Resistive superconducting films for photonsensing devices

conventional superconductivity in 'bad metals'

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Thanks to the members of my group at Delft and my collaborators at SRON

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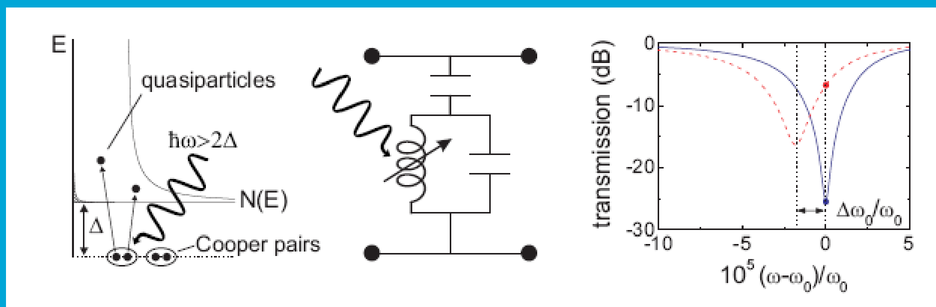
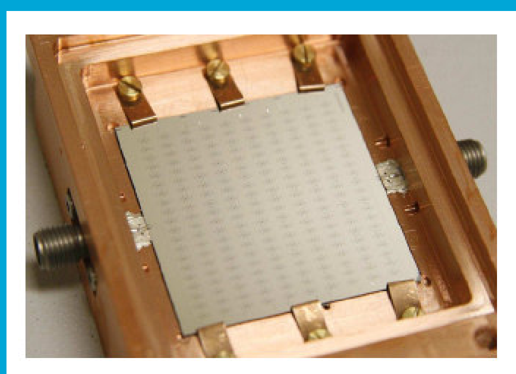
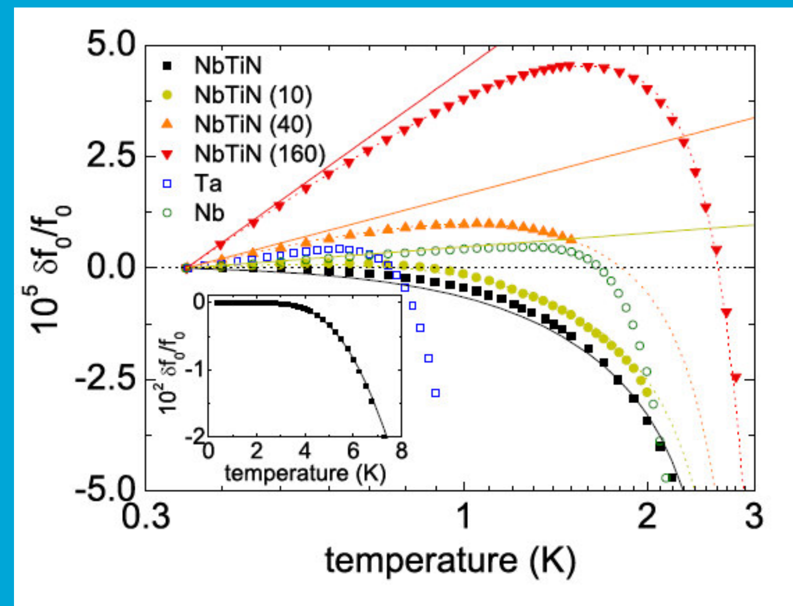
Electrodynamics of the superconductor







Barends et al, Appl.Phys. Lett.**92**,223502(2008)

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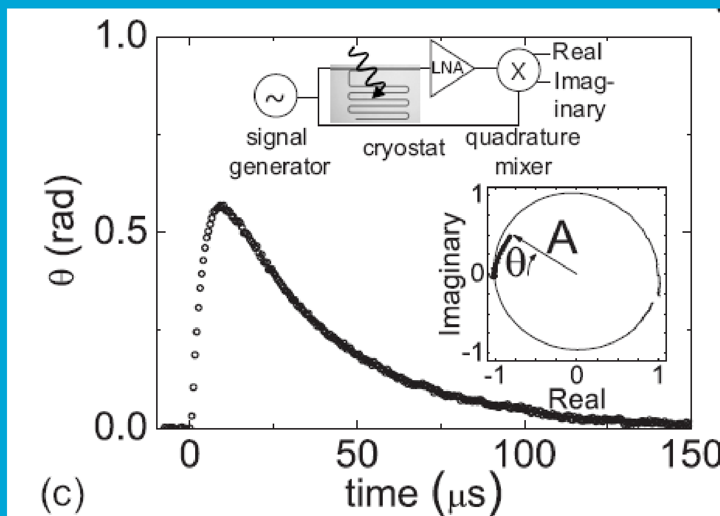
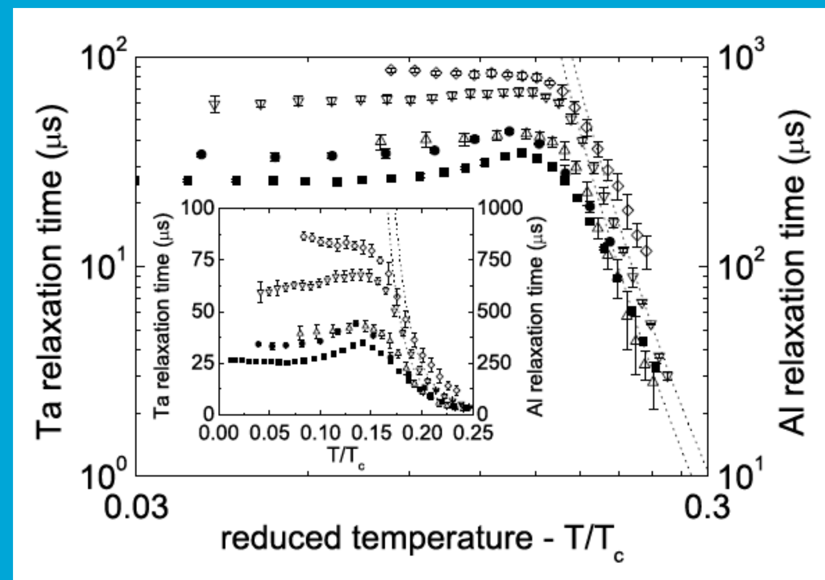
Recombination rates; disorder dependent

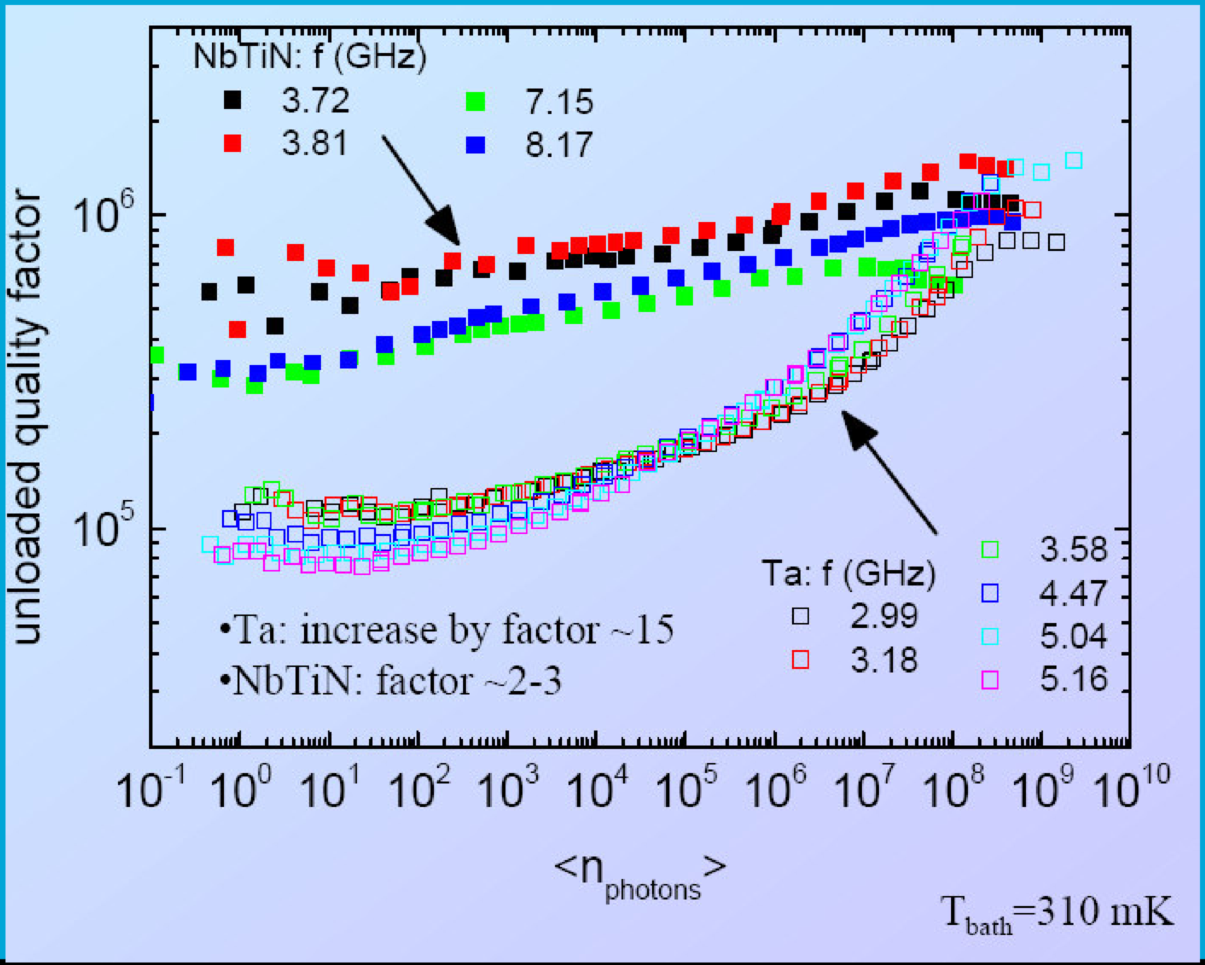
$$\frac{\tau_0}{\tau_r(\Delta)} = \sqrt{\pi}\left(\frac{2\Delta}{kT_c}\right)^{5/2}\sqrt{\frac{T}{T_c}}e^{-\Delta/kT} = \frac{(2\Delta)^2}{(kT_c)^3}\frac{n_{qp}}{2N^a(0)}$$





R.Barends et al, PRL **100**, 257002(2008); PRB **79**, 020509 (2009)

Power dependence quality factor NbTiN



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Materials in use NbN, NbTiN, TiN

- **Hot-electron bolometers** (HEB's): 4 nm thick, R=100Ω/sq, ρ=250μΩcm
- **Superconducting single photon detectors** (SSPD's): >4 nm thick, R≤100Ω/sq, ρ≤250μΩcm, narrow: 90 nm; uniformity
- **Microwave kinetic inductance detectors** (MKIDs): Al, Ta, Nb, *NbN, NbTiN, TiN* , in search of optimal parameters: 60 nm thick, R=10Ω/sq, ρ=100μΩcm, uniformity

Conventional superconductivity in 'bad metals'

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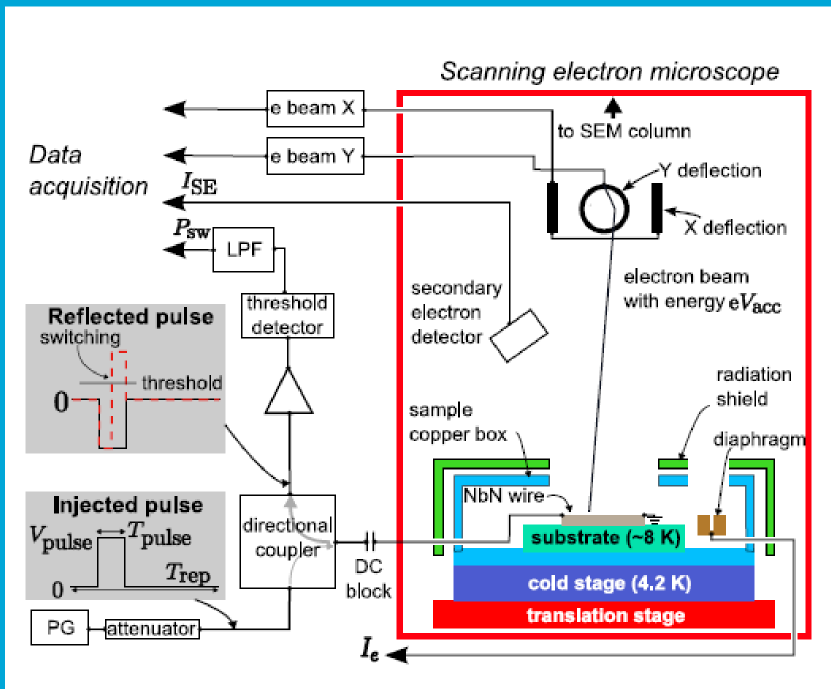
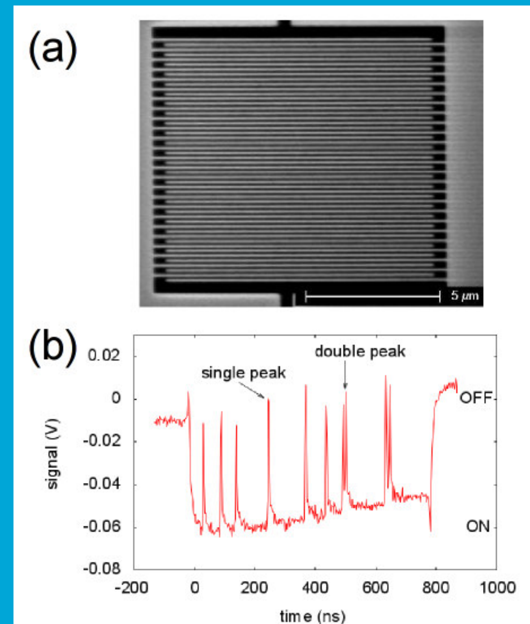
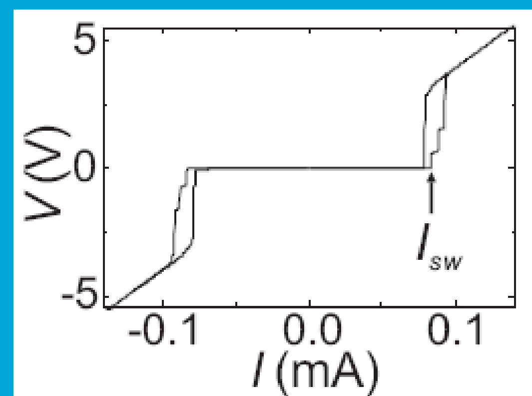
Superconductor single-electron detector



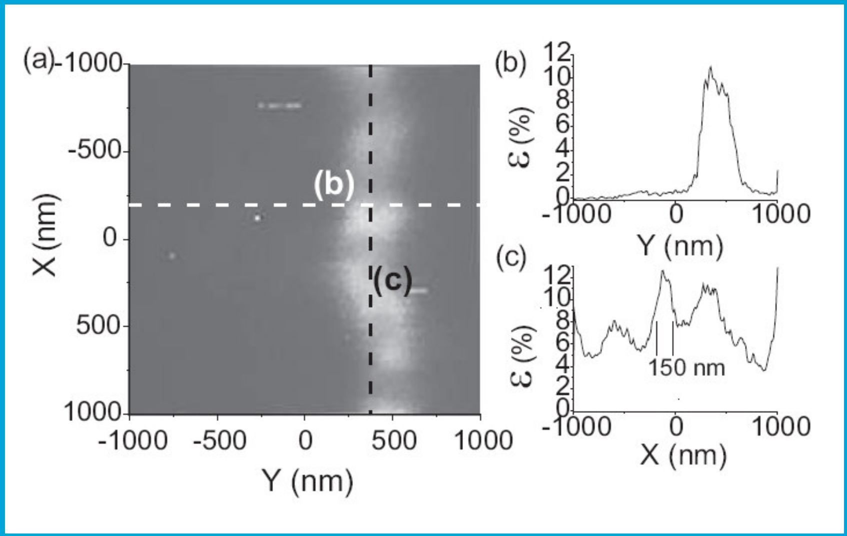




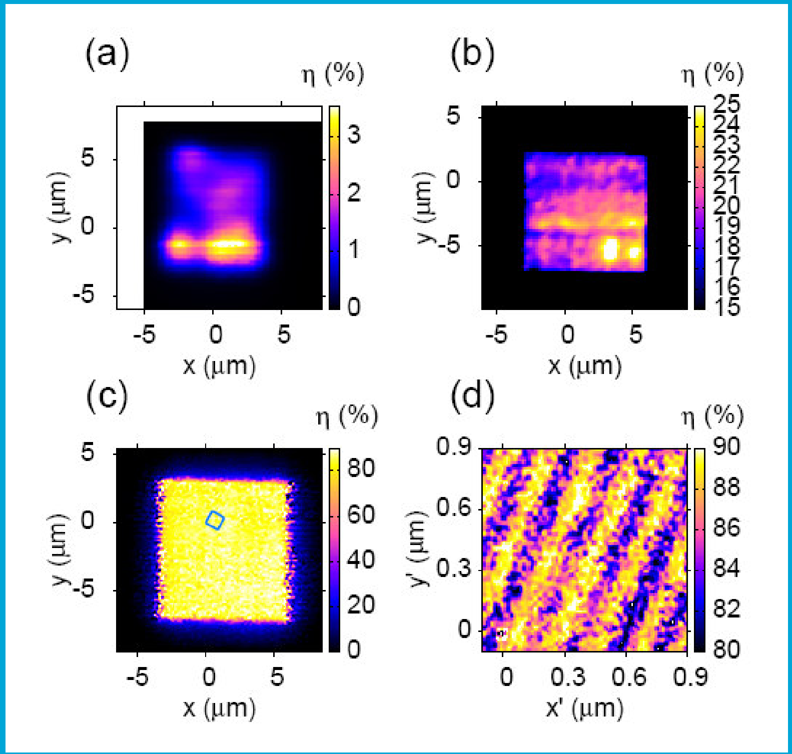
Lupascu et al, arXiv; Rosticher et al, to be publ.

Spatial pattern of optical and electron QE in NbN and NbTiN

Dorenbos et al, APL **93**, 131101(2008): NbTiN

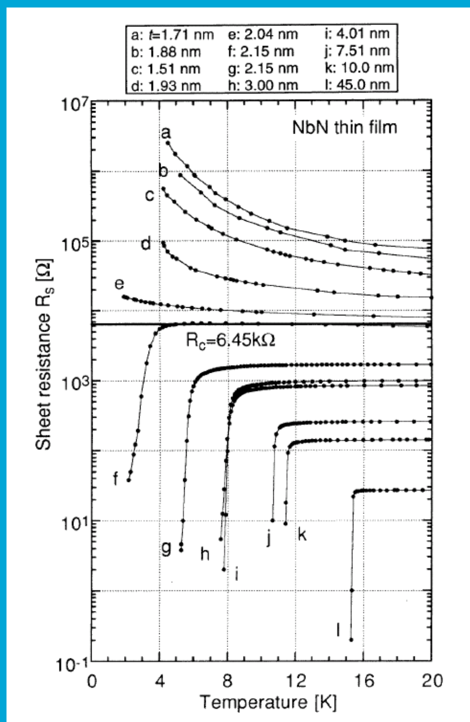


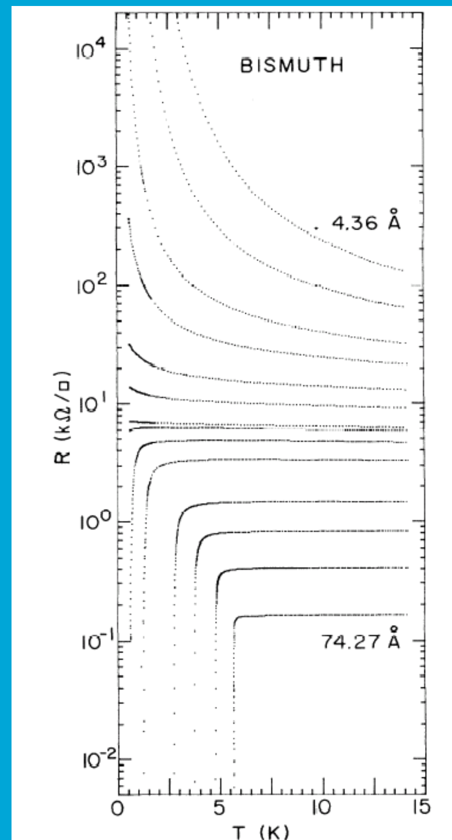
NbN



Rosticher et al, to be published

Thin NbN films and quench-condensed films; superconductor-insulator transition





- Disorder driven
- Magnetic field driven

Su *et al*, SST **9**, A152 (1996)

Haviland, Jaeger, Goldman, 1986/1989

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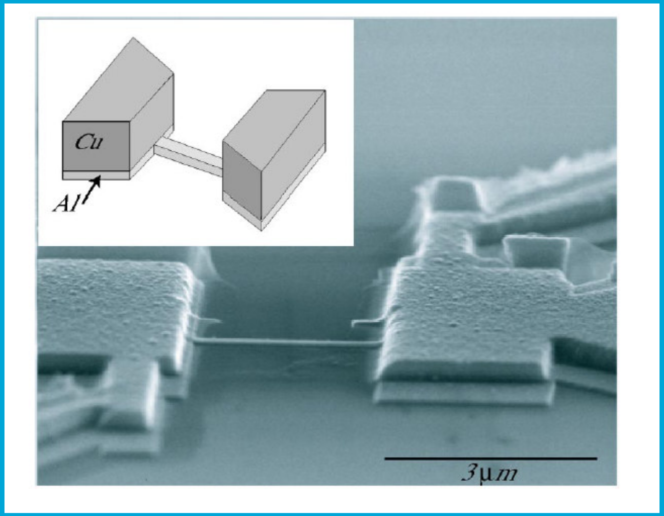
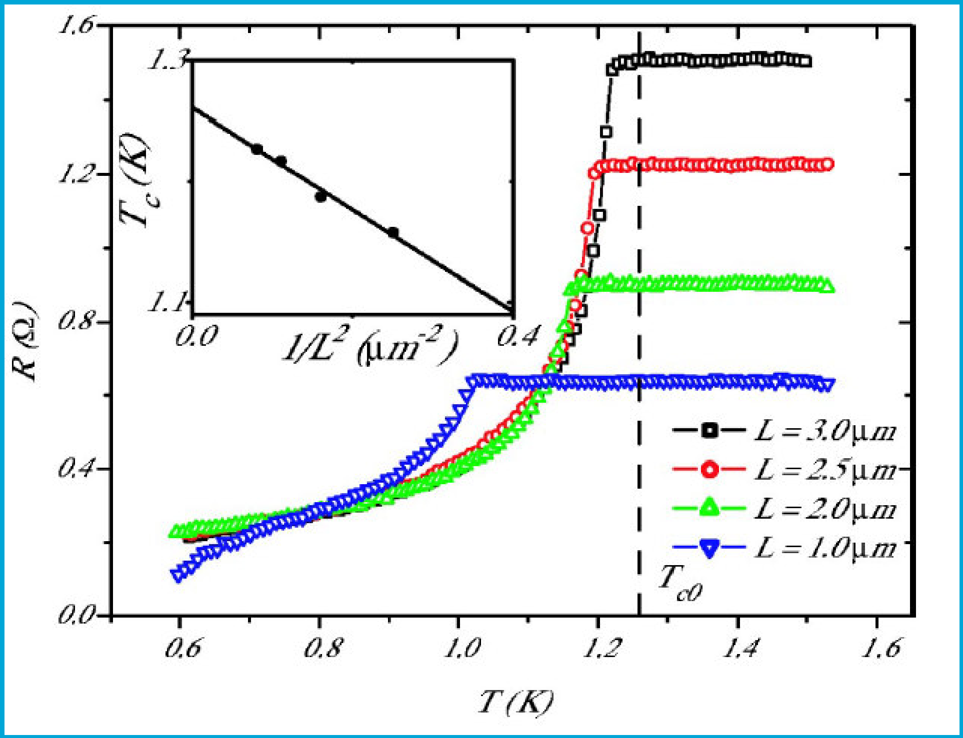
Superconductor differs from a resistive metal !!

- Electron temperature vs distribution function
- Resistance *not* simply due to single-electron back-scattering processes, but:
  - Current conversion processes (static)
  - Phase-slip/flux-flow (dynamic)

Microwave impedance????

Resistance of a NSN structure: static resistance of S (temperature close to Tc)





Boogaard et al, 2004?

Electrodynamics of superconducting thin films

$$k_F l = 1$$

$$\sigma = 2e^2 N(0) D$$

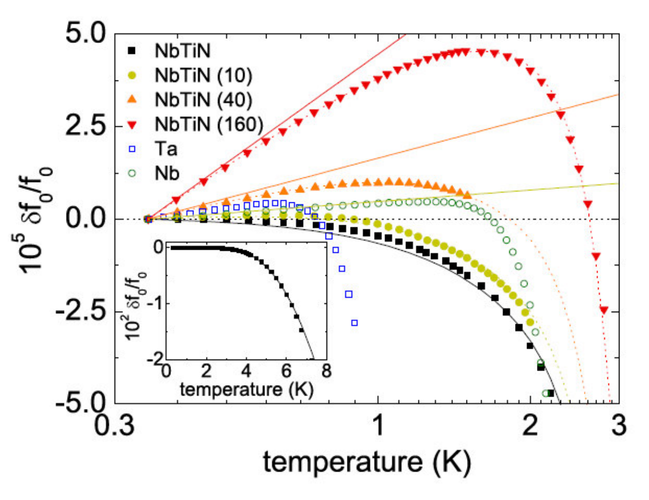
$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_\Delta^\infty [f(E) - f(E+\hbar\omega)] g_1(E) dE + \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{-\Delta} [1 - 2f(E+\hbar\omega)] g_1(E) dE$$

$$\frac{\sigma_2}{\sigma_N} = \frac{1}{\hbar\omega}\int_{\max(\Delta-\hbar\omega,-\Delta)}^{\Delta} [1 - 2f(E+\hbar\omega)] g_2(E) dE$$

$$g_1(E) = \left(1 + \frac{\Delta^2}{E(E+\hbar\omega)}\right) N_S(E) N_S(E+\hbar\omega)$$

$$g_2(E) = \frac{E(E+\hbar\omega)+\Delta^2}{\sqrt{(E+\hbar\omega)^2-\Delta^2}\sqrt{\Delta^2-E^2}} = -i g_1(E)$$

- Localization: D
- Correlations: N(0)

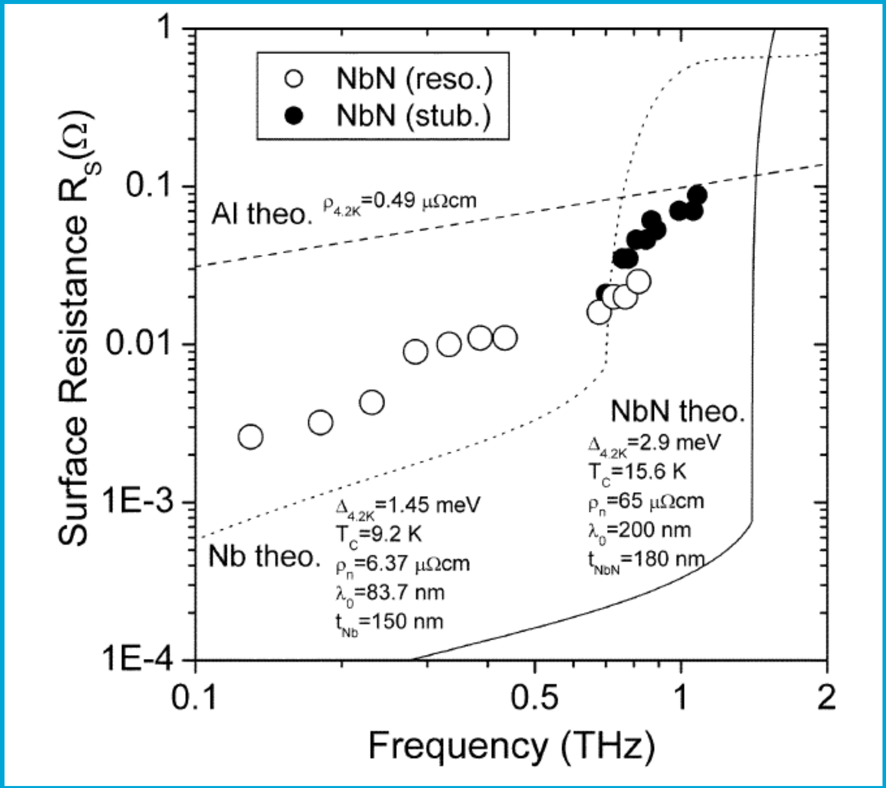


E to E+iΓ

$$\Gamma = 17\ \mu\text{eV}$$

Dynes broadening parameter

Good quality NbN: too much surface resistance



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Macroscopic quantum state

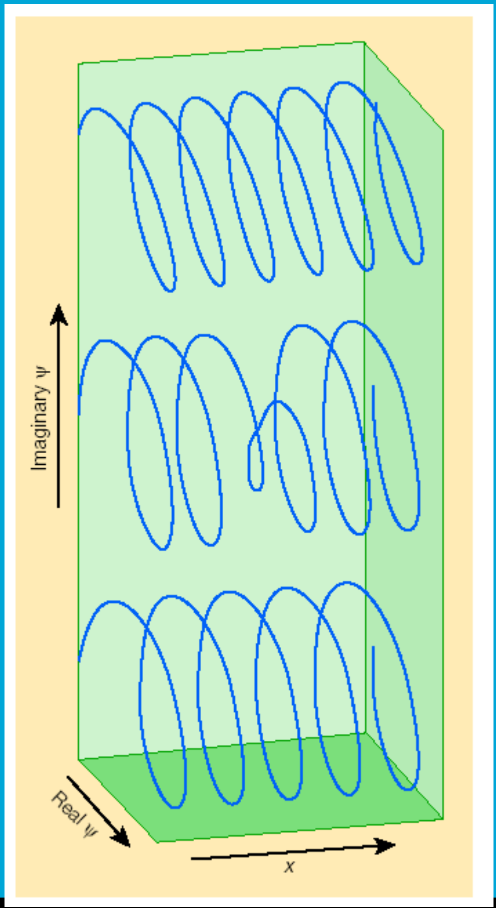
1-dimensional

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

$$|\psi| = \sqrt{n_s}$$

$$j_s \propto \nabla \varphi$$

$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar}$$



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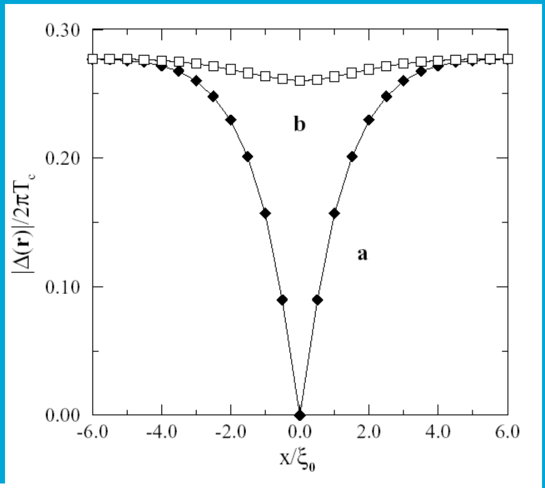
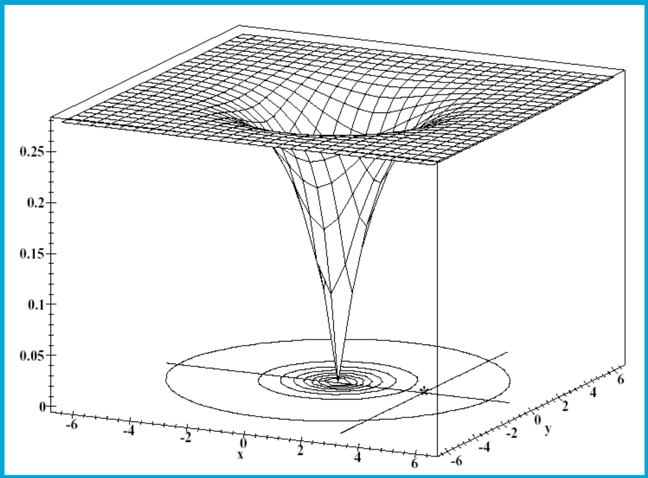
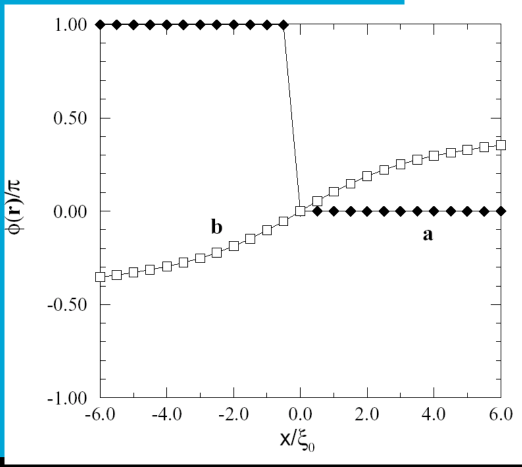
Vortex core on the scale of ξ and circulating current

$$B(r) = \frac{\Phi_0}{2\pi\lambda^2} K_0\left(\frac{r}{\lambda}\right) \approx \sqrt{\frac{\lambda}{r}} \exp\left(-\frac{r}{\lambda}\right),$$

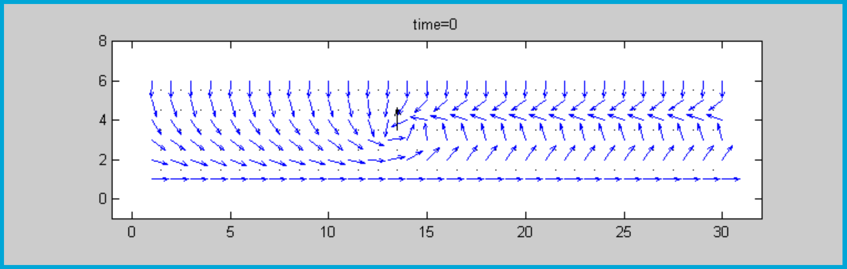


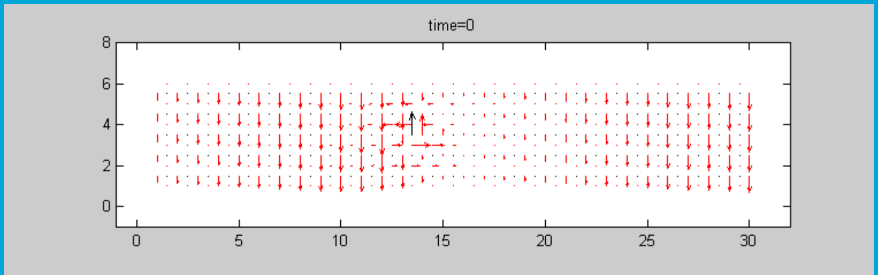




Rainer et al, PRB 1996

Dynamics of flux flow





$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar}$$

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Berezinskii-Kosterlitz-Thouless transition in 2D superconducting films

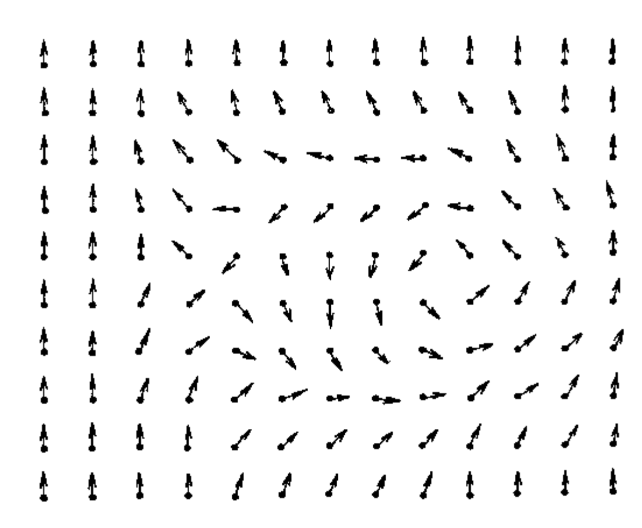
$$\left\{ \frac{\Delta(T)}{\Delta(0)} \tanh\left[\frac{\beta\Delta(T)}{2} \right] \right\}^{-1}$$

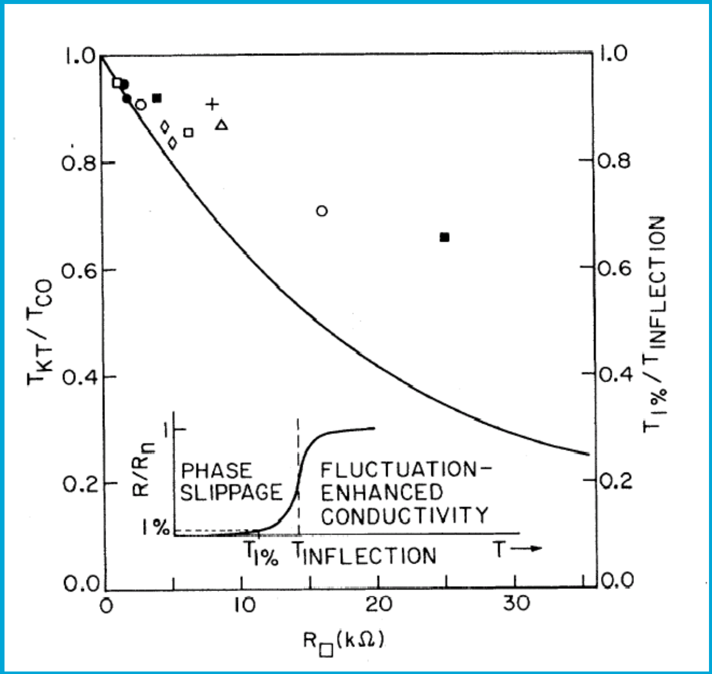
$$\lambda_{\perp} = 1.78 \, \frac{\Phi_0^{\,2}}{4\pi^5} \, \frac{e^2}{\hbar} \, \frac{R_{\Box}}{k_B T_{c0}} \, f^{-1}\left(\frac{T}{T_{c0}}\right).$$

$$k_B T_{KT} = \tfrac{1}{2}\pi\hbar^2 n_s^{\,2D}/m^*$$

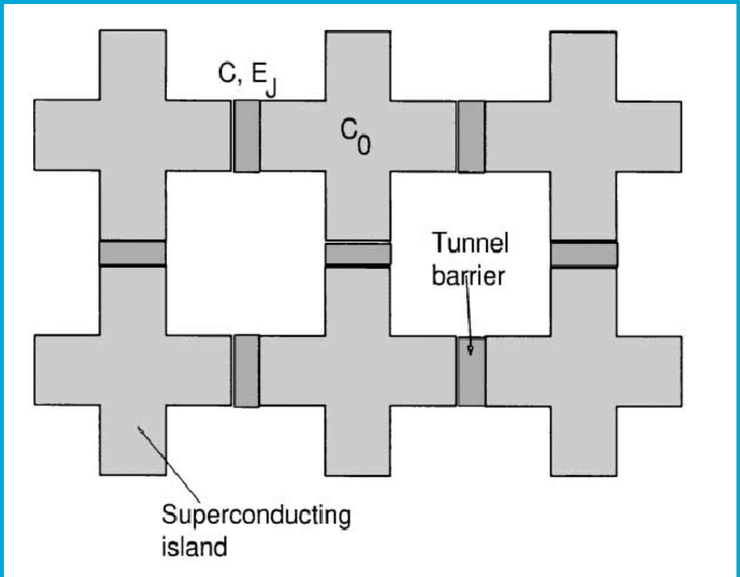
$$\frac{T_{KT}}{T_{c0}} f^{-1}\left(\frac{T_{KT}}{T_{c0}}\right) = 0.561 \, \frac{\pi^3}{8}\left(\frac{\hbar}{e^2}\right)\frac{1}{R_{\Box}}$$

$$= 2.18 \, \frac{R_c}{R_{\Box}},$$





Coulomb blockade and Josephson coupling



$$H \sim \frac{1}{2}\sum_{i,j} Q_i C_{ij}^{-1} Q_j - \frac{E_\mathrm{J}}{2}\sum_{\langle i,j\rangle}(\phi_i - \phi_j)^2$$

$$\frac{\mathrm{d}\phi_i}{\mathrm{d}t} = \frac{2e}{\hbar} V_i = \frac{2e}{\hbar} C_{ij}^{-1} Q_j$$

$$\begin{aligned} H &= H_\mathrm{ch} + H_\mathrm{J} \\ &= \frac{1}{2}\sum_{i,j}(Q_i - Q_{\mathrm{x},i}) C_{ij}^{-1} (Q_j - Q_{\mathrm{x},j}) - E_\mathrm{J}\sum_{\langle i,j\rangle}\cos(\phi_i - \phi_j - A_{ij}) \end{aligned}$$

Three competing processes

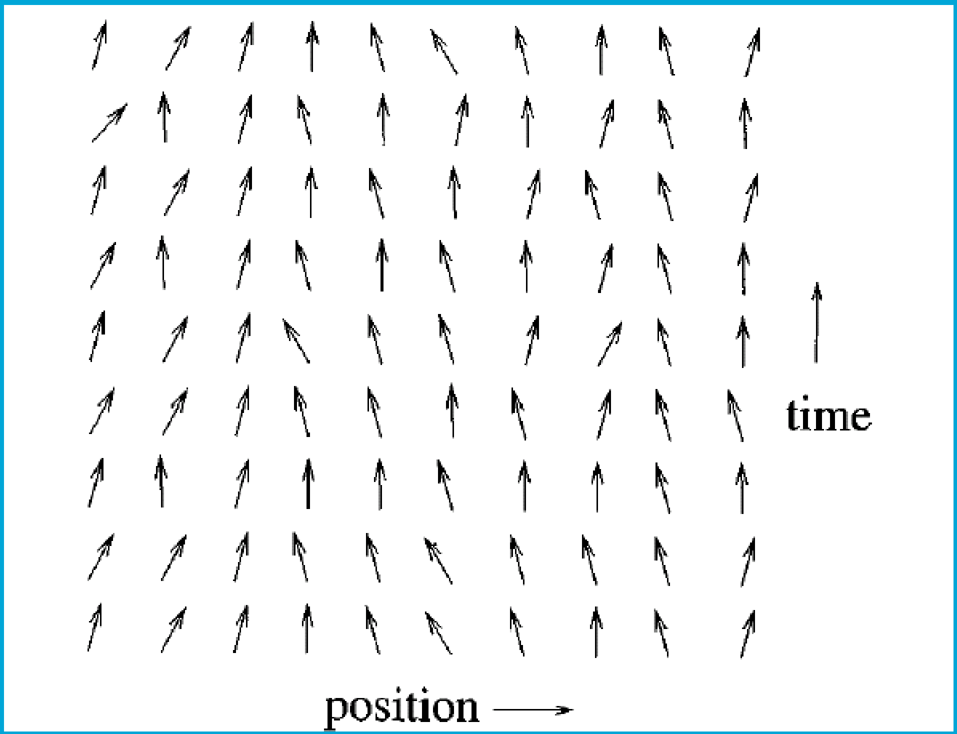
$$\boxed{\sigma = 2e^2 N(0) D}$$

1. Disorder: quantumcoherent elastic scattering: localization
2. Electron-correlations: opening of a Coulomb gap
3. Superconducting correlations

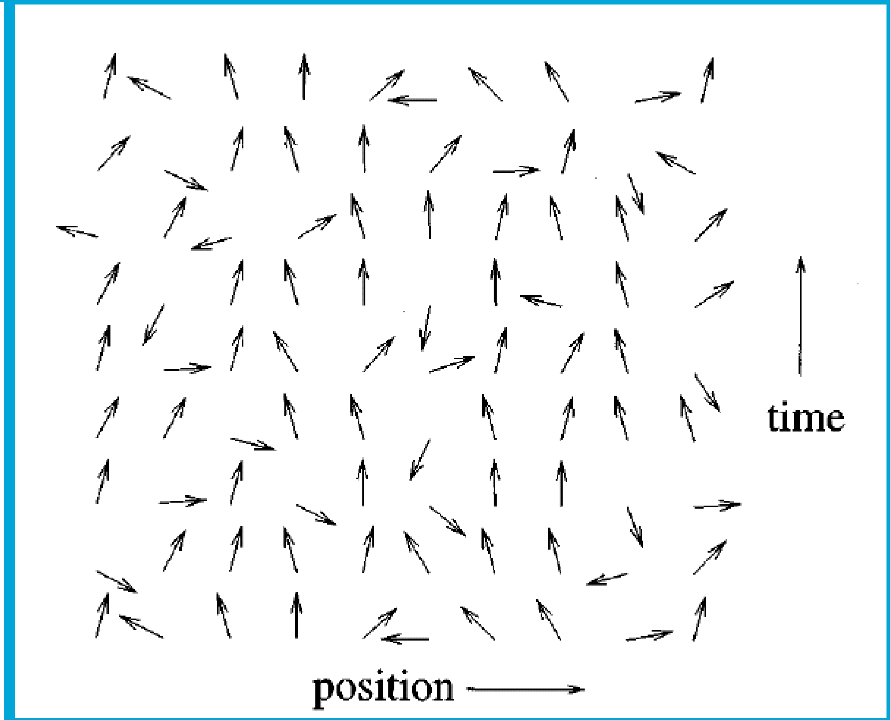
- Superconducting state disappears by decrease of *amplitude*
- Superconducting state disappears by *phase fluctuations*

Evolution in time

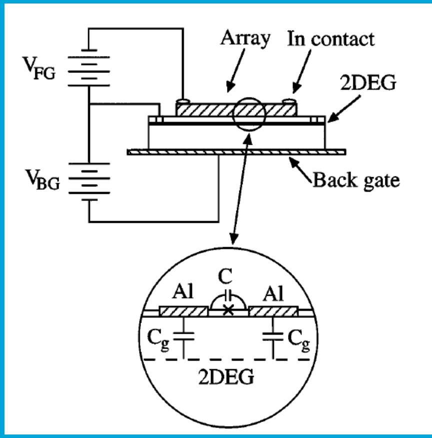
Josephson coupled

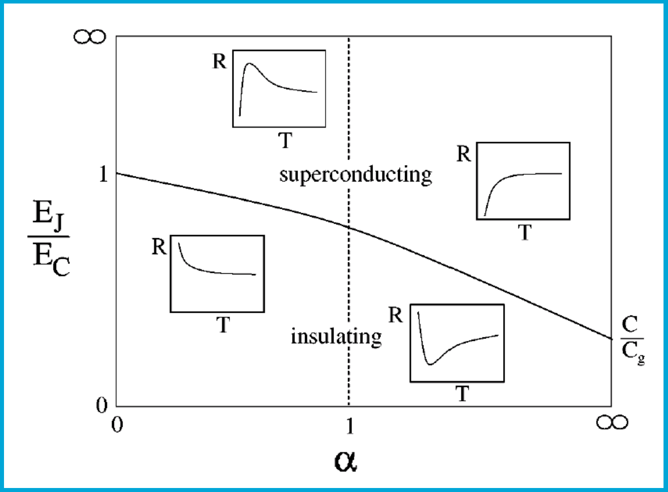


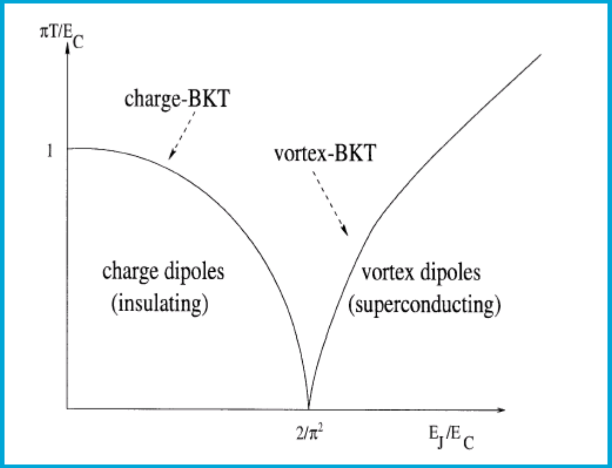
Coulomb coupled

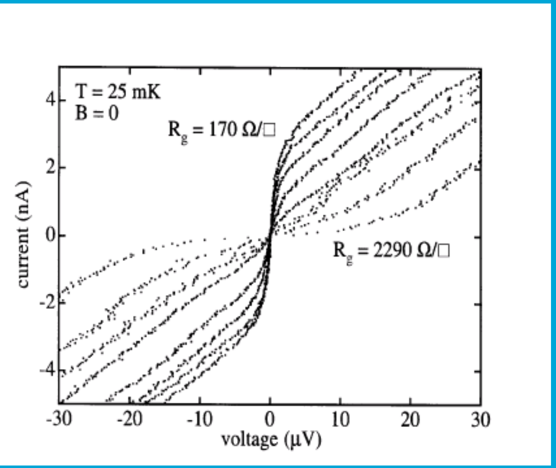


Dissipation in electromagnetic environment



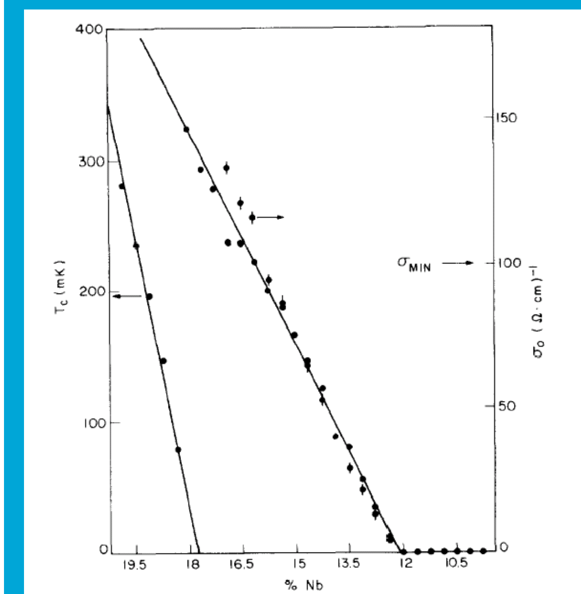


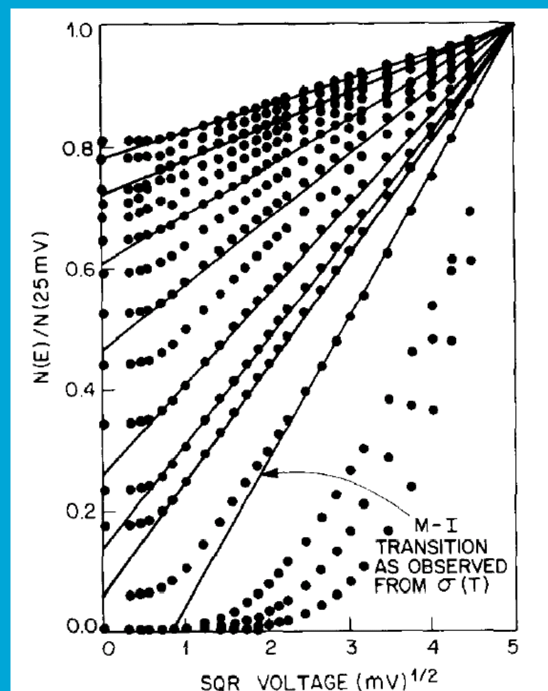


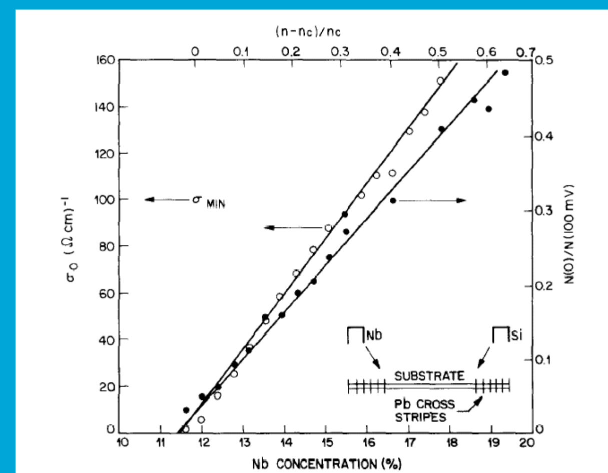


Rimberg et al, PRL **78**, 2632 (1997)

Example N(0): superconductor-metal-insulator transition: Nb(x)Si(1-x)



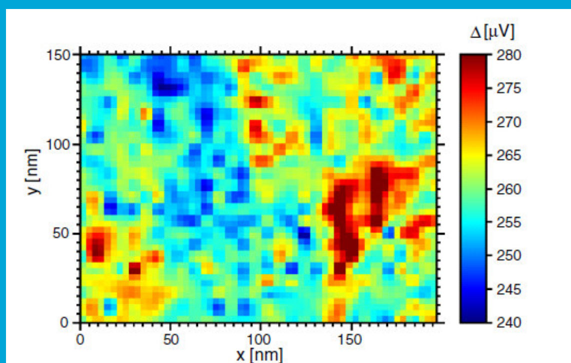


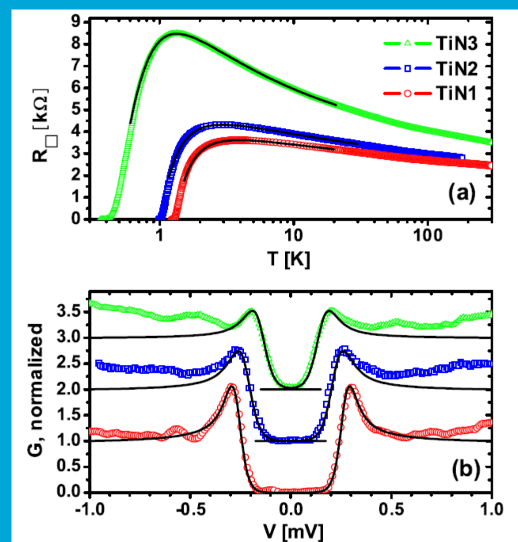


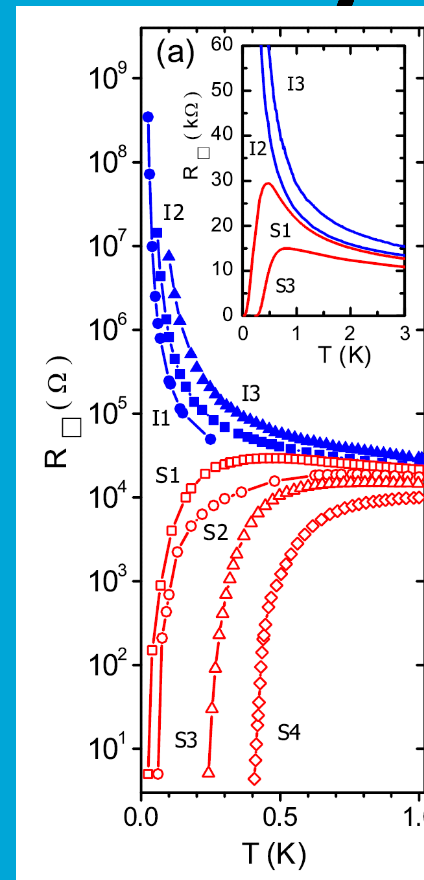
Bishop,Dynes et al, 1983/1985

Disordered superconducting films: intrinsic inhomogeneous pair-density

- Localization: electrons get 'trapped'
- Correlations: reduction in density of states at Fermi level
- Superconducting correlations







$$T_c = \frac{\hbar}{\tau_*}\left[\frac{\sqrt{2\pi g} - \ln(\hbar/T_{c0}\tau_*)}{\sqrt{2\pi g} - \ln(\hbar/T_{c0}\tau_*)}\right]^{\sqrt{\pi g/2}}$$

T.I.Baturina et al, Phys. Rev. Lett. **99**, 257003 (2007)
B. Sacepe et al, Phys. Rev. Lett. **101**, 157006 (2008)

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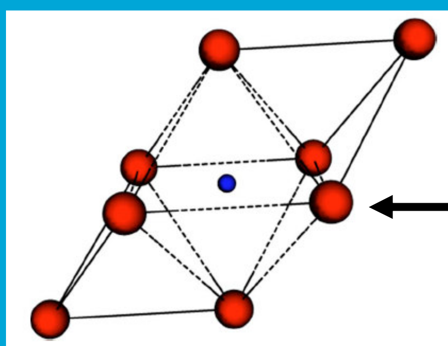
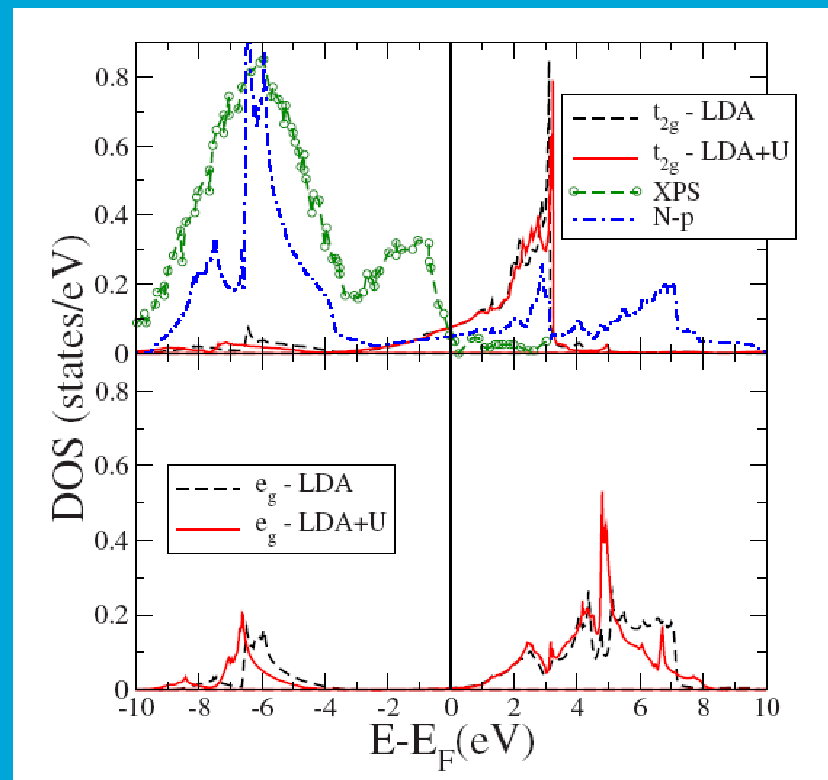
Density of states: bandstructure calculations; combined electronic structure and many-body approach.

Crystalline?



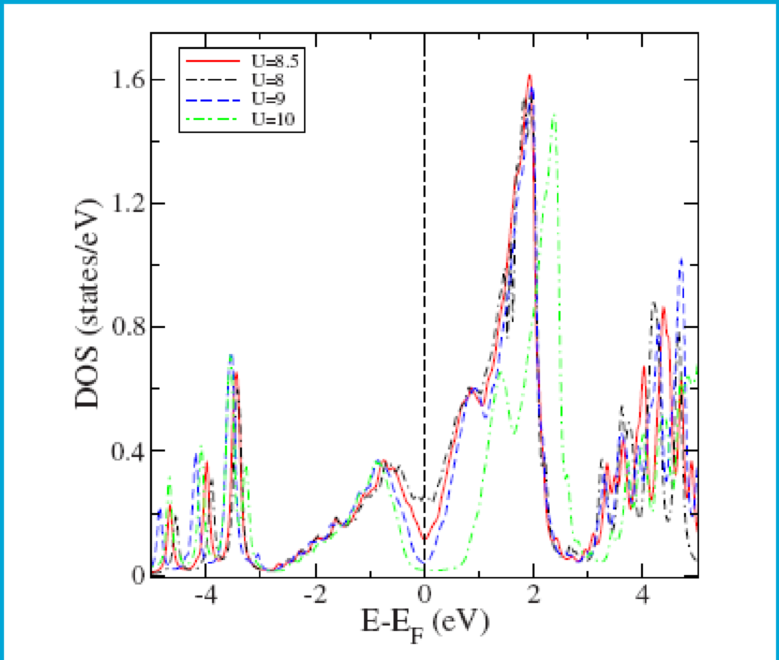
Ti

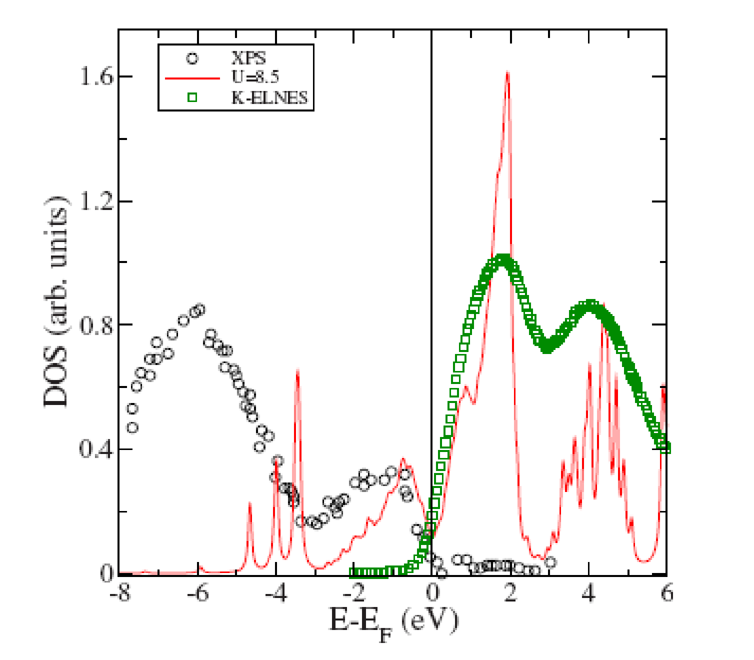
$a=7.65a_0=0.4$ nm



Allmaier et al, PRB **79**, 235126 (2009)

Mott correlation gap in ordered TiN





Our results suggest that TiN is a peculiar metal with a pseudogap at the Fermi level, indicating the proximity to a metal-insulator transition. In our calculations the pseudogap regime is best described for a value of $U = 8.5$ eV for the Coulomb interaction.

Consequences for superconductivity?

Summary

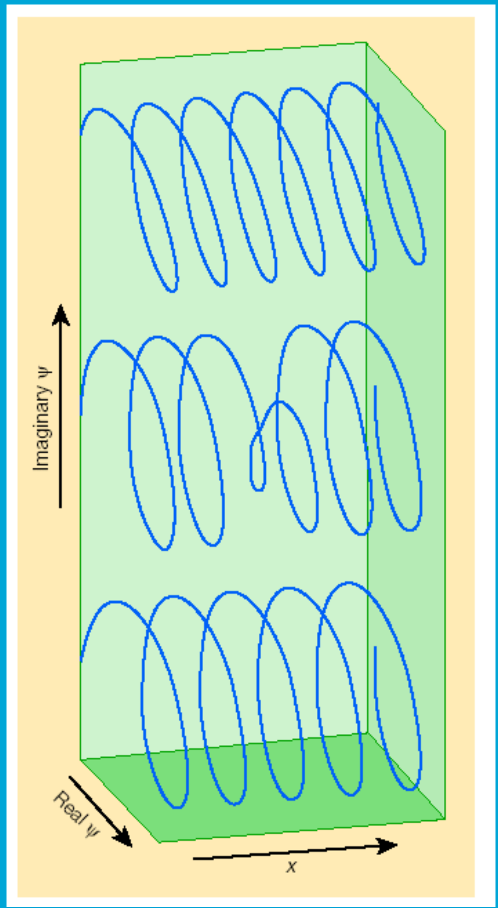
- NbTiN and TiN have quality factors over 1 M
- These superconductors are 'bad metals'
- Superconducting properties may be non-uniform
- Surface resistance in good quality NbN might be an indication
- Dynes parameter in Mattis-Bardeen might signal the same
- However, the films might be well-ordered.

Thermally activated phase slip (1 dimension)

$$|\psi(x)|^2 \frac{d\varphi}{dx} = constant \propto I$$

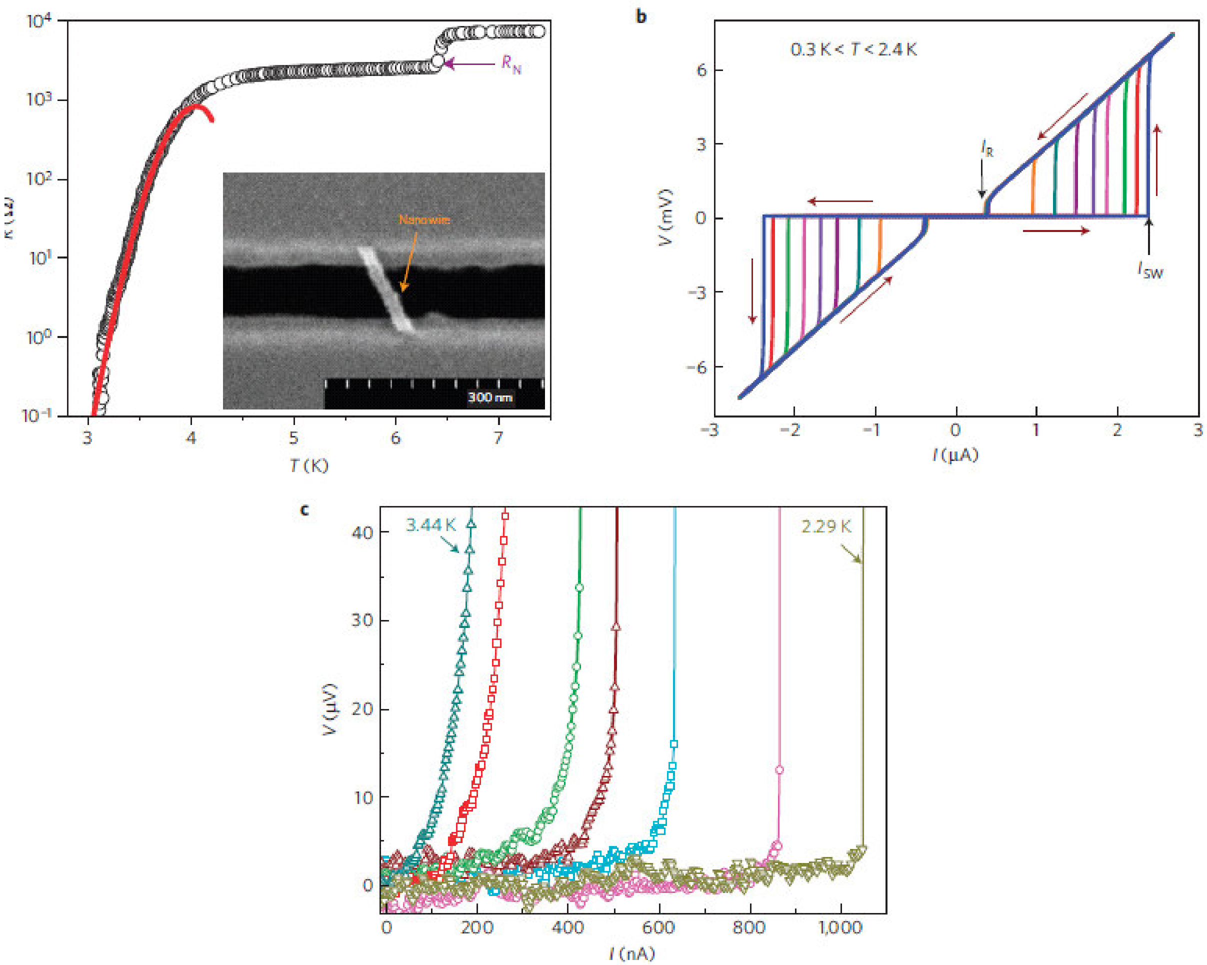
$$\Delta F_0 = \frac{8\sqrt{2}}{3} \frac{H_c{}^2}{8\pi} A\xi$$

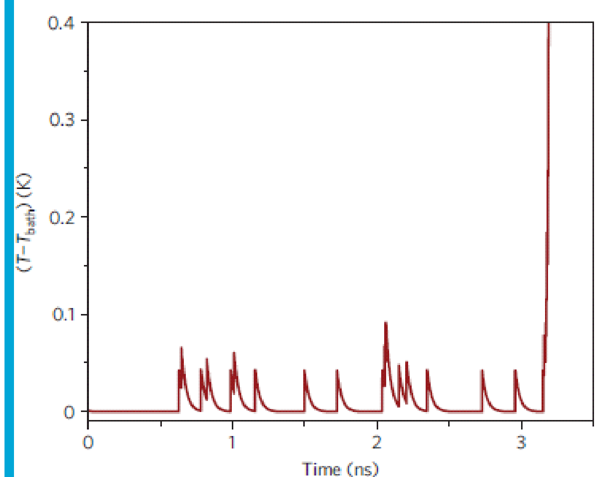
$$\delta F = \Delta F_- - \Delta F_+ = \frac{h}{2e} I$$



$$\frac{d\varphi_{12}}{dt} = \Omega[exp(-\frac{\Delta F_0 - \delta F/2}{kT}) - exp(-\frac{\Delta F_0 + \delta F/2}{kT})] = 2\Omega e^{-\Delta F_0/kT} \sinh \frac{\delta F}{2kT}$$

MoRe nanowires: Sahu et al, Nature Physics 5, 503(2009)





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Superconductor-insulator transition

- Phase-coherence: phase-fluctuations
- Disorder
- Coulomb interactions: electron-electron interactions

- Berezinskii-Kosterlitz-Thouless vortices: flux flow
- Anderson-localization
- Mott-insulator

$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar}$$

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Conclusions

• Superconductors at these 100 mK temperatures with so few qp's are poorly explored territory

• Nonuniformity which is not microstructure related?

• Characterization might provide interesting data relevant outside the engineering community

• Example: why does Tc decrease so nicely with N-content in TiN?

$$T_c = \frac{\hbar}{\tau_*}\left[\frac{\sqrt{2\pi g} - \ln(\hbar / T_{c0}\tau_*)}{\sqrt{2\pi g} - \ln(\hbar / T_{c0}\tau_*)}\right]^{\sqrt{\pi g/2}}$$

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