Puzzles of transport at the Superconductor-Insulator Transition

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Discussions with

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Rutgers, Feb 4, 2009

Outline

- The superconductor-insulator transition (SIT) – an old, but still interesting quantum phase transition
- Review of transport experiments on the insulating side of the SIT
- Discussion where and why many standard scenarios fail.
- Proposal for a mechanism explaining simple activation, as well as over-activation (using ideas of many-body localization)

SI transition in thin films

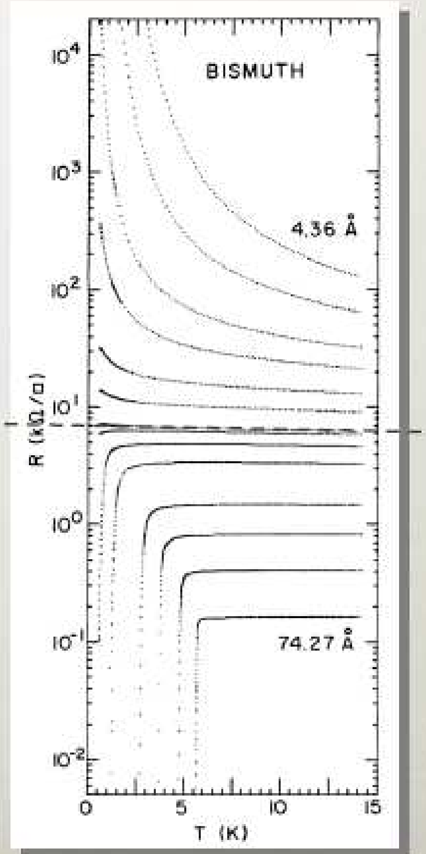
M. Strongin, et. al., Phys. Rev. **B1**, 1078 (1970).

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

Thickness tuned transition

T = 0 transition

2D



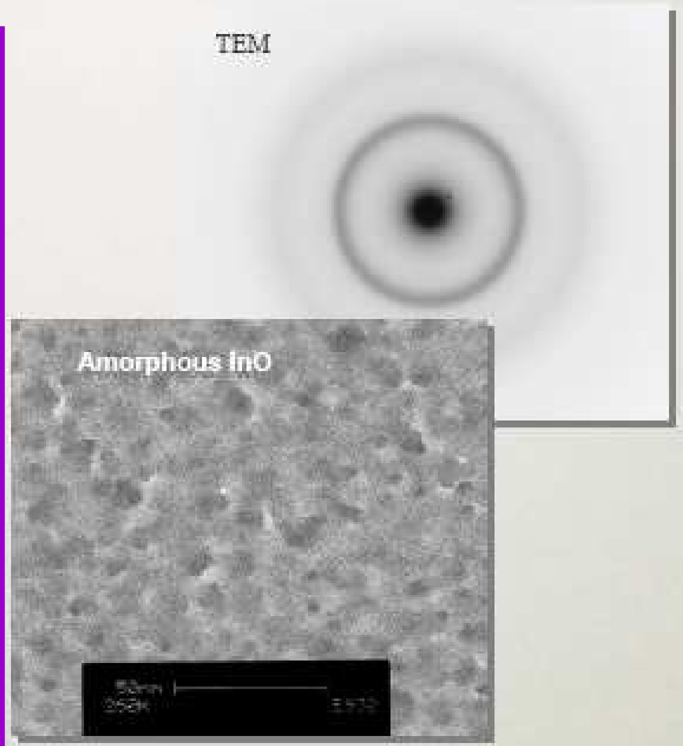
Review: Finkl'stein ('94),
Markovic and Goldman ('98).

Indium-oxide (InO_x)

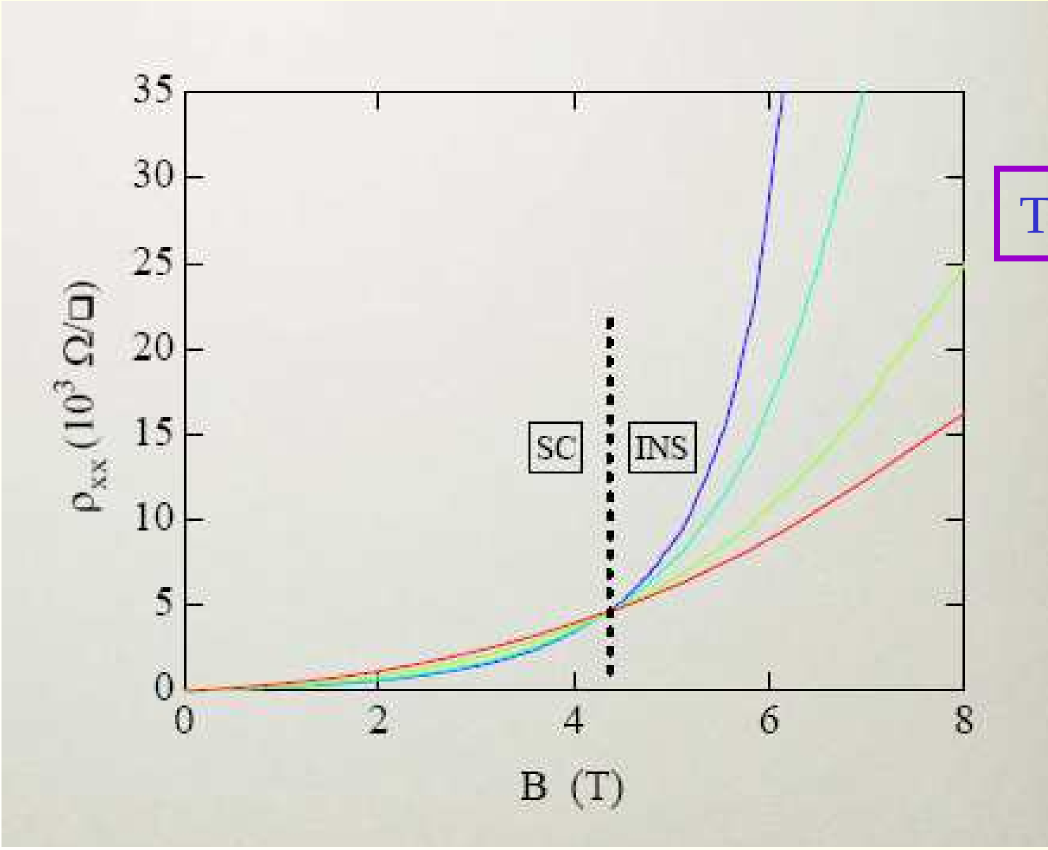
One of the major materials used in experiments:

• Strong disorder,
• High carrier density
• Tunability

Other similar experiments in TiN films



Field driven transition

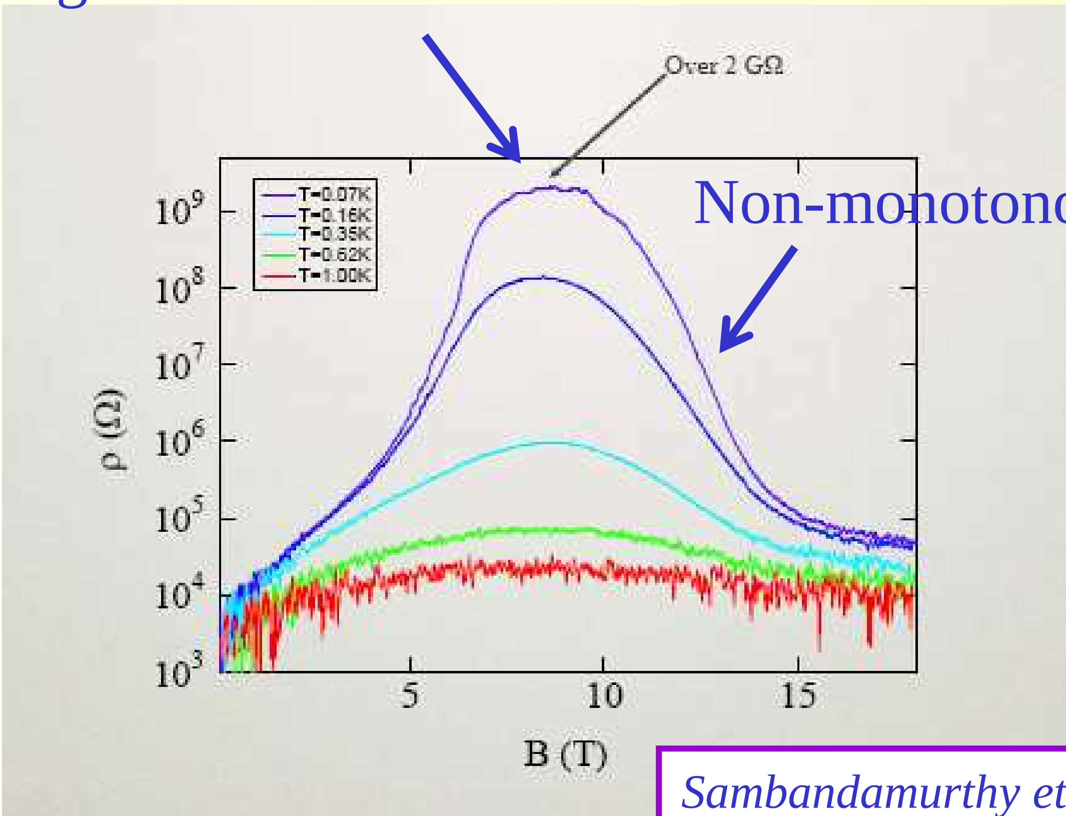


T = const.

Gantmakher, Shahar, Kapitulnik, Goldman, Baturina

Insulator: Giant magnetoresistance

Giant magnetoresistance



Non-monotonous R(B)!

Sambandamurthy et al. (PRL 2005)

Insulating behavior **enhanced** by local superconductivity!

What is the nature of the insulating state?

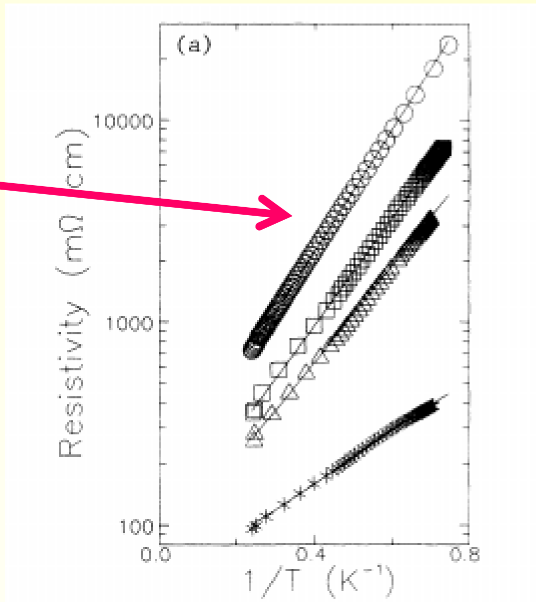
What is the transport mechanism?

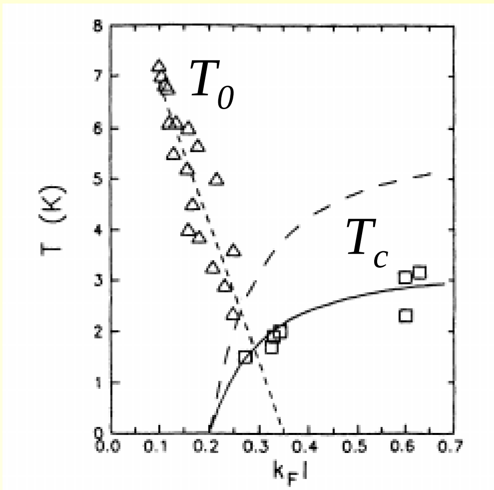
Activated transport near the SIT

*D. Shahar, Z. Ovadyahu, PRB **46**, 10971 (1992).*

Insulating InO_x

Simple activation!





Activation energy increases with distance to SIT

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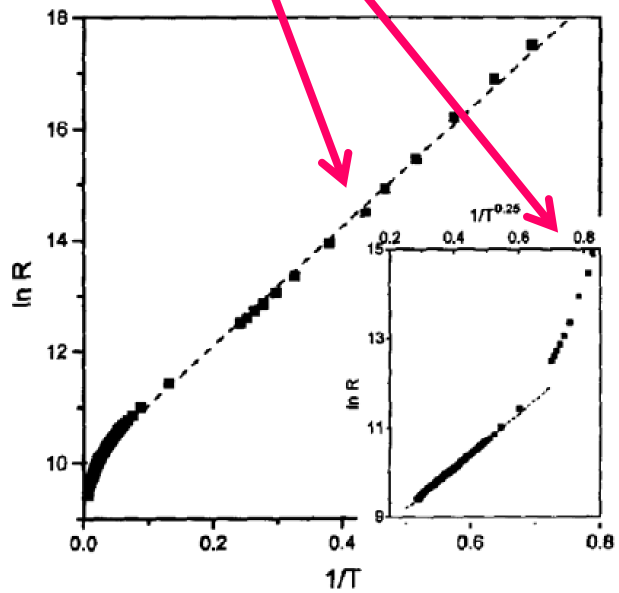

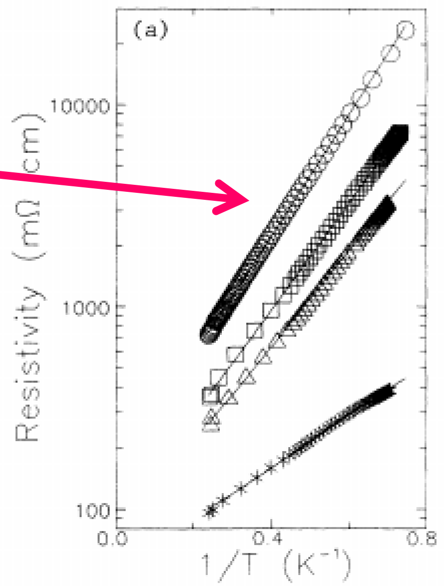

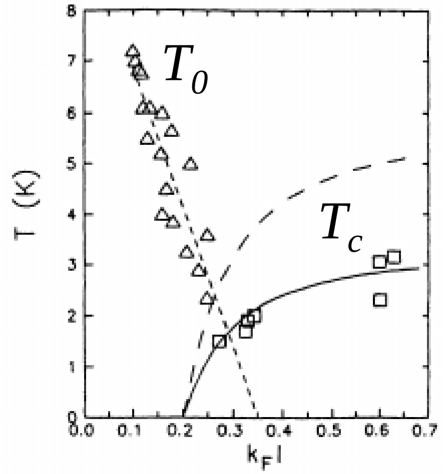

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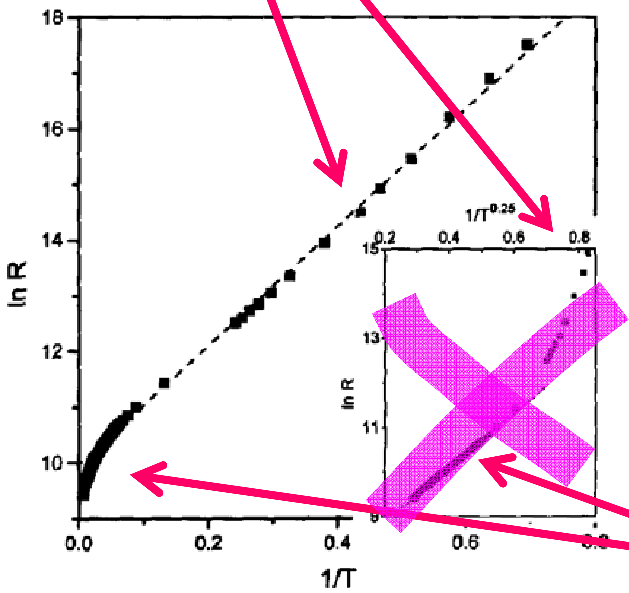

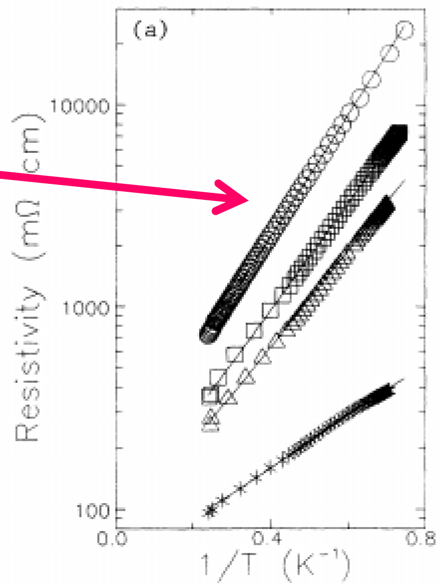

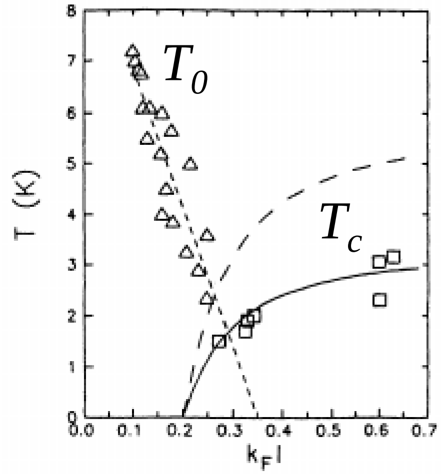

Activation energy increases with distance to SIT

Fit to variable range hopping over small range of high T is unjustified!

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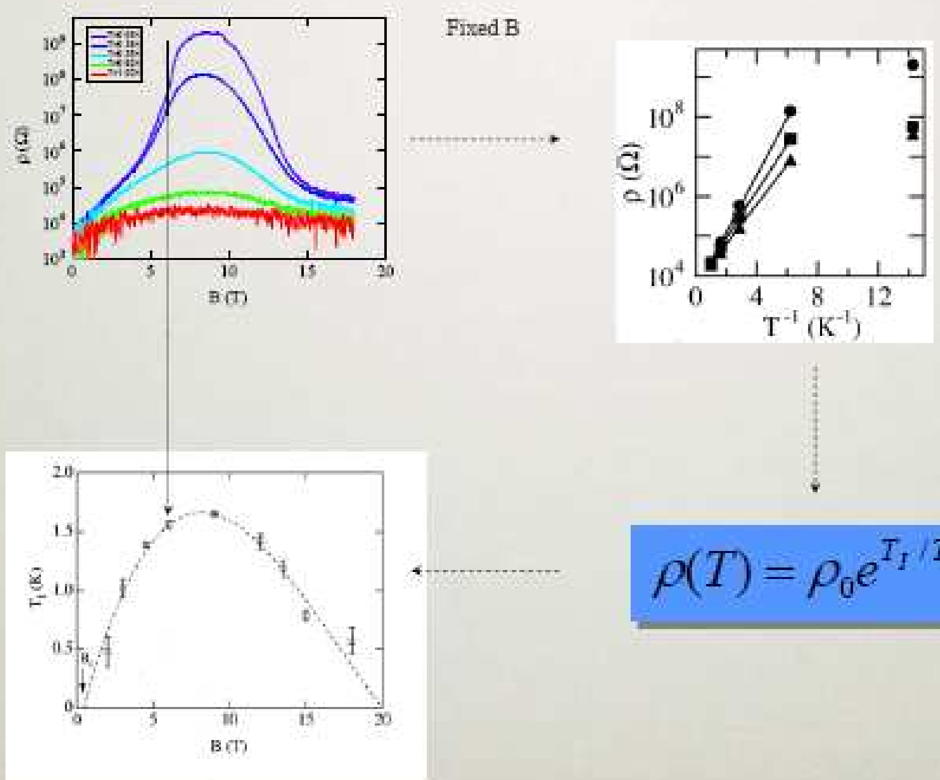
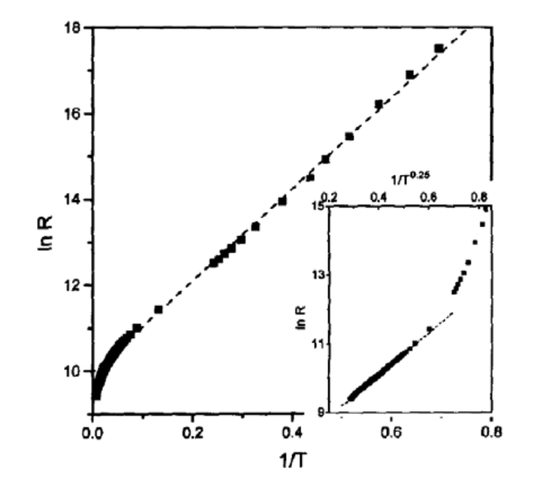
Activated transport near the SIT

Insulating InO_x B-dependence



$$\rho(T) = \rho_0 e^{T_I / T}$$



D. Kowal and Z. Ovadyahu, (1994).

*G. Sambandamurthy, L.W. Engel, A. Johansson, and D. Shahar, PRL **97**, 107005 (2004).*

Activated transport near the SIT

*V. F. Gantmakher, M. V. Golubkov, J. Lok, A. K. Geim, Sov. Phys. JETP, **82**, 951 (1996).*

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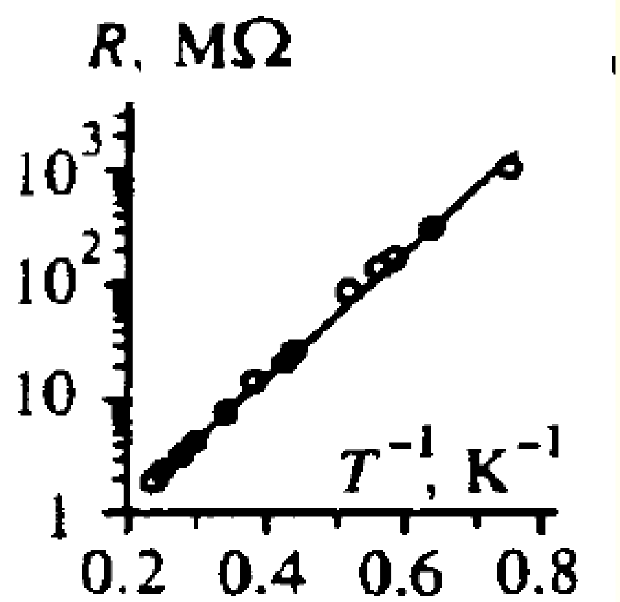

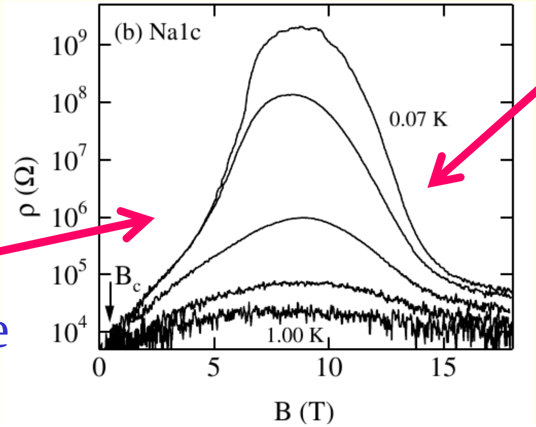

Competing mechanisms:
SC suppressed ↔
Single e's easier to liberate

Simpler to understand (simple activation with tendency to VRH)

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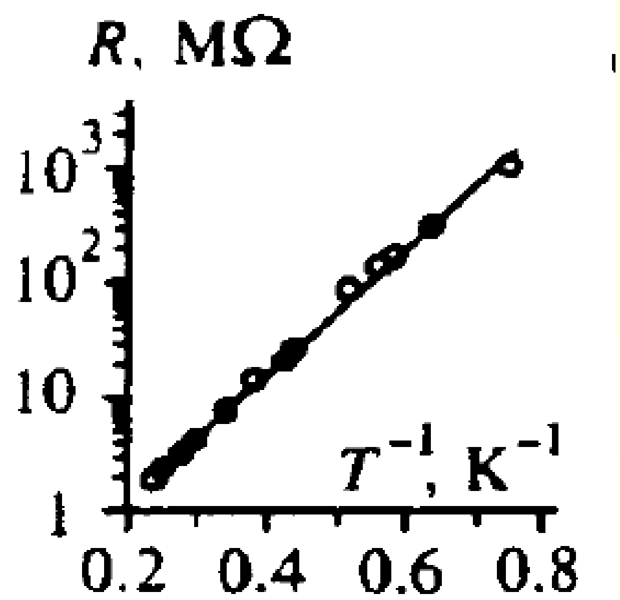

Origin of simple activation?

- Gap in the DOS
- Or: mobility edge

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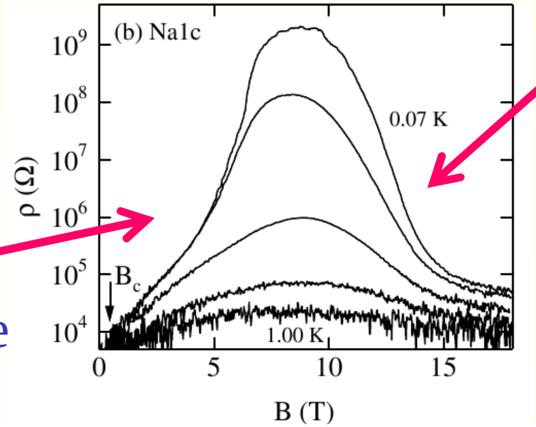

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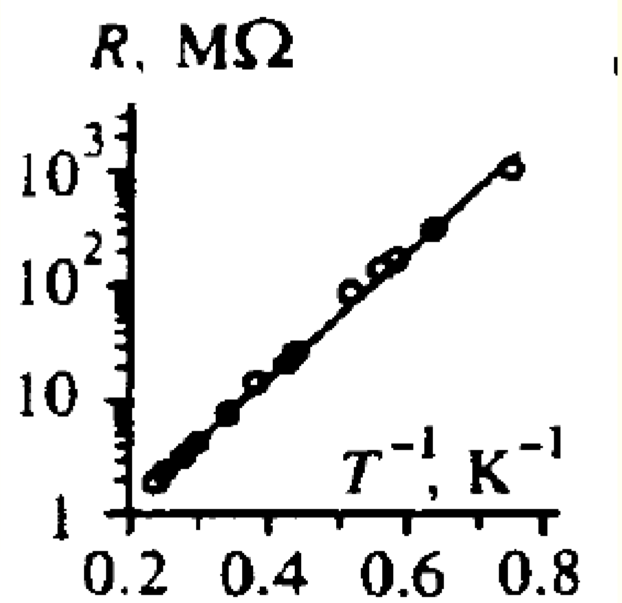

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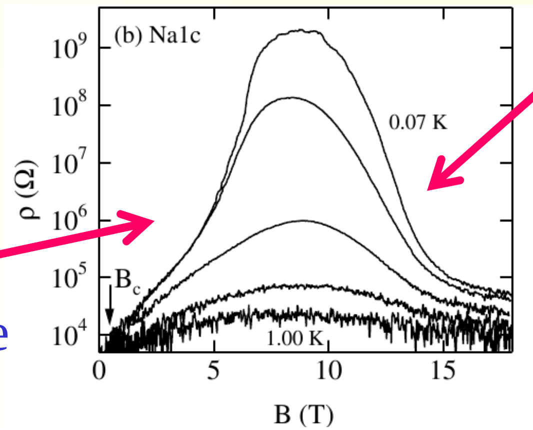

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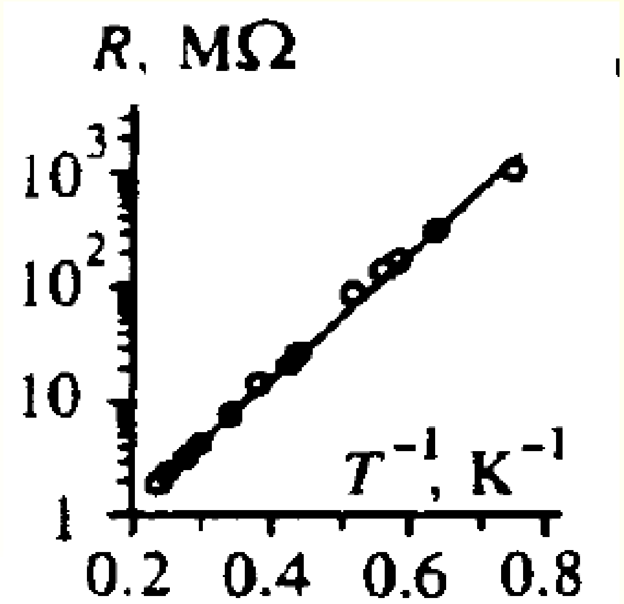
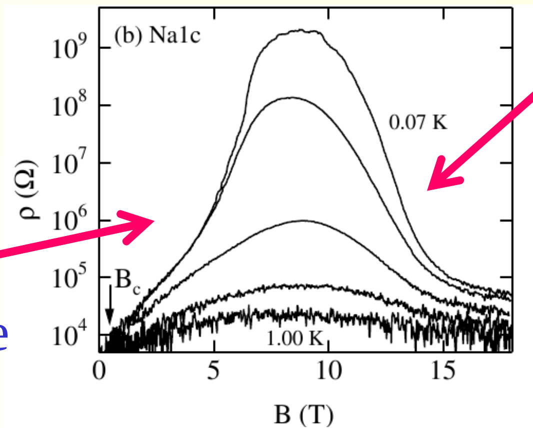


Origin of simple activation?

- ~~Gap in the DOS~~
- Or: mobility edge

- Electrons or pairs?
- Nearest neighbor hopping?
- Why no variable range hopping?

Competing mechanisms:
SC suppressed ↔
Single e's easier to liberate



Simpler to understand (simple activation with tendency to VRH)

Remark on high field behavior

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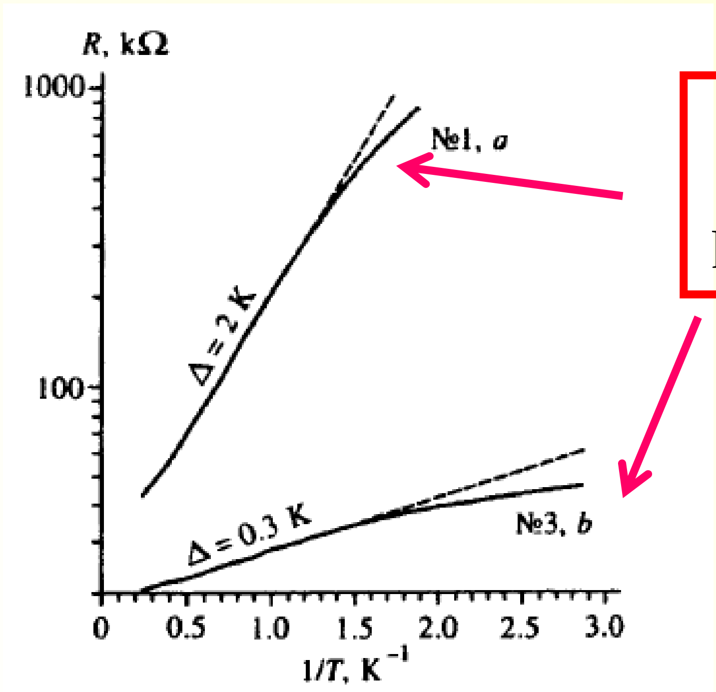
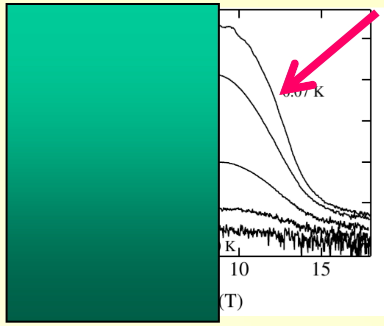


Tendency to subactivation at high B fields, low T



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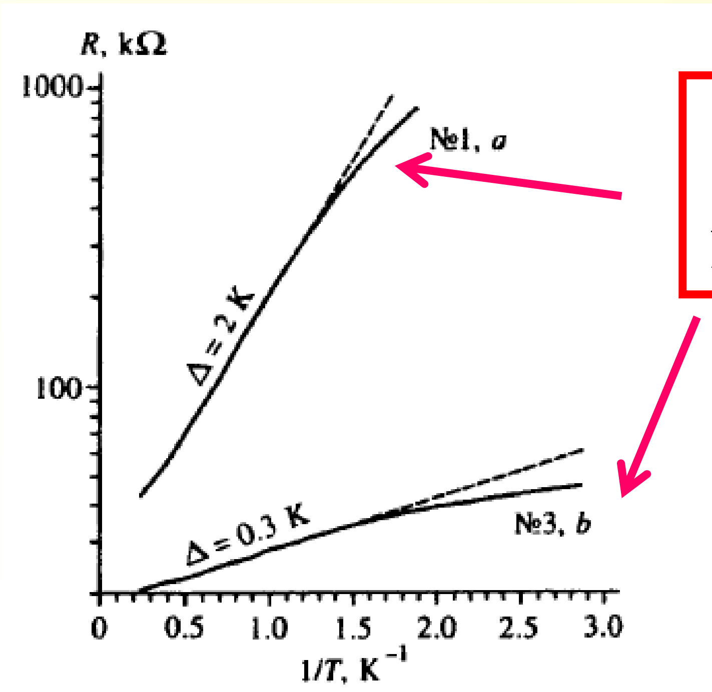

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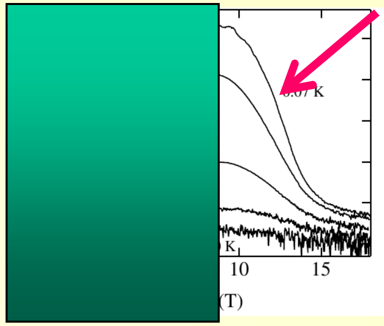
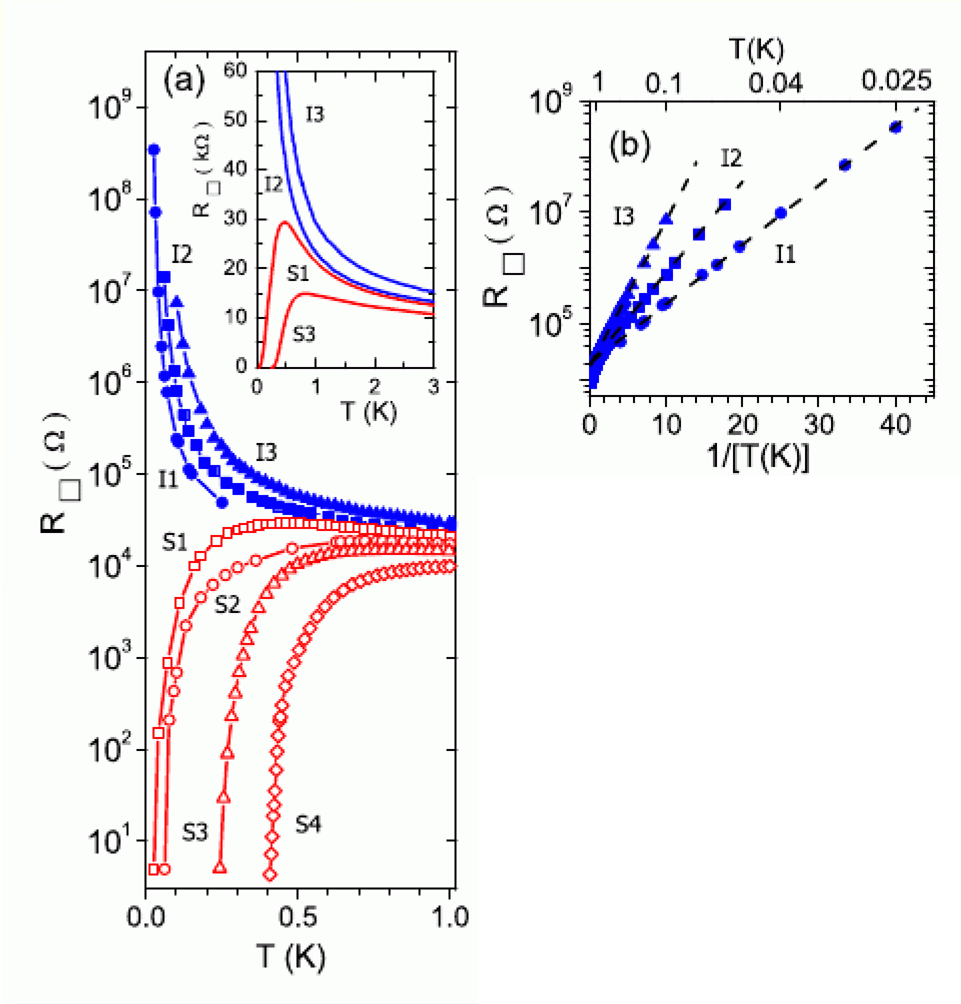


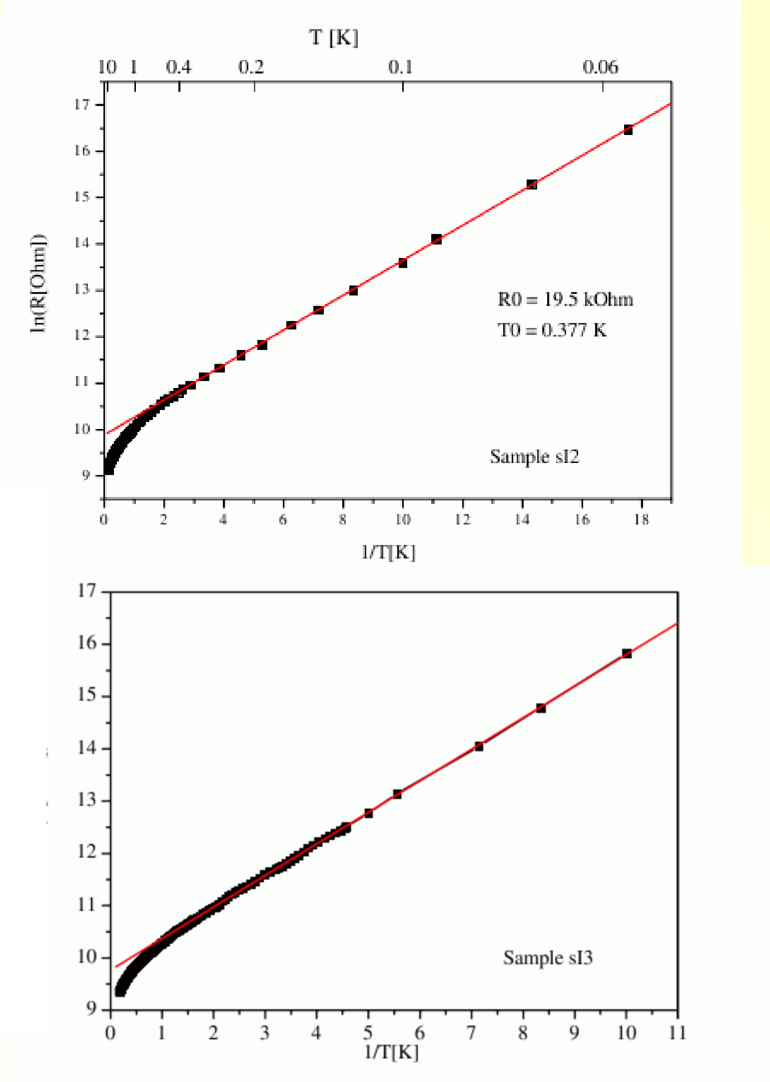
Most likely interpretation:
Single electron transport:
Bottle neck: depairing e's from pairs
(possibly paired in fractal wavefunctions, *Feigelman, Ioffe, Kravtsov Yuzbashyan*)
+ variable range hopping of single e's

Activated transport near the SIT

Insulating TiN

T. I. Baturina et al., PRL ***99****, 257003 (2007)*





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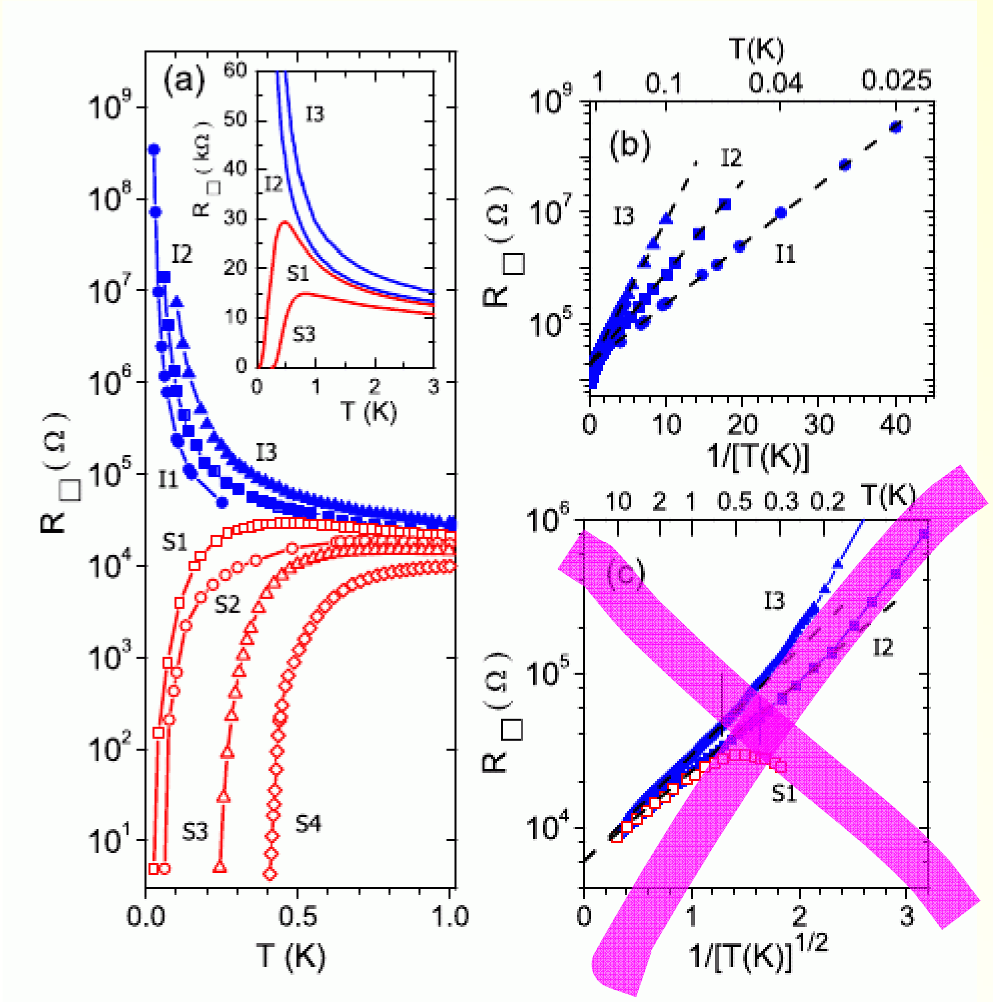

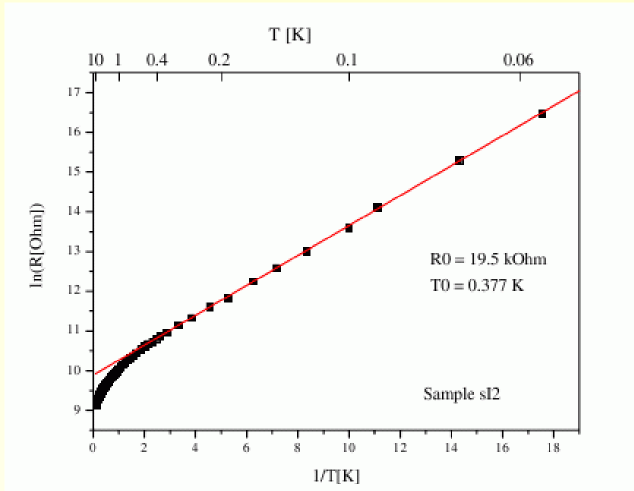

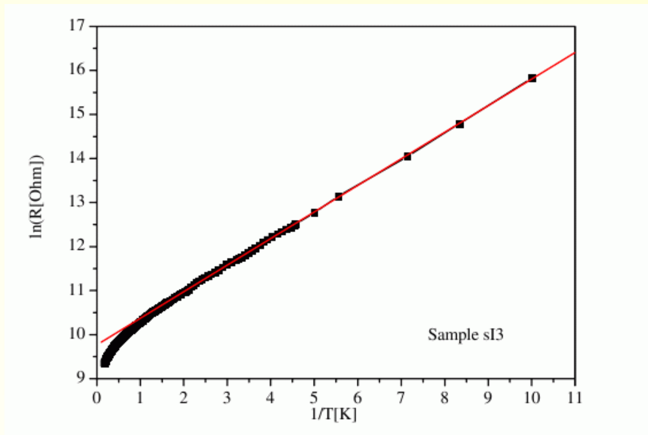

Summary

1. Close to SIT the transport is essentially simply activated

Why?

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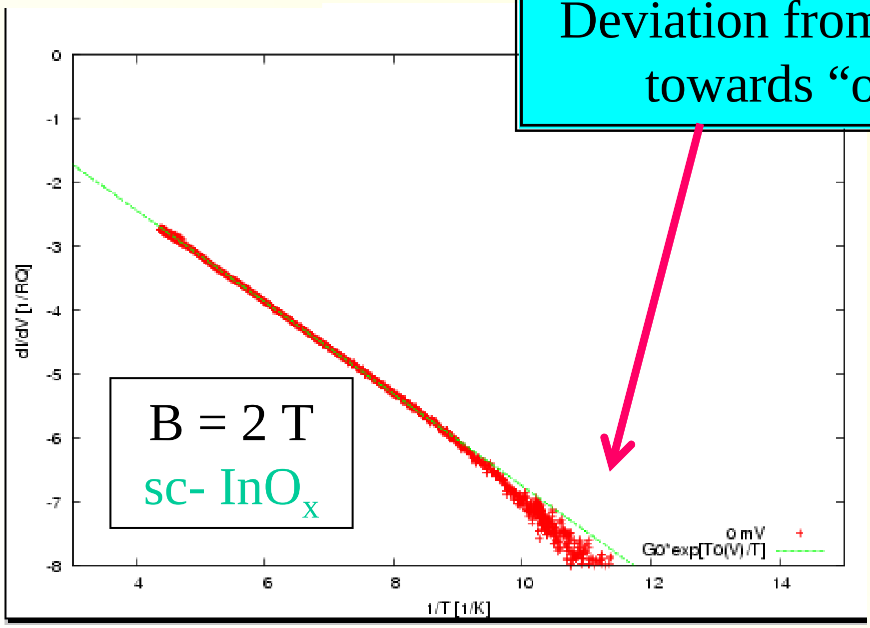
2. Beyond the MR peak transport becomes subactivated at low enough T

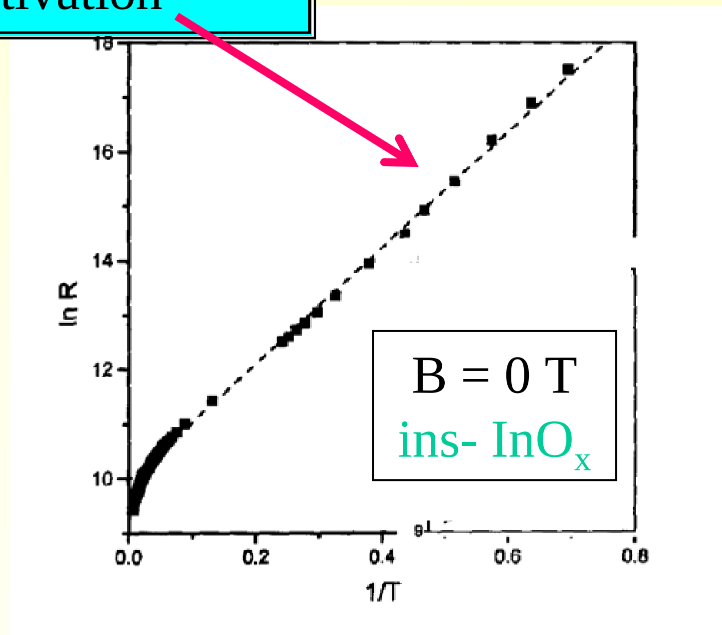
But this is not the whole story yet!

Trend to overactivation

G. Sambandamurthy, L.W. Engel, A. Johansson, and D. Shahar, PRL ***97****, 107005 (2004).*

Deviation from simple activation towards "overactivation"





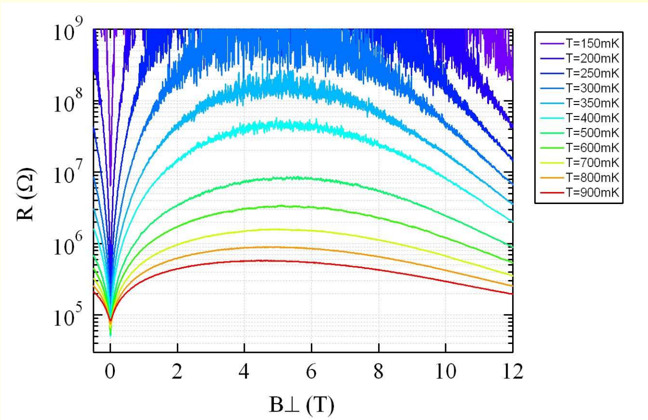
D. Kowal and Z. Ovadyahu, Sol. St. Comm. ***90****, 783 (1994).*

Trend to overactivation close to SIT

ins- InO_x

B. Sacépé et al. (unpublished - 2008).

Magnetoresistance
(isotherms)



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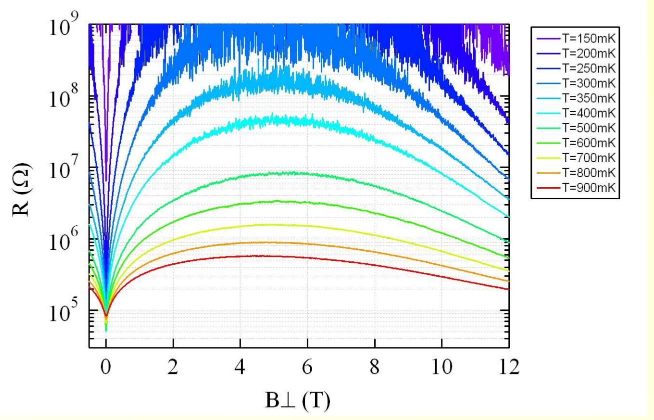
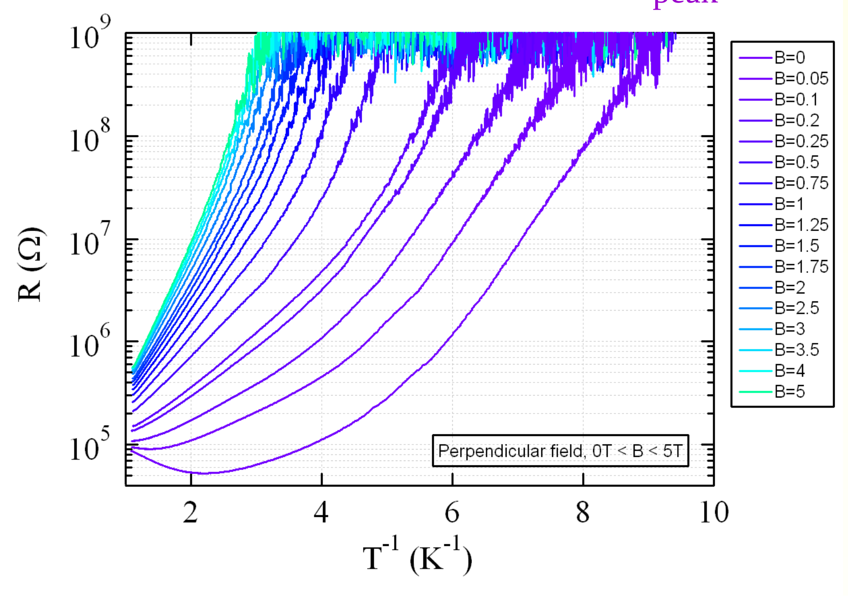


Resistance at fixed $B < B_{peak}$



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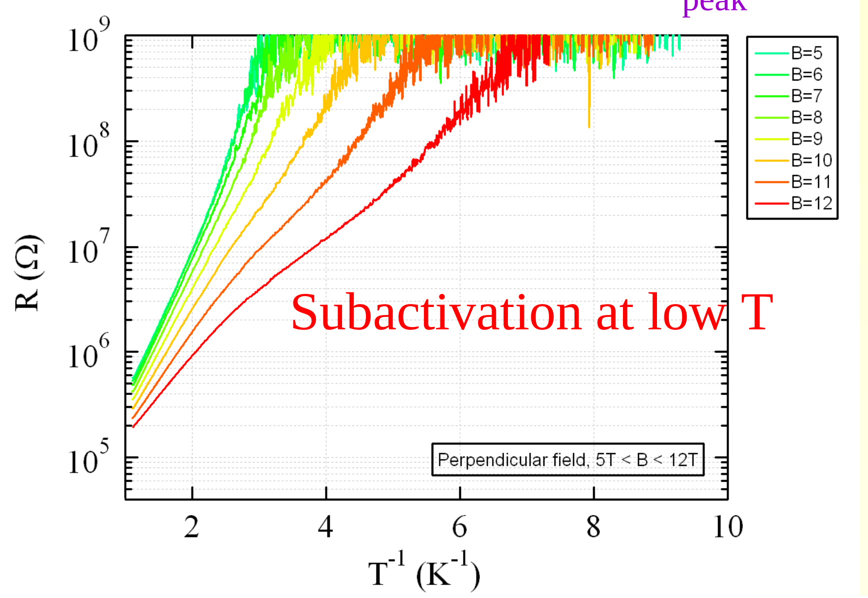

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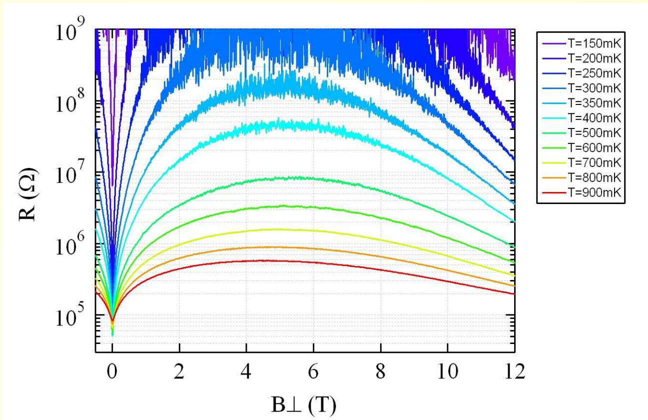

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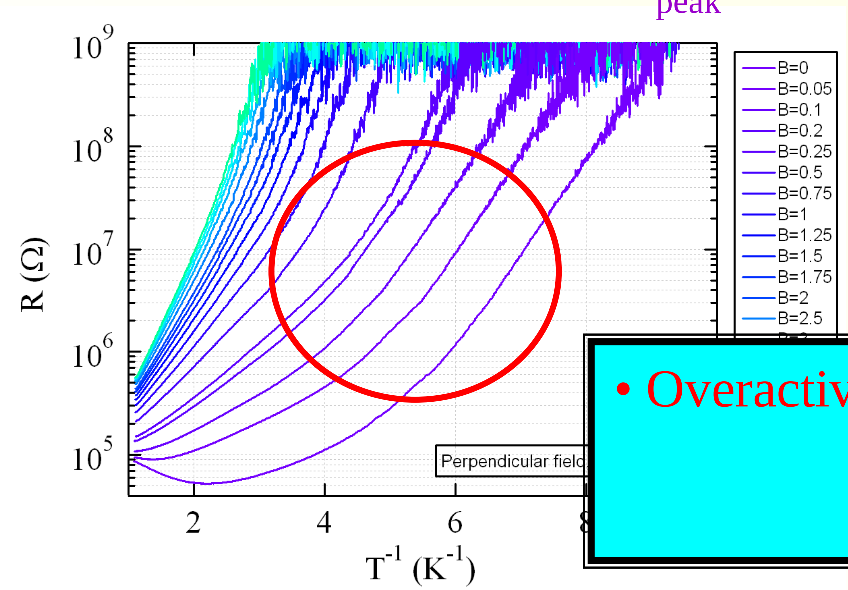

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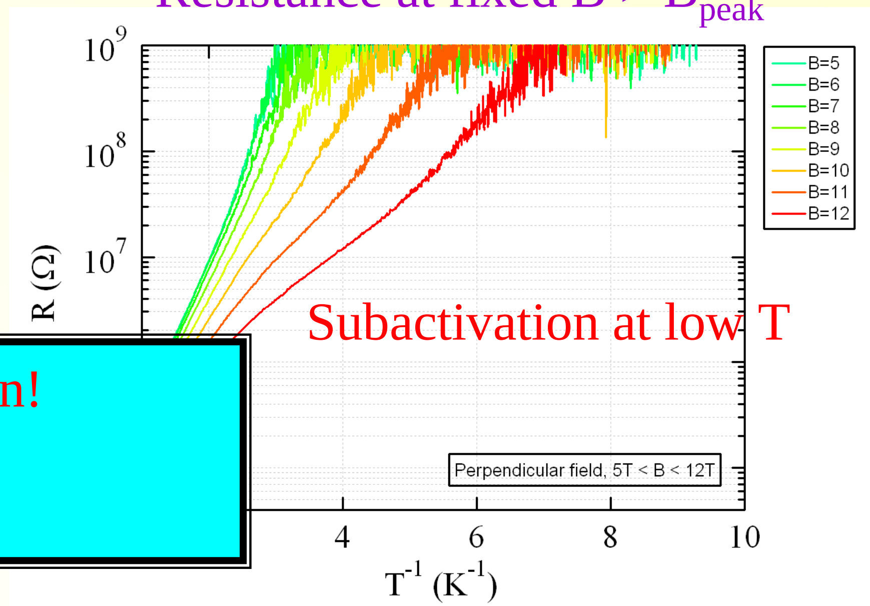

Subactivation at low T

- Overactivation!

Trend to overactivation close to SIT

ins- InO_x

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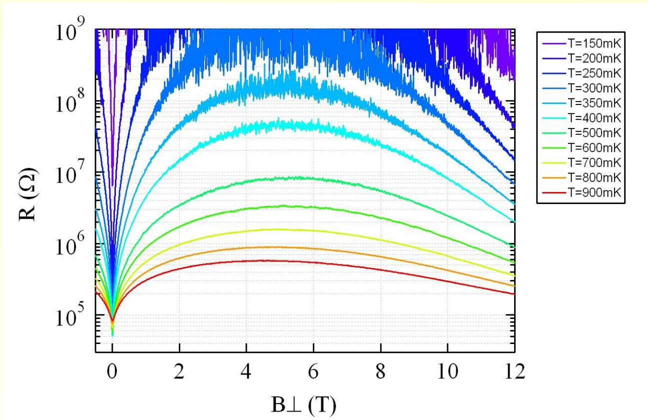
Magnetoresistance
(isotherms)



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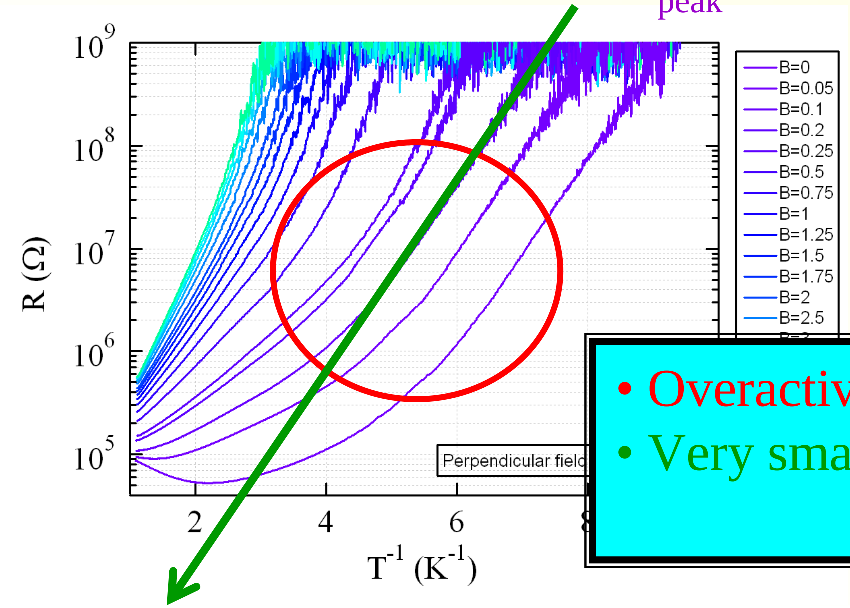

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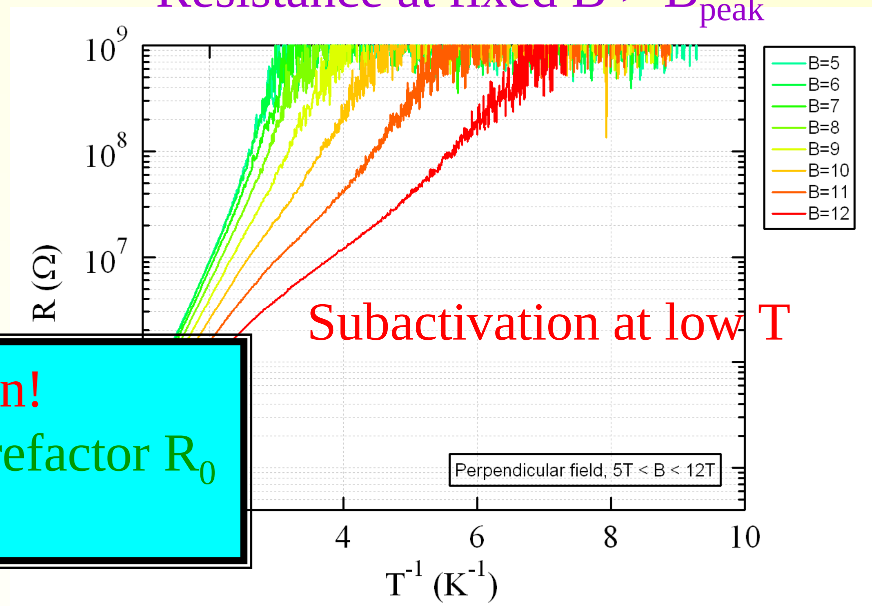


Subactivation at low T

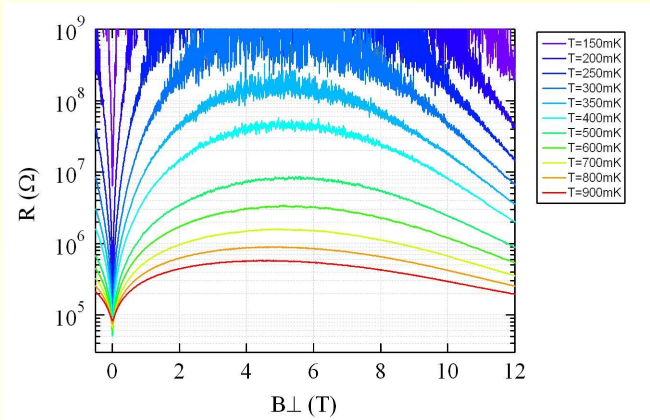
- Overactivation!
- Very small prefactor R_0

Trend to overactivation close to SIT

ins- InO_x

B. Sacépé et al. (unpublished - 2008).

Magnetoresistance (isotherms)



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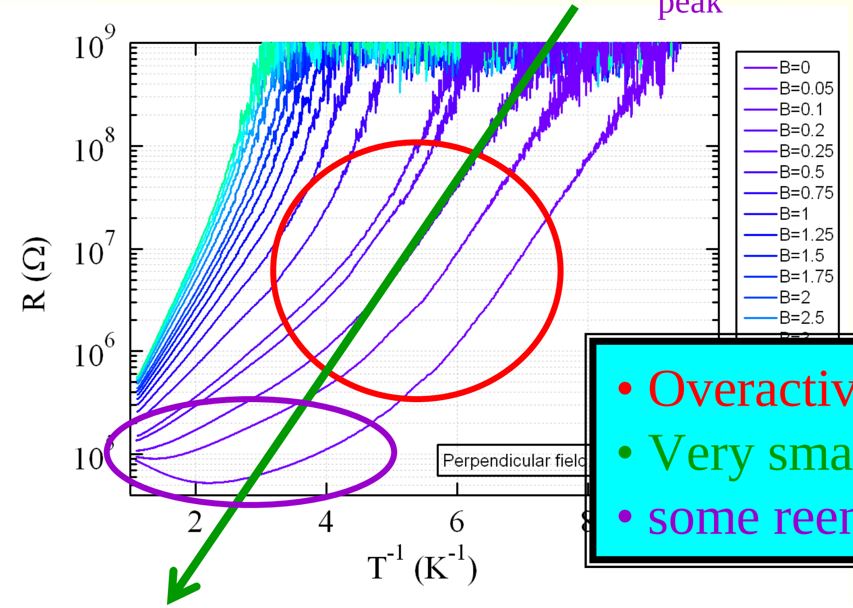
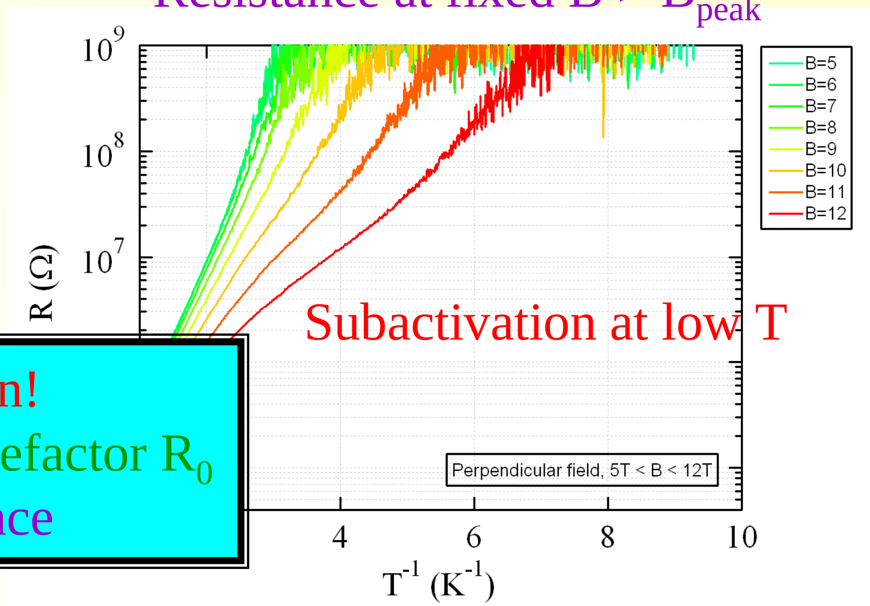


Resistance at fixed $B > B_{peak}$



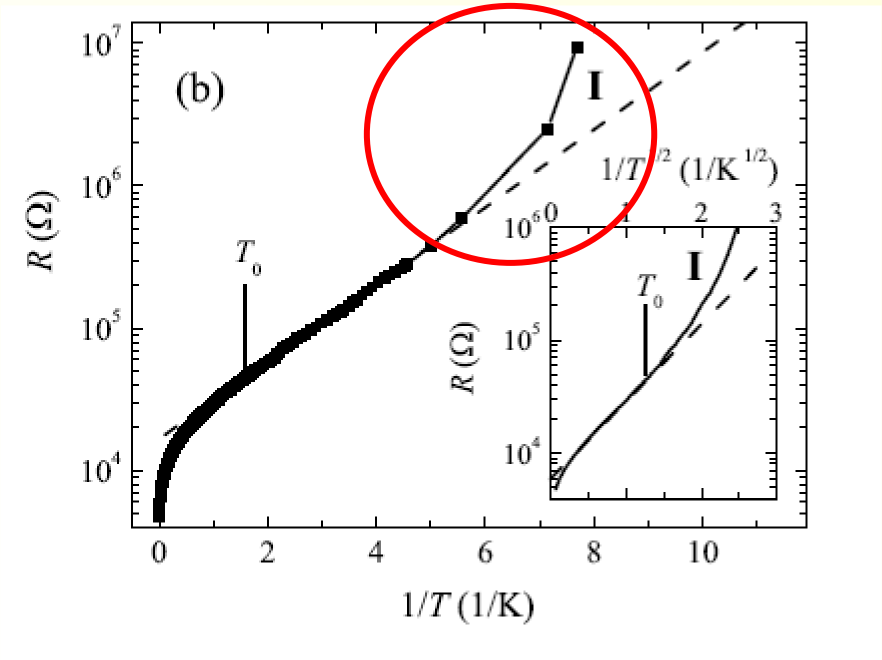
Subactivation at low T

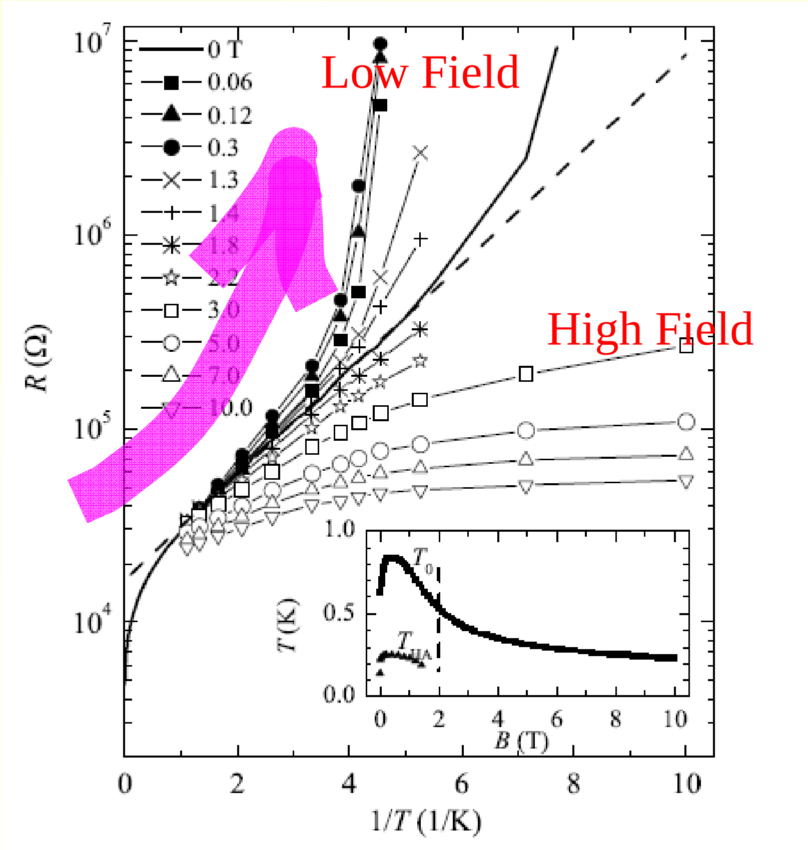
- Overactivation!
- Very small prefactor R_0
- some reentrance

Trend to overactivation close to SIT

T. Baturina et al. (condmat 0810.4351).

sc- TiN





Summary II

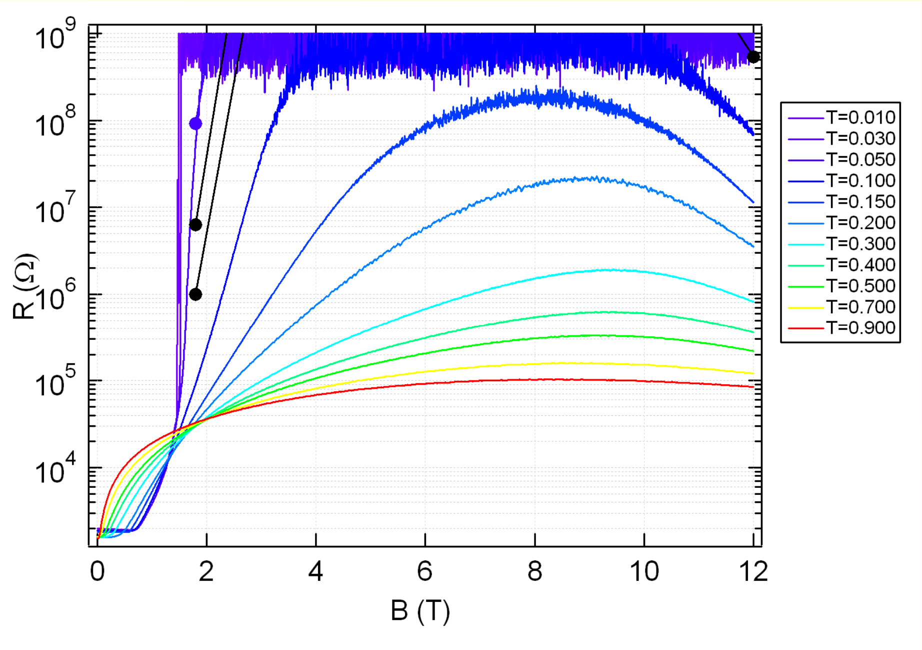
- Transport is simply activated at low T over several orders of magnitude

- There is a tendency to

  - overactivation close to the SIT
  (saturating to simple activation at low T)
  This is very unusual in a disordered system!

  - subactivation beyond the MR peak (at lowest T)

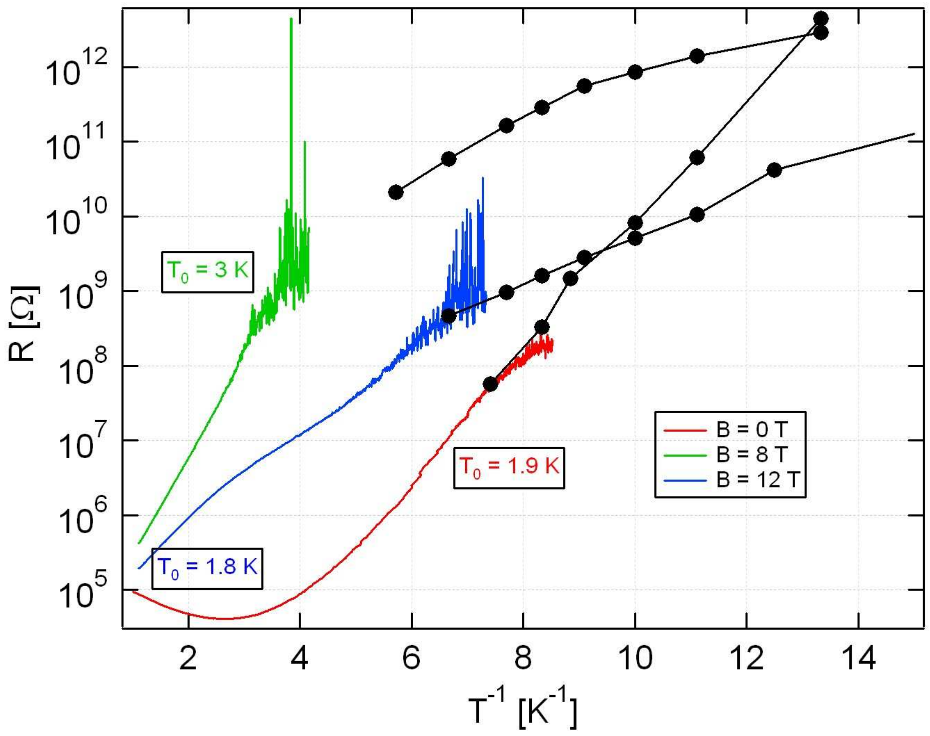
Magnetoresistance near the SIT



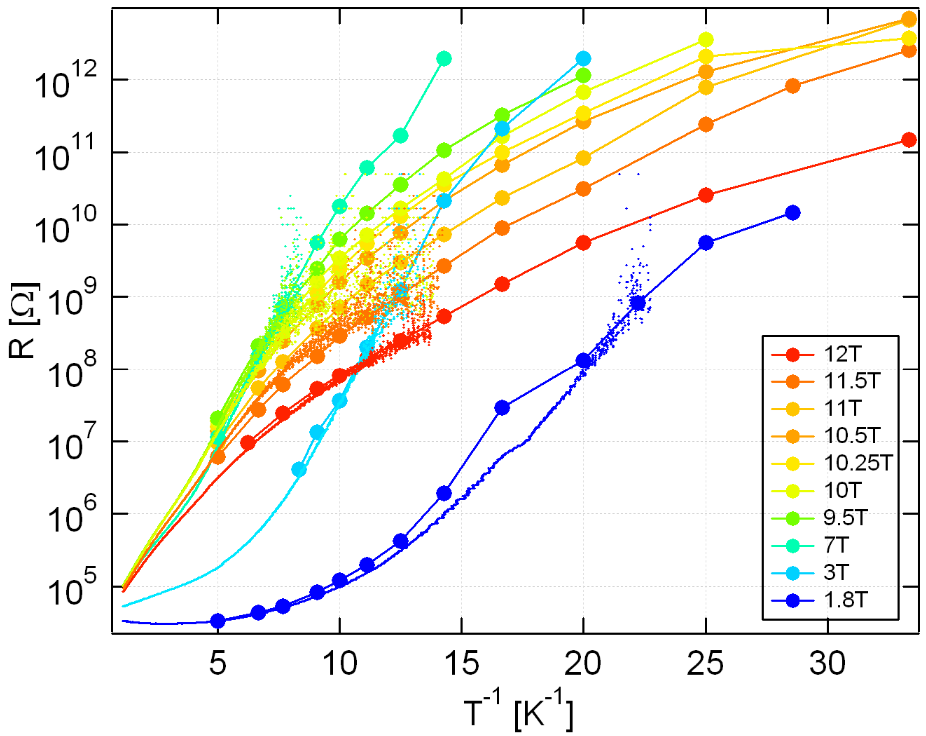
Magnetoresistance near the SIT

(B perpendicular)

InO-I

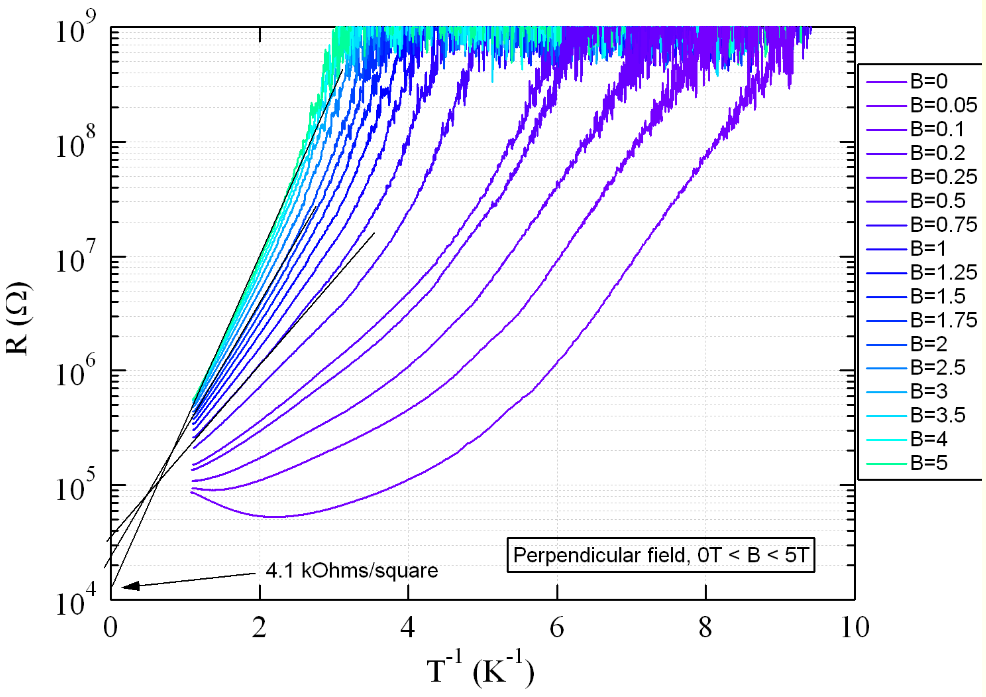


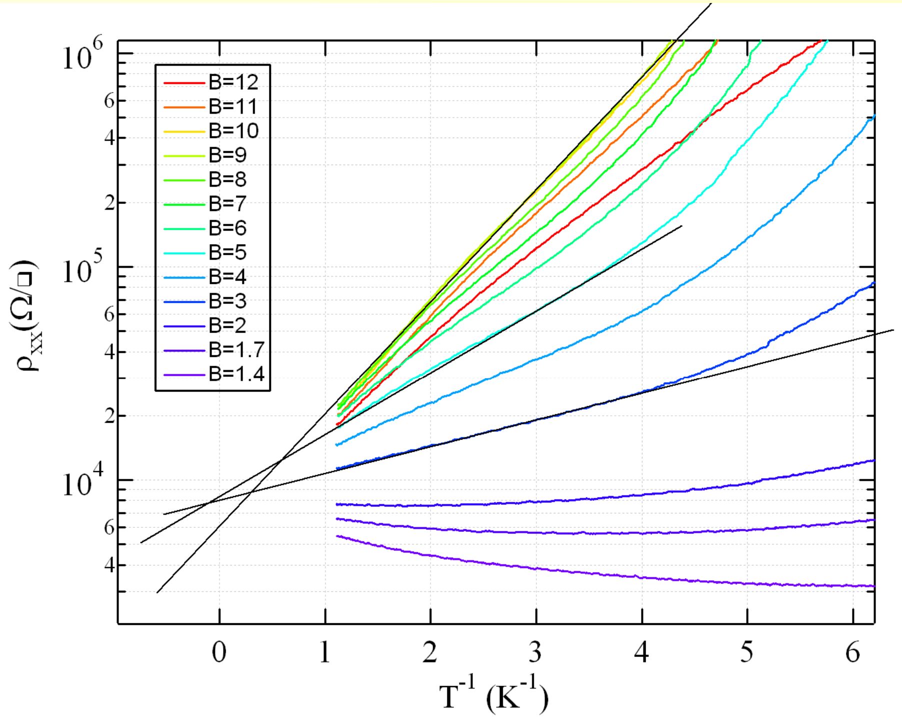
InO-S



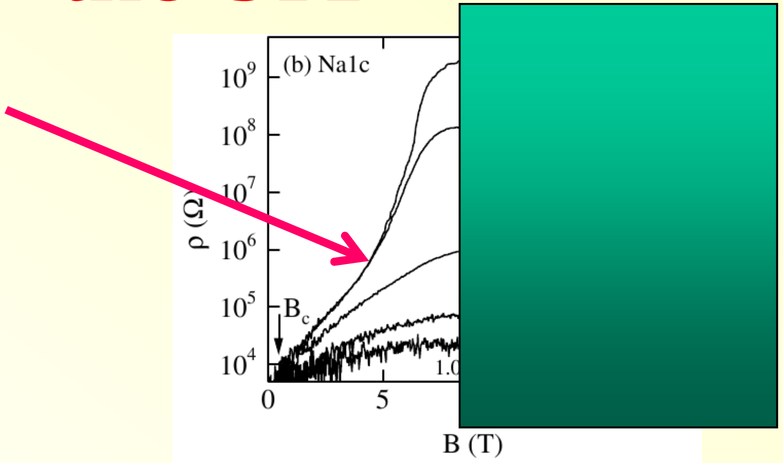
Arrhenius behaviour « seems » to hold at low field (< MR peak)

Magnetoresistance near the SIT



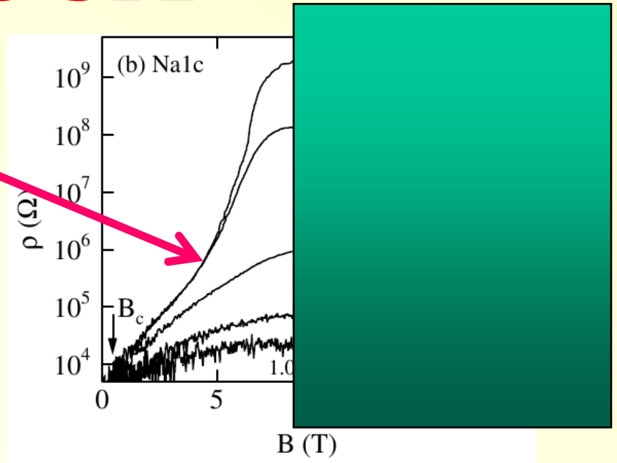


Transport must be by pairs close to the SIT



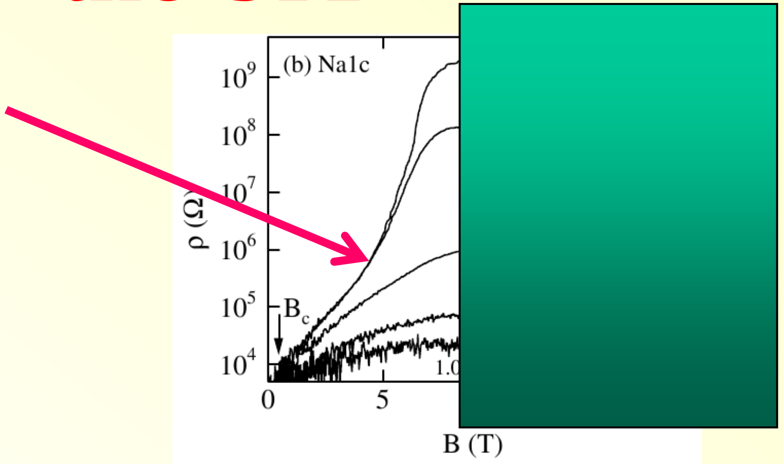
1. B↑ → Pairs are less delocalized → positive MR

Transport must be by pairs close to the SIT



1. B↑ → Pairs are less delocalized → positive MR
2. If transport were carried by electrons, MR would be negative: it becomes easier to depair electrons at higher fields.

Transport must be by pairs close to the SIT



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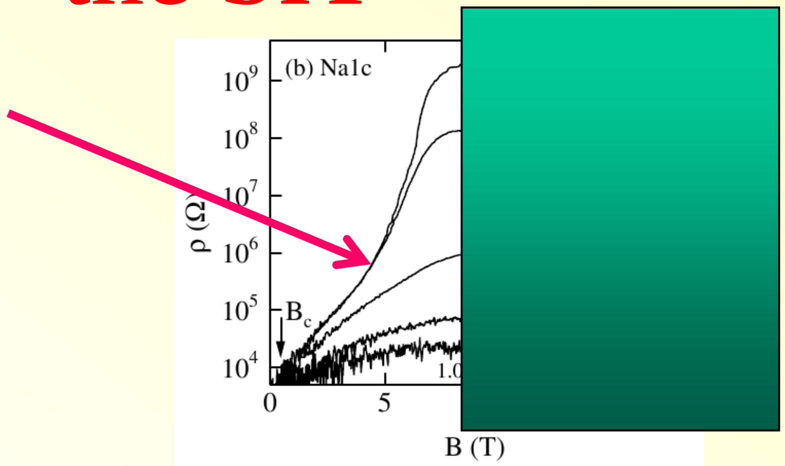

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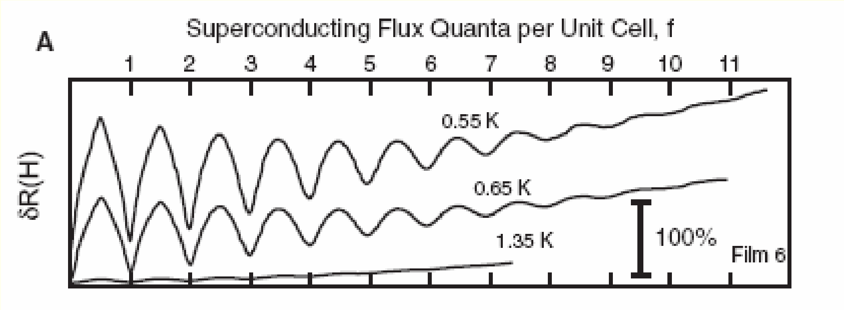
Magnetoresistance in a film
with a regular array of holes
Period $\Phi_0/2$ → pair transport!



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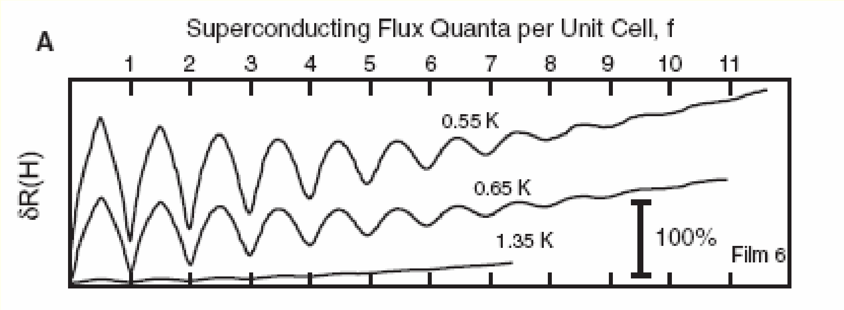

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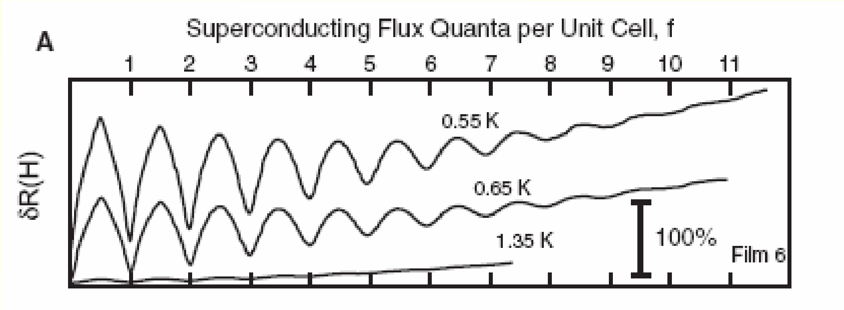

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• Why? Pairs survive in the insulator! (Pairing in time-reversed localized wavefunctions (Anderson 1956, Feigelman et al.) – as suggested by STM).
• As long as $E_{act} < E_{bind}$ it does not pay to depair electrons at lowest T.

Scenarios for simple activation in the positive MR regime

? ?

A. Global charge gap?
- effectively granular material?
- Wigner crystal?

B. Nearest neighbor transport?

If none of the above applies:
C. Why is variable range hopping not observed?

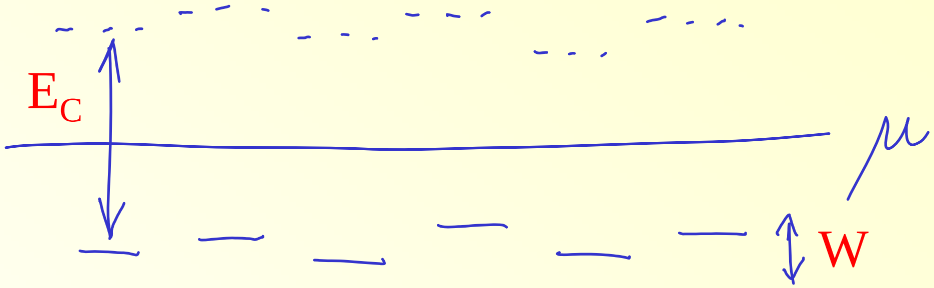
$\rightarrow$ Proposal: Activation to the pair mobility edge

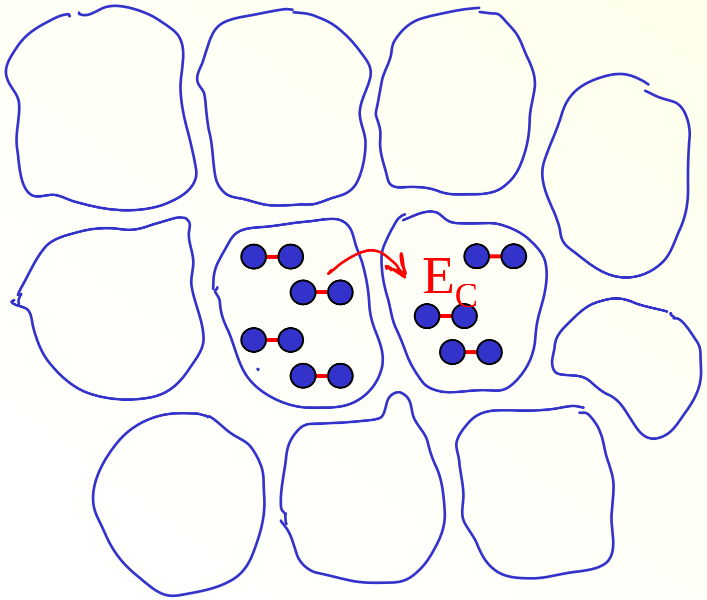
Scenarii for simple activation:
A. Global charge gap I

Vinokur et al. (2007/2008):

Postulates:

- I. Effective granularity:
  Superconducting puddles with low transparency tunnel junctions.
- II.Weak disorder $W < E_C$





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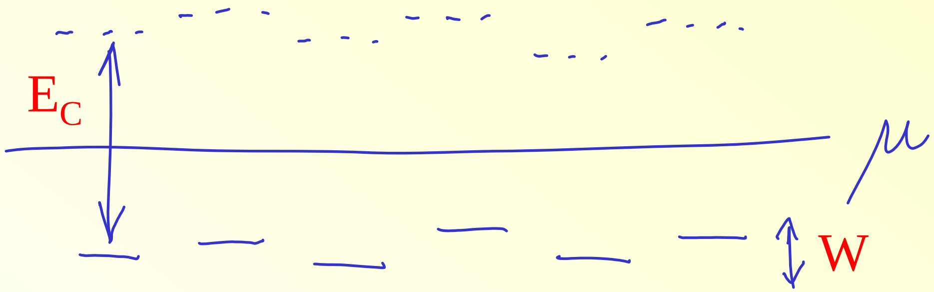

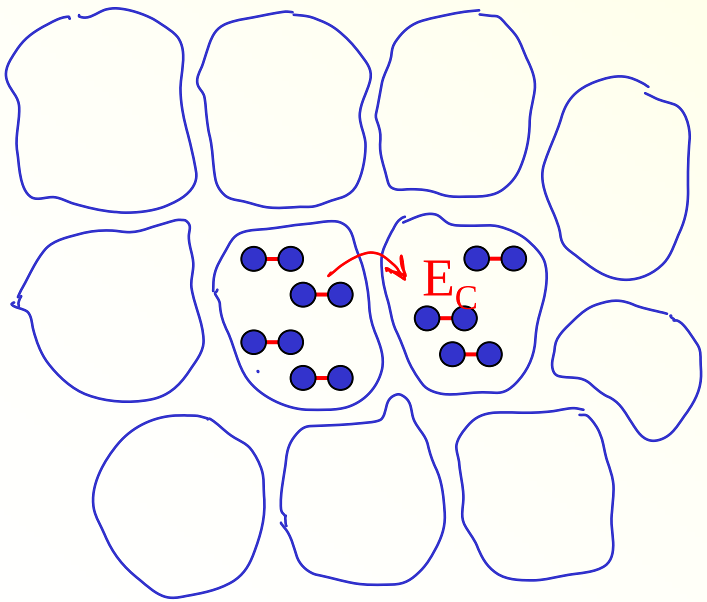

→ Incompressible system
→ Simple activation due to charge gap (Coulomb blockade)

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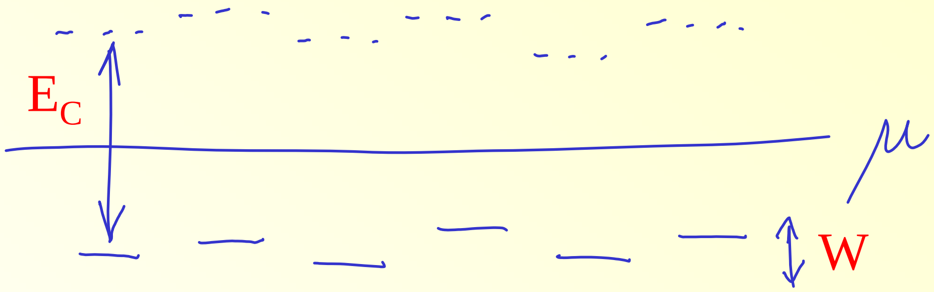

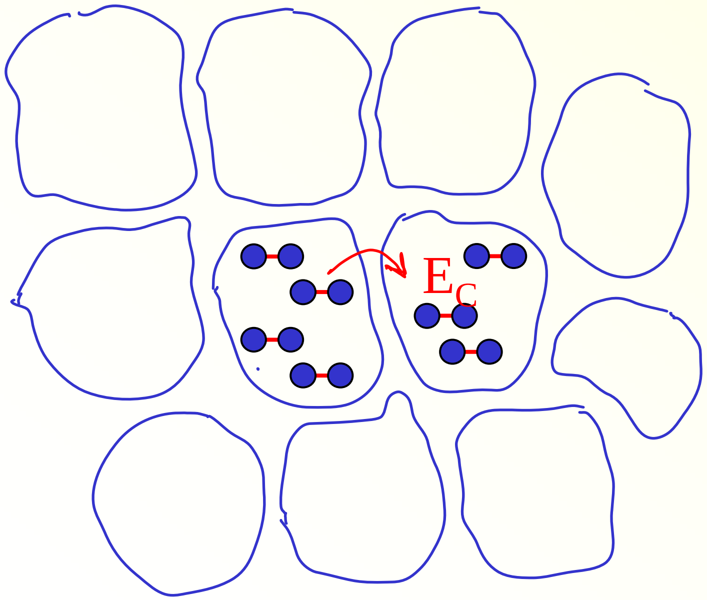

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(I) can occur in strong disorder (MM and B. Shklovskii, 2008), but **(II) is very hard to justify** in the absence of clean physical grains.

Scenarii for simple activation:
A. Global charge gap II

Charged pairs (2e) in a weak background potential (white noise)

Intermediate between

Falco, Nattermann, Pokrovsky (2008) [neutral bosons, white noise]

Müller and Shklovskii (2008) [charged bosons, charged impurities]

$$\frac{\hbar^2}{2m}\nabla^2\psi + (E - U(\mathbf{x}))\,\psi = 0.$$

$$\langle U(\mathbf{x})\,U(\mathbf{x}')\rangle = \kappa^2\delta(\mathbf{x}-\mathbf{x}')$$

$$\mathcal{L} = \frac{\hbar^4}{m^2\kappa^2}, \qquad \mathcal{E} = \frac{\hbar^2}{m\mathcal{L}^2},$$

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e.g., position fractal pseudospins

IF weak disorder/heavy pair masses:

$$\frac{e^2}{\kappa L} > \mathcal{E} \iff L > a_B$$

→

Charge correlated state
(distorted pair Wigner crystal)
at low enough density:

$$n a_B^3 < 1 \qquad a_B = \frac{\hbar^2 \kappa}{m e^2}$$

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Compare to standard Mott insulator:

Transport properties of an organic Mott insulator β'-$(BEDT\text{-}TTF)_2ICl_2$

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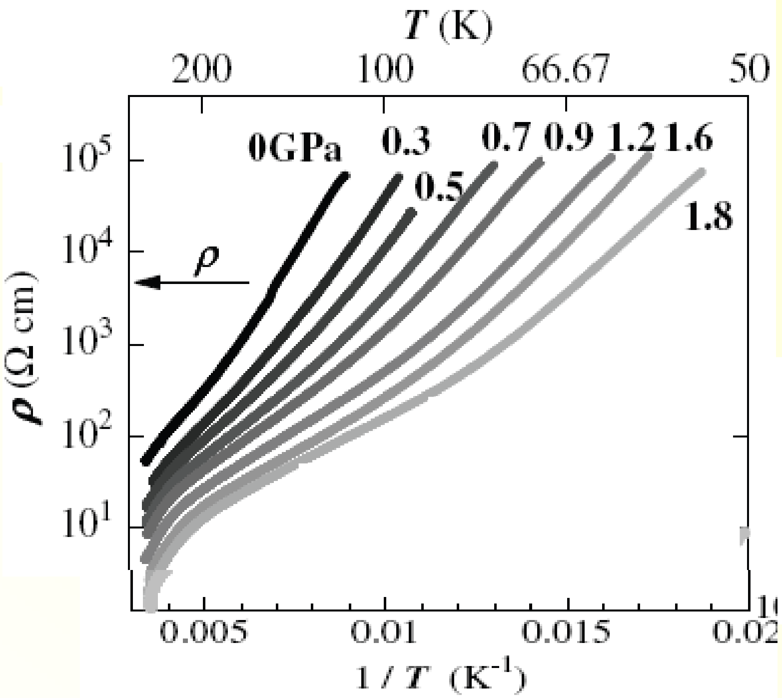
EPL, 83 (2008) 27008



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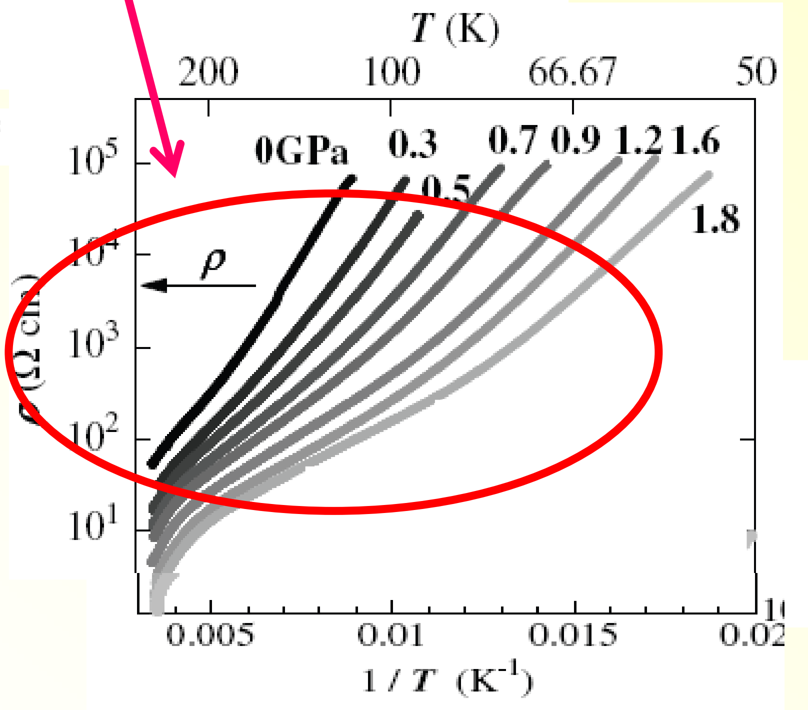


Partial conclusion:

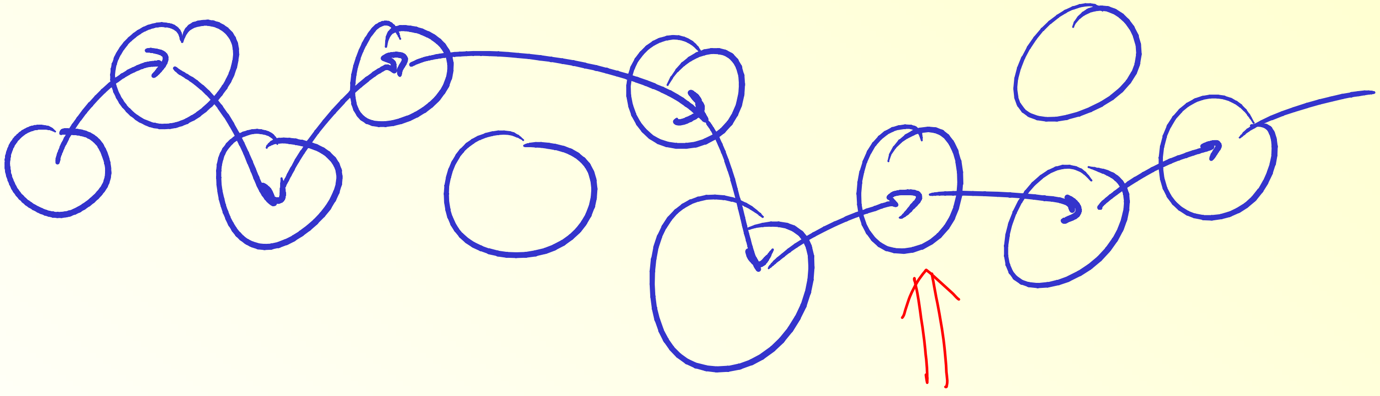
• Global charge gap (incompressibility) seems very unlikely in a non-granular film

• It would require very weak effective disorder

• Should in principle be detectable by pinning frequency of vibration modes of the charge ordered structure (Wigner crystal)

Scenario B: nearest neighbor hopping?

Hopping from puddle to puddle (in strong disorder):



Weakest link (highest barrier along the path)
Determines activation energy

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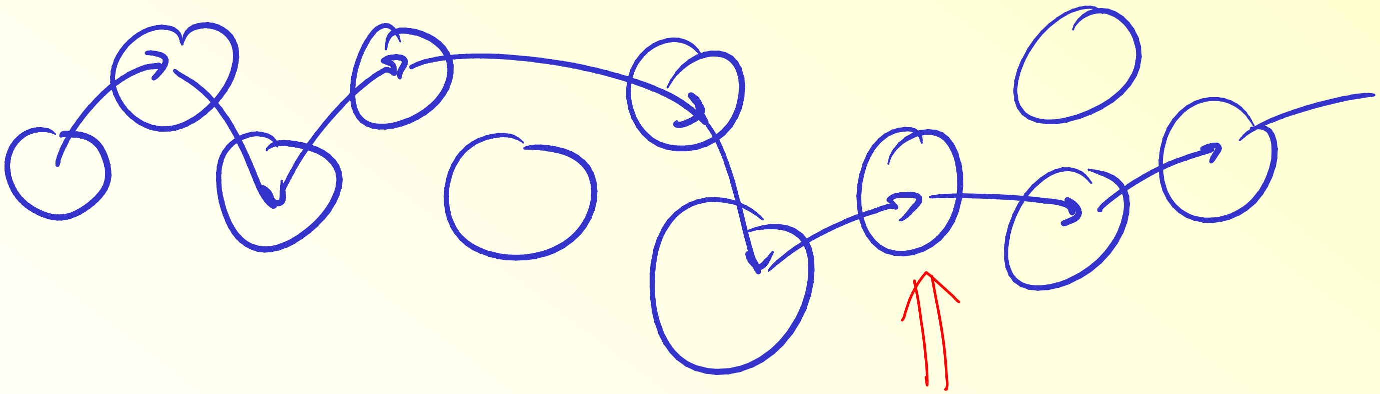

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This ONLY gives simple activation in an appreciable T-window if puddle-puddle resistance is very high, otherwise one obtains VRH!

$$R = R_0 \exp\left[T_0/T\right] \quad \text{with} \quad R_0 >> h/e^2$$

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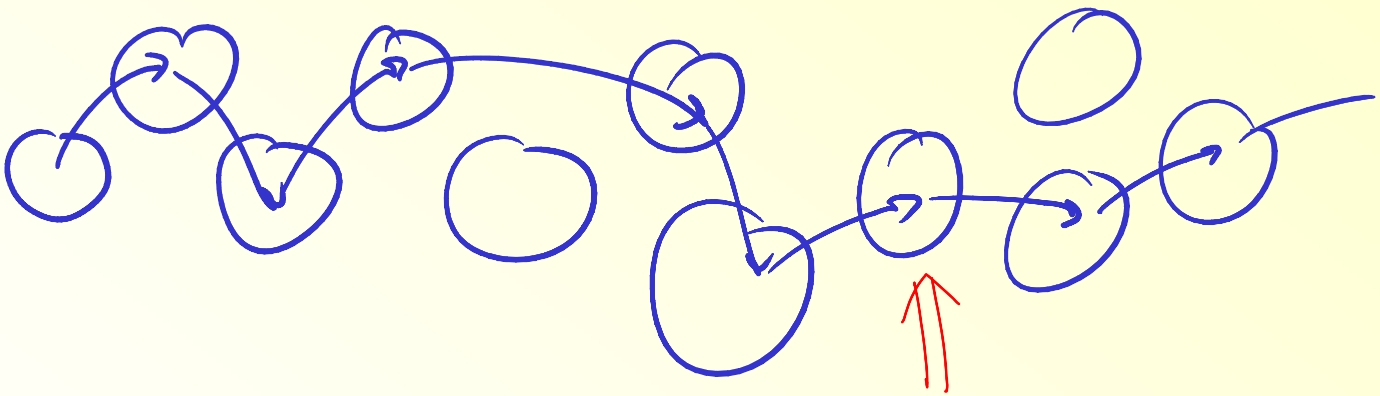

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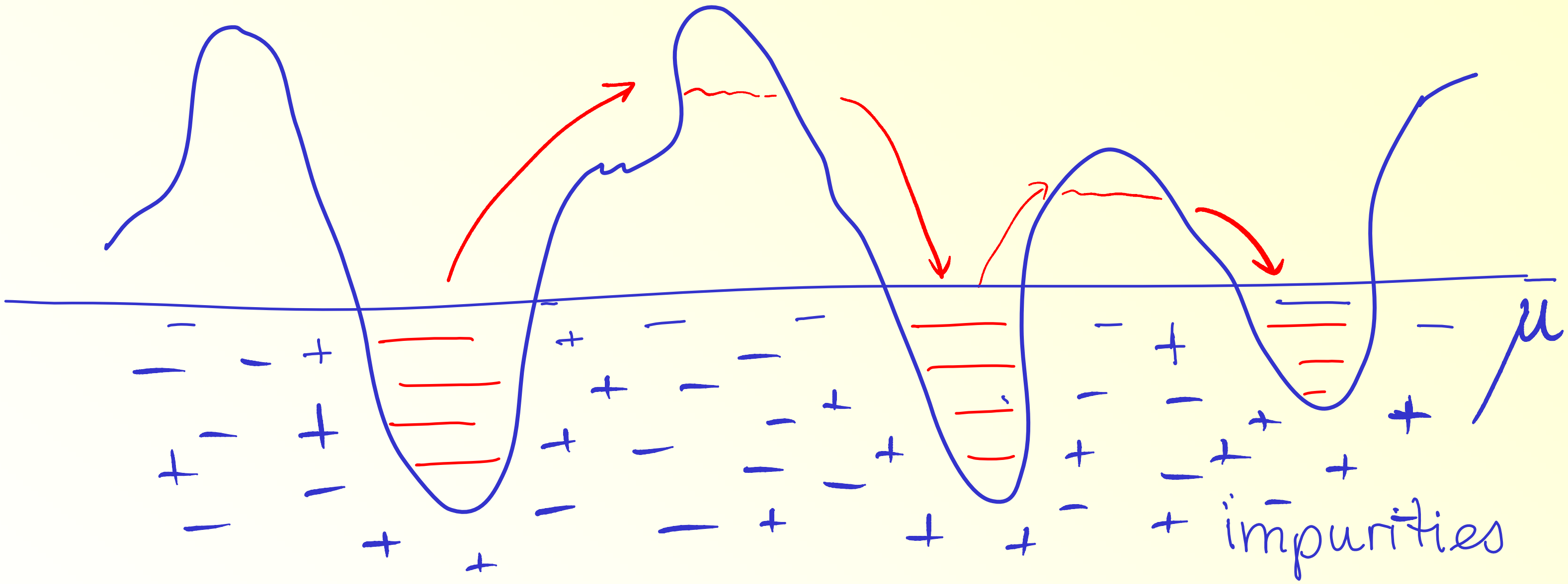
C. Hopping between droplets

High T:



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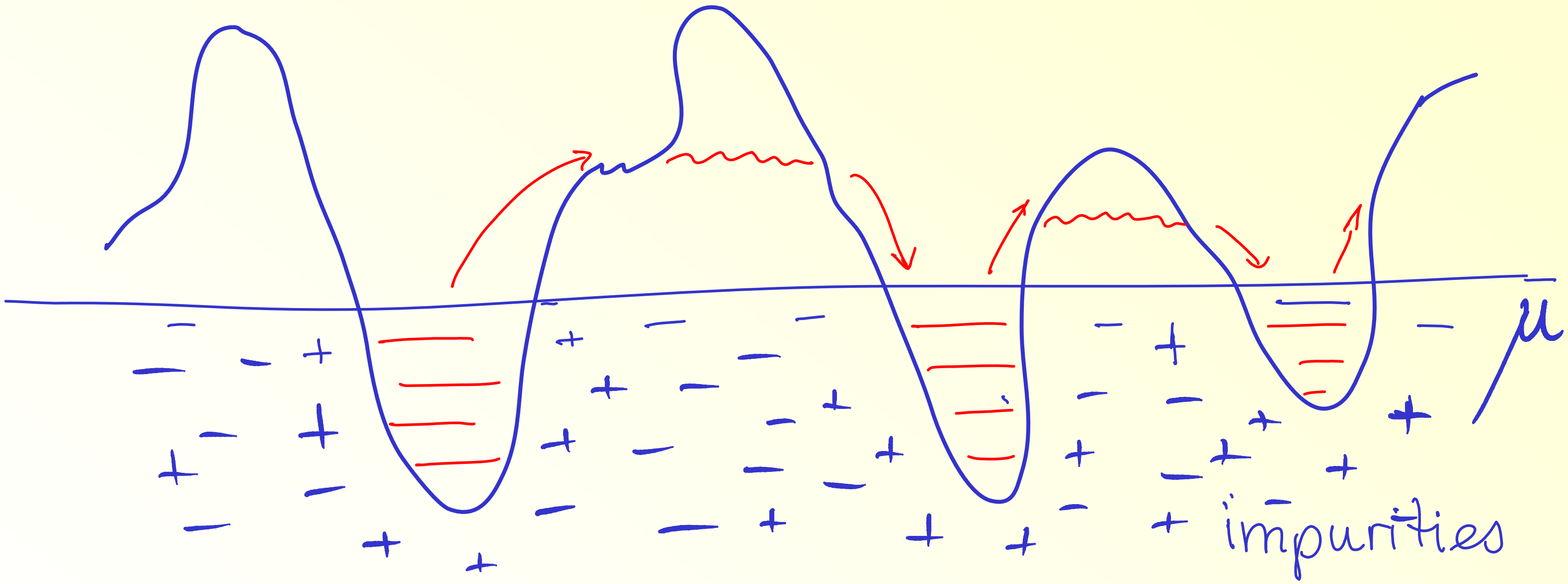

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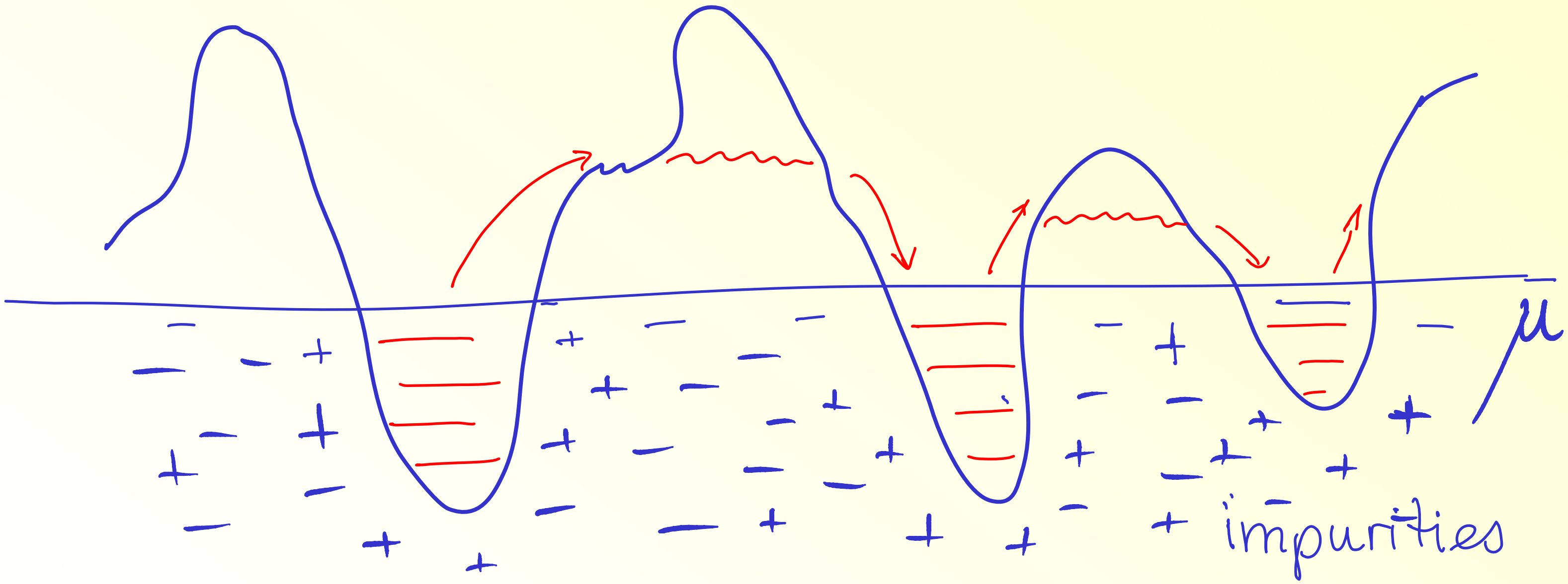


Activation + Tunneling

$\Rightarrow E_{act}(T) \downarrow$ as $T \downarrow$

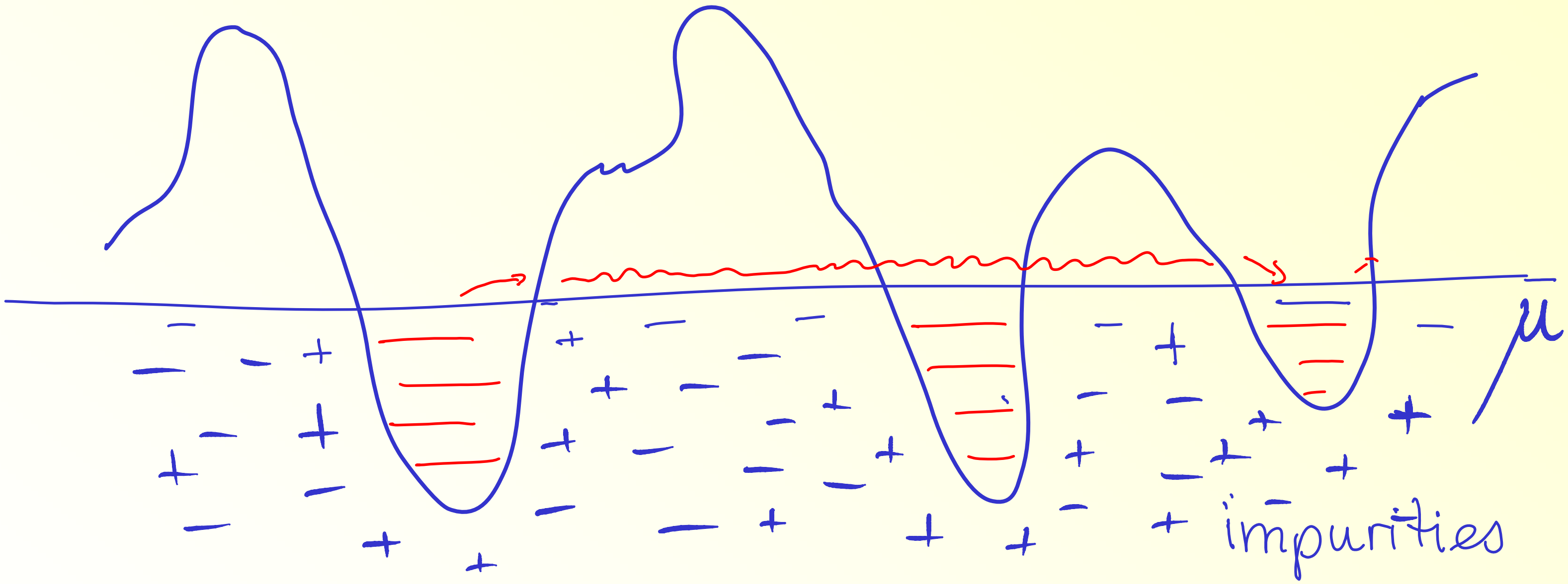
$$E_{act} = E_c - AT^{-2/3}$$

$\Rightarrow$ Subactivation !

(Shklovskii 1973)

C. Hopping between droplets

Lowest T: Variable range hopping



Activation + Tunneling

$$R = R_0 \exp\left[\left(T_0/T\right)^{\gamma}\right] \qquad \gamma \approx \frac{1}{2} \quad (= 5/11)$$

Subactivation !

(Shklovskii 1973)

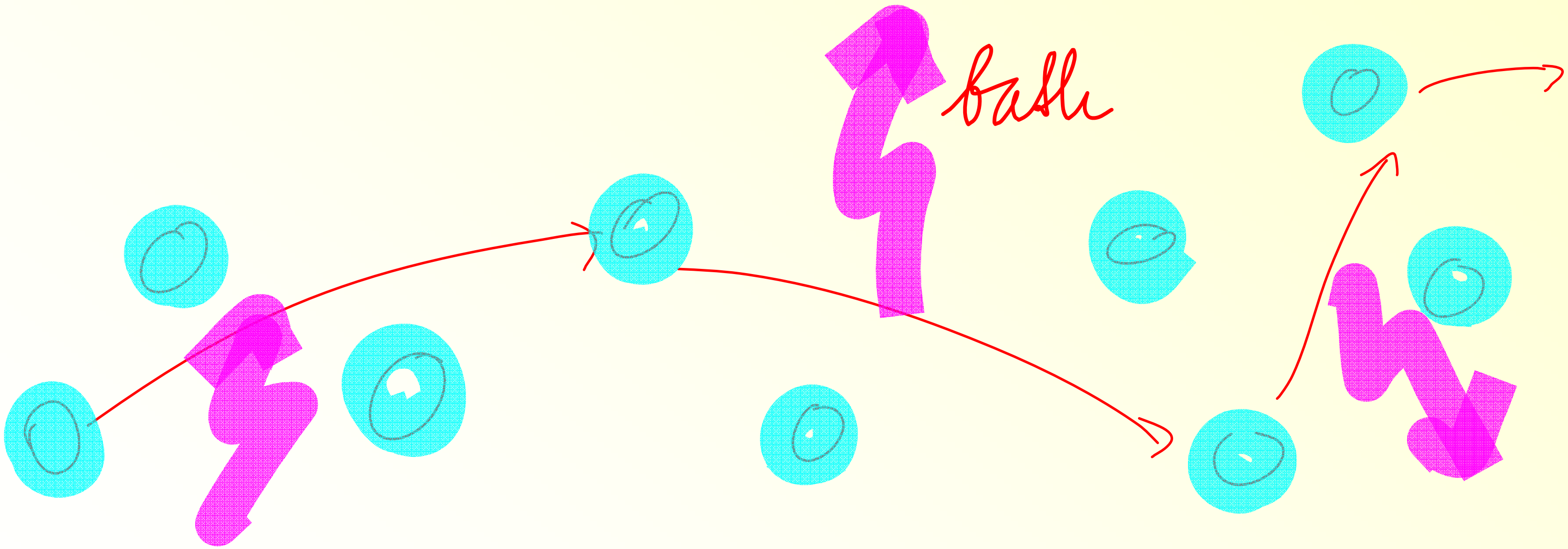
D. Activation to mobility edge –

No variable range hopping, but overactivation instead ? !

- Review of essentials of VRH
- Necessity of a continuous bath!
- Argue that there is NO BATH: get simple and over-activation!

? How to understand that variable range hopping is not seen, but instead overactivation? ?

Essential ingredient into VRH:
Continuous bath which activates the hops!



Candidates for the bath:

- Phonons: at low T for pair hopping are very inefficient!

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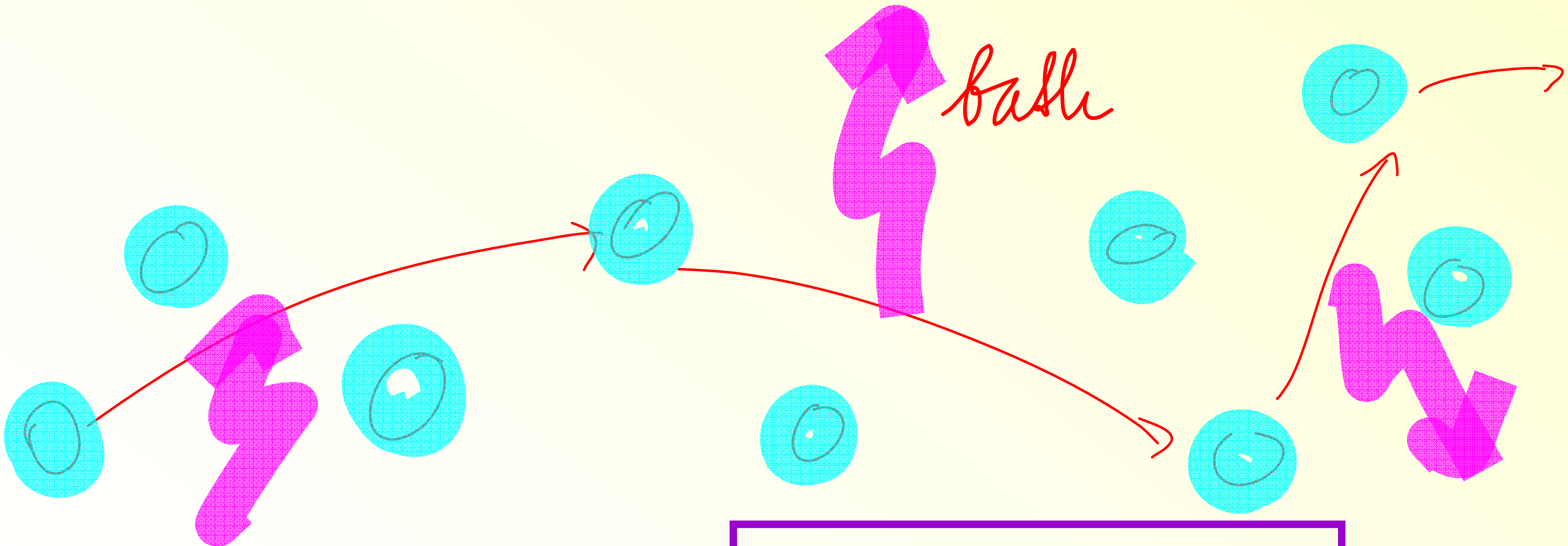

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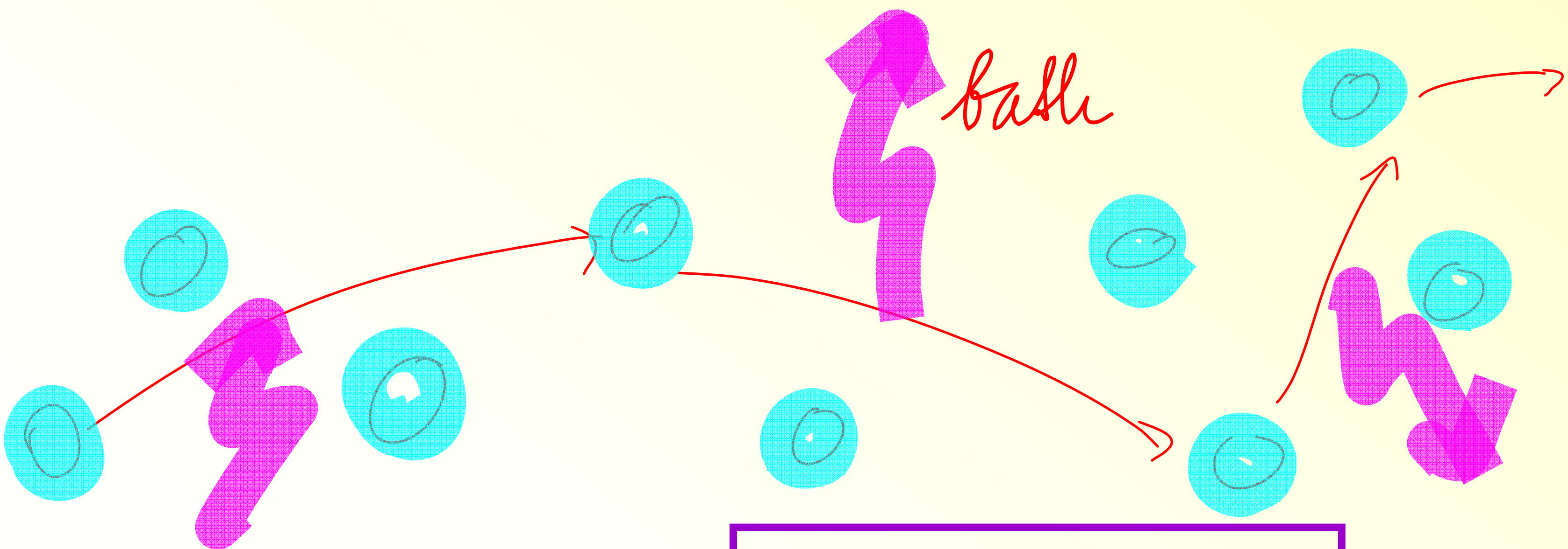


Candidates for the bath:

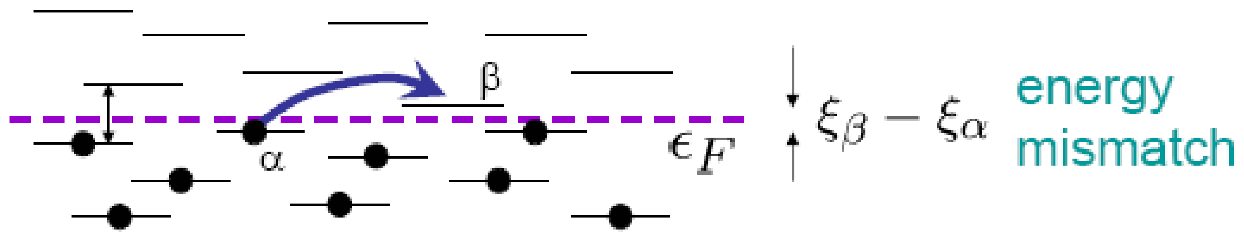
Too weak → not considered

- ~~Phonons: at low T for pair hopping are very inefficient!~~
- Collective electronic (i.e., pair) excitations ?

Localization despite interactions?

Fleishman, Anderson, Licciardello (1980, 1982)
Basko et al., Gornyi et al. (2005, 2006)

Is there many-body localization (localization in Hilbert space) ↔ absence of diffusion; even at finite T?



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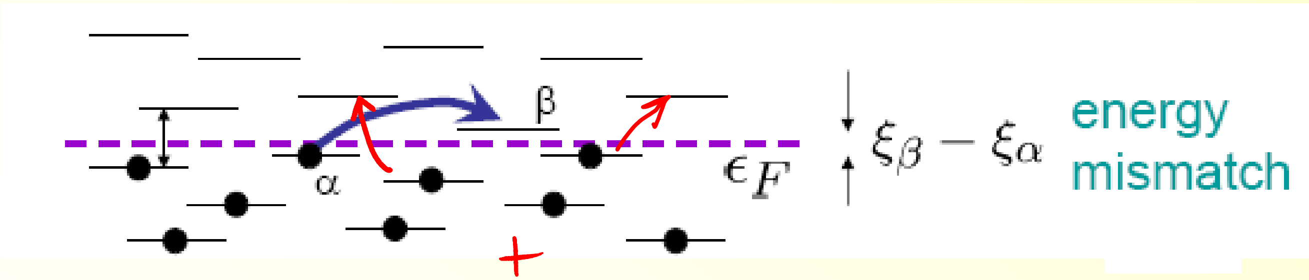

Can multi-particle arrangements bridge the energy mismatch?

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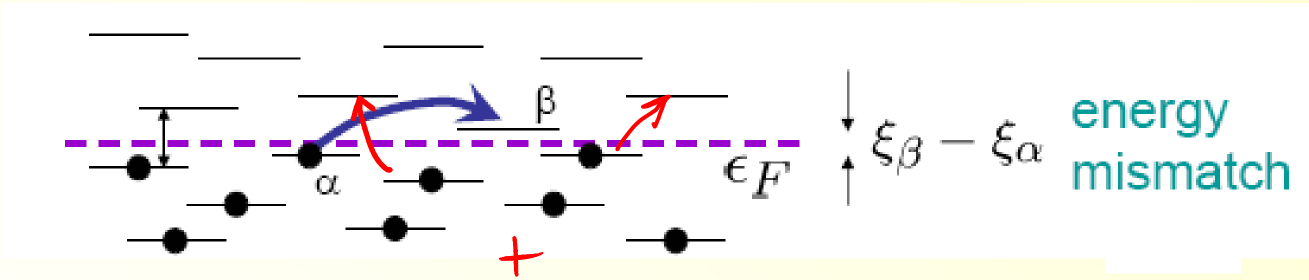


Assumptions:
1. Low dimensions → all single particle states are localized
2. Weak short range interactions
3. No phonons

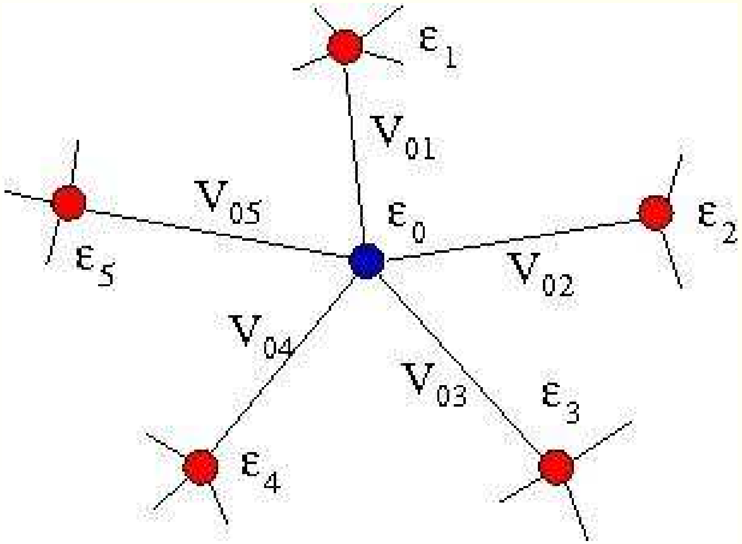
Answer: For $T < \delta_\xi / \lambda$ ($\lambda << 1$: interaction parameter)
- Energy conservation impossible: electrons do not constitute a continuous bath!
- All many body excitations remain discrete in energy!
- Conductivity = 0 even at finite T!

Localization with interaction?

Investigation to all orders in perturbation theory:

*I. V. Gornyi, A. D. Mirlin, and D. G. Polyakov, PRL **95**, 206603 (2005).*
*D. M. Basko, I. L. Aleiner, and B. L. Altshuler, Ann. Phys. **321**, 1126 (2006).*

Assumption: Weak interactions: $V_{int} << \delta_\xi$ (level spacing).
Conclusion: An energy crisis (and thus a **metal-insulator transition** in the absence of phonons) occurs at high temperature $T >> \delta_\xi$ -- due to “localization in Fockspace”.



$$T_{MIT} \approx \frac{\delta_\xi^2}{V_{\text{int}}} >> \delta_\xi \approx T_{\text{Mott-hopping}}$$

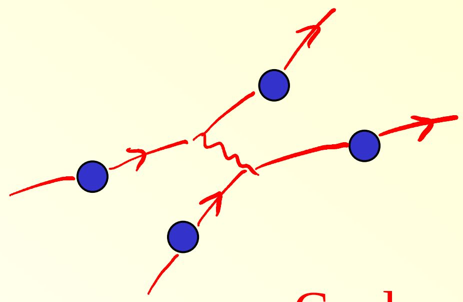
Argument:
Same as for usual Anderson localization
But: ● Sites: Many-body states
— Links: off-diagonal interactions

Why to expect many body localization at the SIT?

- Electrons are bound in localized pairs
- Phase volume for inelastic processes is strongly reduced as compared to the single electron problem MIT

Cooper + hard core rep.

↔



Coulomb

→ Less fluctuations → stronger tendency to localize

Many body localization is easier at the SIT!

Probably important difference to the MIT!

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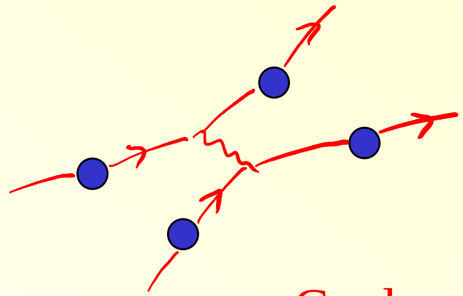

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- At strong magnetic field pairs are dissolved

→ Many body localization eventually disappears

→ (electronically activated) VRH is possible again.

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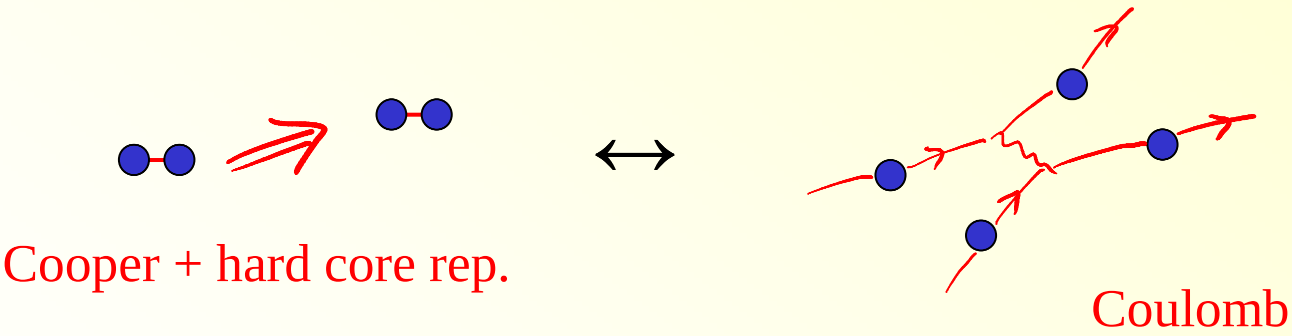

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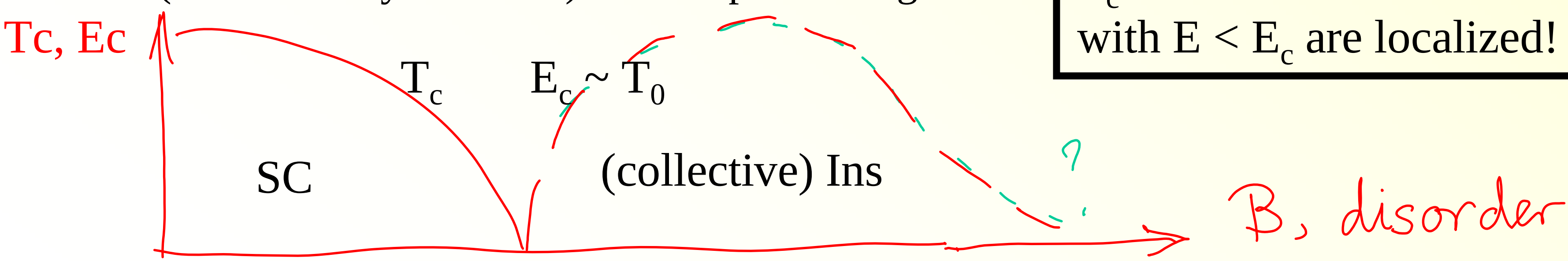
E_c: At T=0 all excitations with $E < E_c$ are localized!



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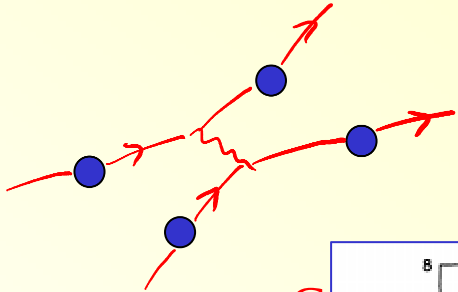

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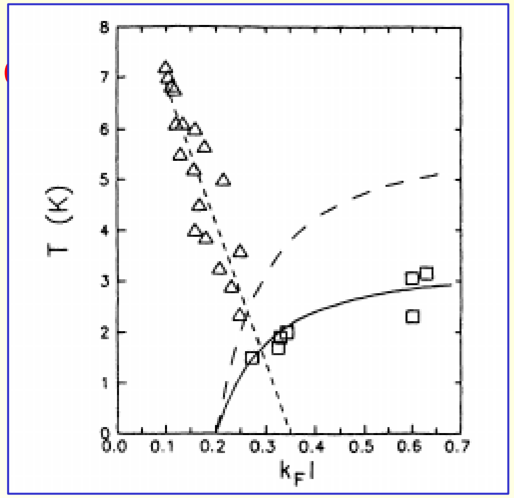

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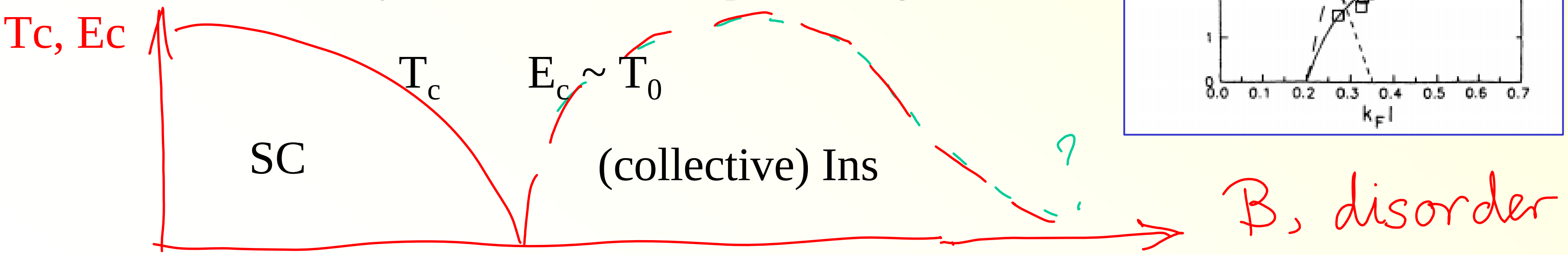
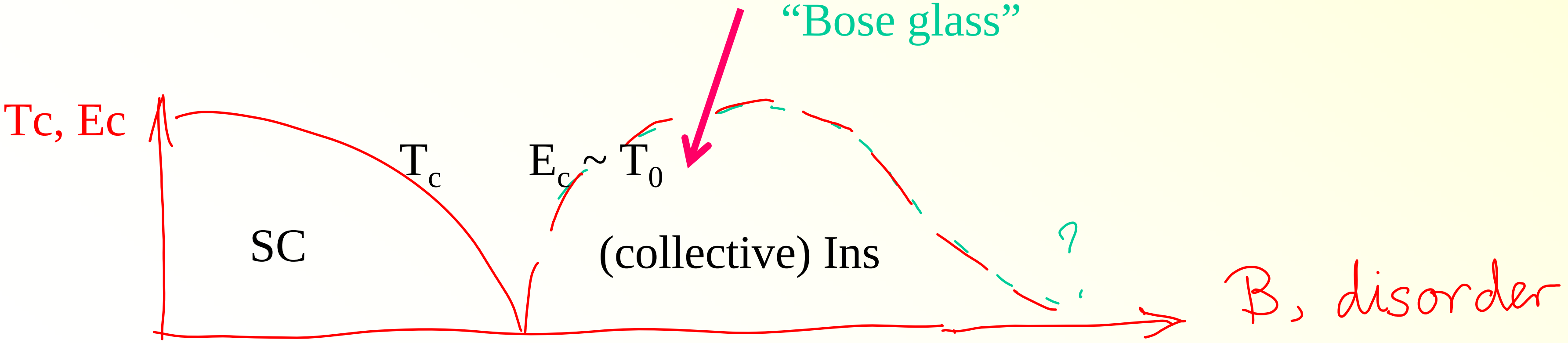


Transport in the collective insulator



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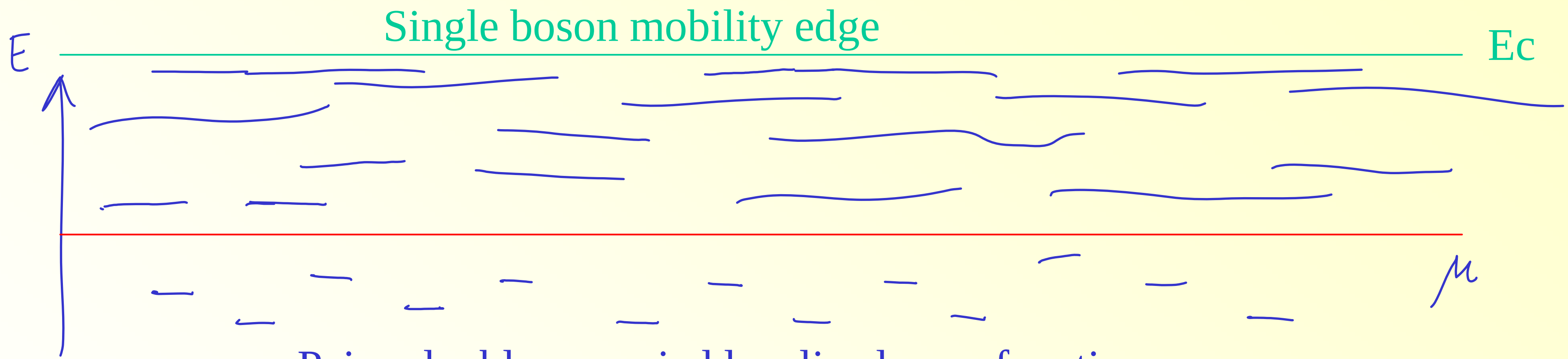
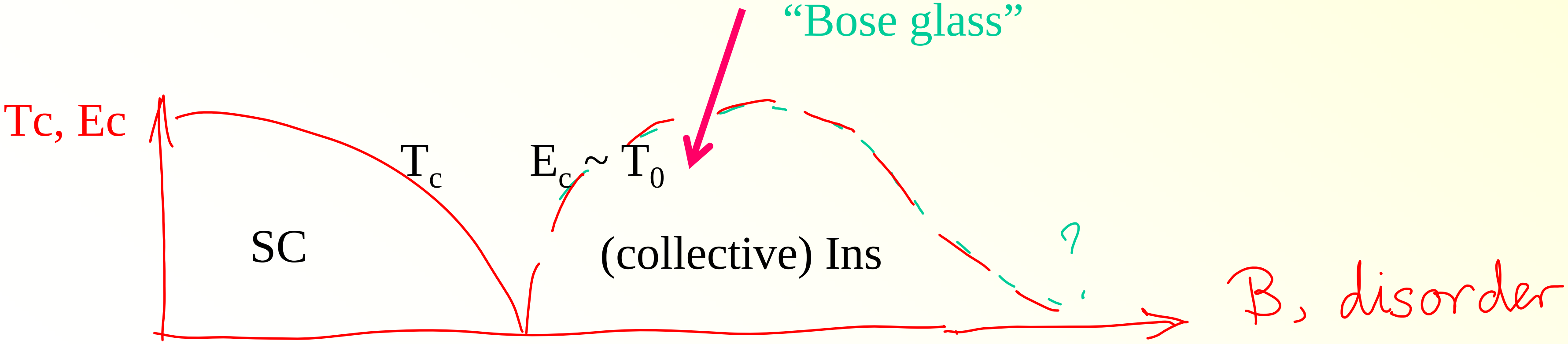


Pairs: doubly occupied localized wavefunctions

$$H_{pair} = \sum_i \varepsilon_i \sigma_i^z + \sum_{ij} t_{ij}(B) \sigma_i^+ \sigma_j^- + \sum_{ij} J_{ij} \sigma_i^z \sigma_j^z$$

(Anderson, Ma+Lee [+Halperin])



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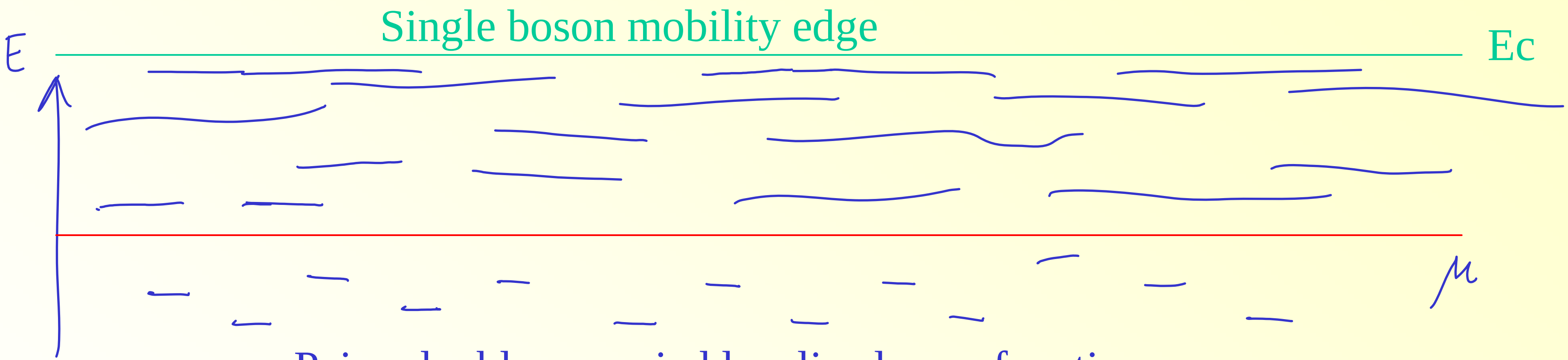

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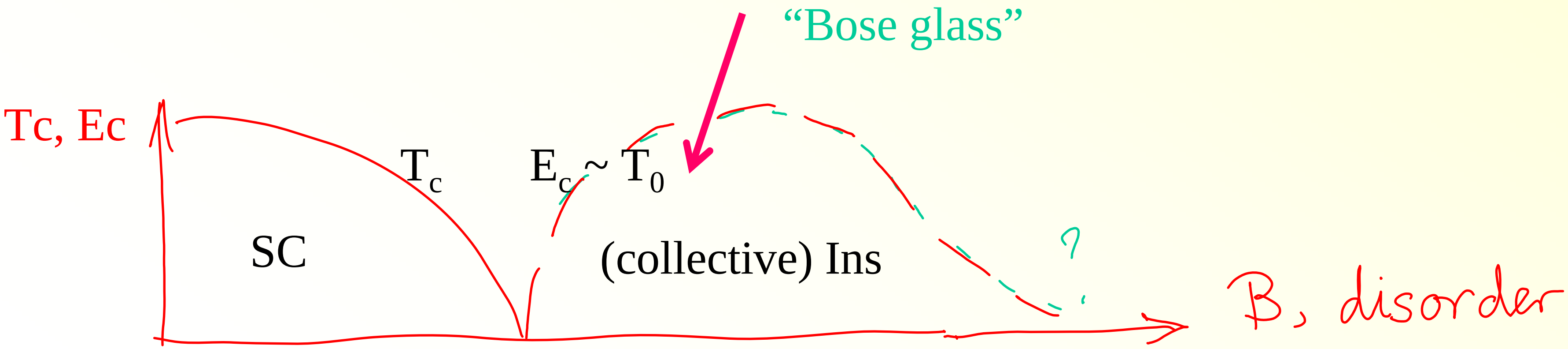

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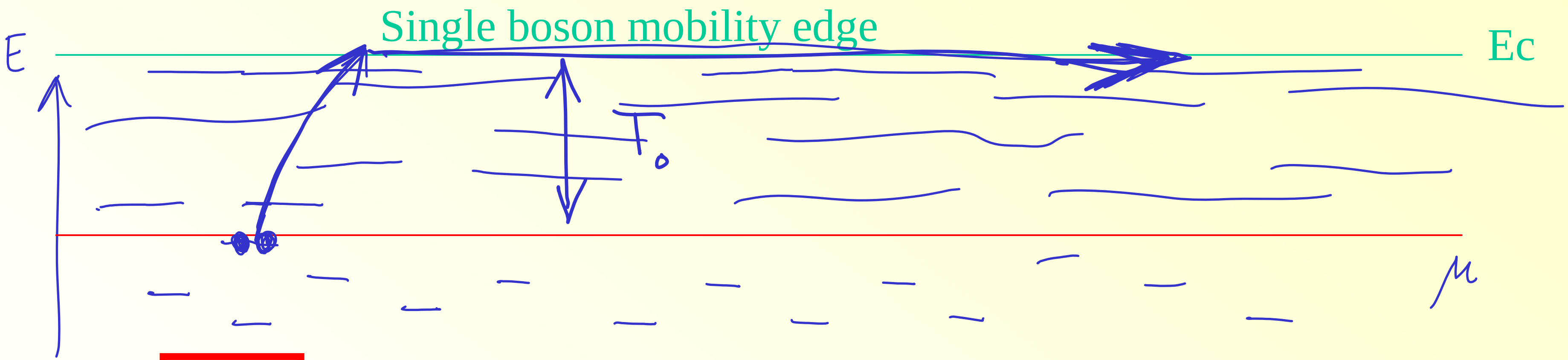
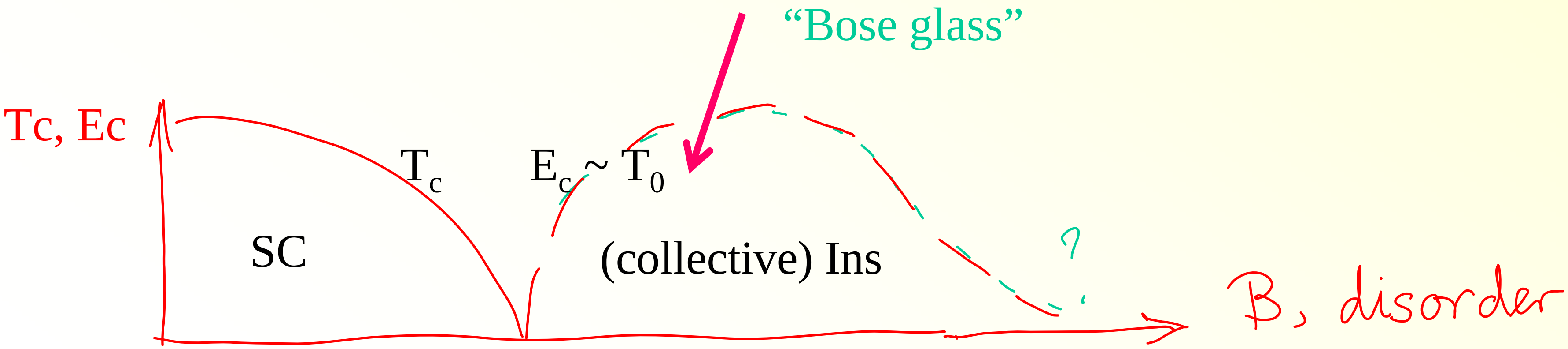
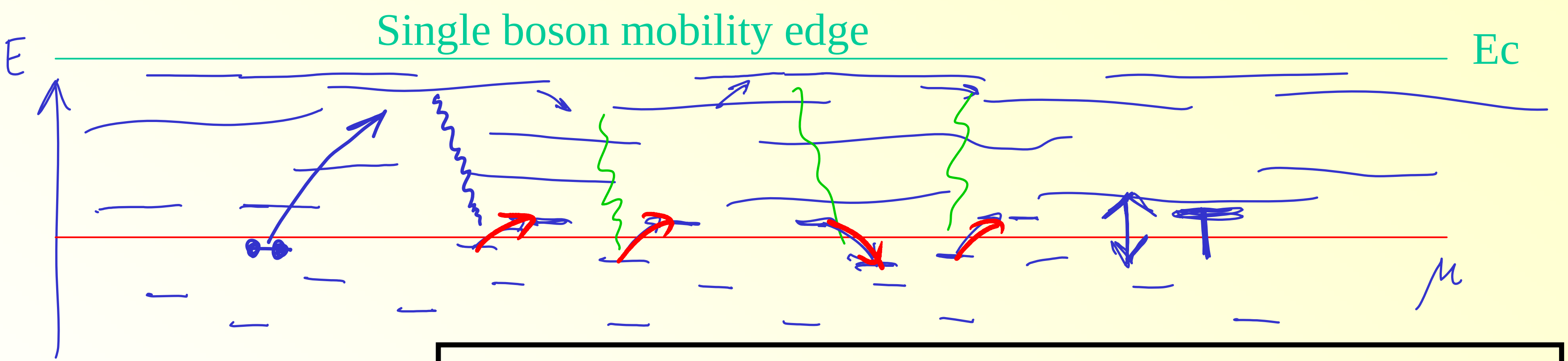


T ~ 0

Simple activation!
T_0 ~ typical hopping amplitude of preformed pairs
~ T_c close to SIT (Ma + Lee!)



Transport in the collective insulator



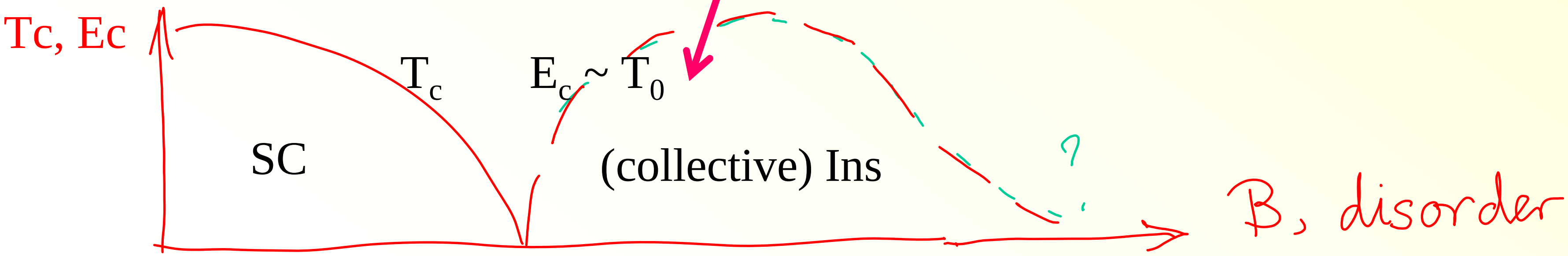
Ec > T > 0

Diffusion already at energy where

$$L_{inel}\left(T;E^*(T)\right) < \xi\left(E^*(T)\right)$$

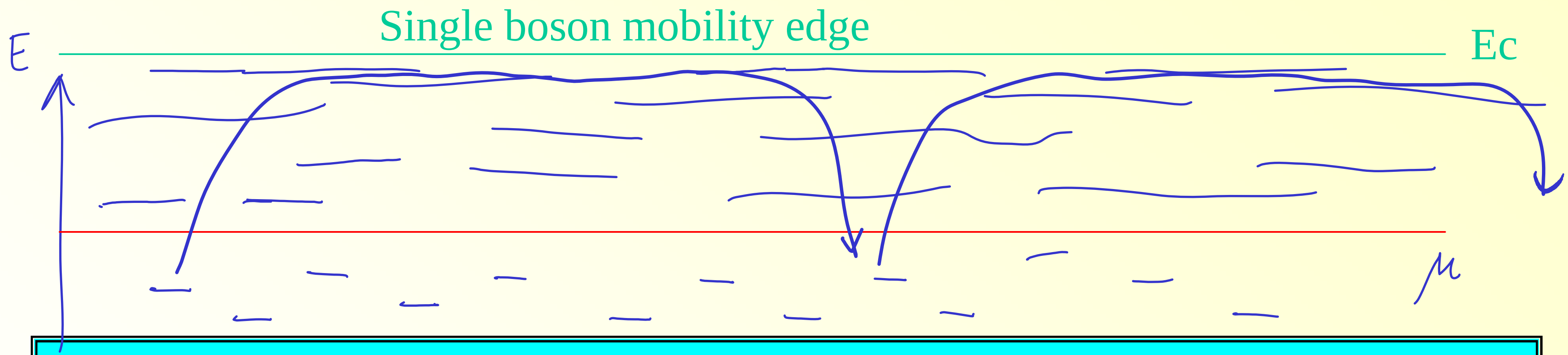
$$E^*(T) = E_c - AT^{\gamma} - \ldots \qquad (\gamma = 1/\nu d)$$

Overactivation! *(cf.: Semiconductors: Mott, Thomas, Overhof, 1988)*

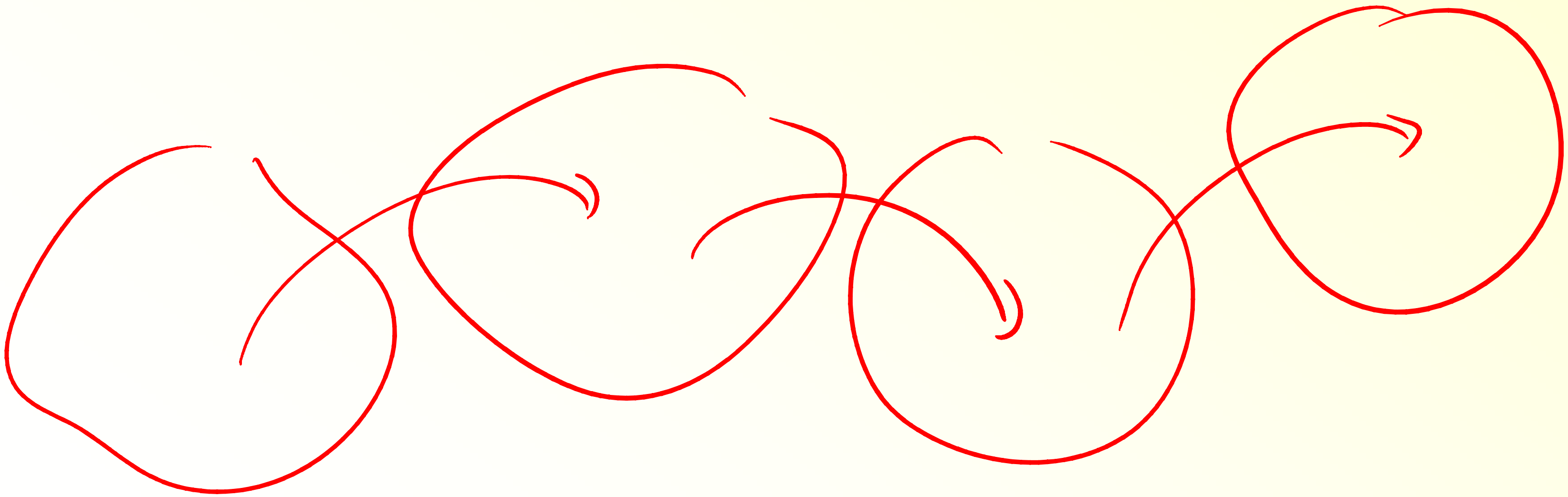


Transport in the collective insulator

Transport on large scales:



• Essential ingredient: Elementary step of transport is simply activated (no VRH)!
• Eventual d.c. transport is percolative in nature as in ANY disordered insulator



Experimental recall: Summary II

• Transport is simply activated at low T over several orders of magnitude

• There is a tendency to

- overactivation close to the SIT
(saturating to simple activation at low T)
Highly unusual in a disordered system!

- subactivation beyond the MR peak (at lowest T)

Experimental recall: Summary II

• Transport is simply activated at low T over several orders of magnitude

Activation to mobility edge of pairs!

• There is a tendency to

- overactivation close to the SIT
(saturating to simple activation at low T)
Highly unusual in a disordered system!

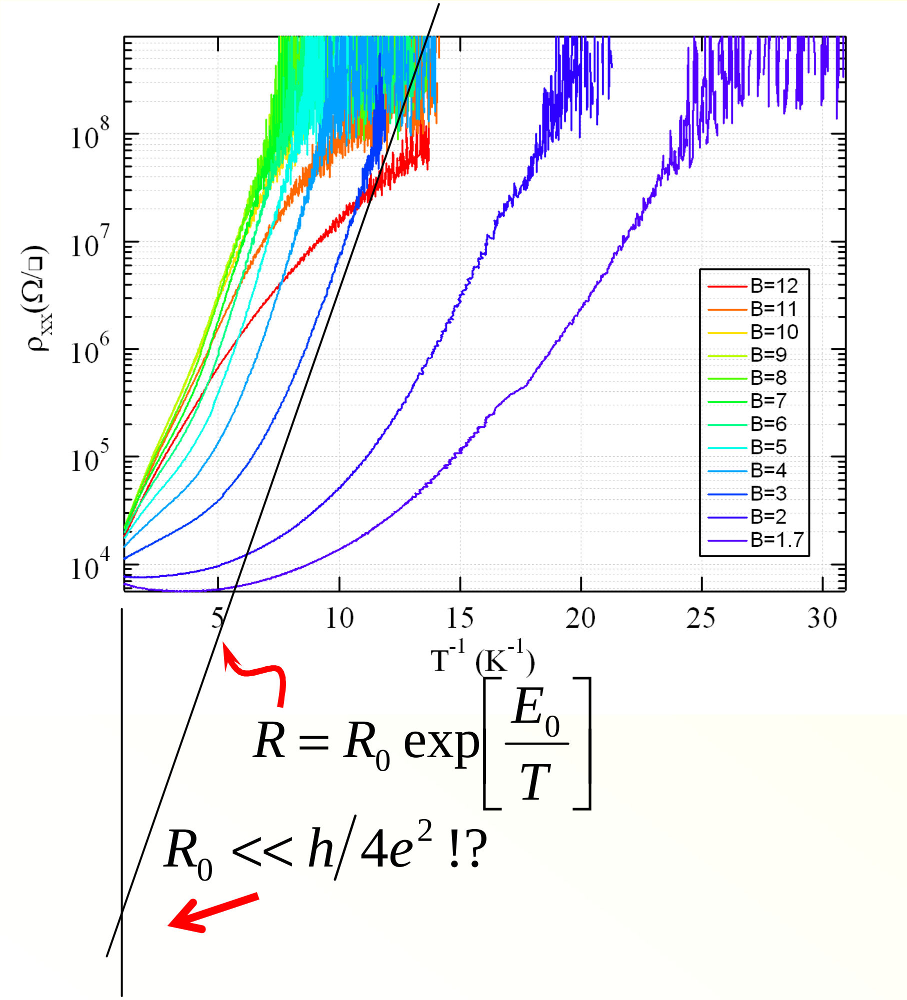
T-induced lowering of diffusion edge

- subactivation beyond the MR peak (at lowest T)

VRH of depaired electrons,
Destruction of manybody localization due to single electrons and their stronger tendency to delocalize.

Overactivation near the SIT

B. Sacépé et al. (unpublished - 2008) – InO$_x$.



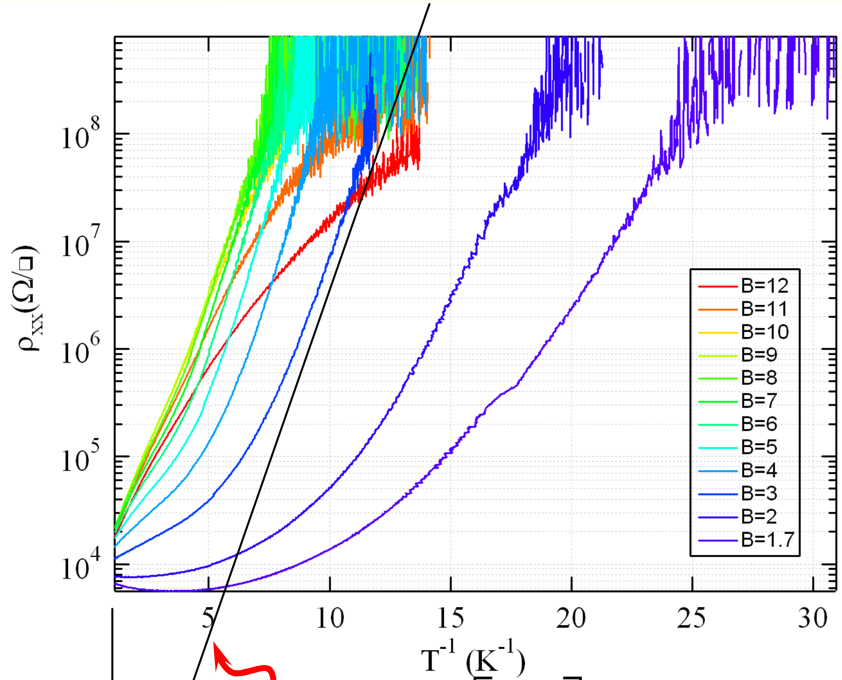
$$R = R_0 \exp\left[\frac{E_0}{T}\right]$$

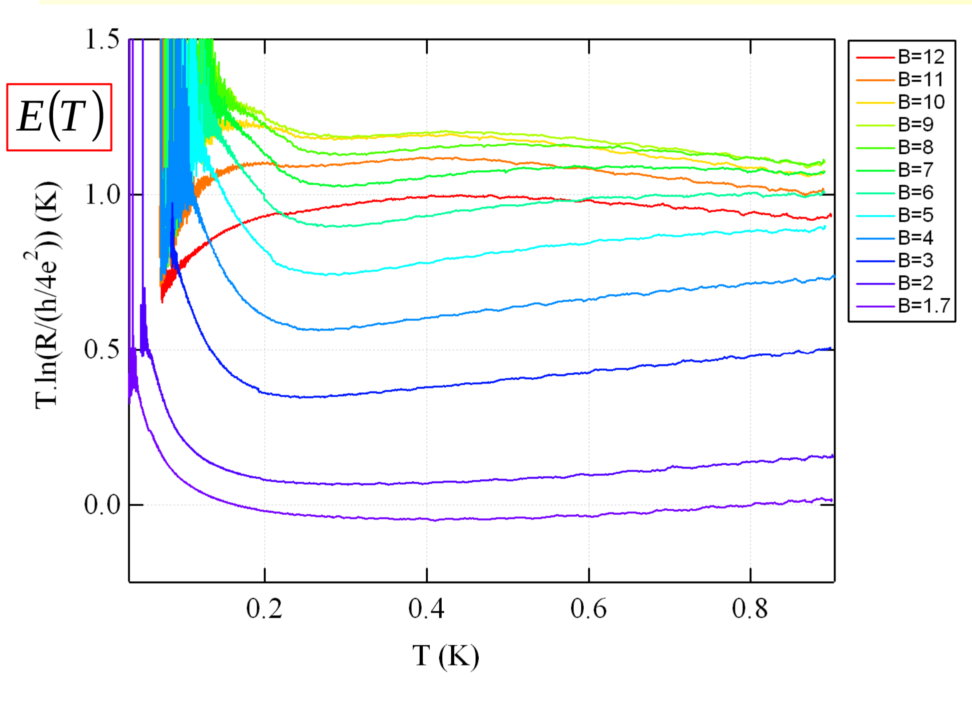
$$R_0 << h/4e^2 \text{ !?}$$

Overactivation near the SIT

B. Sacépé et al. (unpublished - 2008) – InO_x.

Activation energy plot!





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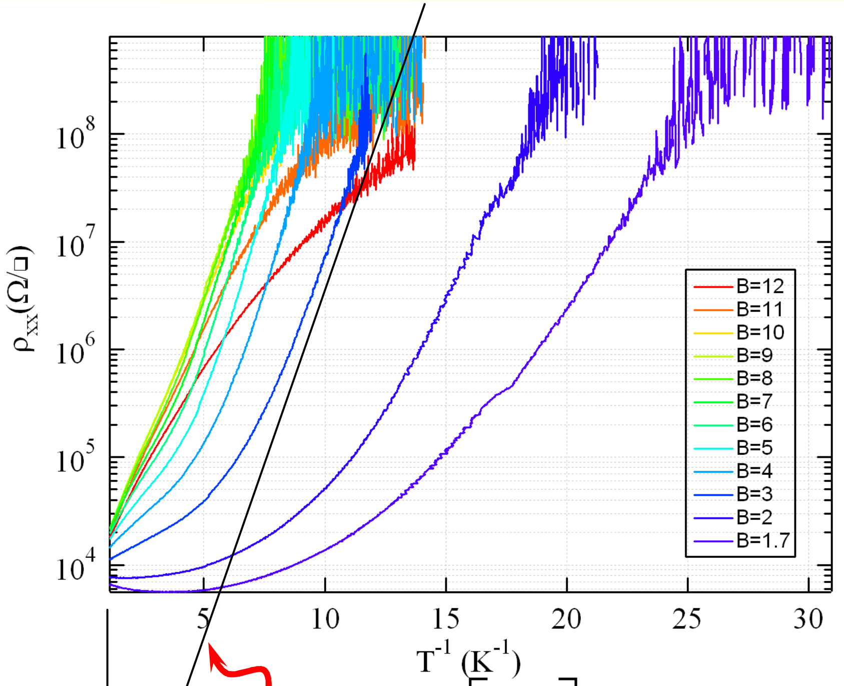
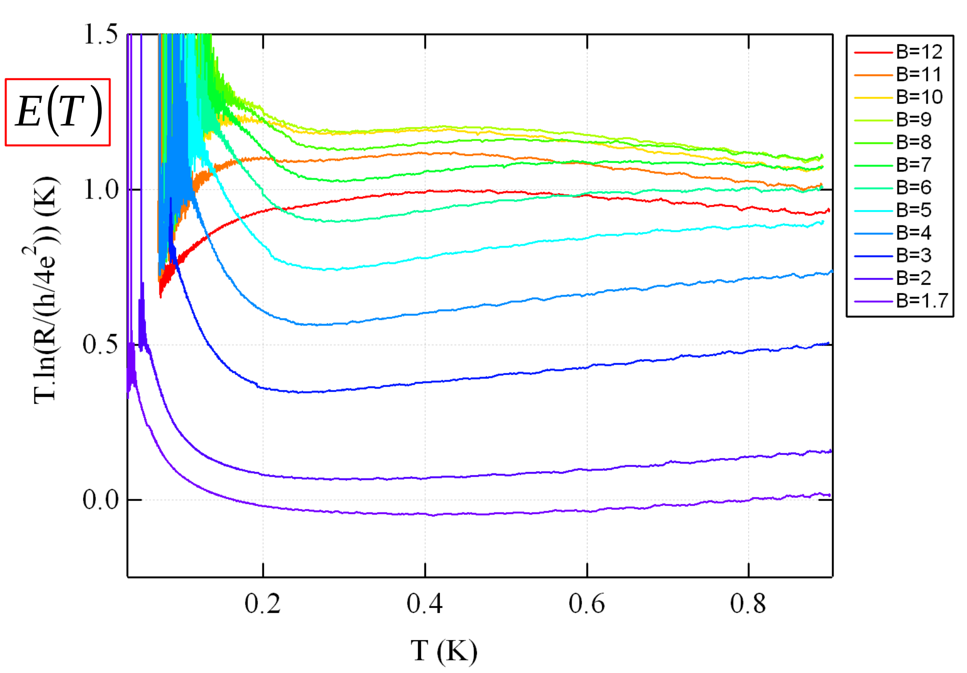


$$R = R_0 \exp\left[\frac{E_0}{T}\right]$$

$$R_0 << h/4e^2 \text{ !?}$$

$E(T)$



Different interpretation:
T-dependent mobility edge:

$$R = C\frac{L_\varphi(T)}{d}\frac{h}{4e^2}\exp\left[\frac{E^*(T)}{T}\right]$$

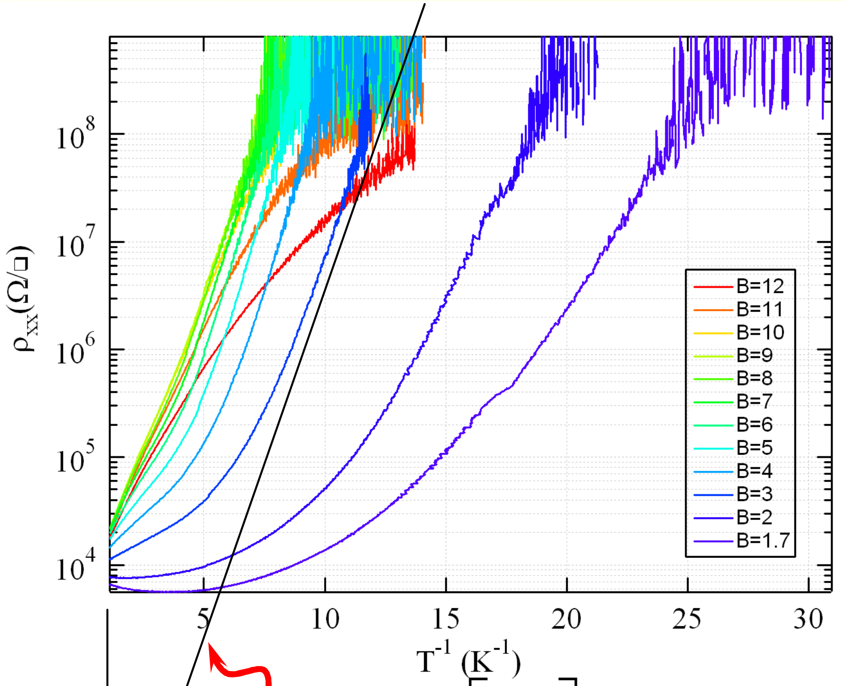
Overactivation near the SIT

B. Sacépé et al. (unpublished - 2008) – InO_x.

Approximate: $E^*(T) = E_c - BT - \dots$

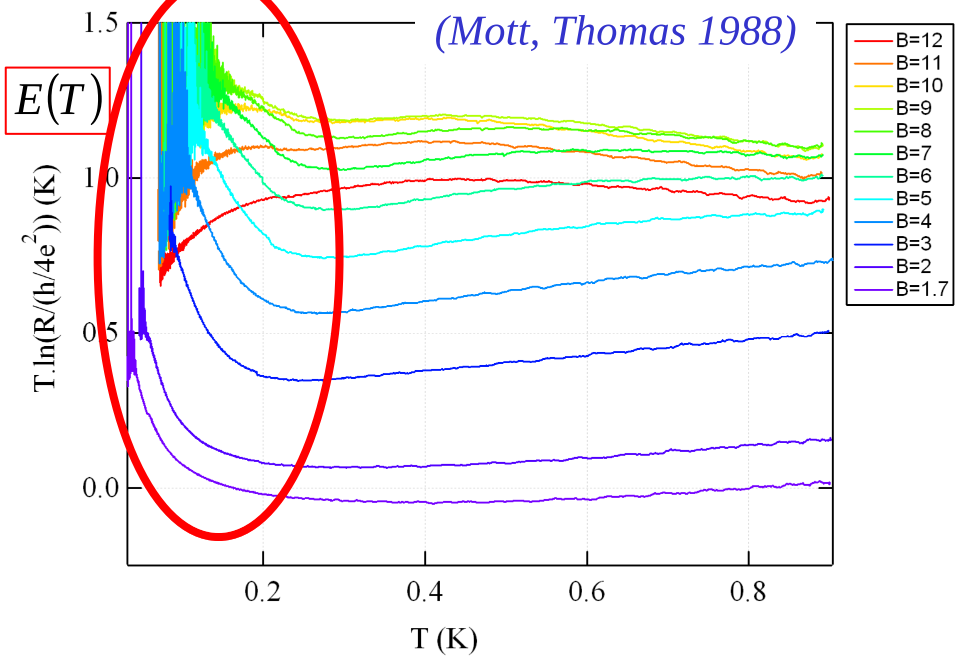
Prefactor: $R_0 \frac{4e^2}{h} = C \frac{L_\varphi(T)}{d} \exp[-B] << 1$

(Mott, Thomas 1988)



$R = R_0 \exp\left[\frac{E_0}{T}\right]$

$R_0 << h/4e^2$!?



Different interpretation:

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Summary

- Global charge gap for pairs unlikely due to disorder (except for distorted Wigner crystal of pairs or granular superconductors):

  → Remaining consistent model for simple activation:

  Conductivity of pairs at their mobility edge.
- Variable range hopping excluded by remnant of many body localization in the low energy sector.
- Dephasing of nearly delocalized states

  → diffusion below the mobility edge

  → might explain observed overactivation and an apparently very small pre-exponential factor R_0.
- Destruction of many body localization by depairing (high B) reestablishes VRH of single e's → subactivation.

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