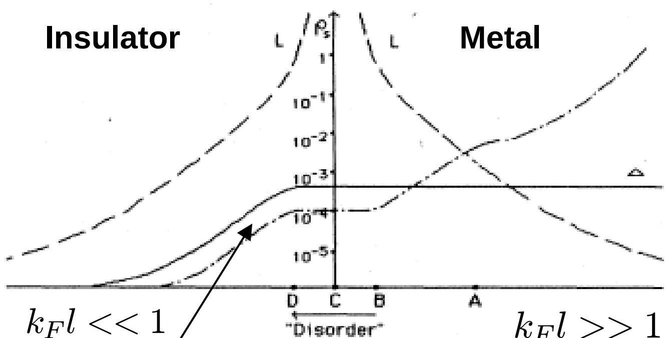
Coulomb interaction :

- Aronov-Altshuler anomaly at E_F
- Continuous decrease of Tc and Δ with disorder
- Keeps Δ /Tc ratio constant
- Spectra are often associated with a Dynes parameter
- Spatial mesoscopic fluctuations of Tc and subgap states

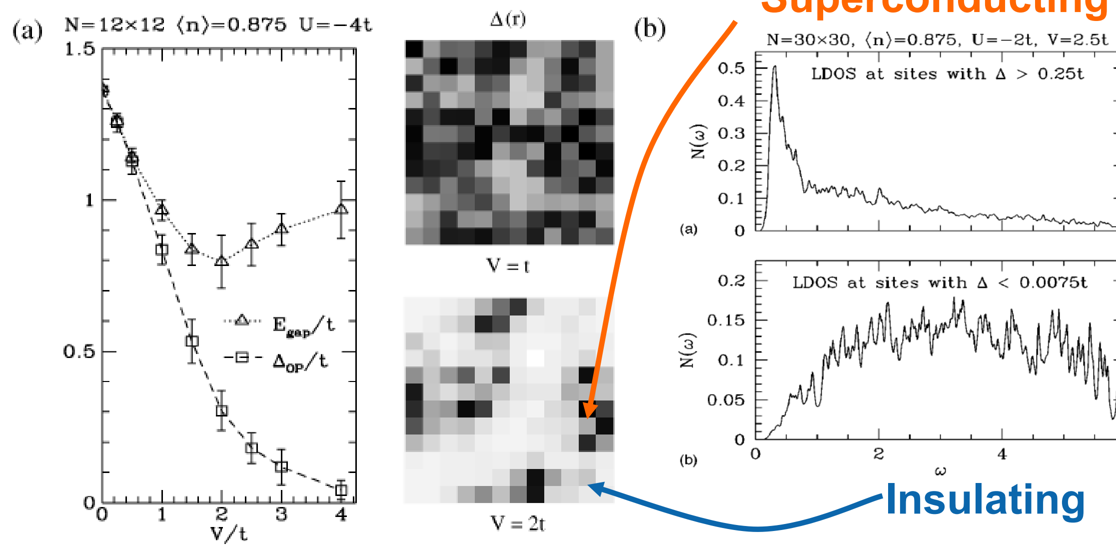
Localization and superconductivity



P.W. Anderson, *Phys. Rev.* ***109***, 1492(1958)



Inhomogeneous superconducting state



Superconducting

Insulating

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

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

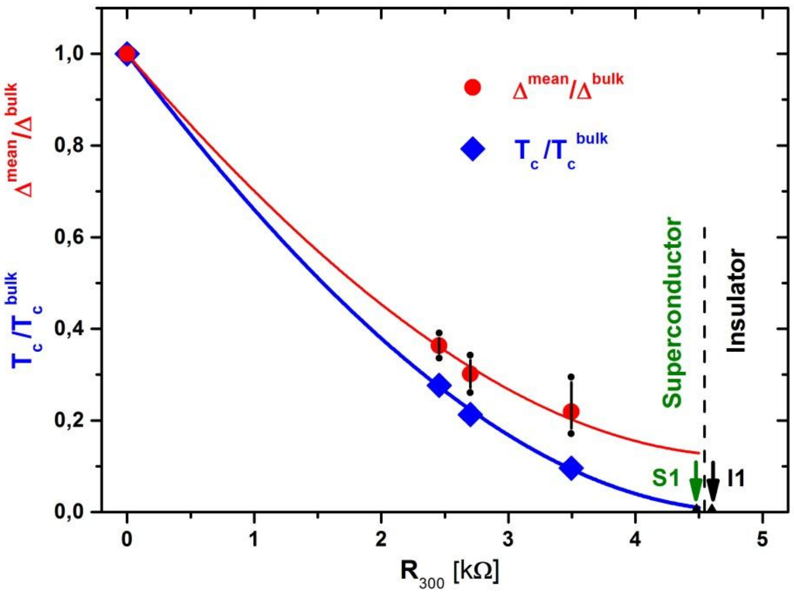
G. Kotliar, A. Kapitulnik, *Phys. Rev. B* ***33***, 3146 (1986)

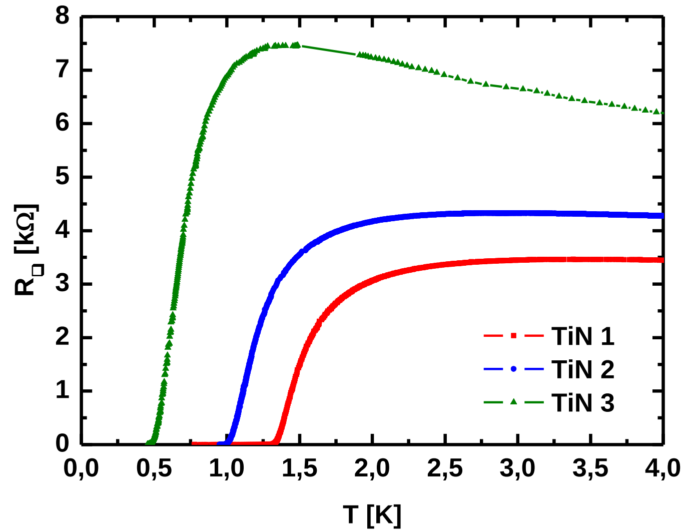
M.V. Sadowskii, *Phys. Rep.,* ***282***, 225 (1997)

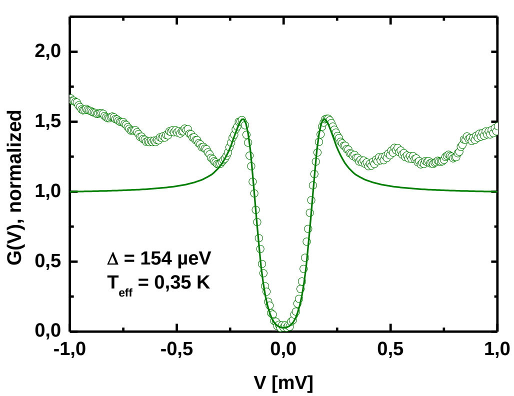
A. Ghosal *et al*., PRL ***81***, 3940 (1998) ; PRB ***65***, 014501 (2001)

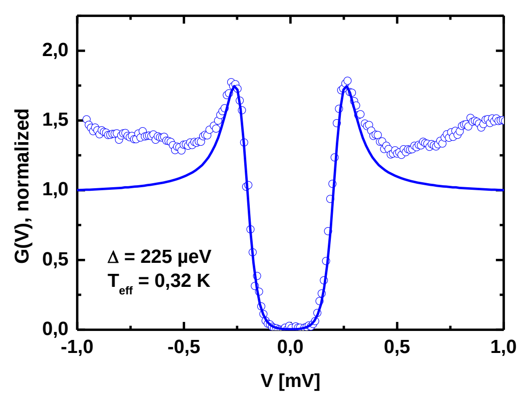
M. Feigel'man *et al*., *Phys. Rev. Lett.* ***98***, 027001 (2007) ; *Ann.Phys.* **325**, 1390 (2010)

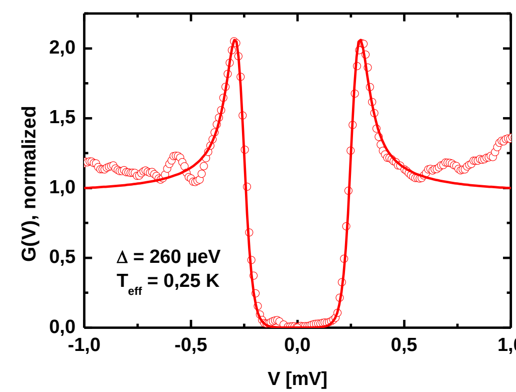
TiN









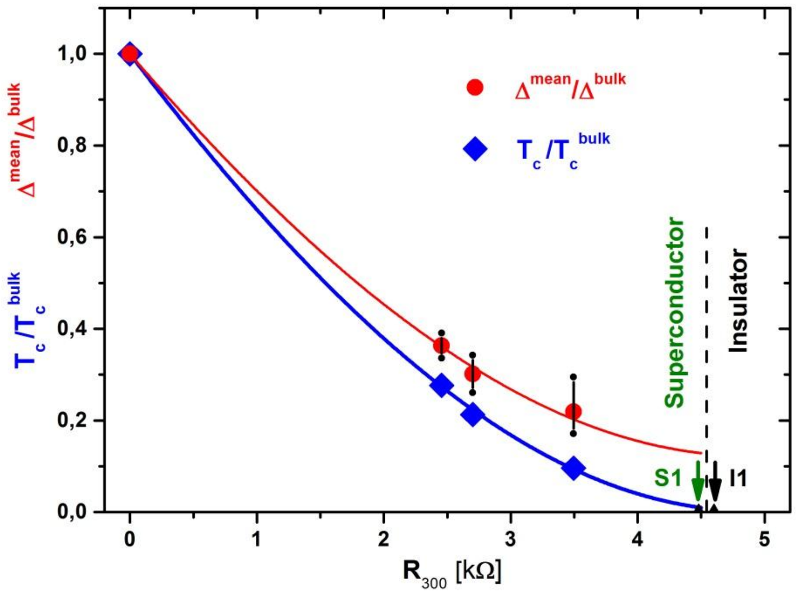


Increasing disorder

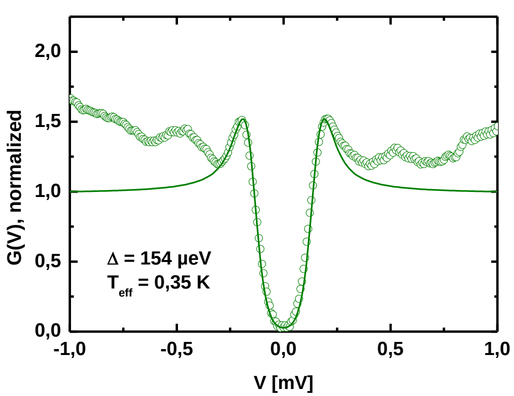
Sacépé et al., *PRL **101**, 157006 (2008)*

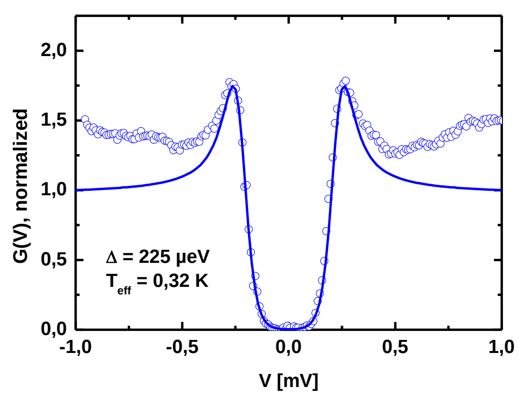
TIN Superconductor-Insulator transition

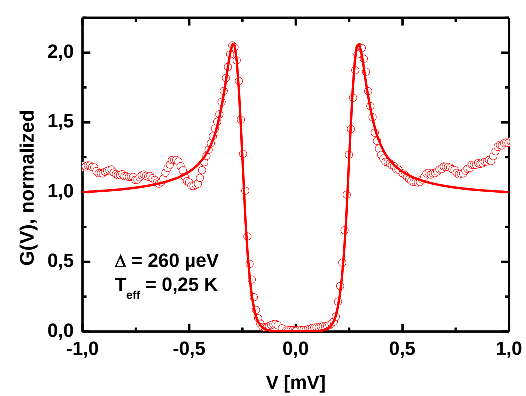
TiN



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







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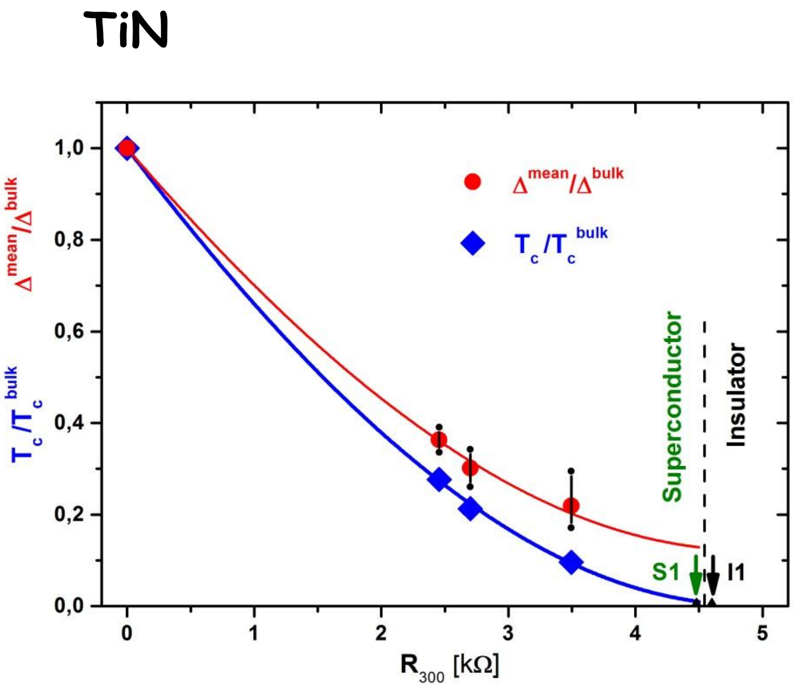
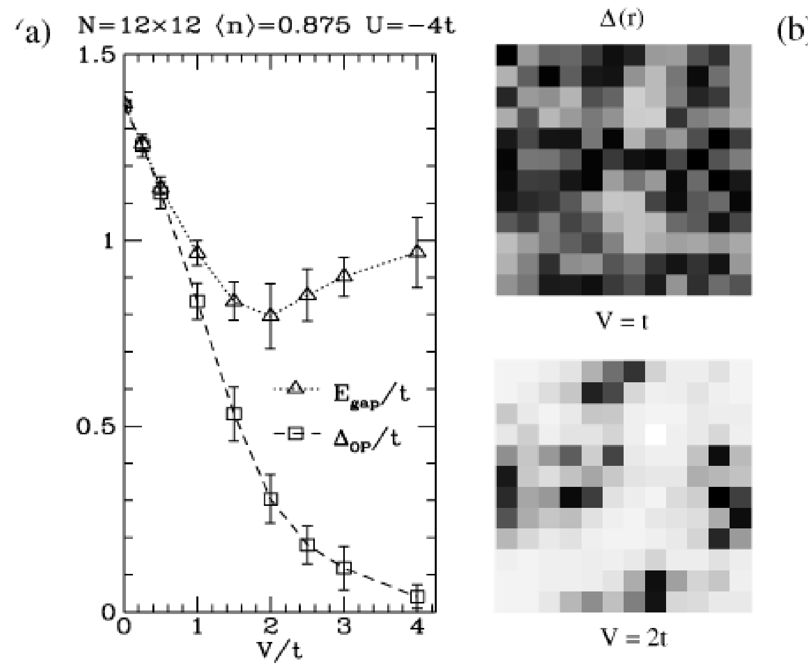
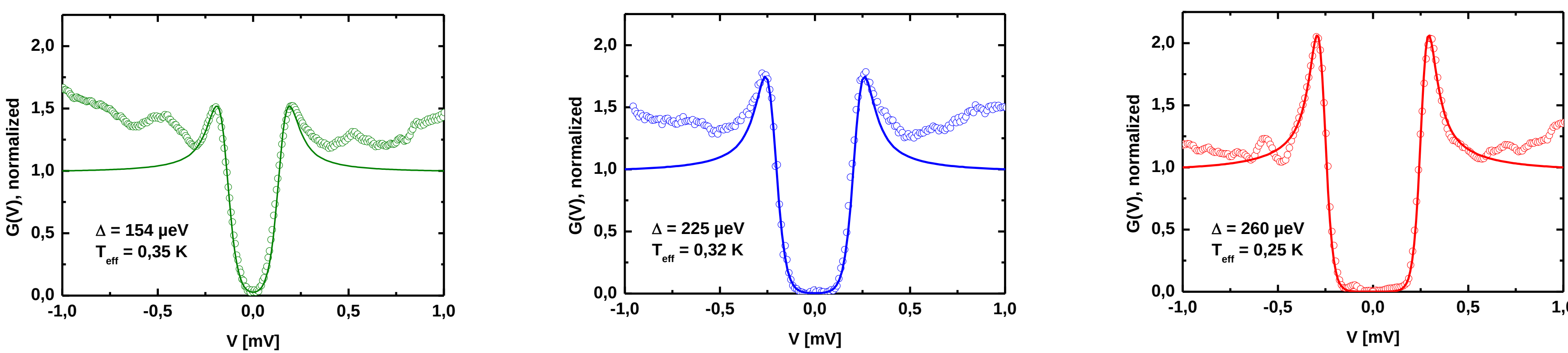




A. Ghosal et al., *Phys. Rev. Lett* ***81****, 3940 (1998);*
Phys. Rev. B ***65****, 0145001 (2001)*



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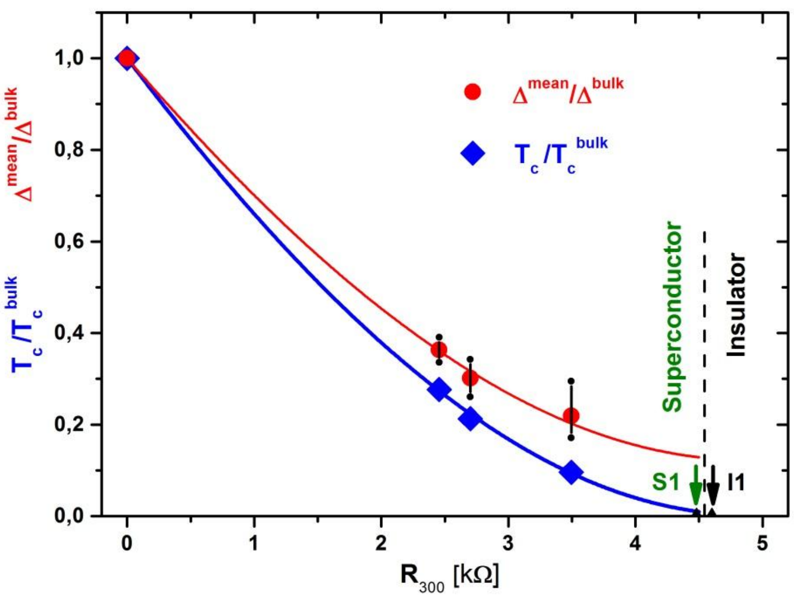
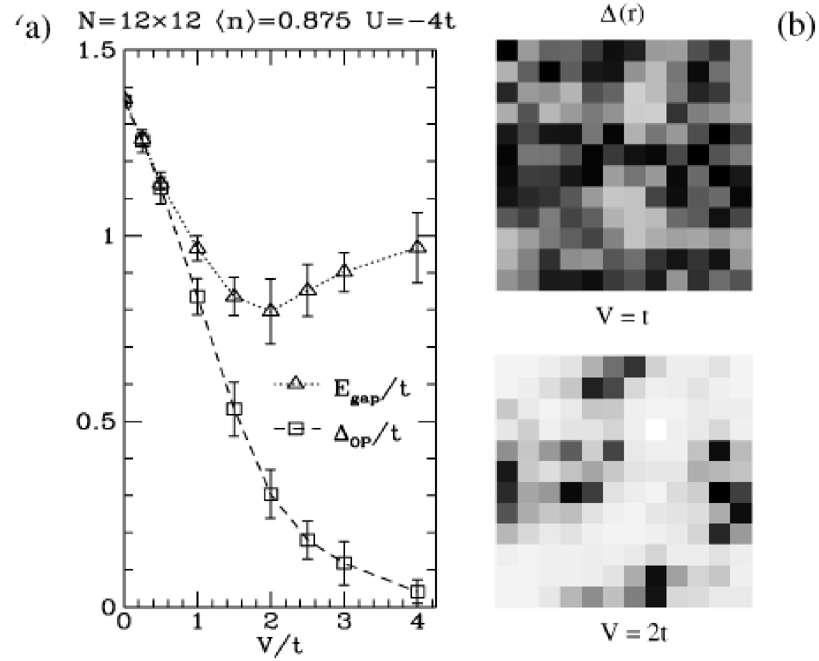
Sacépé et al., *PRL* ***101****, 157006 (2008)*

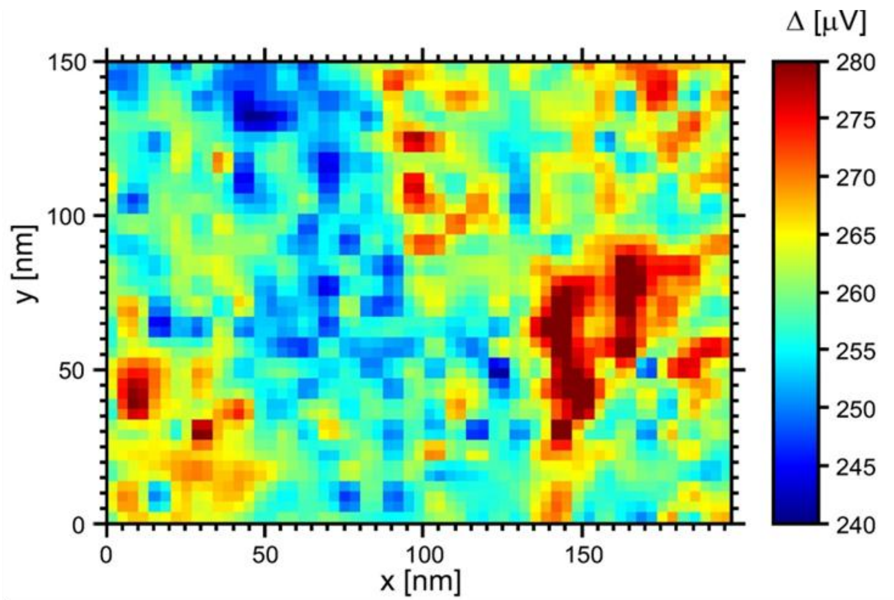
TiN



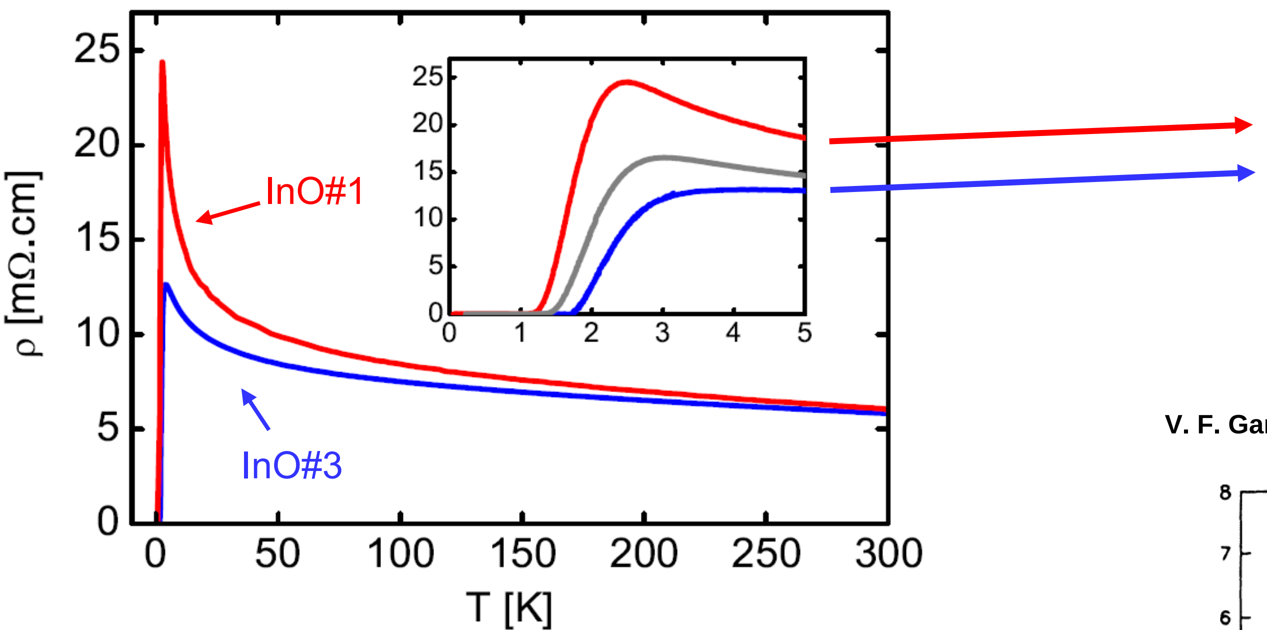


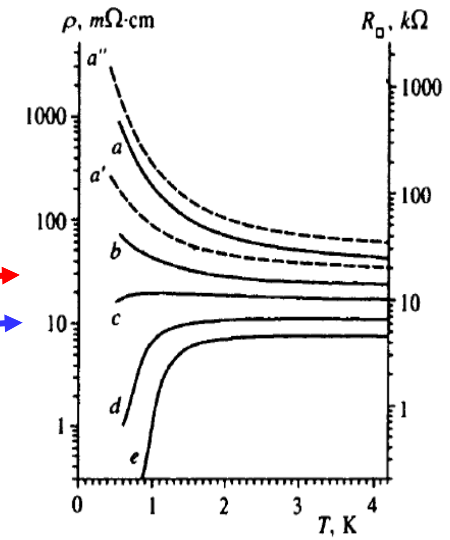
A. Ghosal et al., *Phys. Rev. Lett* ***81****, 3940 (1998);*

Phys. Rev. B ***65****, 0145001 (2001)*

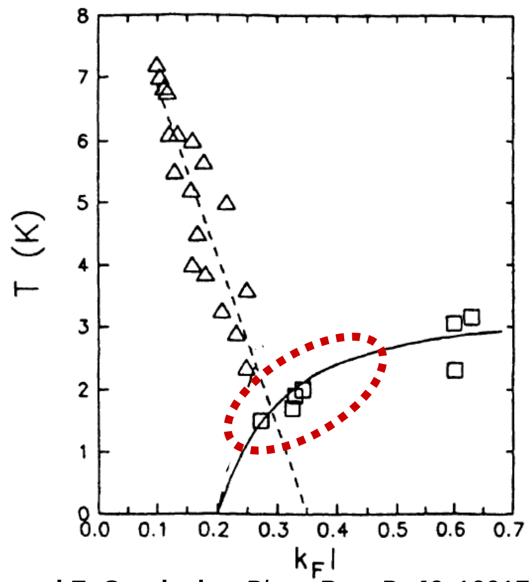


InO_x





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

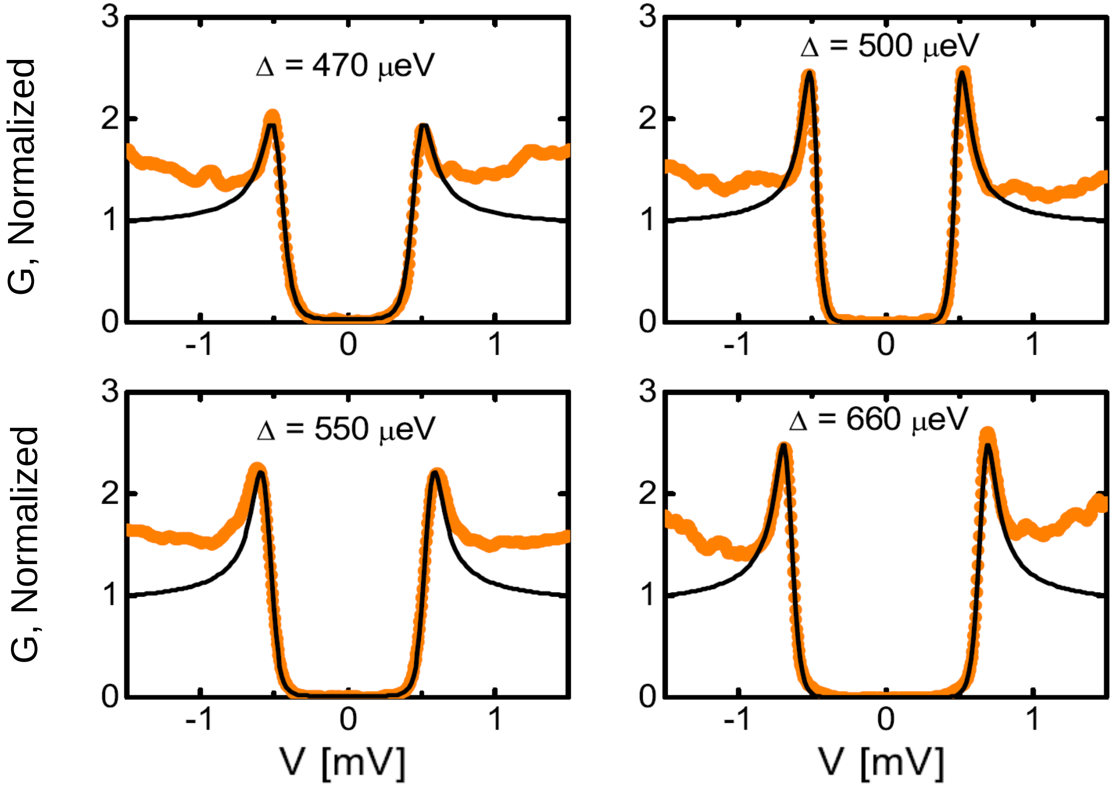


D. Shahar and Z. Ovadyahu, *Phys. Rev. B* ***46***, 10917 (1992)

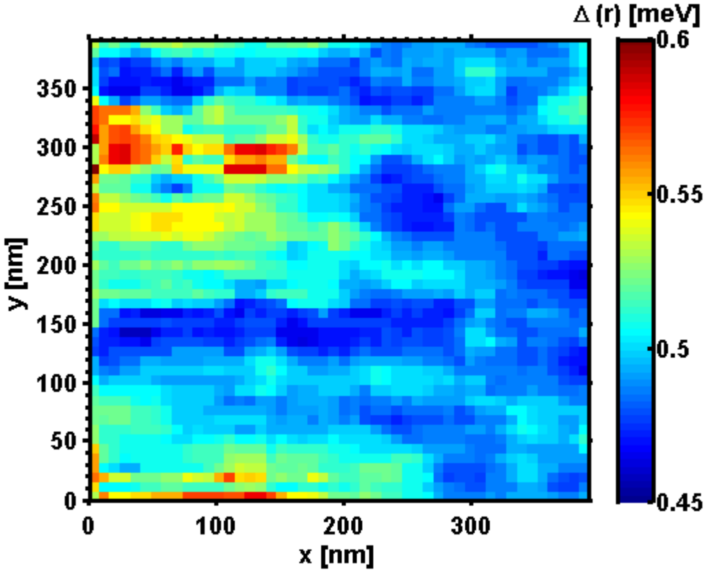
InOx Superconductor-Insulator transition

InO_x

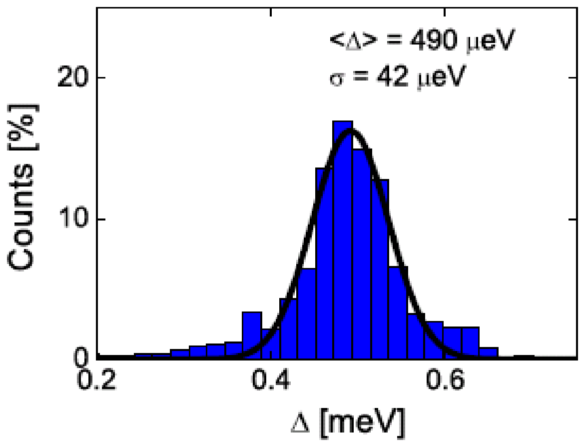
Spectra measured at different locations (T=50mK)



Map of the spectral gap



Gaussian distribution

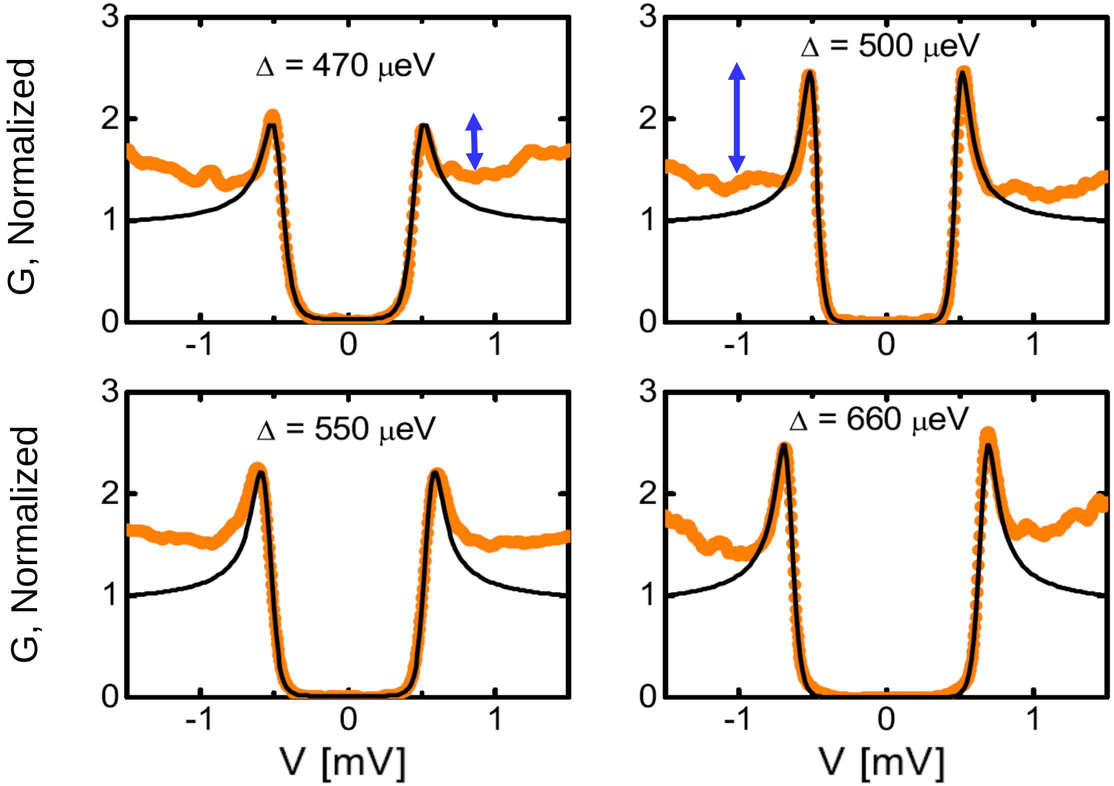


$$3 \leq \frac{\Delta(r)}{k_B T_C} \leq 5.5$$

InOx Superconductor-Insulator transition

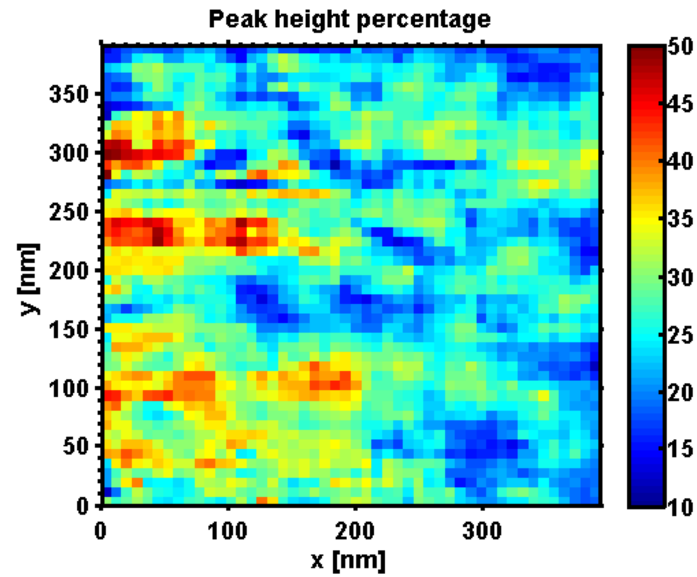
InO_x

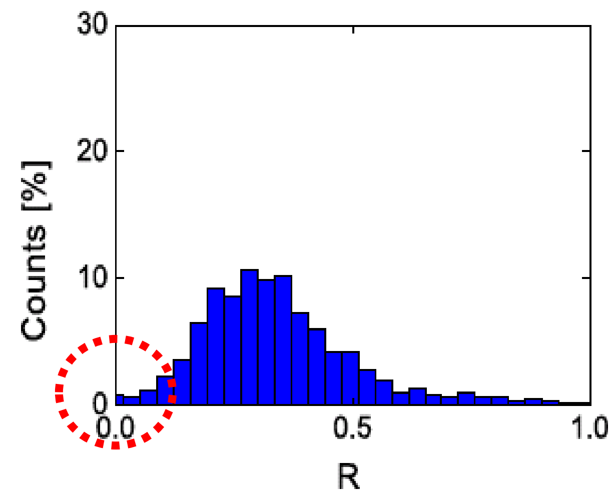
Spectra measured at different locations (T=50mK)



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

Map of the coherence peak height

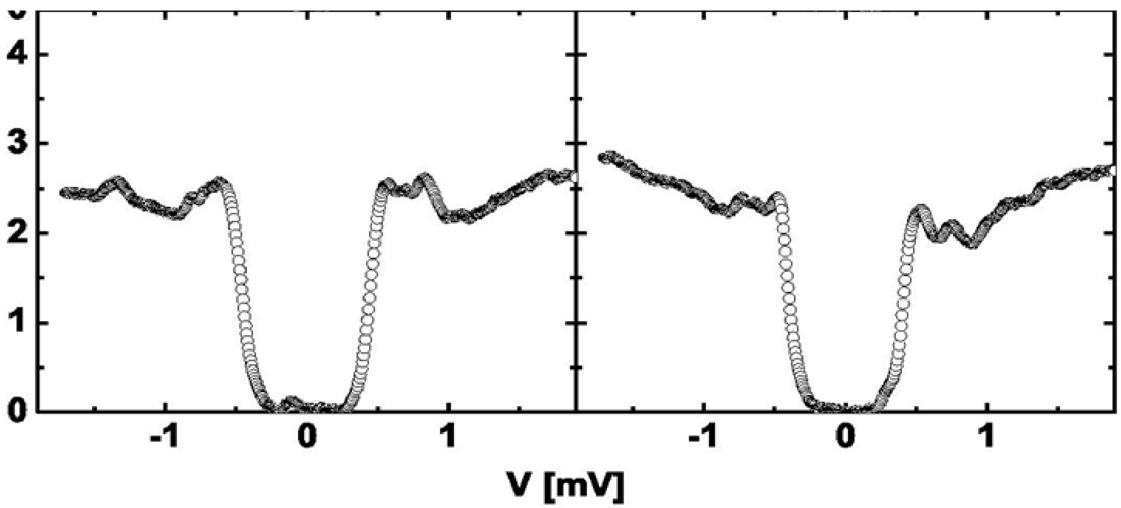




$$R = \frac{G(\Delta) - G(eV > \Delta)}{G(eV > \Delta)}$$

InOx Superconductor-Insulator transition

InO$_x$



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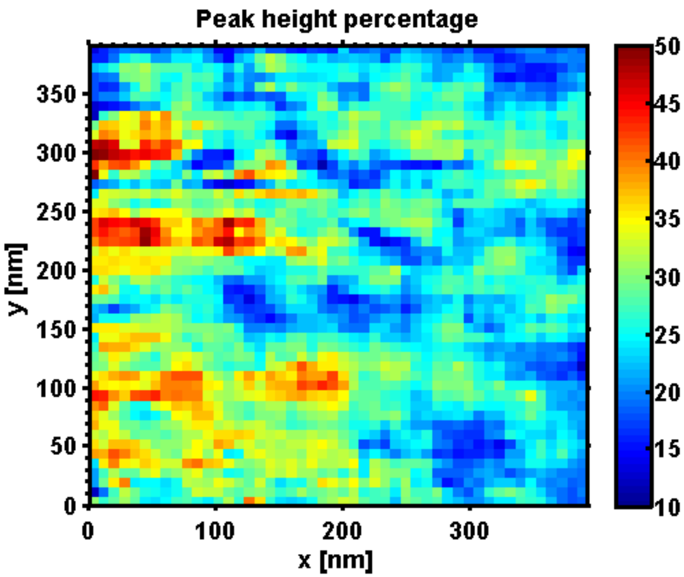
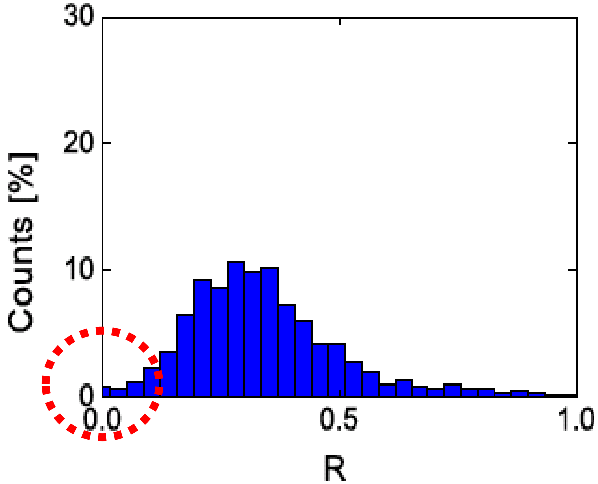


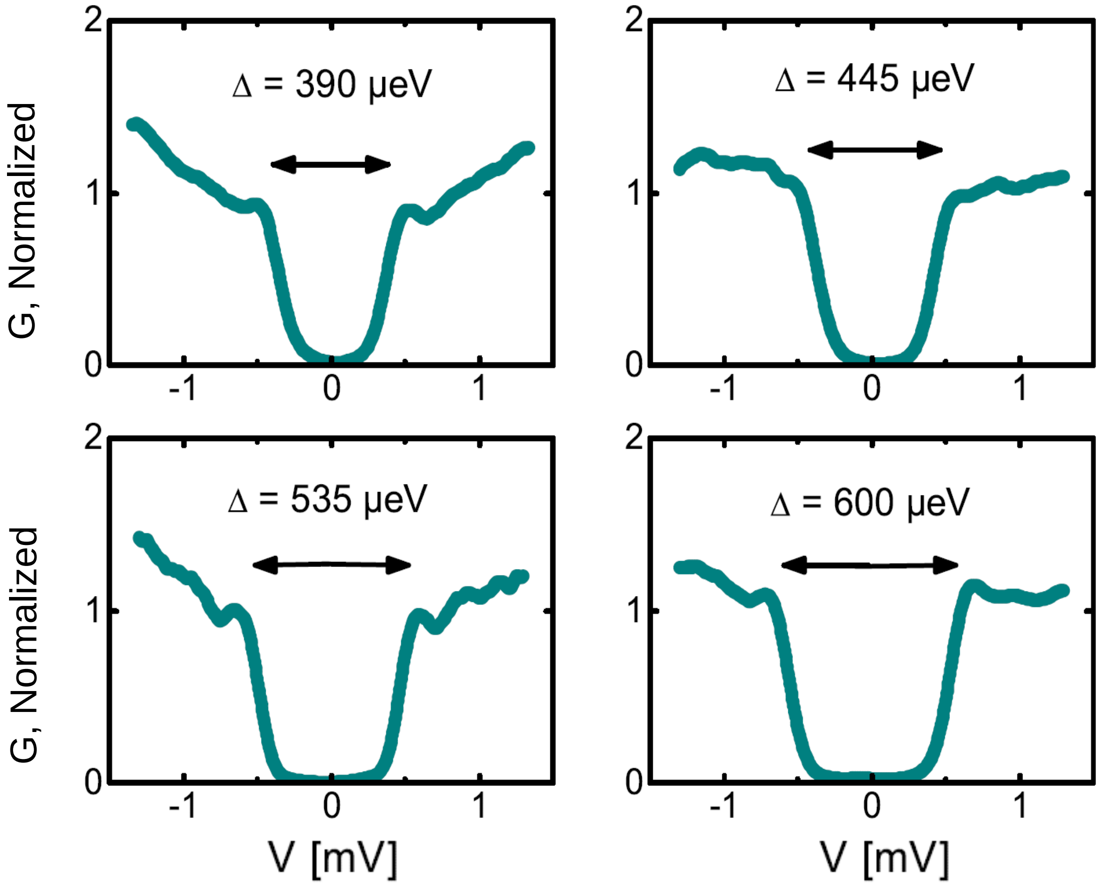


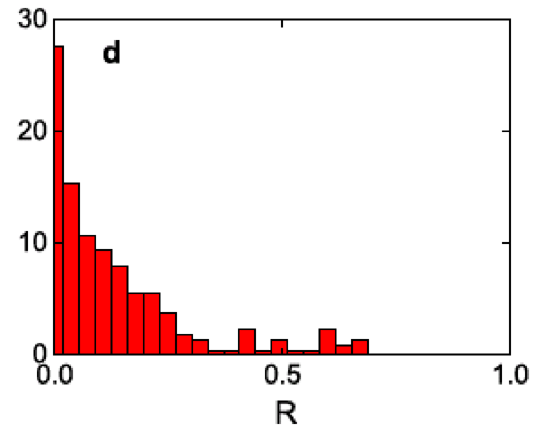
$$R = \frac{G(\Delta) - G(eV > \Delta)}{G(eV > \Delta)}$$

InOx Superconductor-Insulator transition

InO_x

More disordered film





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

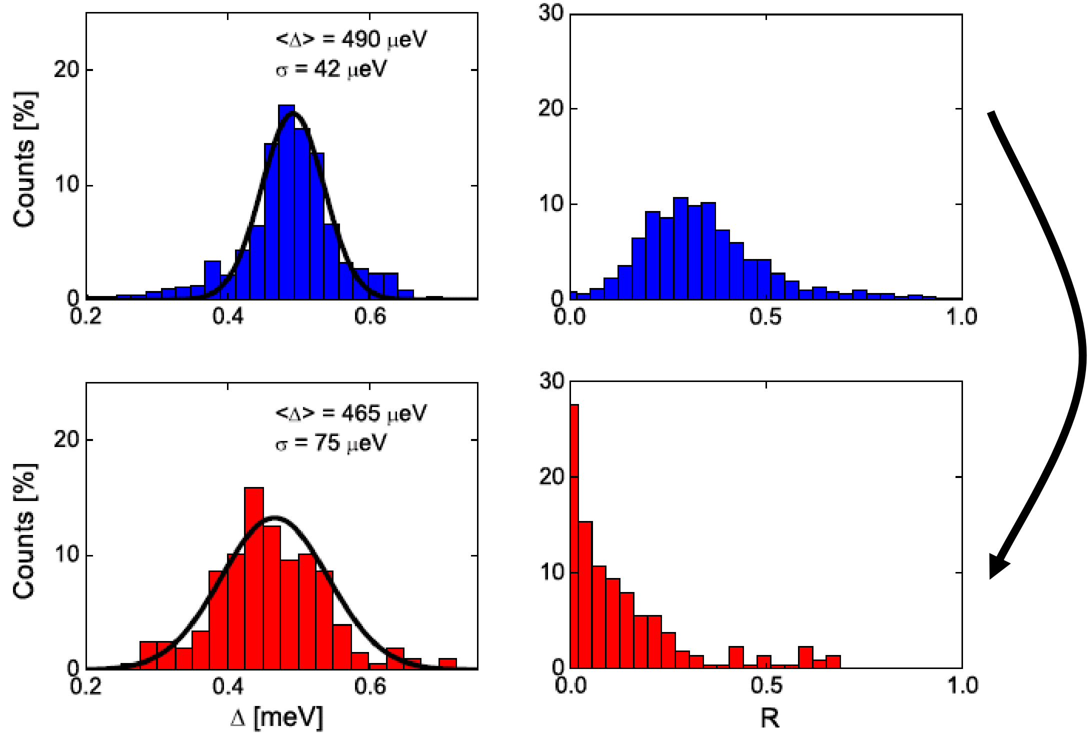
InOx Superconductor-Insulator transition

InO_x

Role of disorder

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

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

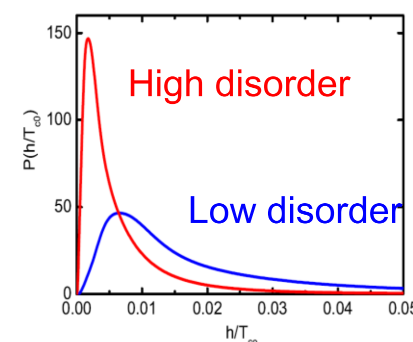


InO#3
T_c ~ 1.7 K

resistivity × 2

InO#1
T_c ~ 1.2 K

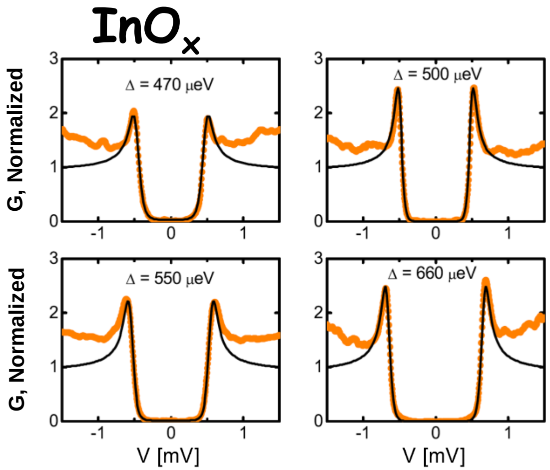
➢ **Proliferation of spectra without coherence peaks**



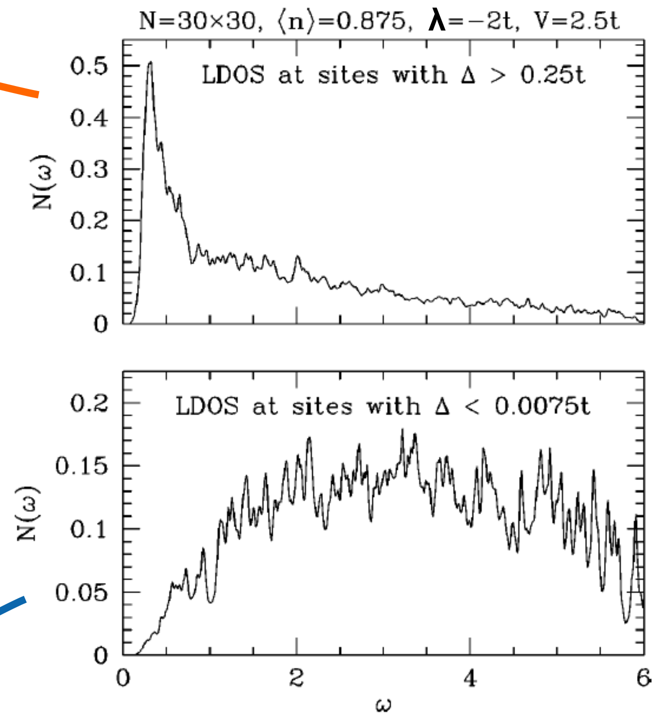
B. Sacépé et al., *Nat. Phys.* (2011)

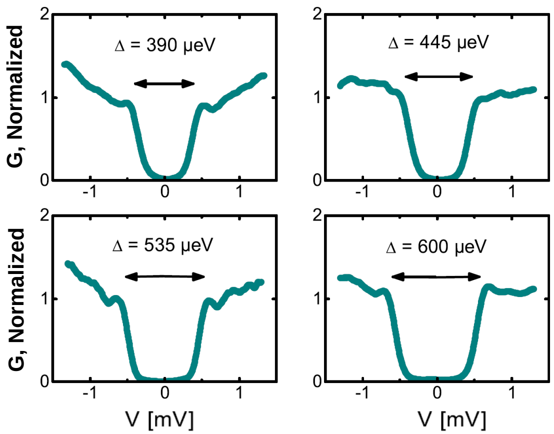
M. Feigel'man *et al.*, *Phys. Rev. Lett.* ***98***, 027001, (2007)
M. Feigel'man *et al.*, *Ann. Phys.* **325,** 1390 (2010)

InOx Superconductor-Insulator transition

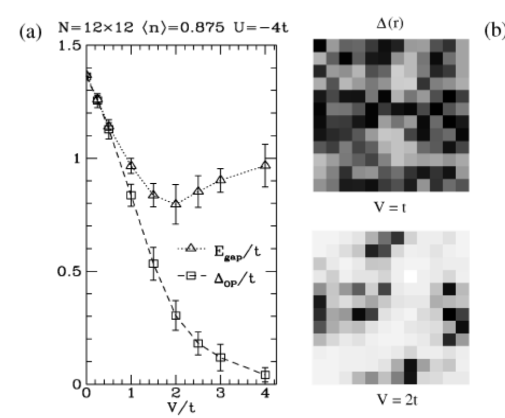


Superconducting gap Δ
⇒ delocalized Cooper pairs





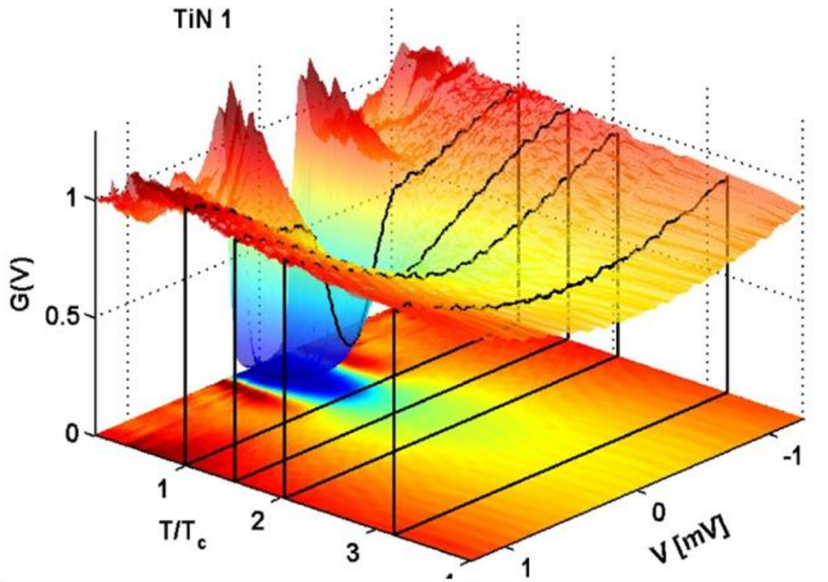
« Insulating » gap E_{gap}
⇒ Localized Cooper pairs

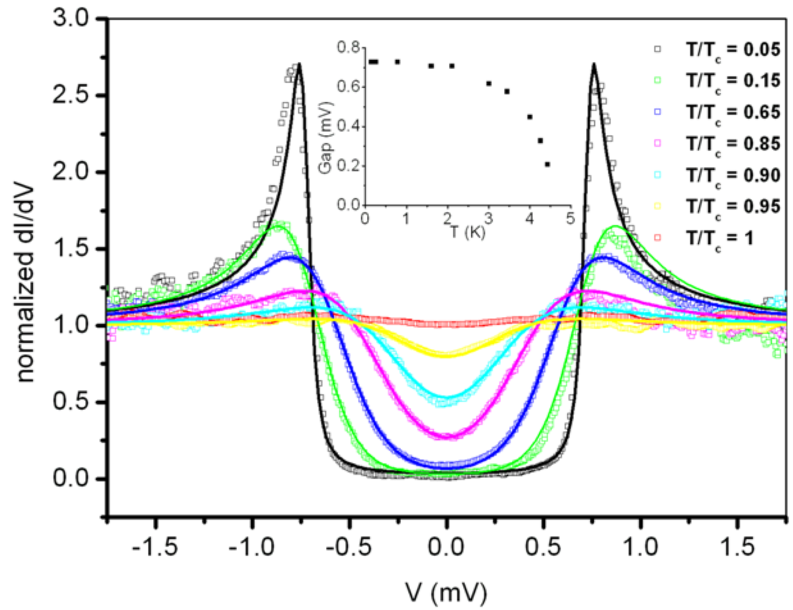


A. Ghosal, M. Randeria, N. Trivedi, *Phys. Rev. Lett.* ***81***, 3940, (1998) & *Phys. Rev. B* ***65***, 014501 (2001)

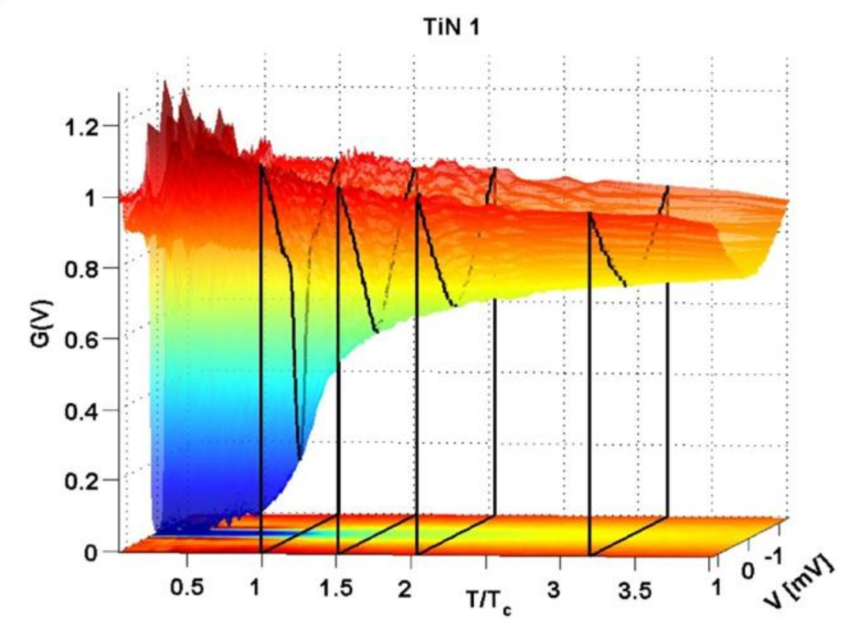
Thermal dependence of the Density of States

TiN Pseudogap above Tc



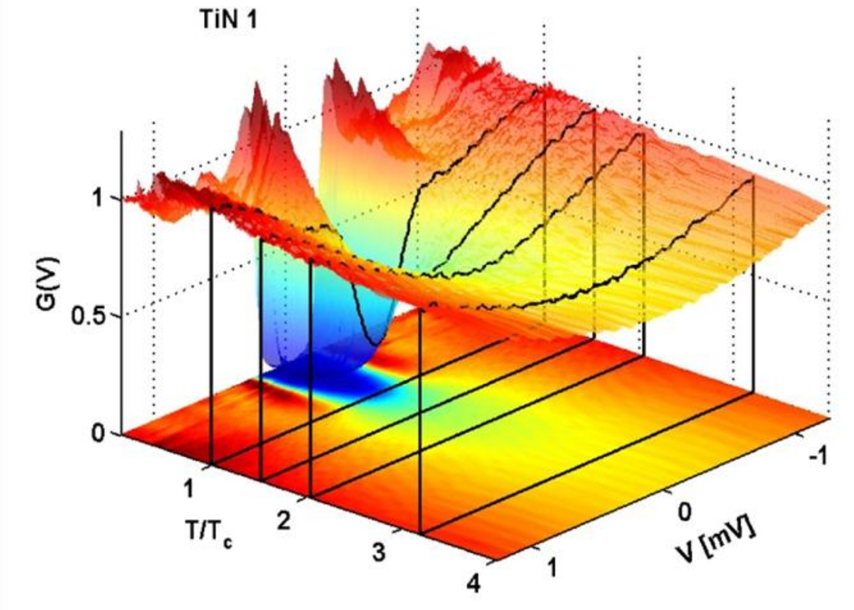


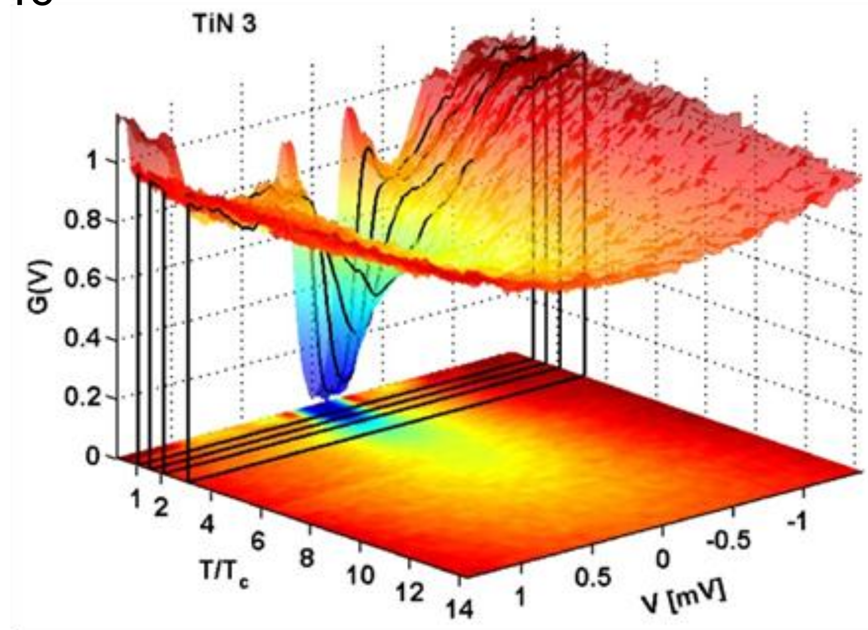
W. Escoffier *et al.* **,** *Phys. Rev. Lett.* ***93***, 217005, (2004)

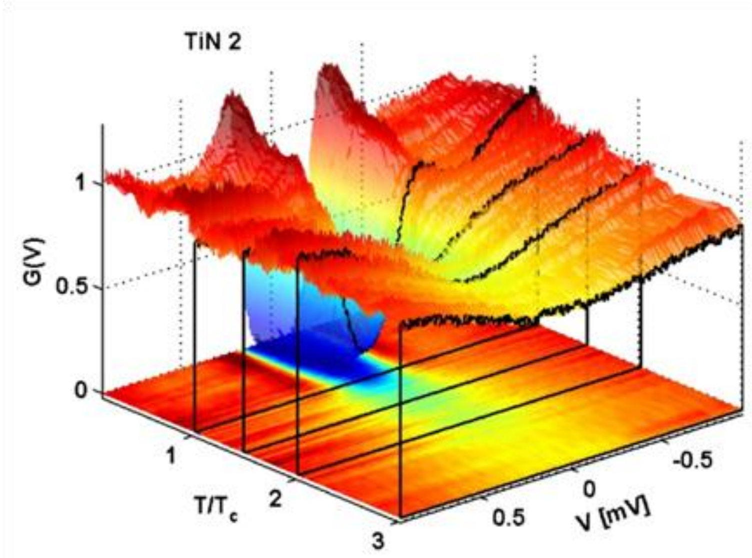


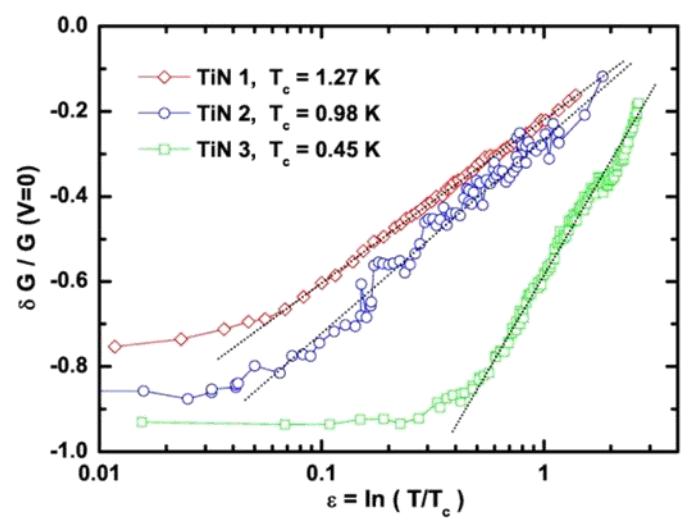
B. Sacépé et al., *Nat. Comm.*, (2010)

TiN Pseudogap above Tc





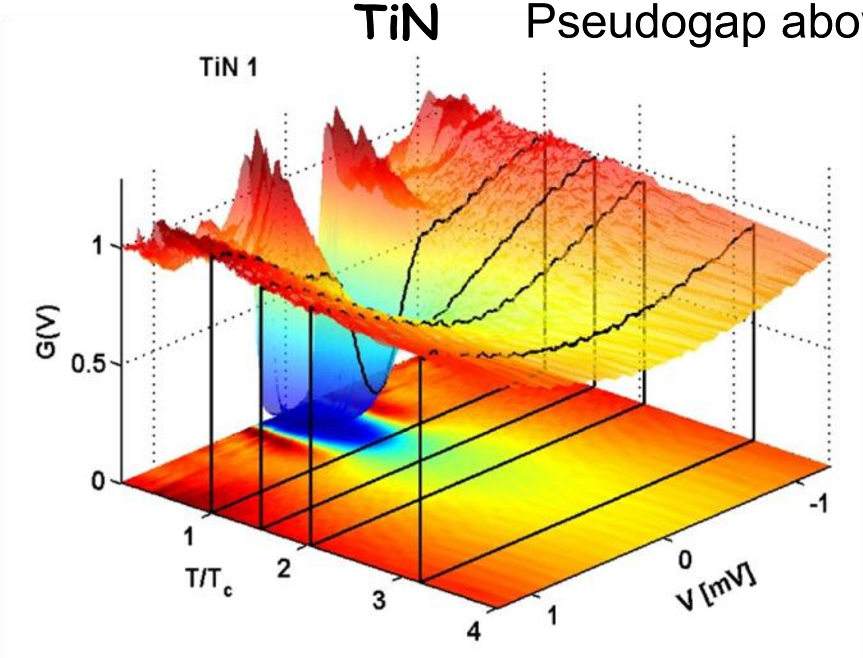


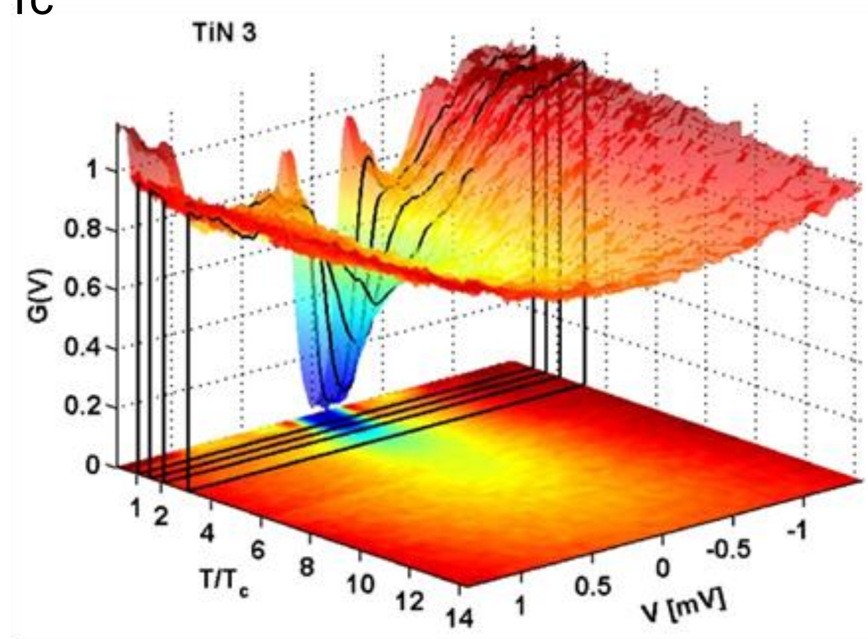


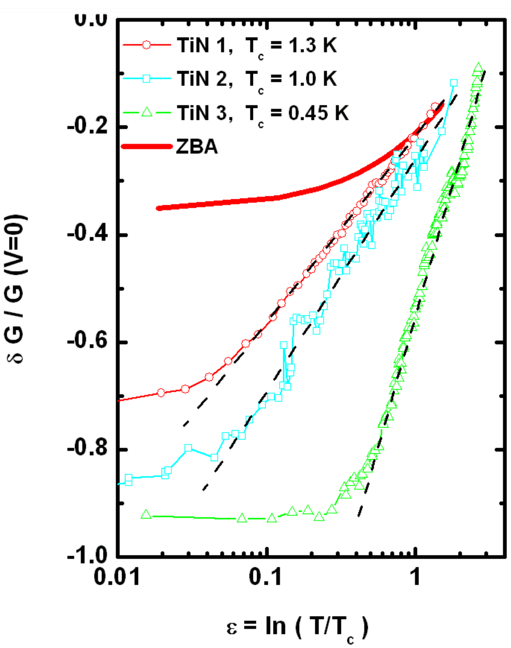
B. Sacépé et al., *Nat. Comm.*, (2010)

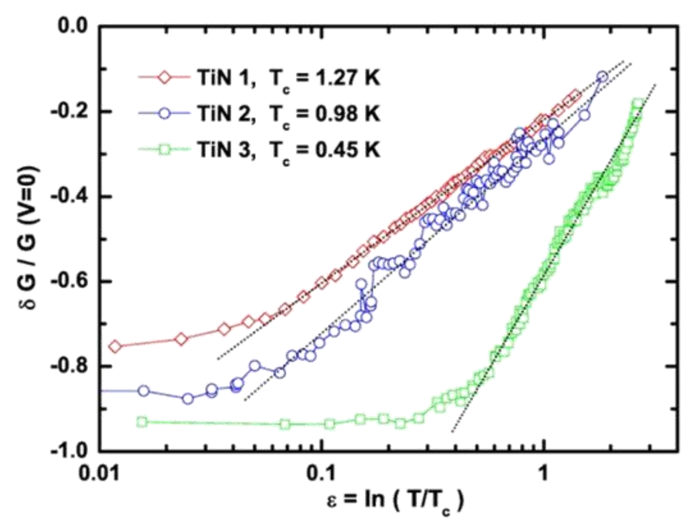
Thermal dependence of the Density of States

TiN Pseudogap above Tc





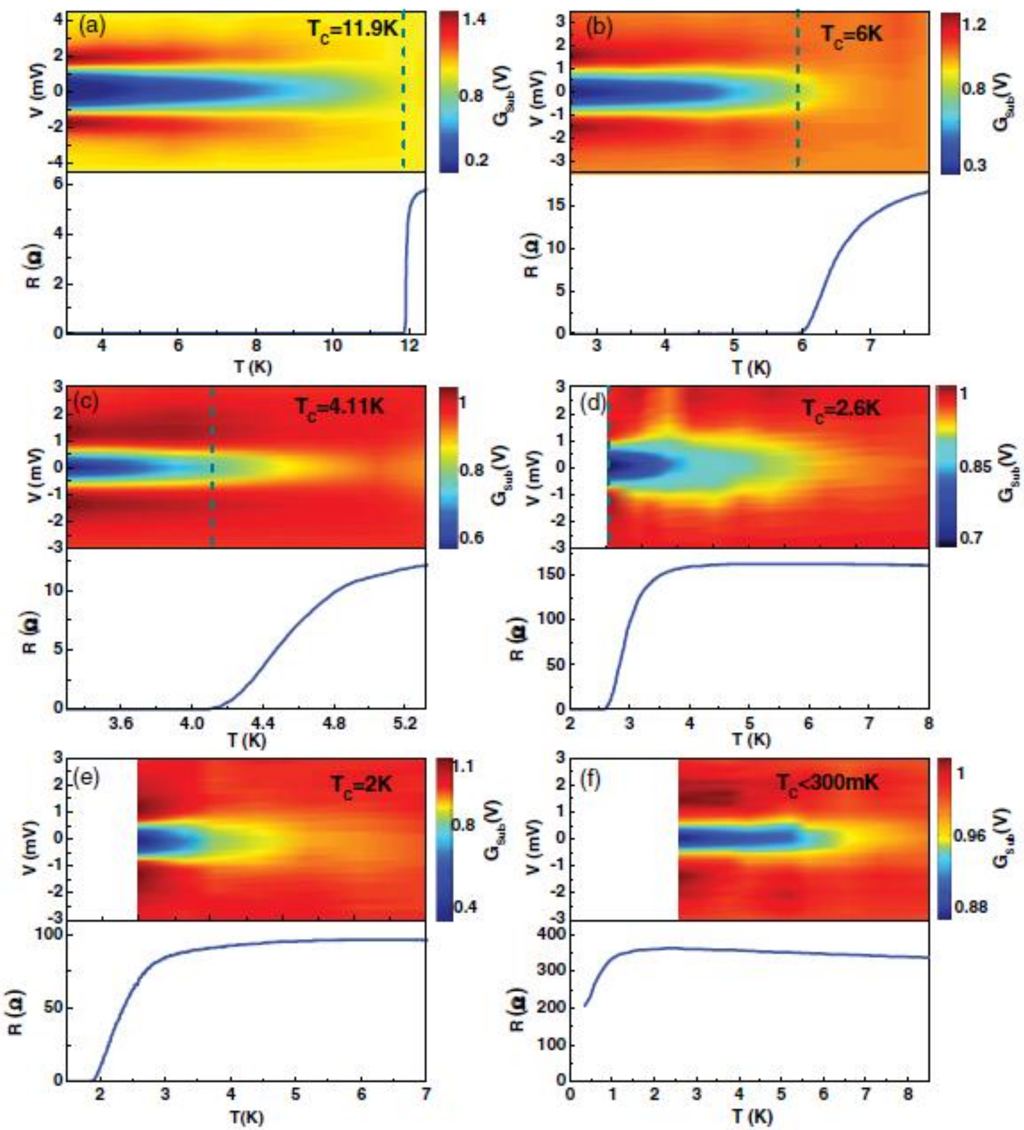




B. Sacépé et al., *Nat. Comm.*, (2010)

NbN

Pseudogap above Tc

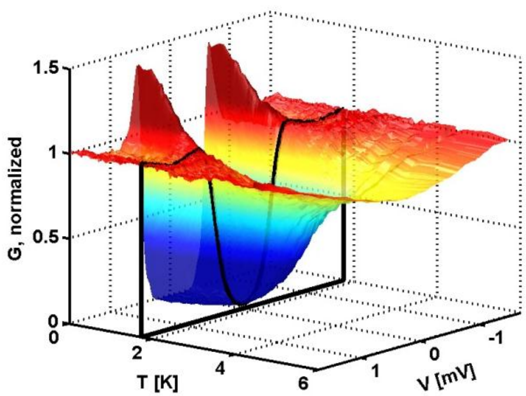


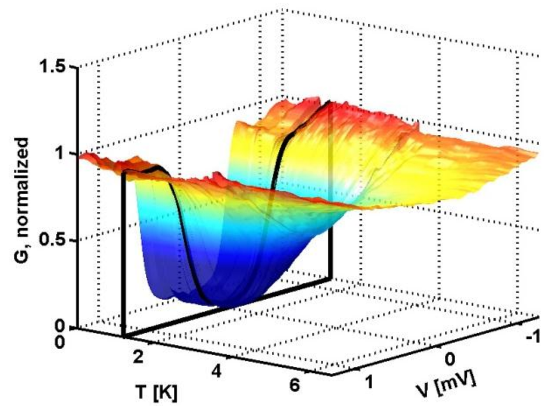
Madhavi Chand et al., *Phys. Rev. B* ***85***, *014508*, (2012)

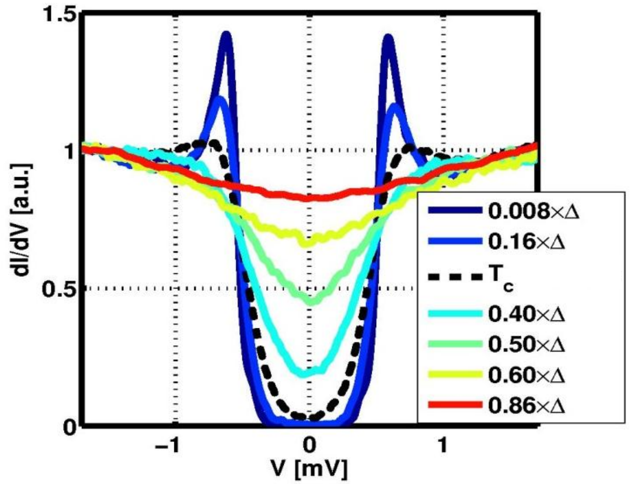
Thermal dependence of the Density of States

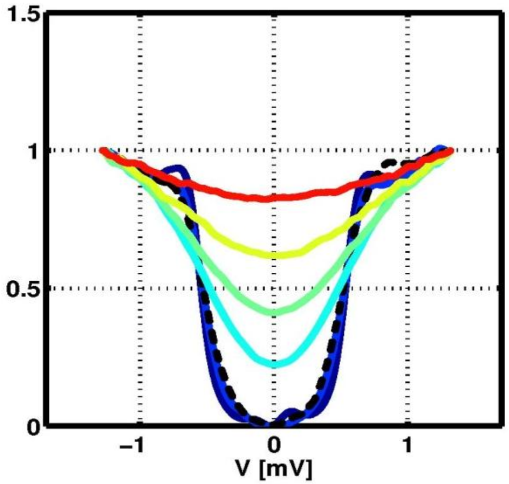
InO_x

Pseudogap above Tc

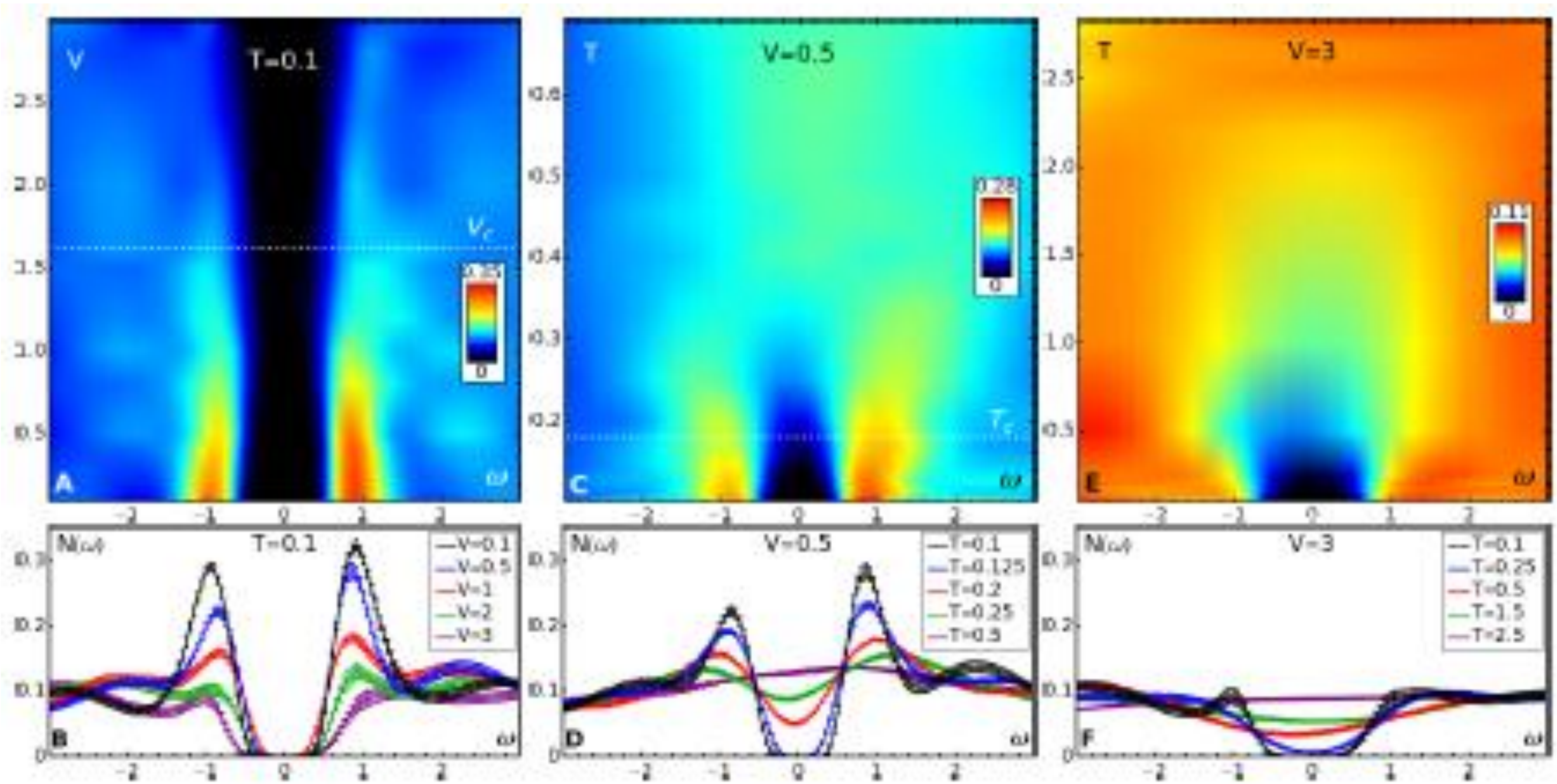








Thermal dependence of the Density of States



K. Bouadim, Y. L. Loh, M. Randeria, N. Trivedi, *Nat. Phys. 7, 884 (2011)*

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

M. Feigel'man *et al.*, *Ann. Phys.* **325,** 1390 (2010)

Coulomb interaction :

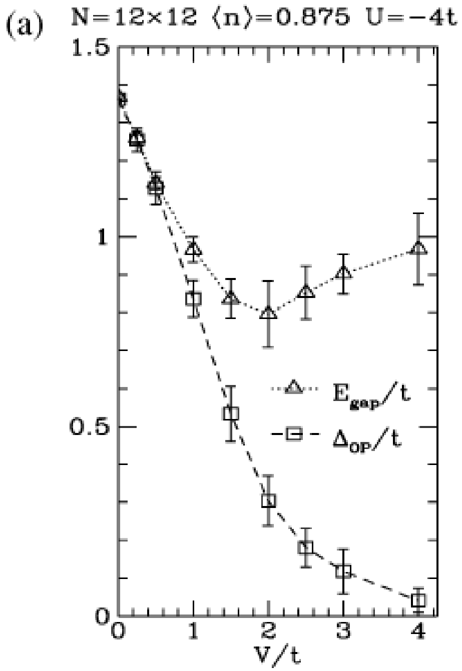
- Aronov-Altshuler anomaly at E_F
- Continuous decrease of Tc and Δ with disorder
- Keeps Δ/Tc ratio constant
- Spectra are often associated with a Dynes parameter
- Spatial mesoscopic fluctuations of Tc and subgap states

Localization :

- Tc decreases faster than Δ with disorder : huge Δ/Tc ratio
- Hard gap : no states at the Fermi level, no need of a Dynes parameter
- Strong spatial fluctuations of Δ
- Localized Cooper pairs characterized by spectra without coherence peaks
- Pseudogap abobe Tc due to preformed Cooper pairs

Fractal superconductivity near the mobility edge

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



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

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

Fractal superconductivity near the mobility edge

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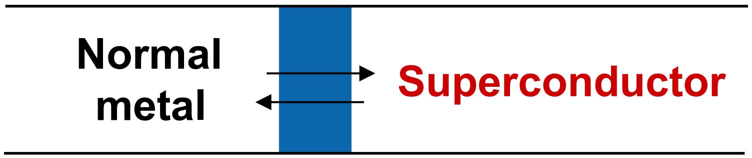
M. Feigel'man *et al.*, *Phys. Rev. Lett.* ***98***, 027001, (2007)
M. Feigel'man *et al.*, *Ann. Phys.* **325,** 1390 (2010)

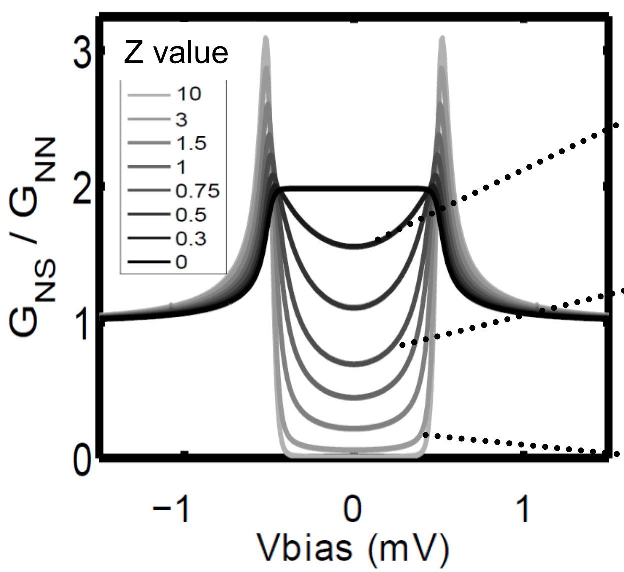
Barrier : parameter Z



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

Contact regime

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

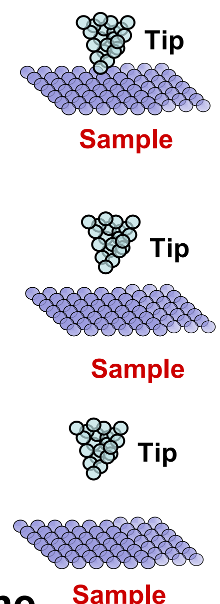


Z » 1

Z ~ 1

Z « 1

Tunnel regime



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

- Point-contact spectroscopy

(Andreev reflection = transfer of pairs)

Transparent interface

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

- Tunneling spectroscopy

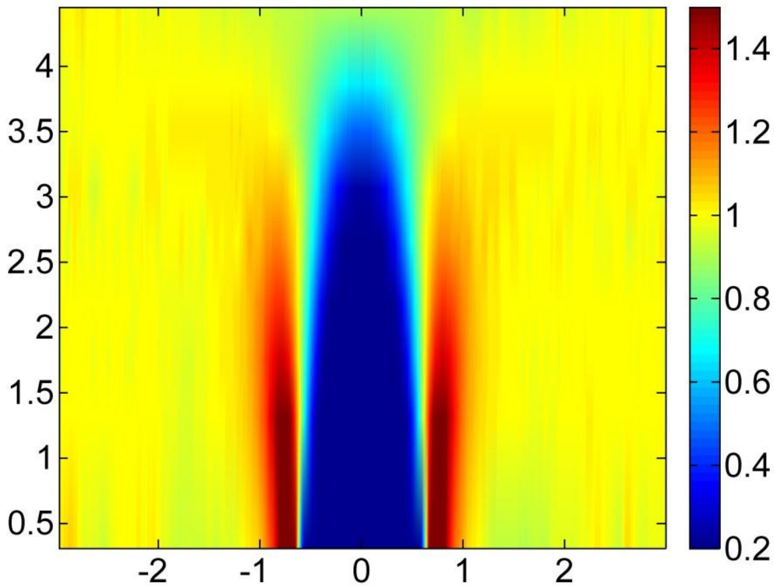
(single-particle DOS)

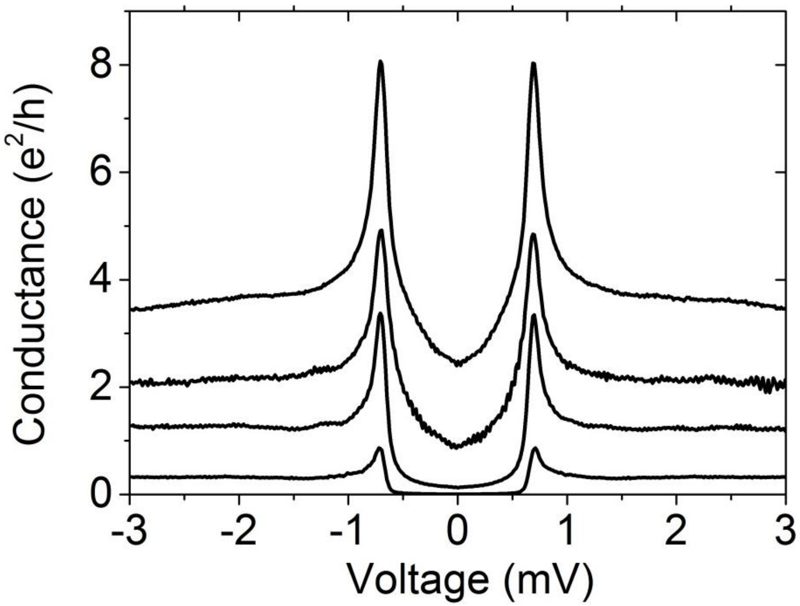
Tunnel barrier

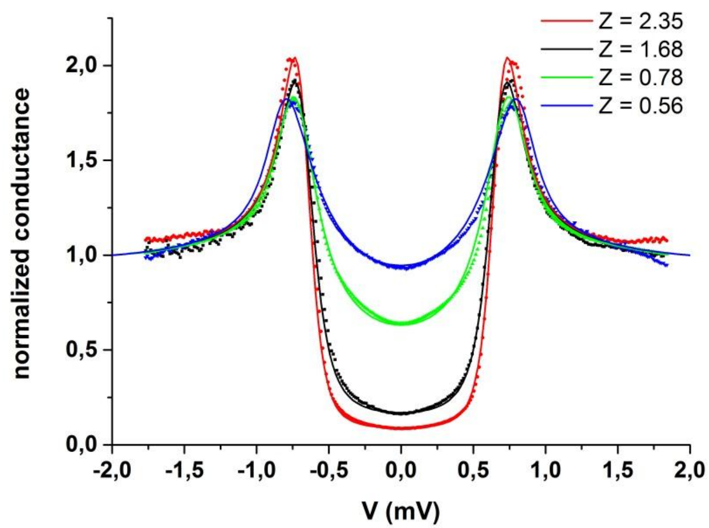
Point-Contact Andreev Spectroscopy

InO_x

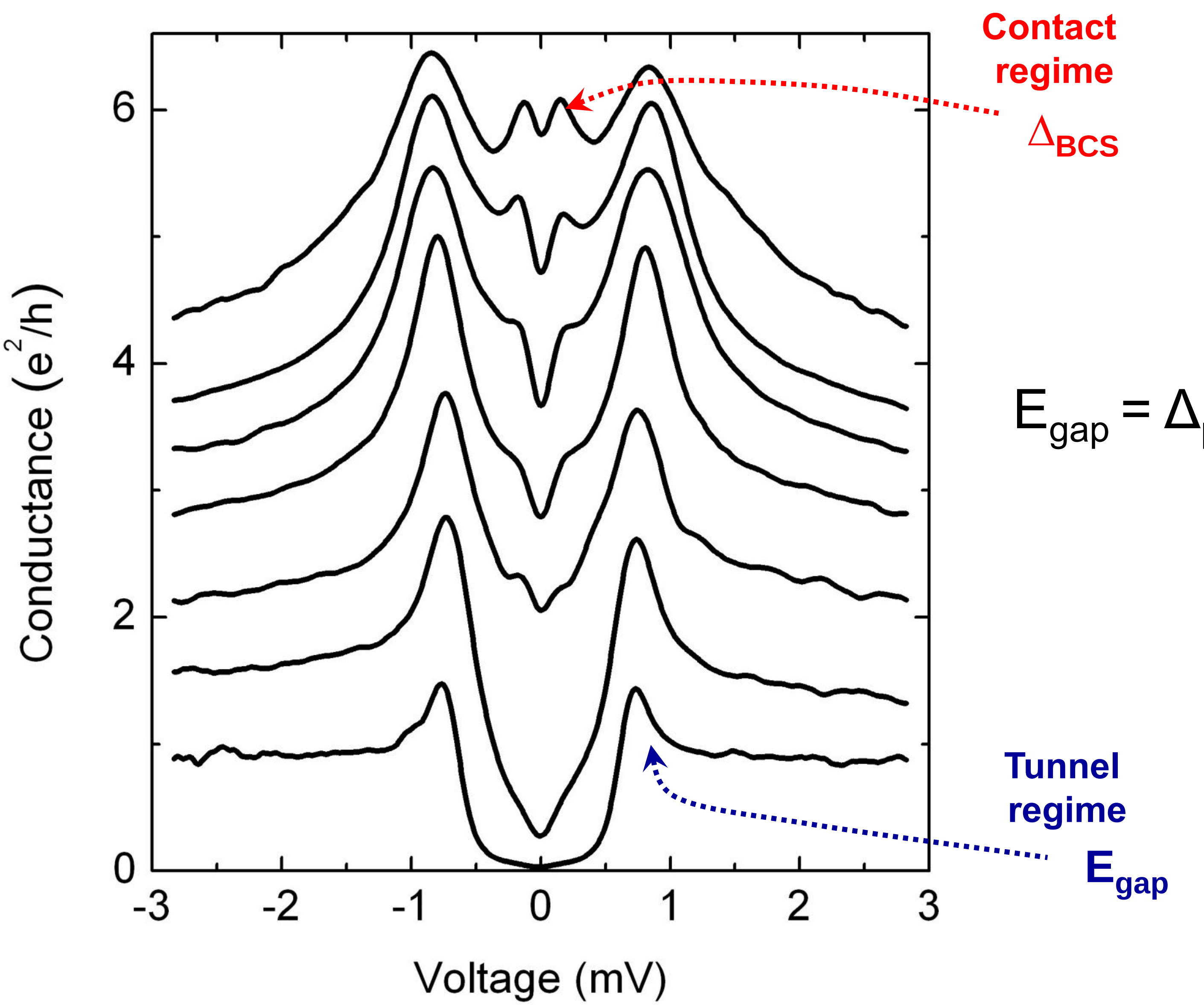
InOx film far from the Superconductor-Insulator Transition : Tc = 3.5K







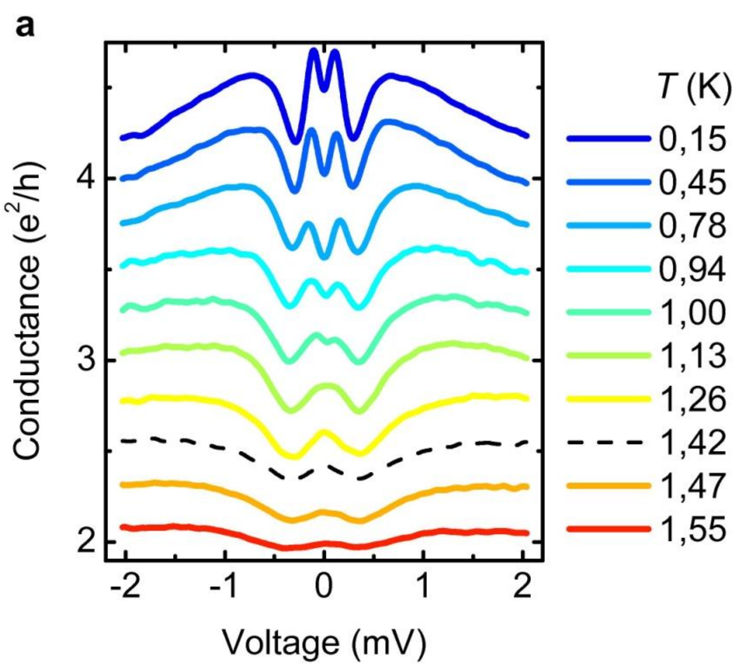
InO_x From tunnel to contact in disordered InOx film Tc = 1.2 K

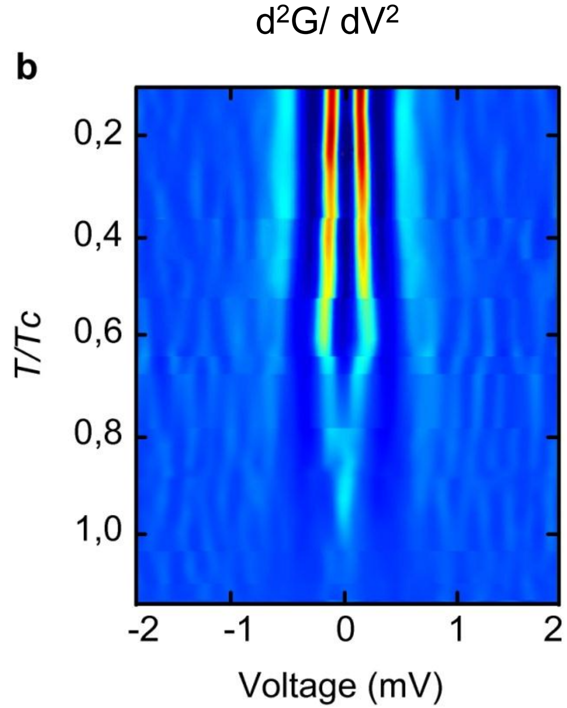


$$E_{gap} = \Delta_p + \Delta_{BCS}$$

InO$_x$

T-evolution of Andreev signal



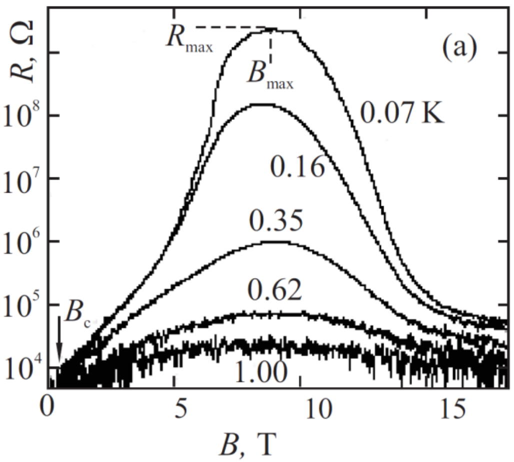


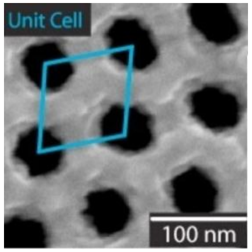
$$E_{gap}(T) = \Delta_p + \Delta_{BCS}(T)$$

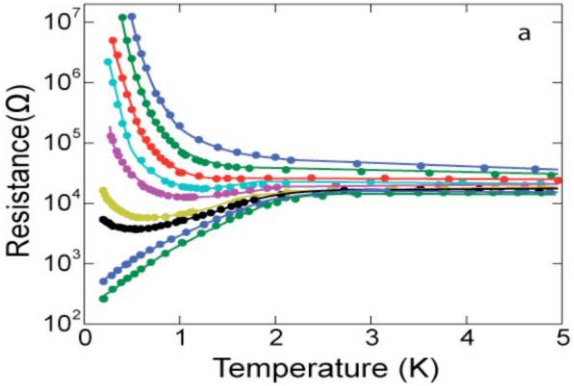
. E_{gap} evolves between 0 and ~3-4T_c

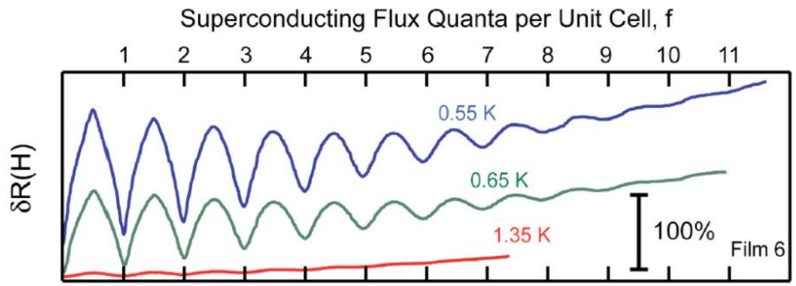
. Δ_{BCS} evolves between 0 and ~ T_c

Magnetic field studies through the SIT





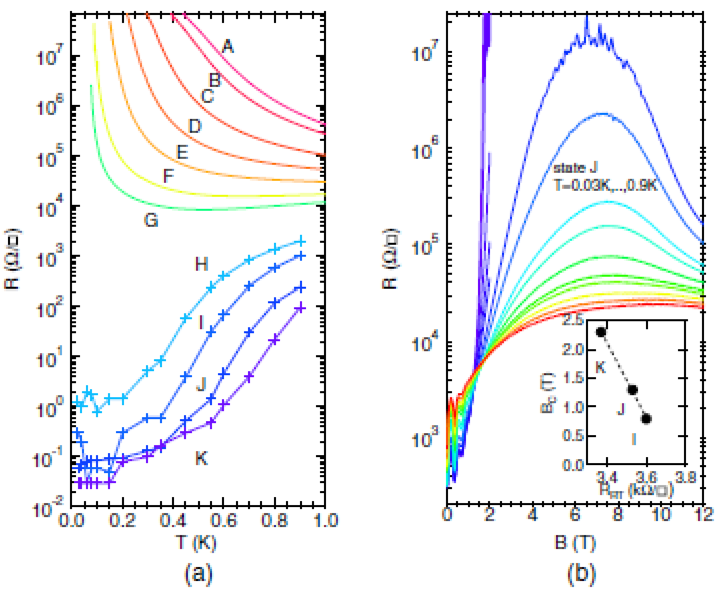


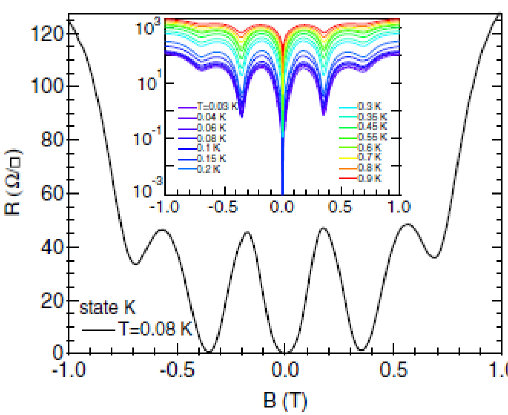


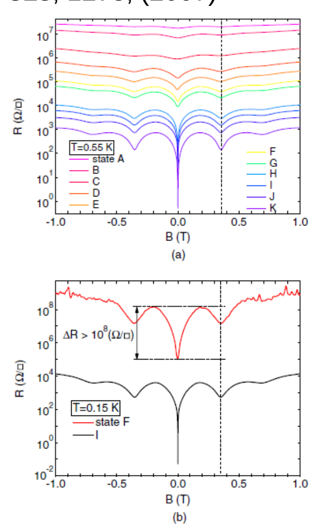
G. Sambandamurthy *et al., Phys. Rev. Lett.* ***92***, 107005, (2004)

Stewart, Jr. *et al.* , *Science* **318**, 1273, (2007)

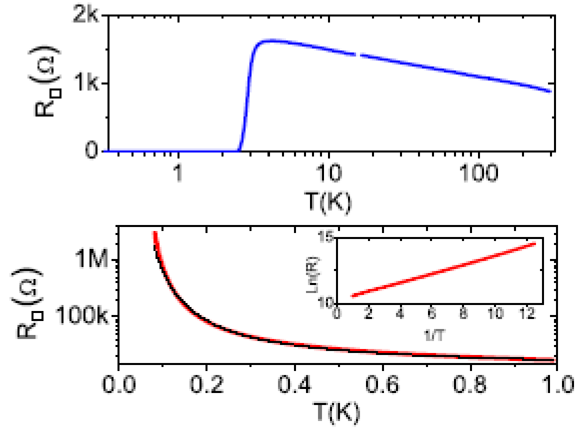
G. Kopnov*et al., Phys. Rev. Lett.* ***109***, 167002, (2012)

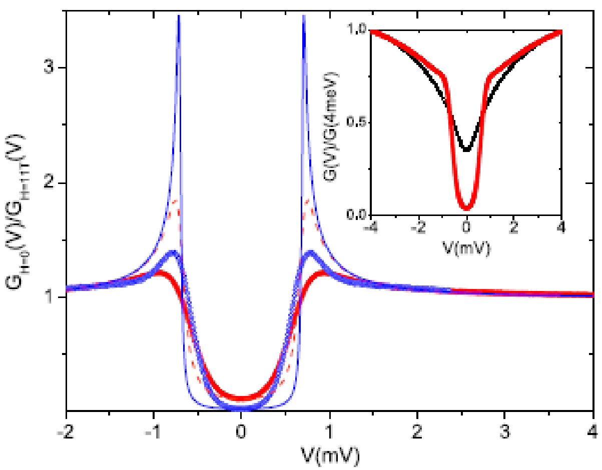


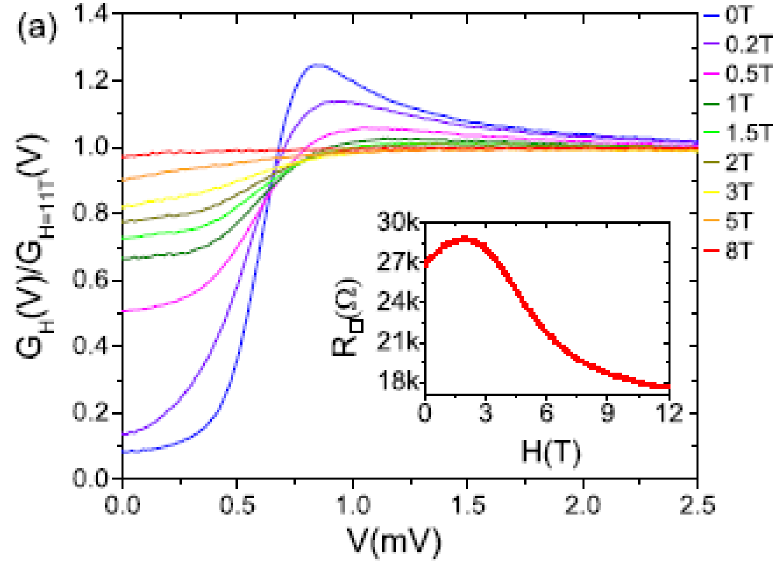


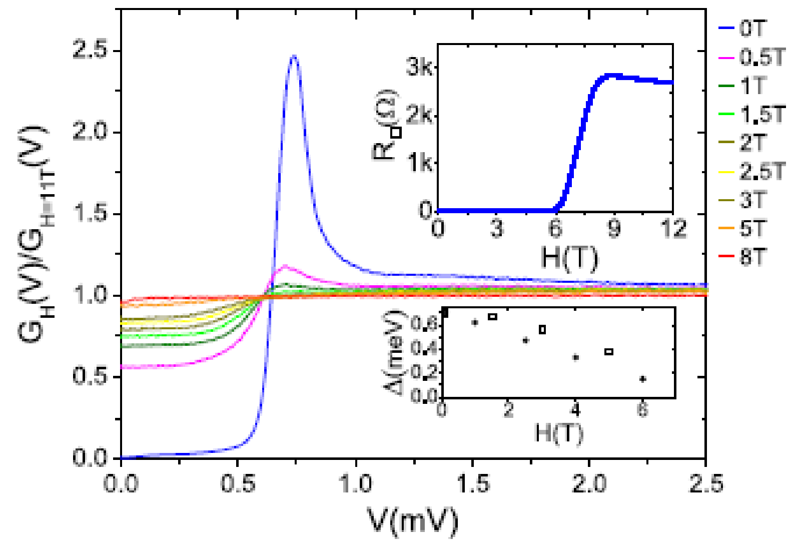


Magnetic field studies through the SIT



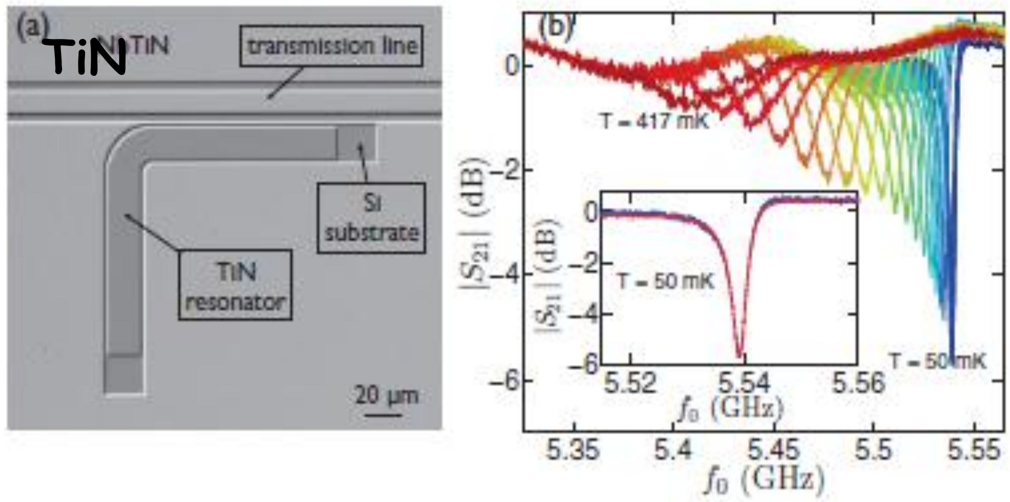


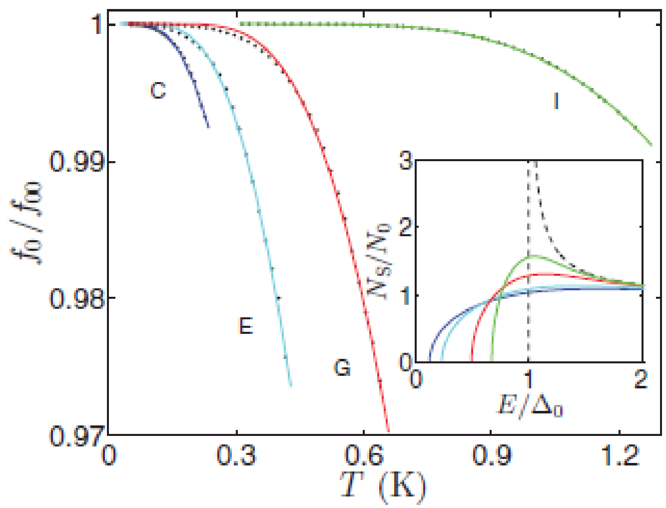




D. Sherman et *al.*, *Phys. Rev. Lett.* ***108***, 177006, (2012)

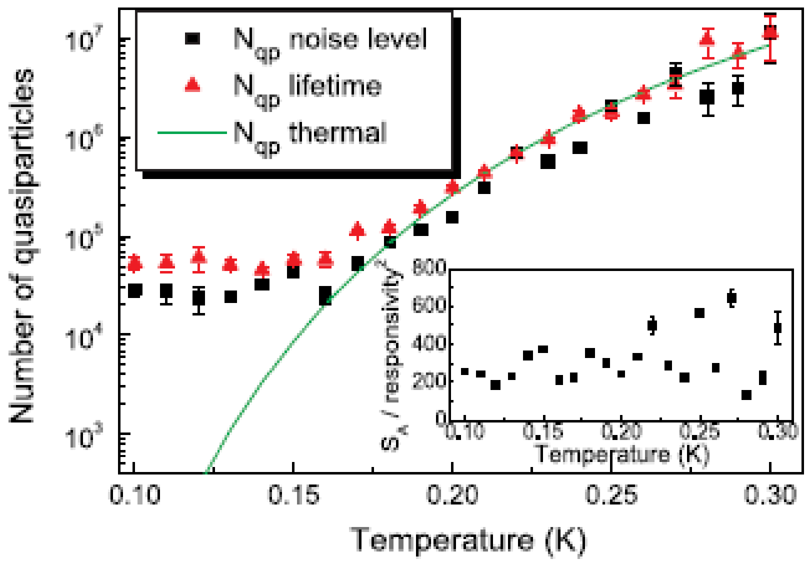
Photon detectors



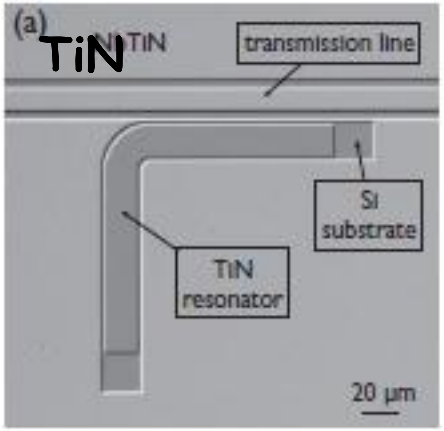


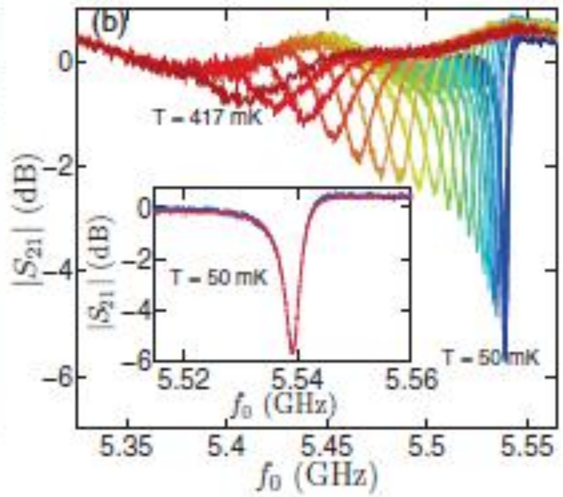
E.F.C. Driessen et *al.*, *Phys. Rev. Lett.* ***109***, 107003, (2012)

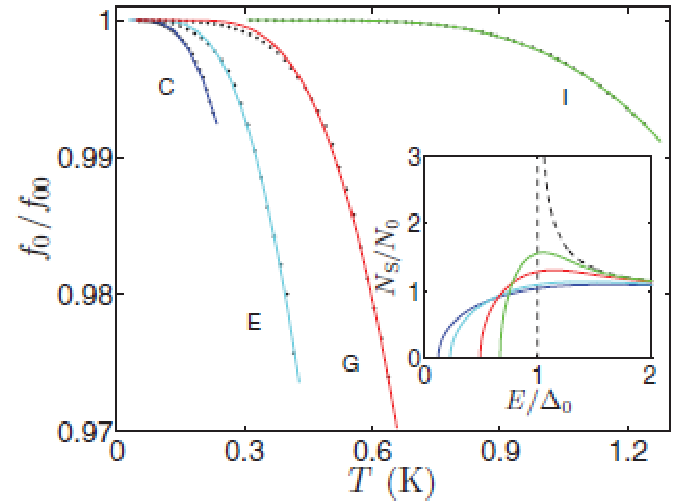
M.V. Feigelman and M.A. Skvortsov, *Phys. Rev. Lett.* ***109***, 147002 (2012)



P.J. de Visser et al.,Phys. Rev. Lett. 106, 167004 (2011)

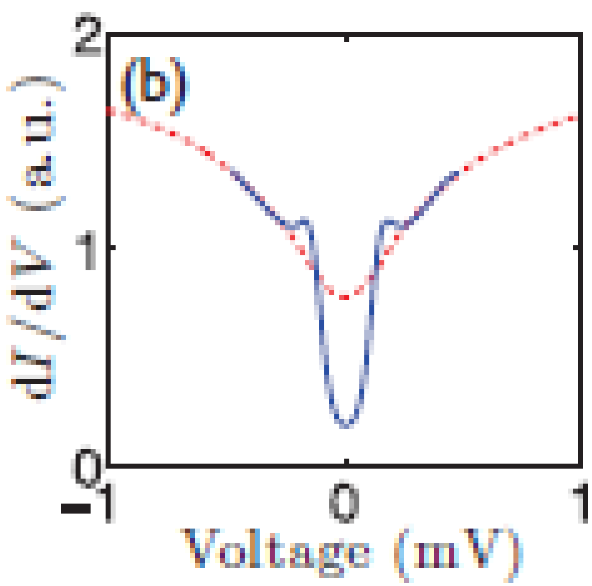


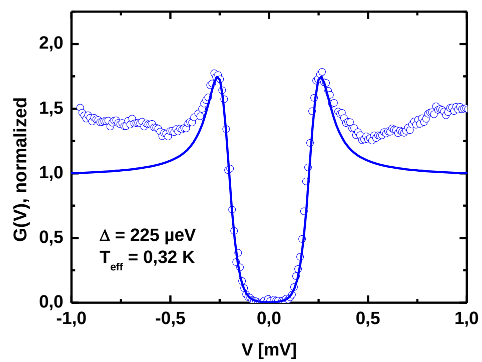


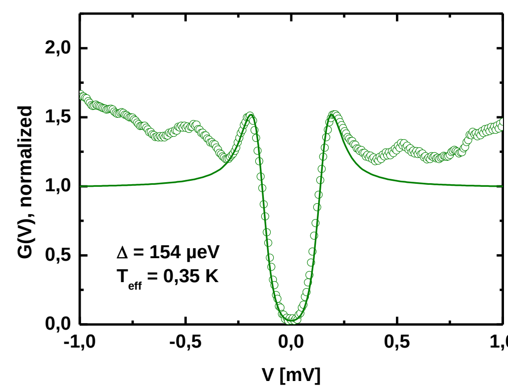


DRIESSEN et *al.*, *Phys. Rev. B* ***88***, 180505(R), (2013)

M.V. Feigelman and M.A. Skvortsov, *Phys. Rev. Lett.* ***109***, 147002 (2012)

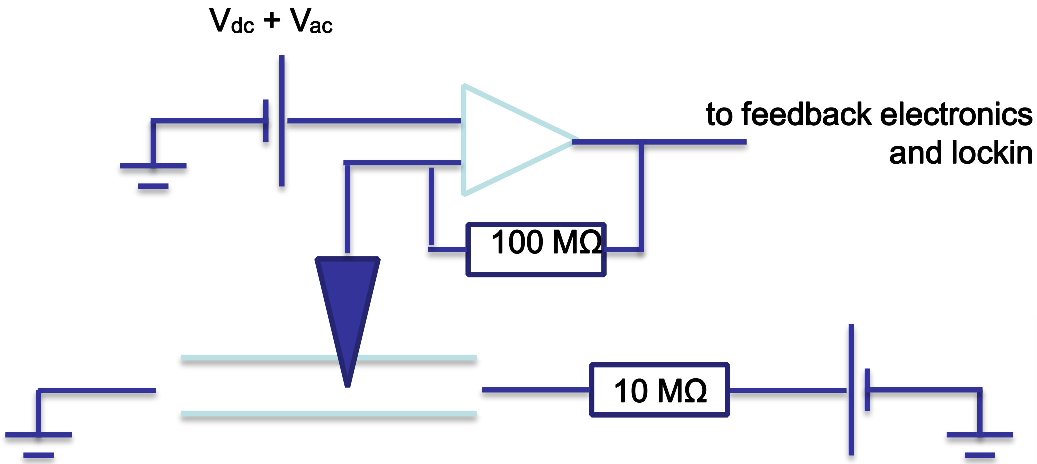


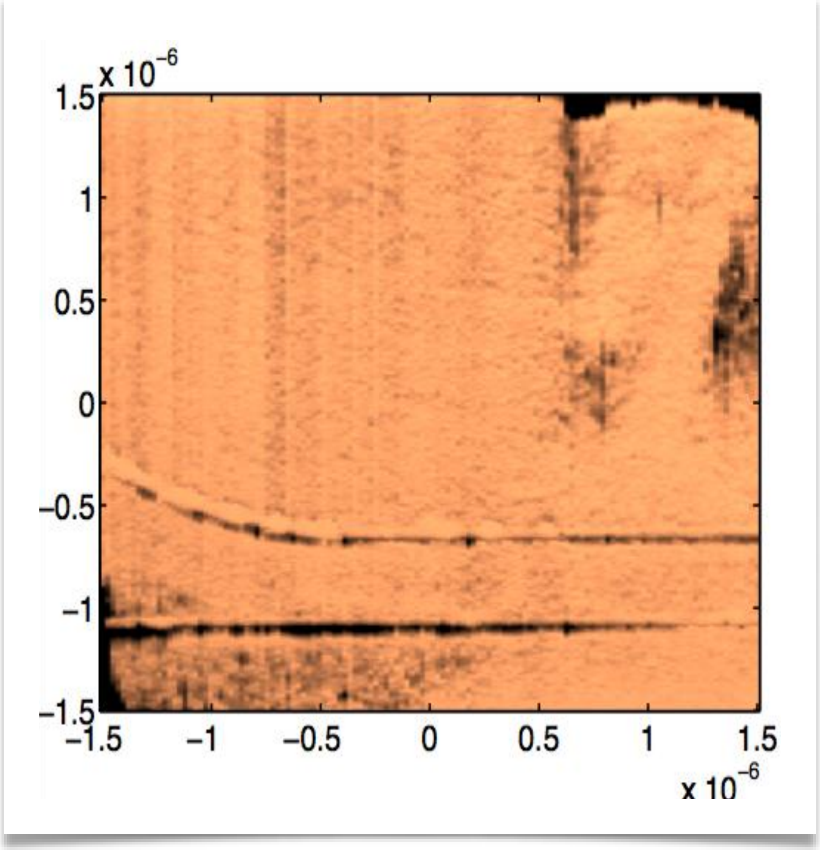




P.C.J.J. Coumou et *al.*, *Phys. Rev. B* ***88***, 180505(R), (2013)

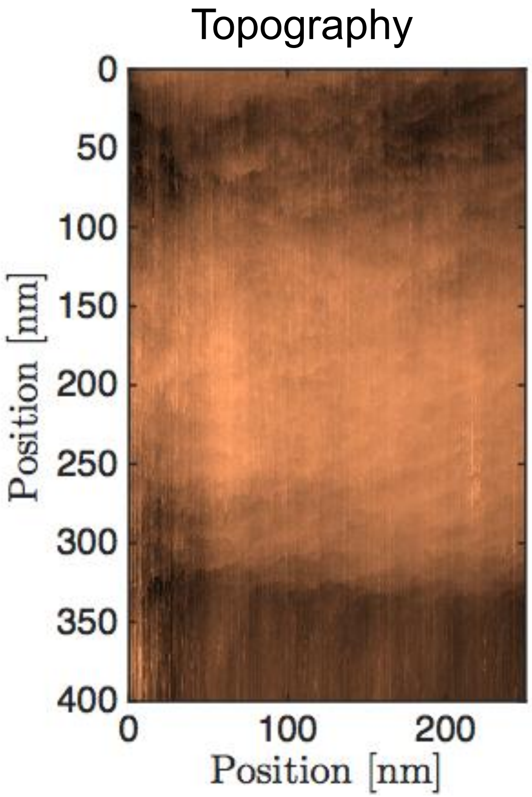
TiN



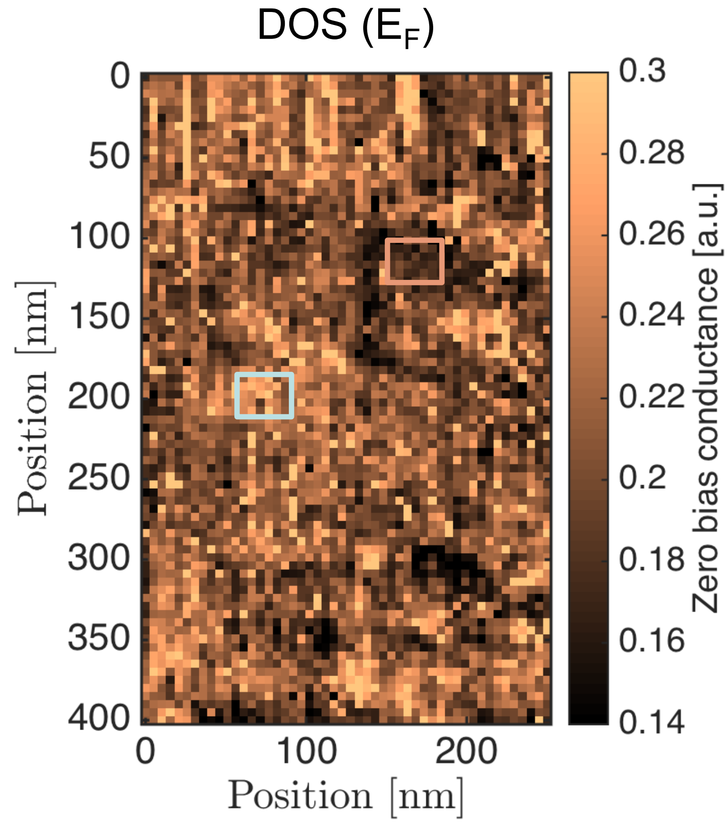


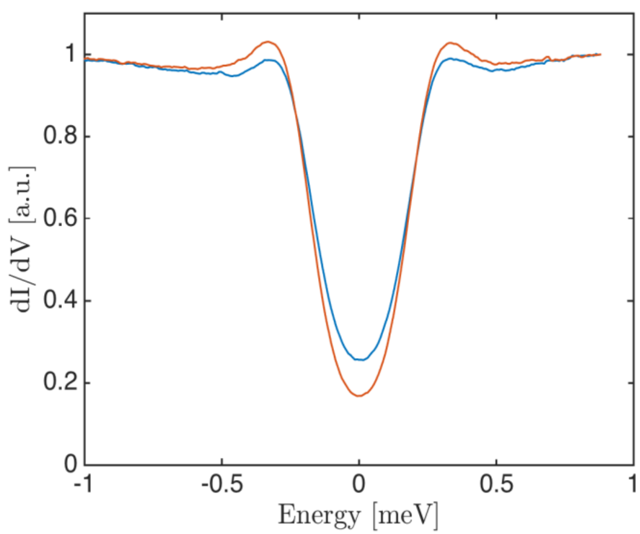
- Device fabrication in Kavli Nanolab
- Nanowire: 5nm x 200 nm x 4 μm
- T_c = 1.5 K, R_s = 1.5 kΩ
- Δ = 300 μV, Δ/T_c = 2.5

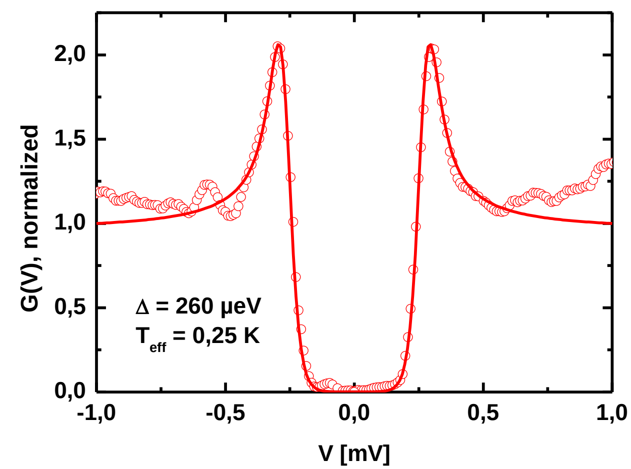
Inhomogeneous superconducting state



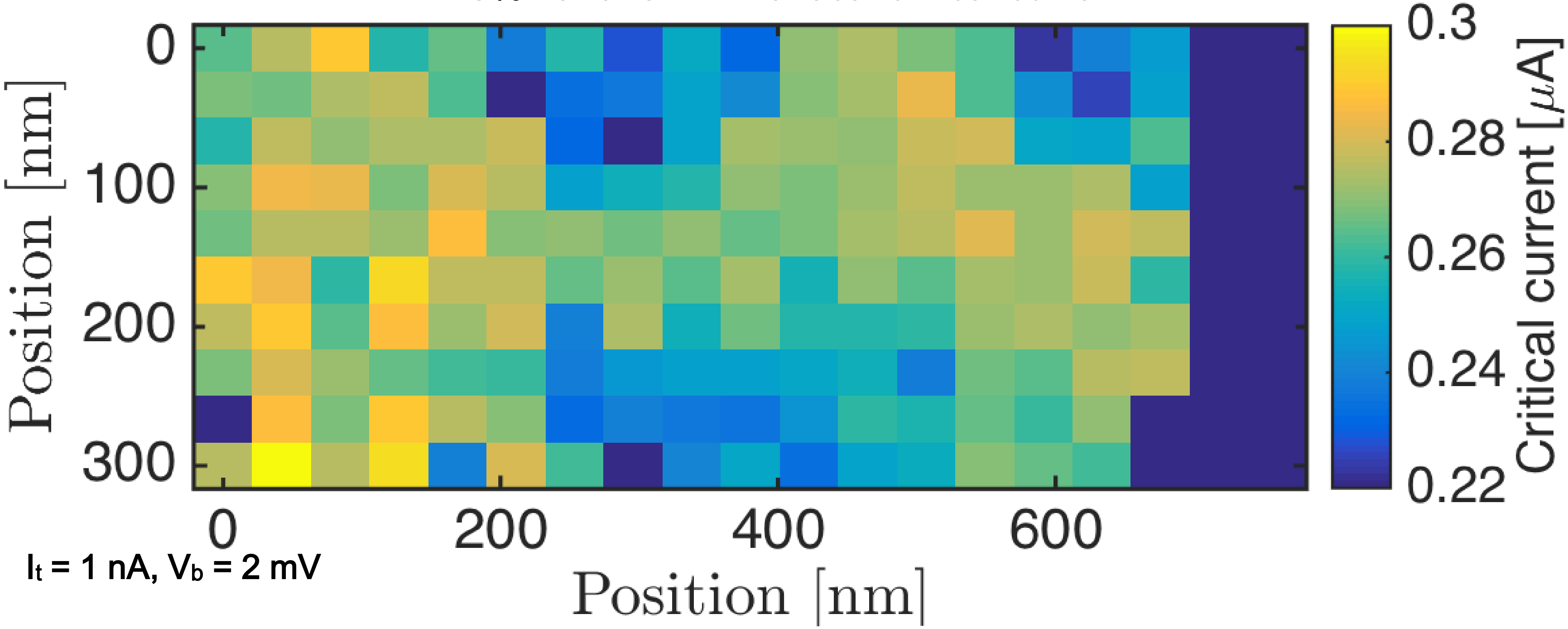
TiN



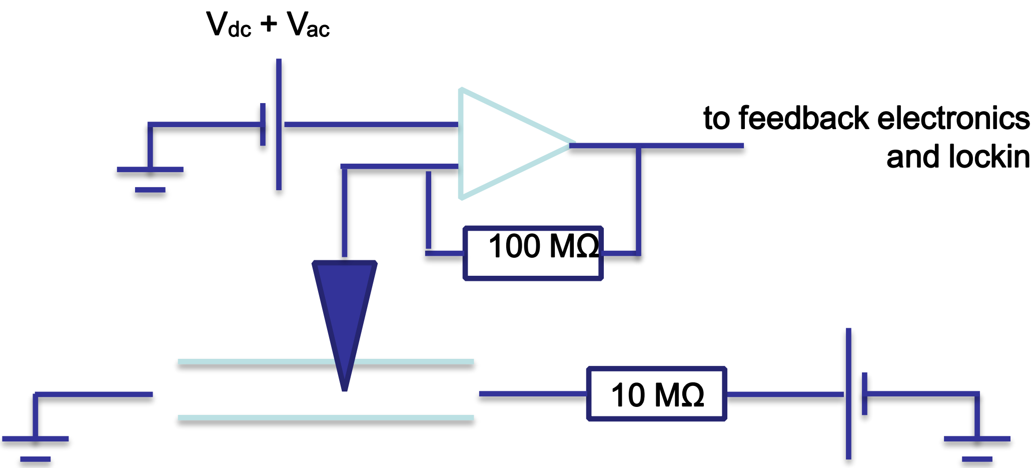


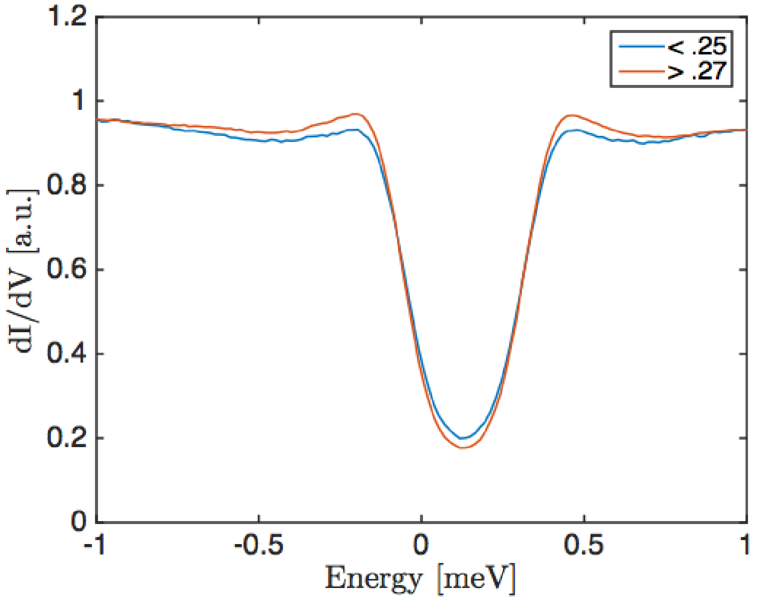


25% variation in the local critical current!

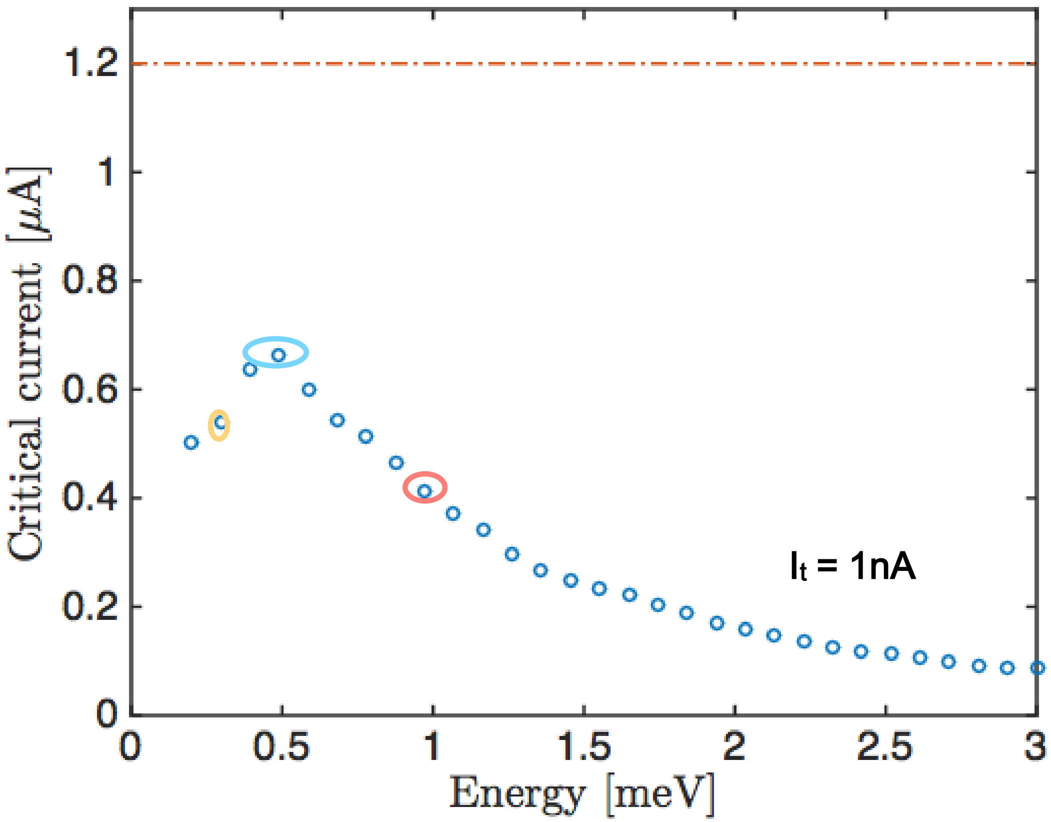


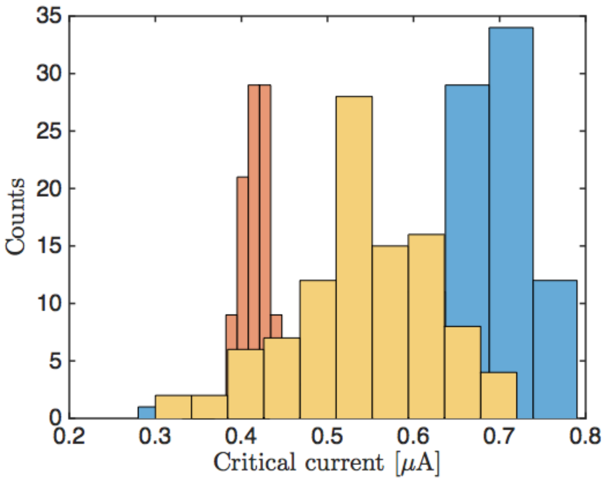
I_t = 1 nA, V_b = 2 mV





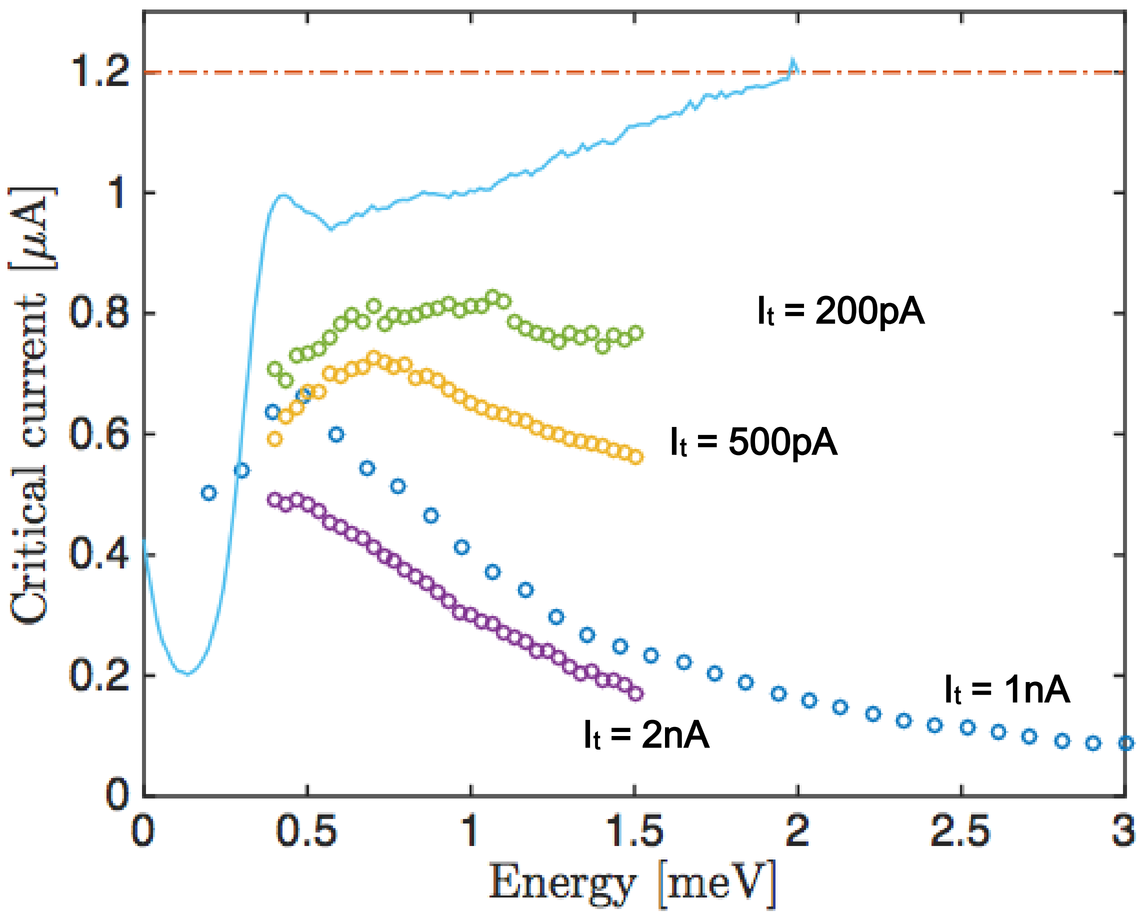
Local non-equilibrium!





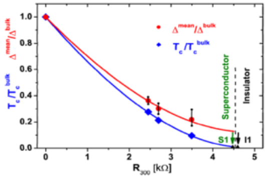
Critical current microscopy

Quasiparticles close to the gap

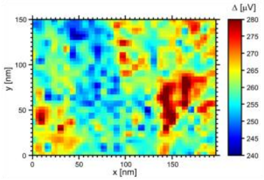


Conclusion

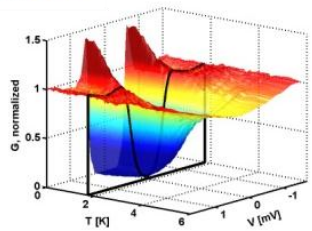
- Coulomb interaction and localization play different roles in the SIT



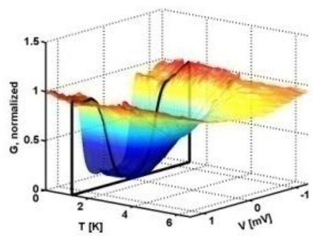
- Inhomogeneous superconducting state



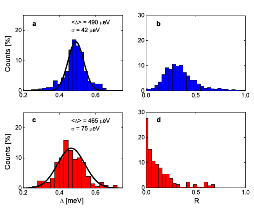
- Pseudogap : Preformed Cooper-Pairs above Tc



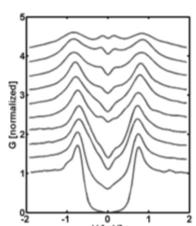
- Localized Cooper pairs below Tc



- SIT occurs through the localization of Cooper-pairs in InO_x



- Distinct energy scales for pairing and coherence



- Local critical current microscopy