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IAEA International Atomic Energy Agency

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Conference on Superconductor-Insulator Transitions

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Tunneling studies in a disordered s-wave superconductor close to the Fermi glass regime

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Tunneling studies on a 3-dimensional disordered s-wave superconductor close to the Fermi Glass regime

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Vikram Tripathi

Johan Vanacken, Gufei Zhang

Leuven

Plan of the talk

♥

Introduction

♥

What is good about NbN (films)?

Tuning the disorder with deposition conditions

Transport and Hall measurements

S. P. Chockalingam, Madhavi Chand et al., Phys. Rev. B **77**, 214503 (2008)

♥

Evolution of superconducting properties with disorder

Tunneling measurements

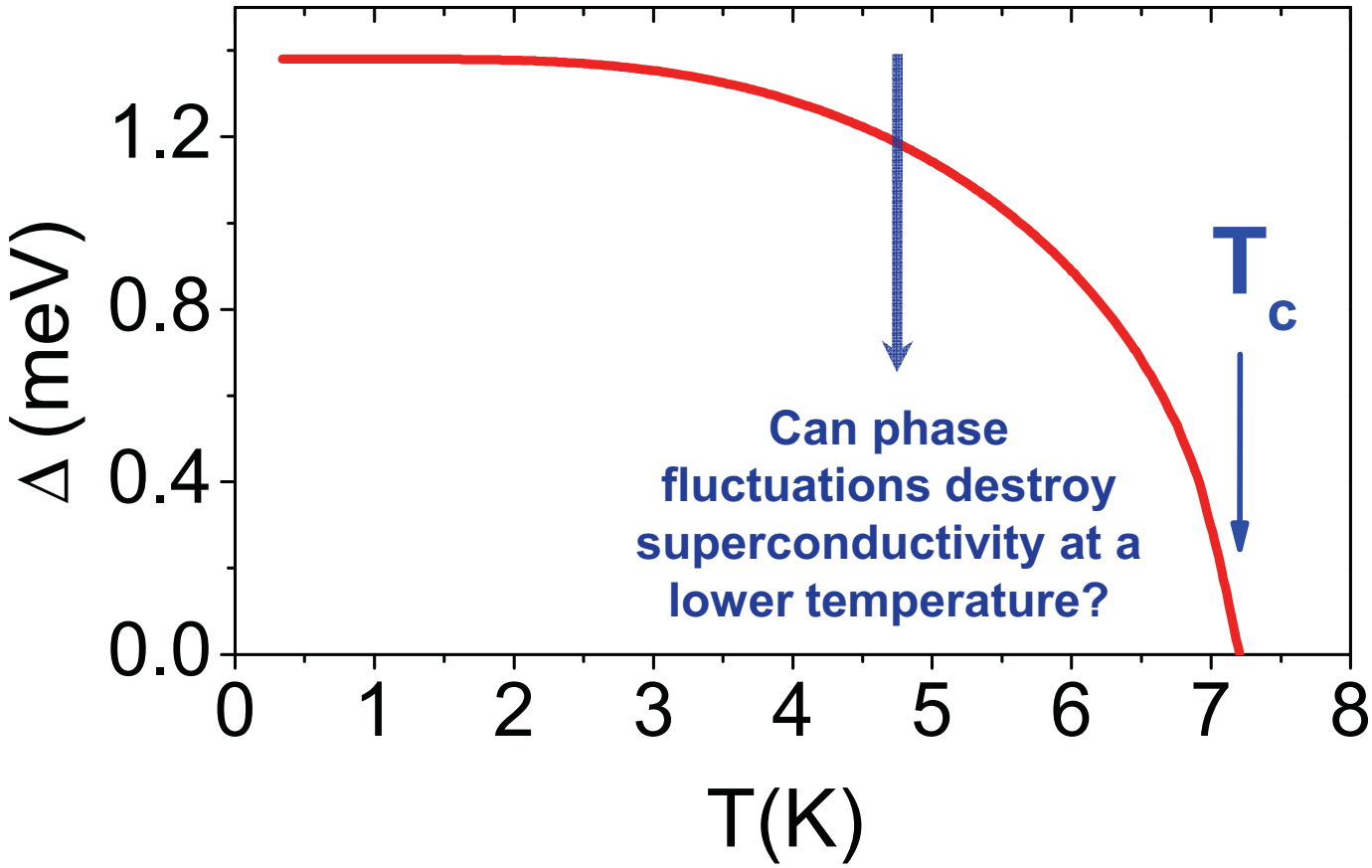
S. P. Chockalingam, Madhavi Chand et al., Phys. Rev. B **79,** 094509 (2009).

♥

Introduction

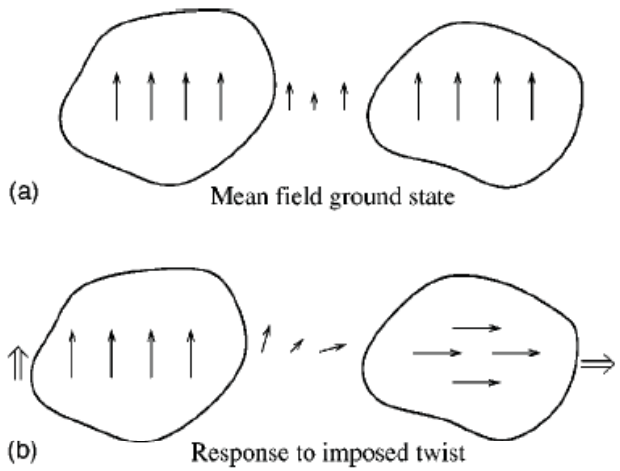
Δ:
Binding energy of Cooper Pair

$$\Psi=\Psi_0 e^{i\theta}$$



Beyond Anderson Theorem

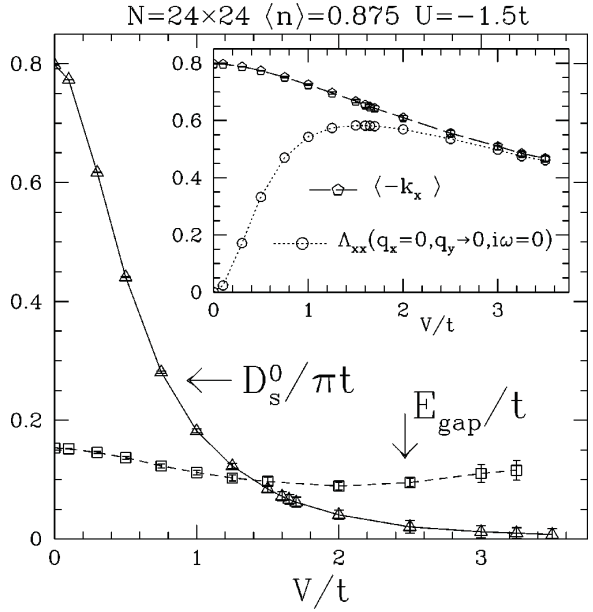
2-dimension T=0



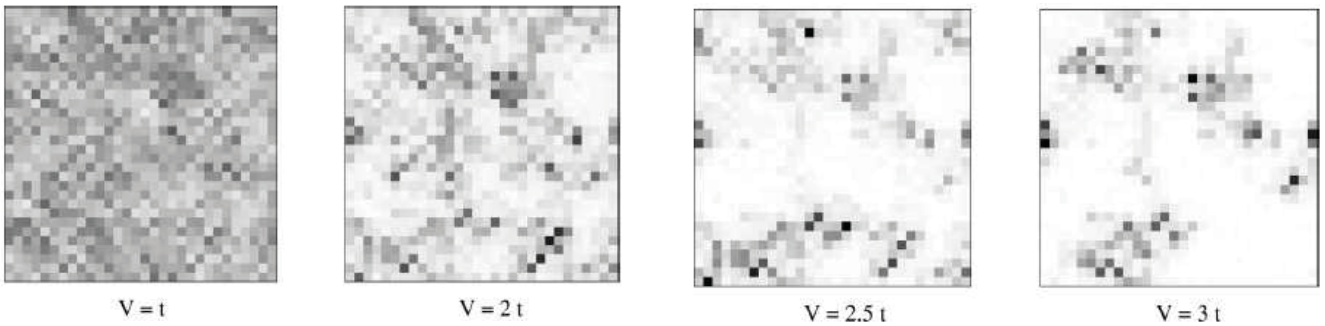
$$H = -J \sum_{<i,j>} \cos(\theta_i - \theta_j)$$

Continuous system

$$H = -\rho_s \int d^3 r \left| \nabla \theta \right|^2$$



Increasing disorder

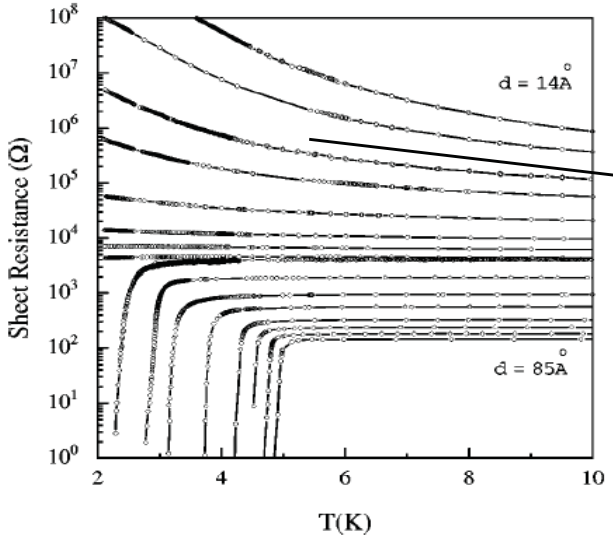


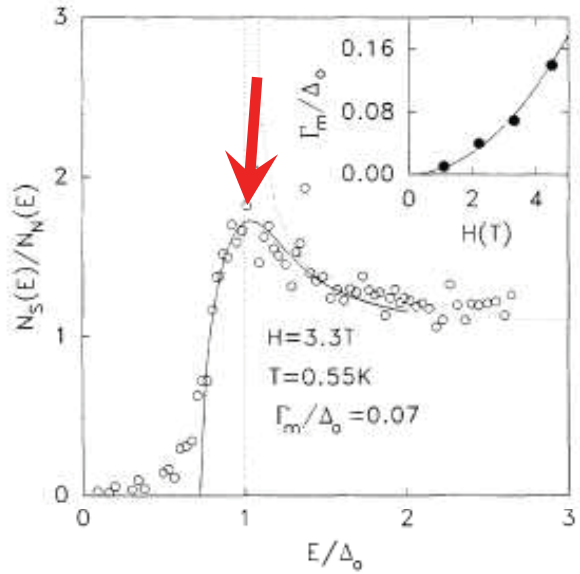
Amit Ghosal, Mohit Randeria and Nandini Trivedi, Phys. Rev. Lett. **81**, 3940 (1998)

also M. V. Feigelman et al., Phys. Rev. Lett. **98,** 027001 (2007).

Superconductor-Insulator Transitions

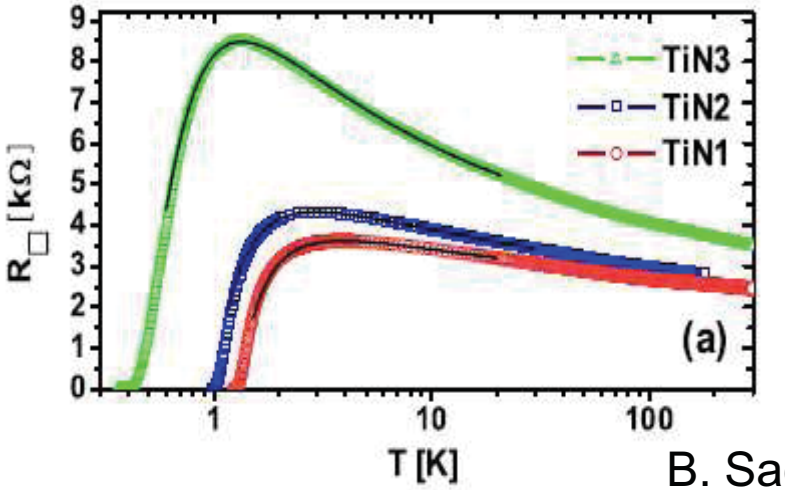
Quench-condensed Bi films

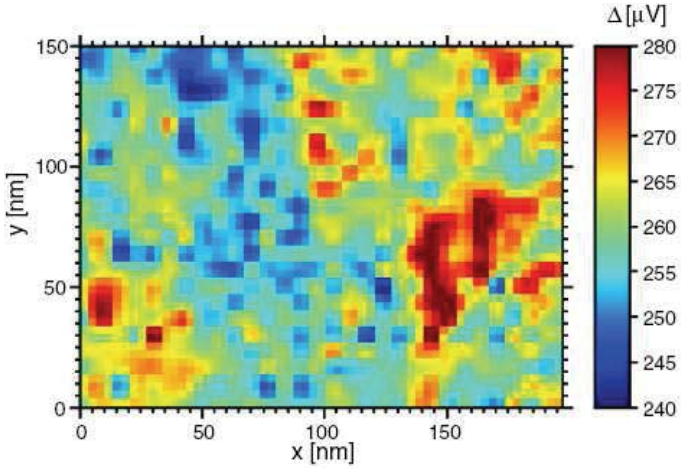




Sambandamurthy et al., Phys Rev B **64,** 104506 (2001)
Y. Liu et al., Phys Rev B **47,** 5931 (1993)

R P Barber et al, Phys. Rev. B **49,** 3409 (1994)





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

Can Superconductivity get destroyed by (thermal) phase fluctuations in a 3D disordered film?

Ideal Sample: A disordered superconductor with no intentional source of granularity

3D single crystal / epitaxial thin film with vacancy.

At which level of disorder does this effect manifest itself?

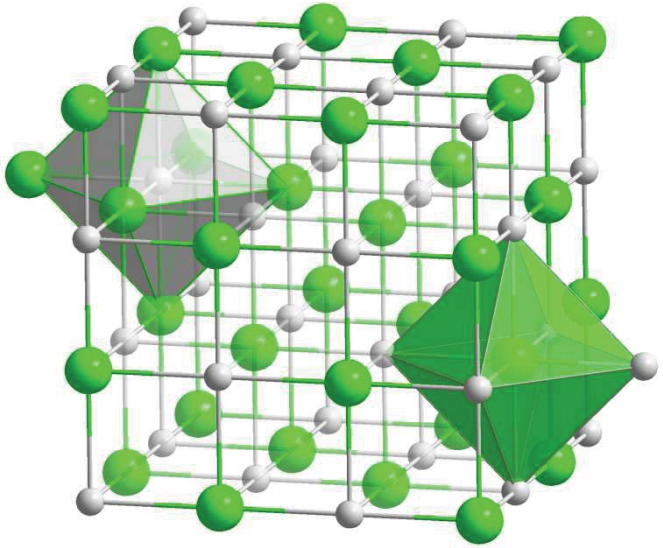
NbN

T_c~16K

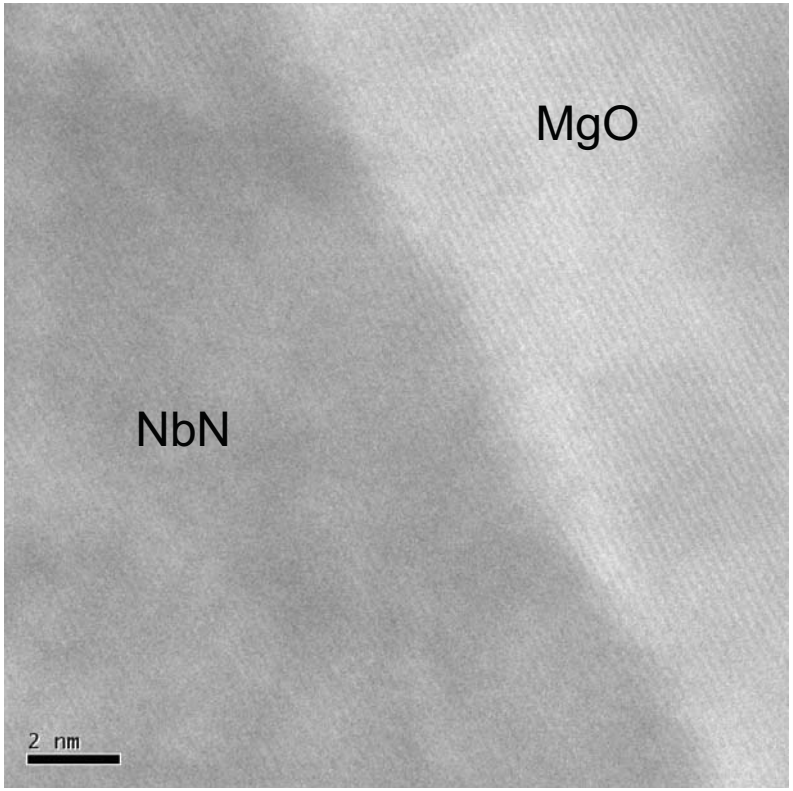
ξ~5nm λ~200nm

Thickness of our films > 50nm

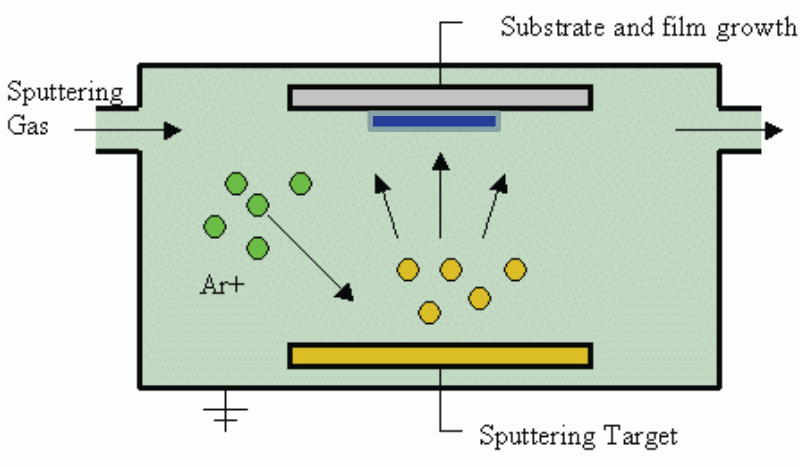
Grows as epitaxial thin film on (100) MgO substrate using reactive magnetron sputtering:

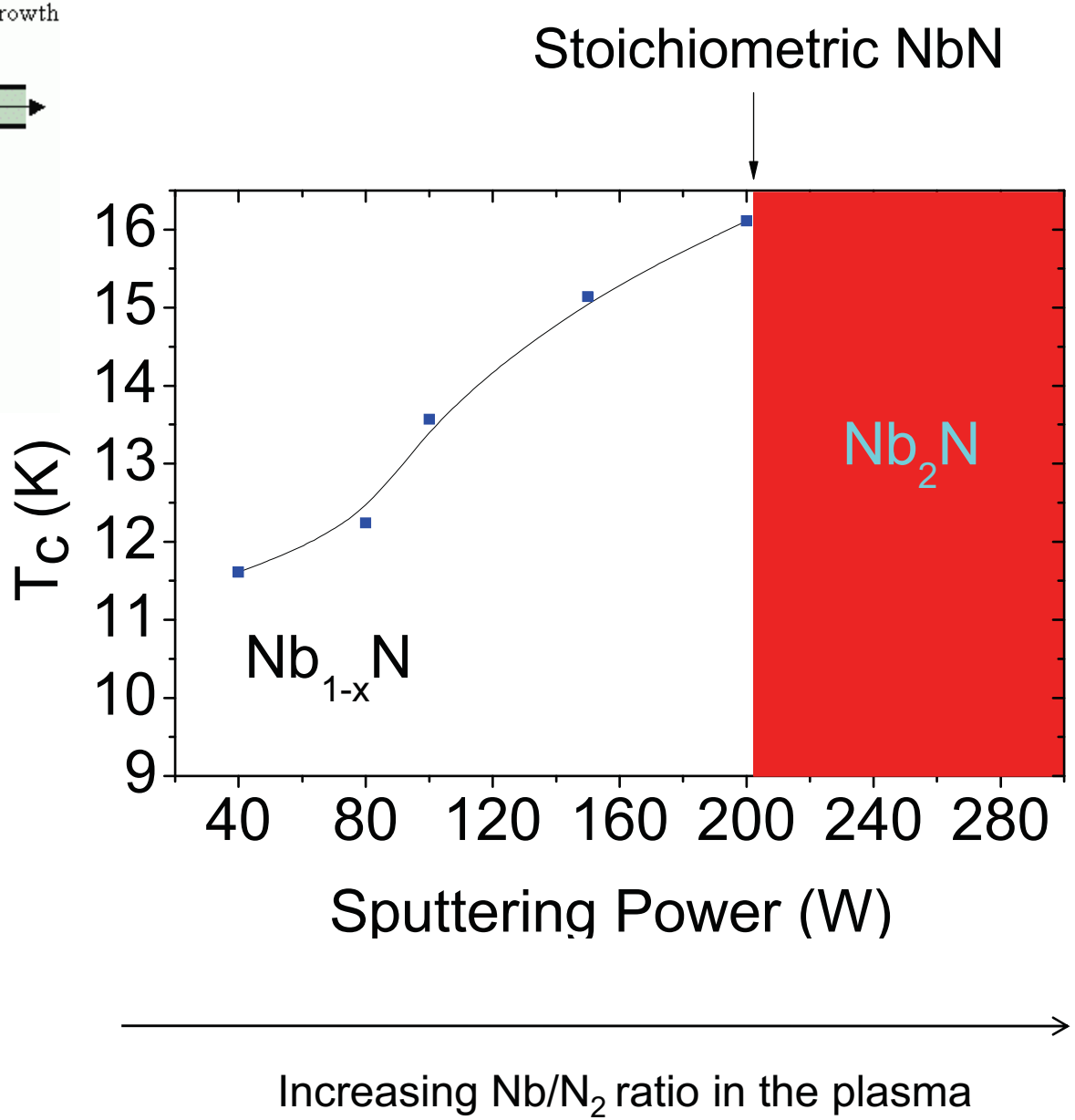


NaCl structure

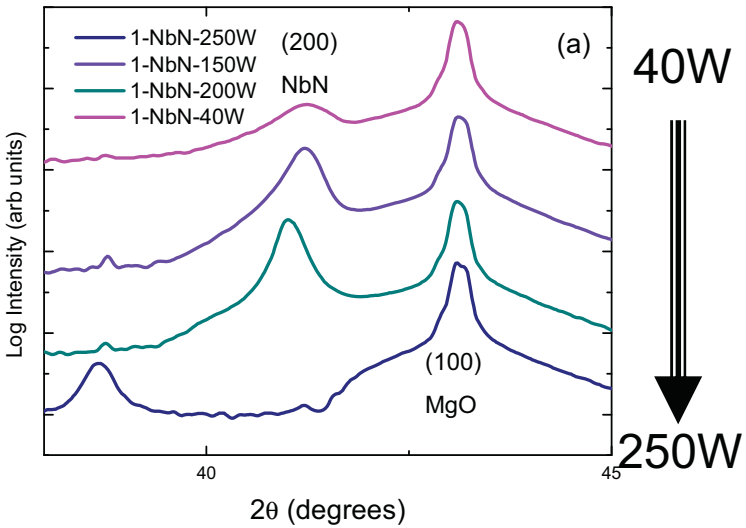


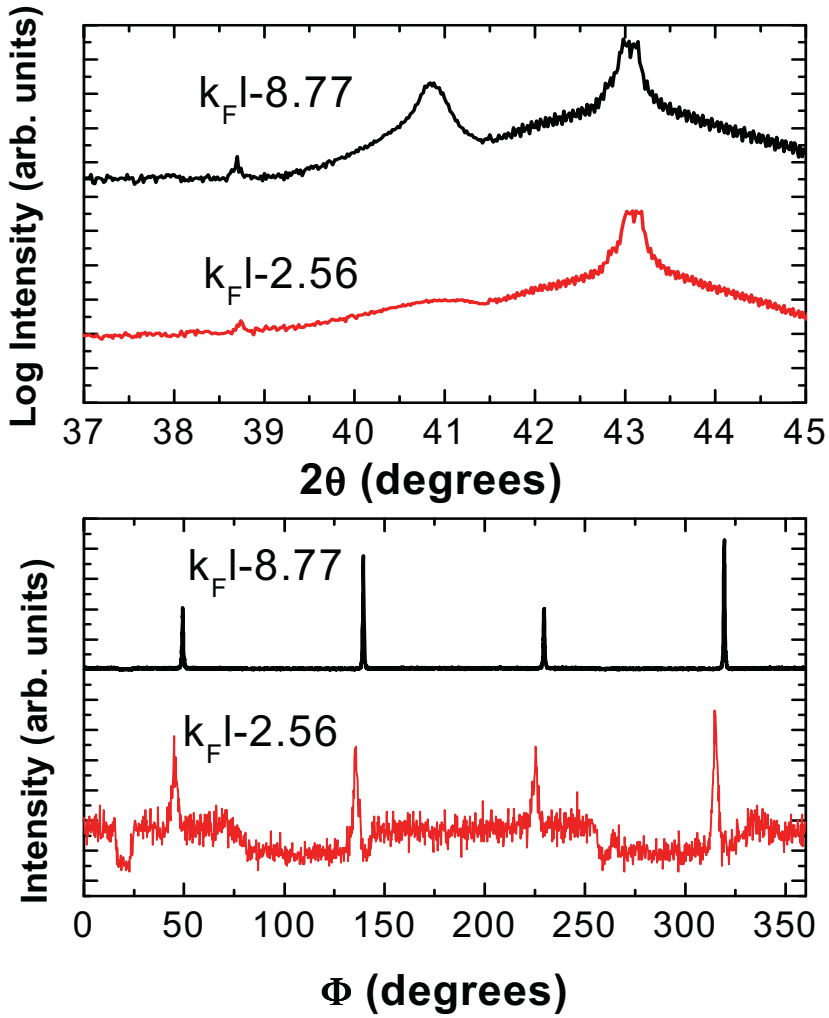
Stability Phase diagram of NbN





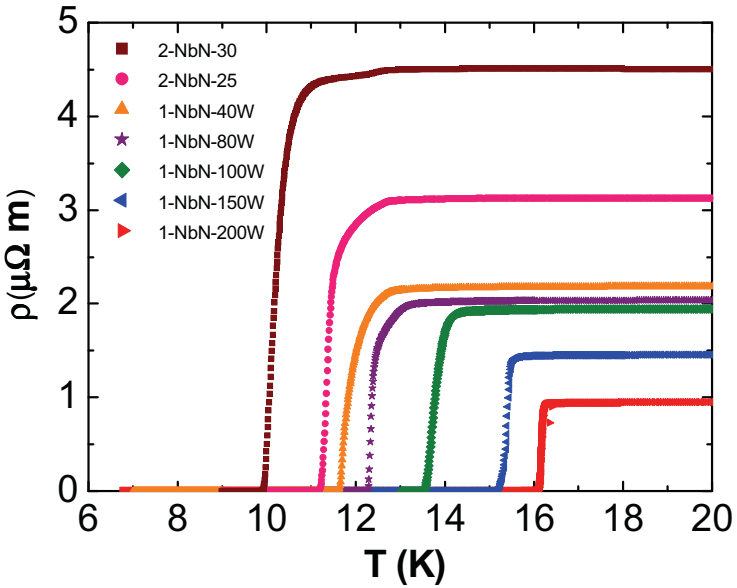
Growth Protocols of dc sputtered of NbN films
Substrate Temperature: 600^0C, Total Ambient pressure ($Ar+N_2$): 5mTorr

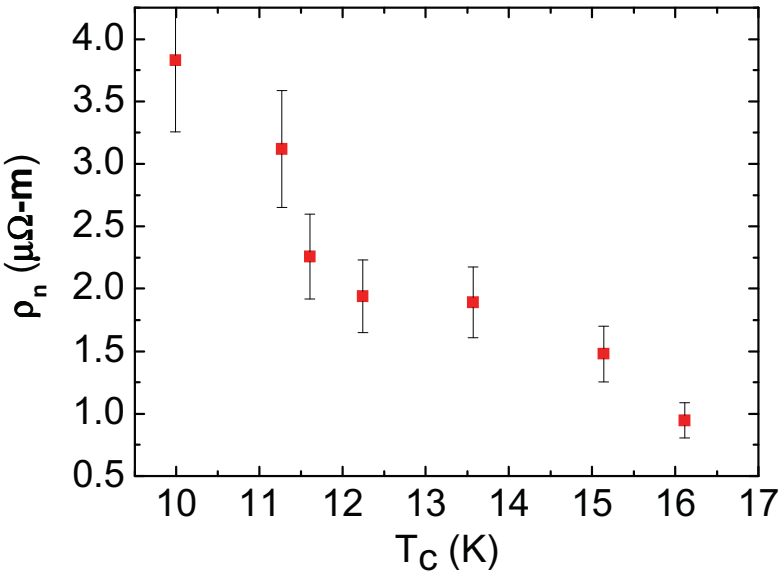




NbN films on MgO (100)

Correlation between ρ_n and T_c





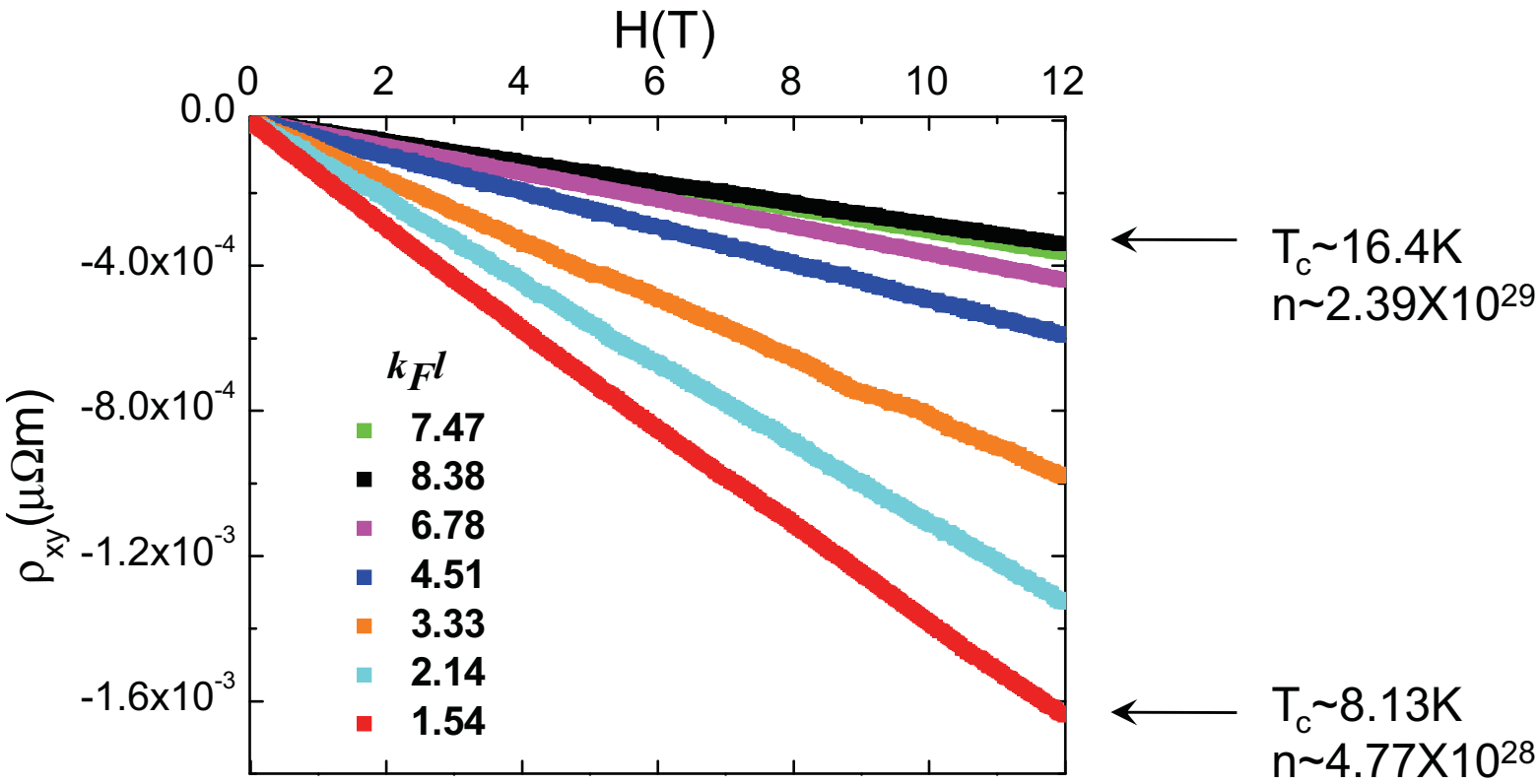
Inverse correlation between normal state resistivity and T_c

Dirty films have lower T_c: Anderson Theorem???

$$\rho = \frac{m}{ne^2\tau}$$

n or τ?

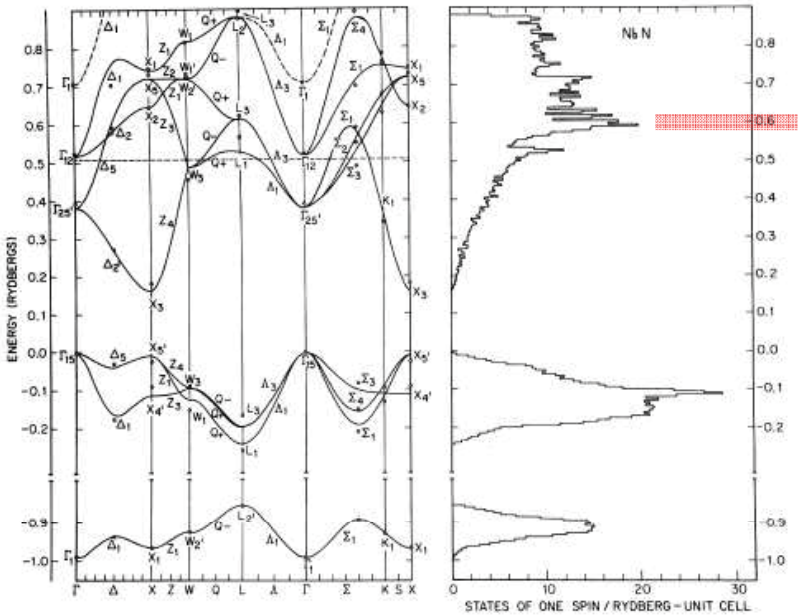
Hall Effect (20K)



Carrier density varies by a factor of 5 from

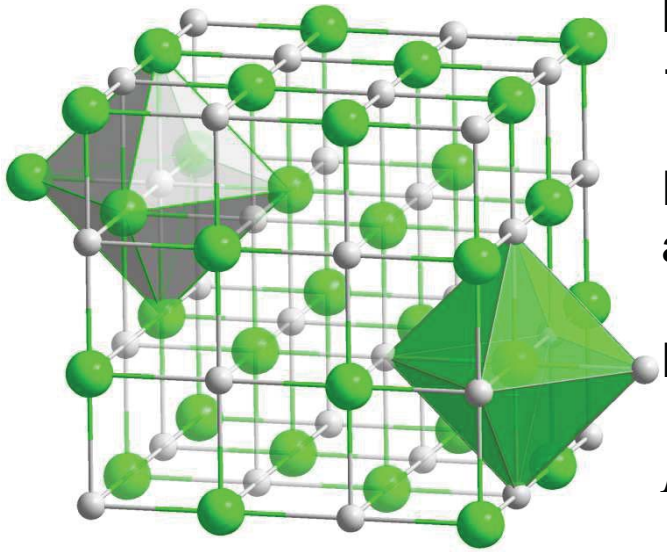
$4.77*10^{28}$ electrons/m^3 to $2.39*10^{29}$ electrons/m^3

(Electronic) Carrier density



Nb 4d band

Matheiss , PRB 5, 315 (1969)

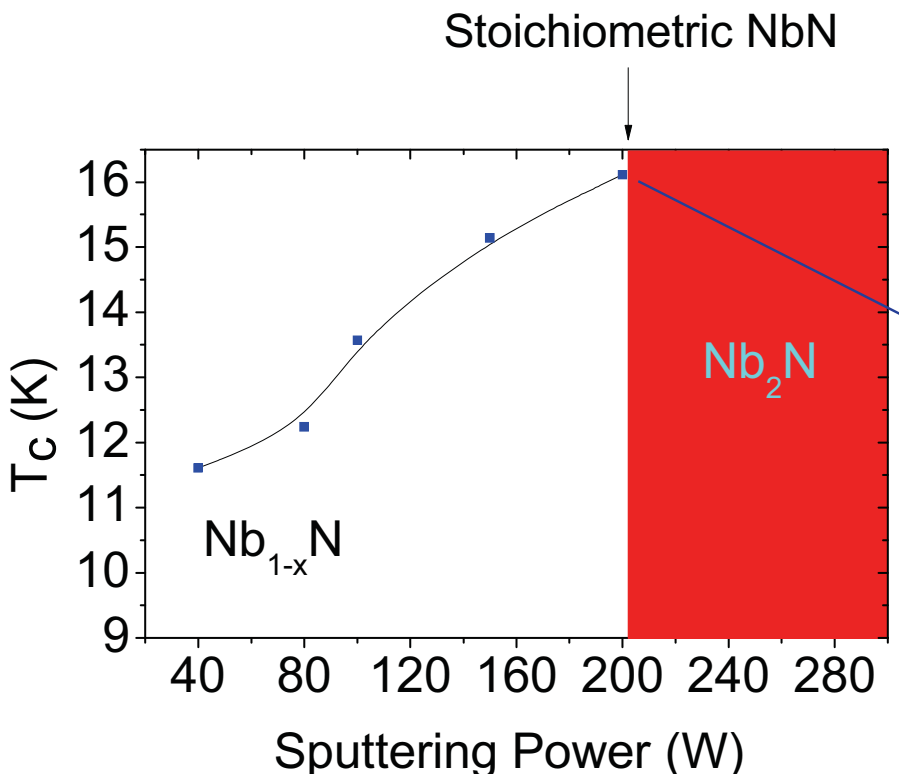


Nb atoms contribute to the carriers
→5 electrons per Nb atom

Face Centered Cubic structure has 4 Nb atoms per unit cell→20 electrons/unit cell

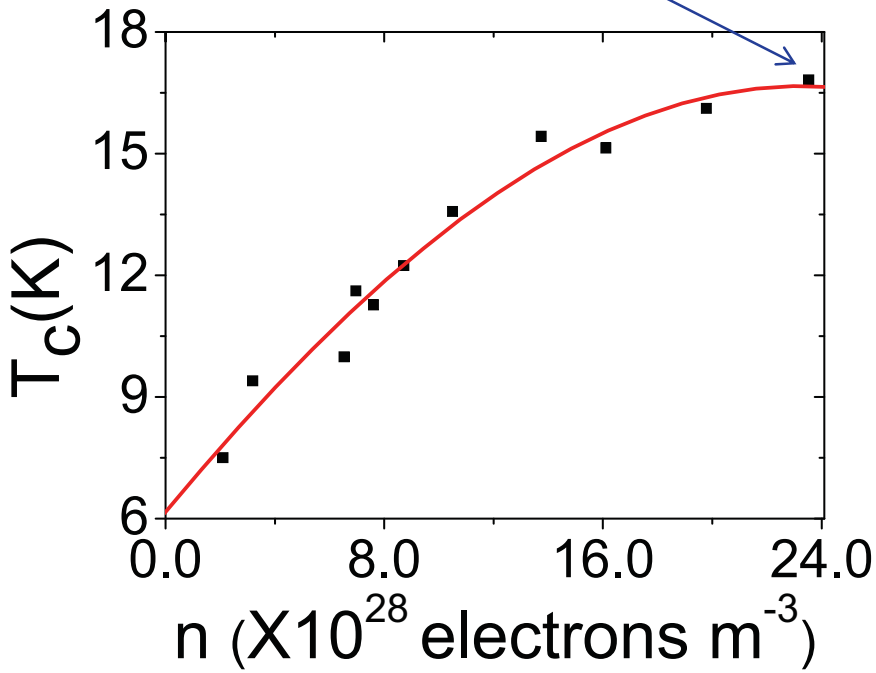
Lattice parameter of the unit cell: a=4.413Å

$$Electronic\ Carrier\ density = \frac{20}{\left(4.413\times10^{-10}\right)^3} = 2.33\times10^{29}\, el/m^3$$



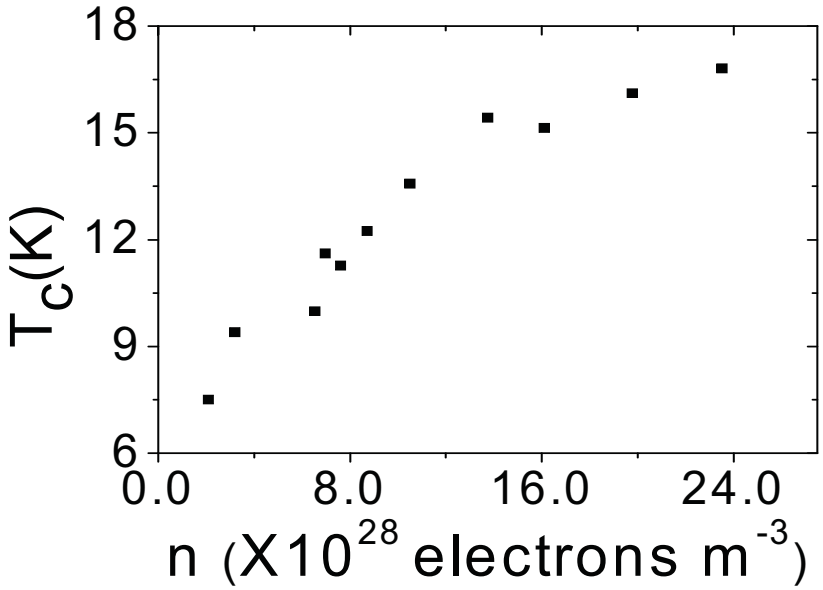
n_{exp}=2.39X10^{29} el/m^3

n_{theo}=2.33X10^{29} el/m^3

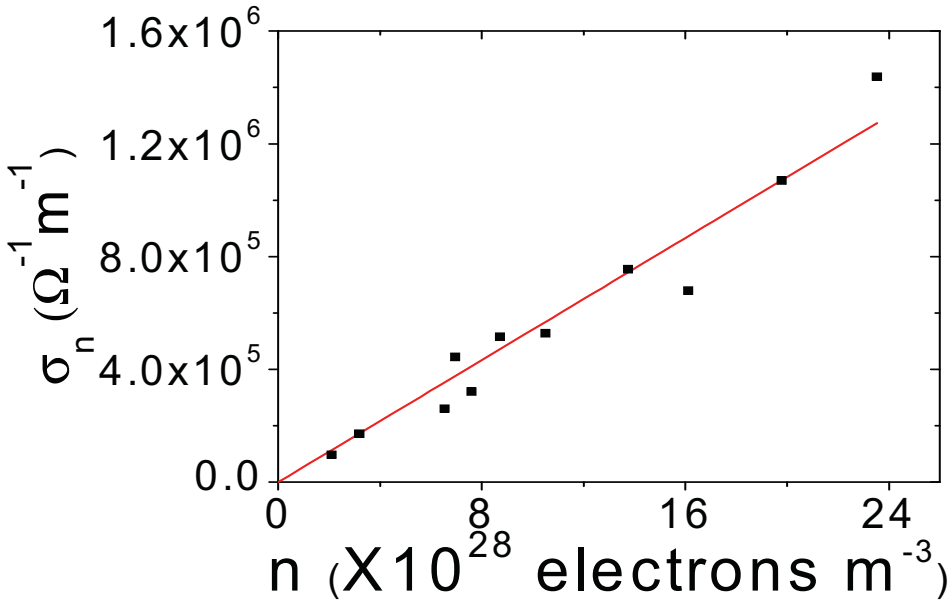


The carrier density changes by 1 order of magnitude:
2.11x10^{28} el/m^3 to 2.39x10^{29} el/m^3

Carrier density and T_c



T_c is likely to be primarily governed by carrier density rather than disorder scattering.



$$\sigma_n \propto n$$

$$\sigma_n = \frac{ne^2\tau}{m}$$

No significant change in carrier mobility.

"Theoretical value" of n for the stoichiometric compound:

$n \sim 2.34 * 10^{29}$ electrons/m^3

Parameters extracted from free electron theory

Sample Name	k_f (m^{-1})	v_f(m/s)	l (Å)	$B_{c2}(0)$ (T)	$\xi_{GL}(0)$ (nm)	N(0) (states/m^3 -eV)	$k_F l$	λ
1-NbN-200	$1.80*10^{10}$	$2.09*10^{6}$	3.96	14.80	4.72	**$2.38*10^{28}$**	7.15	1.50
1-NbN-150	$1.68*10^{10}$	$1.95*10^{6}$	2.91	17.82	4.30	$2.23*10^{28}$	4.90	1.40
1-NbN-100	$1.40*10^{10}$	$1.62*10^{6}$	3.28	17.58	4.33	$1.86*10^{28}$	4.60	1.16
1-NbN-80	$1.37*10^{10}$	$1.59*10^{6}$	3.34	16.65	4.45	$1.82*10^{28}$	4.58	1.14
1-NbN-40	$1.33*10^{10}$	$1.54*10^{6}$	3.04	15.12	4.67	$1.77*10^{28}$	4.05	1.11
2-NbN-25	$1.31*10^{10}$	$1.52*10^{6}$	2.28	14.79	4.72	$1.74*10^{28}$	2.98	1.09
2-NbN-30	$1.24*10^{10}$	$1.44*10^{6}$	2.07	13.08	5.02	$1.65*10^{28}$	2.56	1.03

[a]N(0)=0.511 states/NbN-eV

APW calculations: 0.54 states/NbN-eV *Matheiss (1969)*

Specific heat: 0.50 states/NbN-eV *Geballe (1966)*

Ioffe-Regel disorder parameter: $k_F l = \left(\frac{2\pi}{\lambda_{de-Broglie}} \right) l$

Measure of mean free path as a function of de-Broglie wavelength at Fermi level

McMillan theory for strong coupling superconductor

$$T_c = \frac{\Theta}{1.45}\exp\left(-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\right) \quad \lambda = N(0)\frac{\langle g^2\rangle}{M\langle\omega^2\rangle} = KN(0)$$

λ→electron phonon interaction constant

μ^*→electron-electron repulsive interaction

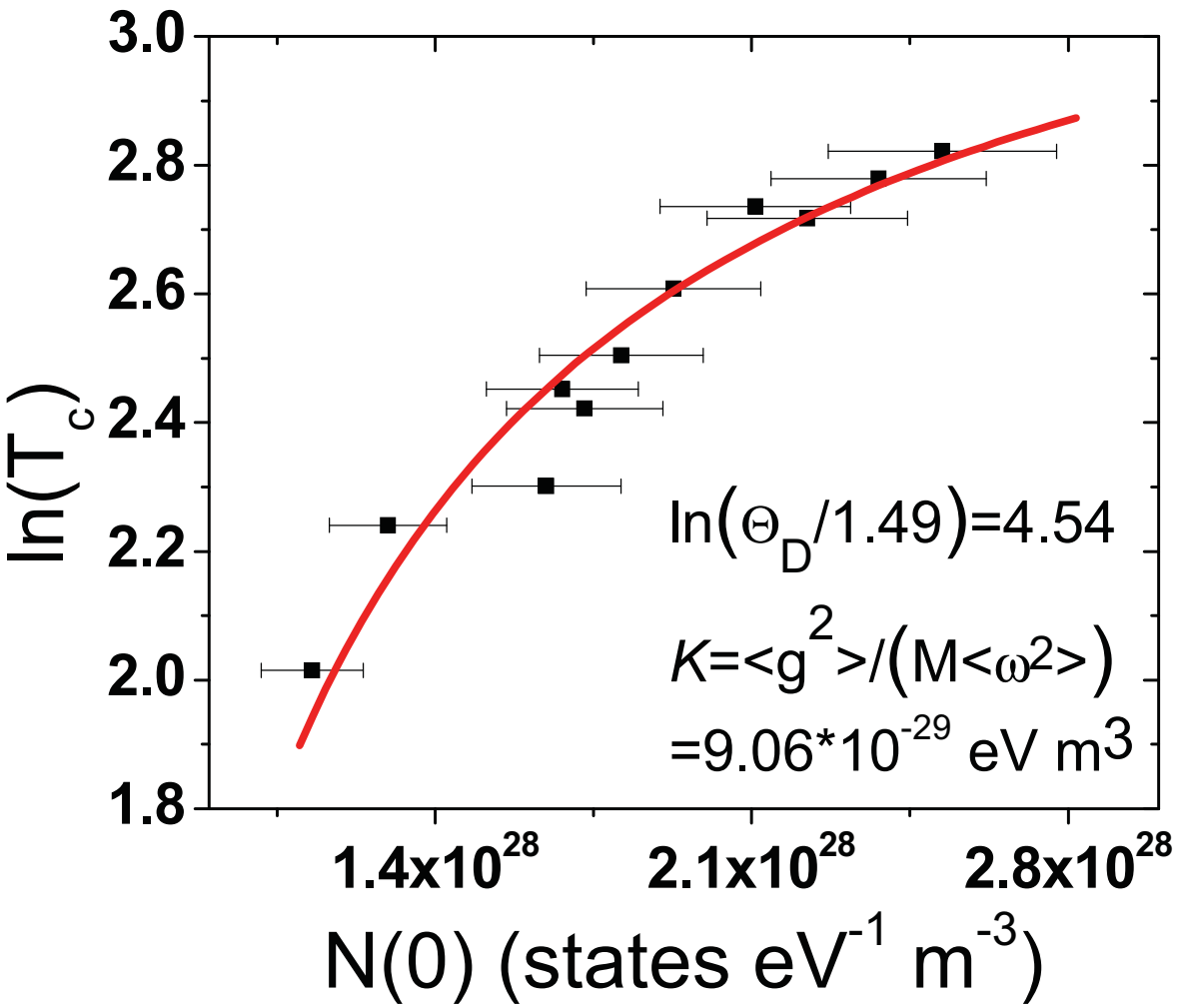
μ^*=0.13

K depends primarily on lattice properties

$$\ln(T_c) = \ln\left(\frac{\Theta}{1.45}\right) - \frac{1.04(1+KN(0))}{KN(0)-\mu^*(1+0.62KN(0))}$$

Fit to McMillan theory

$$\ln(T_c) = \ln\left(\frac{\Theta}{1.45}\right) - \frac{1.04(1+KN(0))}{KN(0)-\mu^*(1+0.62KN(0))}$$



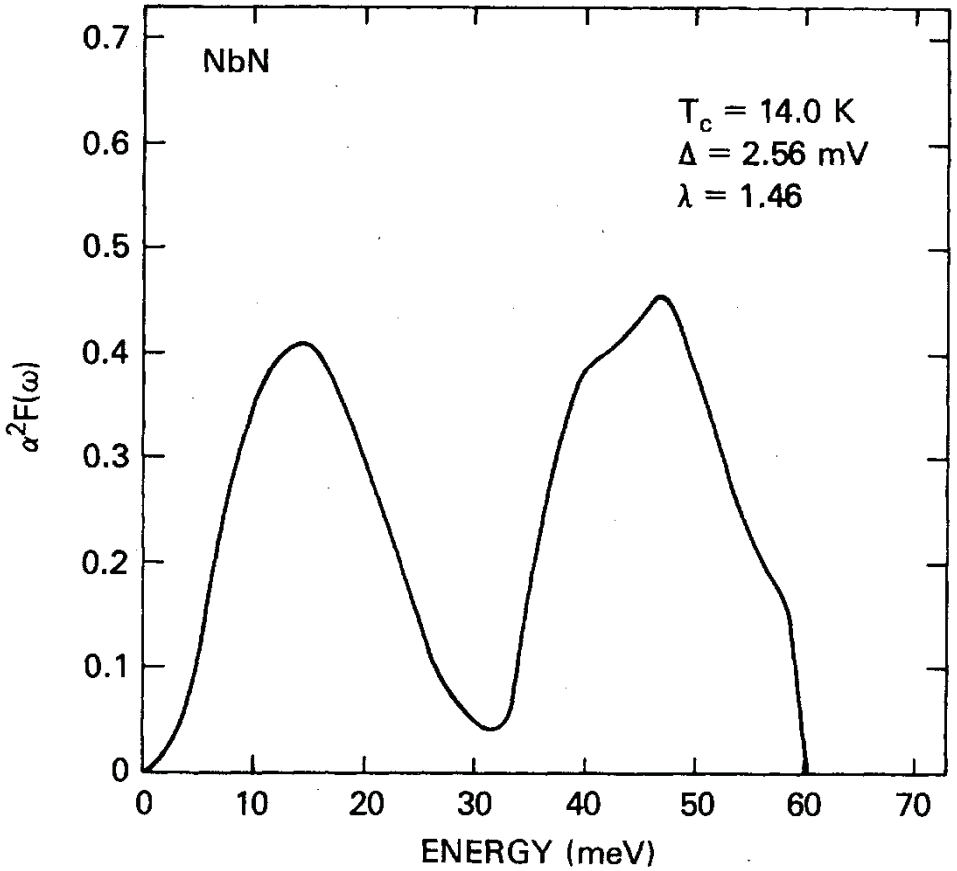
Θ=140±20K

λ=1.02–2.28

Electron Phonon coupling

λ=1.02–2.28

T_c~16.11K



Obtained from McMillan Rowell inversion of tunneling data

T_c~14K

λ~1.45

Kihlstrom et al. (1985)

Studies on disorder

Measure of disorder: $k_F l$

- The Ioffe-Regel parameter is calculated from the ρ_n and R_H, using free electron approximation

$$n = -\frac{1}{R_H e}$$

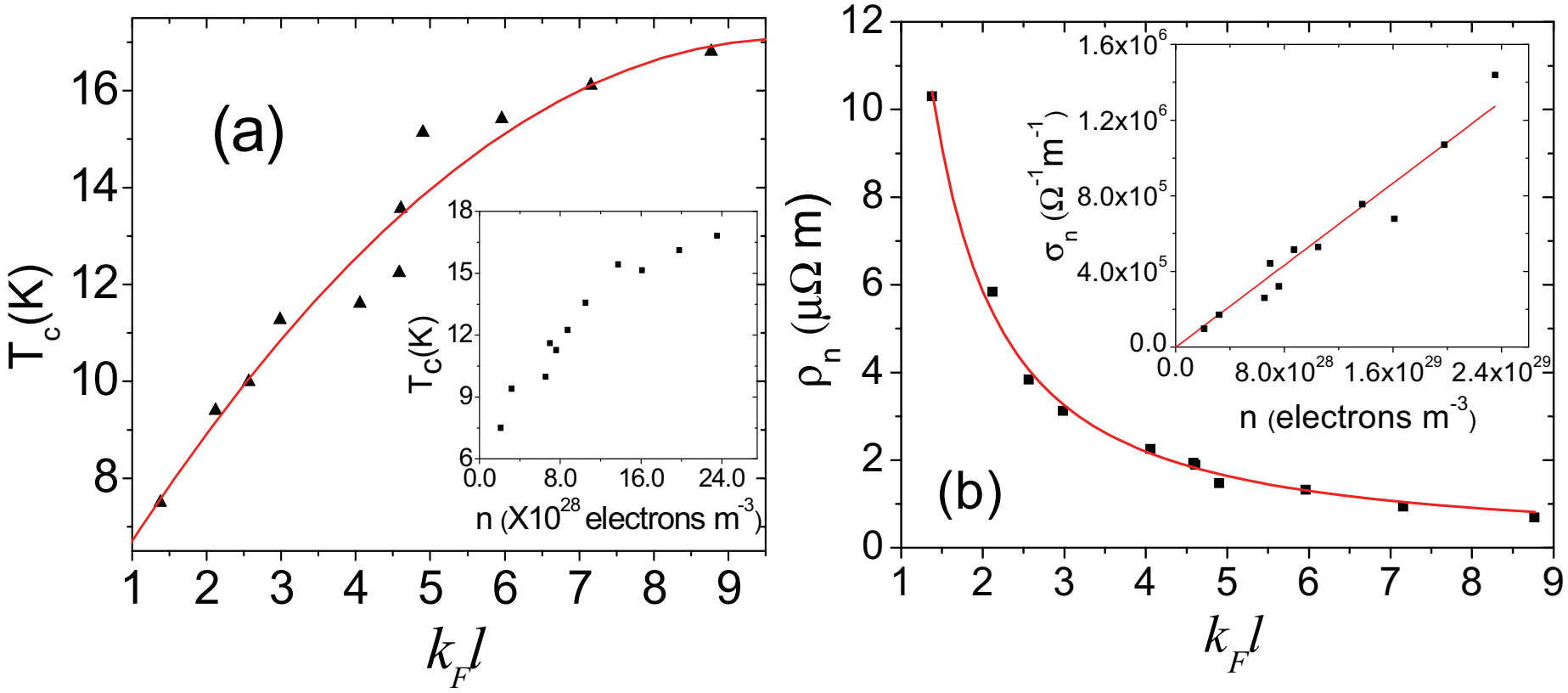
$$k_F = \left(3\pi^2 n\right)^{1/3}$$

$$\rho_n = \frac{m}{ne^2\tau} = \frac{\hbar k_F}{ne^2 l}$$

Ioffe-Regel (at 17K) parameter varies from

1.36-8.77

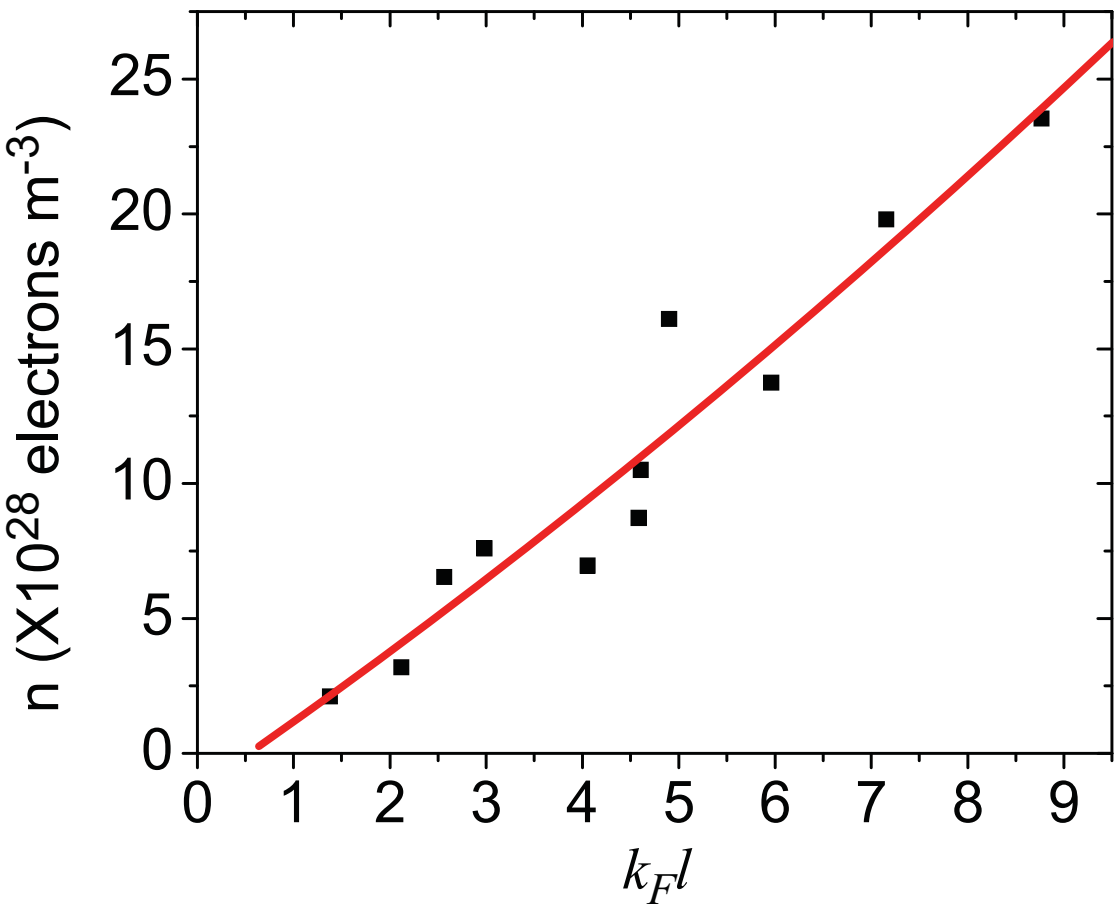
Evolution of T_c and ρ_n with $k_F l$



$k_F l$~1.38-8.77

T_c decreases and ρ_n increases with increase in disorder

Why does the carrier density change with disorder ?

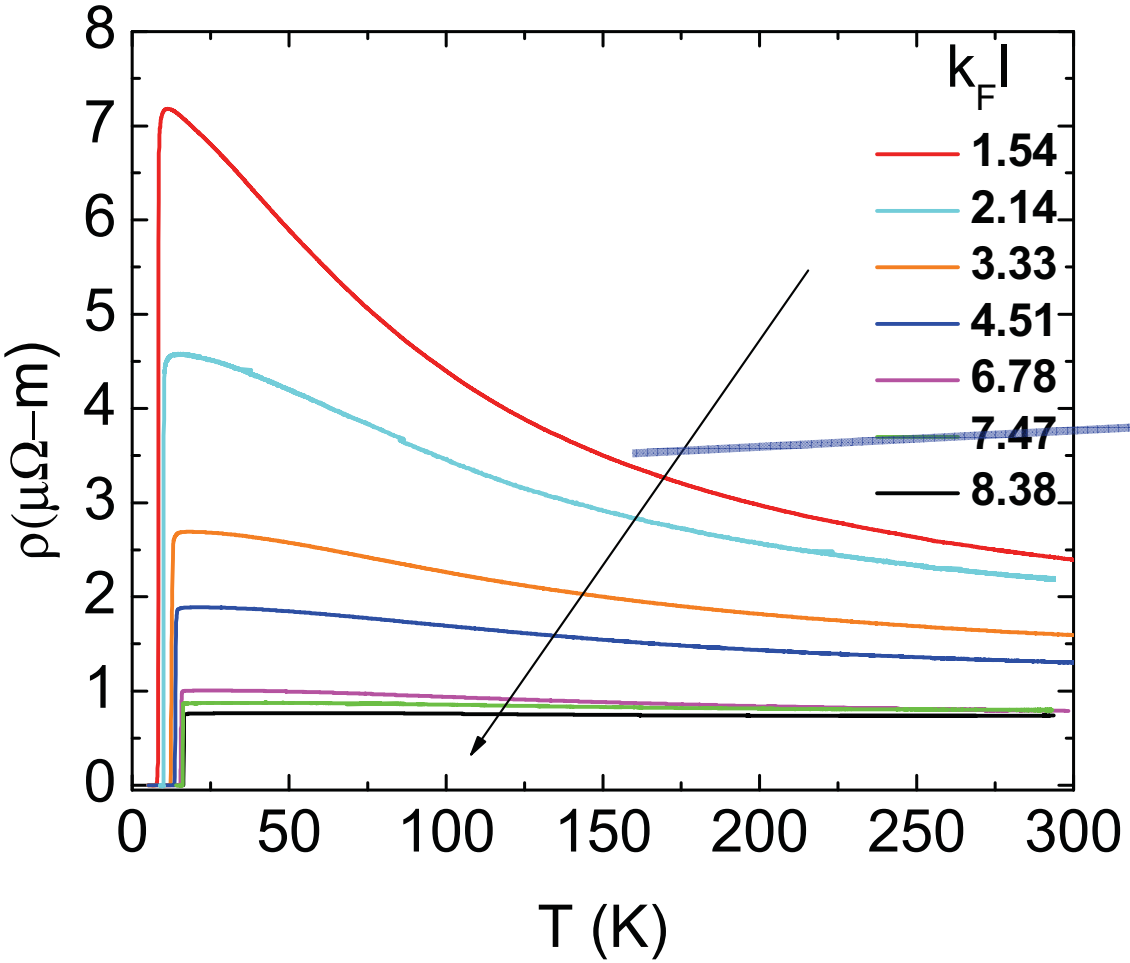


***n* varies with disorder by a factor of 10**

Not accounted for by chemical effects alone

Localization effects?

Evolution of Normal State with disorder

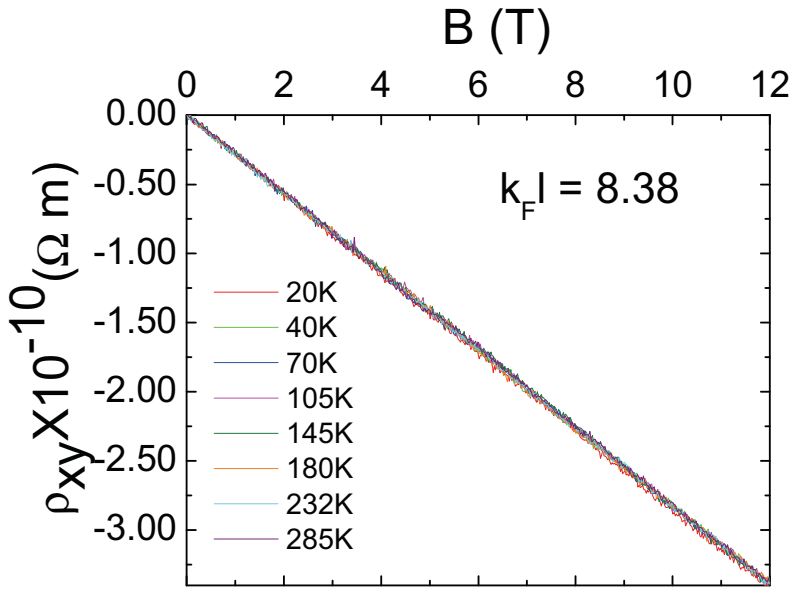


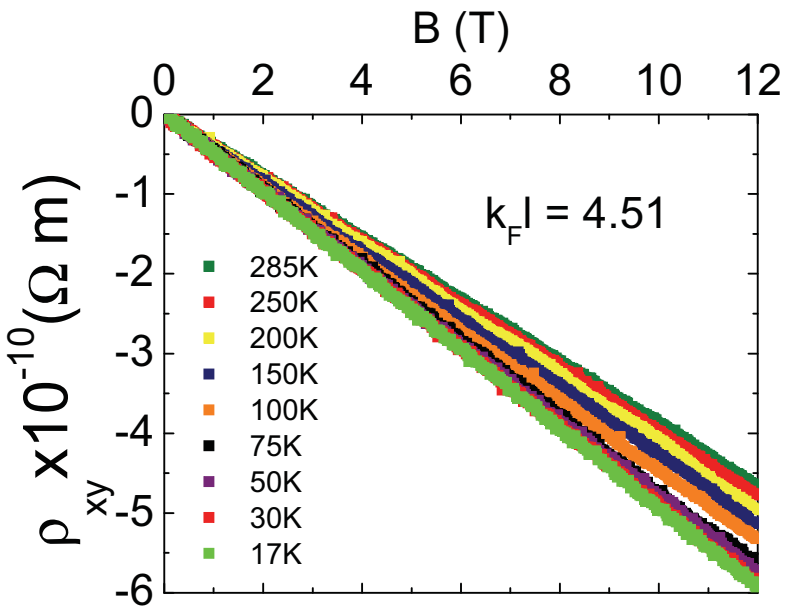
Anderson Insulator or unusual metal?

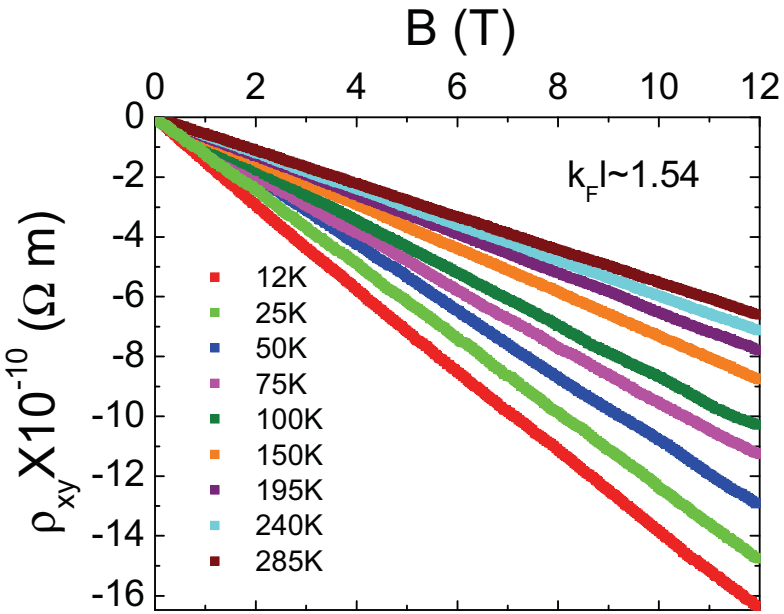
Does not follow Mott Variable range Hopping:

$$\rho \sim \exp\left(-\left(\frac{T_0}{T}\right)^{1/4}\right)$$

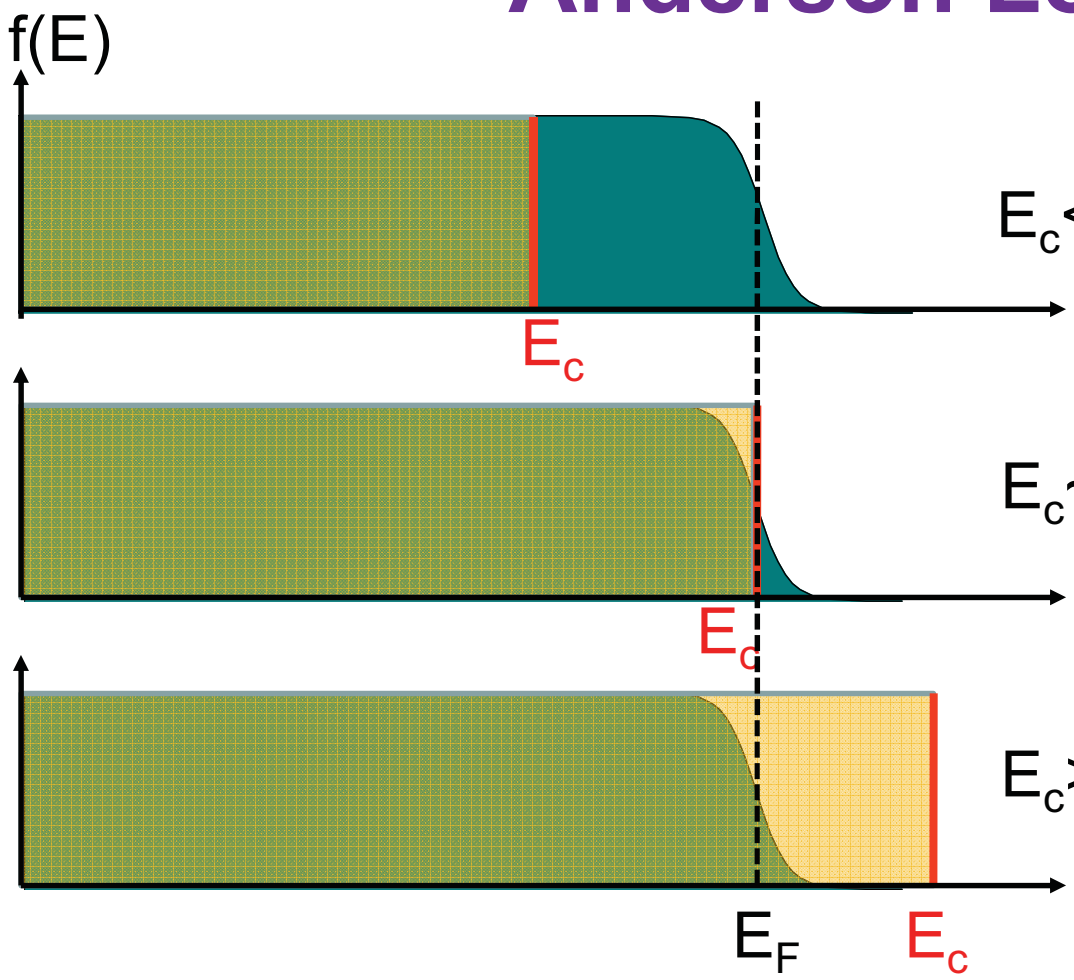
Hall measurement







Anderson Localization



$E_c < E_F$ Small Disorder: Metal

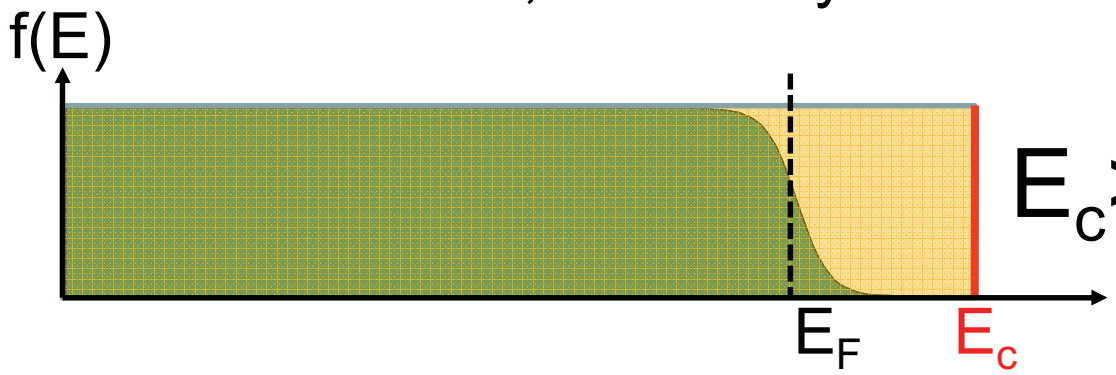
$E_c \sim E_F$ Moderate Disorder: Fermi Glass

$E_c > E_F$ Large Disorder: Insulator

For an Anderson insulator electrical transport takes place through carriers excited over the mobility edge.

Resistivity for an Anderson insulator

L Friedman, J Non-Cryst Solids 6, 329 (1971)



$E_c > E_F$ Insulator

$E_c - E_F \gg k_B T$

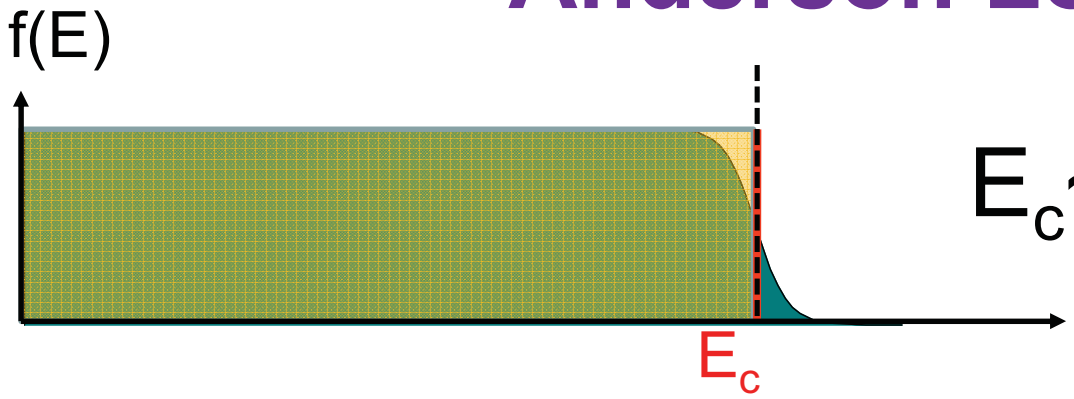
$$\sigma_{xx} \propto \left(N(E_c)\right)^2 \exp\left(-\frac{E_c - E_F}{k_B T}\right) \qquad \sigma_{xy} \propto \left(N(E_c)\right)^3 \exp\left(-\frac{E_c - E_F}{k_B T}\right)$$

$E_c - E_F > k_B T$

$$\sigma_{xx} \propto \frac{1}{T}\left(N(E_F)\right)^2 \int_{E_c}^{\infty} f(E)dE \qquad \sigma_{xy} \propto \frac{1}{T}\left(N(E_F)\right)^3 \int_{E_c}^{\infty} f(E)dE$$

$$R_H(T) = \frac{1}{H}\frac{\sigma_{xy}}{(\sigma_{xx})^2} \propto \rho(T)$$

Anderson Localization

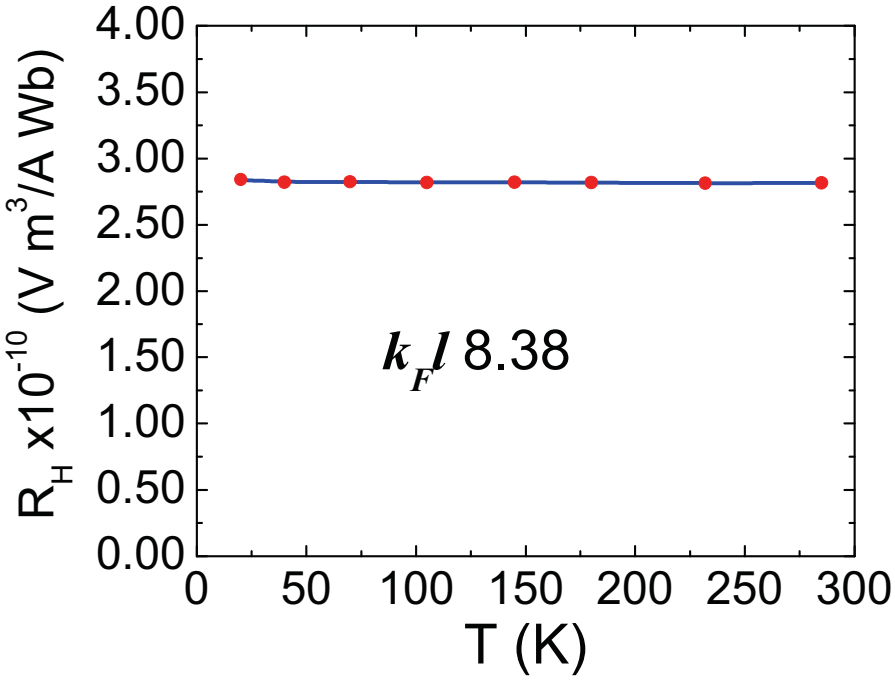


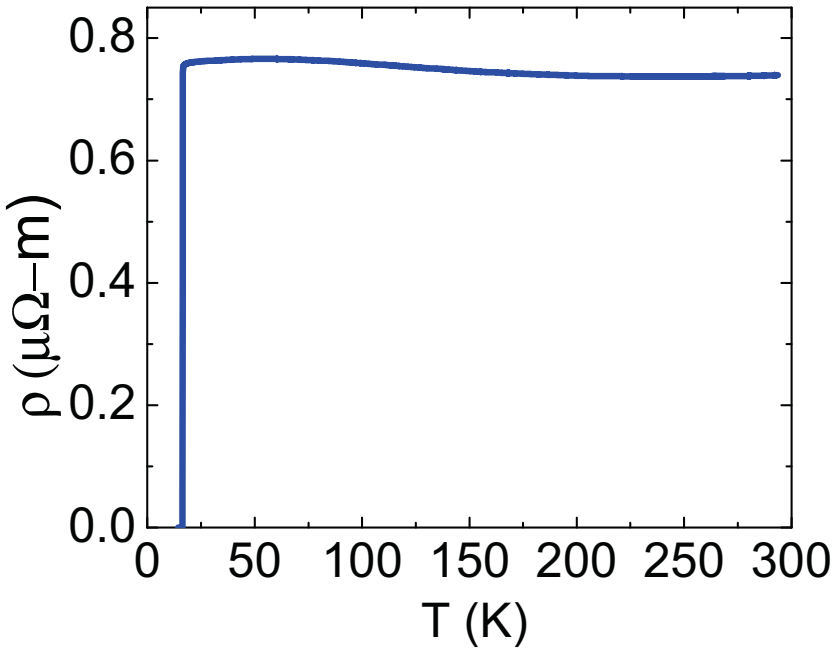
$E_c \sim E_F$ Fermi Glass

$E_c \sim E_F$

$$\sigma_{xx} \propto \left(N(E_F)\right)^2$$
$$\sigma_{xy} \propto \left(N(E_F)\right)^3$$

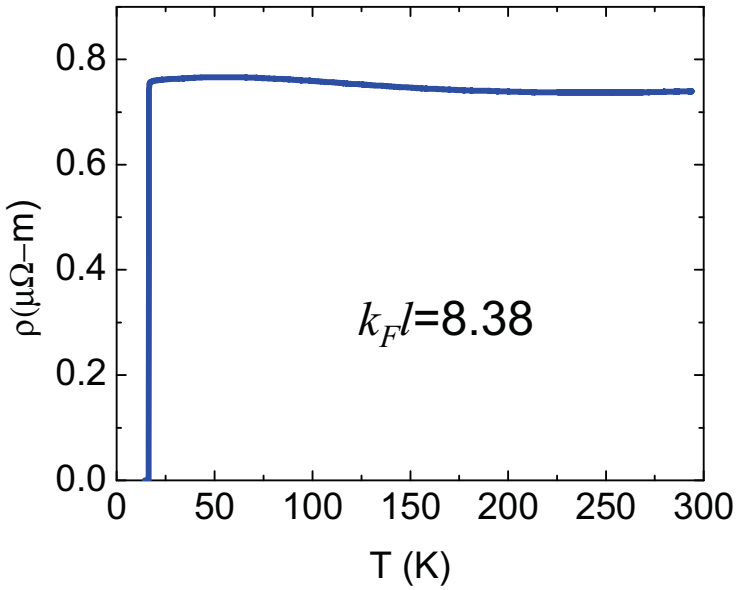
Both temperature independent

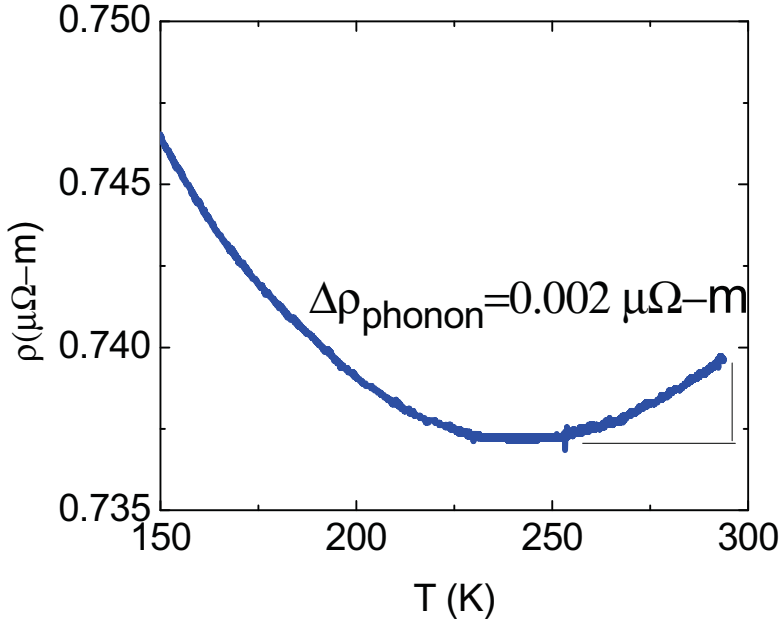




Electron phonon scattering?

$$\frac{1}{\tau(T)} = \frac{1}{\tau_{\text{impurity}}} + \frac{1}{\tau_{phonon}(T)}$$

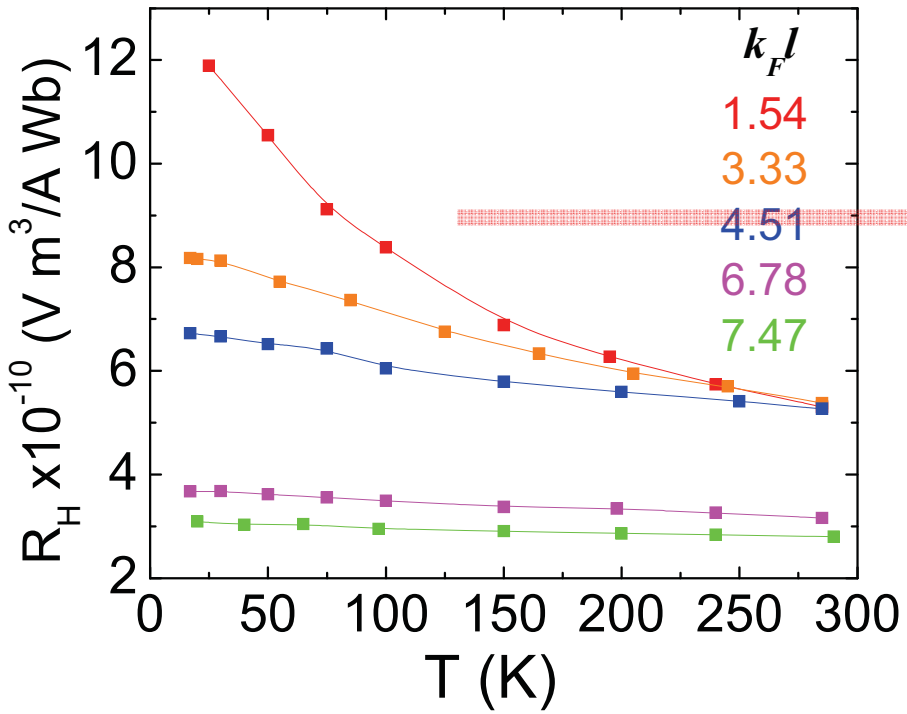




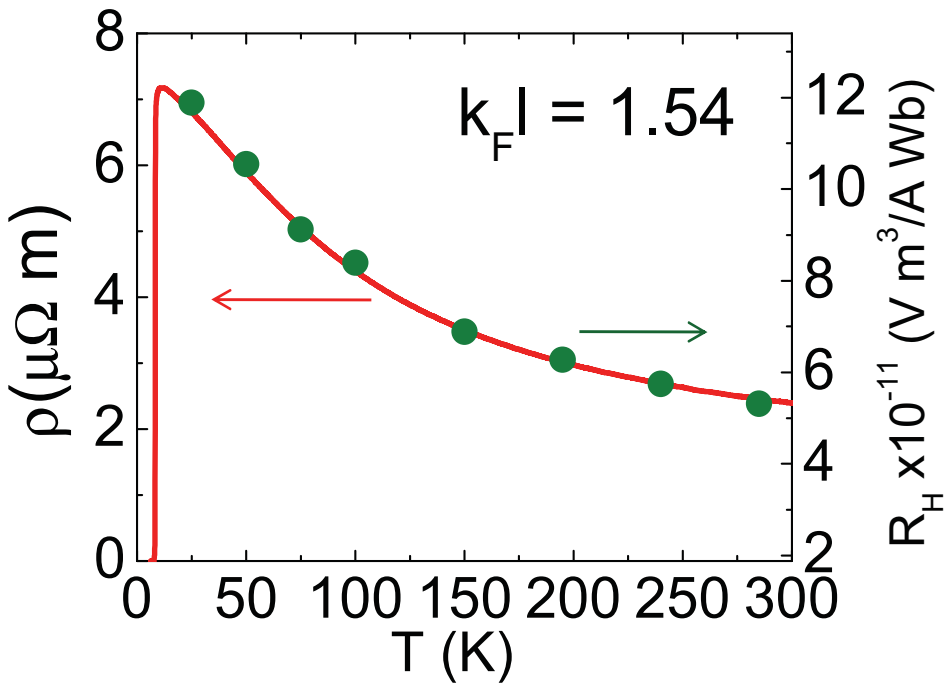
$$\frac{0.002}{0.7} = 0.03 \Rightarrow 3\%$$

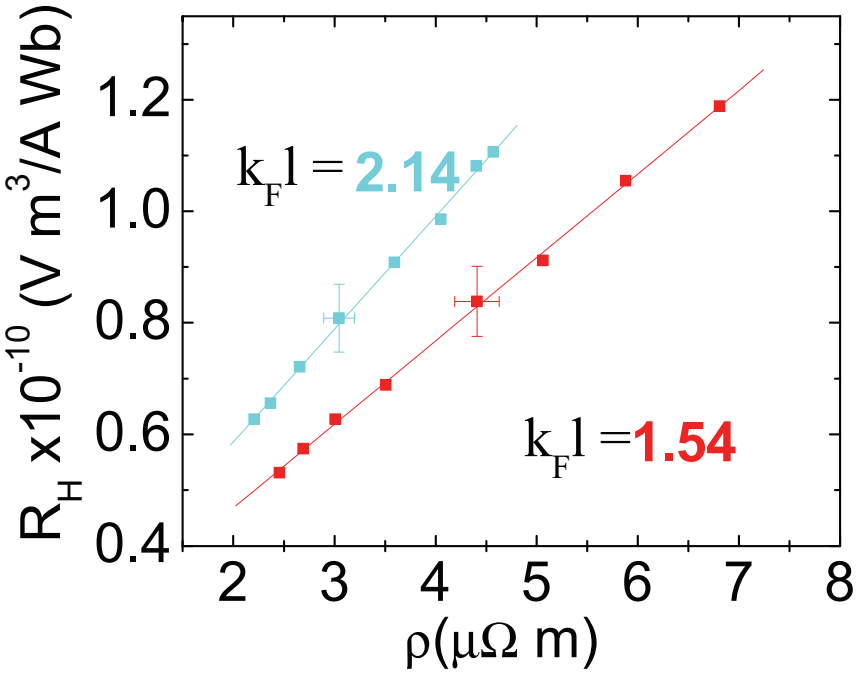
The effect of phonons is overshadowed by impurity scattering

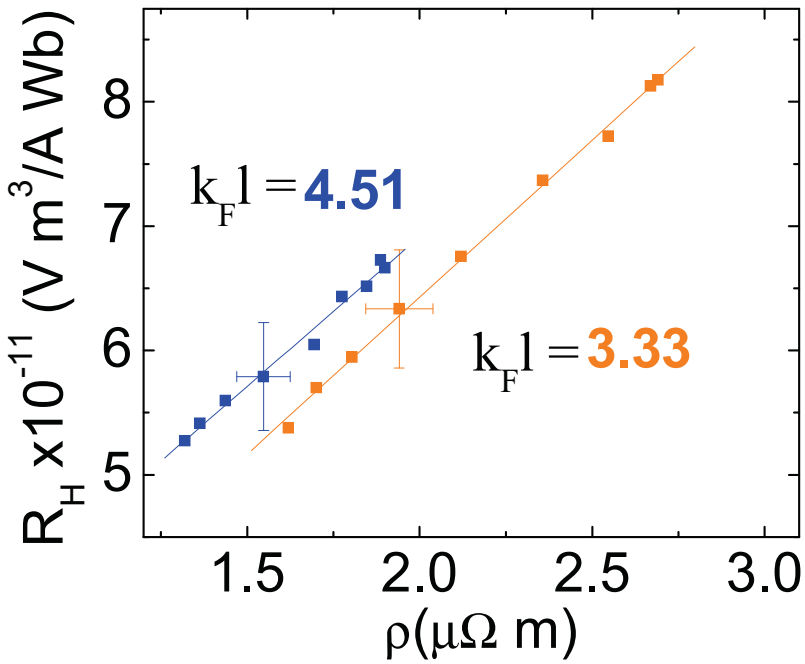
Temperature dependence of the Hall resistance

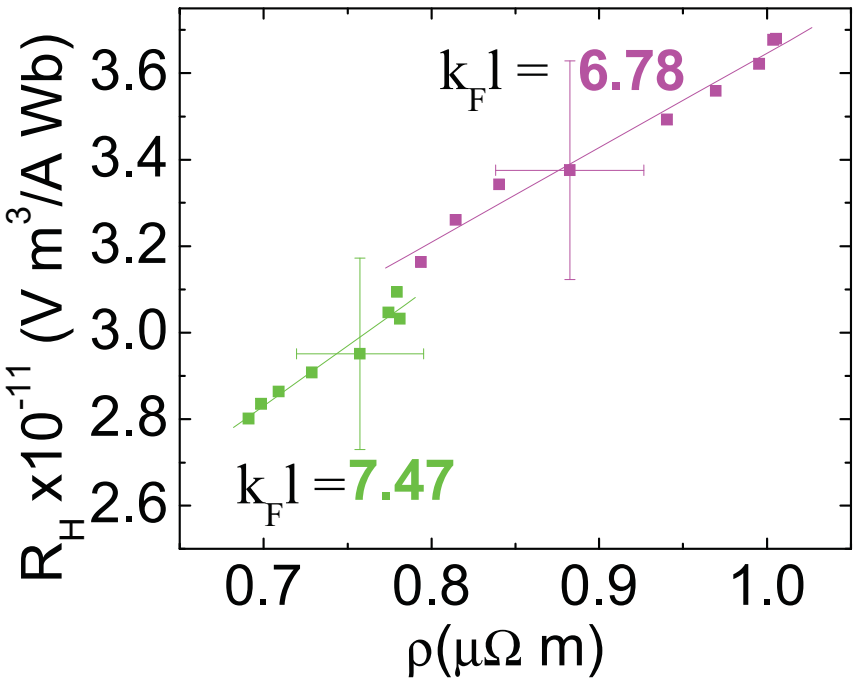


$$R_H = \frac{V_H t}{IB}$$





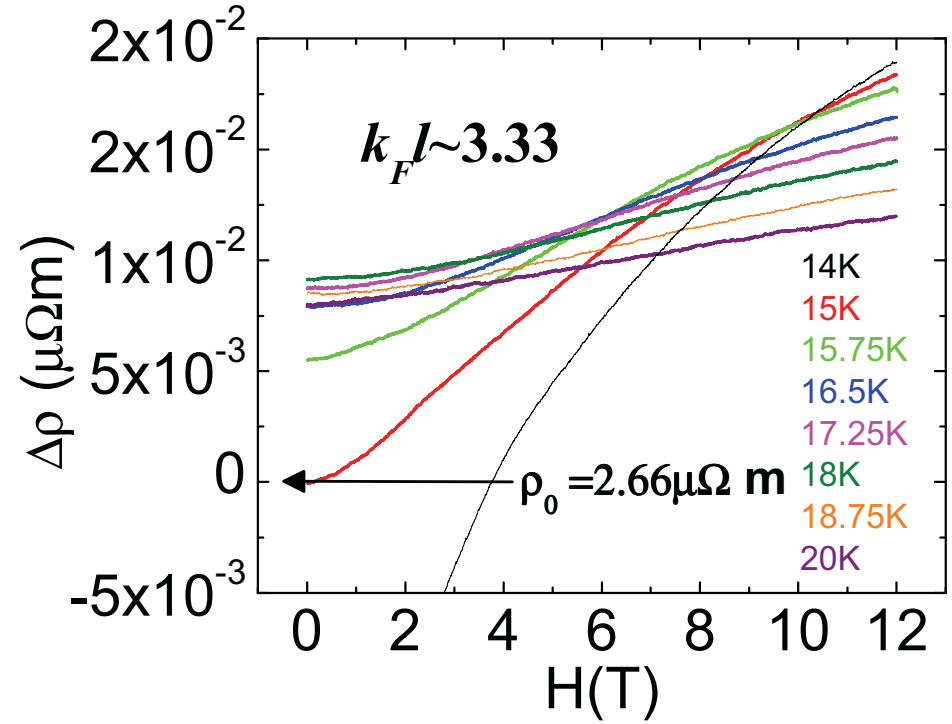


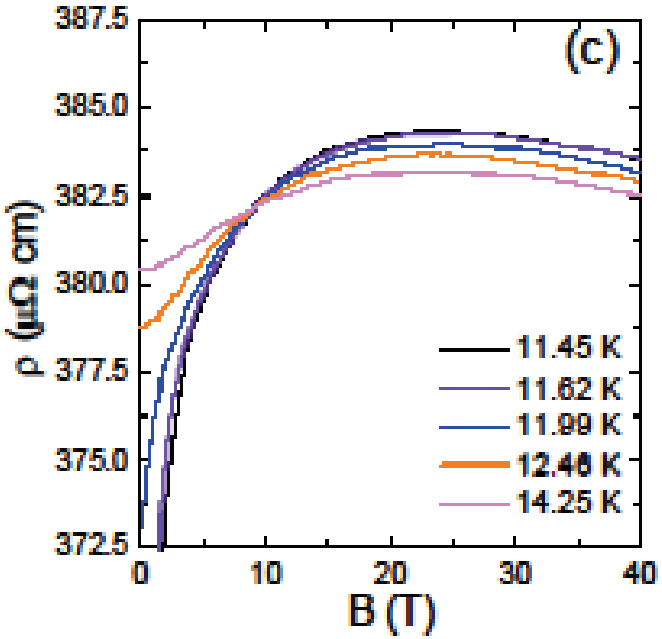


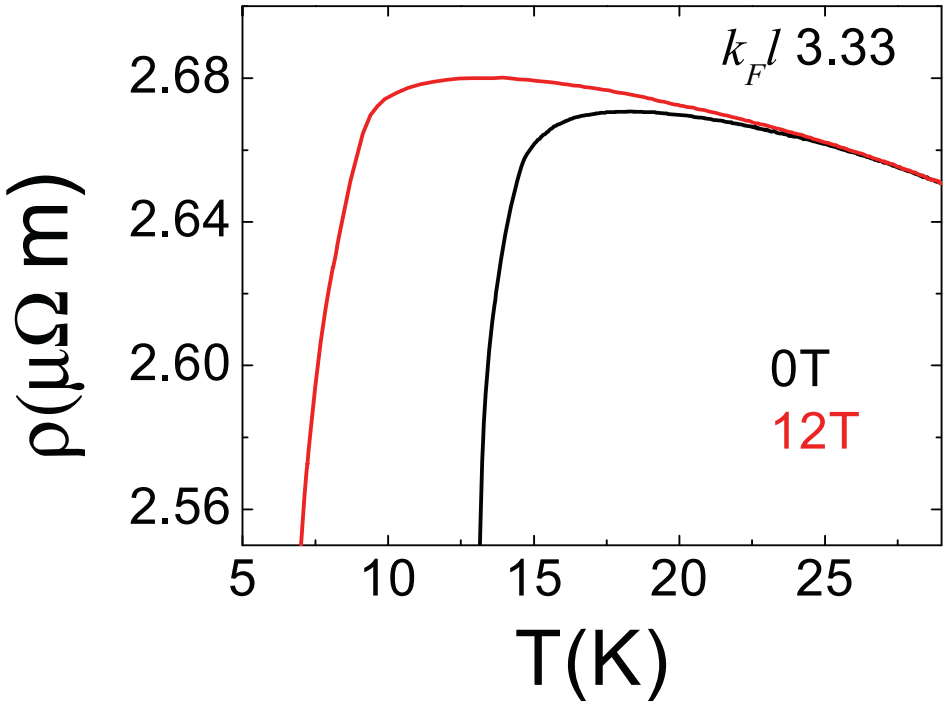
$$R_H(T) = A\rho(T)$$

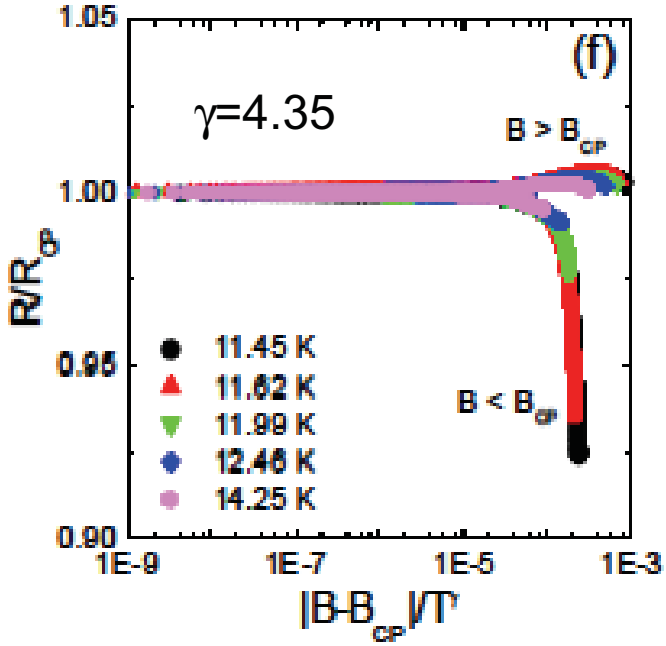
$$R_H(T) = R_{H0} + A\rho(T)$$

R_{H0}~1.0-2.0×10^{-11} V m^3/A Wb

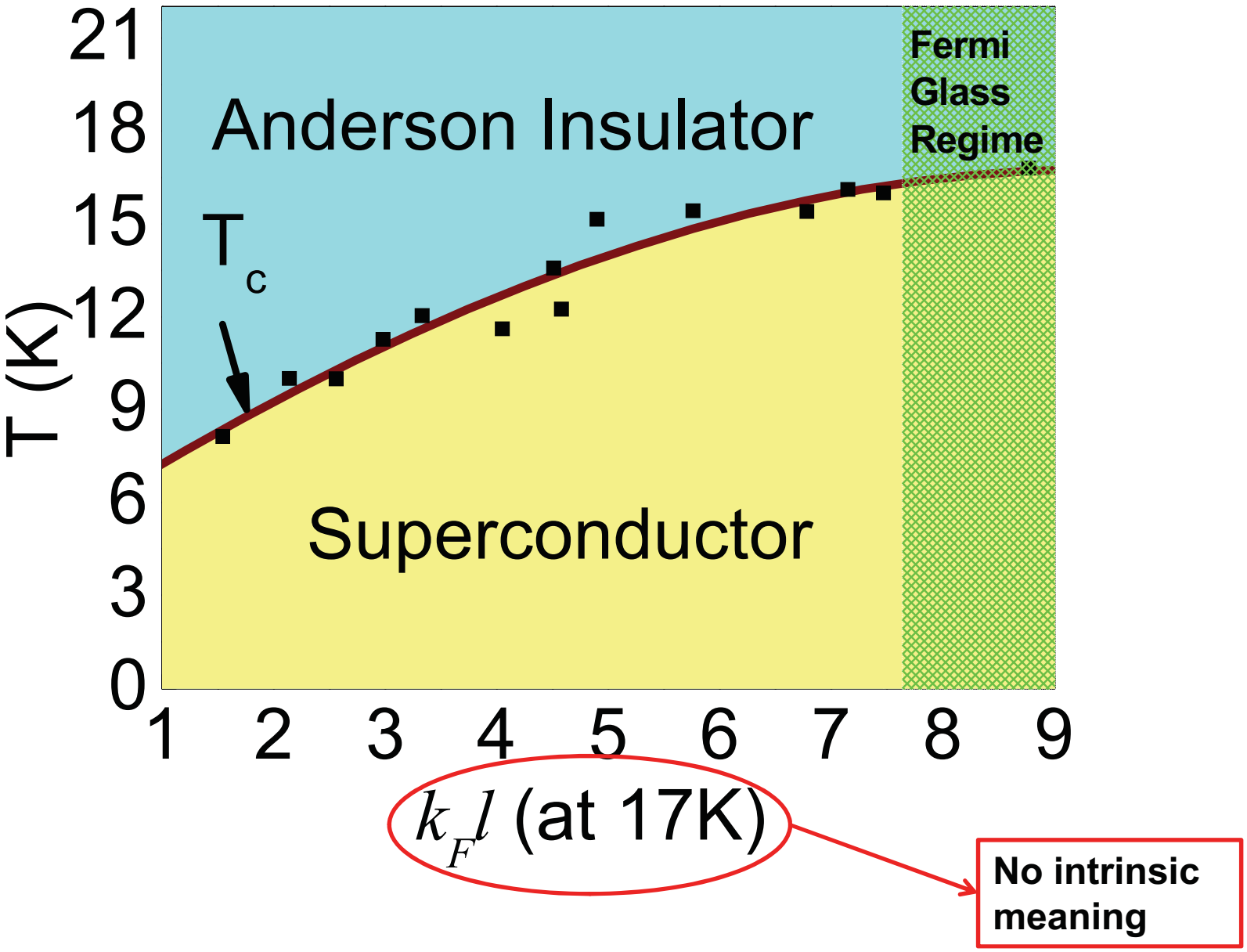

$k_F l$~3.33
ρ_0 =2.66μΩ m
14K
15K
15.75K
16.5K
17.25K
18K
18.75K
20K
Δρ (μΩm)
H(T)


(c)
11.45 K
11.62 K
11.99 K
12.46 K
14.25 K
ρ (μΩ cm)
B (T)

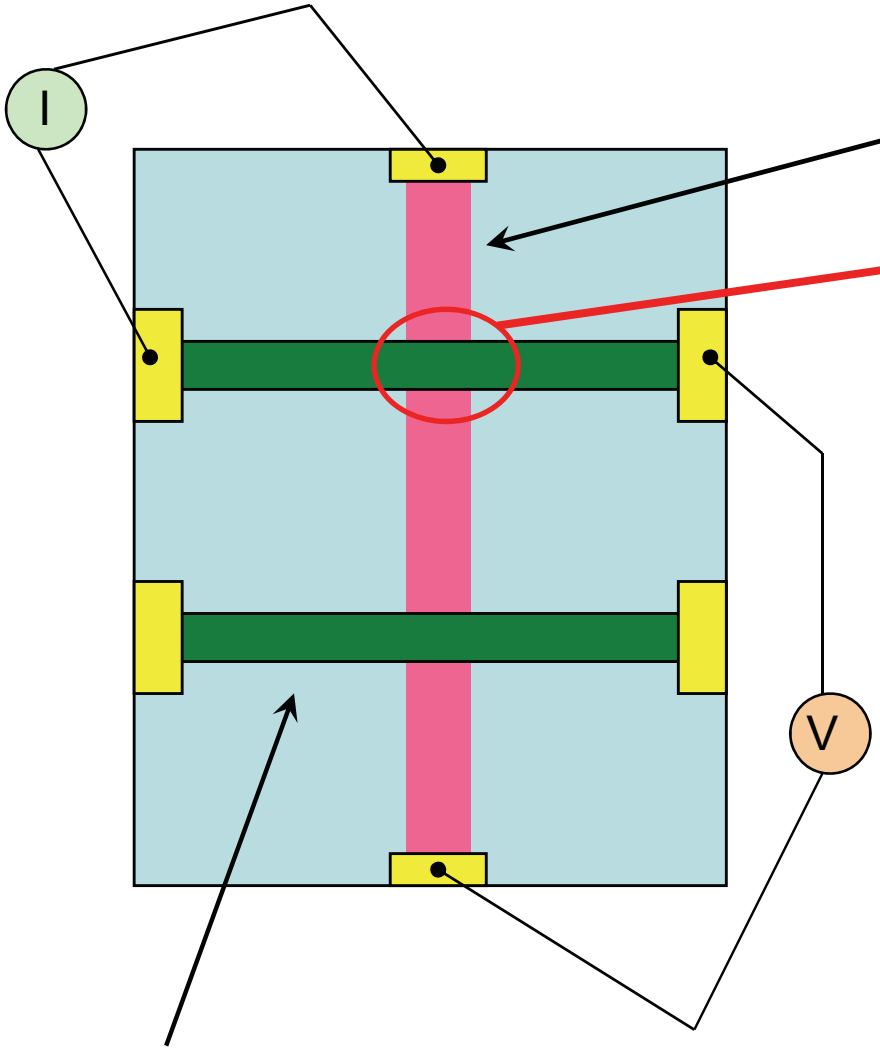

$k_F l$ 3.33
0T
12T
ρ(μΩ m)
T(K)


(f)
γ=4.35
B > B_{cp}
B < B_{cp}
11.45 K
11.62 K
11.99 K
12.46 K
14.25 K
R/R_{cp}
$|B-B_{cp}|/T^{\gamma}$

Phenomenological Phase Diagram

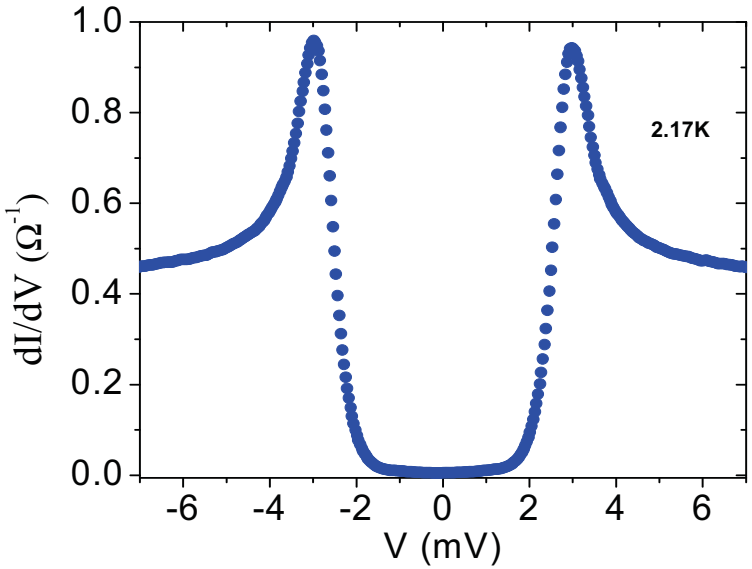


Tunneling measurement



NbN/Oxide layer

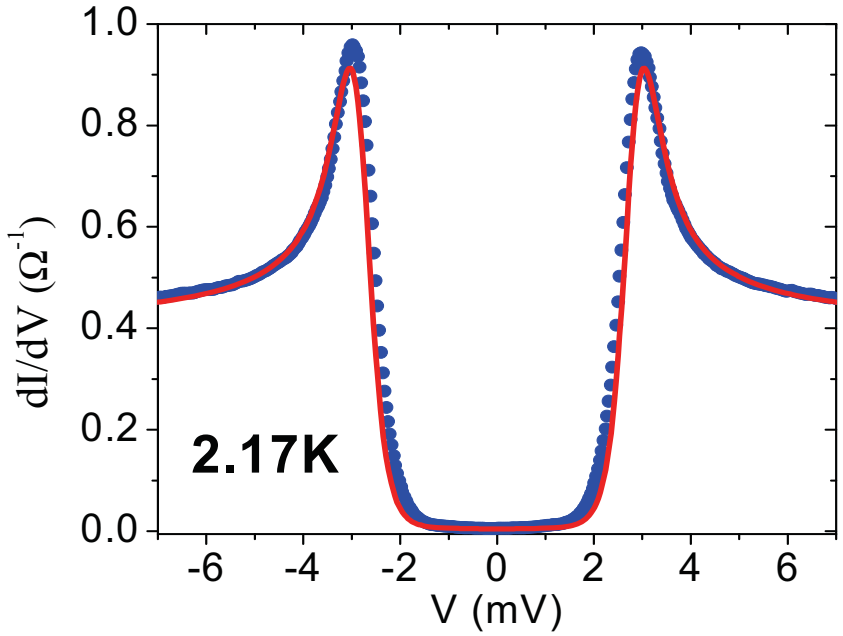
I-V characteristics of the (300X300 μm^2) tunnel junction



Ag Counter electrode

Tunnel junctions with resistance varying between 1-10Ω: Good for tunneling spectroscopy in the Superconducting state.

Fitting the tunneling spectra



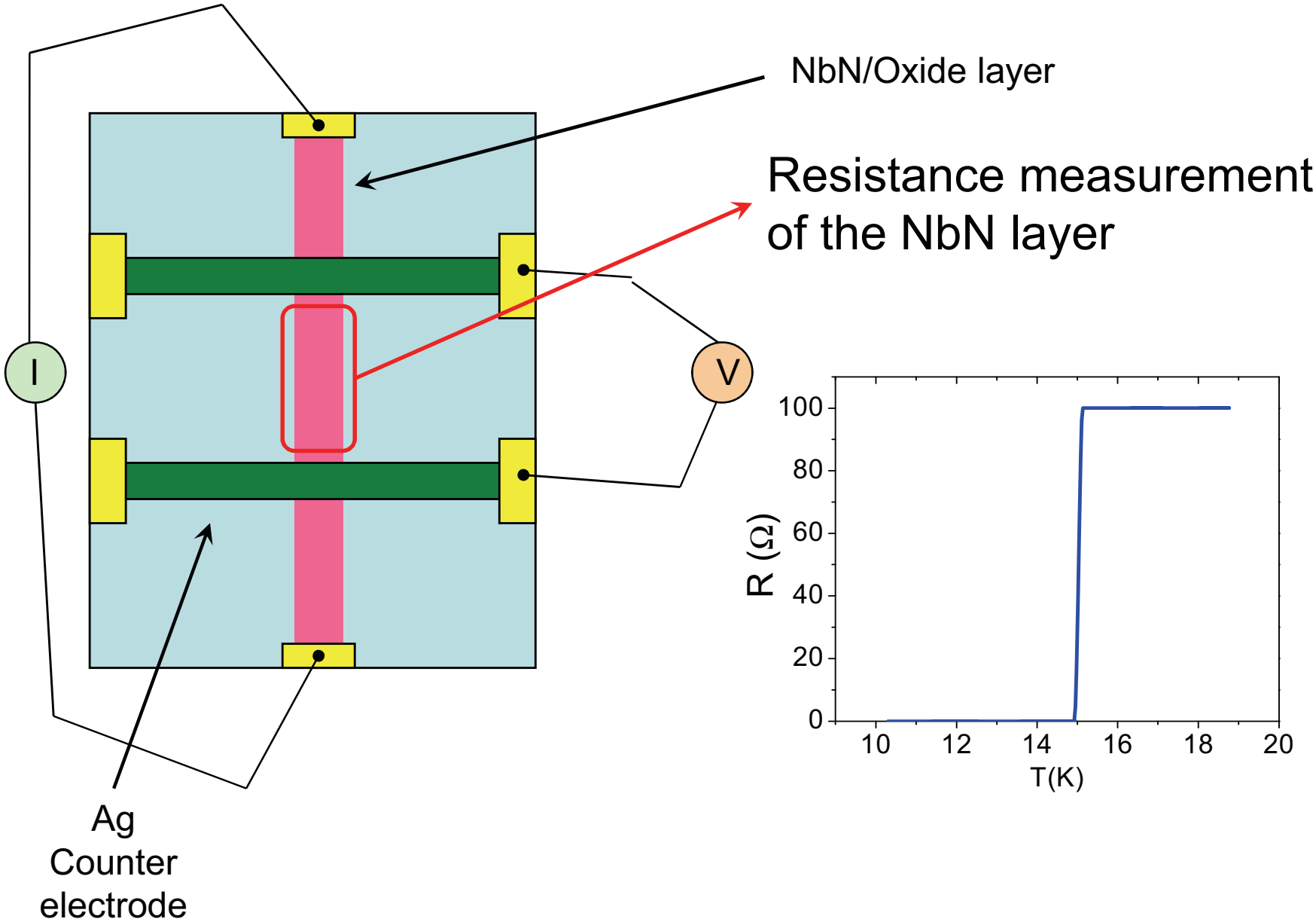
$$N_s(E) = \mathrm{Re}\left\{ \frac{E - i\Gamma}{\left[(E - i\Gamma)^2 - \Delta^2 \right]^{1/2}} \right\}$$

Δ: Superconducting energy gap
Γ: incorporates all non-thermal sources of broadening: Phase fluctuations, spatial inhomegeneity of Δ

$$G(V) = \left.\frac{dI}{dV}\right|_V = \frac{d}{dV}\left\{ \int_{-\infty}^{\infty} N_s(E) N_n(E - eV) \left\{ f(E) - f(E - eV) \right\} dE \right\}$$

R. C. Dynes, V. Narayanamurti, and J. P. Garno, Phys. Rev. Lett. **41,** 1509 (1978).

Resistance measurement

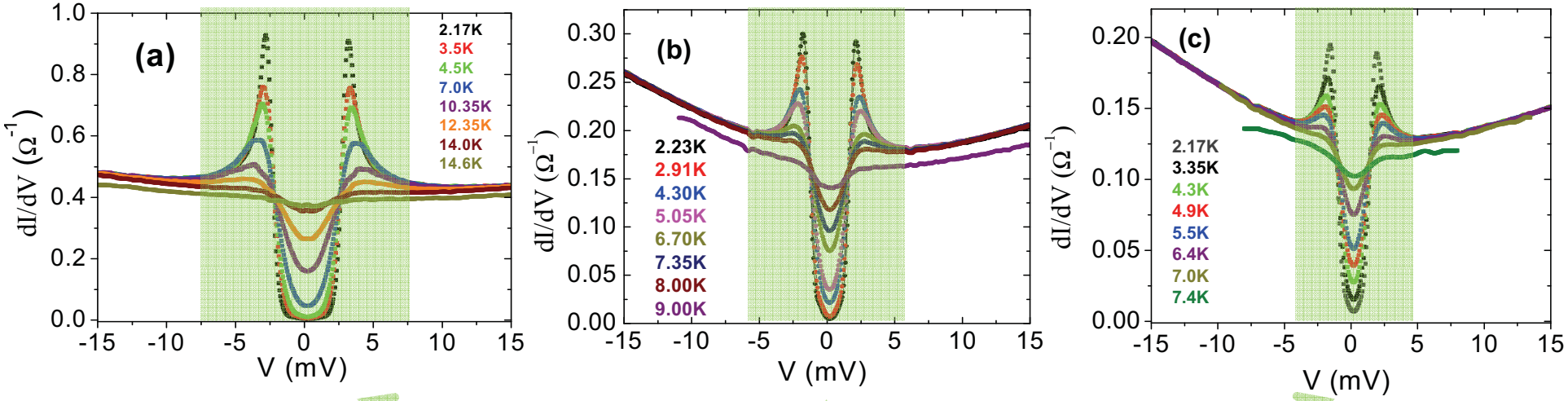


Tunneling spectra

T_c~14.9K
$k_F l$~6

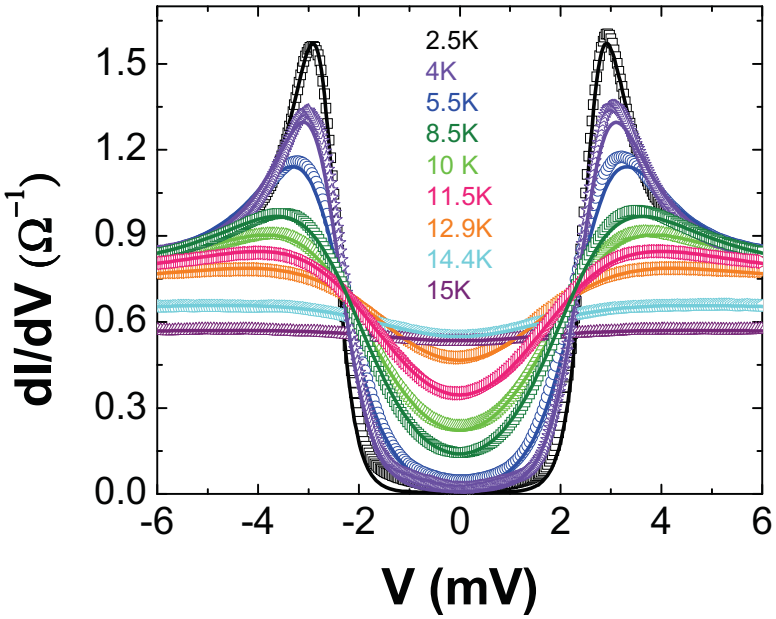
T_c~9.5K
$k_F l$~2.3

T_c~7.7K
$k_F l$~1.4



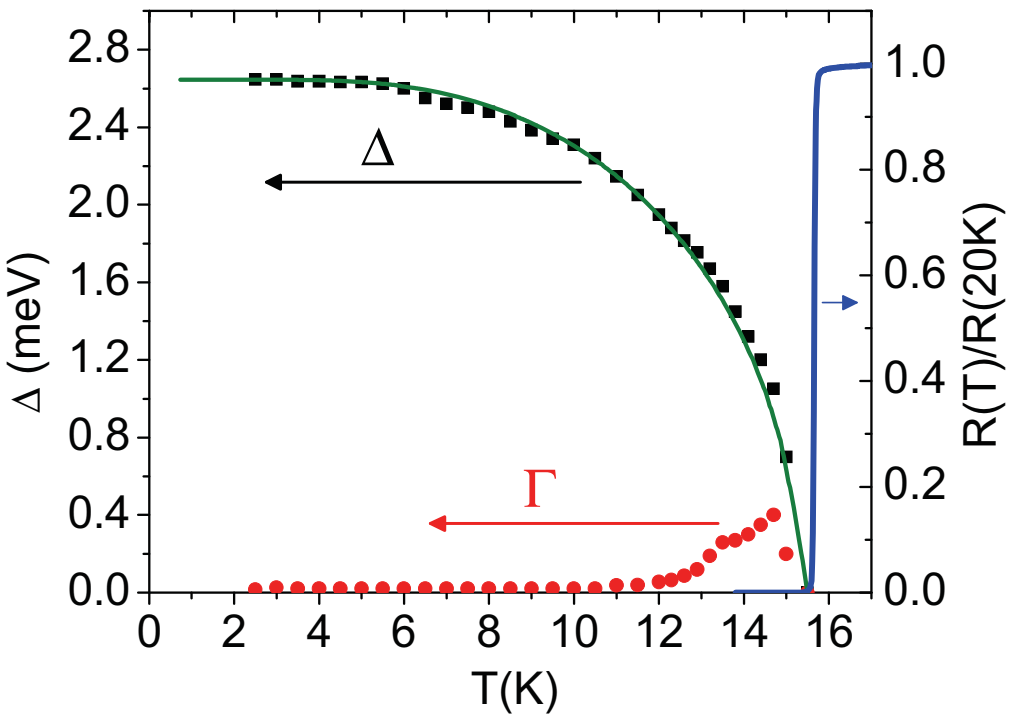
Low bias: Relevant region for superconductivity

T_c~15.6K $k_F l$~6.5

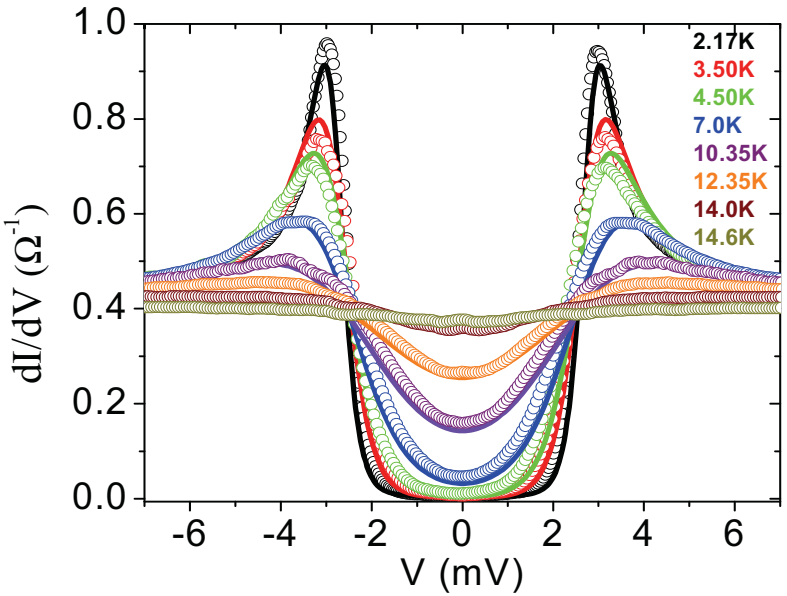


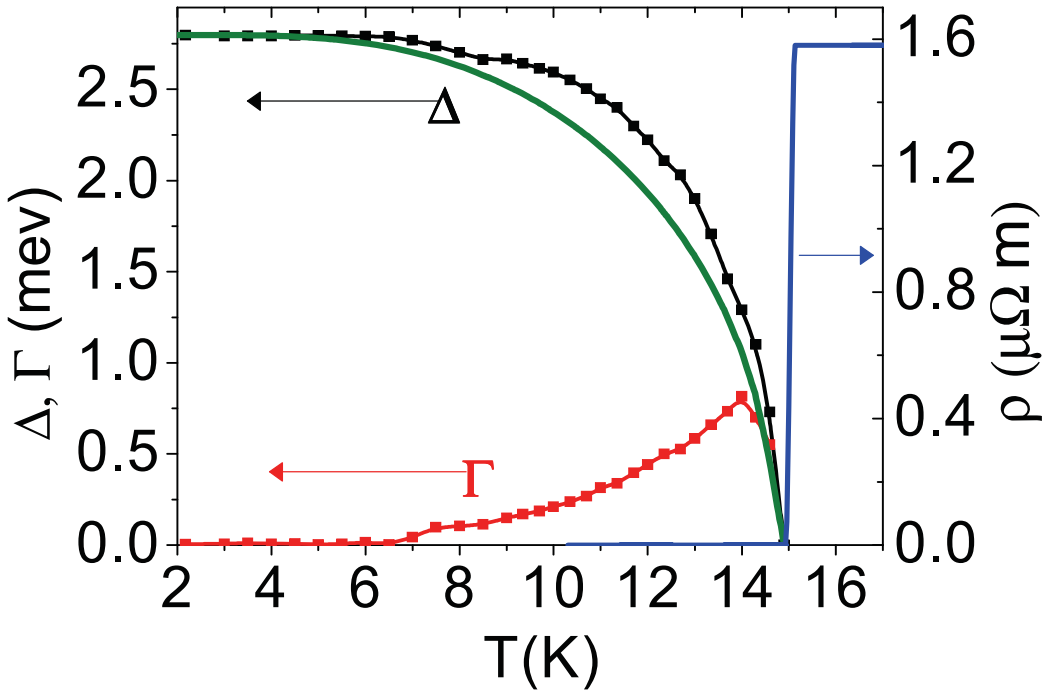
Small increase in Γ due to ph induced recombination of el and hole like quasiparticles:

R. C. Dynes, V. Narayanamurti, and J. P. Garno, Phys. Rev. Lett. **41**, 1509 (1978).

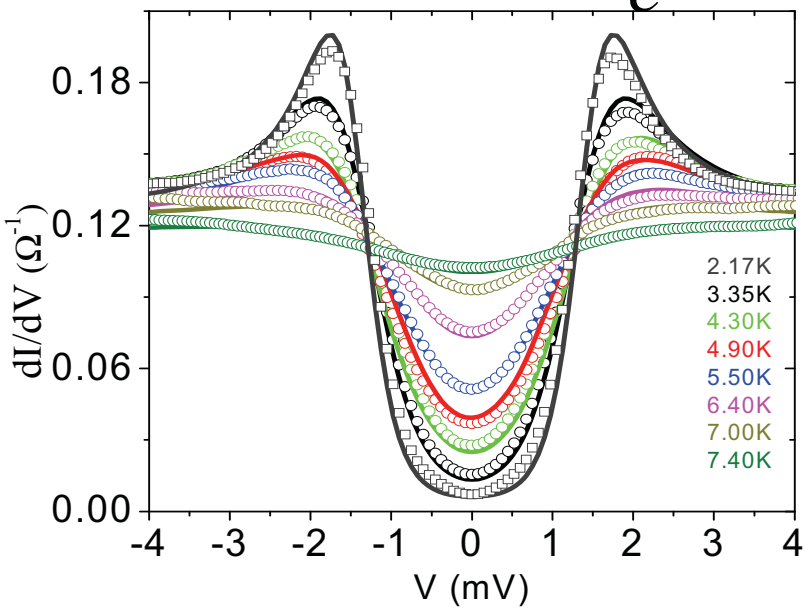


T_c~14.9K $k_F l$~6


2.17K
3.50K
4.50K
7.0K
10.35K
12.35K
14.0K
14.6K
dI/dV (Ω⁻¹)
V (mV)


Δ
Γ
Δ, Γ (mev)
ρ (μΩ m)
T(K)

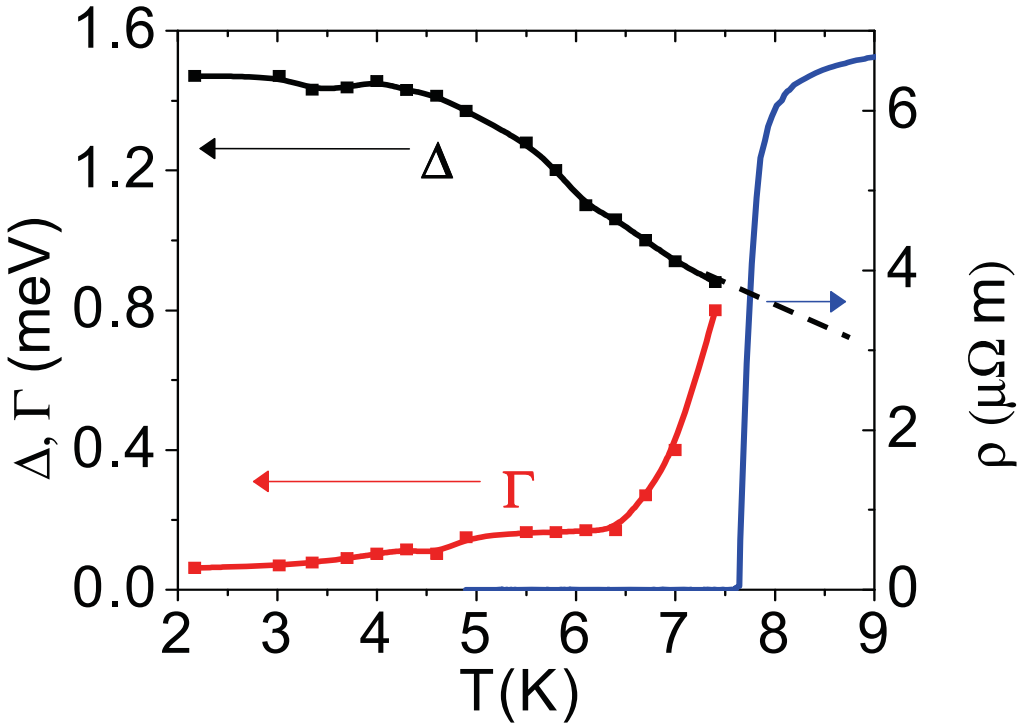
T_c~7.7K $k_F l$~1.4



Δ reduces to 60% of its low temperature value at T_c.

$T \rightarrow T_c$

$\Delta \neq 0 \quad \Delta \approx \Gamma$

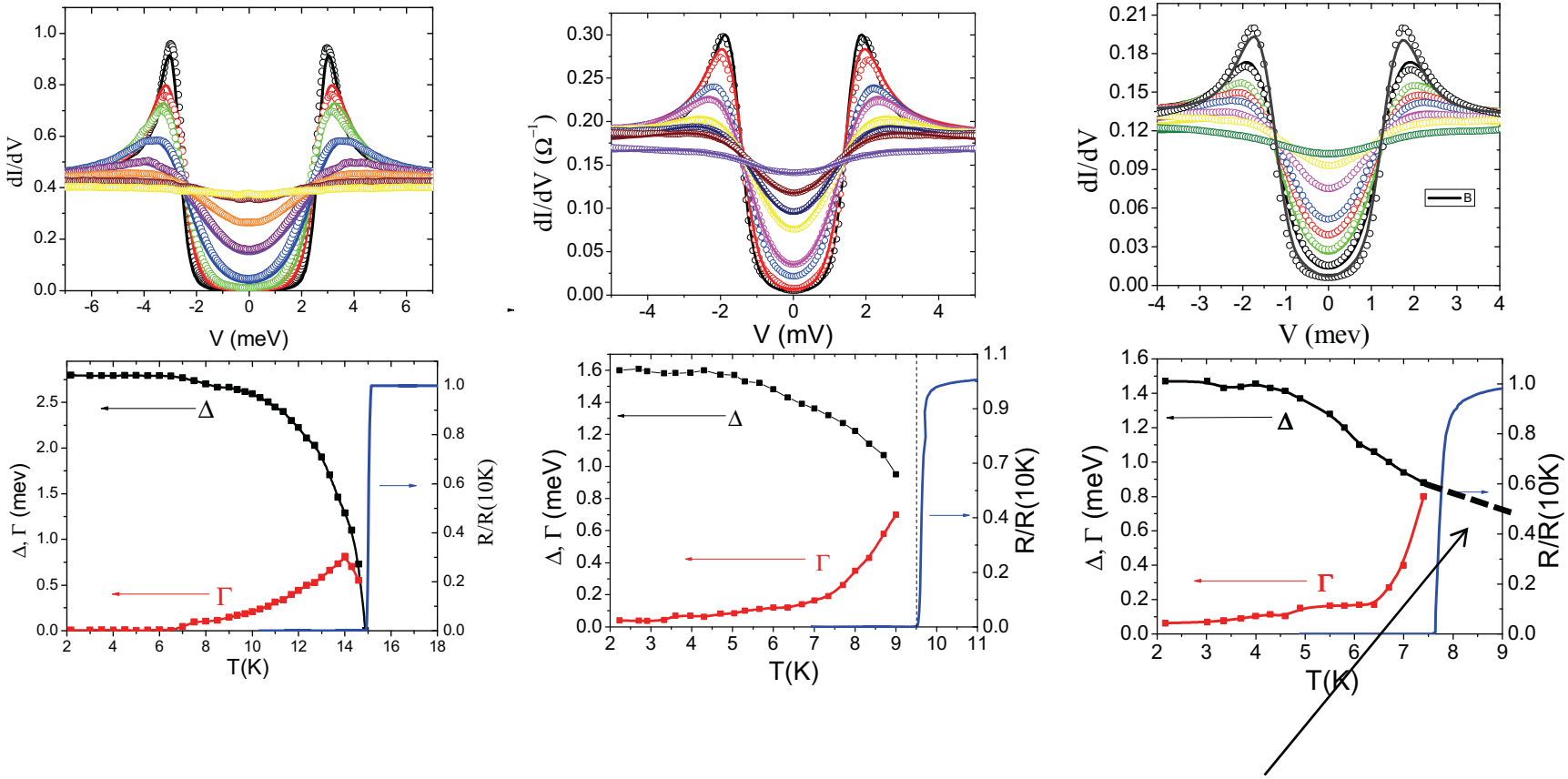


Temperature dependence of Δ and Γ

Least disorder
T_c=14.9K
$2\Delta/k_BT_c$=4.36
k_Fl~6

Intermediate disorder
T_c=9.5K
$2\Delta/k_BT_c$=3.91
k_Fl~2.3

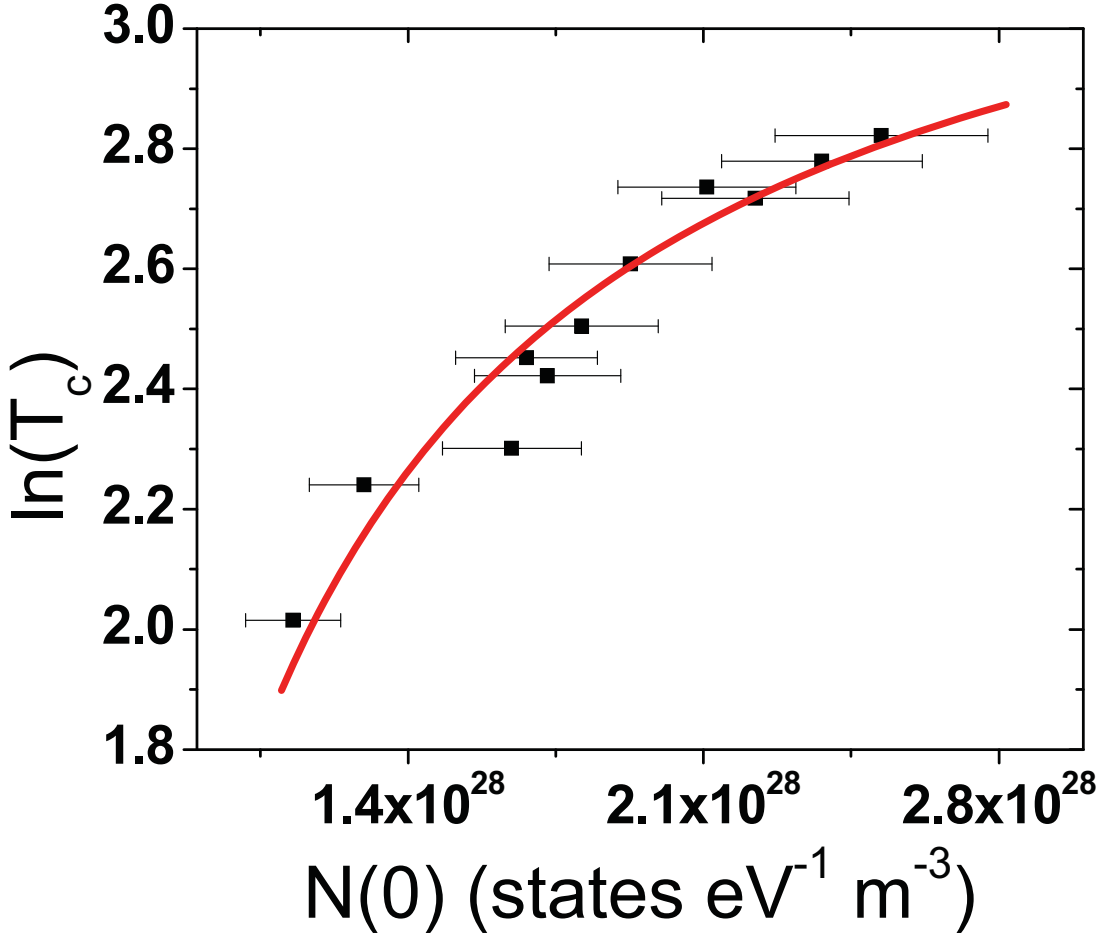
Large disorder
T_c=7.7K
$2\Delta/k_BT_c$=4.43
k_Fl=1.4



Pseudogap state above T_c?

$2\Delta/k_B T_c$

Measure of electron-phonon coupling strength within “mean field” theories of superconductivity.



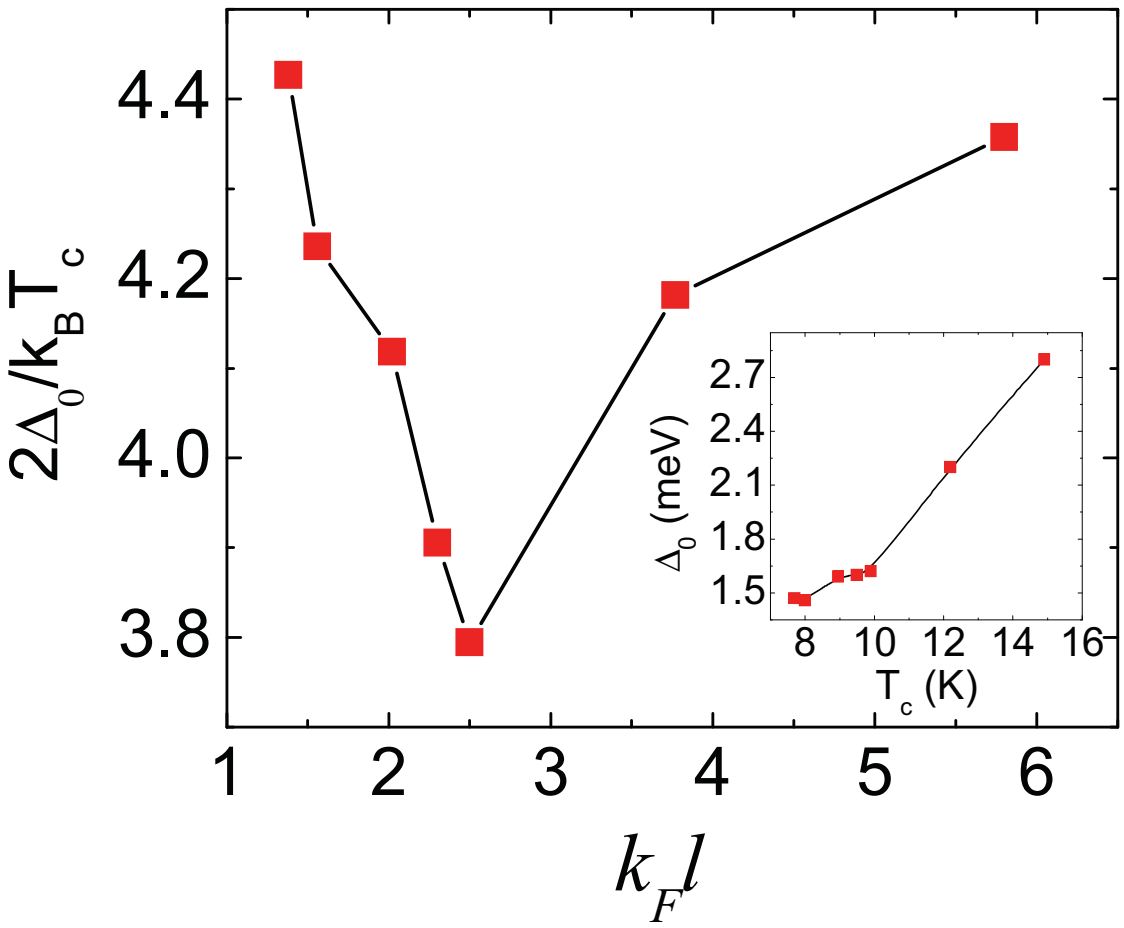
N(0) is expected to decrease for films with lower T_c

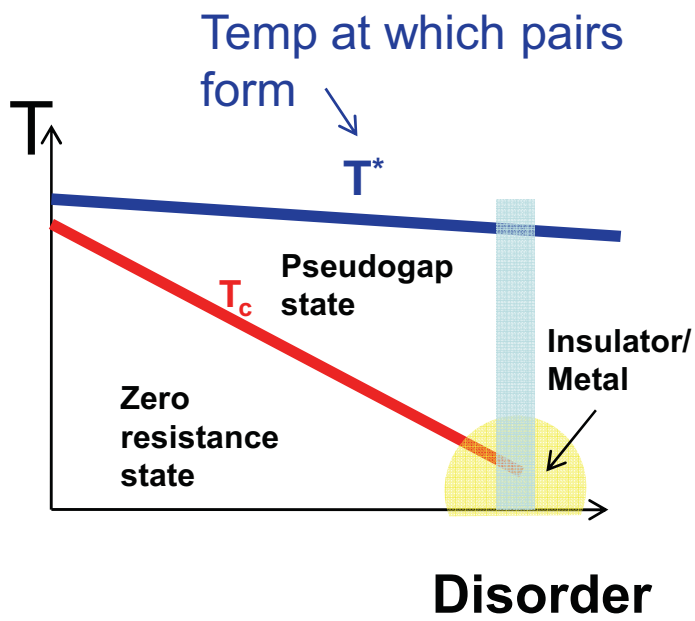
↓

Electron-phonon coupling strength $\lambda \sim N(0)V$ is expected to reduce.

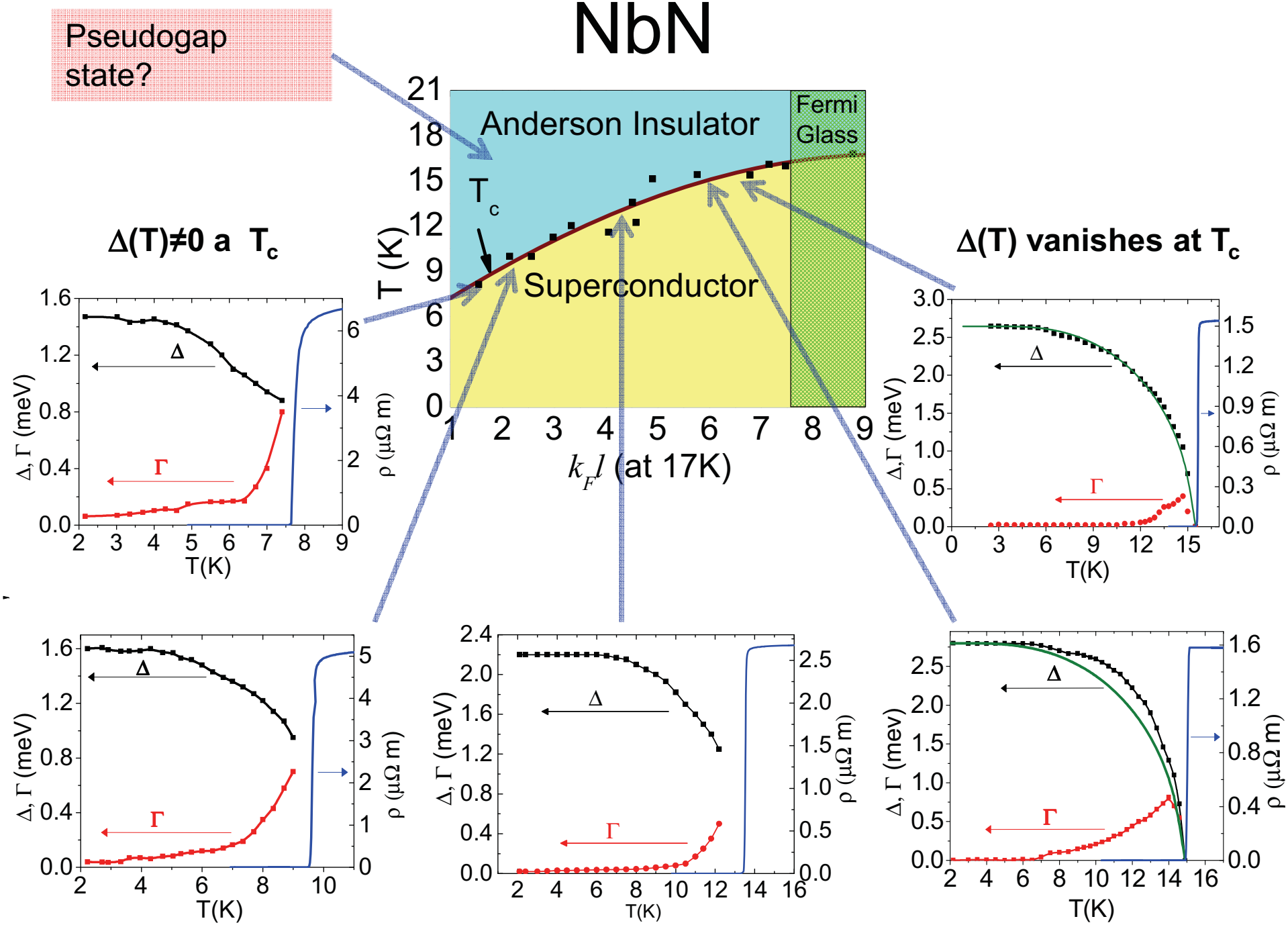
↓

Measure of electron-phonon coupling strength: $2\Delta/k_B T_c$


4.4
4.2
4.0
3.8
$2\Delta_0/k_BT_c$
1
2
3
4
5
6
k_Fl
2.7
2.4
2.1
1.8
1.5
Δ_0 (meV)
8
10
12
14
16
T_c (K)

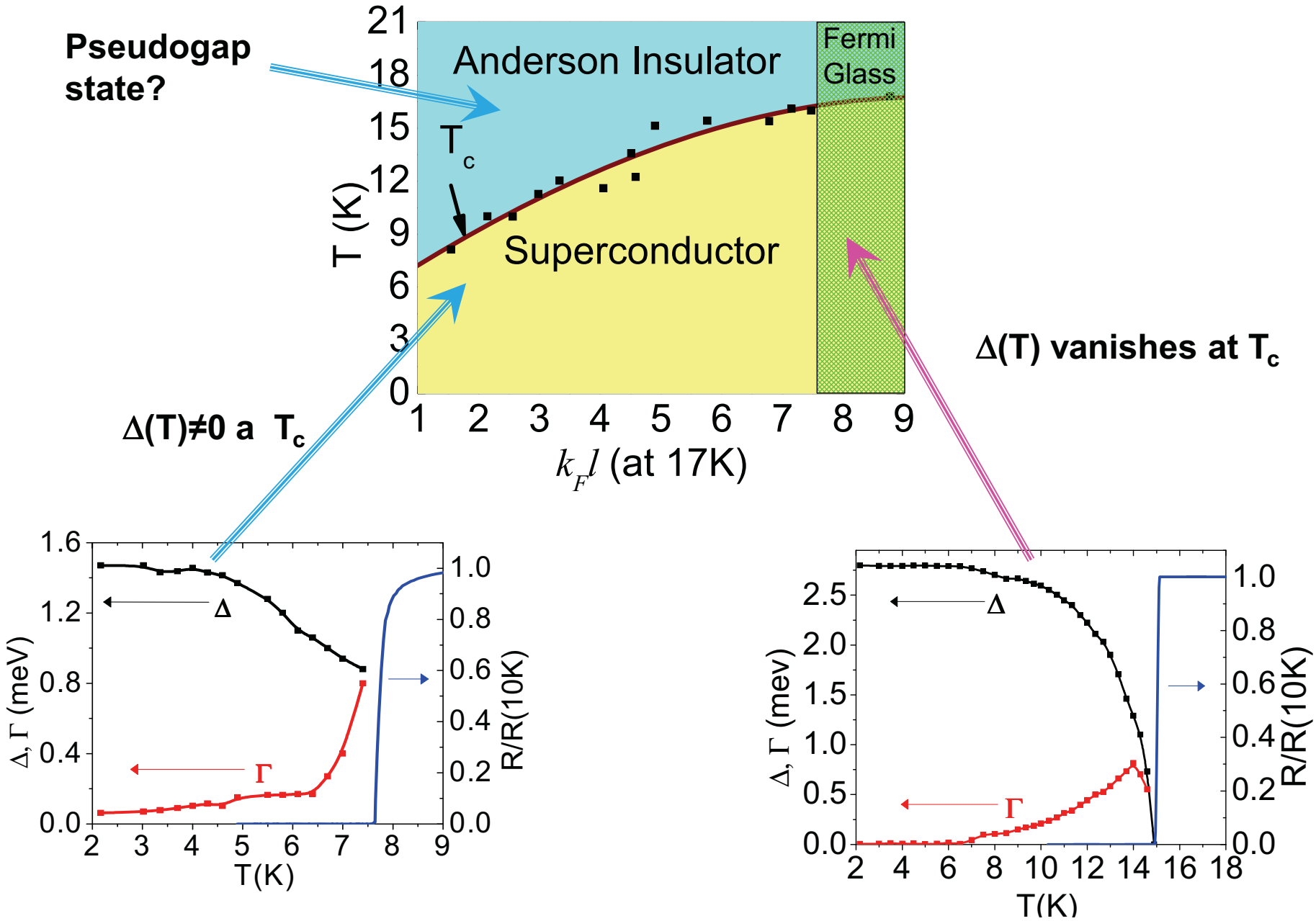

Temp at which pairs form
T
T*
Pseudogap state
T_c
Insulator/ Metal
Zero resistance state
Disorder

NbN


Pseudogap state?
Anderson Insulator
Fermi Glass
Superconductor
T_c
T (K)
$k_F l$ (at 17K)
Δ(T)≠0 a T_c
Δ(T) vanishes at T_c
Δ, Γ (meV)
ρ (μΩ m)
T(K)
Δ
Γ

Thank you

NbN


Pseudogap state?
Anderson Insulator
Fermi Glass
T_c
Superconductor
T (K)
$k_F l$ (at 17K)
Δ(T)≠0 a T_c
Δ(T) vanishes at T_c
Δ, Γ (meV)
R/R(10K)
T(K)
Δ
Γ

Connection with BEC

All visible matter consists of Fermions