# Visualizing out-of-equilibrium superconductivity

**Claude Chapelier**, *INAC, CEA - UGA*
**Eduard Driessen**, *IRAM*

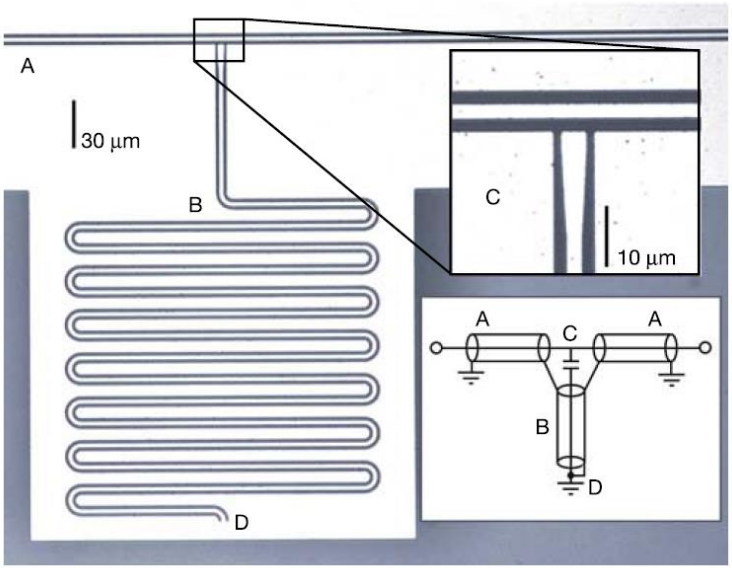
TiN

1- Superconducting Photon detector
2- Critical current microscopy
3- Where do the subgap states come from ?

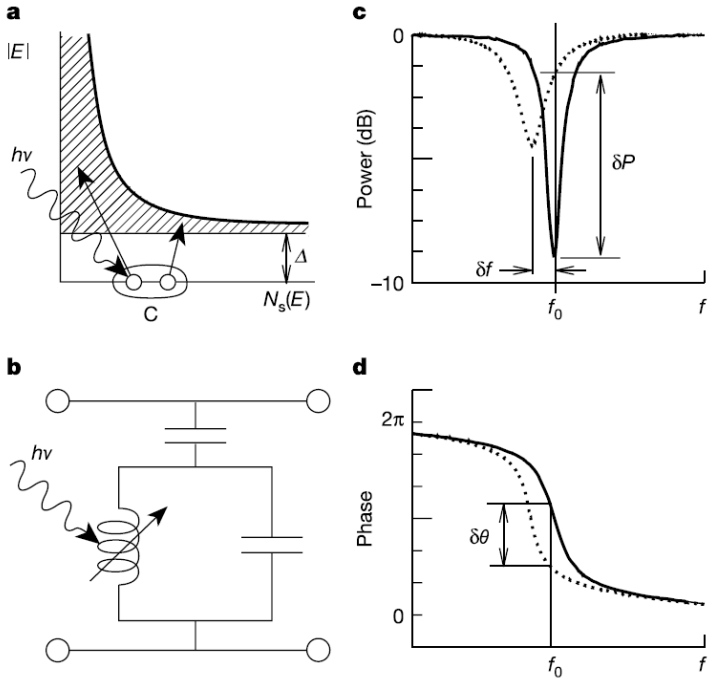
INSTITUT NANOSCIENCES ET CRYOGÉNIE

UNIVERSITÉ Grenoble Alpes

# Superconducting photon detector



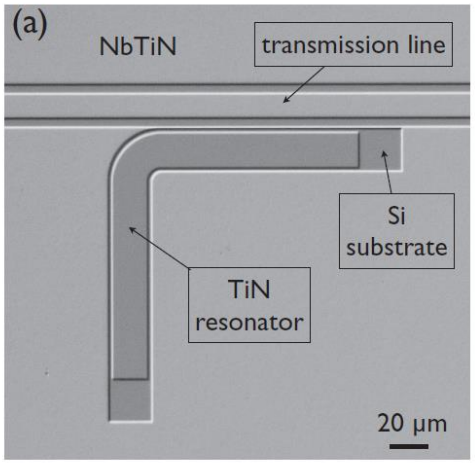

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad L = \frac{m}{n_s e^2} = \frac{\hbar R_n}{\pi \Delta(T) \tanh\frac{\Delta(T)}{2k_B T}}$$

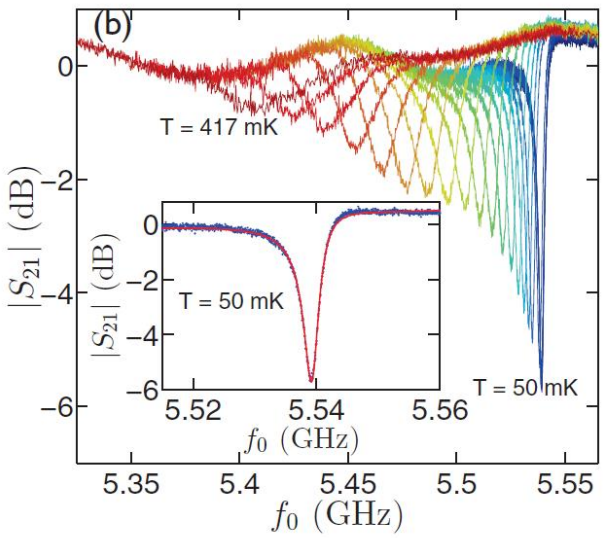



**P.K. Day** et *al.*, *Nature* ***425*** , 817 (2003)

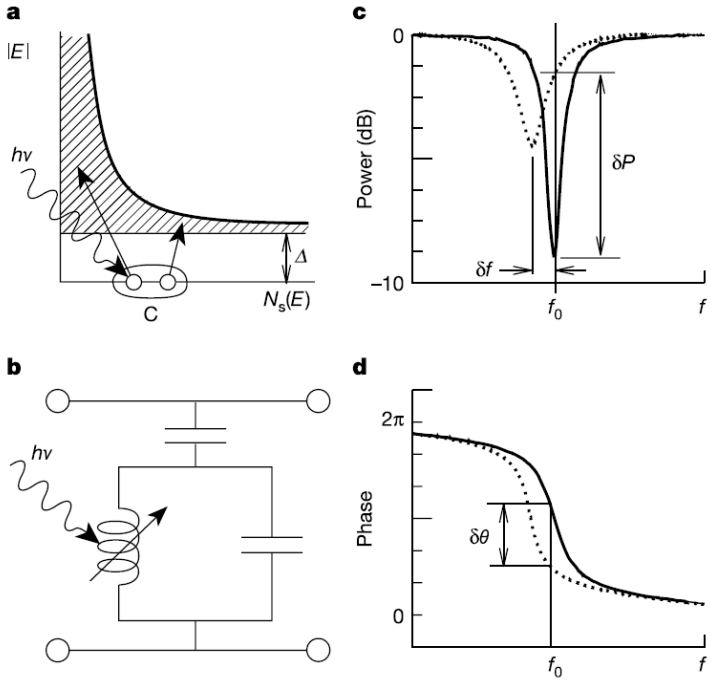
# Superconducting photon detector

## TiN




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




**P.K. Day** et *al.*, *Nature* ***425*** , 817 (2003)

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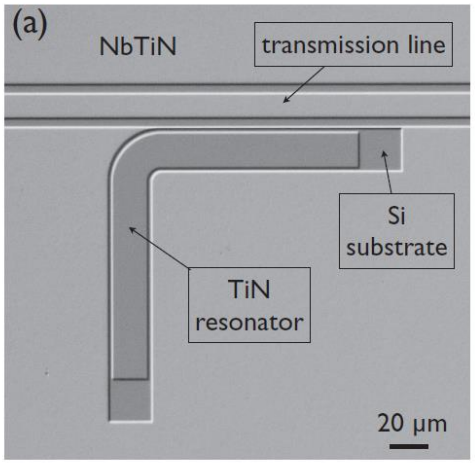


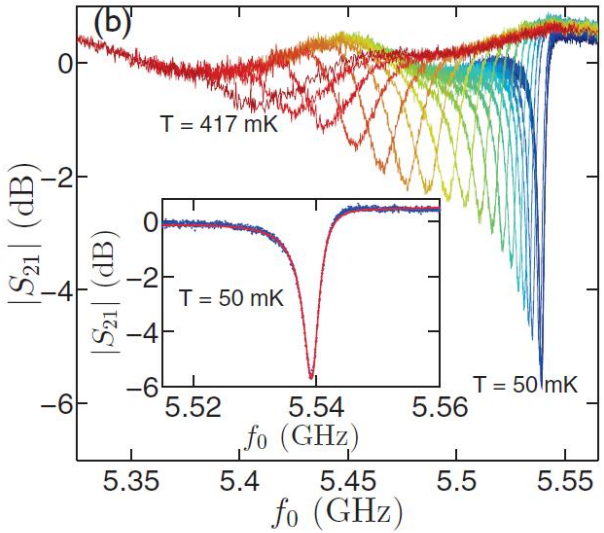


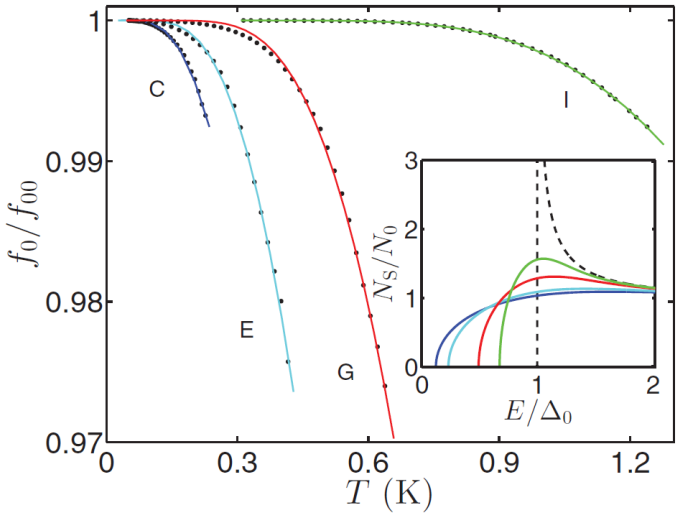


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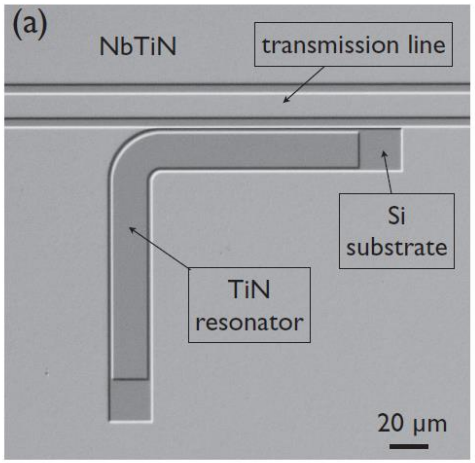


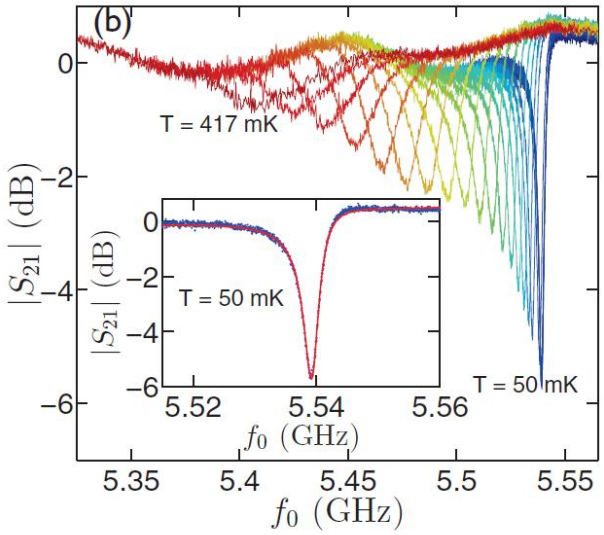


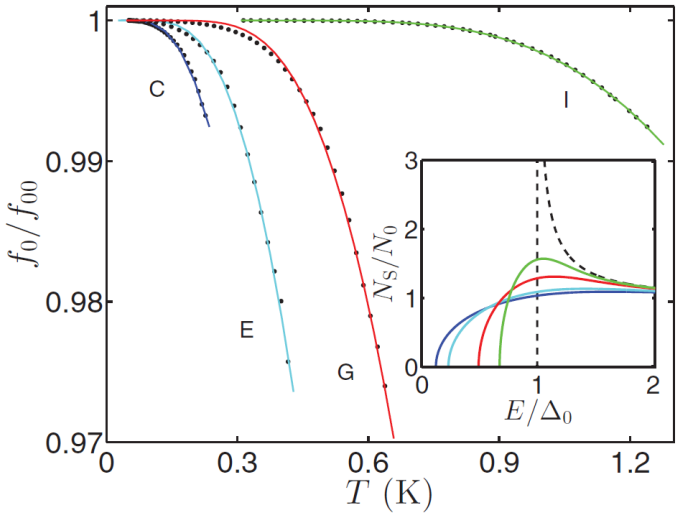


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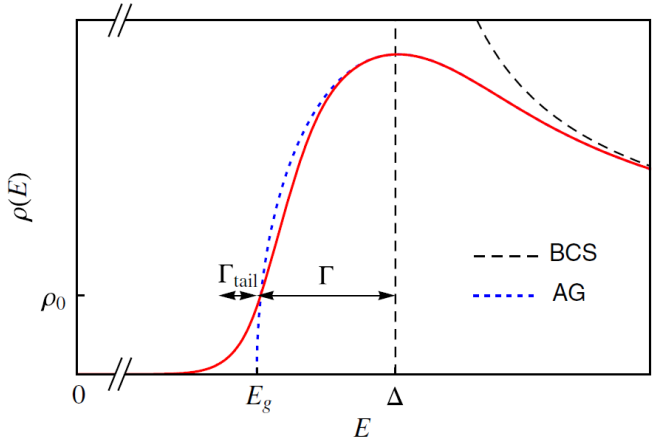
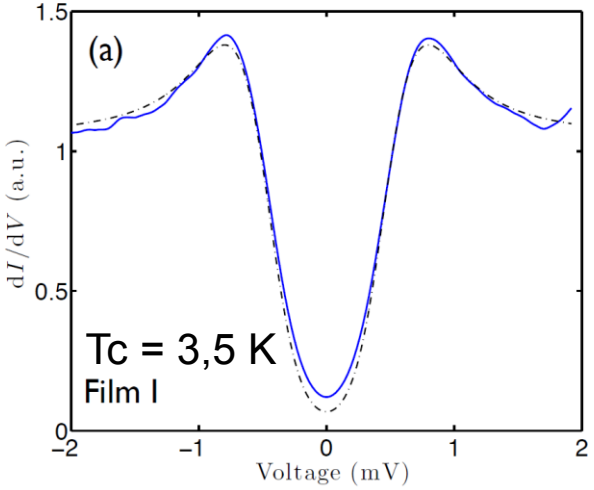



**M.V. Feigelman and M.A. Skvortsov**, *Phys. Rev. Lett.* ***109***, 147002 (2012)
**A.I. Larkin and Yu. N. Ovchinnikov**, Sov. JETP **34**, 1144 (1972)

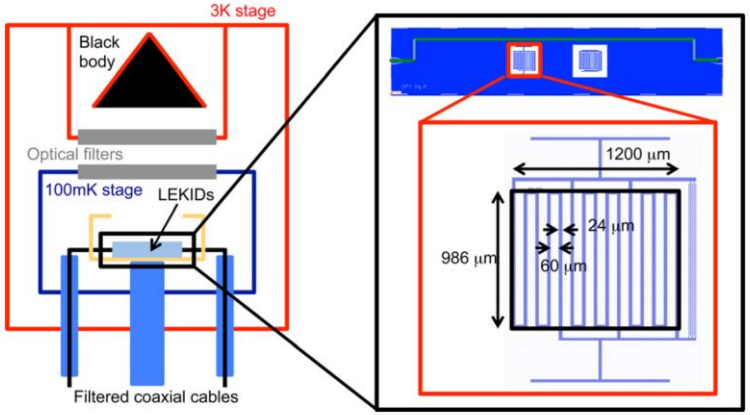



**A. Bespalov** et al, *Phys. Rev. B* ***93,*** 104521 (2016)
**A. Bespalov** et al, *arXiv:1603,04273v1* (2016)
**A. Silva** et al., *Phys. Rev. B* ***72,*** 224505 (2005)

# Superconducting photon detector

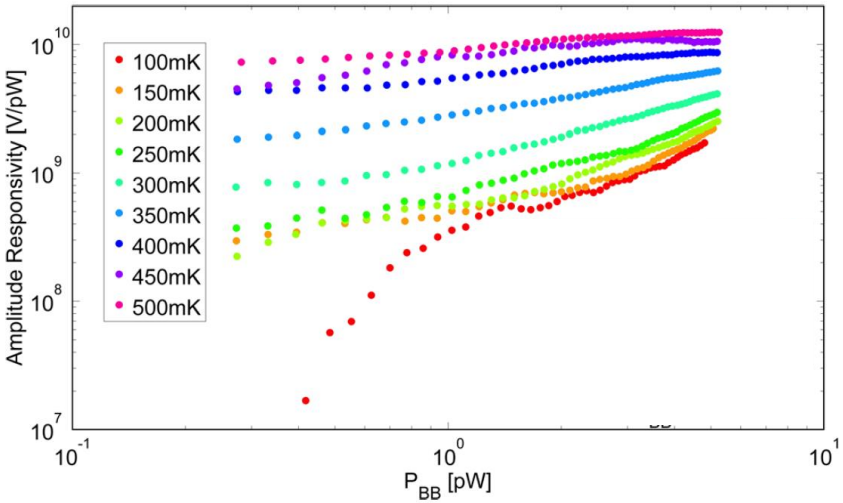
**TiN**

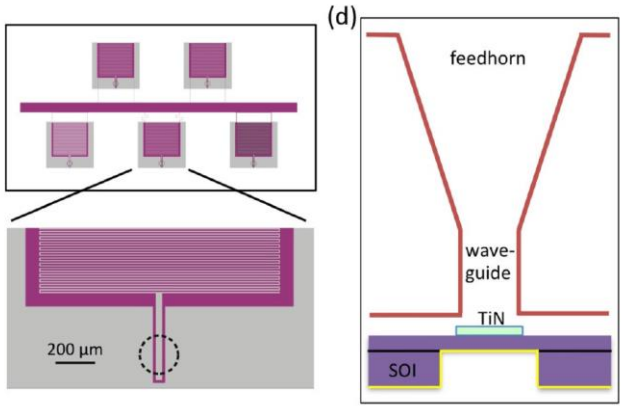
$$N_{qp}\tau_r = \frac{\tau_0 N_0 (k_B T_c)^3 V}{2\Delta^2} \qquad P_{opt} = \frac{N_{qp}\Delta}{\tau_r} \;\alpha\; N_{qp}^2 \qquad \delta A\,,\delta f \;\alpha\; \delta N_{qp} \qquad \frac{\delta A}{\delta P_{opt}},\frac{\delta f}{\delta P_{opt}} \;\alpha\; P_{opt}^{-\frac{1}{2}}$$

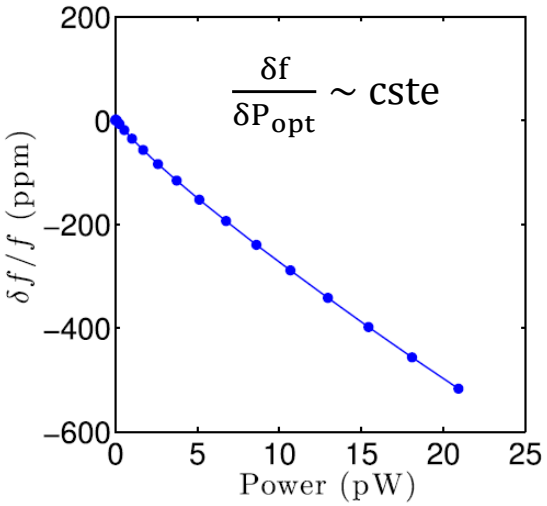


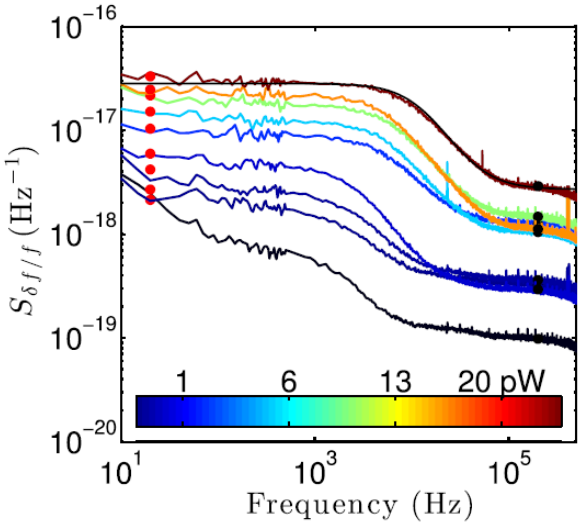

**J. Bueno** et *al.*, *Appl. Phys. Lett.* ***105***, 192601, (2014)

$$\frac{\delta A}{\delta P_{opt}}$$




**J. Hubmayr** et al., *Appl. Phys. Lett.* ***106***, 073505 (2015)

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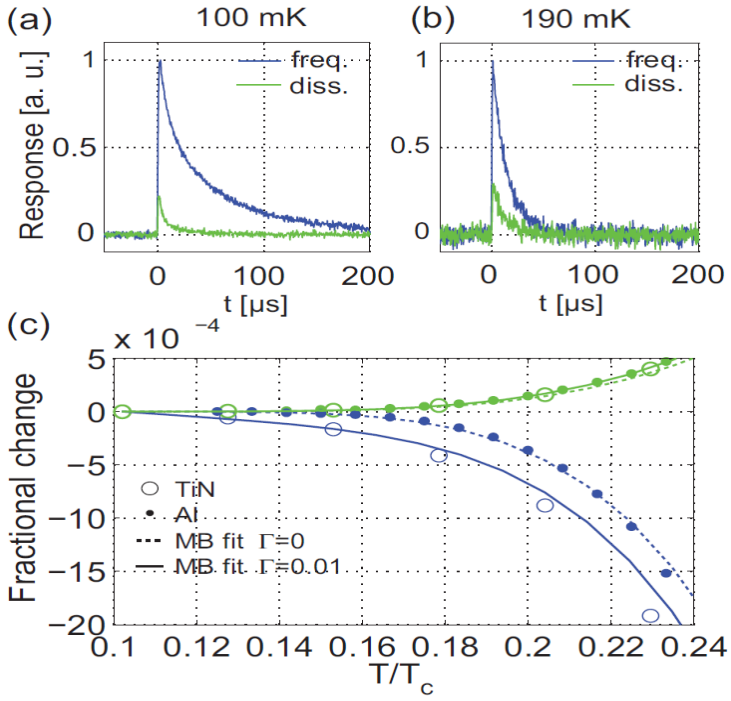


**J. Gao** et al., *Appl. Phys. Lett.* ***101***, 142602 (2012)

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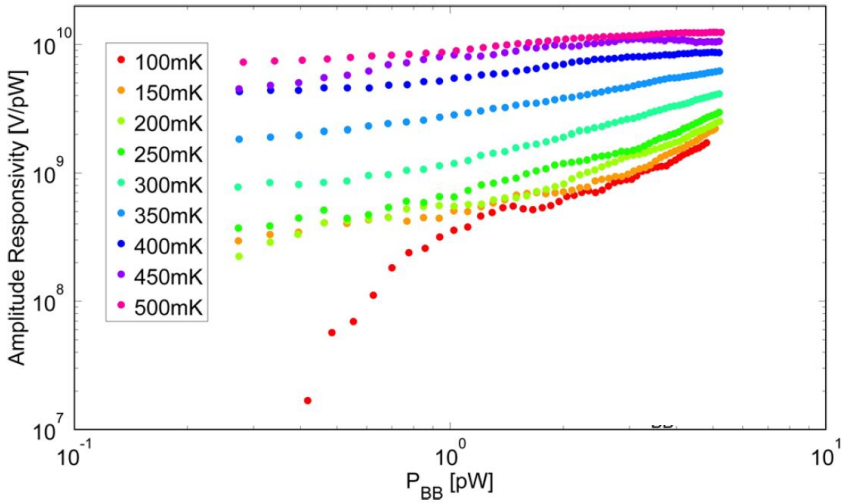


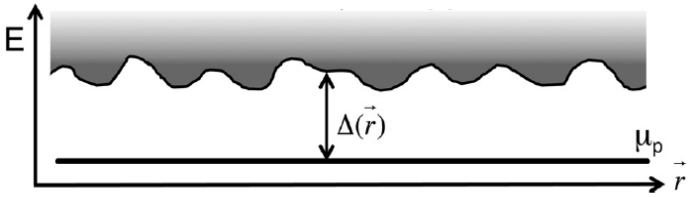


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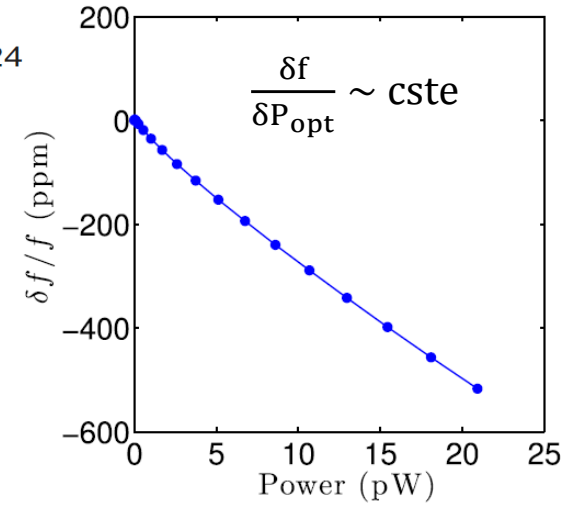


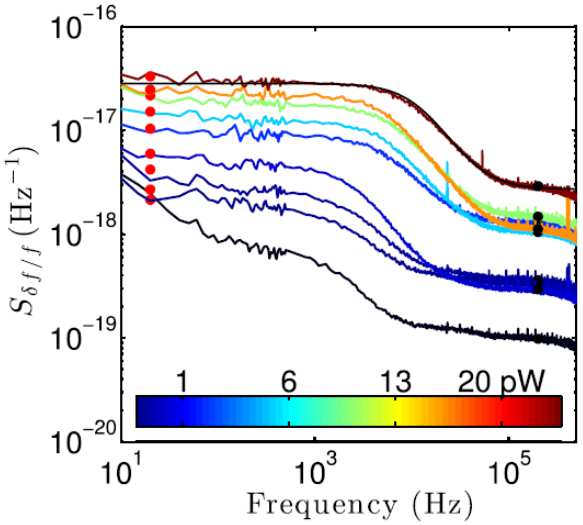

# Superconducting photon detector

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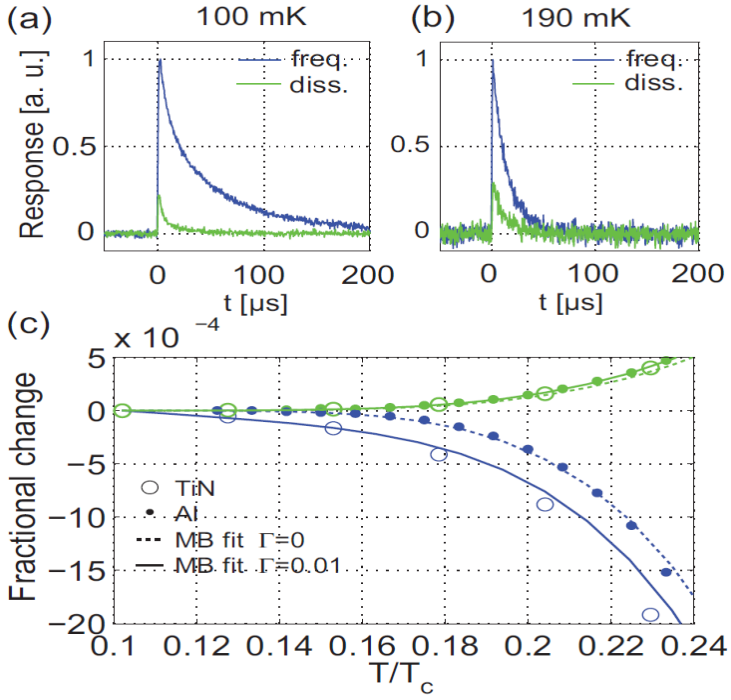
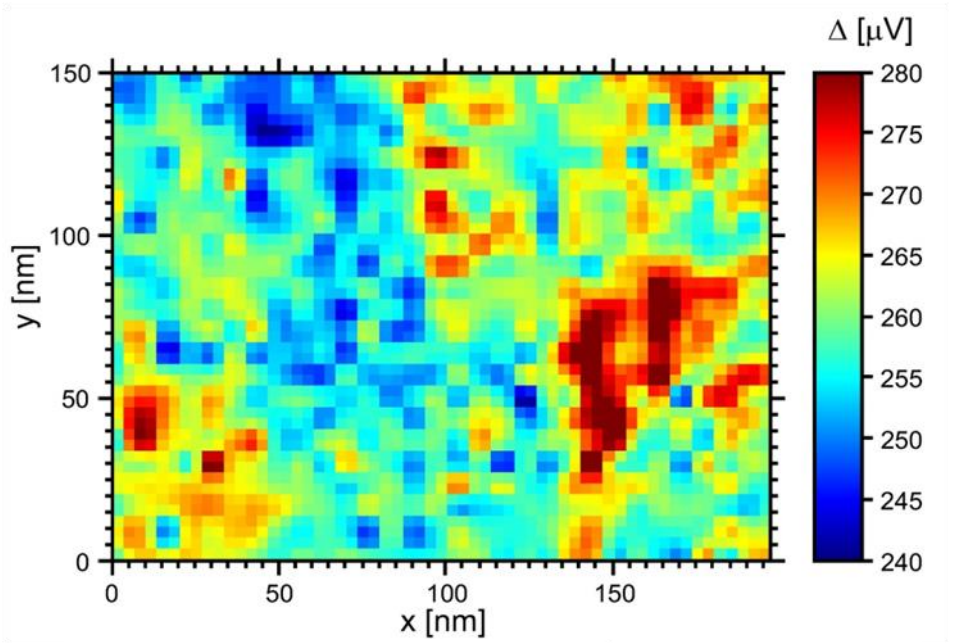



Understanding the recombination physics in TiN is required

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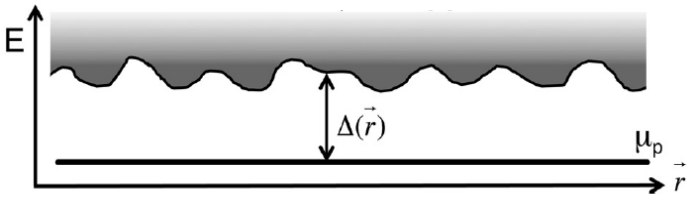


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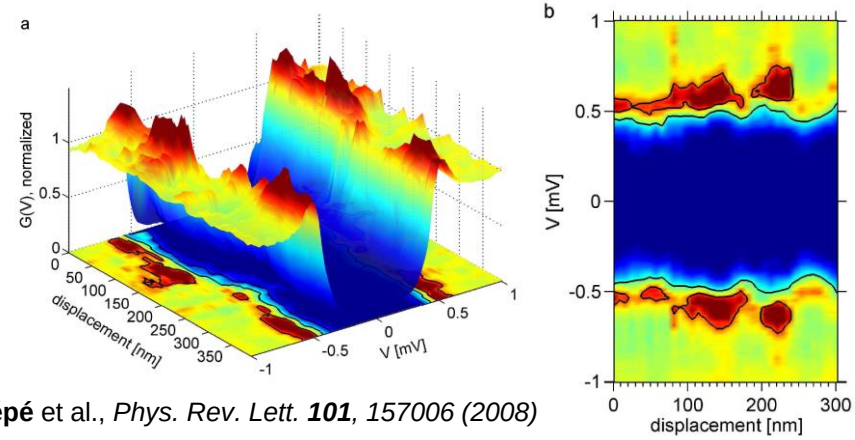


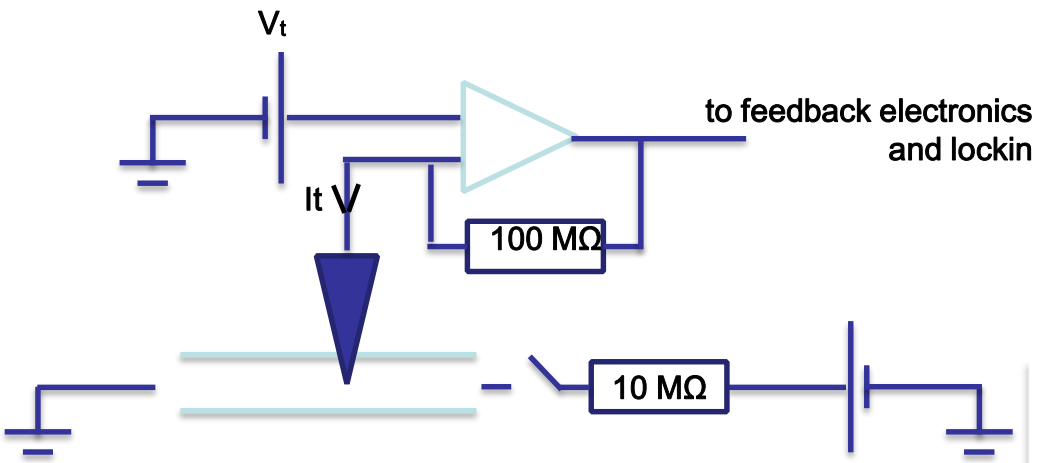

**Sacépé** et al., *Phys. Rev. Lett.* ***101***, *157006 (2008)*

TiN

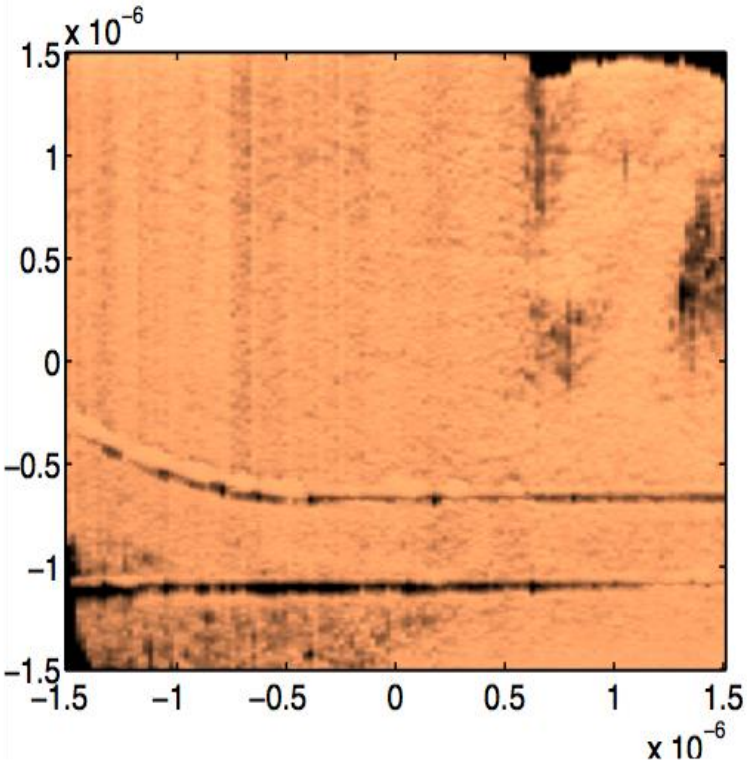
1- Superconducting Photon detector
2- Critical current microscopy
3- Where do the subgap states come from ?

# Critical current microscopy

TiN




- Device fabrication in Kavli Nanolab
- Nanowire: 5nm x 200 nm x 4 μm
- $T_c$ = 1.5 K, $R_s$ = 1.5 kΩ
- $\Delta$ = 250 μV, $\Delta / T_c$ = 1.9




**E. Driessen** et al., *unpublished*

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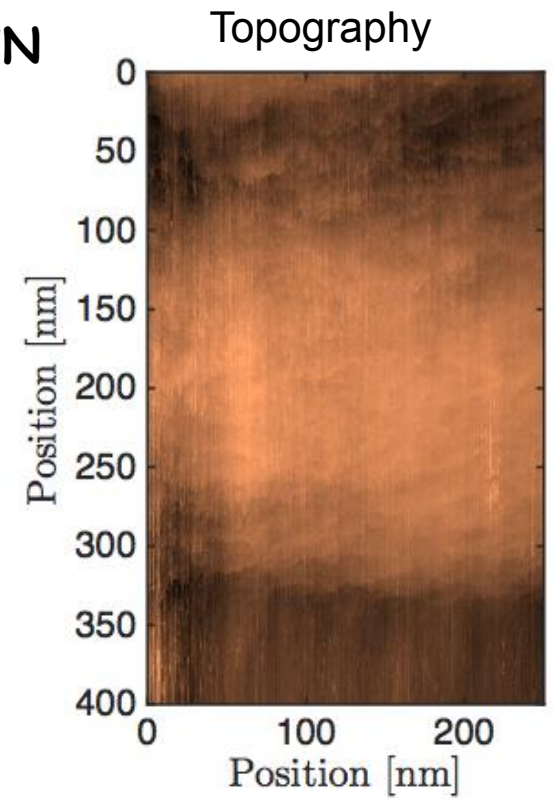
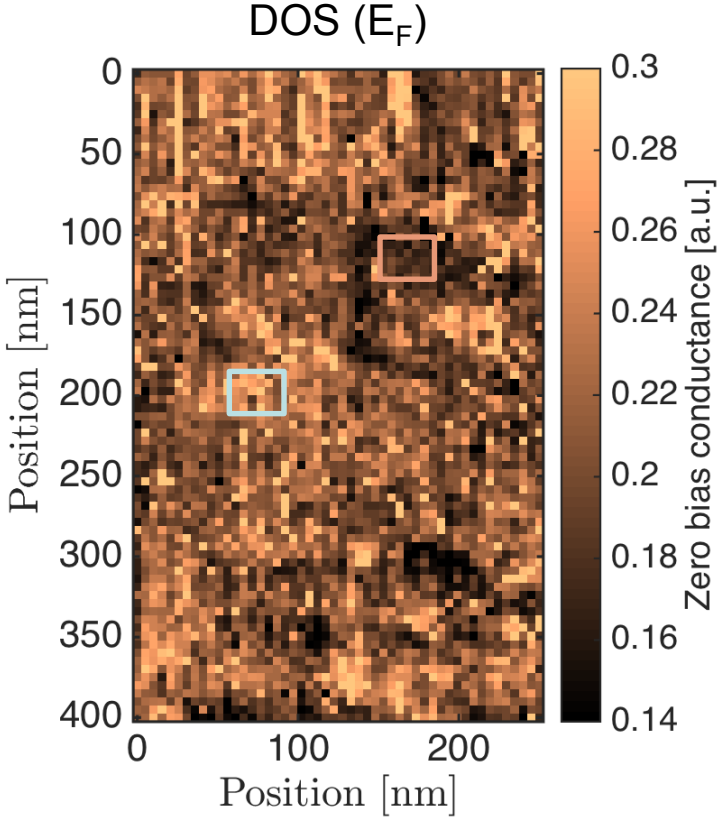
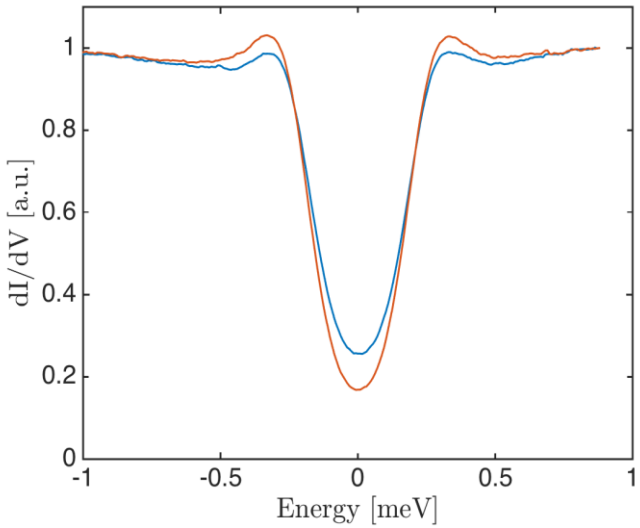


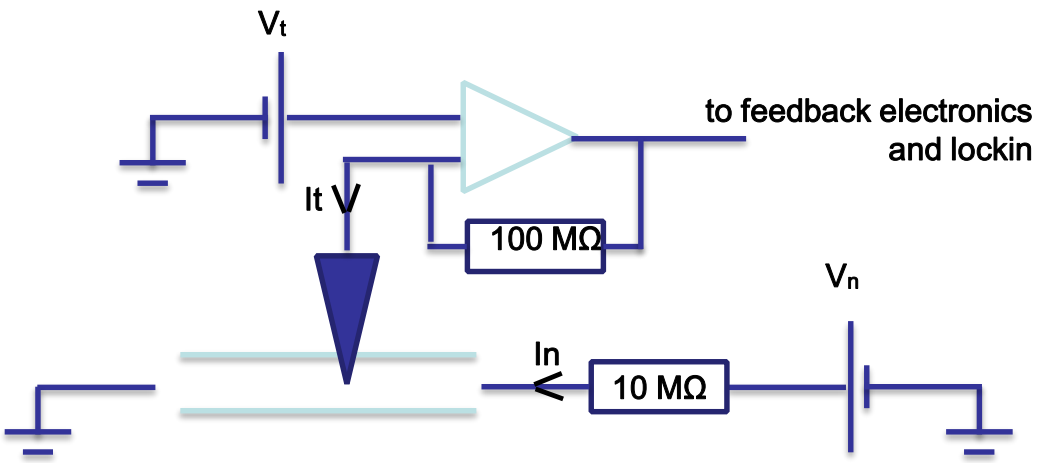



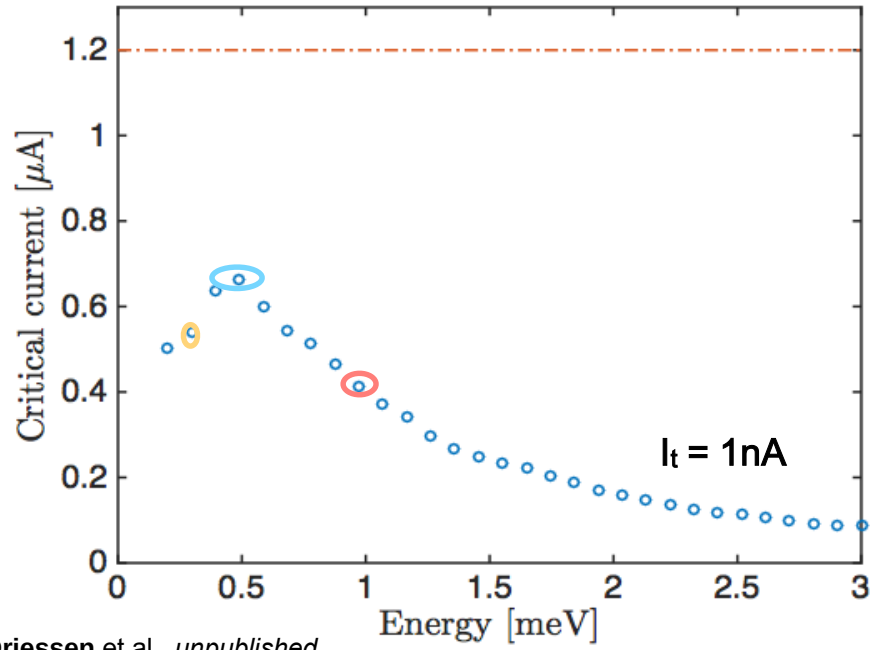

**E. Driessen** et al., *unpublished*

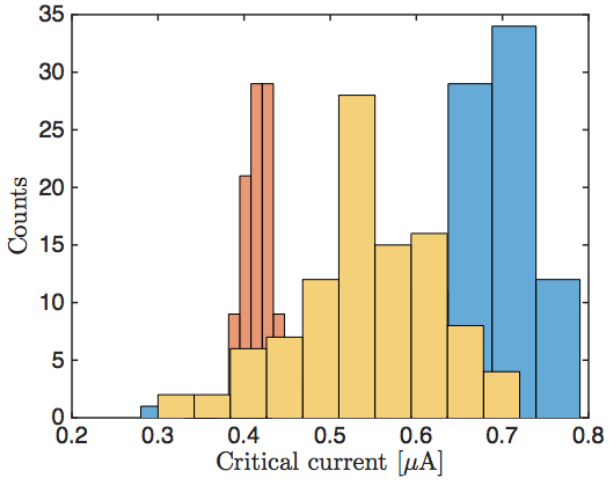
# Critical current microscopy

TiN

Local non-equilibrium!



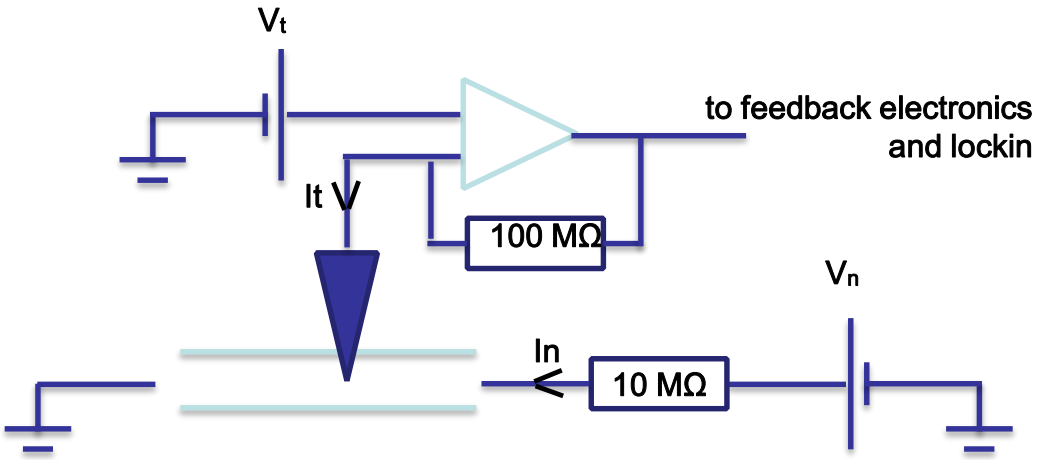



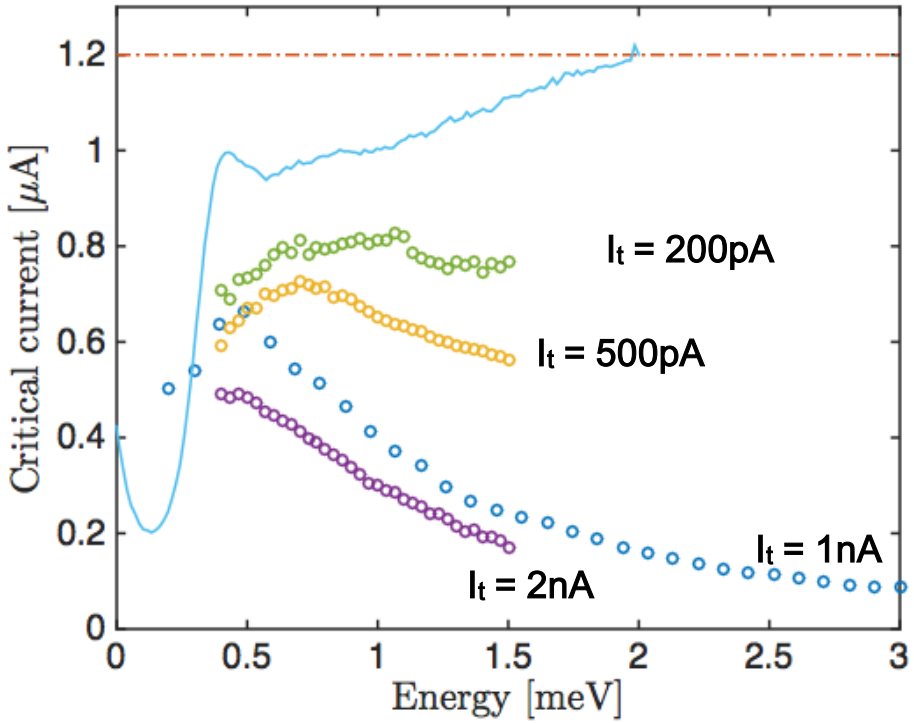

**E. Driessen** et al., *unpublished*

# Critical current microscopy

**TiN**

Long live time of quasiparticles close to the gap



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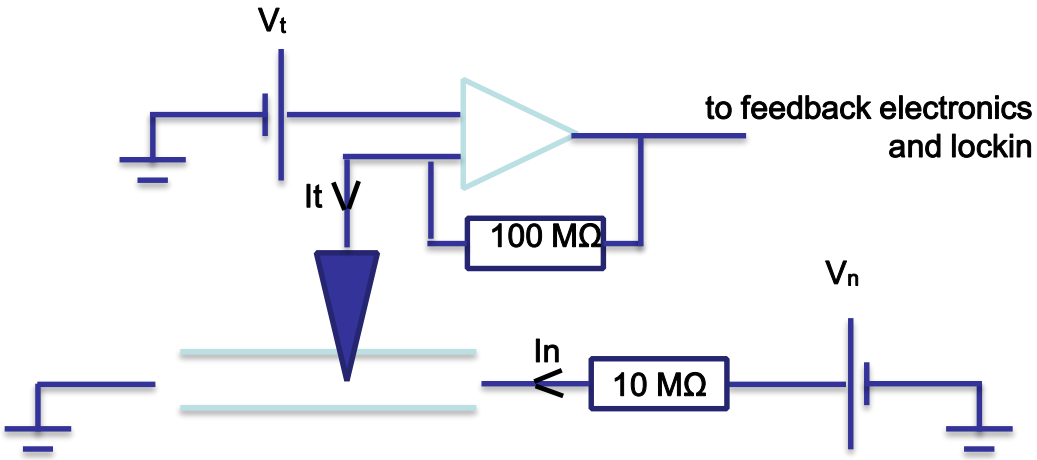


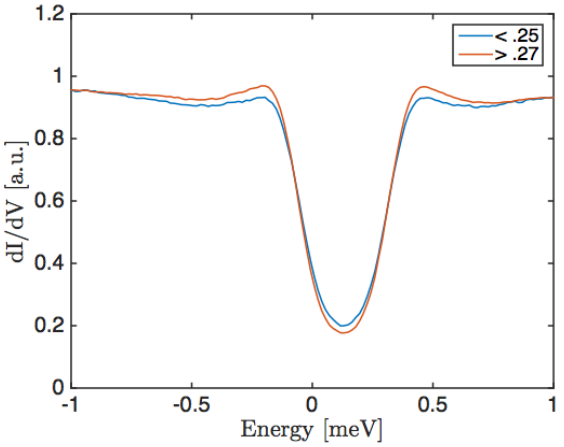


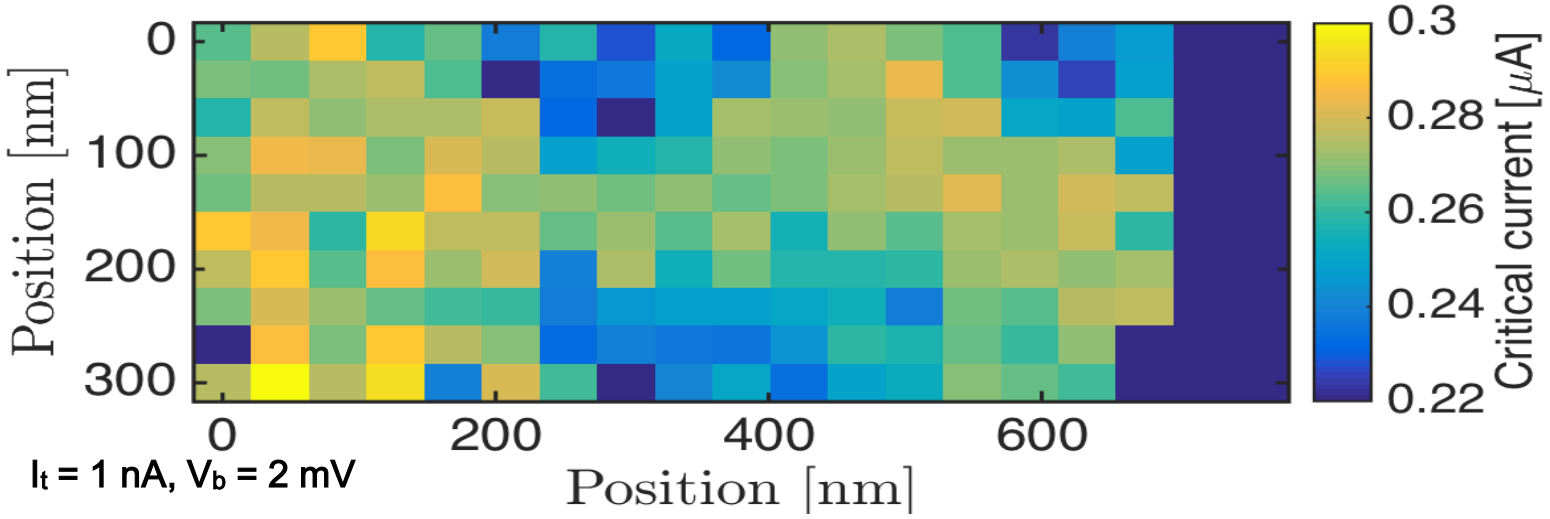


$I_t$ = 1 nA, $V_b$ = 2 mV

**E. Driessen** et al., *unpublished*

# Critical current microscopy

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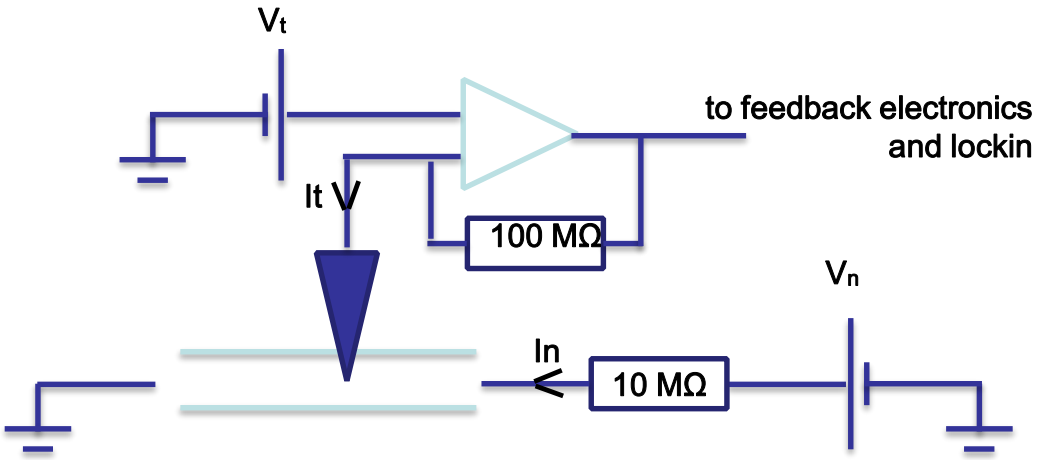
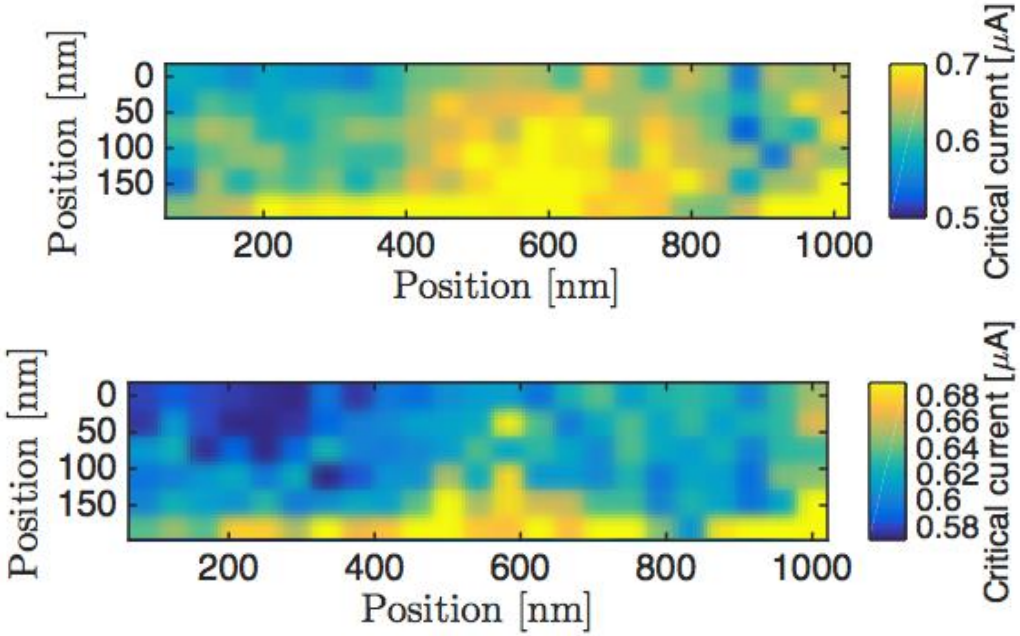
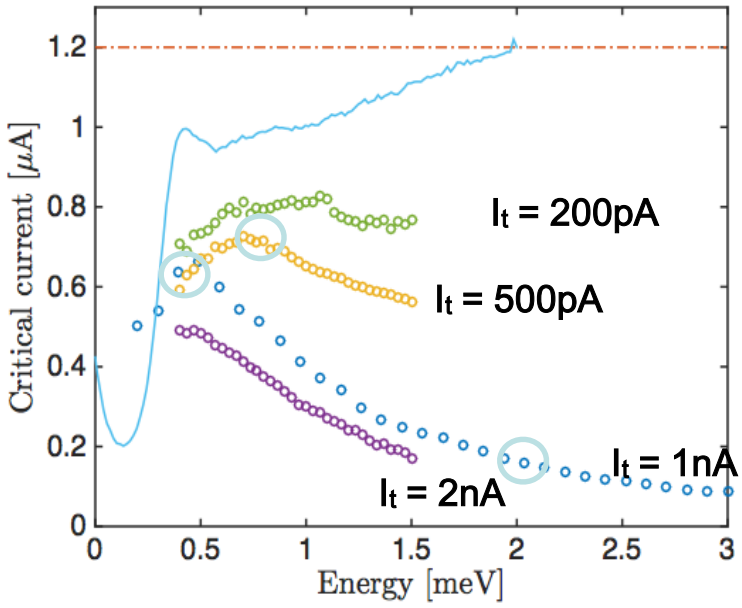
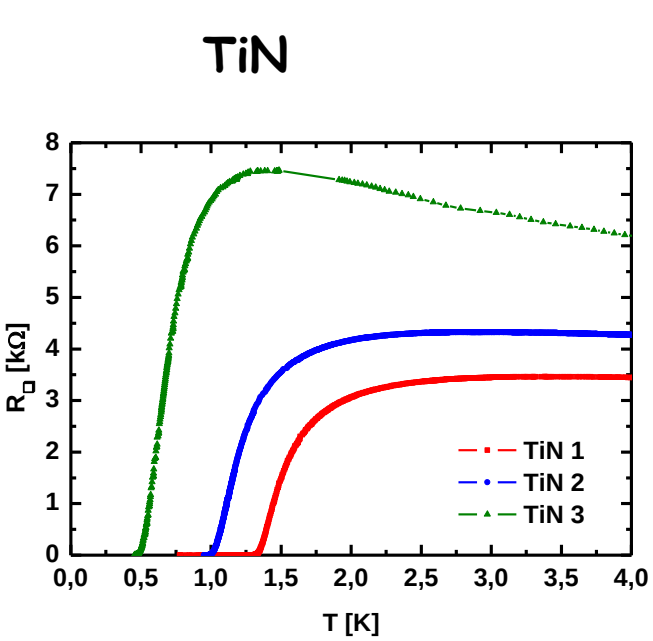
Long live time of quasiparticles close to the gap

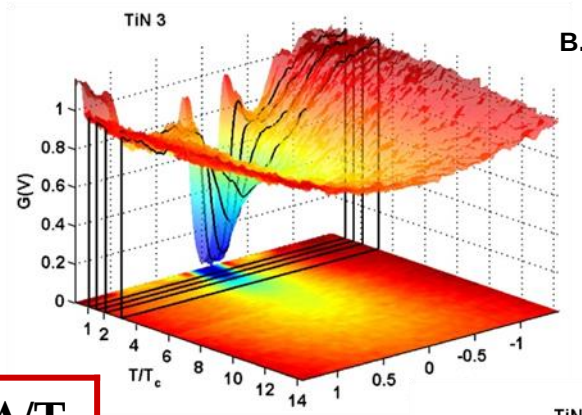


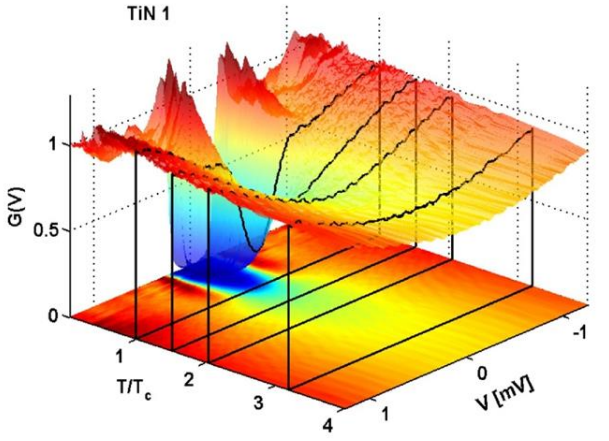
# TIN Superconductor-Insulator transition

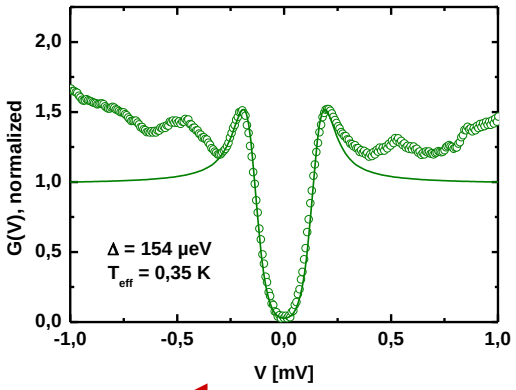


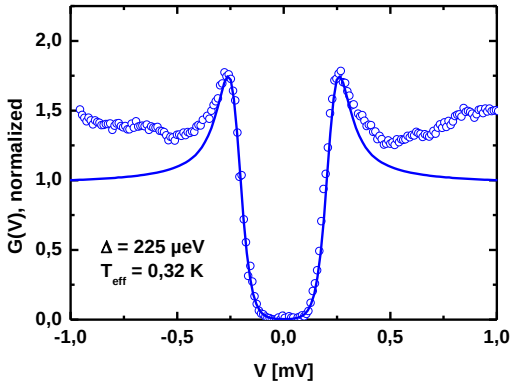



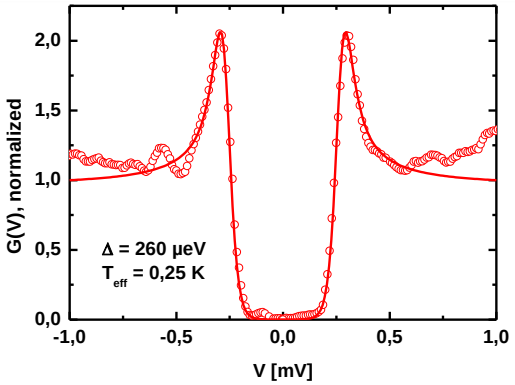

**B. Sacépé** et al., *Nat. Comm.*, (2010)

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



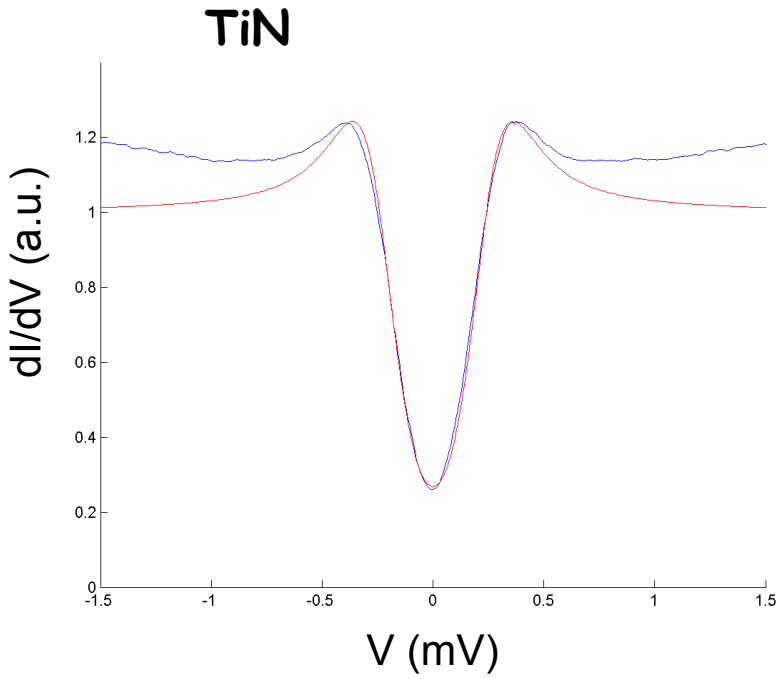



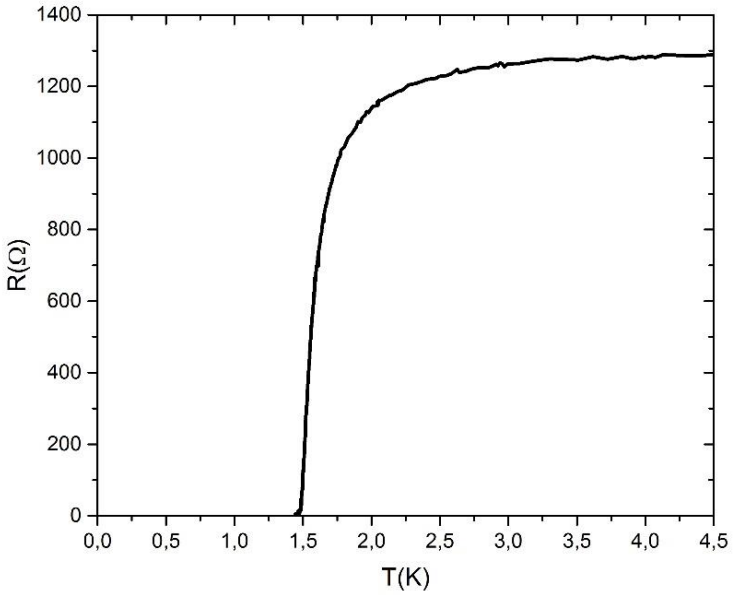




**Increasing disorder**

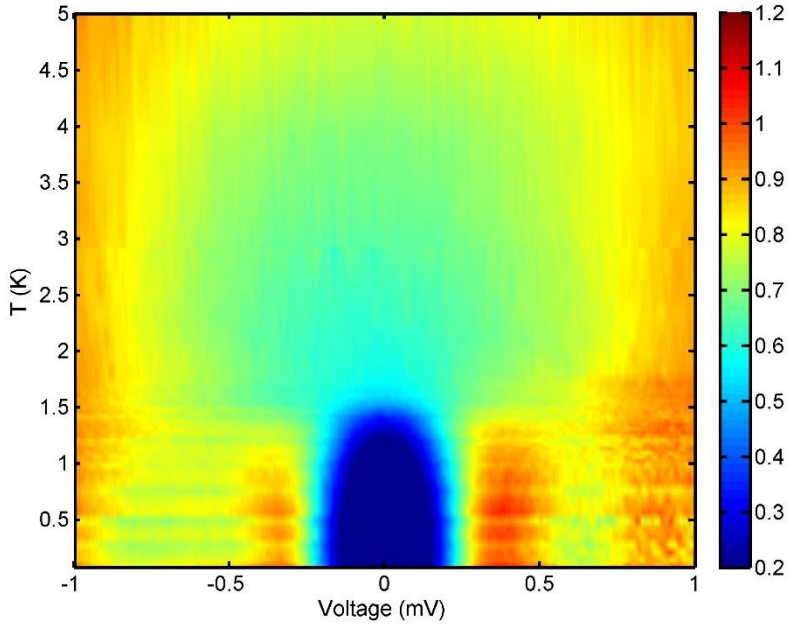
**Sacépé et al.,** *PRL* ***101****, 157006 (2008)*

# TIN Superconductor-Insulator transition




- Device fabrication in Kavli Nanolab
- Nanowire: 5nm x 200 nm x 4 μm
- $T_c$ = 1.5 K, $R_s$ = 1.5 kΩ
- $\Delta$ = 250 μV, $\Delta / T_c$ = 1.9



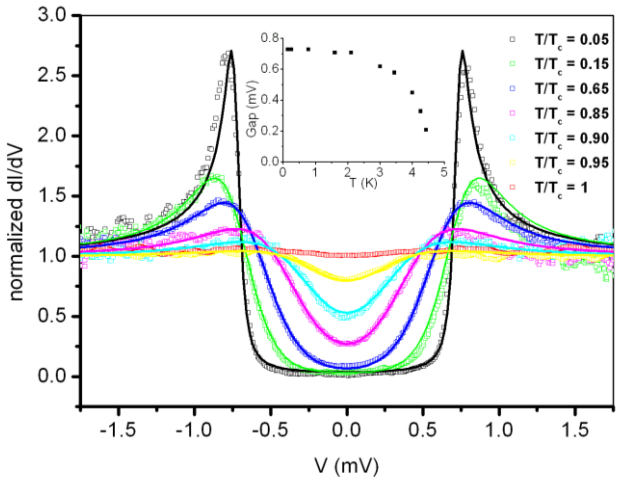
# Where do the subgap states come from ?

TiN

1- Superconducting Photon detector
2- Critical current microscopy
3- Where do the subgap states come from ?

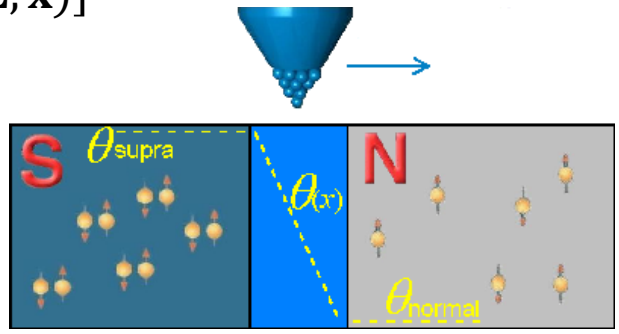
# Where do the subgap states come from ?

TiN $\Delta/T_c = 1.76$



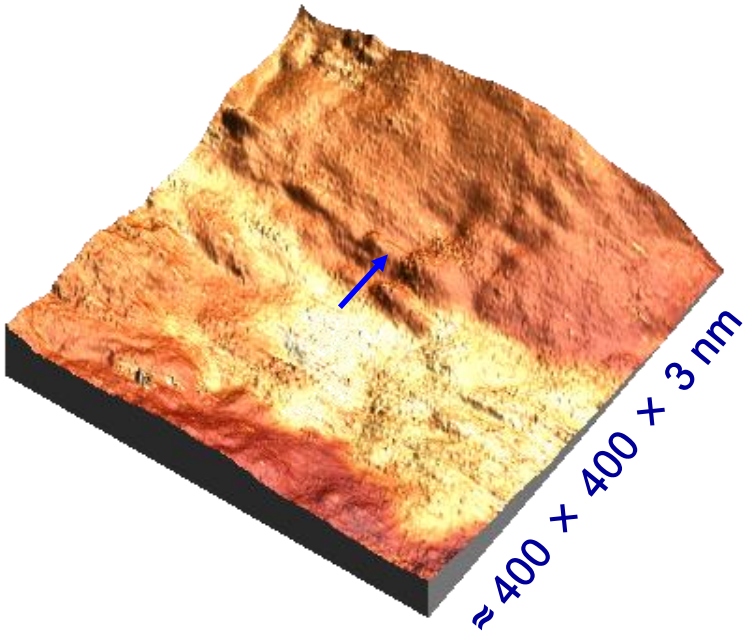

$$\frac{\hbar D}{2}\frac{\partial^2\theta}{\partial x^2} + [iE - \Gamma_{in} - 2\Gamma_{sf}\cos\theta]\sin\theta + \Delta(x)\cos\theta = 0$$

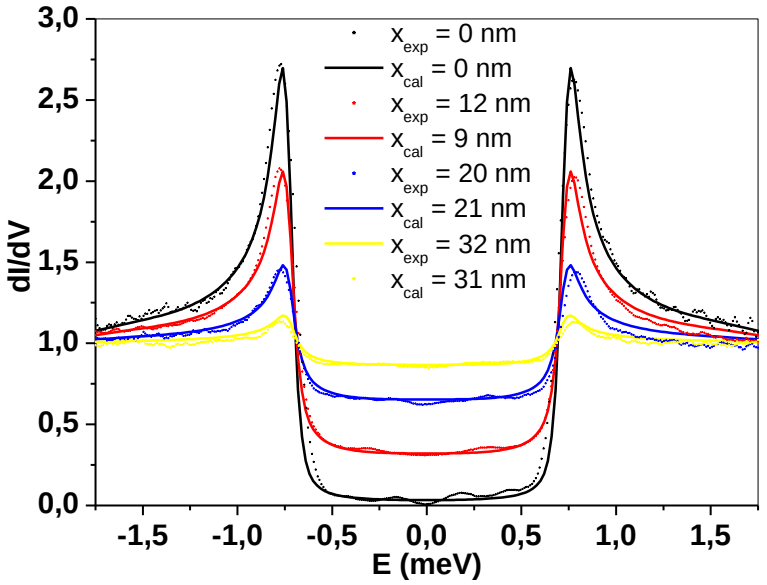
$$n(E,x) = n_0\,\mathrm{Re}[\cos\theta(E,x)]$$




$d_{S,N}$

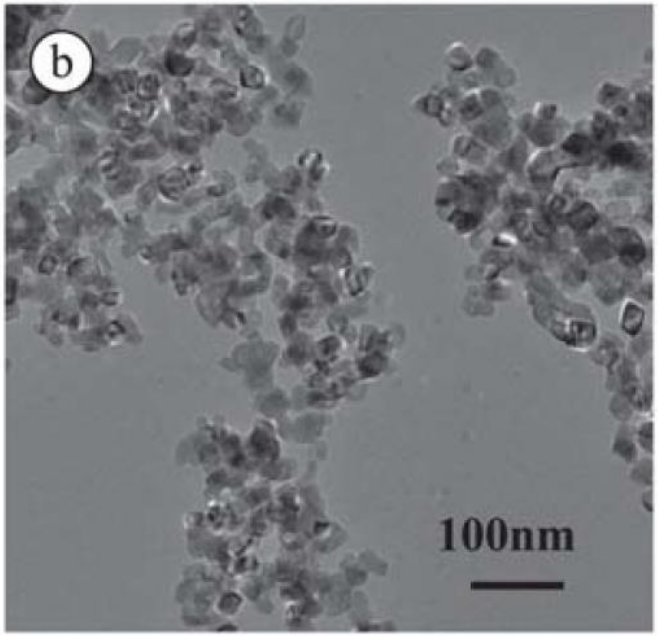
$$\theta_{(x,\epsilon)} = \theta_S \times \left(\frac{d_{sn}-x}{d_{sn}}\right)$$

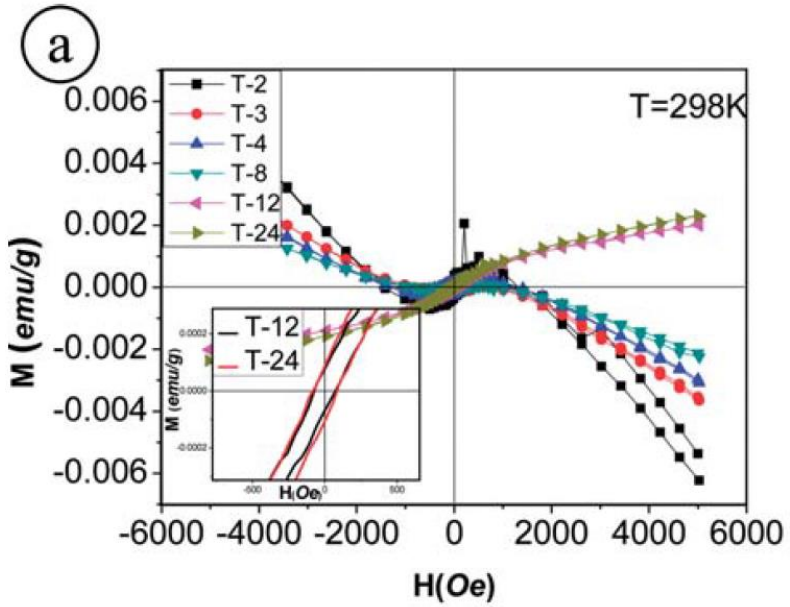


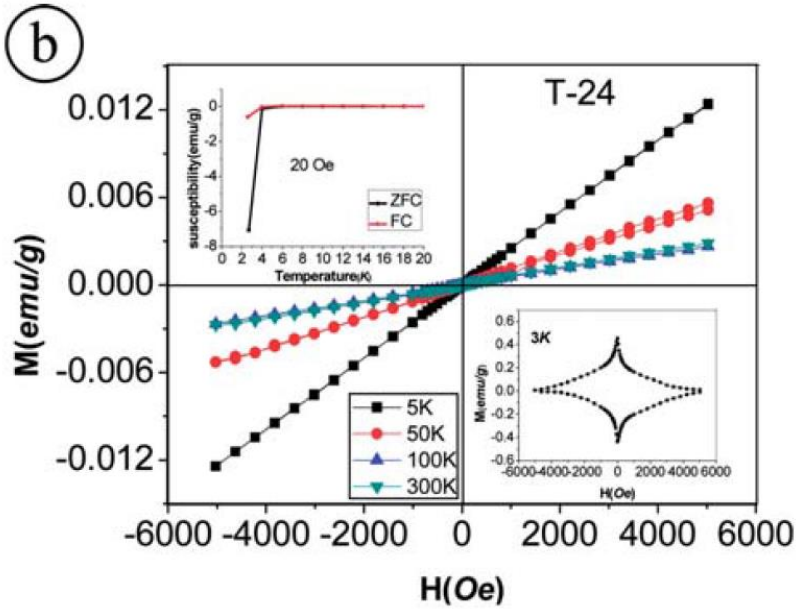




**W. Escoffier** et al., *Phys. Rev. Lett*. **93**, 217005 (2004)

# Where do the subgap states come from ?



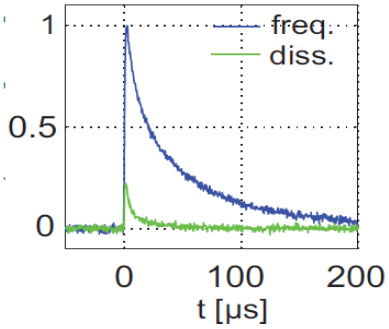



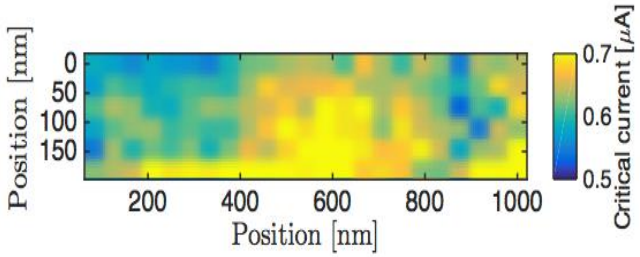

**C. Gong** et al., *J.Mater. Chem*. **21**, 15273 (2011)

# Conclusion

- **Disordered superconductors are promising materials for photon detector however, quasipartricle dynamic must be understood**




- **Critical current microscopy is a powerful tool in order to probe out-of-equilibrium superconductivity**




- **Materials must be well controlled and characterized**