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*International Centre for Theoretical Physics*



**2035-19**

**Conference on Superconductor-Insulator Transitions**

*18 - 23 May 2009*

**Fluctuations in thin superconducting TiN films**

C. Chapelier  
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France*

# Fluctuations in thin superconducting TiN films

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

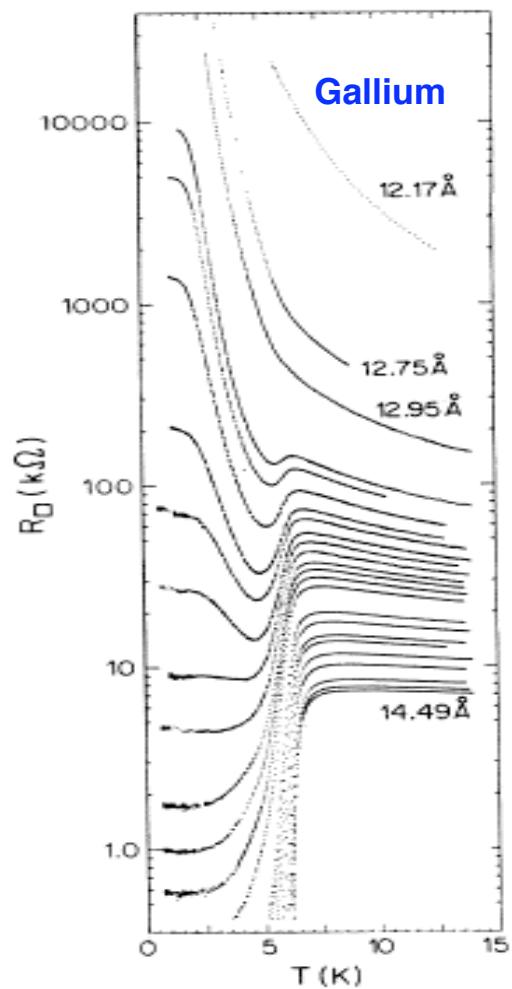
M. Baklanov, A Satta, *IMEC, Leuven*

# **Fluctuations in thin superconducting TiN films**

- TiN : homogeneously disordered superconductor
- Tunneling spectroscopy at  $T=50\text{mK}$
- Pseudogap regime above  $T_c$

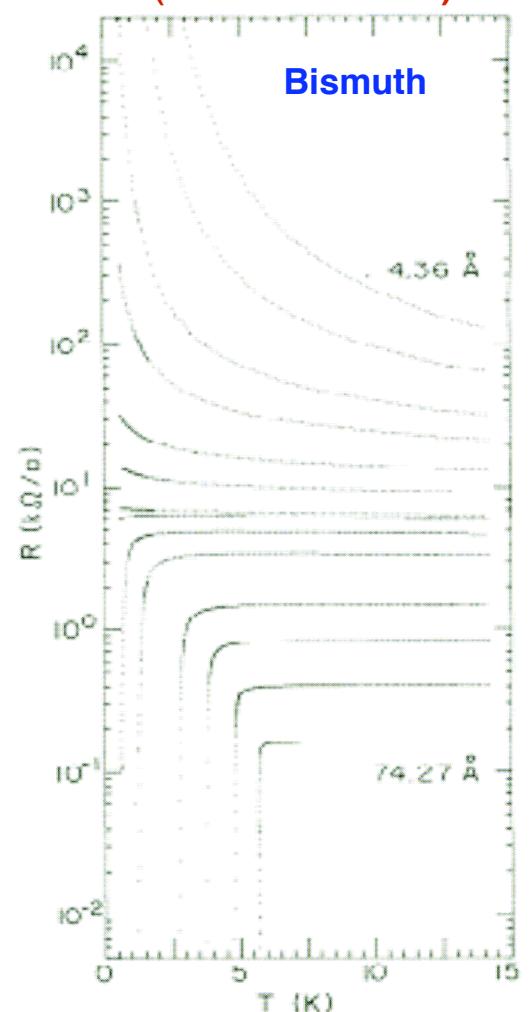
## Superconductor-Insulator Transition

**Granular systems**  
(bosonic model)



H. M. Jaeger, D. B. Haviland, A. M. Goldman and B. G. Orr  
Phys. Rev. B 34, 4920 (1986).

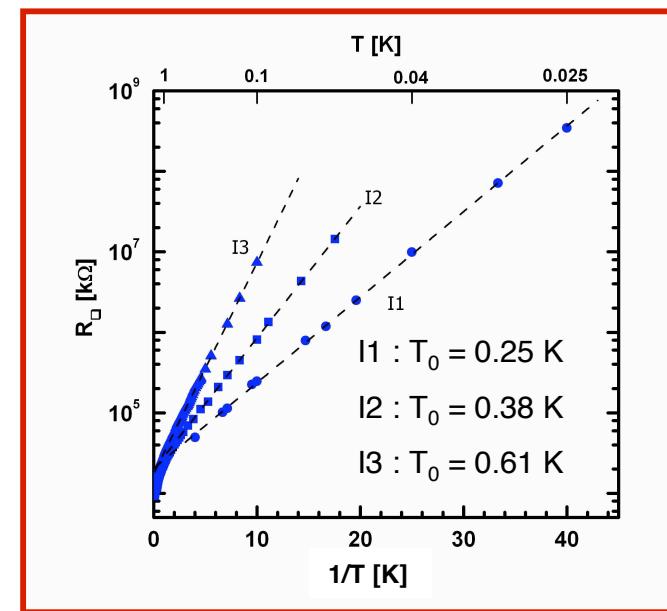
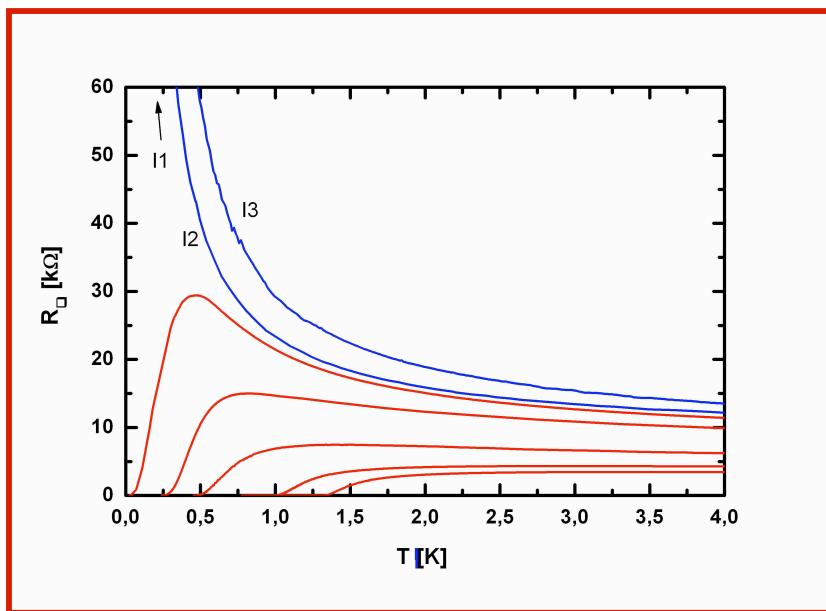
**Homogeneously disordered materials**  
(fermionic model)



D. B. Haviland, Y. Liu and A. M. Goldman  
Phys. Rev. Lett. 62, 2180 (1989).

## Titanium nitride thin films $d = 5 \text{ nm}$

Continuous decrease of  $T_c$  with increasing disorder

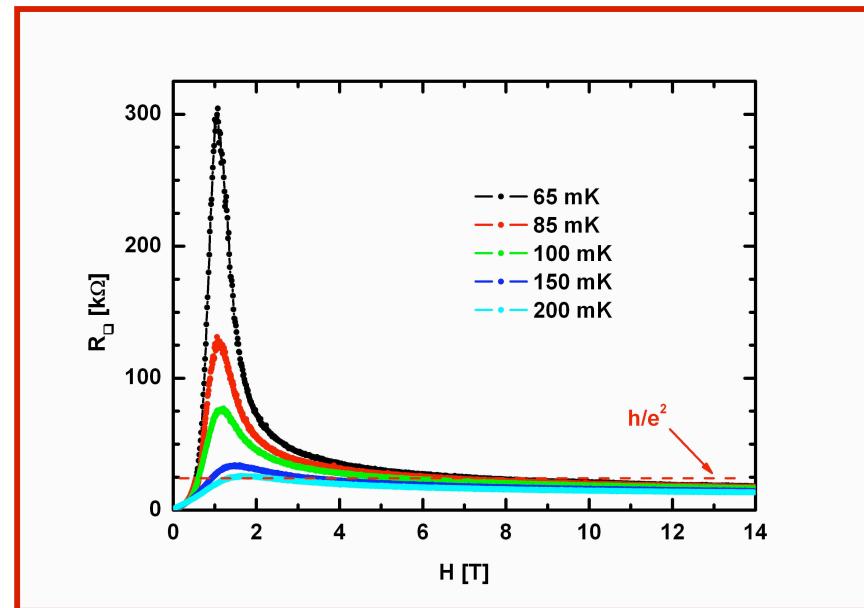
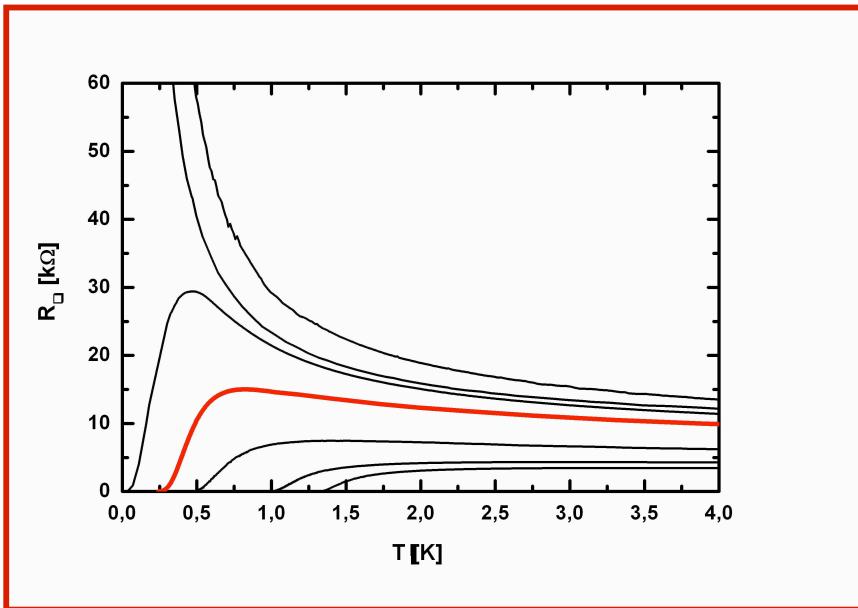


Activated behavior : superconductivity related ?

T. I. Baturina, A Yu Mironov, V. M. Vinokur, M. R. Baklanov and C. Strunk

PRL 99, 257003 (2007)

## Magneto-resistance peak

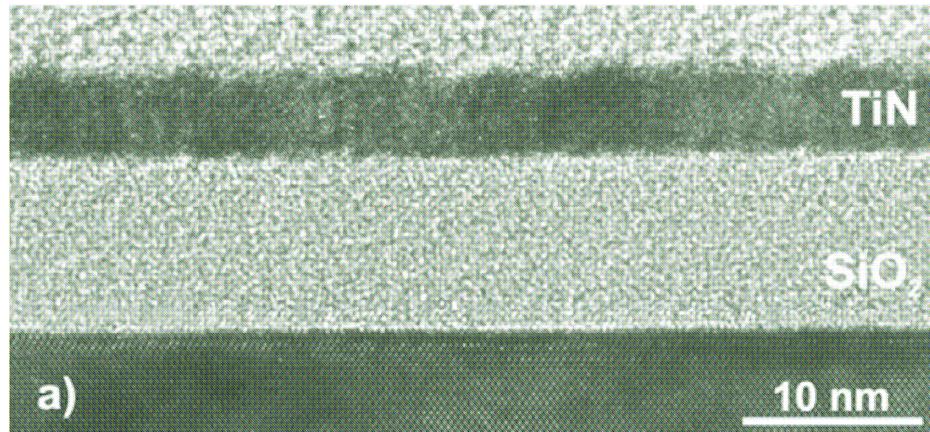


Magneto-resistance peak : superconductivity related ?

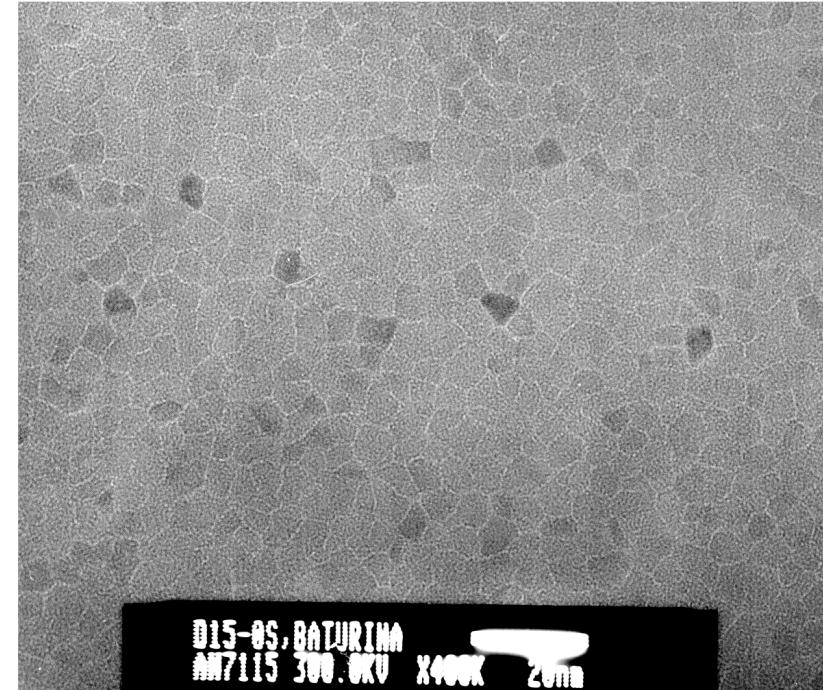
T. I. Baturina, C. Strunk, M. R. Baklanov, and A. Satta

PRL 98, 127003 (2007)

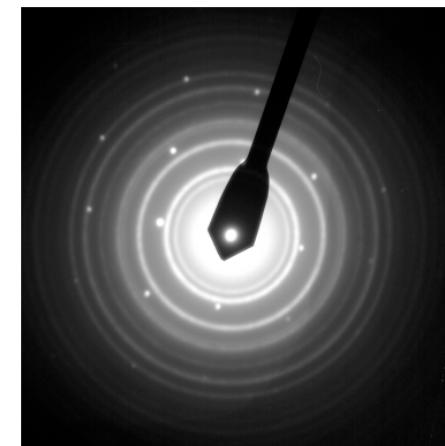
## TiN

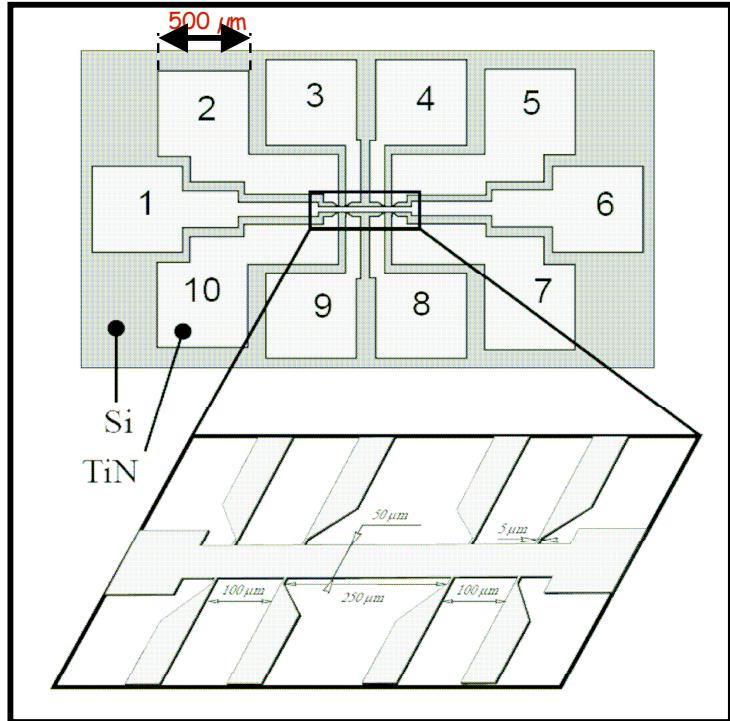


M. Baklanov and A. Satta  
IMEC



- TiN films were formed by **atomic layer chemical vapor deposition** (ALCVD) onto a Si/SiO<sub>2</sub> substrate.
- The films consist of **densely-packed crystallites**
- The average size of the crystallites is ~ 4-6 nm





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

Transport measurements and STM spectroscopy are performed during the same run

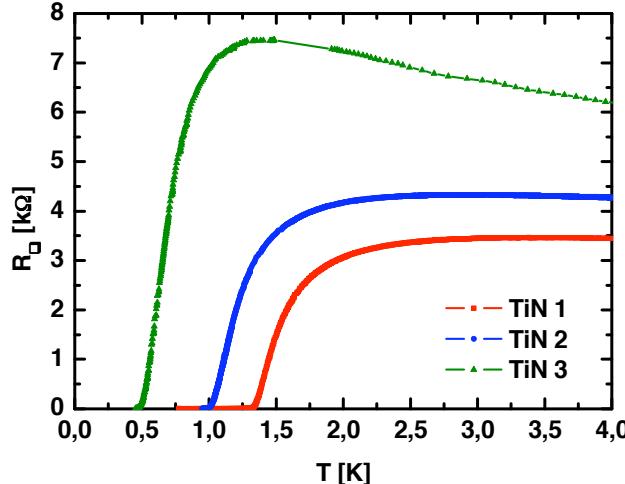
# Fluctuations in thin superconducting TiN films

- TiN : homogeneously disordered superconductor
- Tunneling spectroscopy at T=50mK
- Pseudogap regime above T<sub>c</sub>

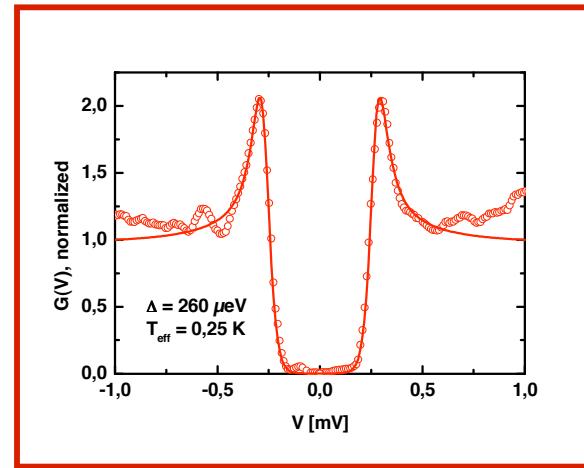
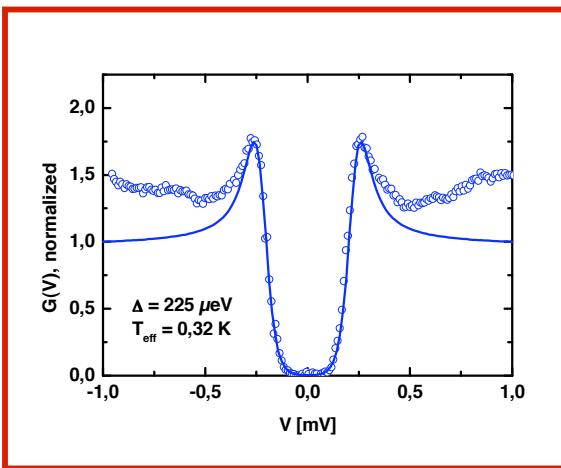
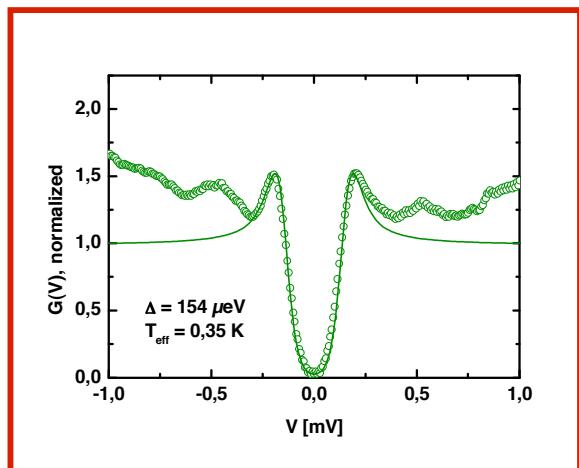
## Tunneling spectroscopy at 50 mK

### Transport and tunneling spectroscopy

Sacépé et al.  
PRL 101, 157006 (2008)



$T_c$ [K]	$\Delta/T_c$
4.7	1.8
1.3	2.3
1	2.6
0.45	4



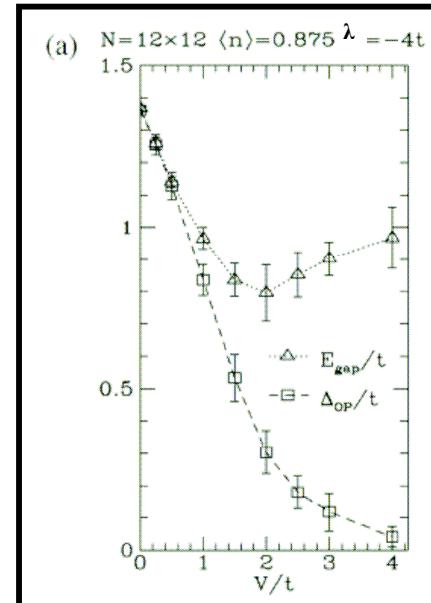
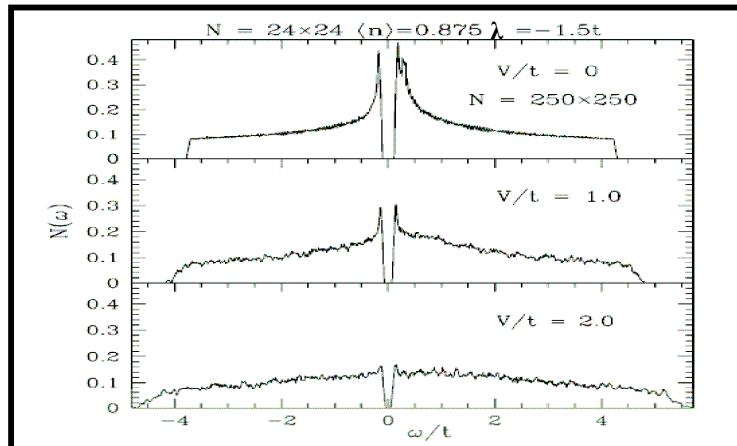
Increasing disorder

## Tunneling spectroscopy at 50 mK

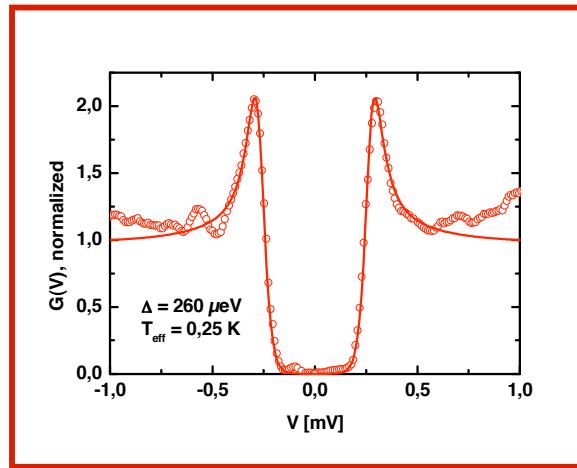
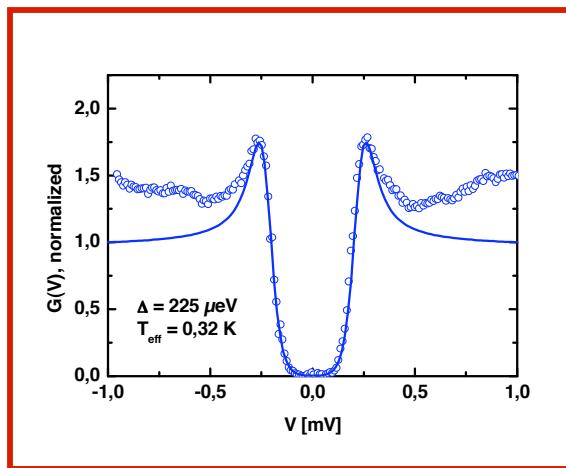
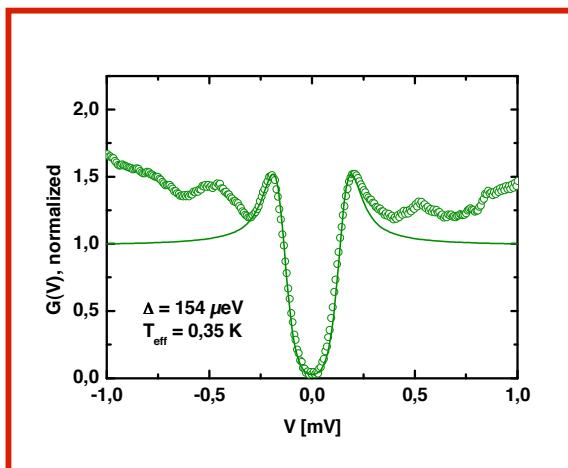
A. Ghosal, M. Randeria, N. Trivedi, *Phys. Rev. Lett.* **81**, 3940, (1998) - *Phys. Rev. B* **65**, 014501 (2001)

$$H_0 = -t \sum_{\langle i,j \rangle, \sigma} (c_{i\sigma}^\dagger c_{j\sigma} + h.c.) + \sum_{i,\sigma} (V_i - \mu) n_{i,\sigma}$$

$$H_{int} = - |U| \sum_i (n_{i\uparrow} n_{i\downarrow})$$



$T_c$ [K]	$\Delta/T_c$
4.7	1.8
1.3	2.3
1	2.6
0.45	4



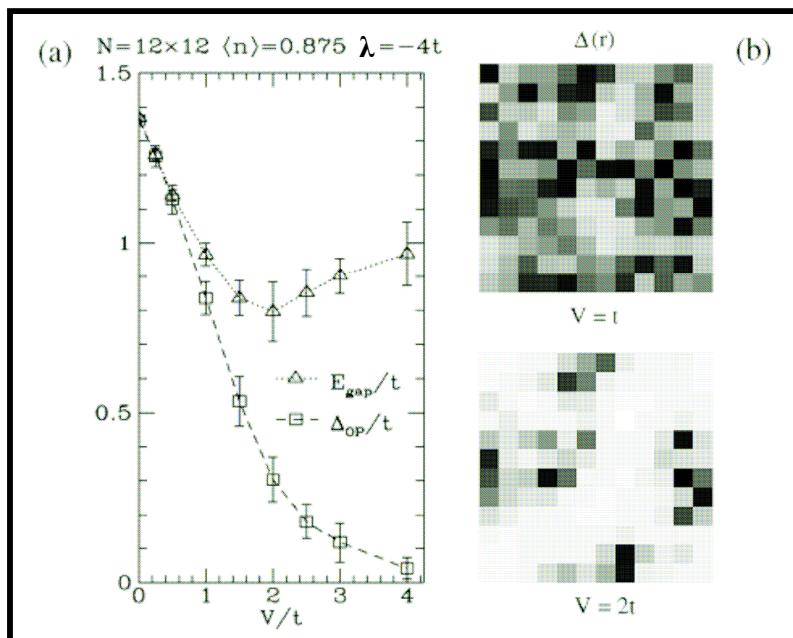
Increasing disorder

## Tunneling spectroscopy at 50 mK

### Inhomogeneous superconducting state

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

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

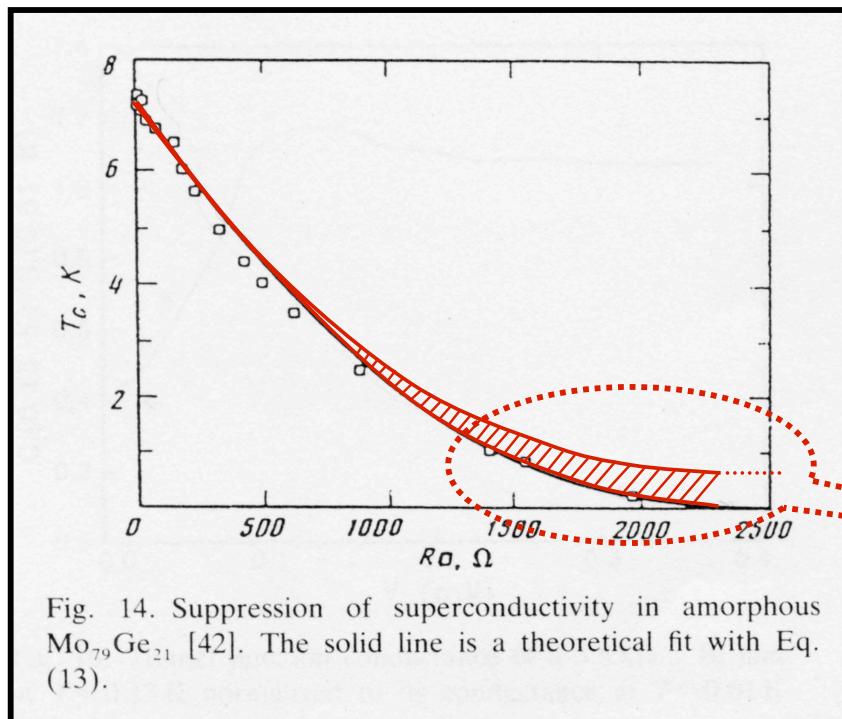


## Tunneling spectroscopy at 50 mK

### Coulomb suppression and mesoscopic fluctuations of Tc

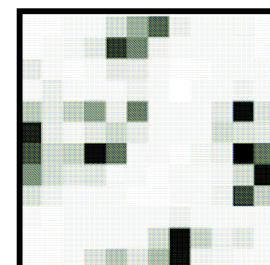
A. M. Finkelstein, Pis'sma Zh. Eksp. Theor. Fiz., **45**, 46 (1987)

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

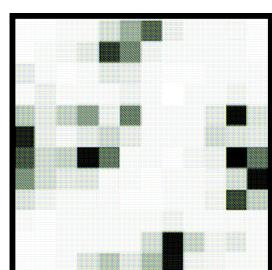
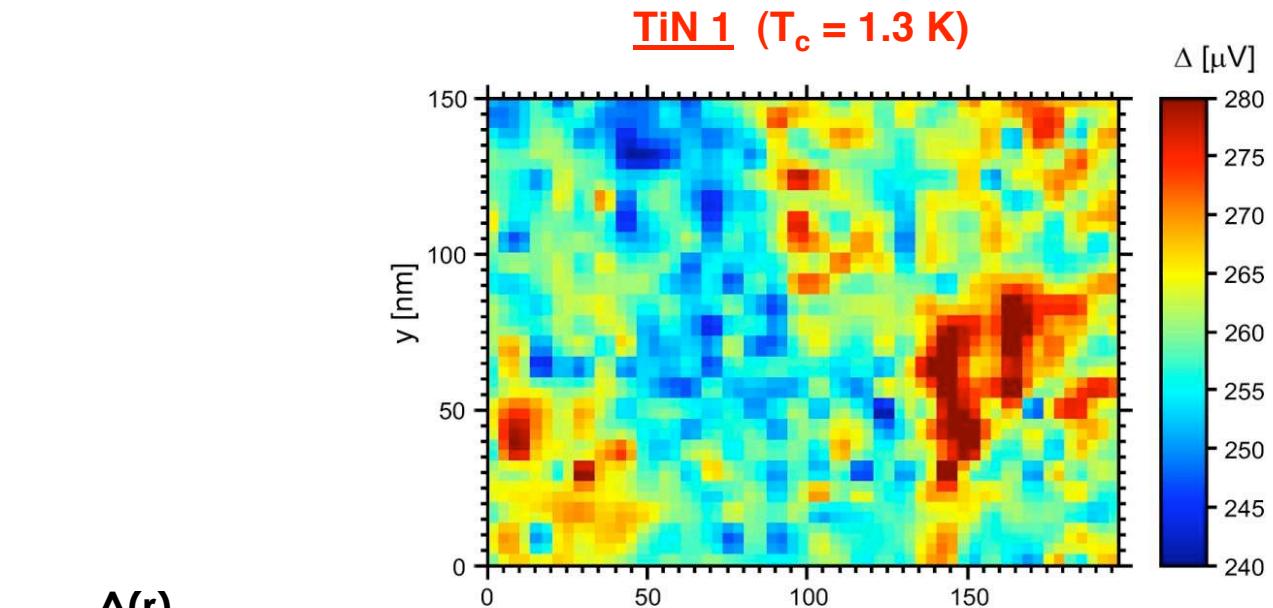


$$\lambda = \lambda_0 - \frac{1}{24\pi g} \log\left(\frac{1}{\epsilon\tau}\right)$$

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



## Inhomogeneous superconducting state



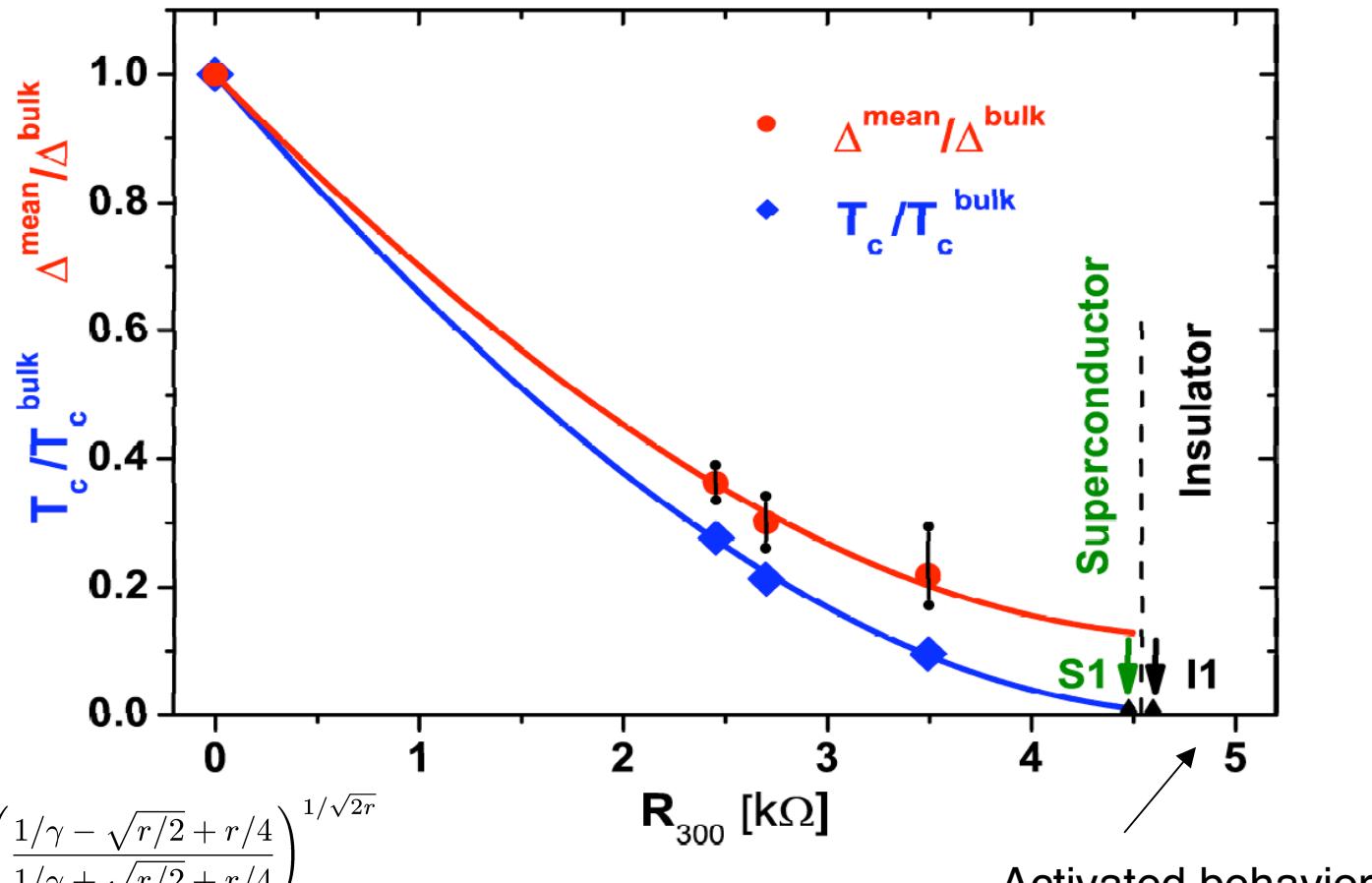
A. Ghosal, M. Randeria, N. Trivedi,  
*Phys. Rev. Lett.* **81**, 3940, (1998)

B. Sacépé, et al. *Phys. Rev. Lett.* **101**, 157006, (2008)

$T_c$ [K]	$\Delta/T_c$	Var. [%]
4.7	1.8	---
1.3	2.3	12
1	2.6	20
0.45	4	50

## Tunneling spectroscopy at 50 mK

### Tunneling spectroscopy at Low temperature Summary



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

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

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

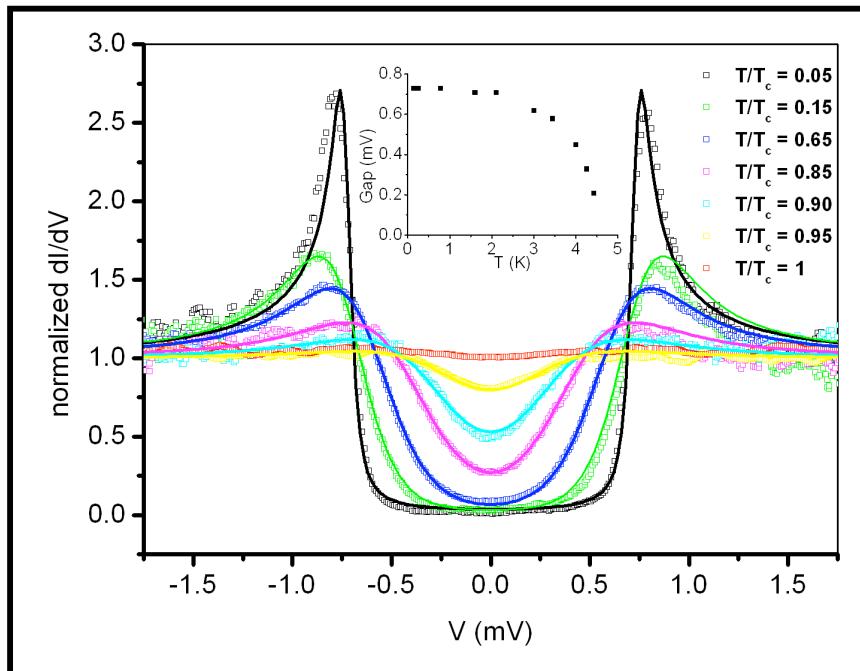
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- Tunneling spectroscopy at  $T=50\text{mK}$
- Pseudogap regime above  $T_c$

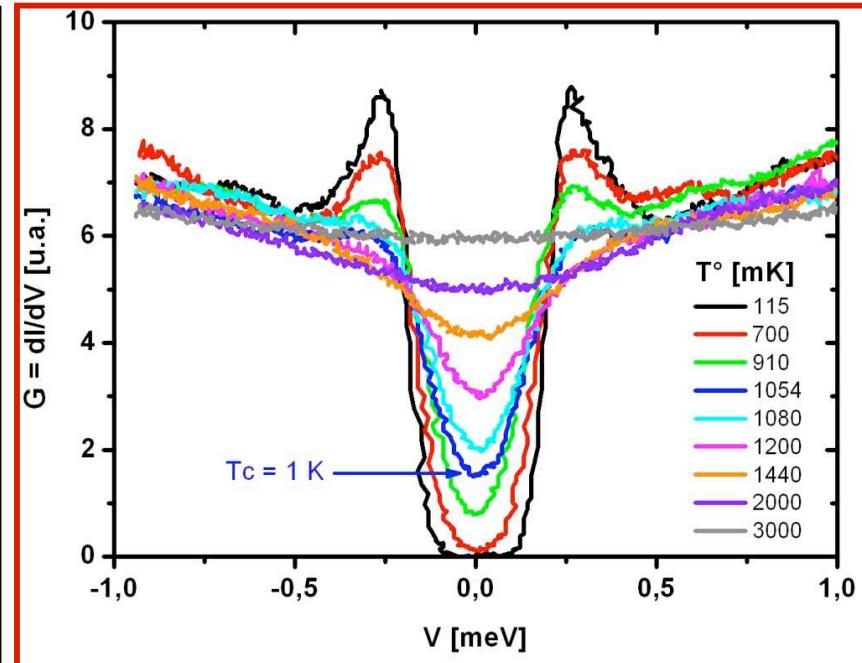
## Pseudogap

### Temperature evolution of the tunneling conductance

TiN bulk -  $T_c = 4.7$  K  
(far from the SIT)

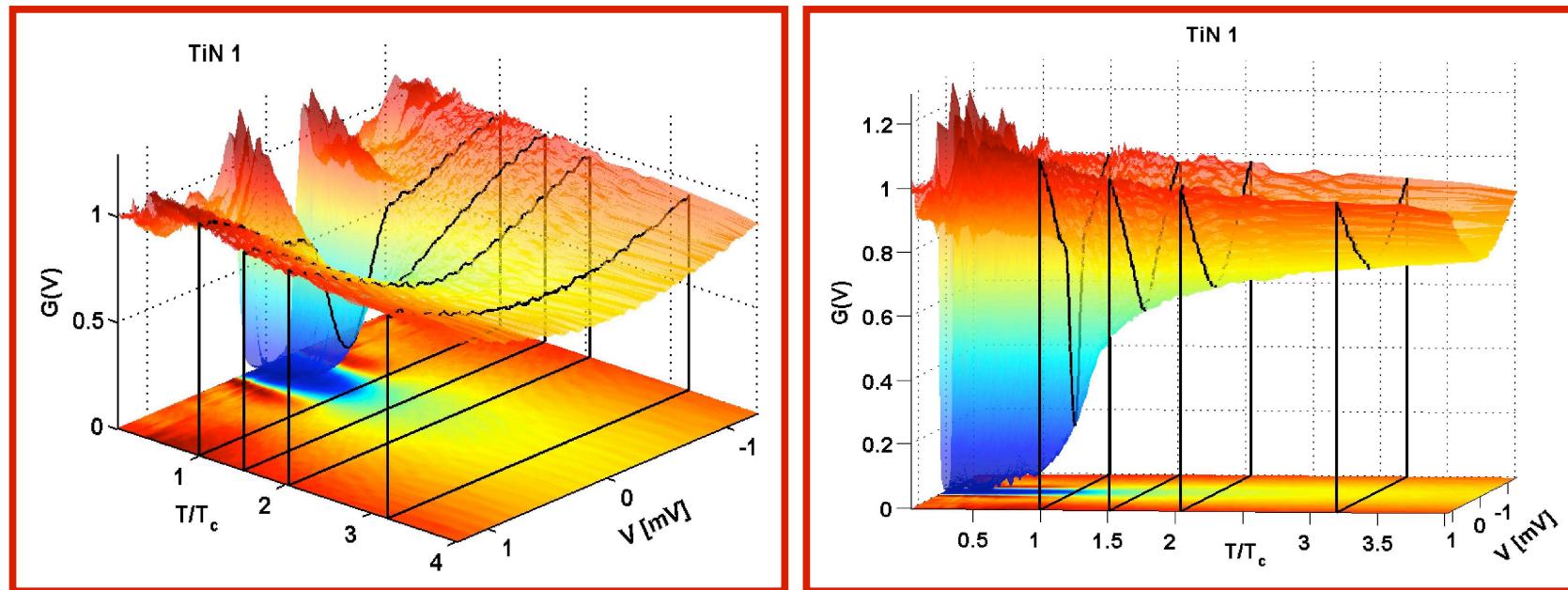


TiN 2 -  $T_c = 1$  K  
(close to the SIT)



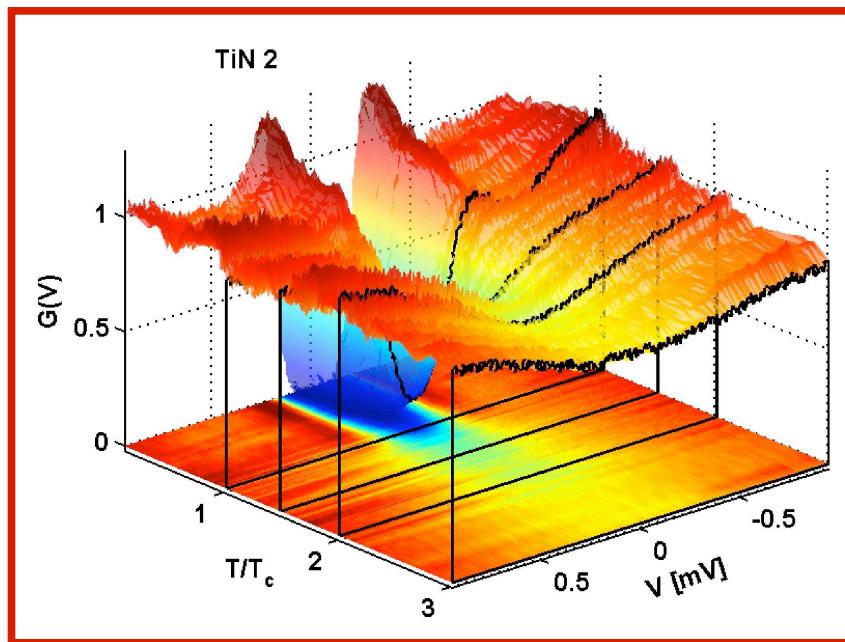
W. Escoffier, et al., *Phys. Rev. Lett.* **93**, 217005, (2004)

## Pseudogap

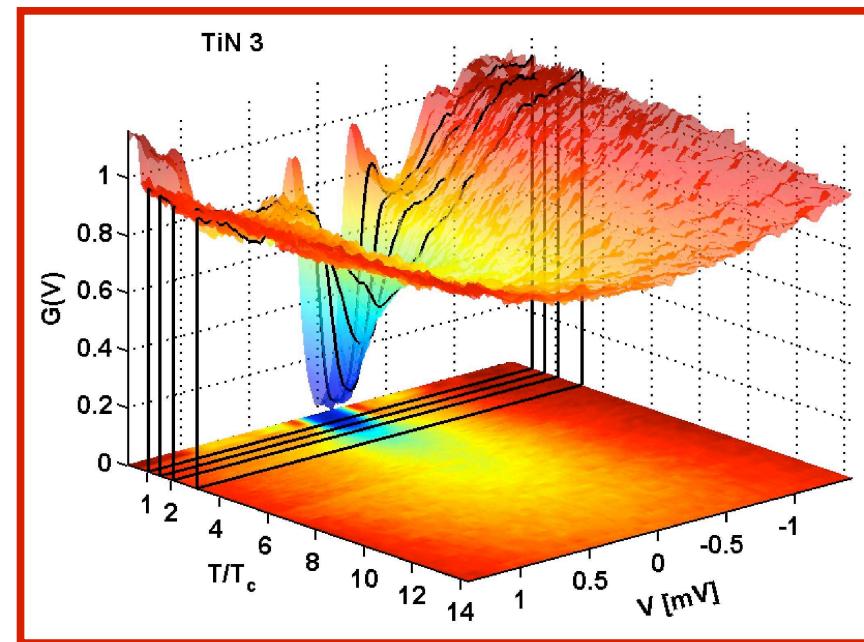


$R_{sq}=2.45\text{ k}\Omega$   $T_c=1.3\text{ K}$

## Pseudogap

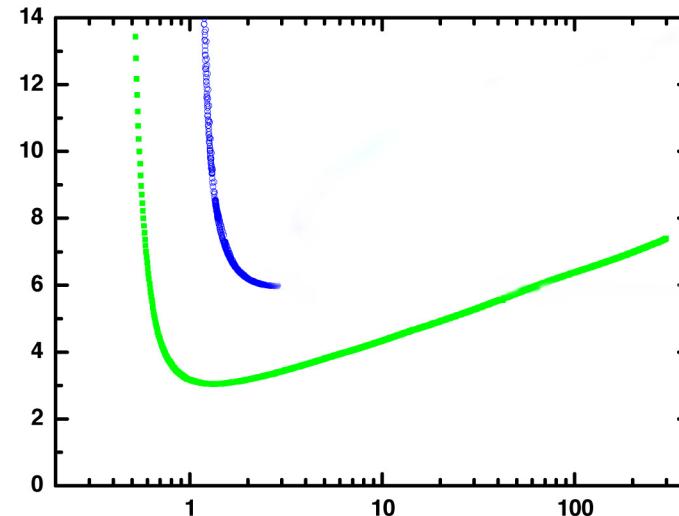
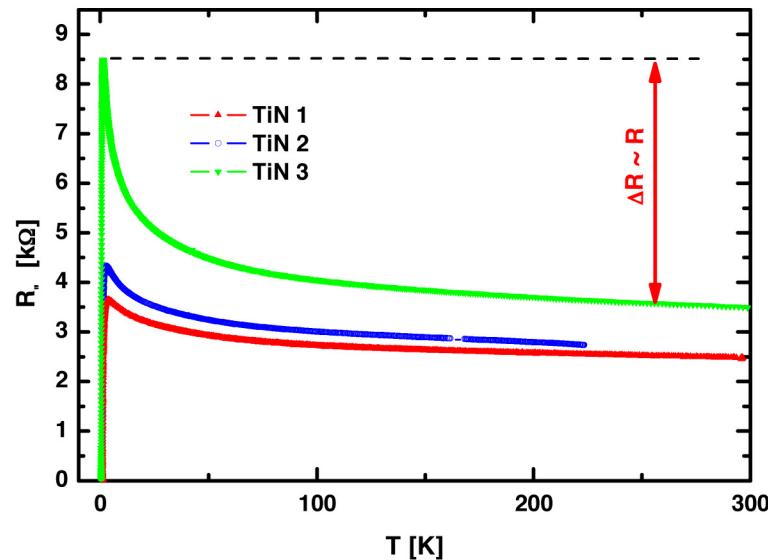


$R_{sq}=2.7 \text{ k}\Omega$   $T_c=1.0 \text{ K}$



$R_{sq}=3.5 \text{ k}\Omega$   $T_c=0.45 \text{ K}$

## Two possible origin of the DOS corrections With quantum signatures in the transport measurements

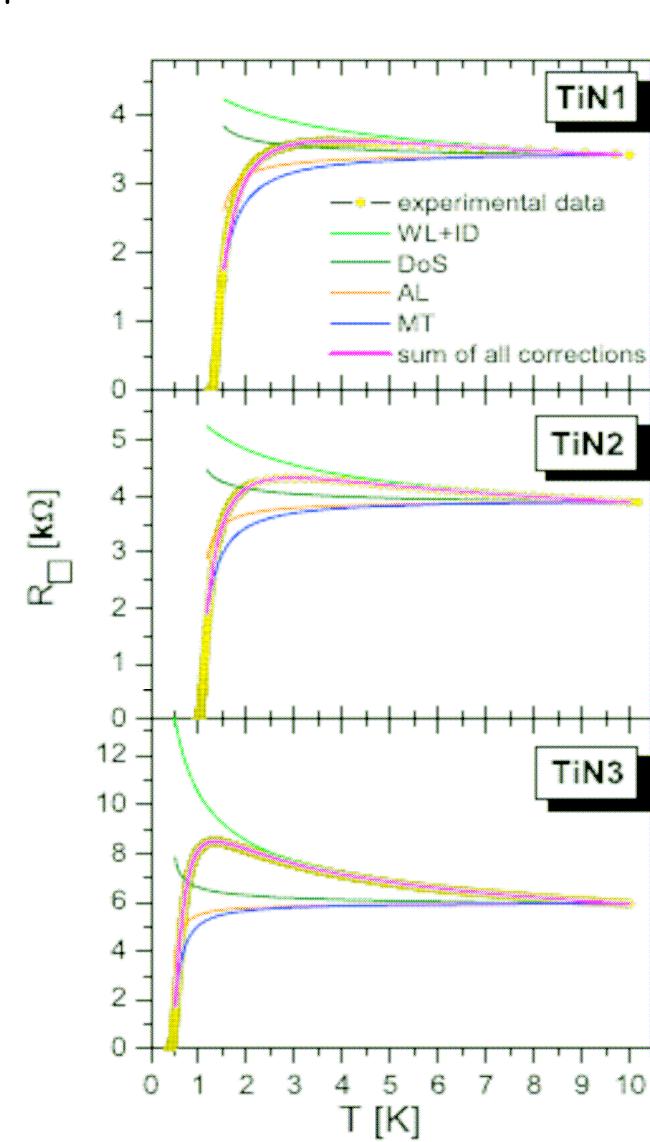
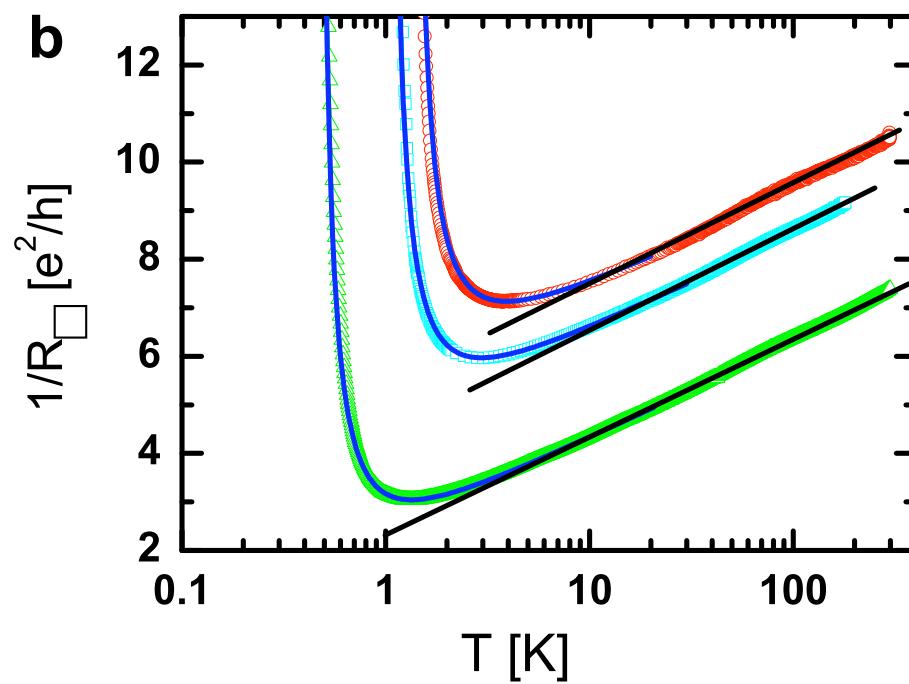


## Pseudogap

$$\Delta\sigma = \Delta\sigma^{WL} + \Delta\sigma^{AA} + \Delta\sigma^{DoS} + \Delta\sigma^{AL} + \Delta\sigma^{MT}$$

One parameter fit :  $T_c$

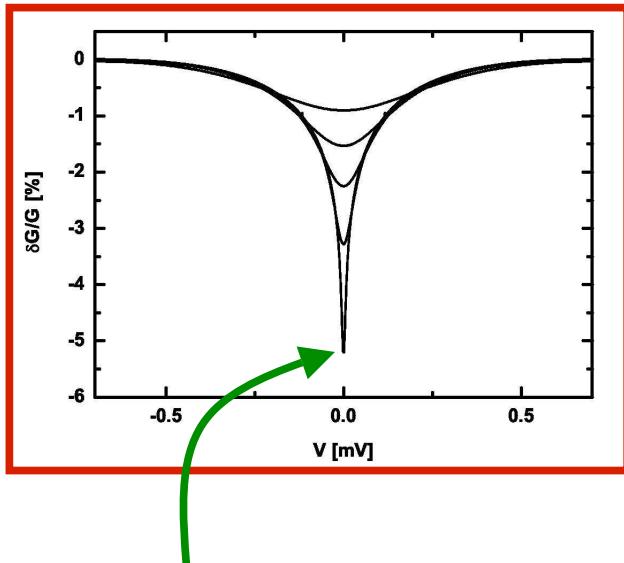
$T_c$ [K]
1.3
1
0.45



## Pseudogap

**Disorder-enhanced Coulomb interaction**  
(Aronov-Altshuler correction)

**Soft coulomb gap**

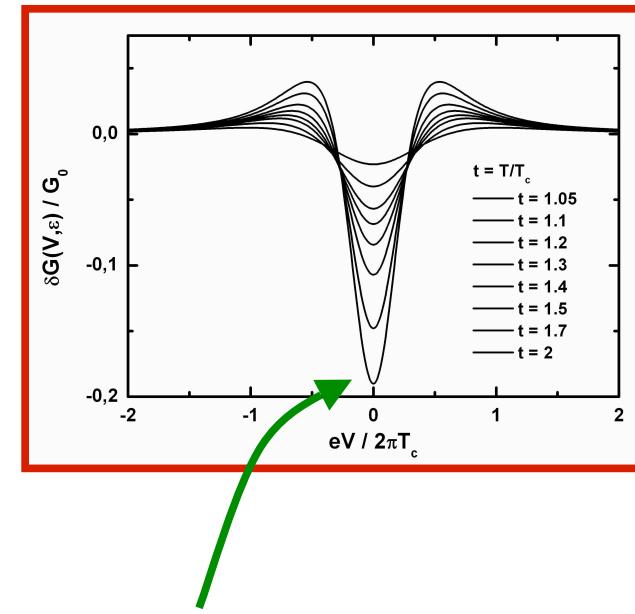


$$\frac{\delta G}{G}(eV = 0) \propto \ln\left(\frac{1}{T\tau}\right)$$

B. Altshuler, et al., *Phys. Rev. Lett.* **44**, 1288, (1980)

**Superconducting fluctuations**  
(DOS correction)

**Superconducting fluctuations**



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

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

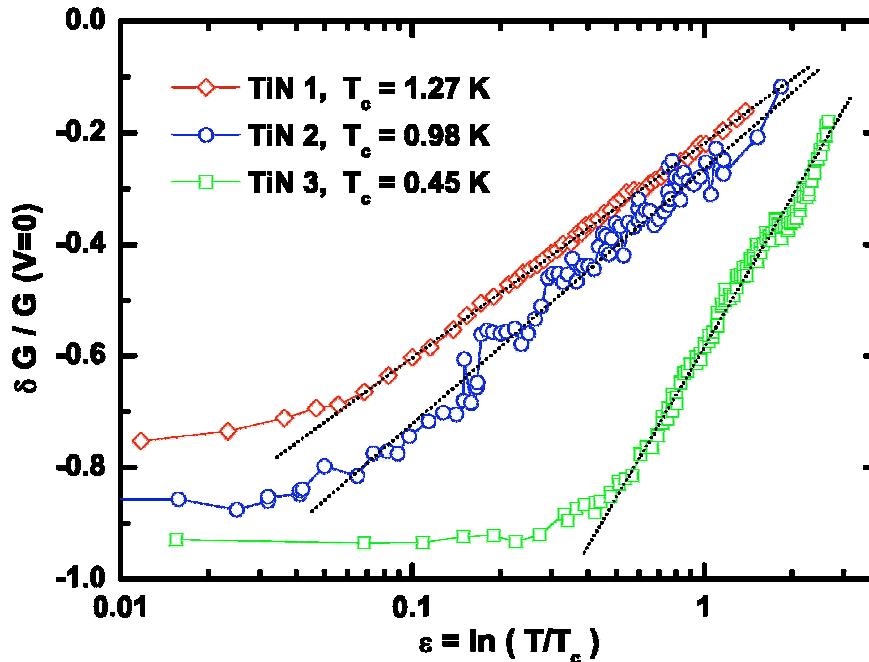
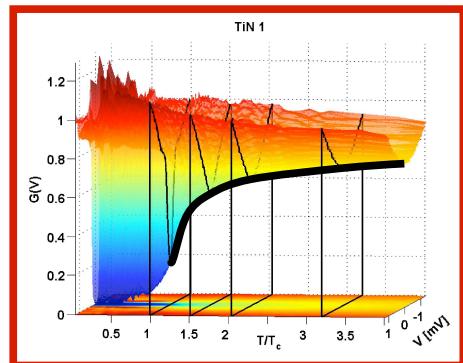
Two distinct evolutions at the Fermi level

## Pseudogap

### Superconducting fluctuations correction to the DOS

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

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



$R_{\square}$ [kΩ]	$T_c(R_{\square})$ [K]	$T_c(\text{DOS})$ [K]
3.5	1.3	1.27
4.3	1.0	0.98
7.4	0.45	0.45

Slopes increase with  $G_i \sim R_{\square}$

Valid up to  $\varepsilon > 1$

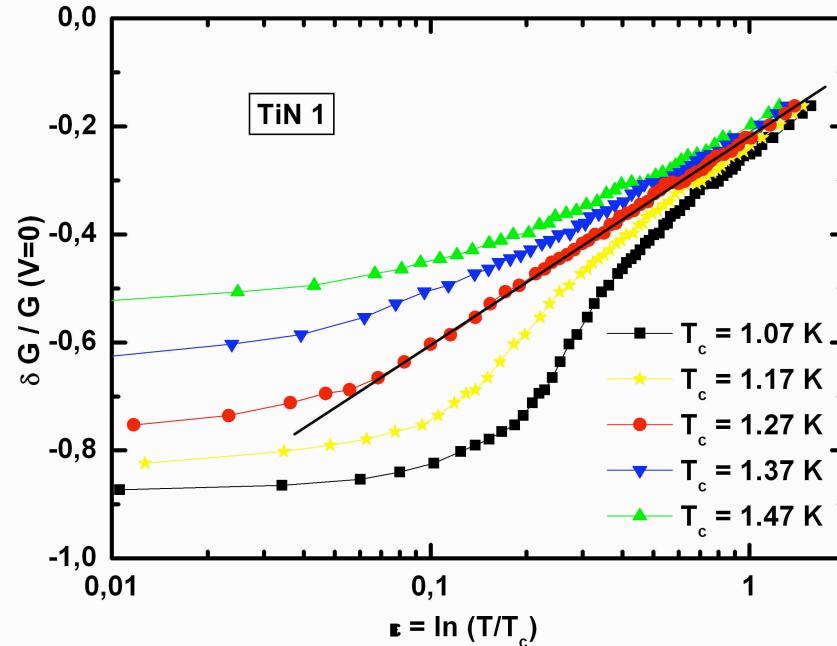
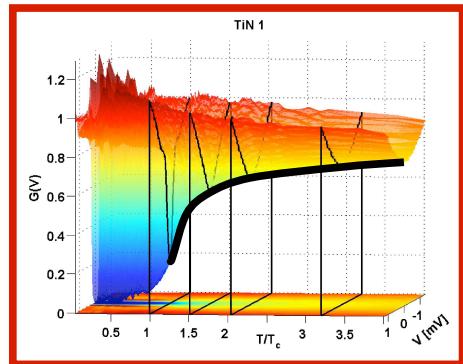
Validity :  $Gi = \frac{\hbar}{16e^2}R_{\square} \ll \ln(\ln \frac{T}{T_c}) \ll 1$

## Pseudogap

### Superconducting fluctuations correction to the DOS

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

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



$R_{\square}$ [kΩ]	$T_c(R_{\square})$ [K]	$T_c(\text{DOS})$ [K]
3.5	1.3	1.27
4.3	1.0	0.98
7.4	0.45	0.45

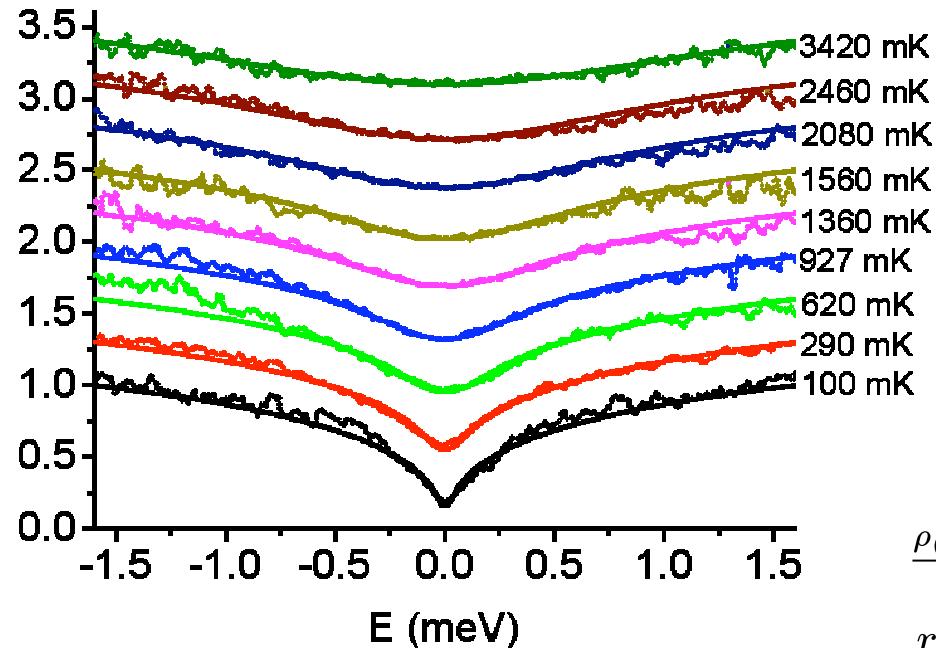
Striking sensitivity to  $T_c$

## Pseudogap

### Highly disordered film

Disorder-enhanced Coulomb interaction

B. Altshuler, et al., *Phys. Rev. Lett.* **44**, 1288, (1980)



W. Escoffier et al., unpublished

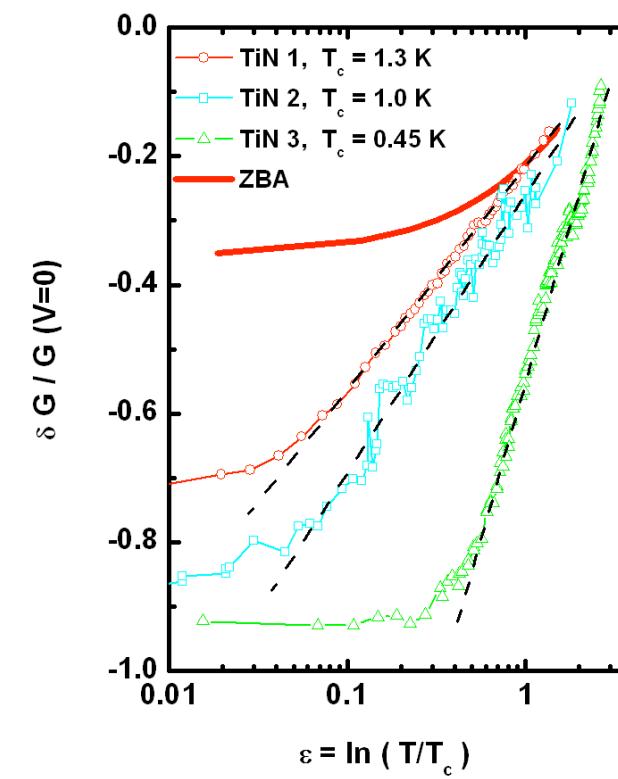
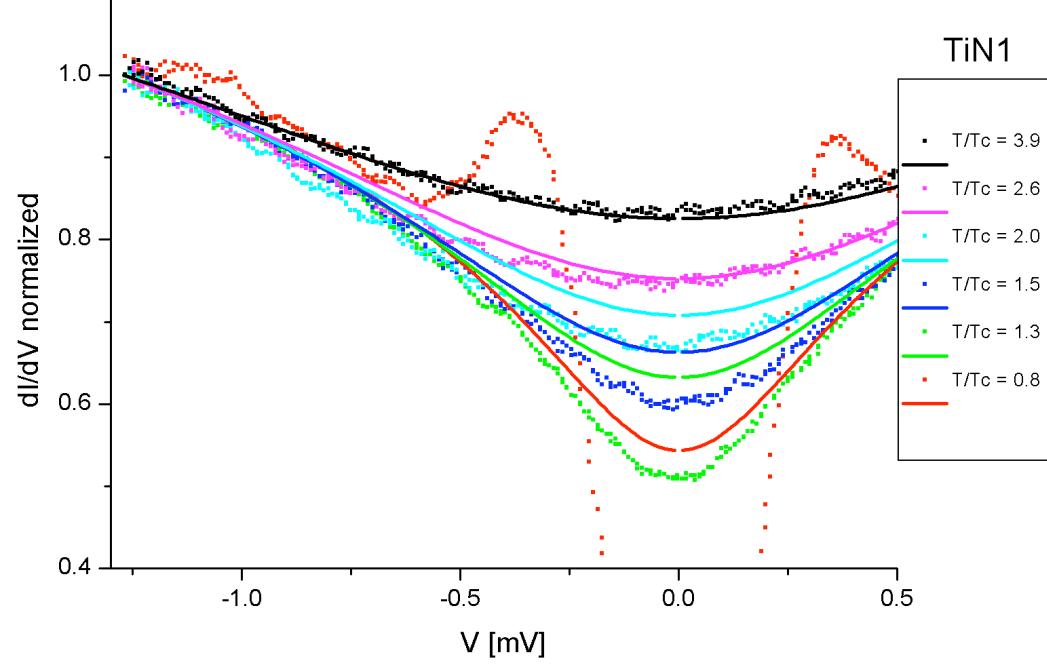
$$\frac{\rho(\epsilon, T)}{\rho_0} \approx \exp \left[ \frac{-r_0}{4} \ln(t/\tau_0) \ln(t/\tau_1) \right]$$
$$r_0 = \frac{R_{\square} e^2}{\pi h}$$

- A. M. Finkelstein, *Zh. Eskp. Teor. 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)

## Pseudogap

TiN 2

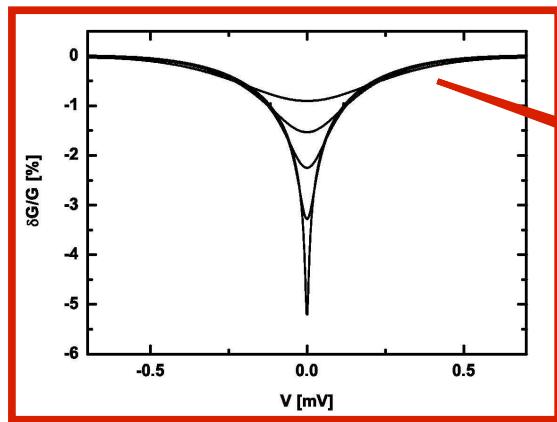
Disorder-enhanced Coulomb interaction



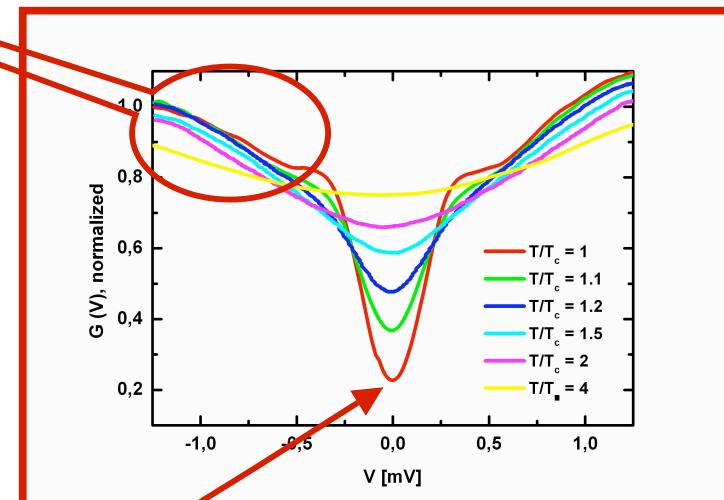
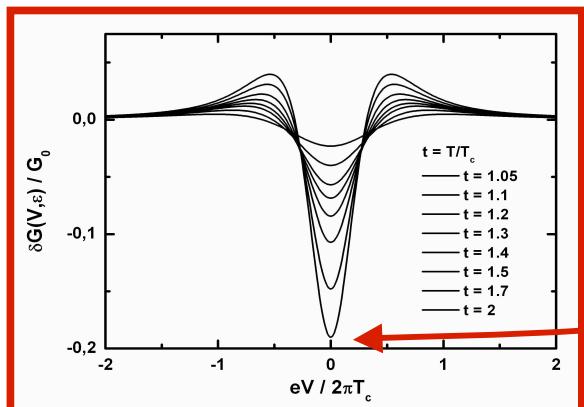
# Pseudogap

## Pseudogap : a lack of global theory

Soft coulomb gap

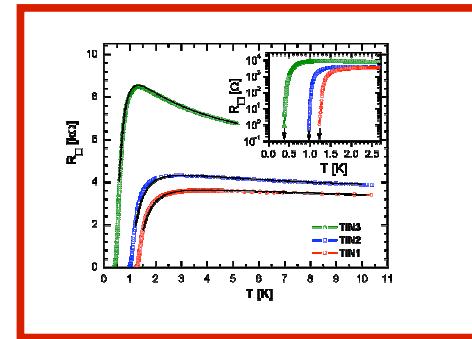


Superconducting fluctuations



## Conclusions

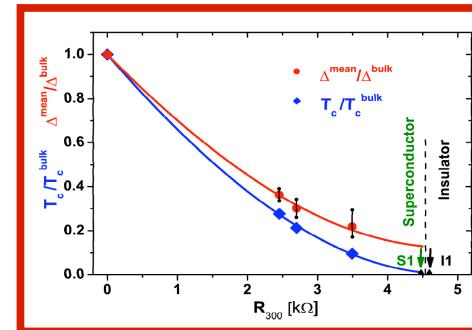
Transport measurements well described by quantum corrections calculated for homogeneously disordered thin films



Superconducting inhomogeneous state with non-zero gap at the SIT at  $T=0$

Activated behavior related ?

Magneto-resistance peak related ?



Pseudogap state above  $T_c$  described by the superconducting fluctuations

