The Abdus Salam International Centre for Theoretical Physics, Trieste Italy

Cooling of hot electrons by phonons: role of pairing interactions and disorder

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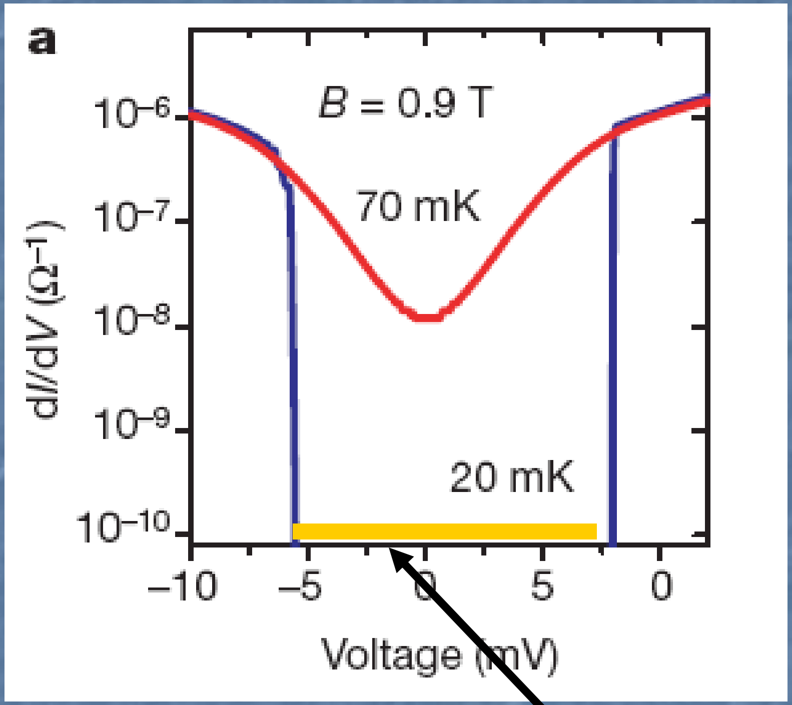
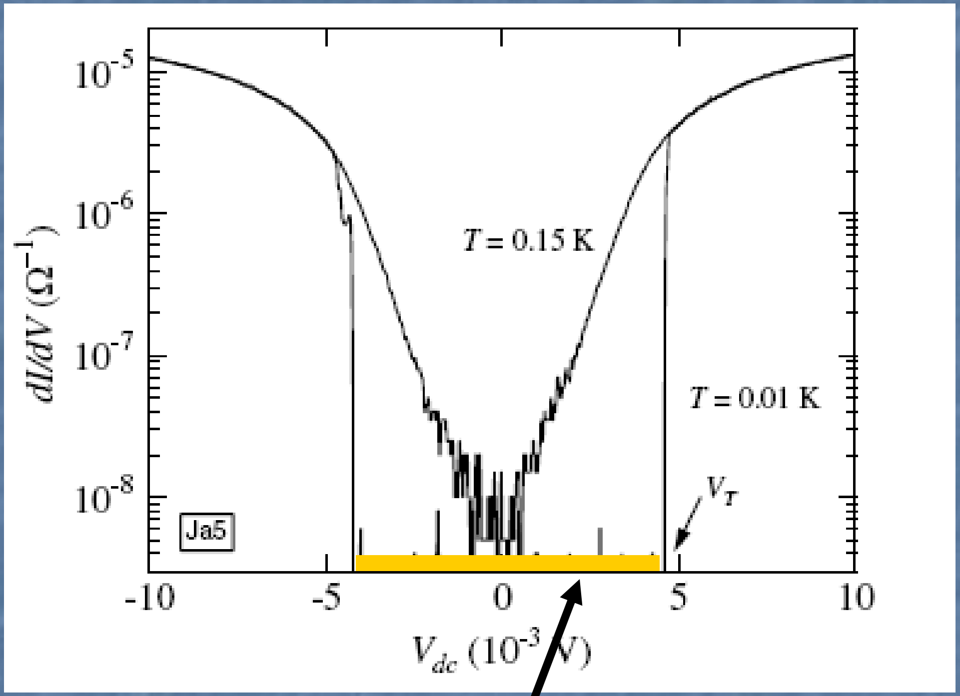
Santa Barbara, October 23, 2012

Super-insulator?

TiN films



InO films



Baturina, Mironov, Vinokur, Baklanov, Strunk,'07

$$\sigma = 0$$

Sambandamurthy, Engel, Johansson, Peled, Shahar, '05

PRL 102, 176802 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Electron-Phonon Decoupling in Disordered Insulators

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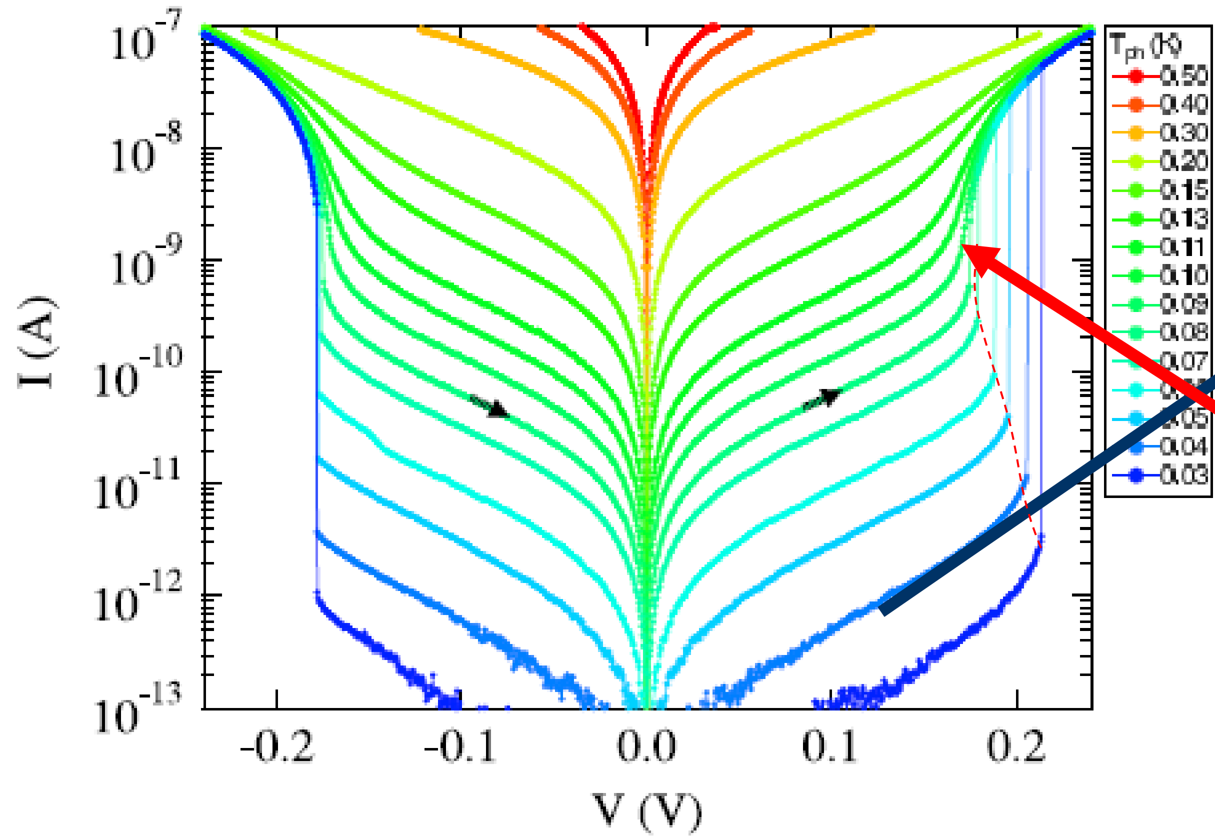
(Received 28 January 2009; published 28 April 2009)



Non-zero conductance: the insulator is not ideal

T_c

Phase transition?

What is the physics behind?

- Is there a new phase???

Our answer:
No new phase but bistability due to overheating of electron system

PRL **102**, 176803 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Jumps in Current-Voltage Characteristics in Disordered Films

Boris L. Altshuler,[1,2] Vladimir E. Kravtsov,[3] Igor V. Lerner,[4] and Igor L. Aleiner[1]

Assumptions

Electron Temperature T_e is decoupled from the phonon bath T_{ph}

T_e depends on voltage V and is determined by the heat balance

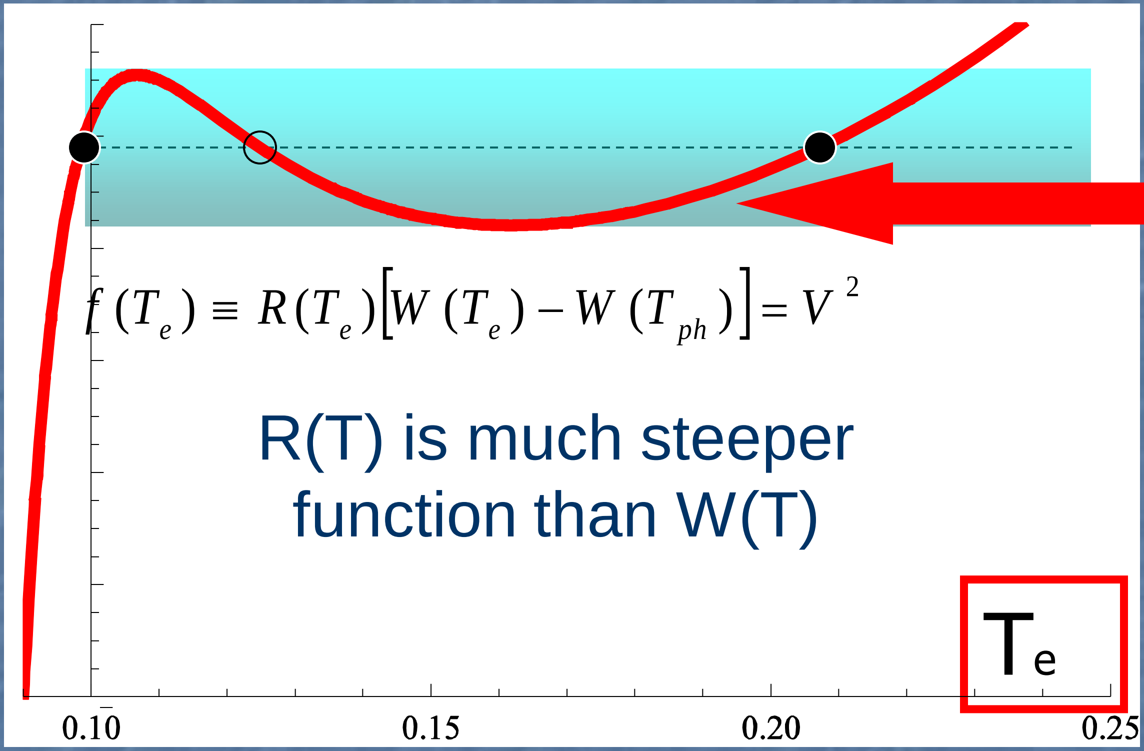
Joule heating (T_e, V) = Phonon Cooling (T_e, T_{ph})

$$\frac{V^2}{R(T_e)} = W(T_e) - W(T_{ph})$$

Bistability

$$R(T) = \exp[-T_0 / T]$$

$$W(T) = \Gamma T^{\beta}$$

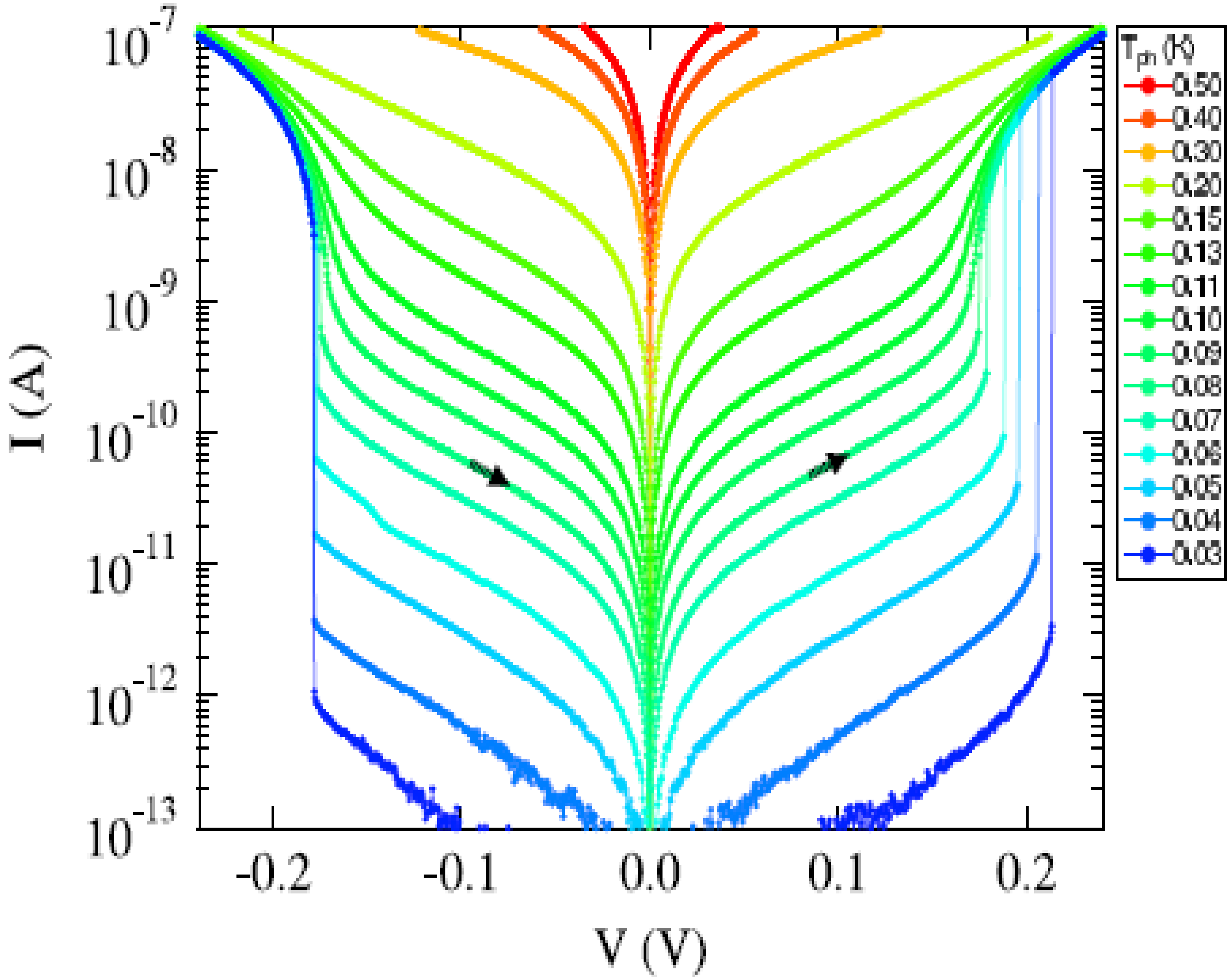


$$f(T_e) \equiv R(T_e)\left[W(T_e) - W(T_{ph})\right] = V^2$$

R(T) is much steeper function than W(T)

Bi-stable region

Two stable electron temperatures at the one and the same voltage



I (A)
V (V)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
-0.2
-0.1
0.0
0.1
0.2
T_{ph} (K)
0.50
0.40
0.30
0.20
0.15
0.13
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03

Electron temperature is strongly decoupled from phonon bath =

No phonon-assisted hopping

Electrons are the bath for themselves

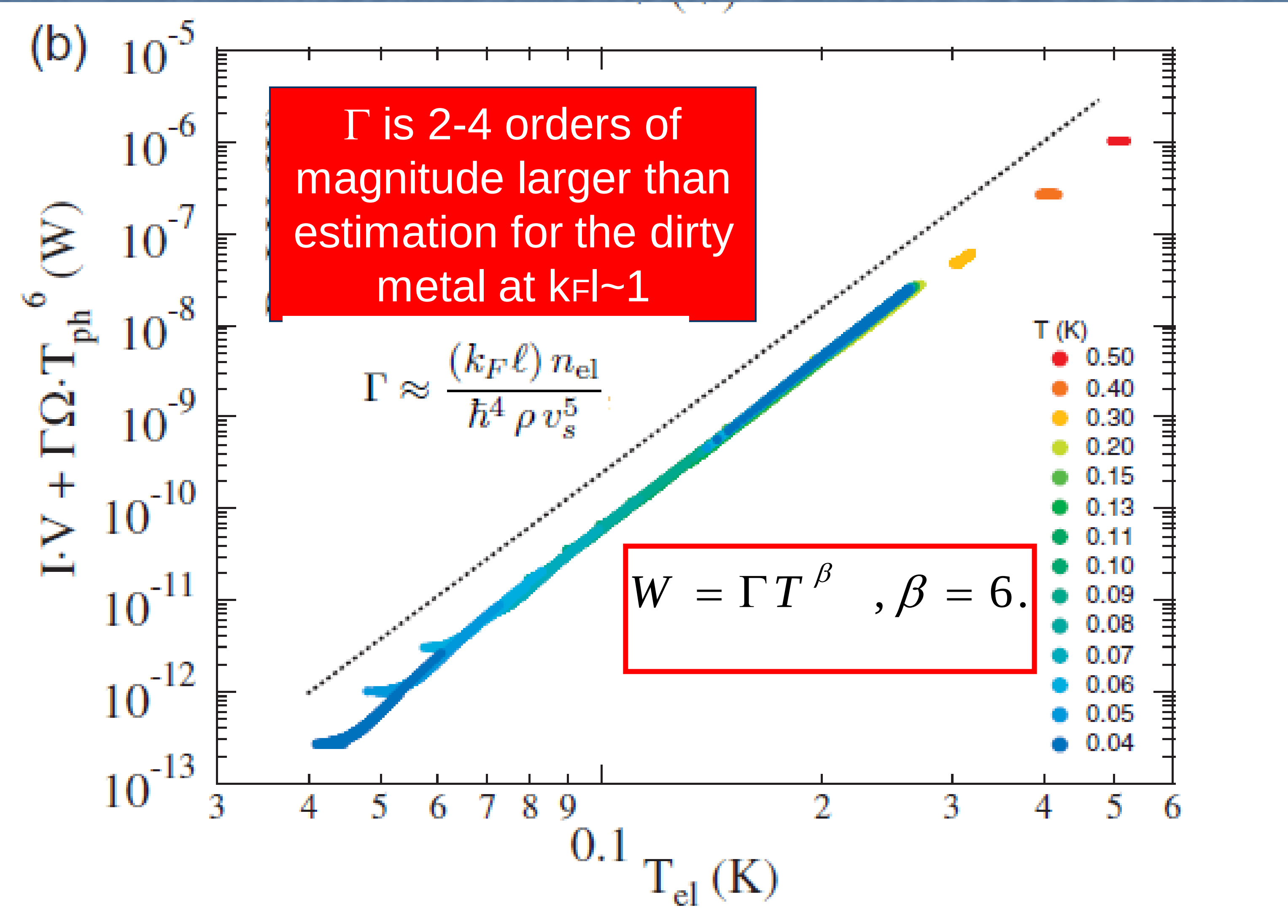
see also: M.Gershenzon,…

S. Marnieros, L. Bergé, A. Juillard, and L. Dumoulin;

But electron cooling W is always due to phonons: electron interaction is energy conserving

Electron cooling rate W(T)

Ovadia, Sacepe, Shahar

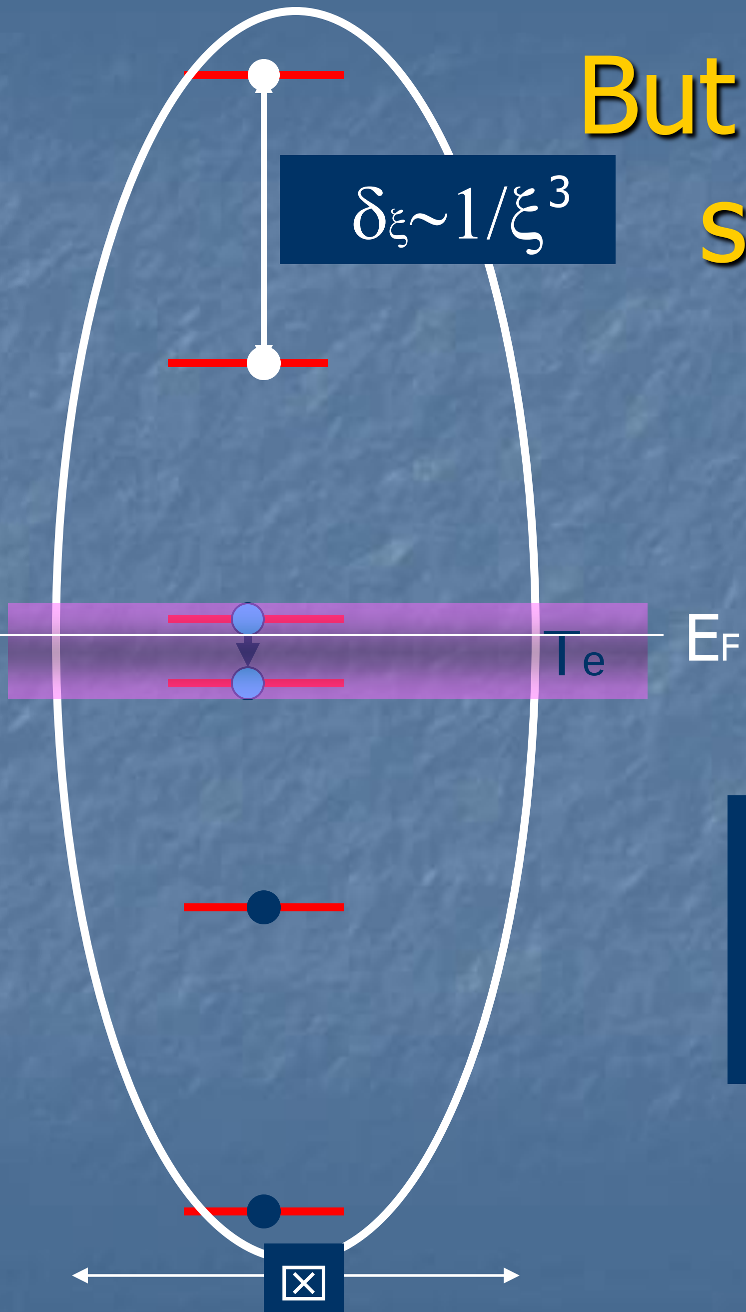


Why power law cooling rate in insulator?

For energy relaxation it is NOT necessary to move in space.

It is only necessary to move in the energy space.

But localization is still relevant



$$P=(T_e/\delta_\xi)^2 \ll 1$$

Small probability of having two close in energy states localized in one place

How to compensate a small factor $(T/\delta_\xi)^2$?

Proximity to superconductor-insulator-transition?

The problem of electron cooling by phonons is revisited in the presence of superconducting fluctuations

A. Shtyk, M.Feigelman and V.E.K. 2012

Naïve idea I

Fermions:

$$W_{out} = \frac{1}{\tau_{ph}(T)} \times \rho \int \delta f(\varepsilon)\varepsilon d\varepsilon = \frac{1}{\tau_{ph}(T)} \times \frac{n}{\varepsilon_F} T^2$$

Bosons:

$$W_{out} = \frac{1}{\tau_{ph}(T)} \times nT$$

Gain at low temperature

$$\frac{T^2}{\varepsilon_F} \Rightarrow T$$

Naïve idea II

$$\frac{1}{\tau_{ph}(T)} \sim \frac{T^3}{\theta_D^2}$$

Standard e-ph cooling in metal:

$$W_{out}^{el} \sim \frac{T^3}{\theta_D^2} n \frac{T^2}{\varepsilon_F} \sim \frac{T^5}{\theta_D^2 \varepsilon_F} n$$

pair-ph cooling:

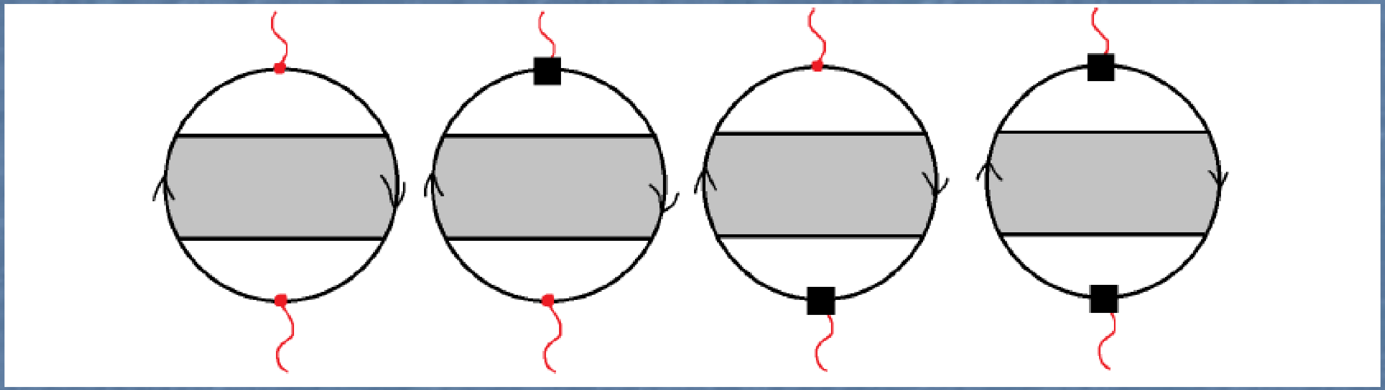
Metal ($\delta_\xi << T$) :

$$W_{out}^{pair} \sim \frac{T^4}{\theta_D^2} n$$

Insulator $\delta_\xi >> T$:

$$W_{out}^{pair} \sim \frac{T^4}{\theta_D^2} n \times \frac{T^2}{\delta_\xi^2} \sim \Gamma T^6, \quad \Gamma \sim \frac{n}{\theta_D^2 \delta_\xi^2}$$

Cooling in dirty metal

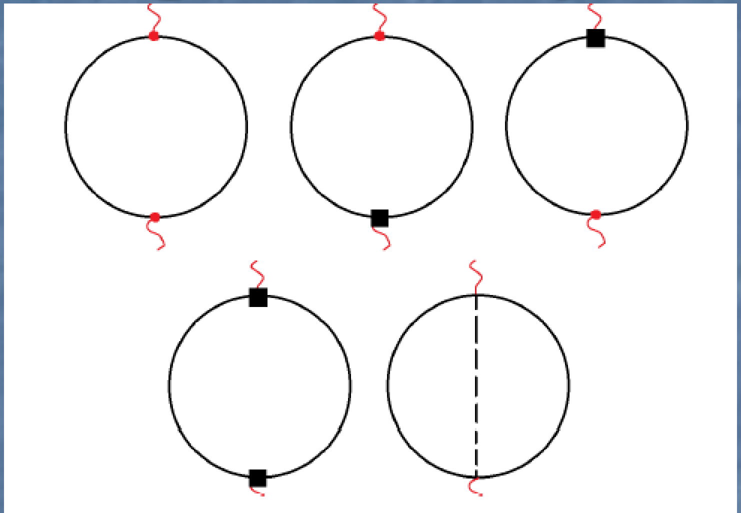


Under assumptions of:

-full involvement of impurity in the lattice motion
-universal limit of screened Coulomb interaction

ALL diagrams with diffusons cancel out!

Cooling in dirty metal



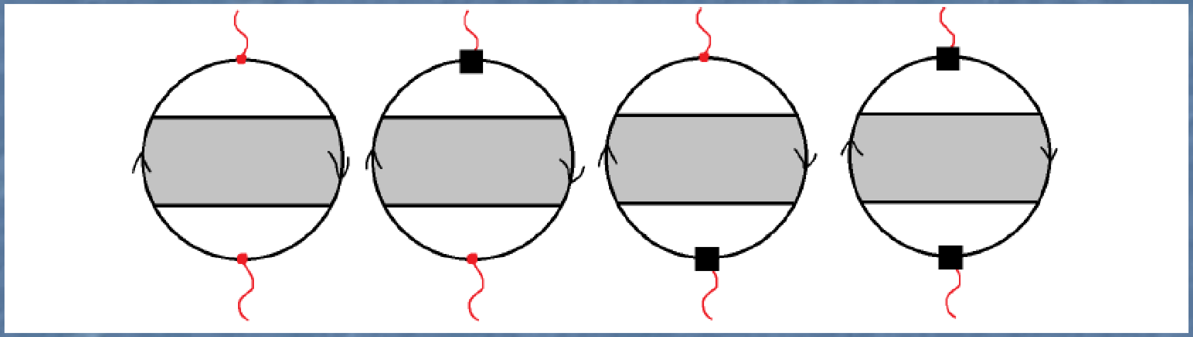
Diagrams without diffusons make a contribution smaller than in a clean metal:

$$\frac{T}{\varepsilon_F}\frac{v_F}{v_s}$$

$$W_{out} \sim \frac{T^3}{\theta_D^2}\frac{nT^2}{\varepsilon_F}(q\ell) \sim T^6, \quad q = \frac{T}{v_s}$$

A.Schmid,
M.Reyzer, Sergeev

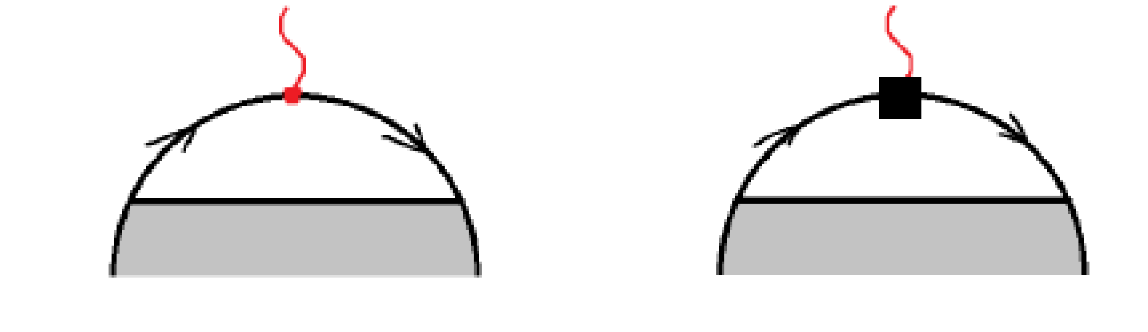
Cooling in a dirty metal



If no cancellation, the result would be larger than in clean metal:

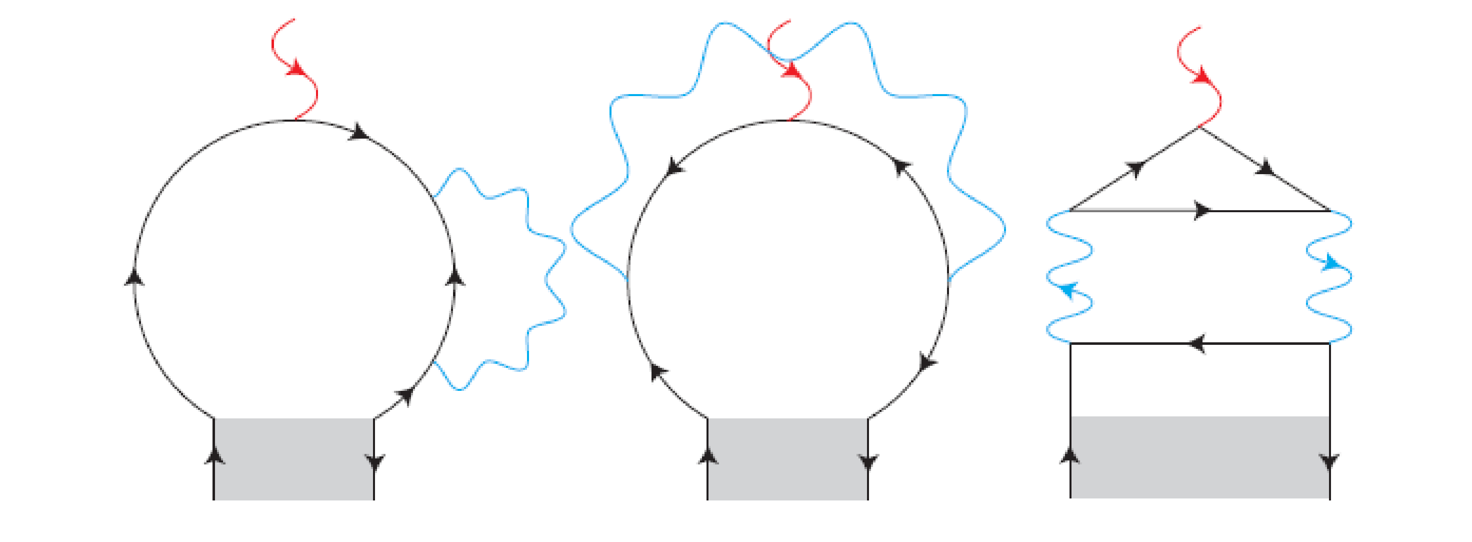
$$W_{out} \sim \frac{T^3}{\theta_D^2} \frac{nT^2}{\varepsilon_F} \frac{1}{(q\ell)} \sim T^4, \quad q = \frac{T}{v_s}$$

Cancellation of phonon-diffuson vertices



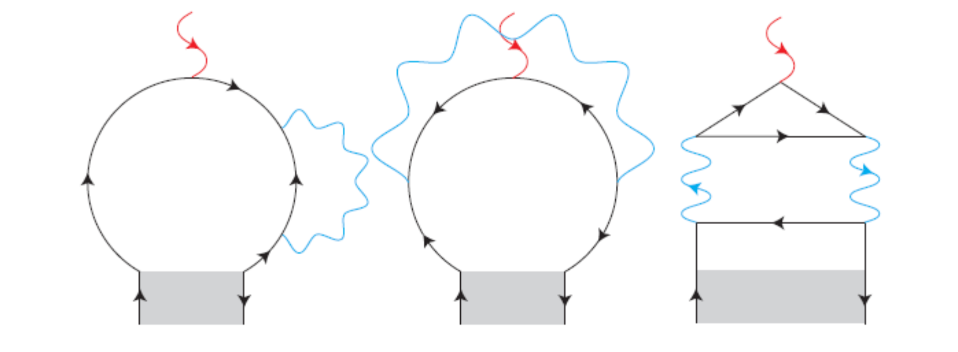
= 0

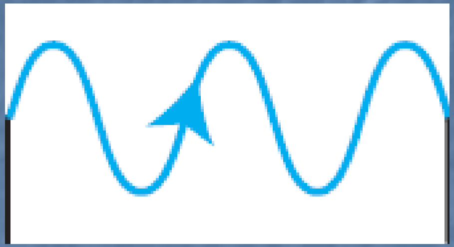
Corrections due to superconducting fluctuations



=?

BCS and BEC limits



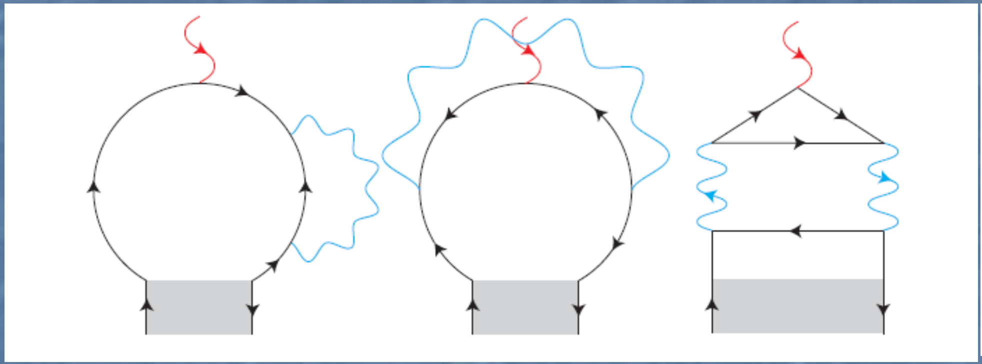


Fluctuation propagator, corresponding to Ginzburg-Landau or Gross-Pitaevskii functional

$$-\frac{\partial \Psi}{\partial t} = \frac{\delta F_{GL}}{\delta \Psi}$$

$$i\frac{\partial \Psi}{\partial t} = \frac{\delta F_{G-P}}{\delta \Psi}$$

The sum of corrections is only non-zero if Re γ is non-zero



$$\neq 0$$

$$i\gamma \frac{\partial \Psi}{\partial t} = \frac{\delta F}{\delta \Psi}, \quad \gamma = \gamma' + i\gamma''$$

BEC resonance: real pair formation

e-h symmetry and γ'

Pole of the fluctuation propagator:

$$L(i\omega, q) = \frac{1}{Dq^2 + (T - T_c) + |\omega|\gamma'' - \gamma' i\omega}$$

$$\nu(E) = \nu_0 + \nu_1(E - E_F)$$

Can be obtained if e-h symmetry is violated

There is the e-h symmetry in the canonical BCS with $\nu(E)=\nu_0$.
There is no e-h symmetry in BEC where the condensate occupies the bottom of spectrum.

Detailed theory of BCS-BEC crossover in dirty metals is needed!

Diagrams with diffuson do not cancel out in the presence of Cooper attraction if γ′ is non-zero!

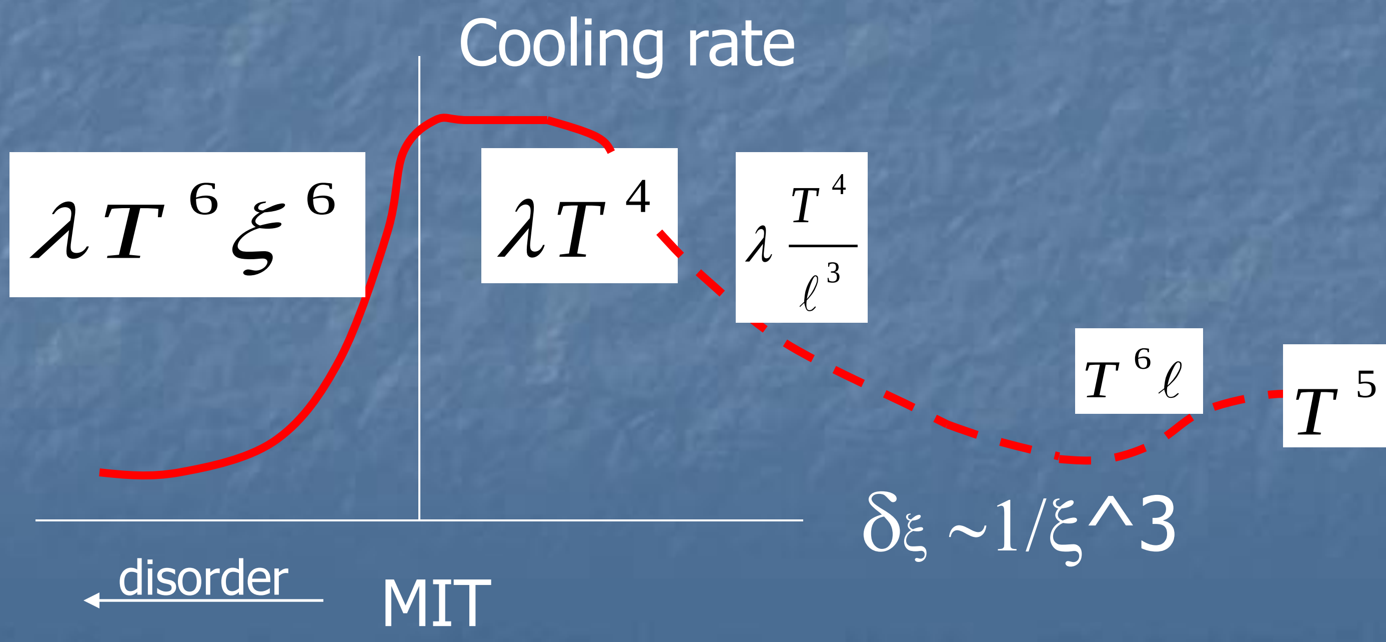
$$W_{out}^{pair} \sim T^6 \frac{\lambda}{(q\ell)^2} \sim \lambda T^4$$

Correspondence to naïve picture

$$W_{out} \sim \frac{T^3}{\theta_D^2}(q\ell) \times \frac{nT^2}{\varepsilon_F} \propto \frac{T^3}{\theta_D^2} nT \times \left(\frac{T}{\varepsilon_F}\right)^2$$

Enhancement of cooling rate by virtual pairs near MIT

$$W_{out} \propto \lambda \; T^4 \min\{\, 1, \frac{T^2}{\delta_\xi^2} \}$$



Conclusion

- Power-law cooling rate in the insulator
- How to get T^6 cooling rate? $1/T^2$ enhancement due to virtual pairs and T^2 suppression by localization
- ξ^6 enhancement of pre-factor near MIT