Karlsruhe Institute of Technology

Superconductor-insulator transition in disordered FeSe thin films

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Thin Films and Interfaces

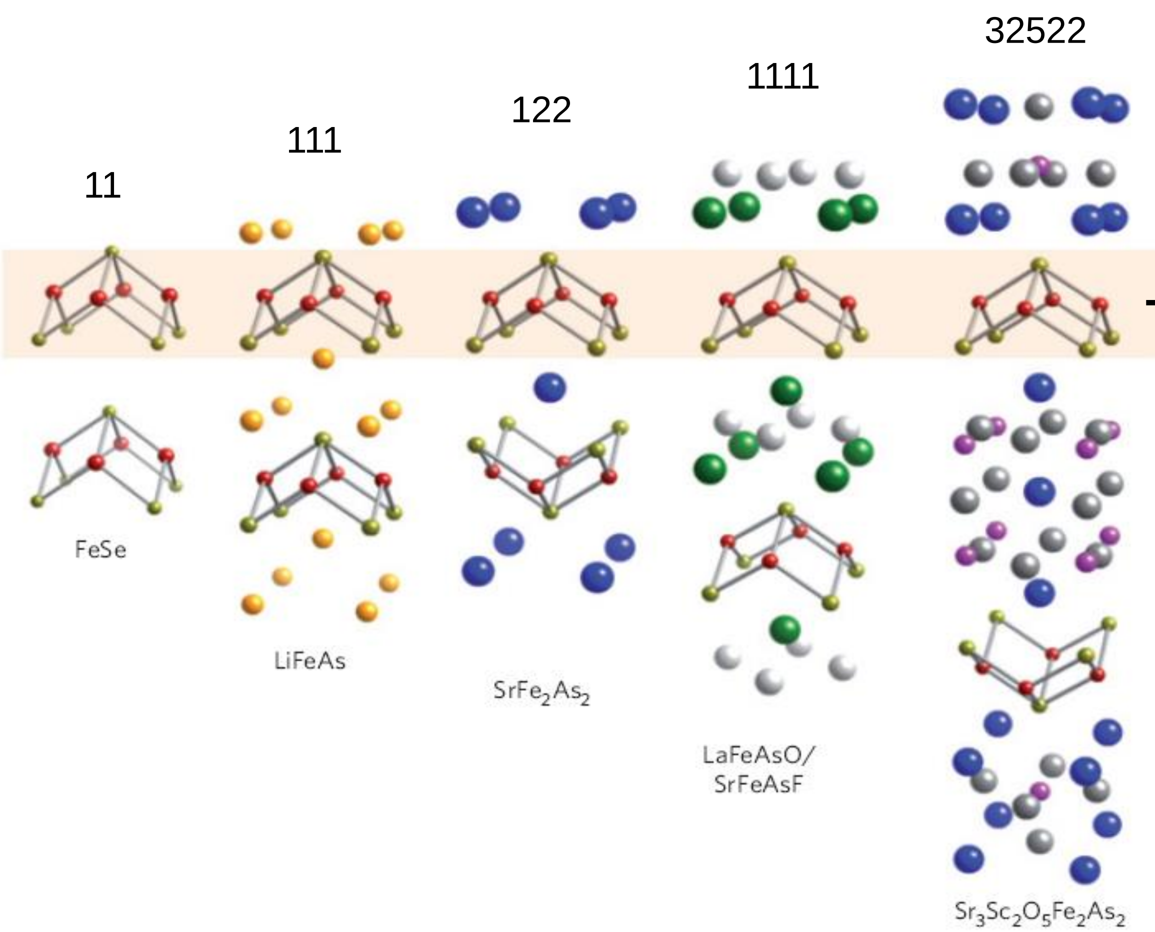
Outline

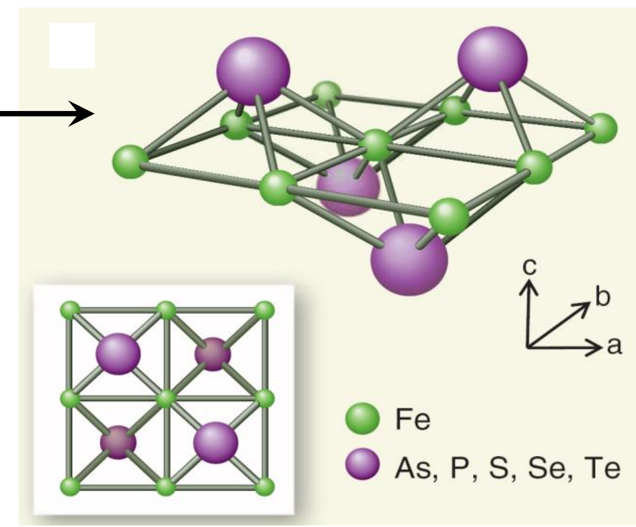
- overview of iron-based superconductors
- FeSe thin films: preparation and properties
- ordered FeSe thin films: excess conductivity and BKT transition
- disordered FeSe thin films: superconducting and insulating phases, superconductor-insulator transition
- disordered FeSe thin films in a magnetic field
- summary

Material classes of superconducting FePn / Ch

- **11** $FeTe_{1-x}Se_x$ T_c = 15K for x = 0.5 and T_c = 8K for x = 1
- **122*** $A_{1-x}Fe_{2-y}Se_2$ $T_c \approx$ 32K (A = K, Rb, Cs, (Tl,K), (Tl,Rb))
- **122** $BaFe_2As_2$ T_c = 38K in $Ba_{0.6}K_{0.4}Fe_2As_2$
- **111** LiFeAs T_c = 18K
- **1111** $ReFeAsO_{1-x}F_x$ T_c = 25 - 56K
- **21311** Sr_2VO_3FeAs T_c = 37K ”(n+1)n(3n-1)22”

Unit cells and structural motif



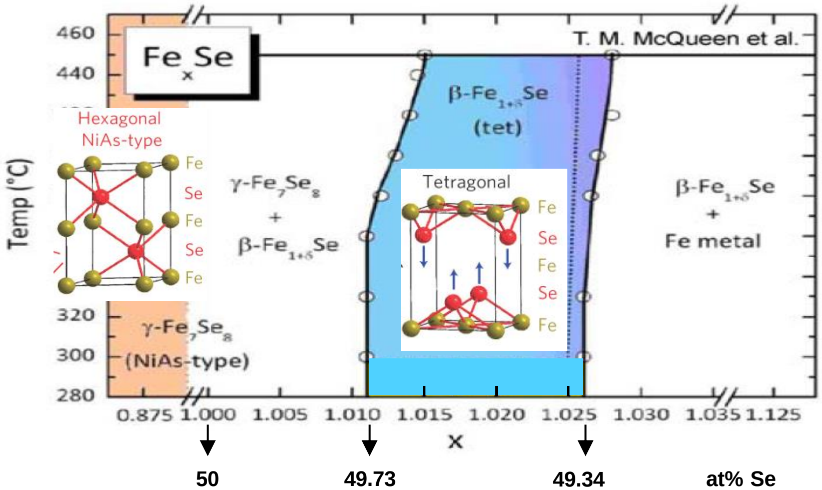


J. Paglione, R.L. Greene, Nature phys. **6**, 645 (2010)

F. Wang, D.-H. Lee, Science **332**, 200 (2011)

β - FeSe

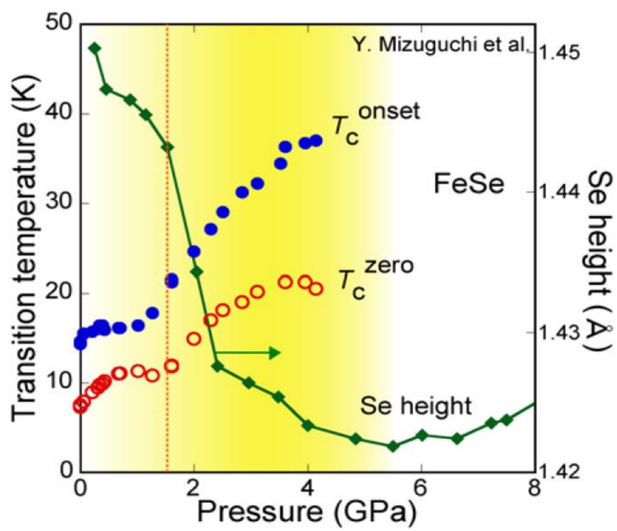
T.M. McQueen *et al.*, Phys. Rev. B **79**, 014522 (2009)

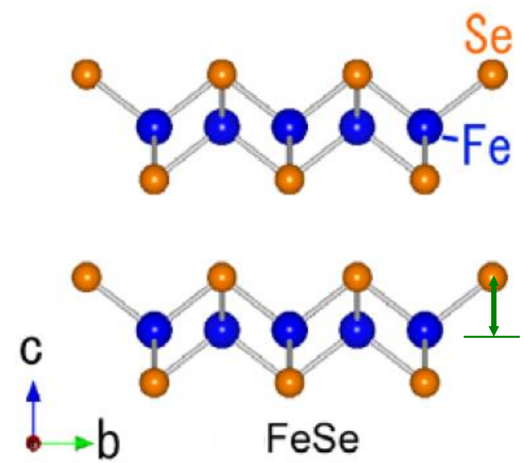


- concentration range of the β-phase very small
- tetragonal phase turns to orthorhombic below 90 K
- structural transition not accompanied by magnetic ordering
- superconductivity sensitive to composition

Pressure effect

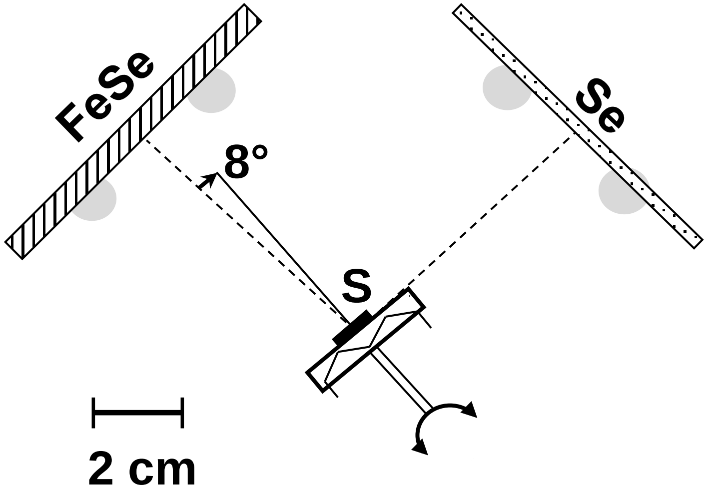
- largest among Fe Pn/Ch
- T_c increase to 37 K at 4 GPa
- connected with decreasing Se height
- superconductivity sensitive to structure



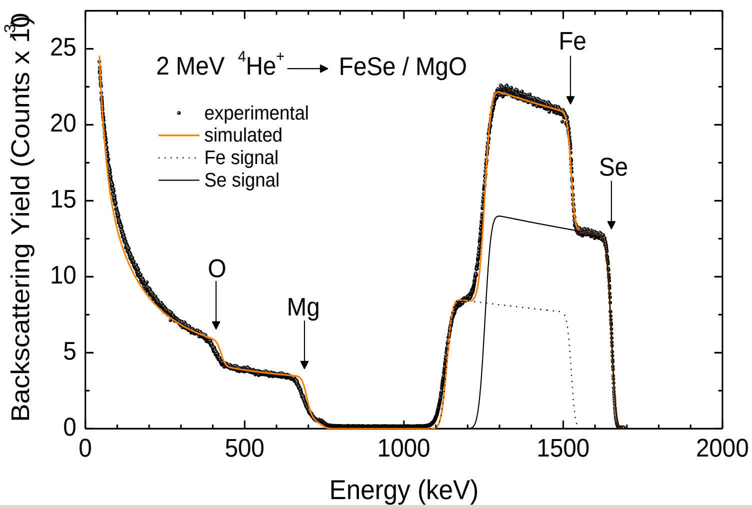


Y. Mizuguchi, Y. Takano, J. Phys. Soc. Jpn. **79**, 102001 (2010)

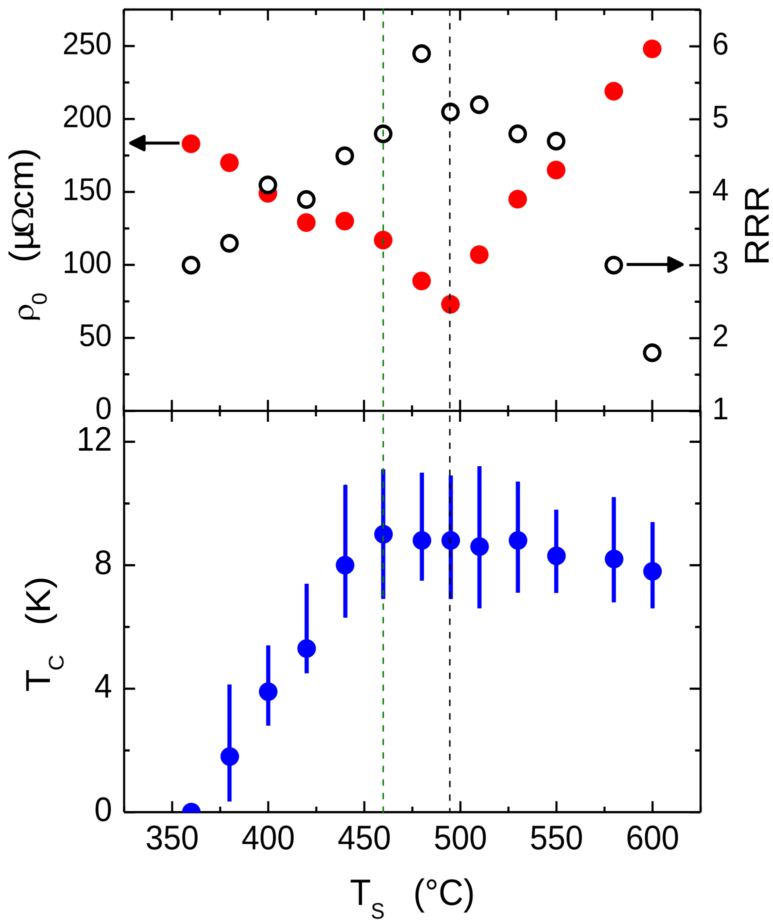
FeSe thin films: deposition and optimization



optimized sputtering power



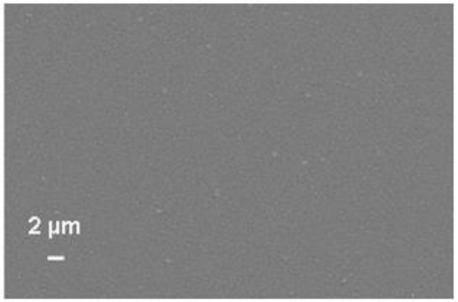
optimized substrate temperature



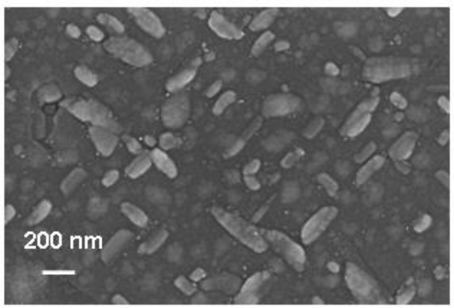
R. Schneider *et al.*, Supercond. Sci. Technol. **26**, 055014 (2013)

Surface and orientation

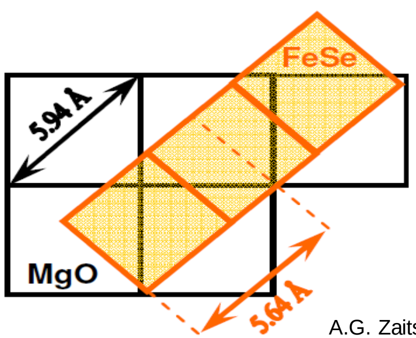
SEM



- 500 nm thick film
- smooth
- free of precipitates



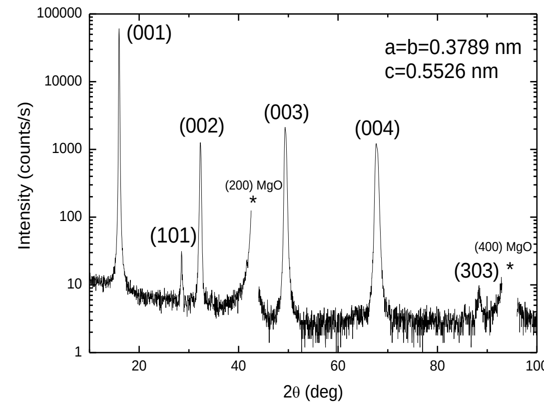
- aligned grains
- rectangular shape
- sizes 100 to 400 nm



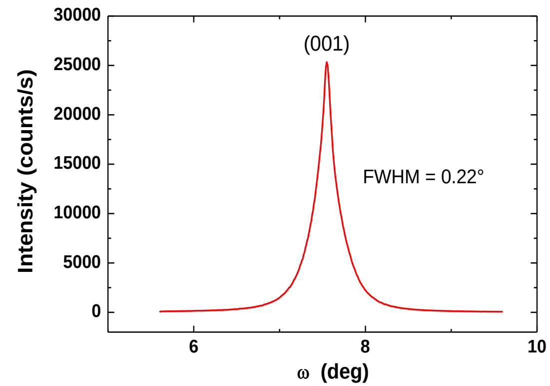
- lattice mismatch minimized to 5%

A.G. Zaitsev *et al.*, J. Phys. Conf. Ser. **507**, 012054 (2014)

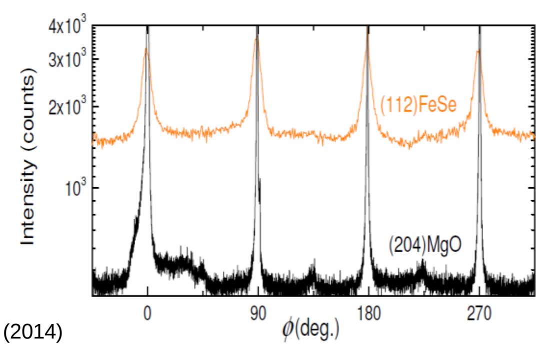
XRD



- (00l) Bragg reflections
- [001] FeSe ‖ [001] MgO
- a $_{film}$ > a $_{bulk}$

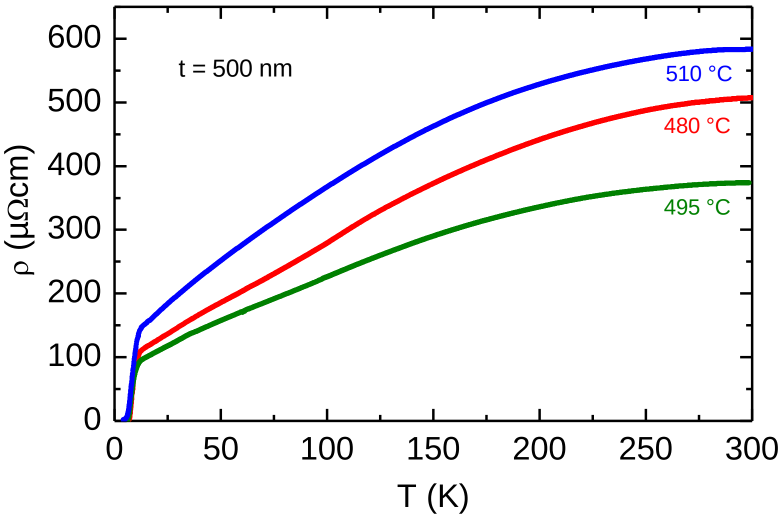


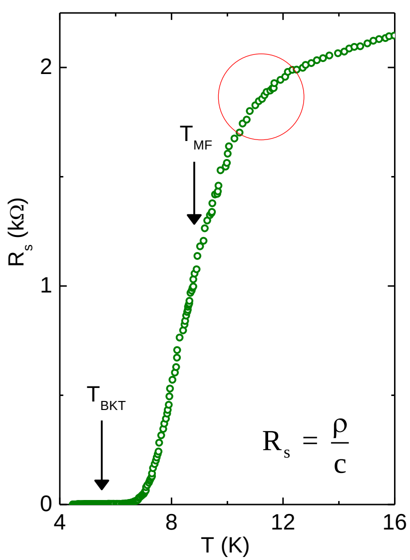
- small value of FWHM
- good growth quality



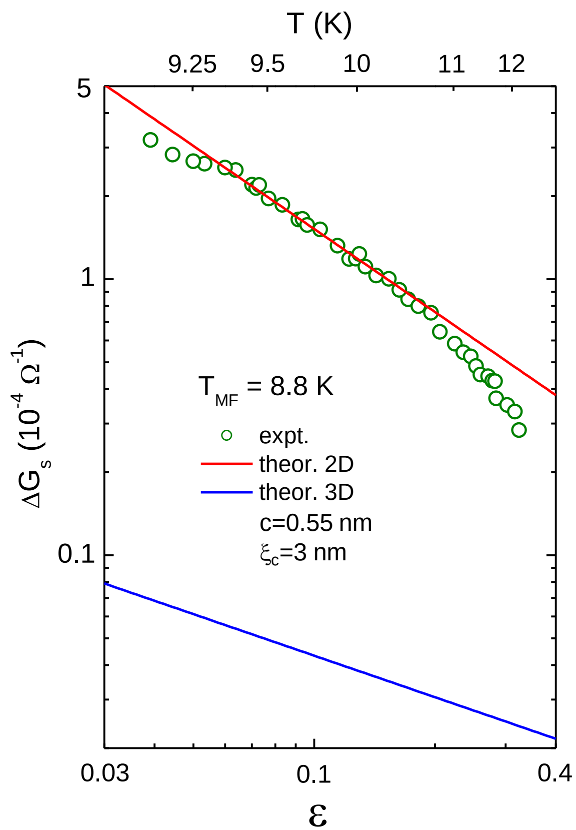
- fourfold rotational symmetry
- [100] FeSe ‖ [110] MgO

Excess conductivity





- linear at low T
- parabolic with negative curvature at high T
- rounding of the transition



Excess sheet conductance per Fe-Se layer:

$$\Delta G_s = G_s - G_s^n$$
$$G_s = 1/R_s$$
$$G_s^n = (a + bT)^{-1}$$

2D Aslamazov-Larkin theory:

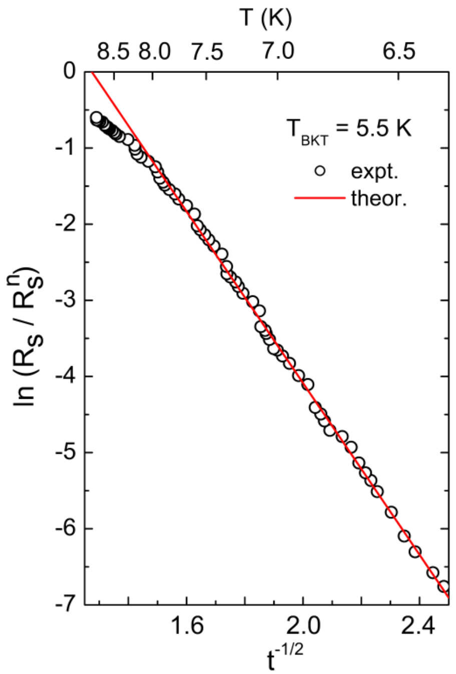
$$\Delta G_s = \frac{e^2}{16\hbar} \times \frac{1}{\varepsilon}$$
$$\frac{e^2}{16\hbar} = 1.52 \times 10^{-5}\ \Omega^{-1}$$
$$\varepsilon = \ln \frac{T}{T_{MF}} \approx \frac{T - T_{MF}}{T_{MF}}$$

L.G. Aslamazov, A.I. Larkin Phys. Lett. A **26**, 238 (1968)

- 2D character of the superconducting fluctuations

R. Schneider *et al.*, J. Phys.: Condens. Matter **26**, 455701 (2014)

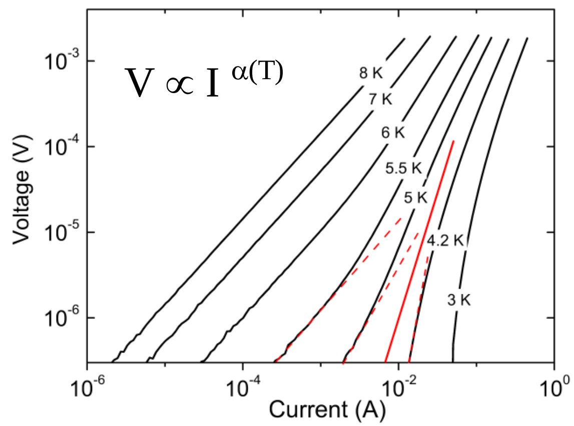
BKT transition and *Gi*

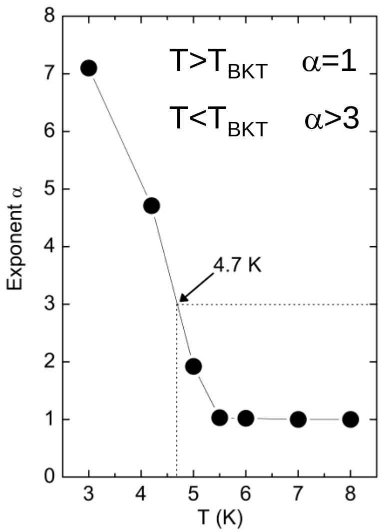


B.I. Halperin , D.R. Nelson, J. Low Temp. Phys. **36**, 599 (1979)

$$\ln \frac{R_s(T)}{R_s^n(T)} = a - bt^{-1/2}$$

$$t = \frac{T}{T_{BKT}} - 1$$





jump in α to 3 at $T_{BKT} \approx 4.7$ K

2D Ginzburg - Levanyuk number *Gi* :

$T_{BKT} = 5.5$ K $T_{MF} = 8.8$ K → $Gi = 5 \times 10^{-2}$

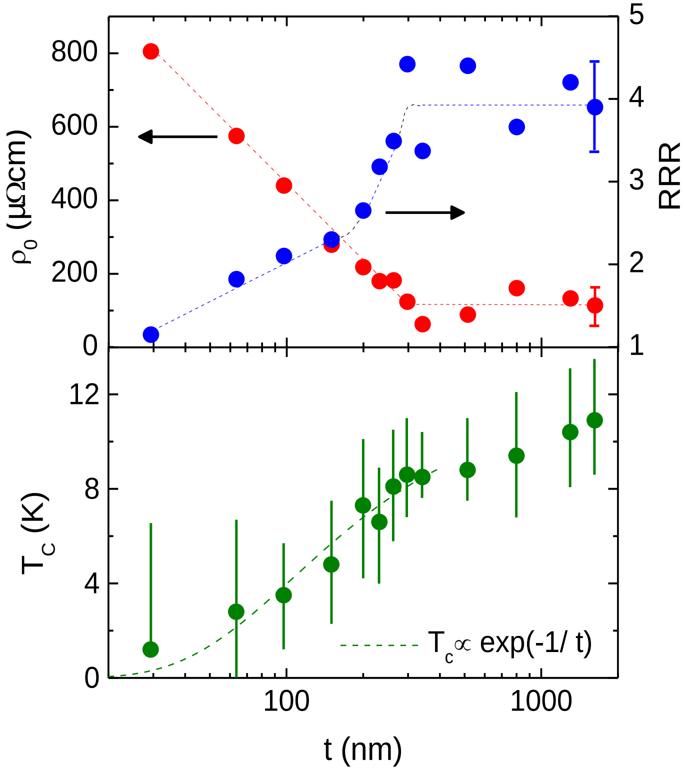
A. Larkin, A. Varlamov
Theory of Fluctuations in Superconductors
N.Y.: Oxford University Press (2005)

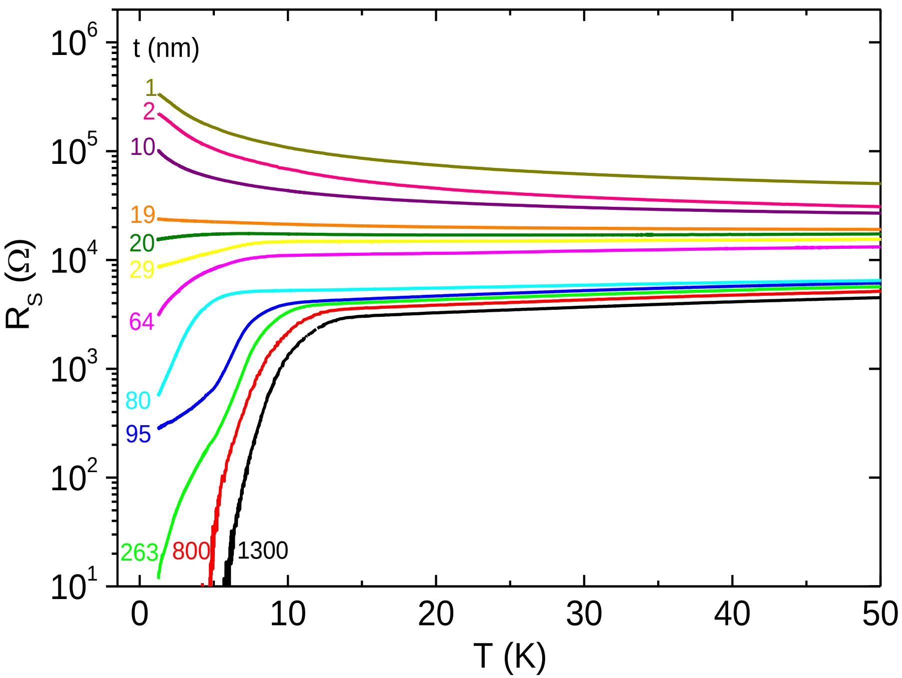
- comparable to $YBa_2Cu_3O_{7-x}$
- large m and low n_s favor large *Gi*
- 2D superconducting fluctuations important in the layered FeSe compound

V.L. Berezinskii, Sov. Phys. JETP **34**, 610 (1972)

J.M. Kosterlitz, D.J. Thouless, J. Phys. C **6**, 1181 (1973)

High sensitivity to disorder





Thickness threshold at 300 nm

- ➢ bulklike features for t > 300 nm
- ➢ increase of ρ_0
- ➢ decrease of RRR
- ➢ decrease of T_c with decreasing t < 300 nm

R. Schneider *et al.*, Phys. Rev. Lett. **108**, 257003 (2012)

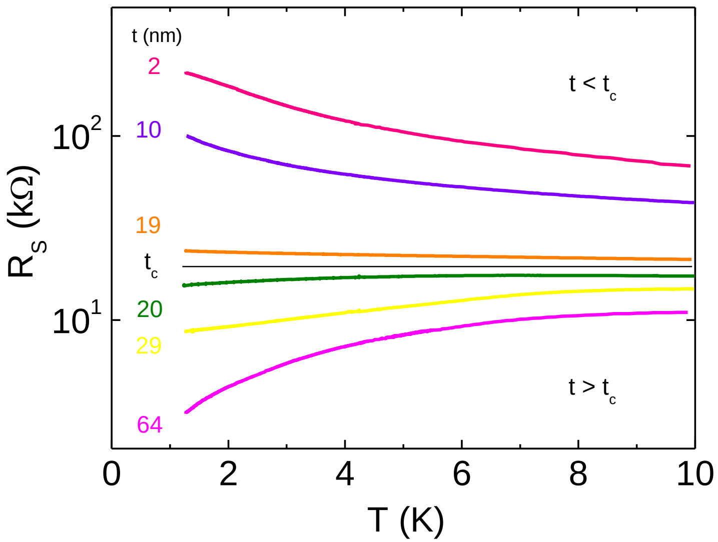
Fanlike set of curves

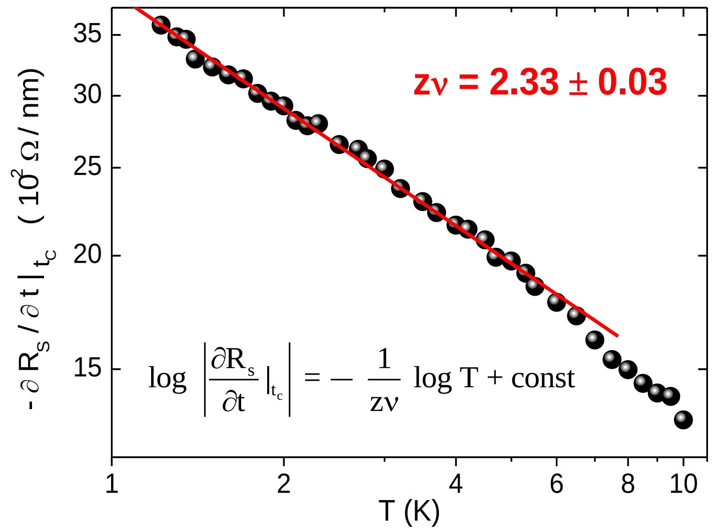
20 nm < t < 300 nm
- R_s(1.2K) ≠ 0
- R_s(0) ≠ 0

19 nm < t < 20 nm
- horizontal separatrix indicating SIT

t < 19 nm
- $\partial R_s(T,t)/\partial T < 0$

Disorder driven SIT

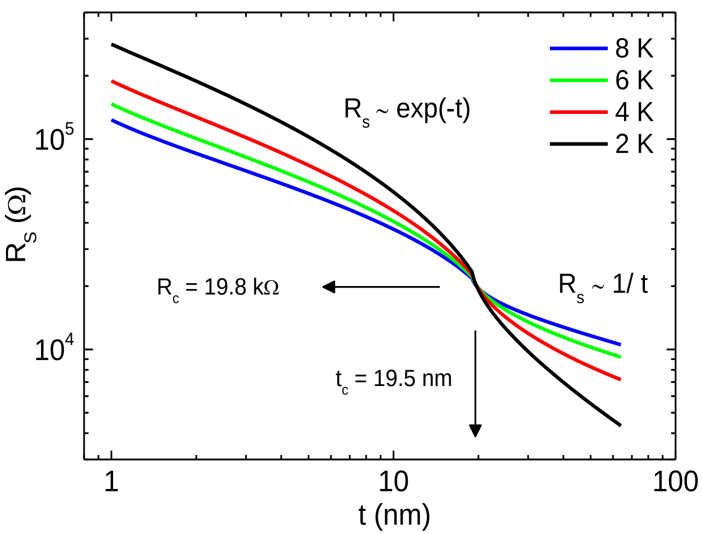




$$R_s = R_c \, f\left(\frac{|t - t_c|}{T^{1/z\nu}} \right)$$

z dynamical critical exponent

ν correlation-length exponent



Boson localization

M.P.A. Fisher, Phys. Rev. Lett. **65**, 923 (1990)

- finite-size scaling of R_s
- linear log-log plot provides zν
- z=1: ν=7/3 consistent with universality class of quantum percolation

Isotherms R_s(t,T=const.)

- crossing point (t_c,R_c)
- strong exponential decrease of R_s with increasing t
- crossover to weak 1/t decrease

R. Schneider *et al.*, Phys. Rev. Lett. **108**, 257003 (2012)

Quantum percolation

D.-H. Lee *et al.*, Phys. Rev. Lett. **70**, 4130 (1993)

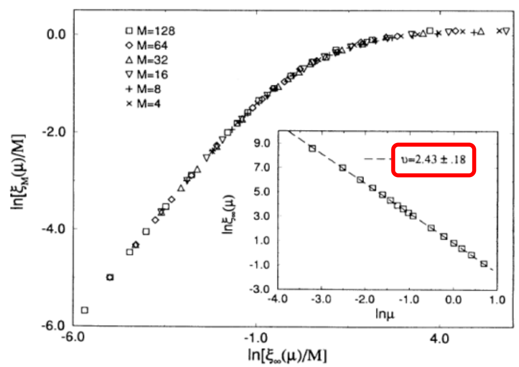
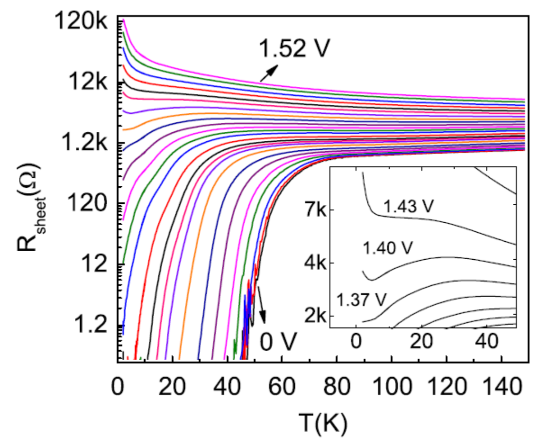


FIG. 3. The scaling plot for quantum percolation. Inset: $\ln\xi_\infty$ vs $\ln\mu$.

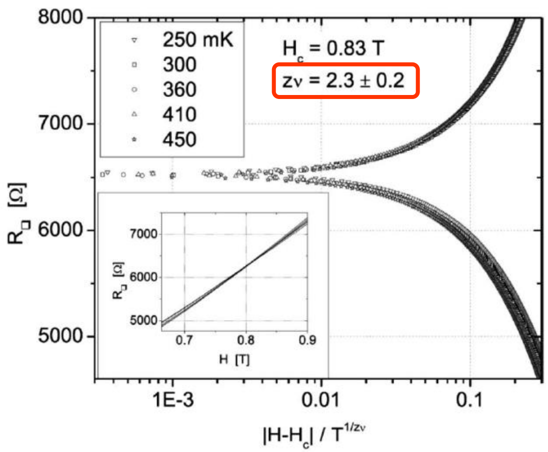
plateau transitions in quantum Hall liquids

X. Leng *et al.*, Phys. Rev. Lett. **107**, 027001 (2011)

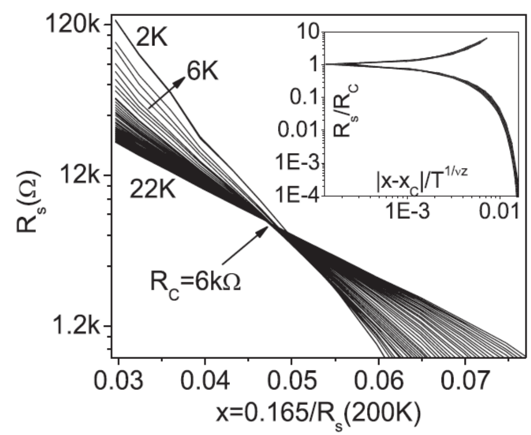
Ultrathin $YBa_2Cu_3O_{7-x}$ films



M.A. Steiner *et al.*, Phys. Rev. B **77**, 212501 (2008)

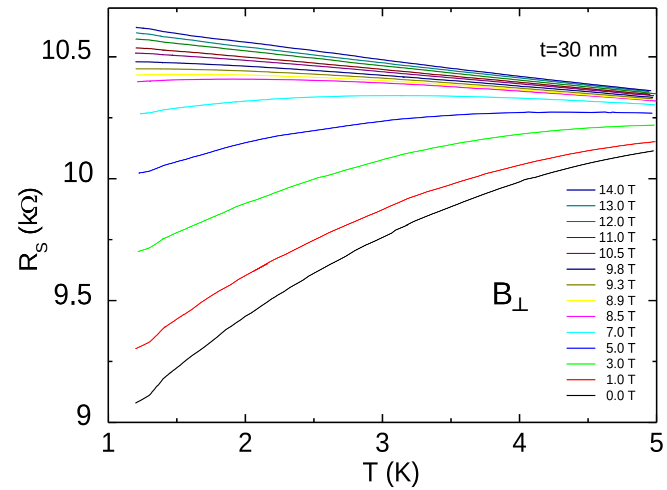


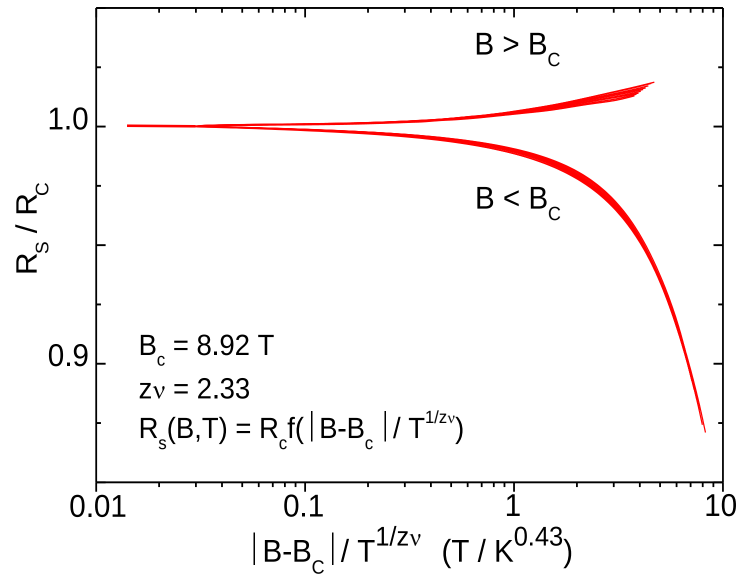
a-InO_x films

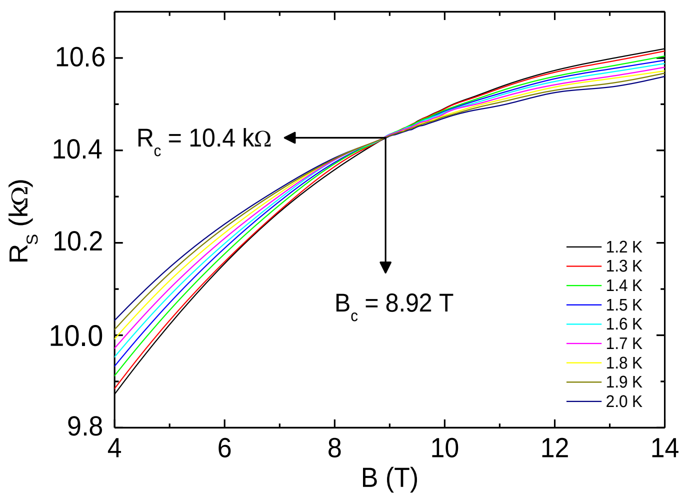


zν = 2.2

Magnetic-field induced SIT







Scaling of $R_s(B,T)$

- collapse of the branches $B<B_c$ and $B>B_c$ onto a single curve
- scaling prediction of the Bose-glass model independently confirmed

Isotherms $R_s(B,T\text{=constant})$

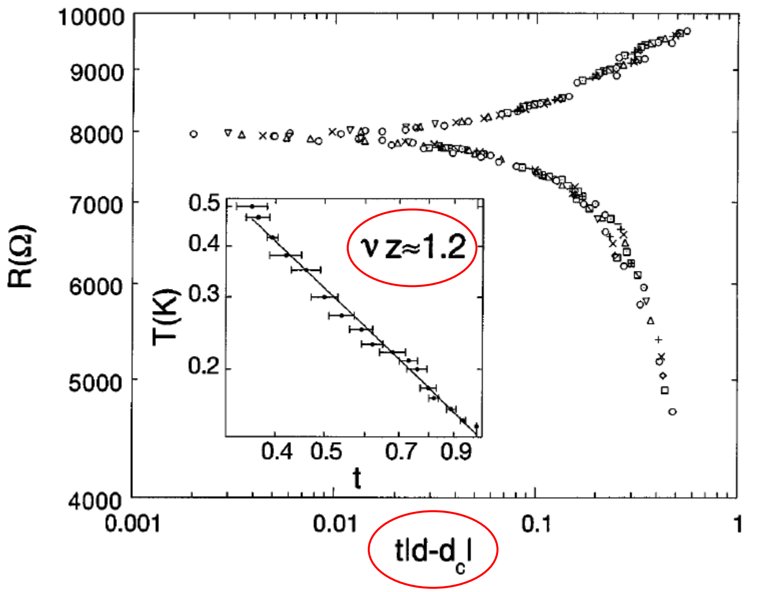
- crossing point (B_c, R_c)
- no magnetoresistance peak below 14 T

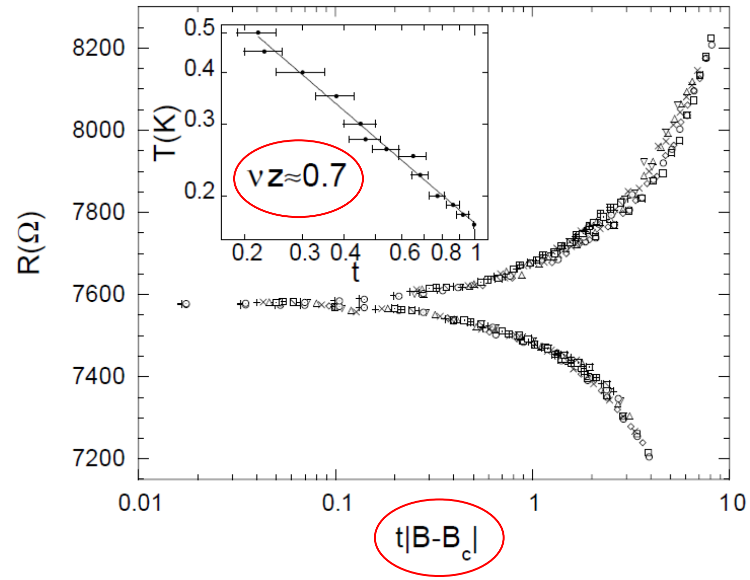
R. Schneider *et al.*, Phys. Rev. Lett. **108**, 257003 (2012)

Different tuning parameters

N. Marković *et al.*, Phys. Rev. Lett. **81**, 5217 (1998)

a - Bi





- thickness d tuned SIT
- $z\nu \approx 1.2$
- universality class of classical percolation in 2D
- describes SIT in a 2D disordered system

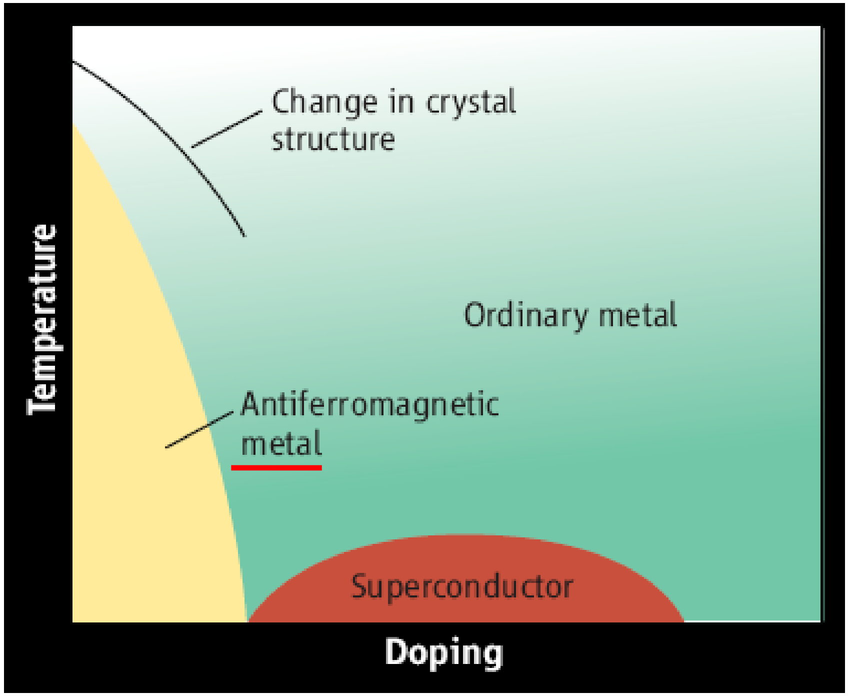
- magnetic field B tuned SIT
- $z\nu \approx 0.7$
- universality class of 3D XY model
- describes SIT in a 2D ordered system

Summary

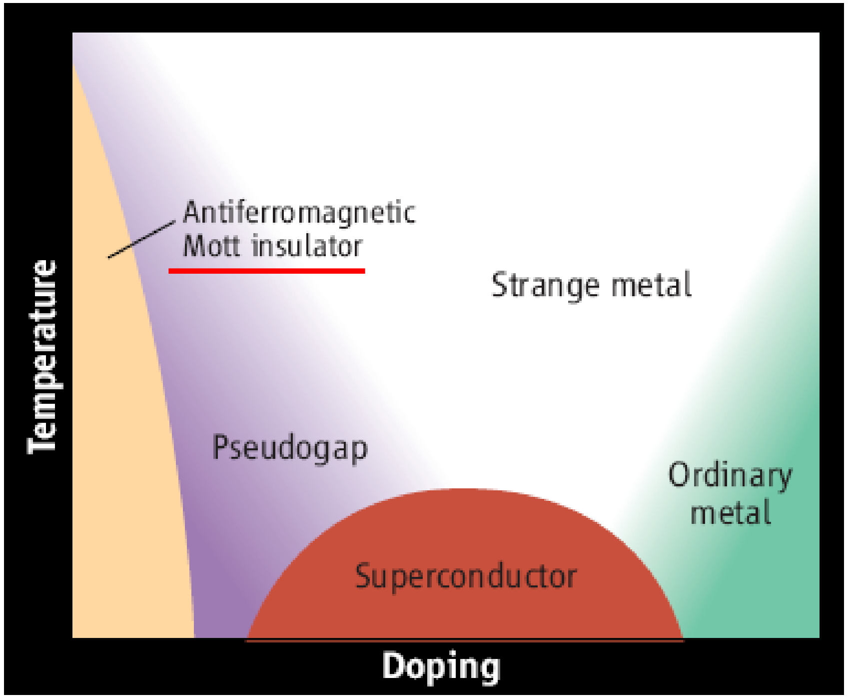
- reproducible synthesis of superconducting β-FeSe thin films by sputtering
- excess conductivity, BKT transition, large *Gi*
  - 2D character of superconductivity
  - importance of thermal fluctuations
- high sensitivity to disorder results in a thickness-driven SIT
- SIT also driven with magnetic field
- finite-size scaling according to the Bose-glass model
- universality class of quantum percolation

Temperature-doping phase diagrams

Magnetism and superconductivity



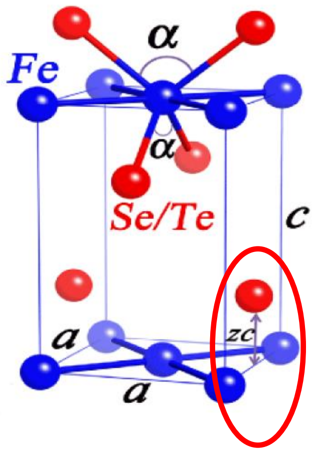
Fe-based superconductors

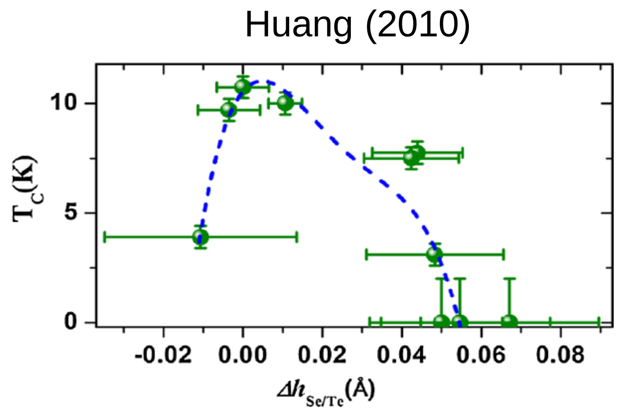


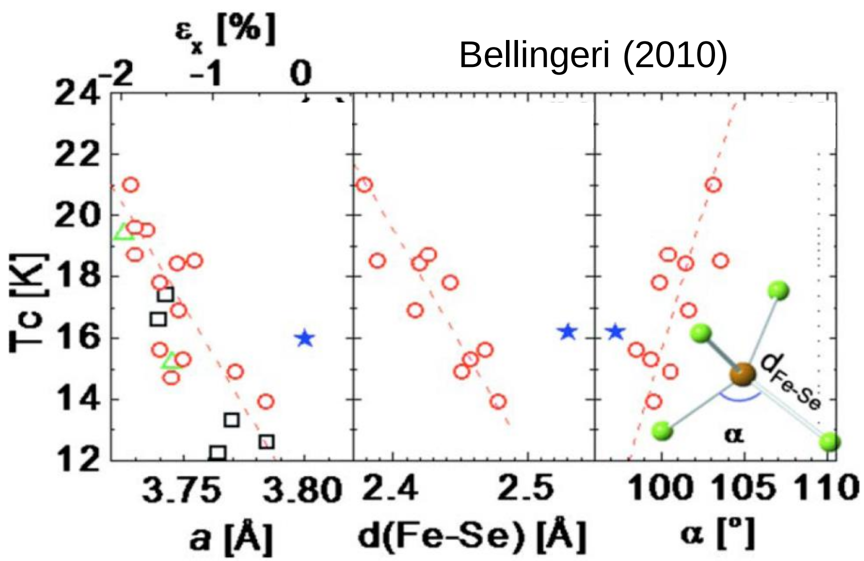
Cuprate superconductors

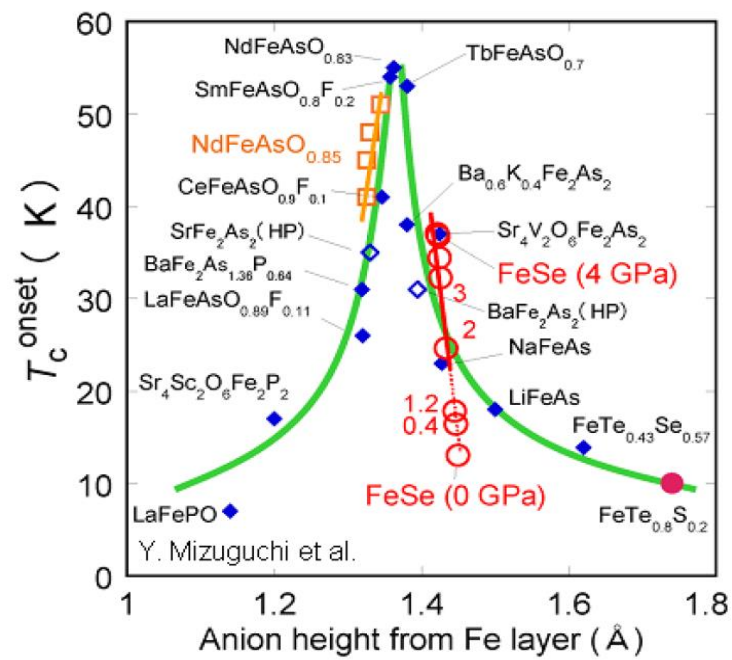
Cho (2010)

T_C and structural details

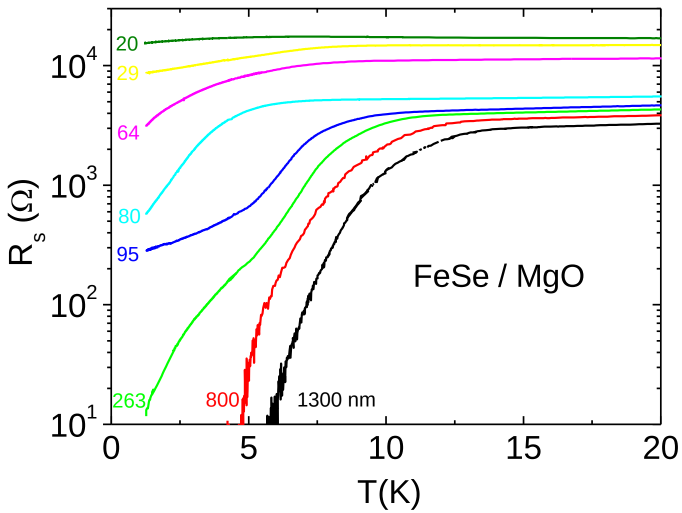


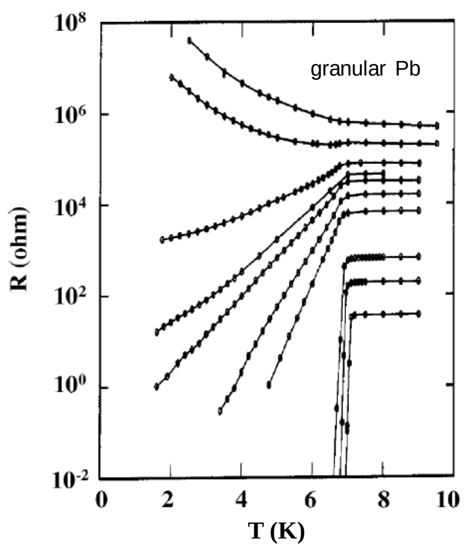




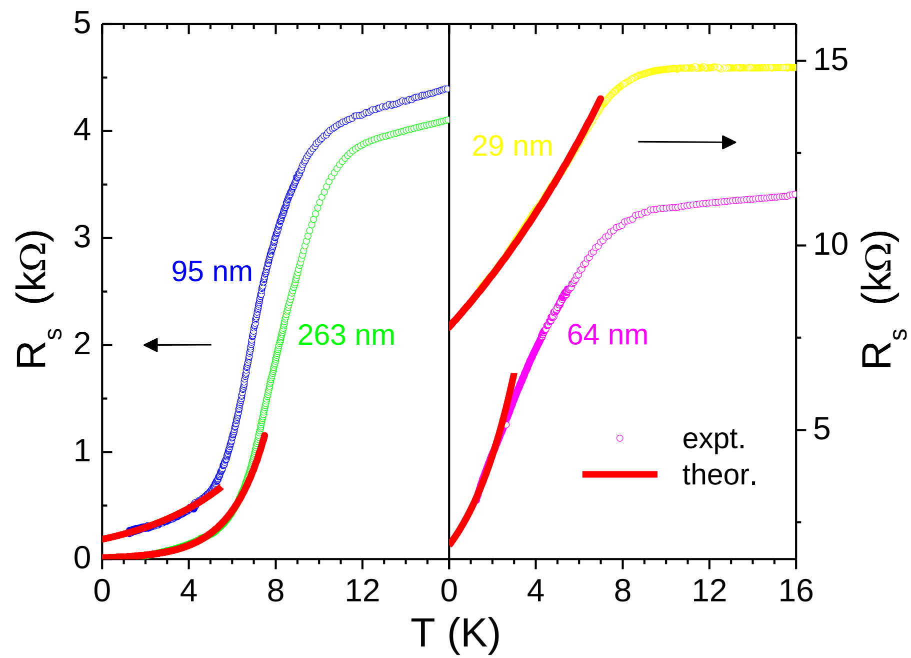


Resistance tails





A. Frydman, Physica C **391**,189 (2003)



- evolution of resistance tails
- described by „Inverse Arrhenius law"

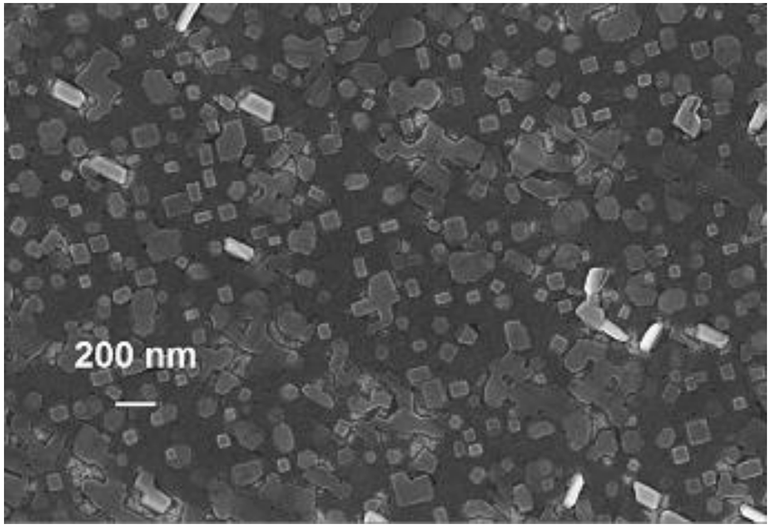
L. Merchant et al., Phys. Rev. B **63**, 134508 (2001)

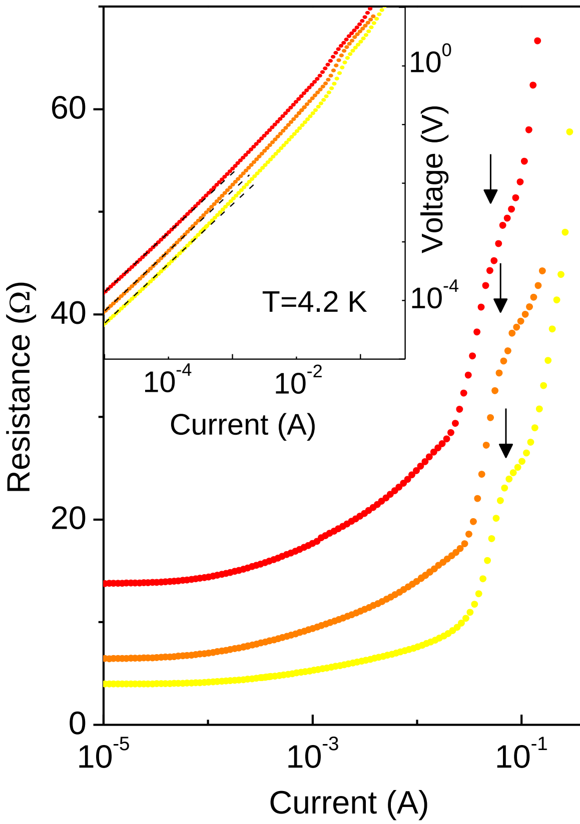
$$R_s(T) = R_s(0)\exp\left(\frac{T}{T_0}\right)$$

- typical for granularity

R. Schneider et al., Eur. Phys. J. B 88, 14 (2015)

Granularity and weak links





- 20-nm-thick film at the edge of the superconducting phase
- individual crystallites
- structureless homogeneous matrix

- nonlinearities in the V(I) characteristics
- current-dependent resistance R=V/I
- weak links with a broad distribution of low critical currents

Theory of boson localization

Fisher (1990)

- predicts a continuous SIT at T=0 as a result of the interplay of the attractive electron-electron interaction and the long-range coulomb repulsion
- SIT is a Quantum Phase Transition (QPT): Transition at T=0 between competing ground states of a quantum system when a parameter x in the Hamiltonian crosses a critical value

Bose Metal with $R_c = R_q = h / (2e)^2$

Superconductor | **Insulator**

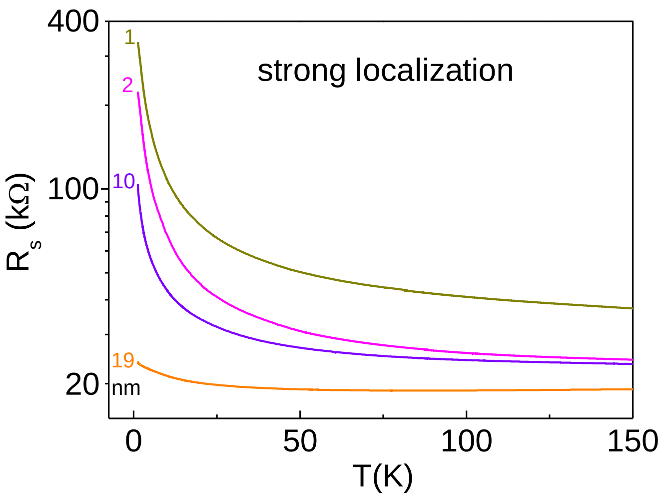
0 Quantum ordered phase | $\mathbf{X_c}$ | Quantum disordered phase **X**

Bound vortex-antivortex pairs —Disorder→ Unbound vortex-antivortex pairs

Condensed Cooper pairs, localized vortices —Magnetic Field→ Condensed vortices, localized Cooper pairs

Value of the critical sheet resistance R_c is *universal* (independent of the material system and the microscopic details) and is equal to the *quantum resistance R_q of electron pairs.*

Insulating phase



sequence of exponential G_s (T) dependencies

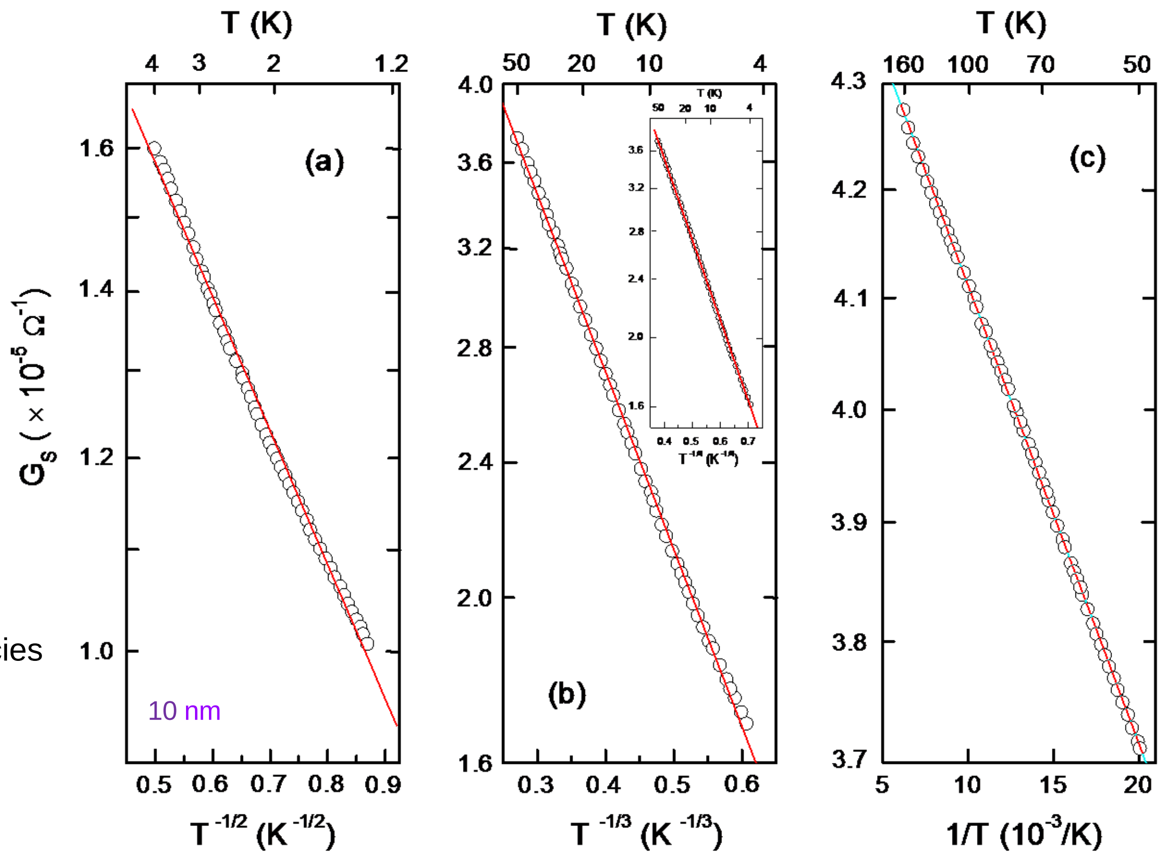
(a) T<4K   Efros-Shklovskii VRH

A.L. Efros, B.I. Shklovskii, J. Phys. C **8**, L49 (1975)

(b) 4K<T<50K   Mott VRH

N.F. Mott, J. Non-Cryst. Solids **1**, 1 (1968)

(c) 50K<T<160K   Arrhenius



$$G_s = A_0 \exp\left(-\left(\frac{T_0}{T}\right)^{1/2}\right)$$

soft Coulomb gap

$$G_s = A_1 \exp\left(-\left(\frac{T_1}{T}\right)^{1/3}\right)$$

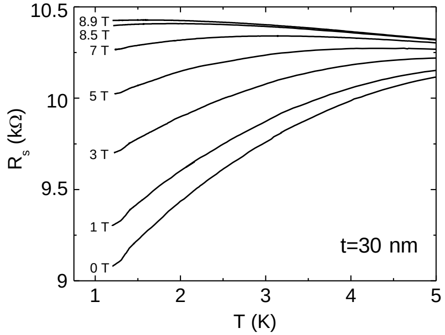
constant DOS

$$G_s = A_2 \exp\left(-\frac{\Delta E_A}{k_B T}\right)$$

hard gap

R. Schneider *et al.*, Eur. Phys. J. B **88**, 14 (2015)

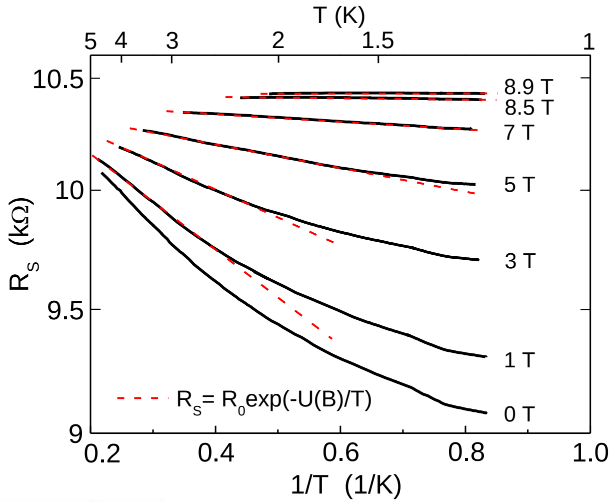
Superconducting phase in a magnetic field

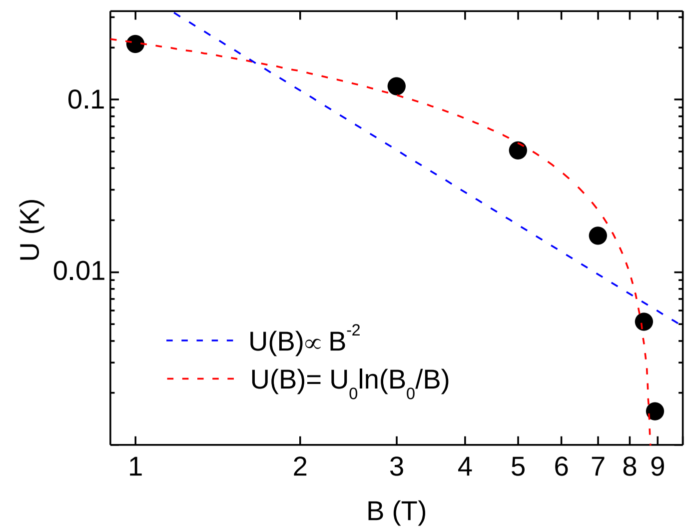


superconducting side of the B-SIT

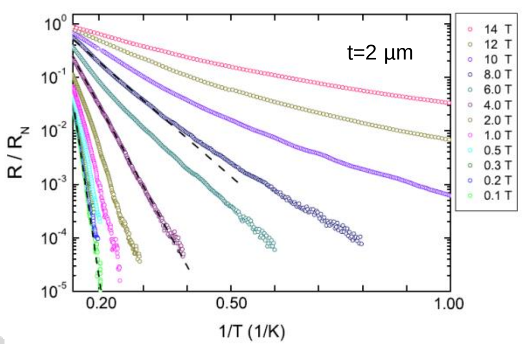
$$R_s = R_0 e^{-\frac{U(B)}{T}}$$

P.H. Kes *et al.*, Supercond. Sci. Technol. **1**, 242 (1989)





- logarithmic field dependence (U_0=0.098 K, B_0=8.85 T)
- possible creep-type dissipation mechanism
- small values of U, low pinning barriers
- power-law fit definitely fails

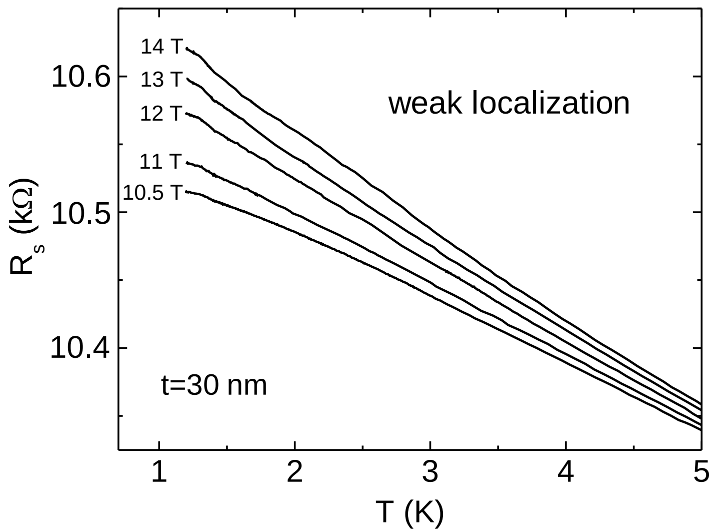


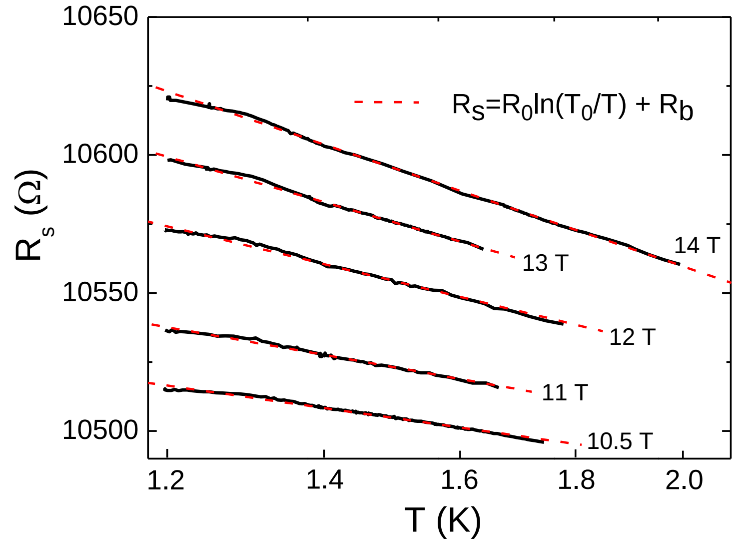
comparison with „bulklike“ FeSe film

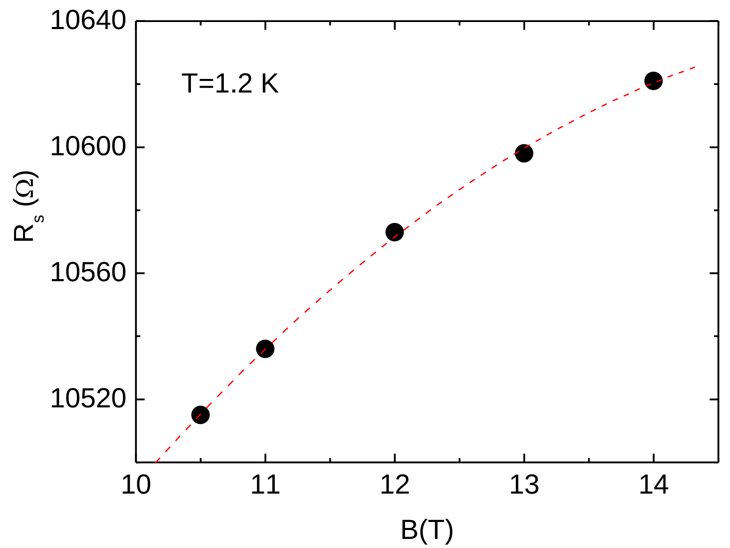
A.G. Zaitsev *et al.*, J. Phys. Conf. Ser. **507**, 012054 (2014)

R. Schneider *et al.*, J. Low Temp. Phys. **178**, 118 (2015)

Insulating phase in a magnetic field







$$R_s = R_0 \ln\left(\frac{T_0}{T}\right) + R_b$$

D. Das, S. Doniach, Phys. Rev. B **57**, 14440 (1998)

- weakly localized Cooper pairs (Bose glass)
- vortices in a quantum liquid phase
- crossover from ln to exp T - dependence
- in line with bosonic description of SIT

R. Schneider *et al.*, J. Low Temp. Phys. **178**, 118 (2015)