High-field termination of a Cooper-pair insulator

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Localization, Interaction, and Superconductivity
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DE LA RECHERCHE À L'INDUSTRIE
cea

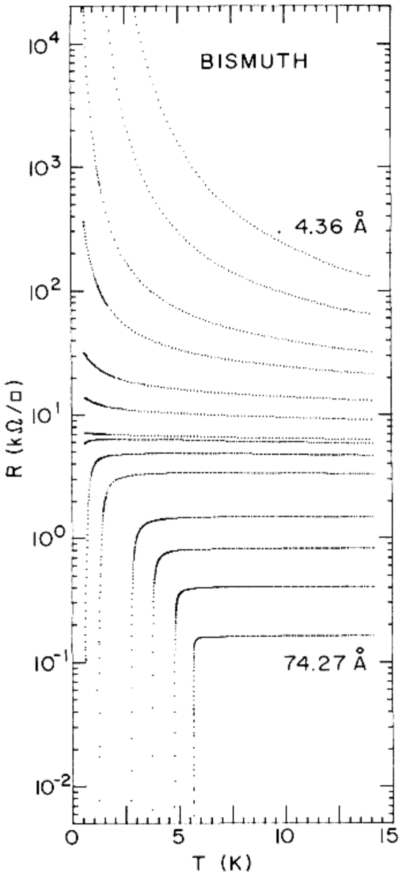
Benjamin Piot

LNCMI

Our playground: thin superconducting films

Superconductor-to-insulator quantum phase transition (SIT)

Quench condensed Bismuth films



D.B. Haviland, Y. Lui, A.M. Goldman, *PRL* ('89)

Measure of disorder: sheet resistance

$$R_{\square} = \frac{\rho}{d}$$

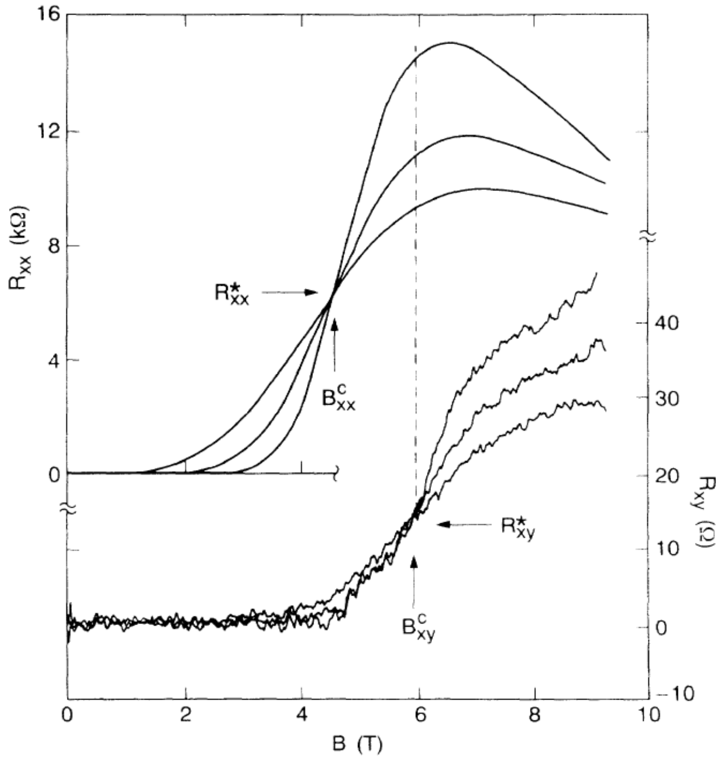
Resistivity

Thickness

Our playground: thin superconducting films

B-tuned SIT

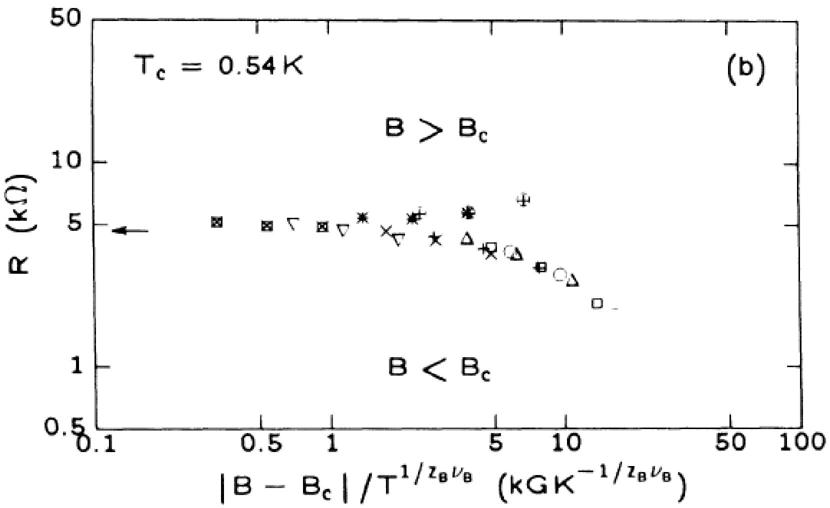
Amorphous InOx films



M. Paalanen, A. Hebard, R. Ruel, *PRL* (‘92)

Finite size scaling

$$\frac{R}{R_c} = f\left(\frac{|B - B_c|}{T^{\frac{1}{z\nu}}}\right)$$

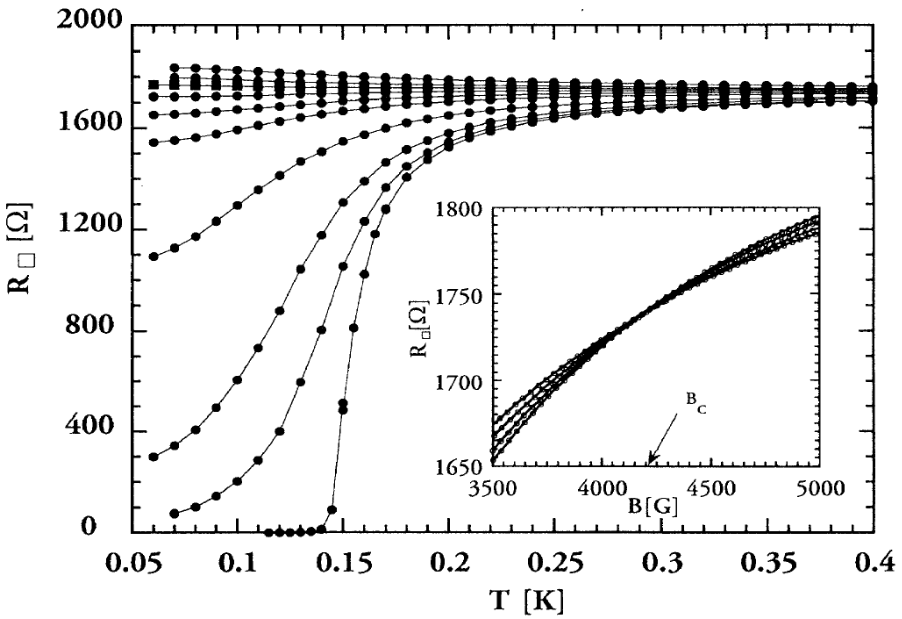


A. Hebard, M. Paalanen, *PRL* (‘90)

Our playground: thin superconducting films

B-tuned SIT

Amorphous MoGe films



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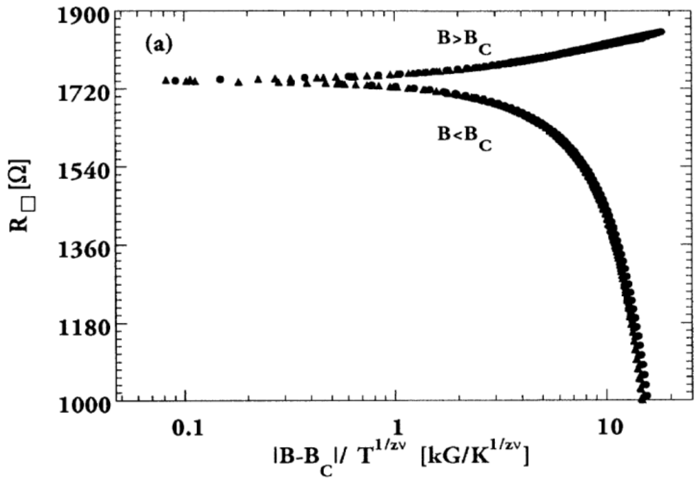


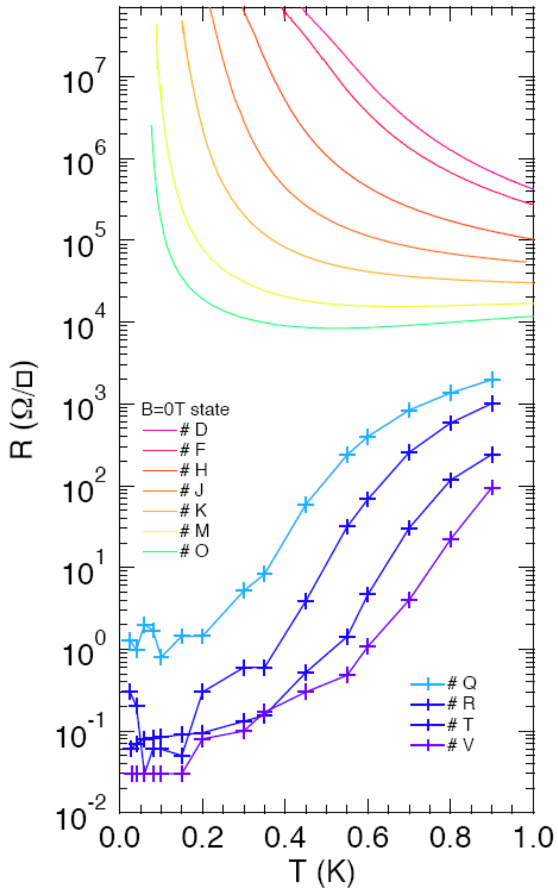
A. Yazdani & A. Kapitulnik *PRL* (‘95)

(*Critical exponents on different materials:* $0{,}7 < z\nu < 2{,}3$)

Direct superconductor-insulator transition

Amorphous indium oxide films

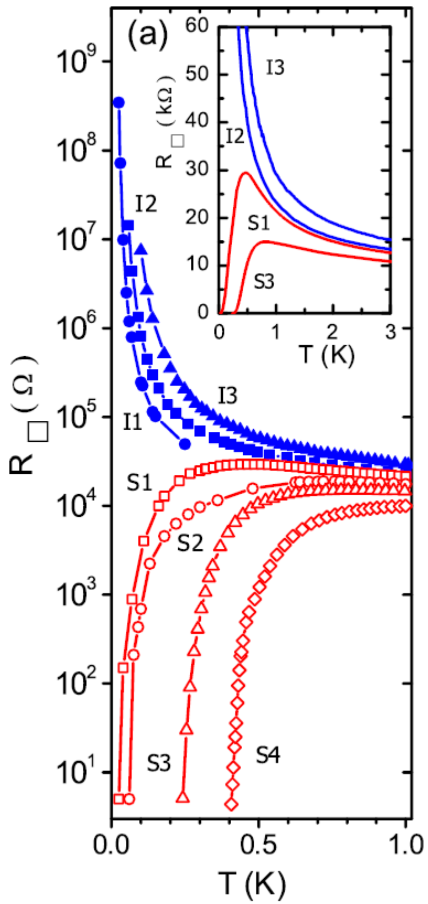
D. Shahar's group



$n \lesssim 10^{21} cm^{-3}$

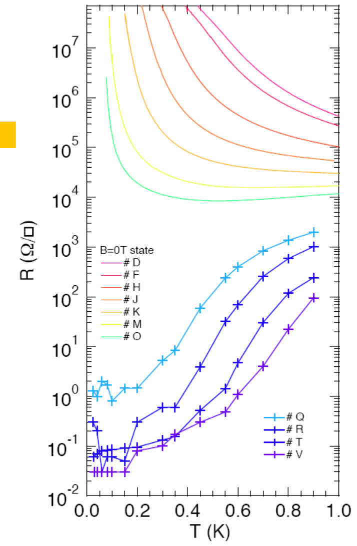
Titanium nitride

T. Baturina PRLs ('07)

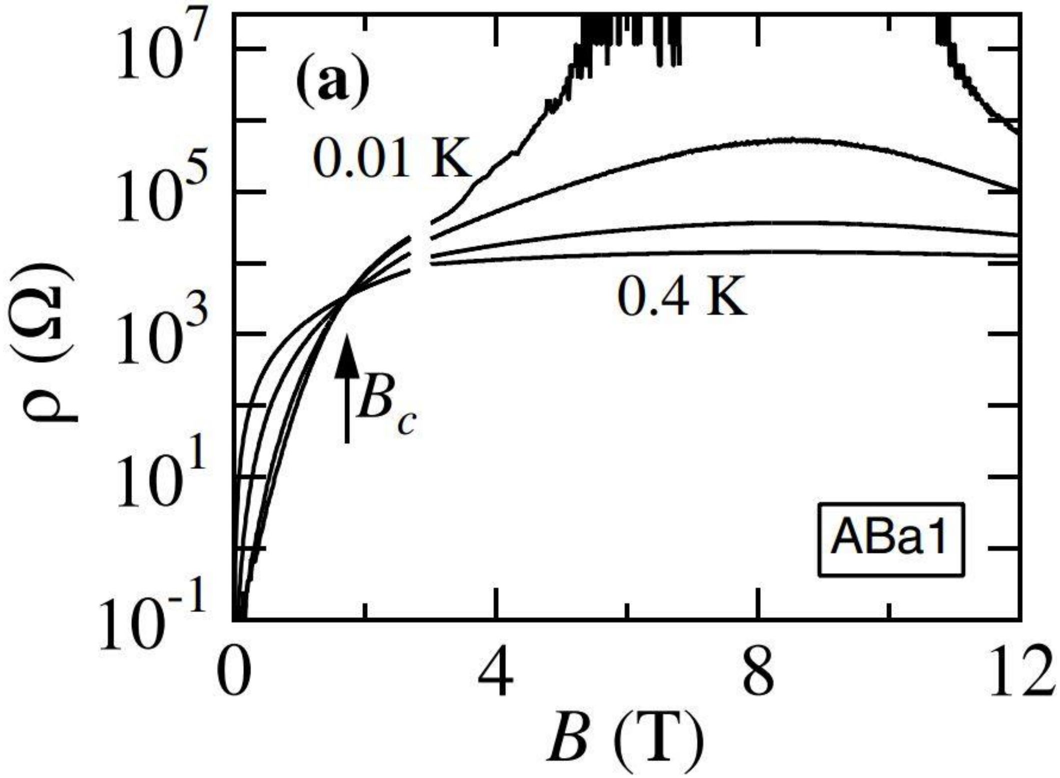


$n \sim 10^{22} cm^{-3}$

Direct superconductor-insulator transition



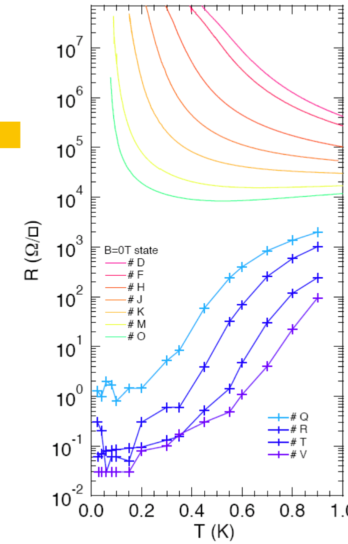
B-induced transition: Giant magneto-resistance peak



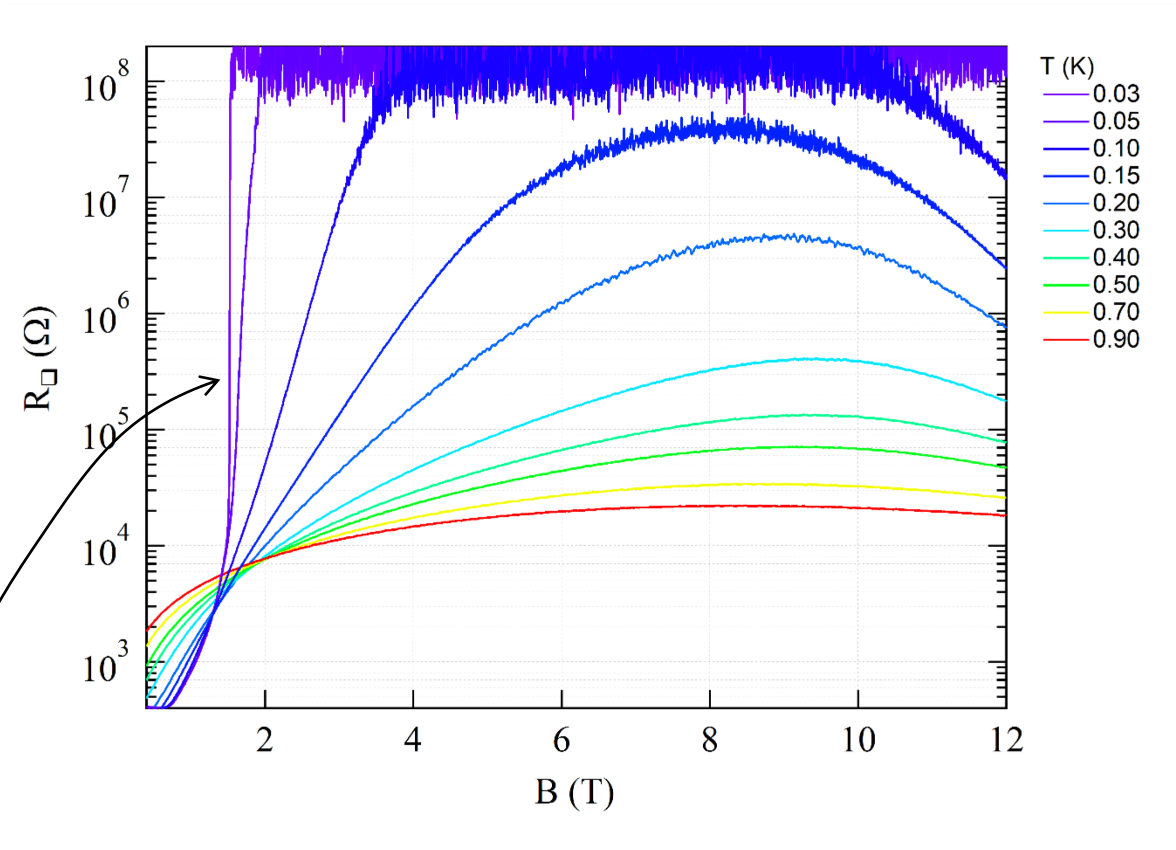
Sambandamurthy et. al. *PRL* ('05)

See also TiN films: Baturina et al. *PRLs* ('07)

Direct superconductor-insulator transition

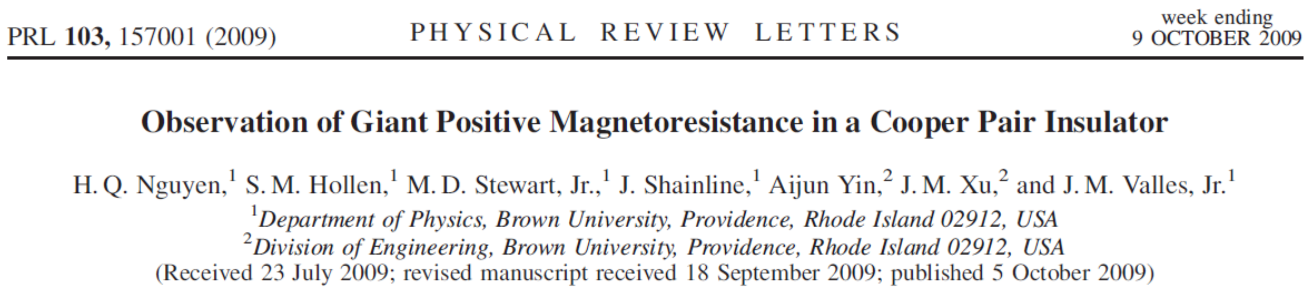


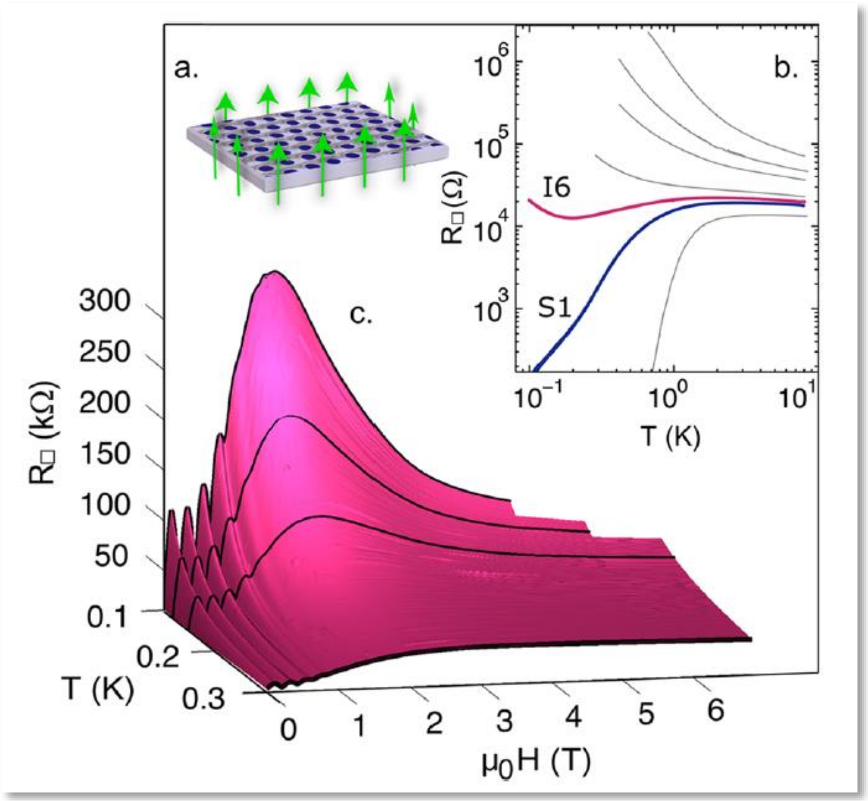
B-induced transition: Giant magneto-resistance peak

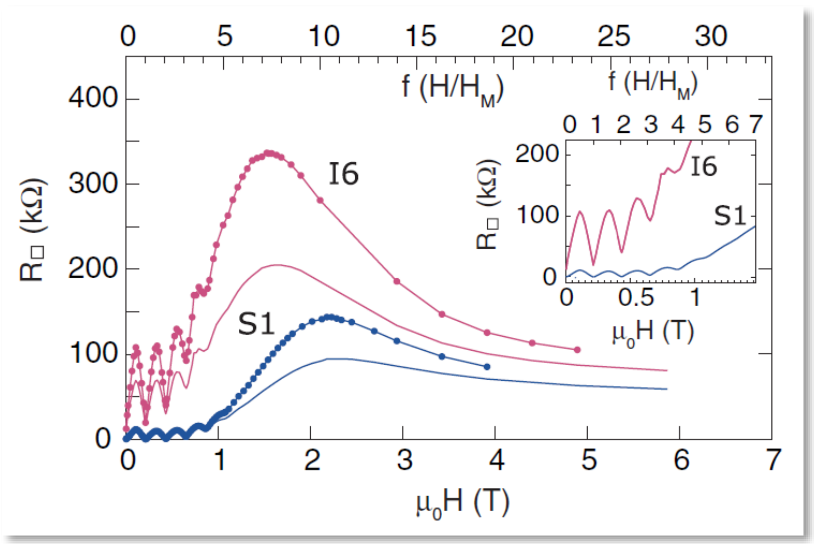


R raises by 1 decade per 0.01 tesla

Cooper-pair insulator



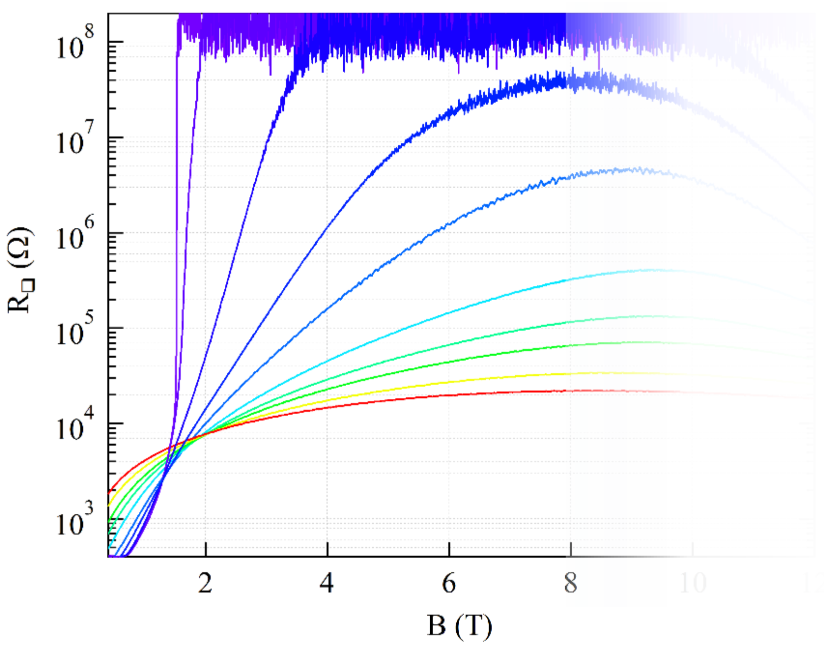




J. Valles group, *Science* ('07), *PRL* ('09)
D. Shahar group, *PRL* ('12)

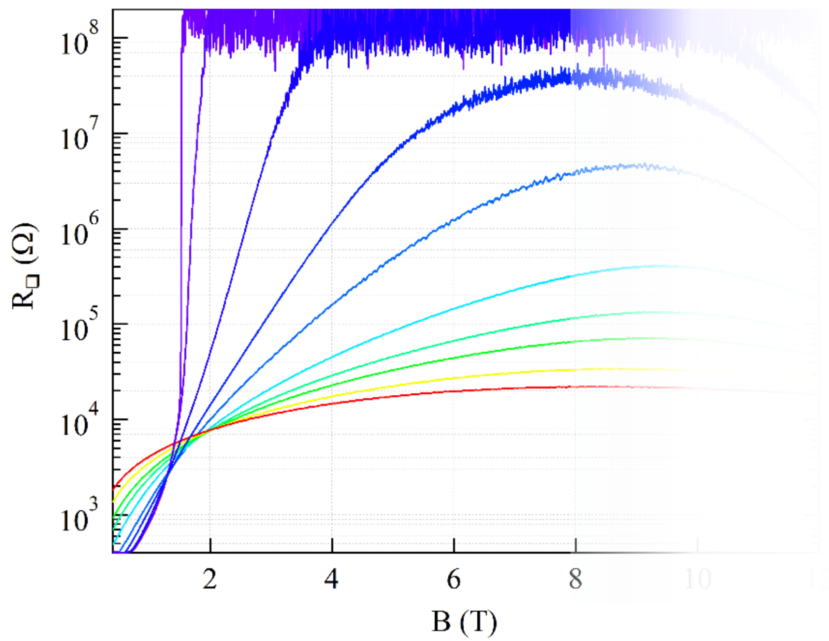
B-tuned superconductor-insulator transition

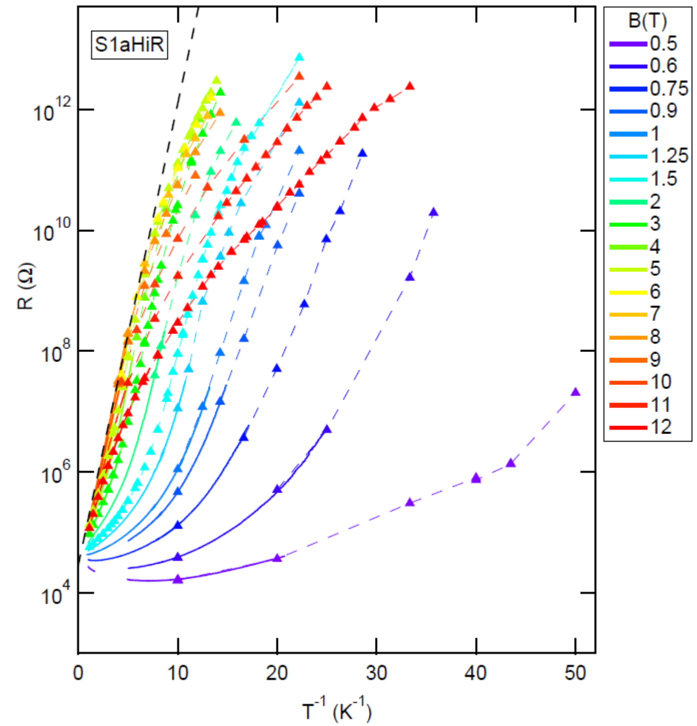
« Cooper-pair insulator »
« Bose insulator »
…



B-tuned superconductor-insulator transition

« Cooper-pair insulator »
« Bose insulator »
MBL ???





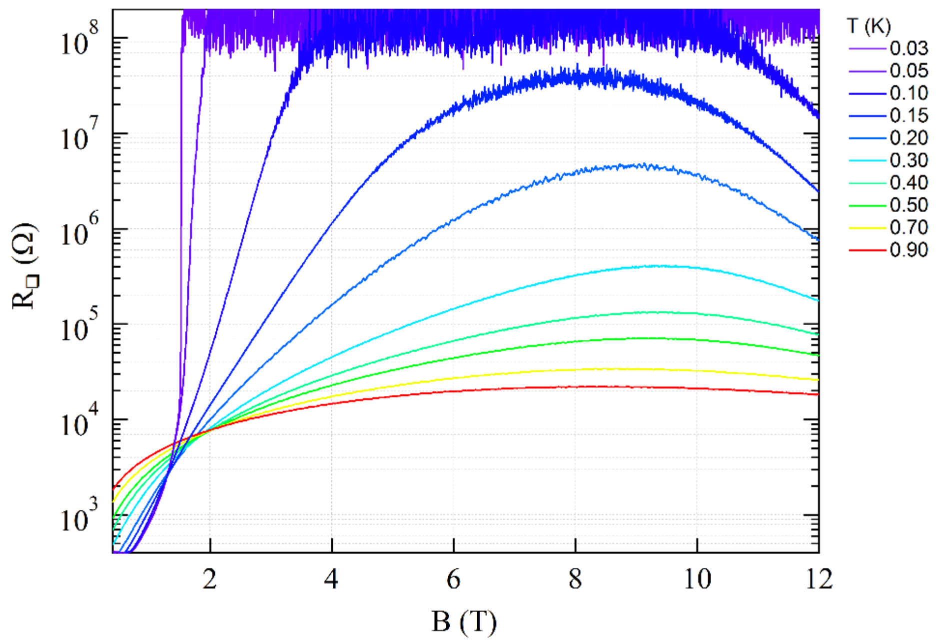
Cooper-pair insulator: R diverges faster than activation

See Idan Tamir talk: « A finite temperature insulator ? »

B-tuned superconductor-insulator transition

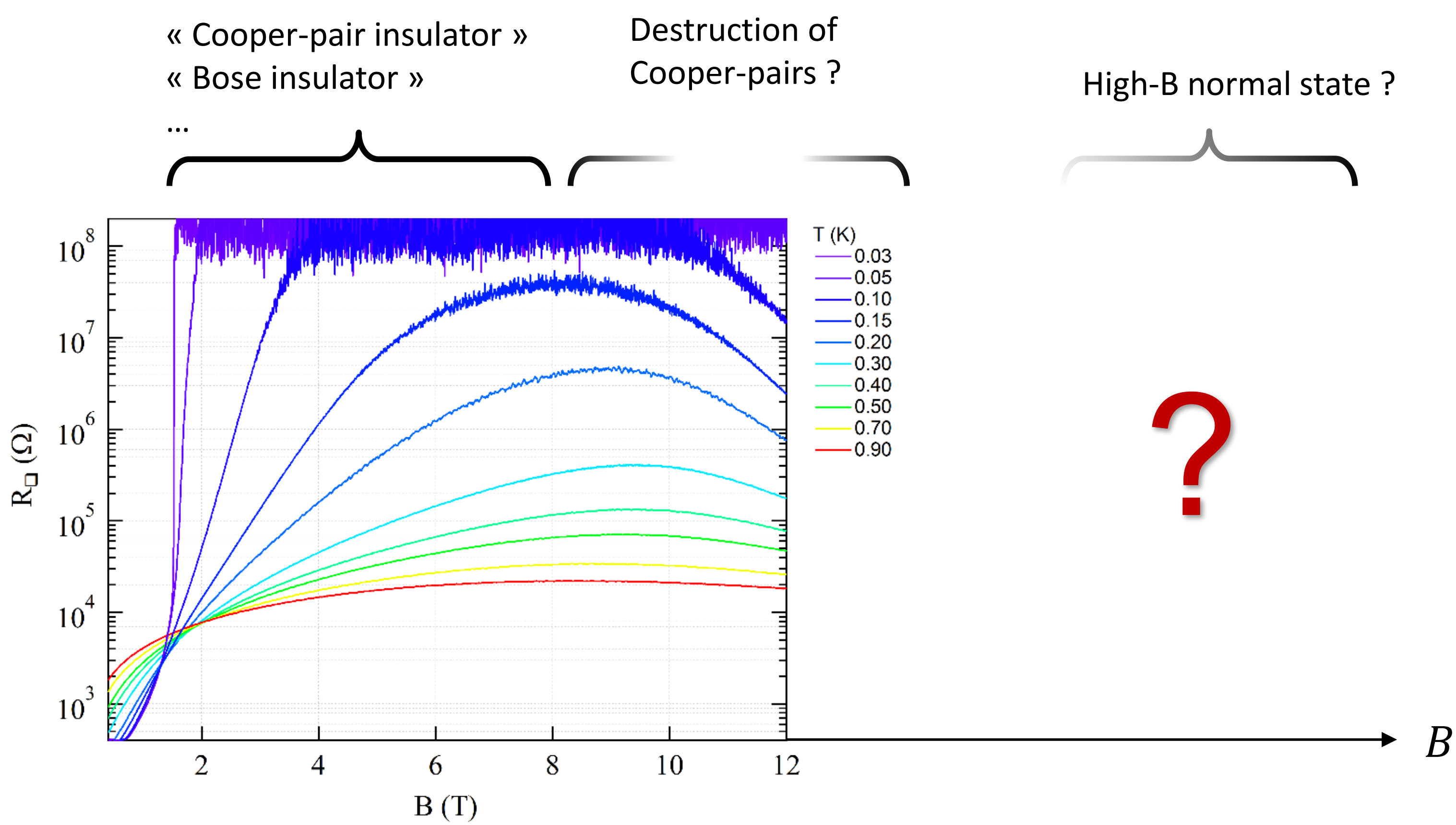
« Cooper-pair insulator »
« Bose insulator »
…

Destruction of
Cooper-pairs ?



Q1: Does Cooper pairing survive up to 12 T ?

B-tuned superconductor-insulator transition

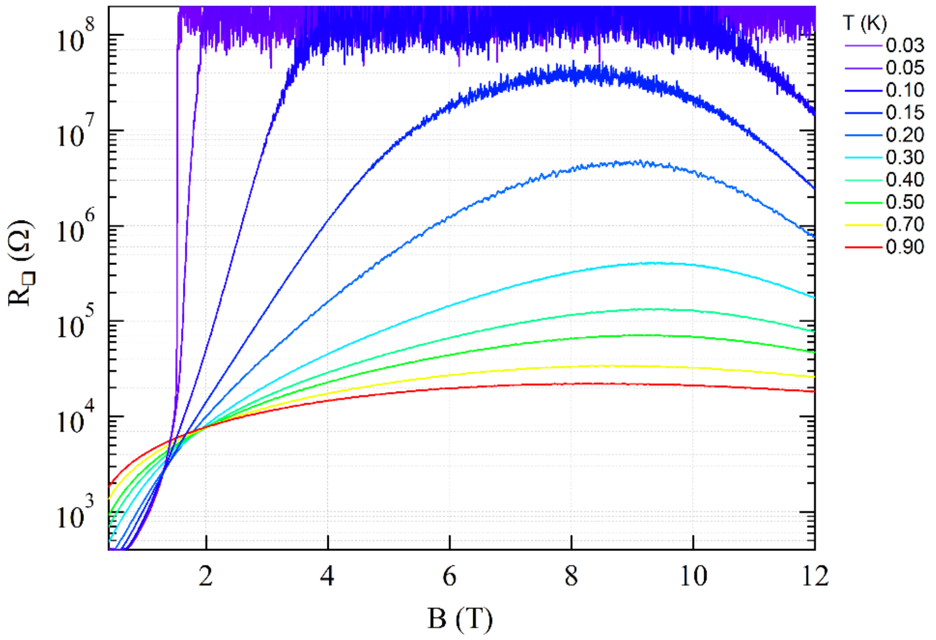


Q1: Does Cooper pairing survive up to 12 T ?

Q2: What's the high-B normal state ?

B-tuned superconductor-insulator transition

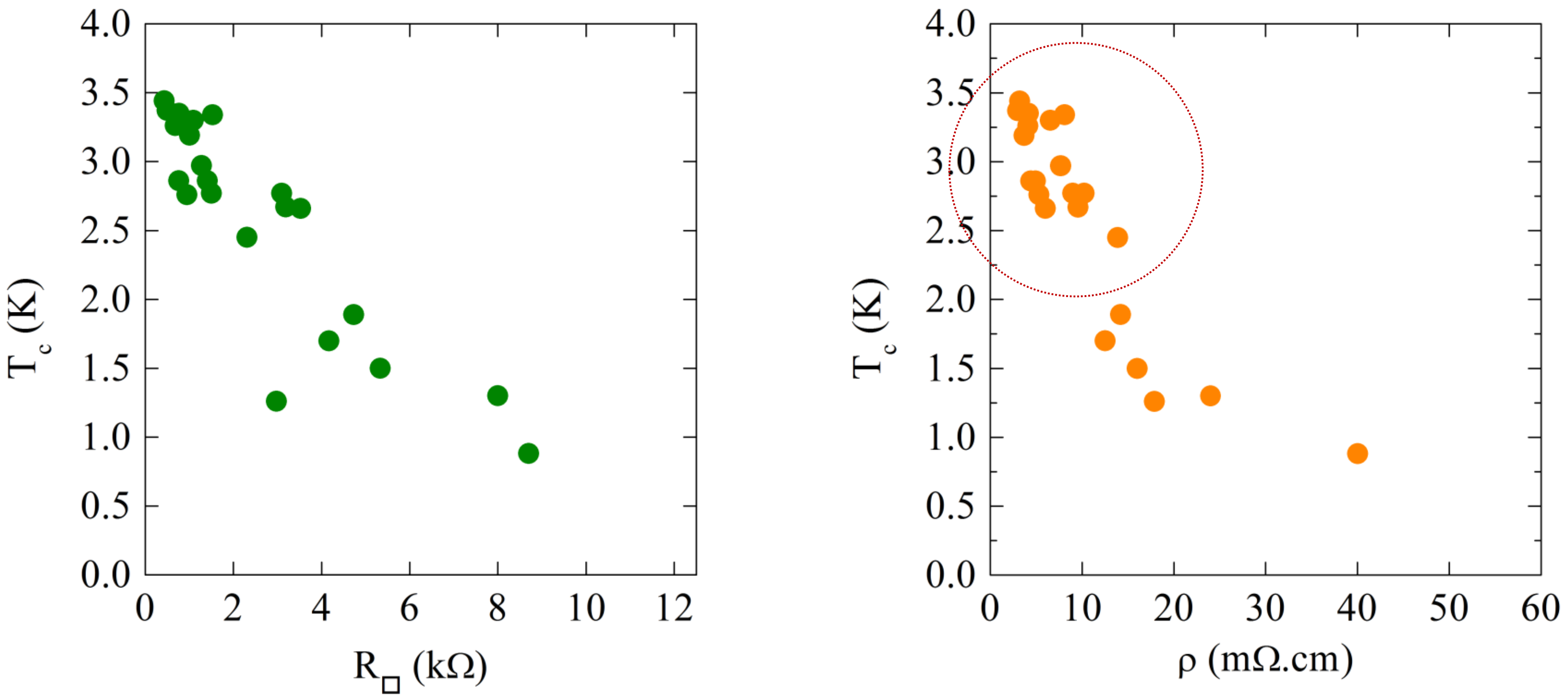
Q1: Does Cooper pairing survive up to 12 T ?



Low disorder InOx films far from SIT

« Low disorder » amorphous InOx films

- E-gun evaporation of In_2O_3 on SiO_2 under O_2 pressure
- 60 nm thick
- $k_F l_e < 1$
- $T_c \geq 2K$



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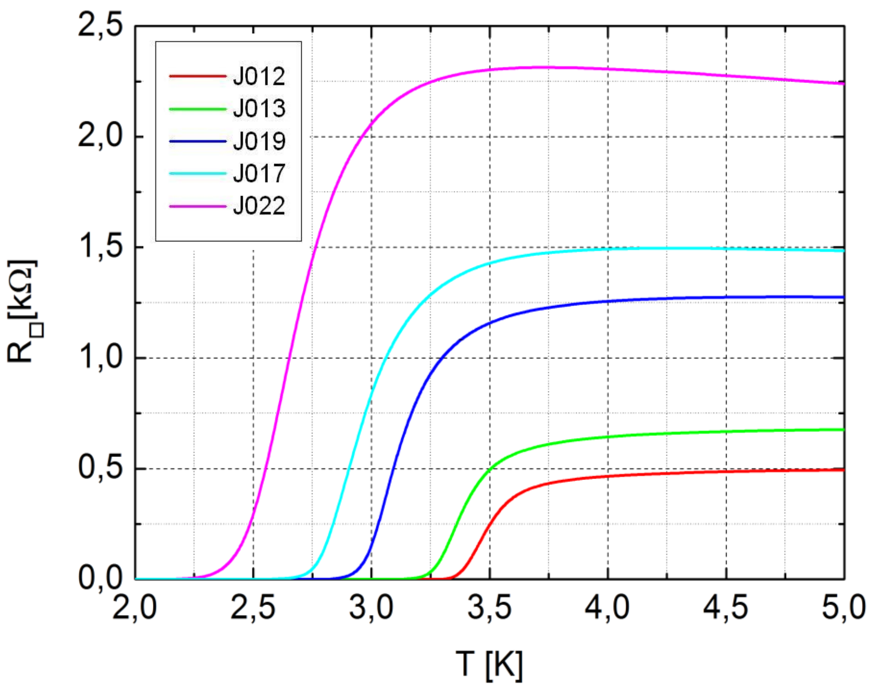
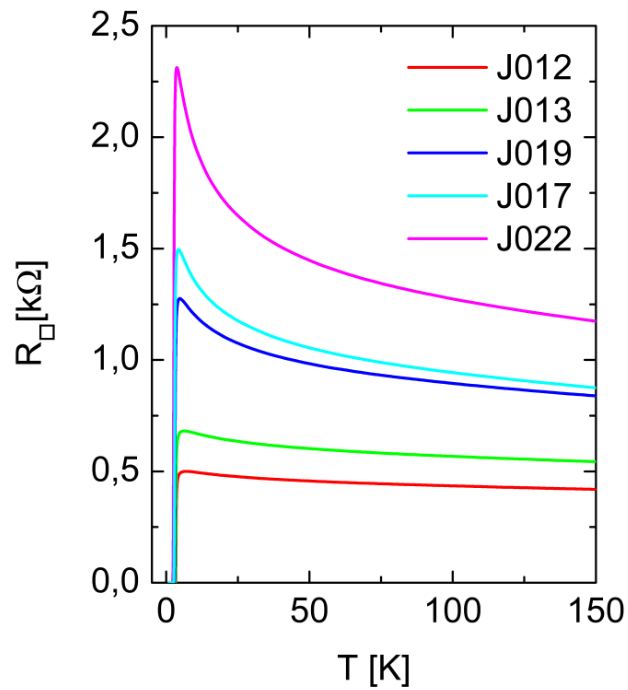
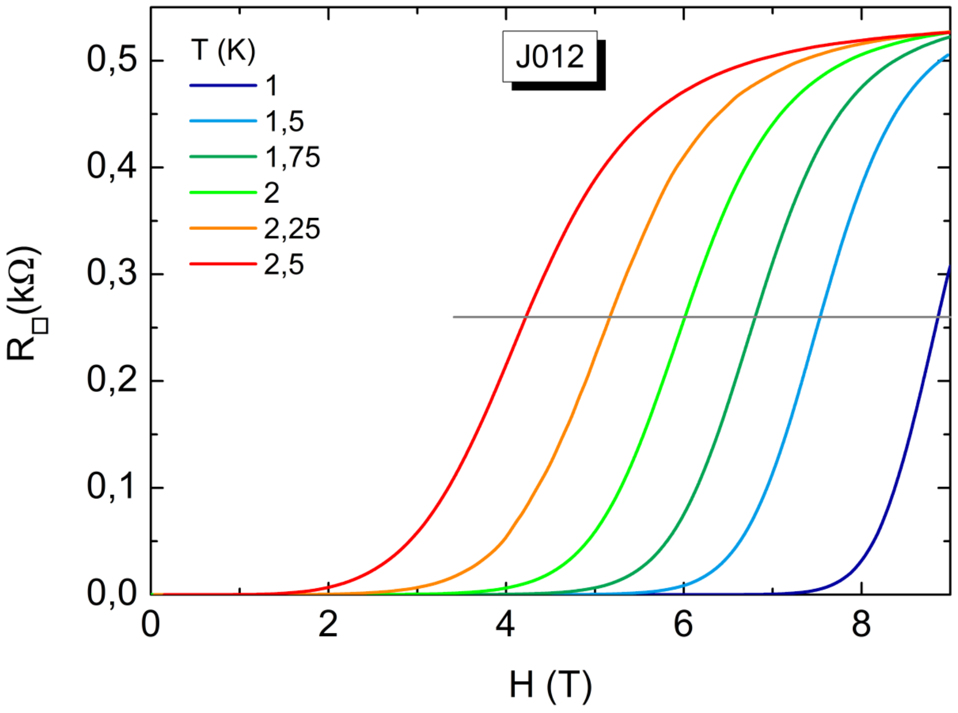
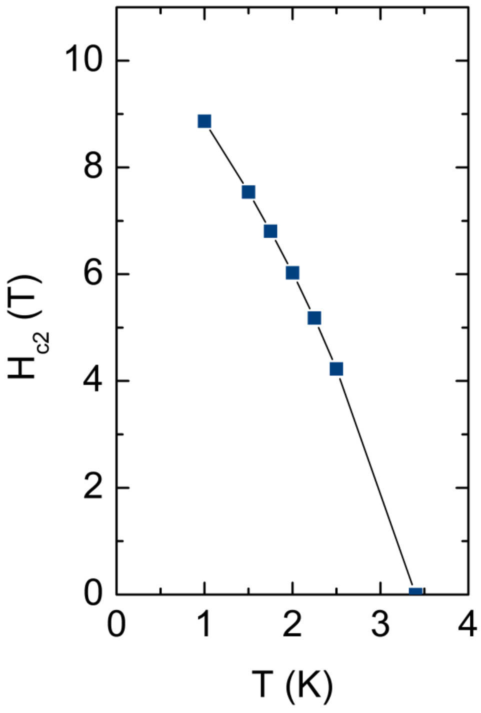




Low disorder InOx films

Magneto-resistance isotherm

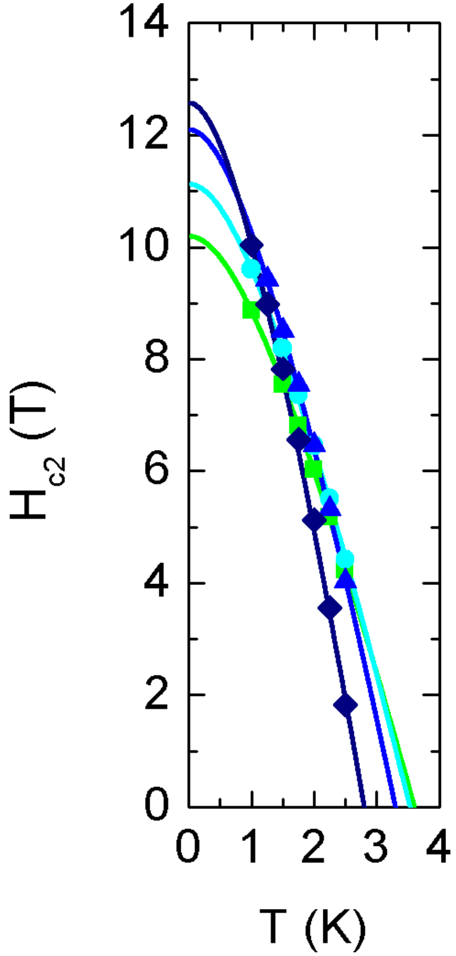




Usual behavior for dirty superconductors

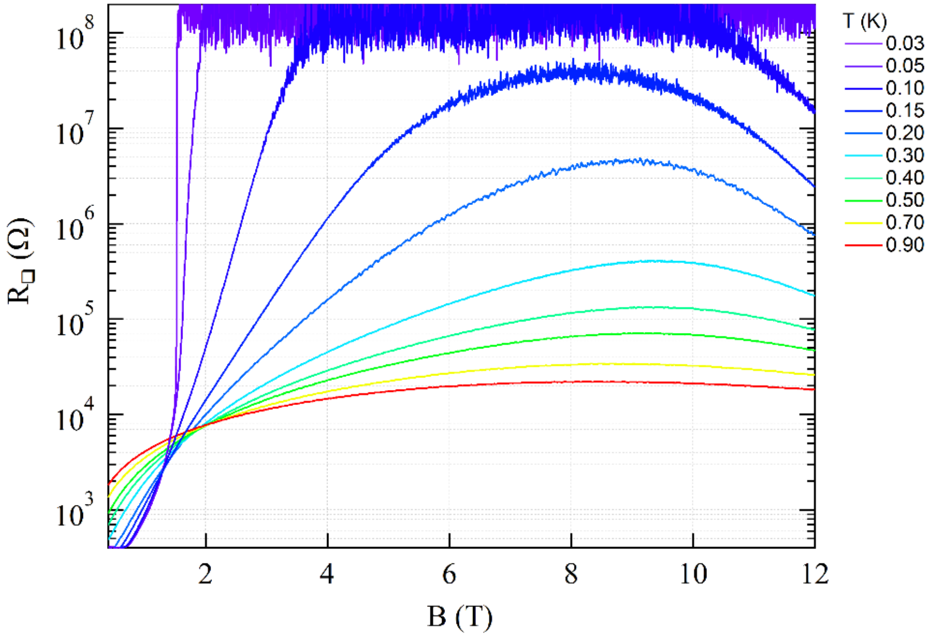
Low disorder InOx films

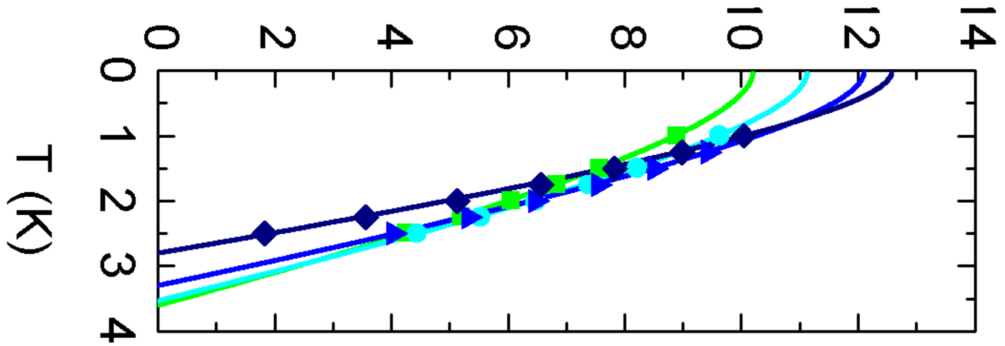
Q1: Does Cooper pairing survive up to 12 T ? **YES**



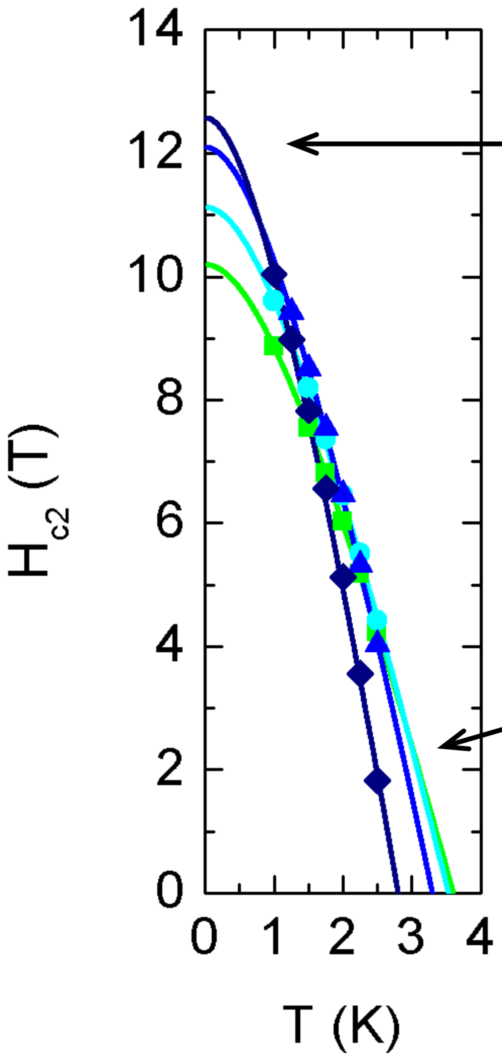
InOx films far from SIT

Q1: Does Cooper pairing survive up to 12 T ? **YES**





Superconducting parameters



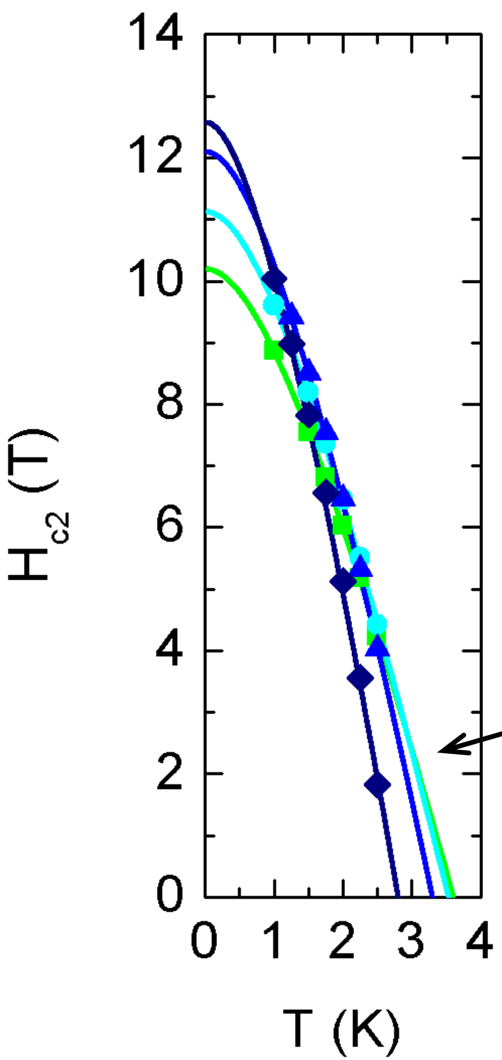
Superconducting coherence length

$$H_{c2}(0) \quad \Longrightarrow \quad \xi_d \approx 4.0 - 4.7\ nm$$

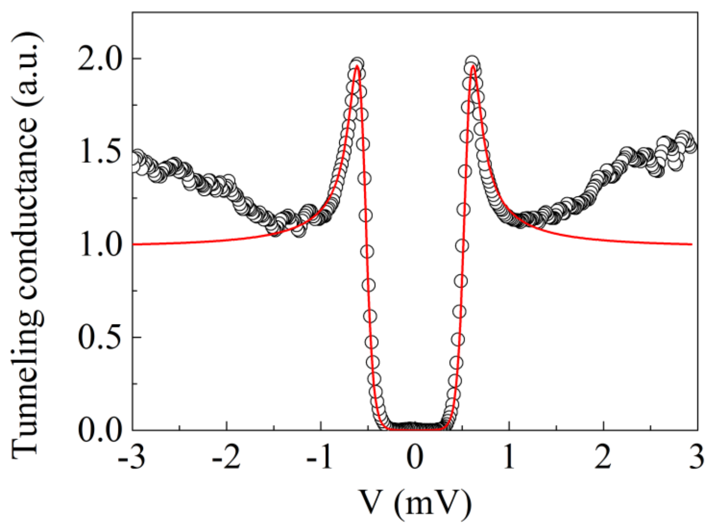
Diffusion coefficient

$$\frac{dH_{c2}}{dT} \propto -\frac{1}{D} \quad \Longrightarrow \quad D \approx 0.18 - 0.28\ \ cm^2/s$$

Superconducting parameters



STM data



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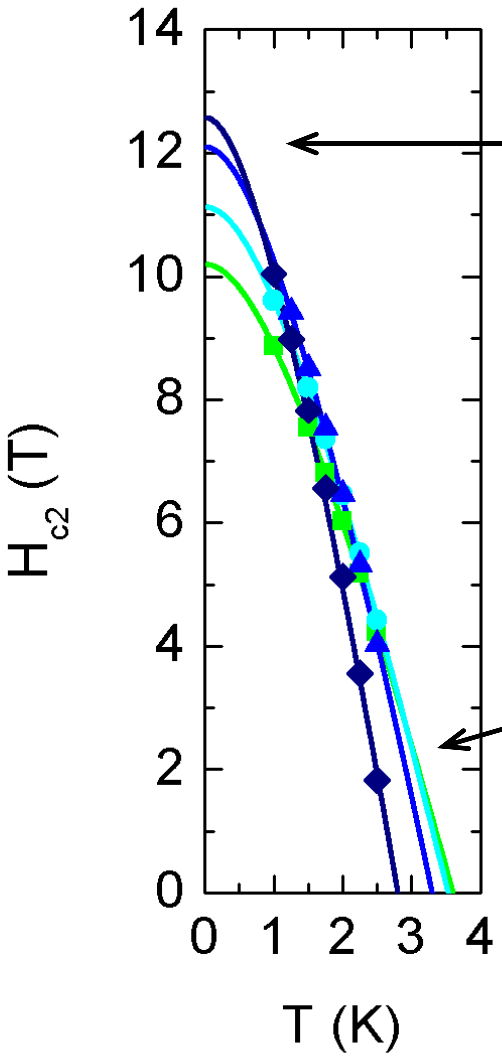
Superconducting gap (STM data)

$$\Delta = 550 \; \mu eV \quad \Longrightarrow \quad \xi_d = 0.83\sqrt{\frac{\hbar D}{\Delta}} \approx 4 \; nm$$

Superconducting parameters



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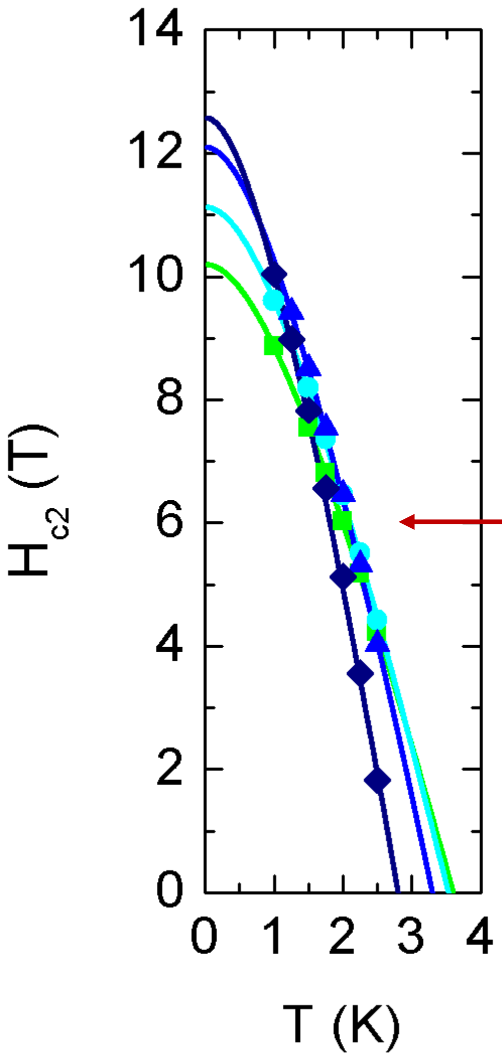
Superconductivity is not quasi 2D in InOx

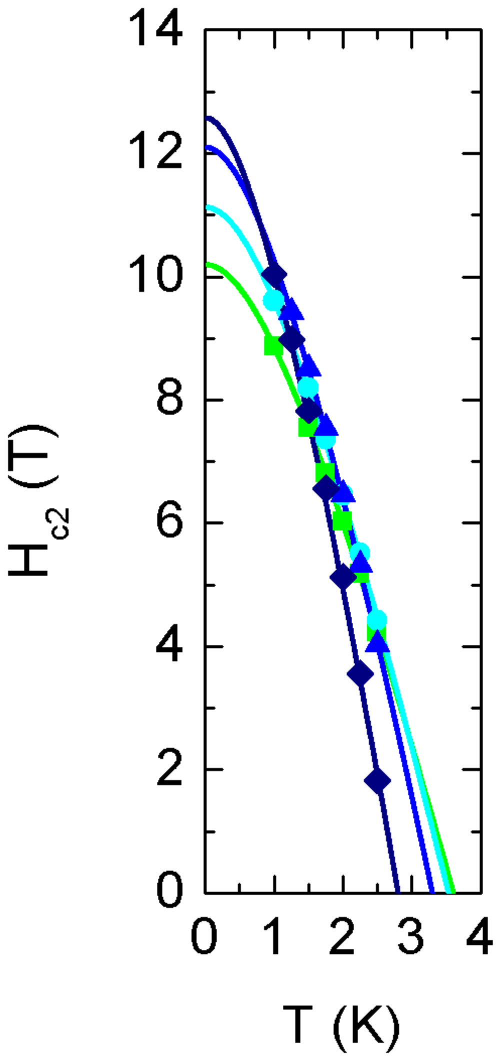
Superconducting parameters



$H_p = 1.8\, T_c \sim 6\, T$!?

Where is the Pauli limit ???

Absence of Pauli limit due to spin-orbit scattering on In atoms



Estimate of the Pauli field with spin-orbit scattering

$$\chi_S/\chi_N \simeq 1 - 2\,\Delta\tau_{so}/\hbar \quad \text{for} \quad \Delta \ll \hbar/\tau_{so}$$

$$\Rightarrow \qquad B_p \propto \frac{1}{\mu_B}\frac{\Delta}{\sqrt{\Delta\tau_{so}/\hbar}}$$

Anderson *PRL* ('59)
Clogston *PRL* ('62)
Feigelman private comm.

Estimate of τ_{so} in InOx

$$\tau_{so} = \frac{\tau}{(Z\alpha)^4} \sim 60.\,\tau$$

$\alpha \simeq 1/137$

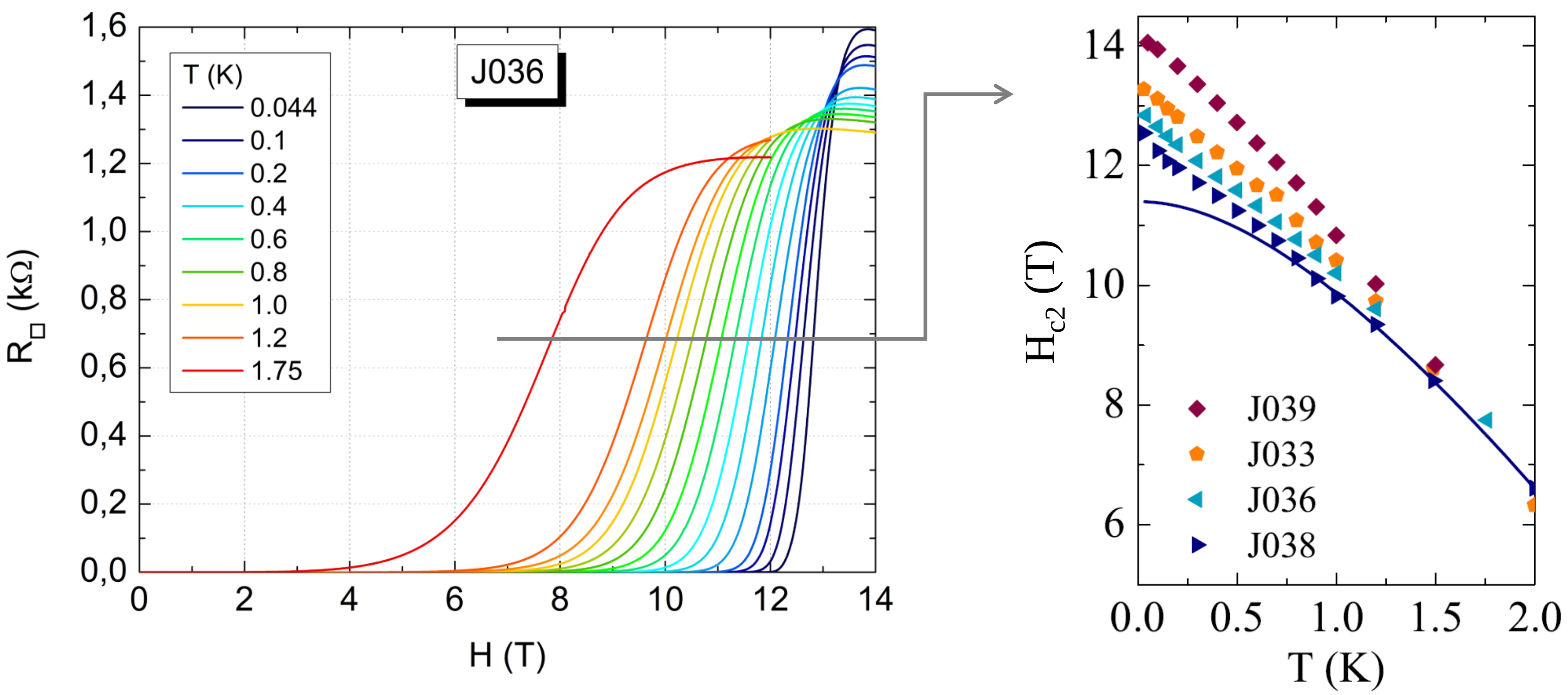
Abrikosov, Gor'kov ('62)

With $\tau \sim 3.10^{-16}\,s \quad \Rightarrow \quad \tau_{so} \sim 2.10^{-14}\,s$

$$\Rightarrow \qquad \frac{1}{\sqrt{\Delta\tau_{so}/\hbar}} \sim 10$$

H_{c2} is limited by orbital effect only

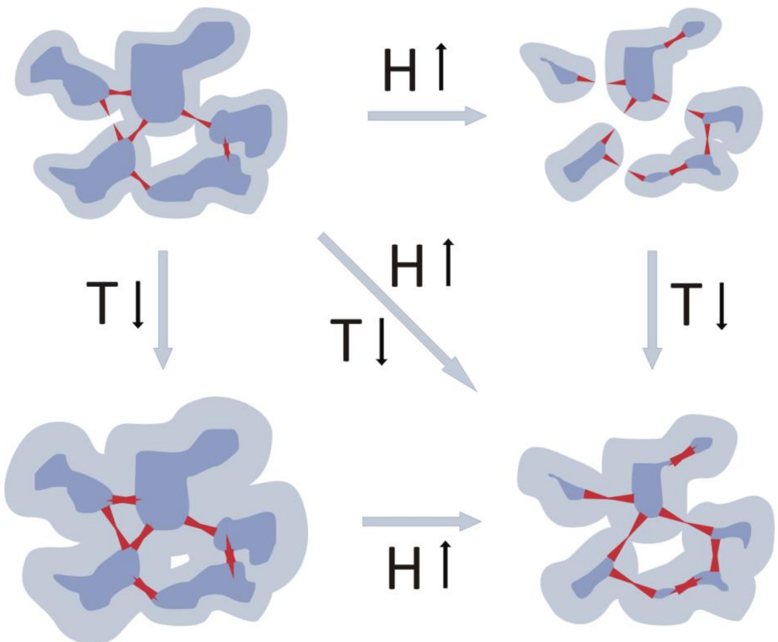
Films far from SIT



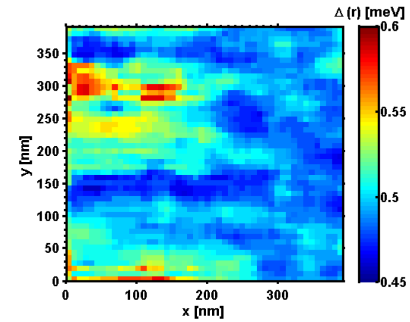
Deviation from BCS behavior at low T

Mesoscopic fluctuations near Hc2(0)

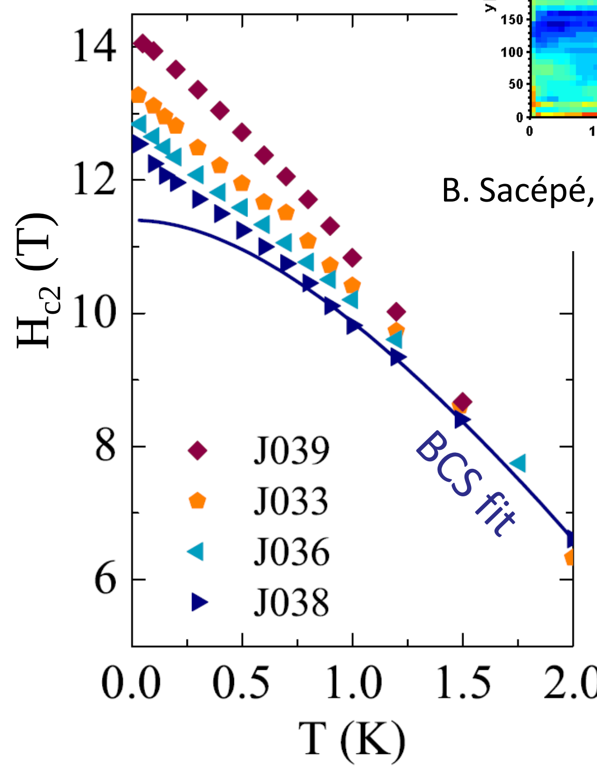
Galitski and Larkin, *PRL* (‘01)



STM mapping of $\Delta(r)$



B. Sacépé, *et al., Nat. Phys.* (‘11)



- $B \nearrow$: decrease of SC island size
- $T \searrow$: increase of SC proximity effect

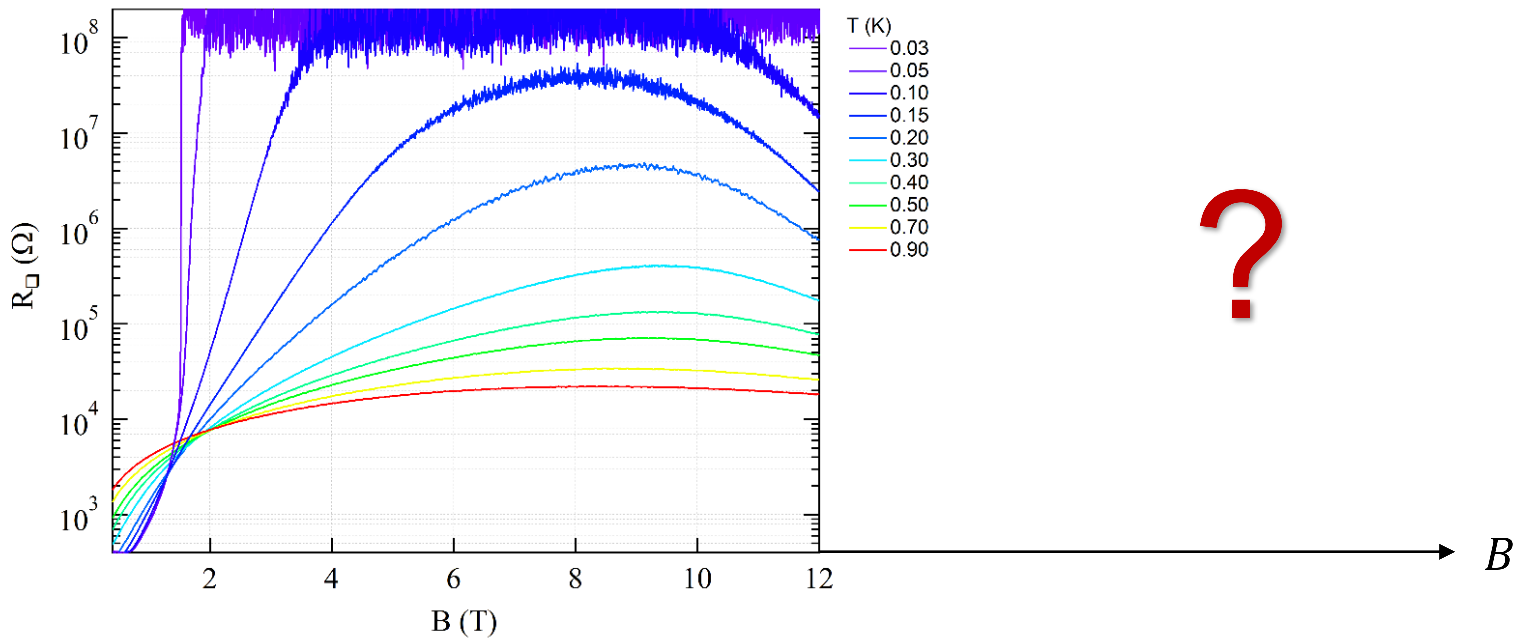
See also Hebard and Paalanen, *PRB* (‘84)

B-tuned superconductor-insulator transition

« Cooper pair insulator »
« Bose insulator »
MBL … ?

Destruction of the
« something » insulator

High-B normal state ?



Q2: What's the high-B normal state ?

High-magnetic field lab of Grenoble (LNCMI)

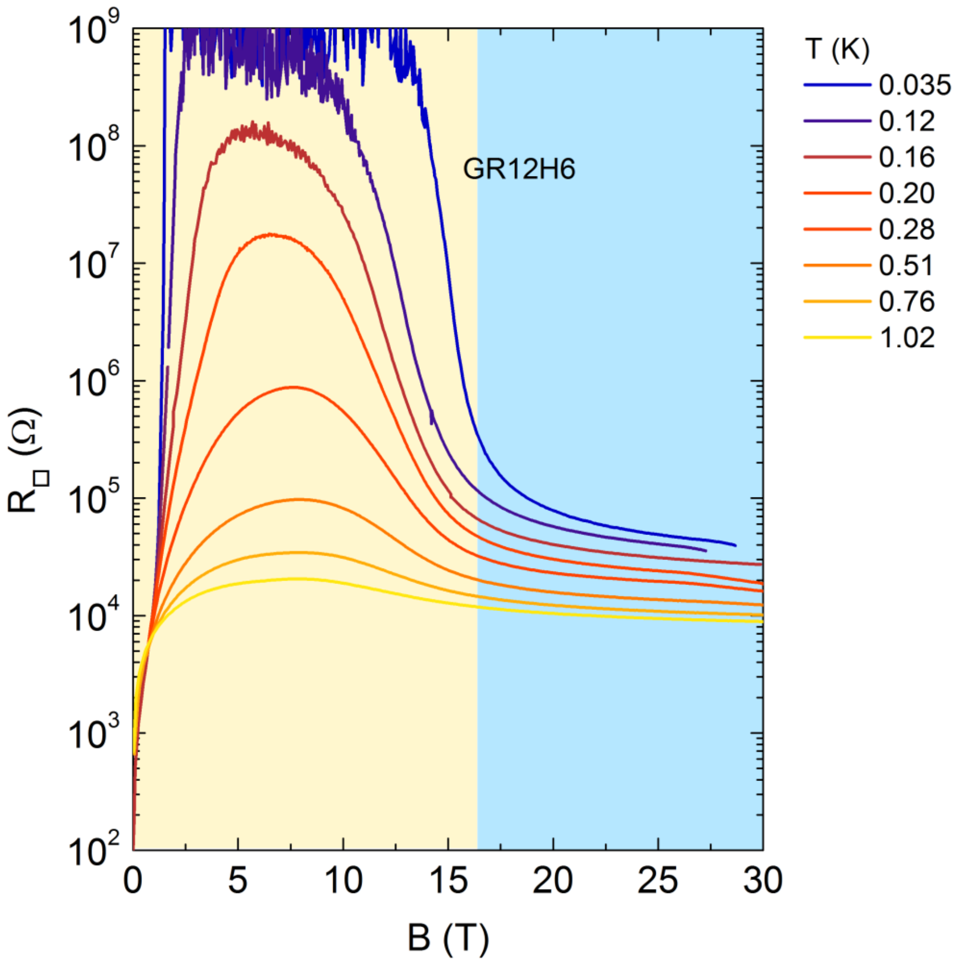
Magneto-resistance measurements

$0.03K \leq T \leq 2\,K \qquad B \leq 35\,T$

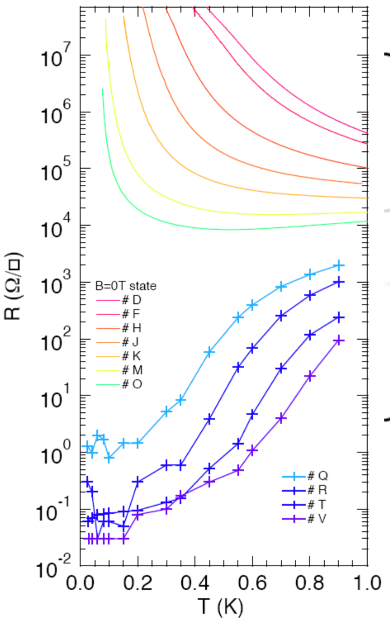
Top-loading dilution fridge

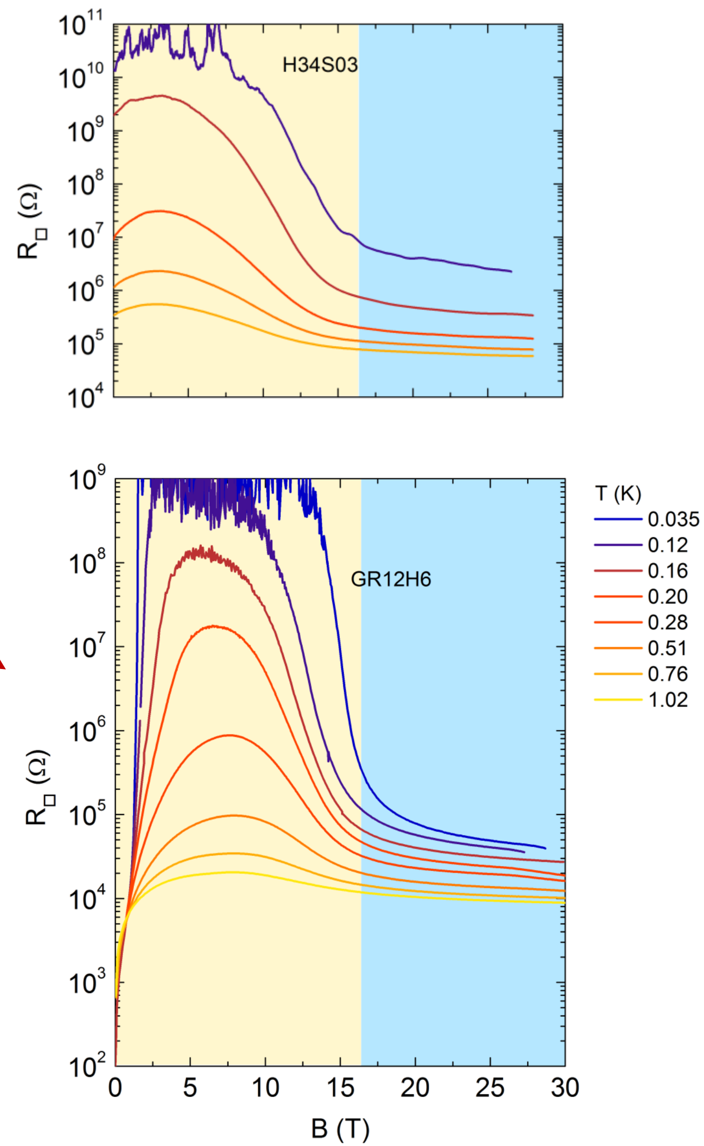
Water-cooled 35 T resistive magnet

High-B termination of the magnetoresistance peak

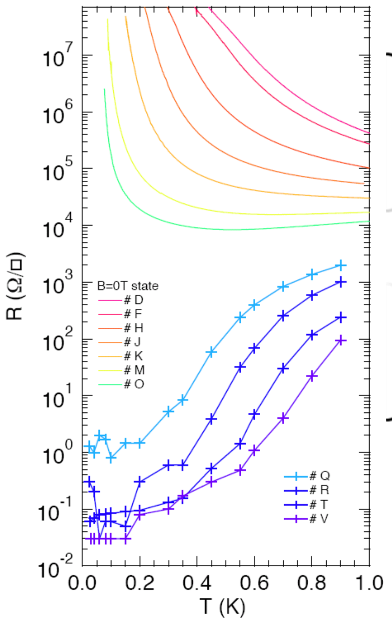


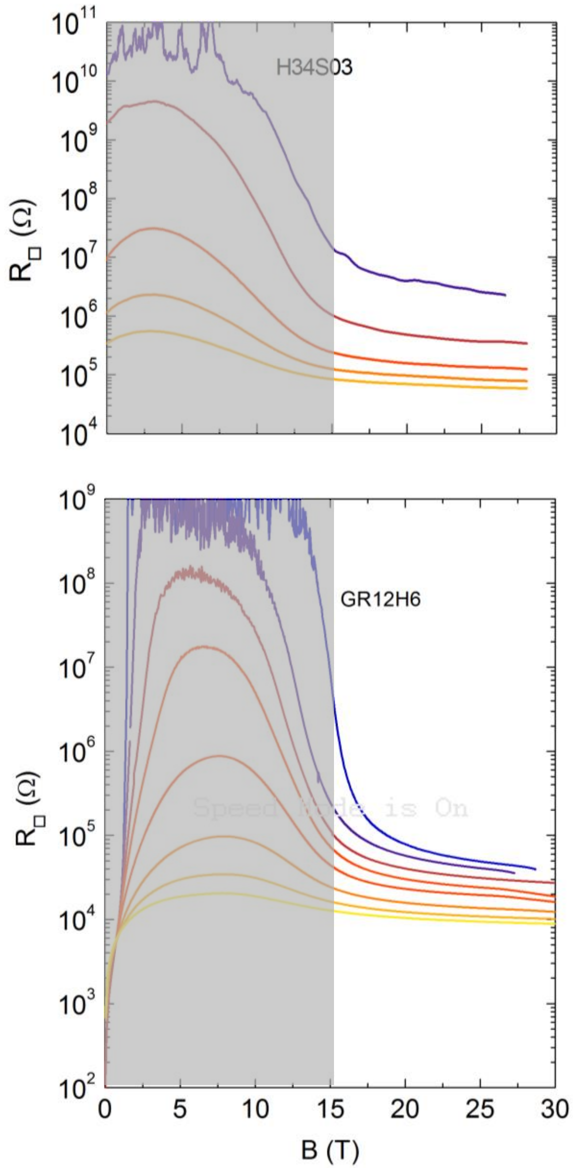
High-B termination of the magnetoresistance peak



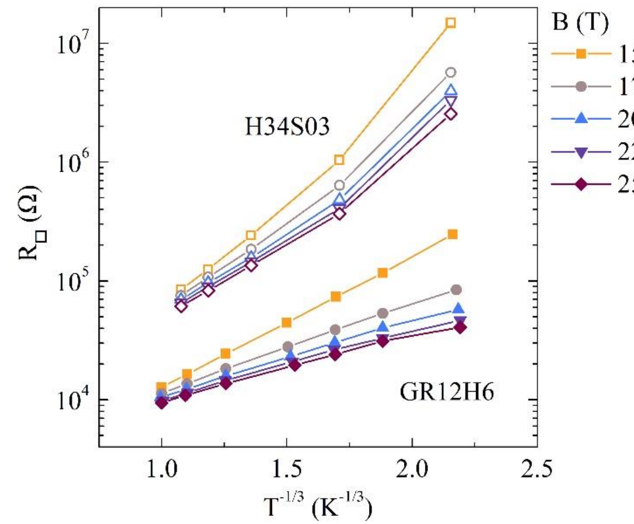


High-B state: Fermionic insulator





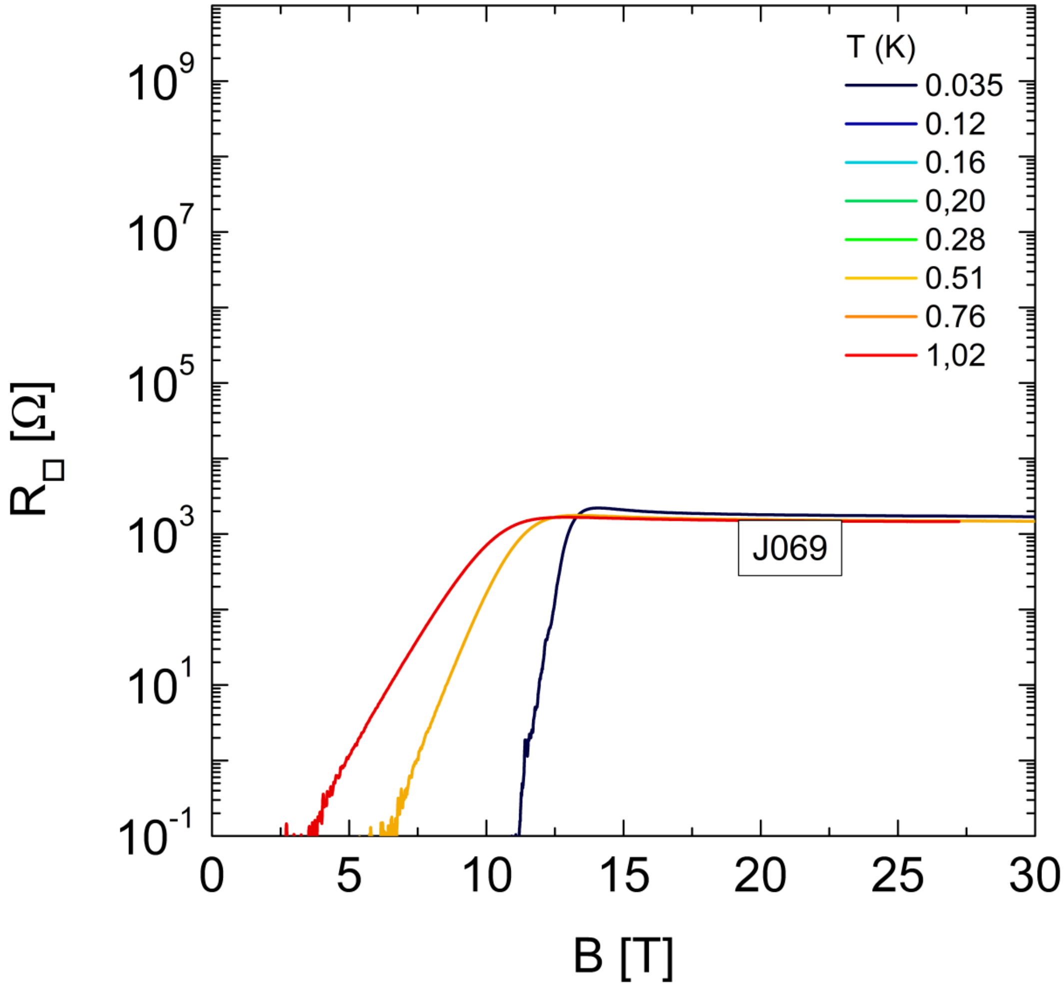
High field state :
Standard Mott hopping



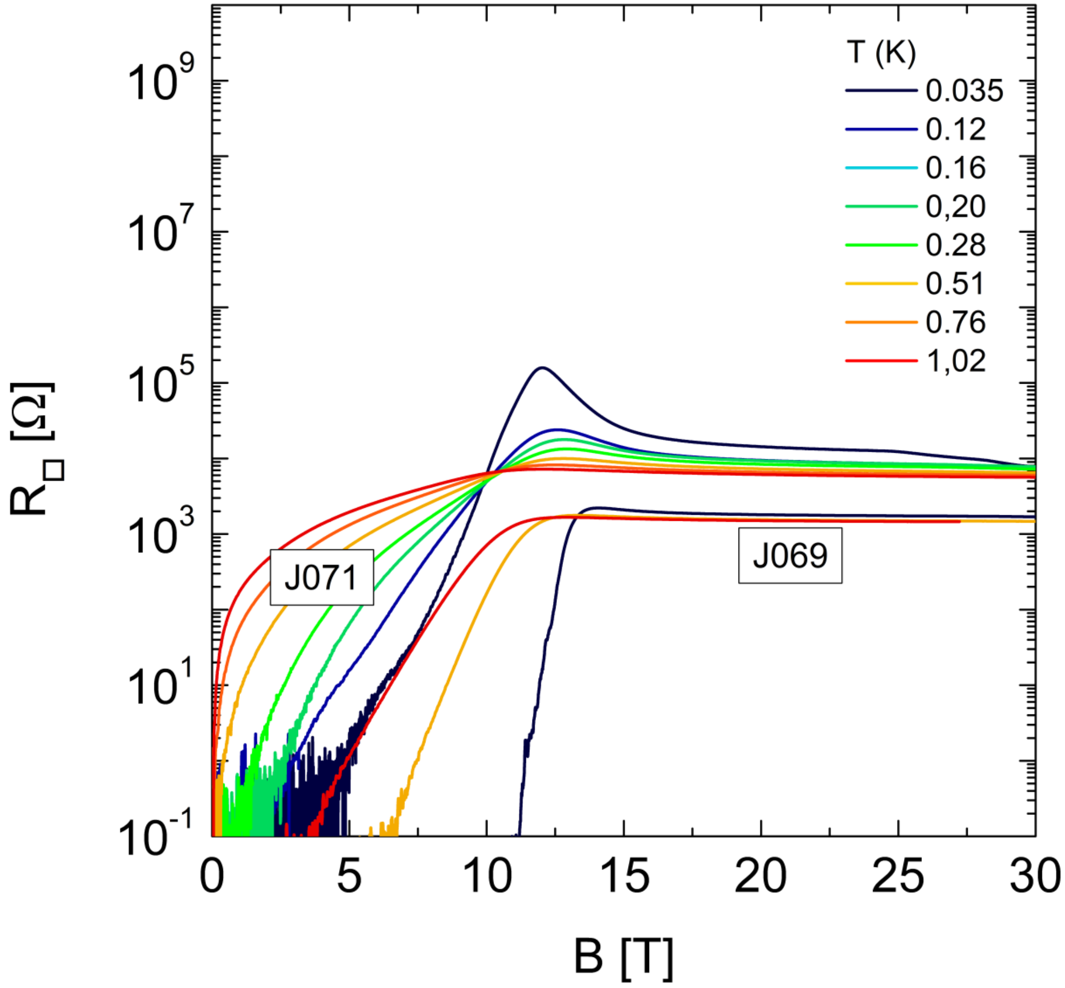
Fermionic insulator

For a « quantum metal » at high field, see T. Baturina PRL (‘07)

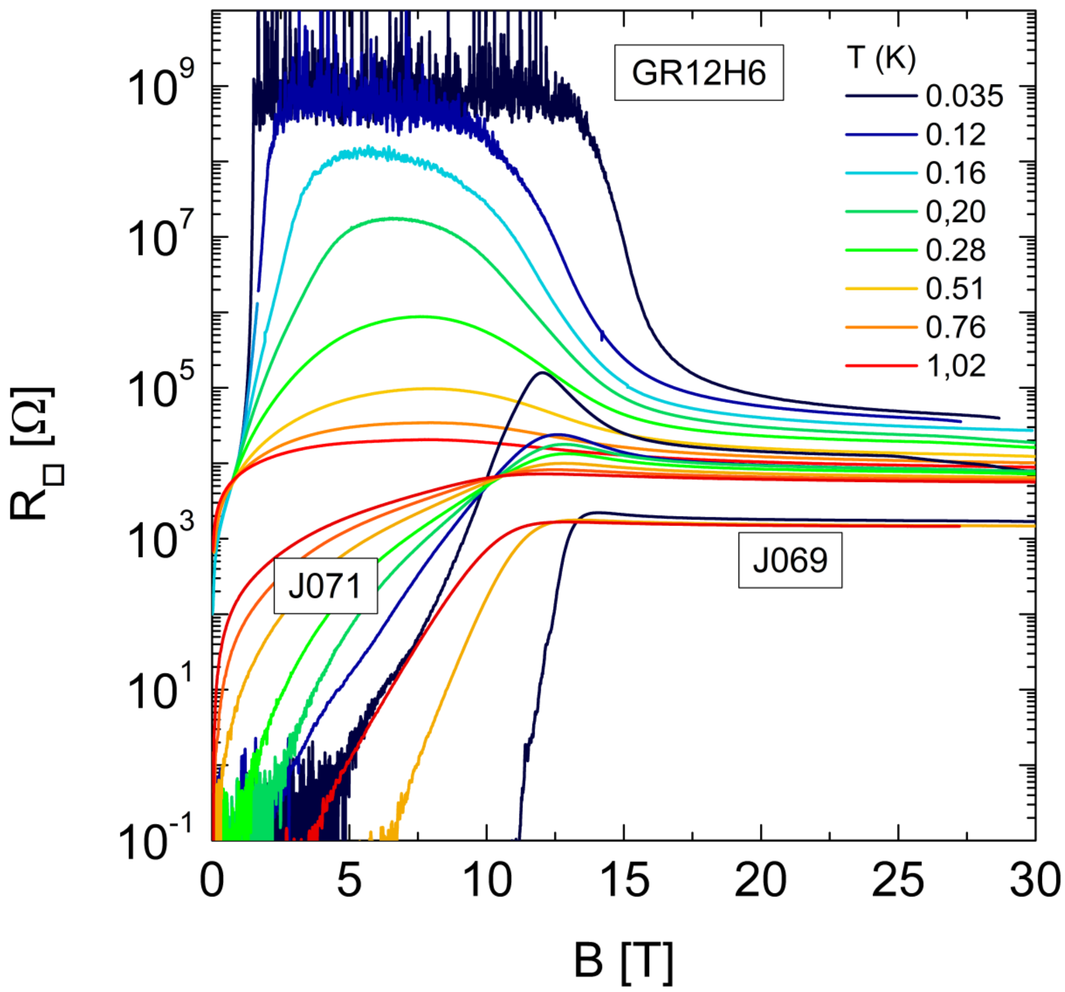
From superconductor to normal state



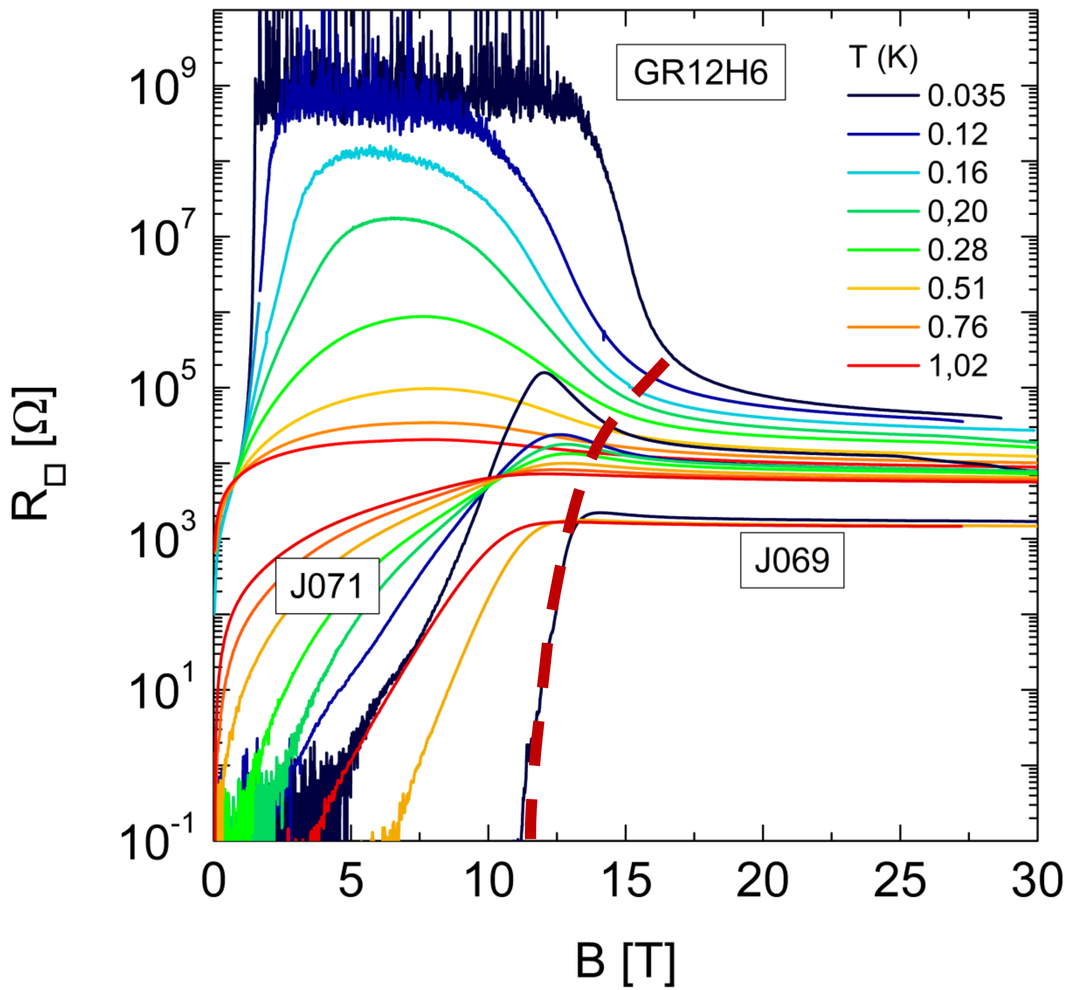
From superconductor to Cooper-pair insulator



From superconductor to Cooper-pair insulator

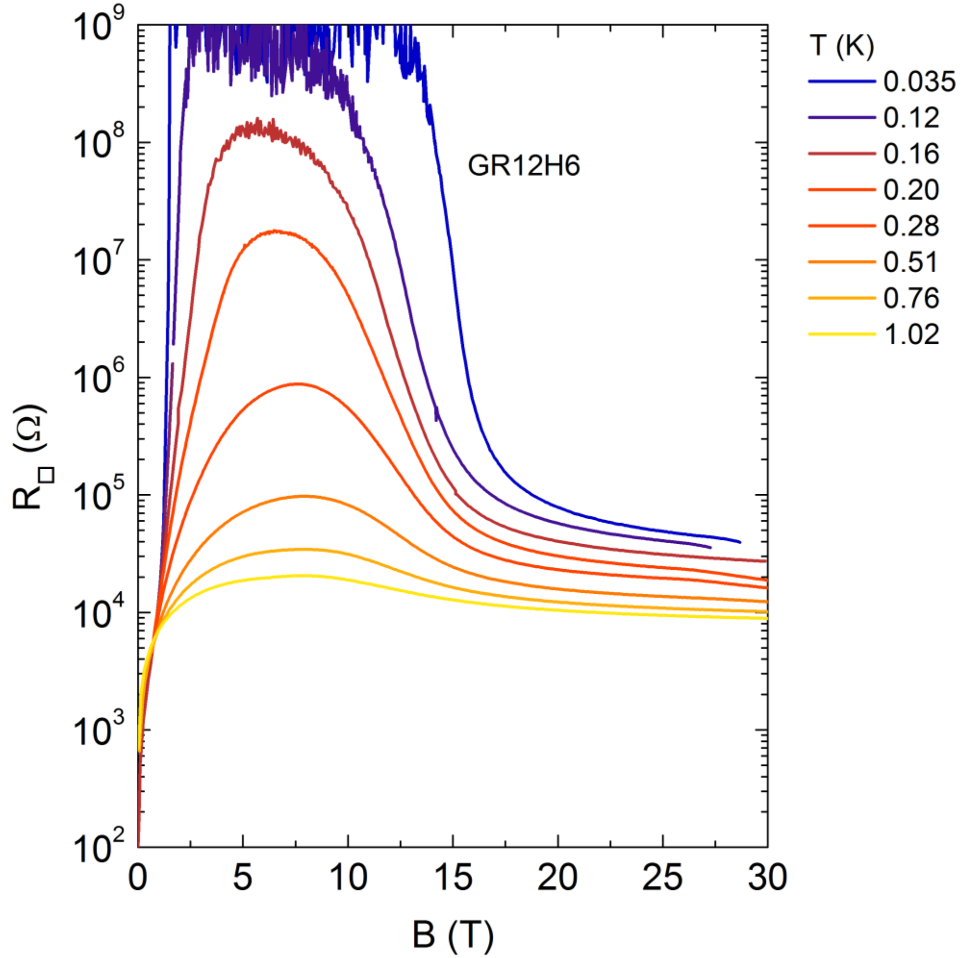


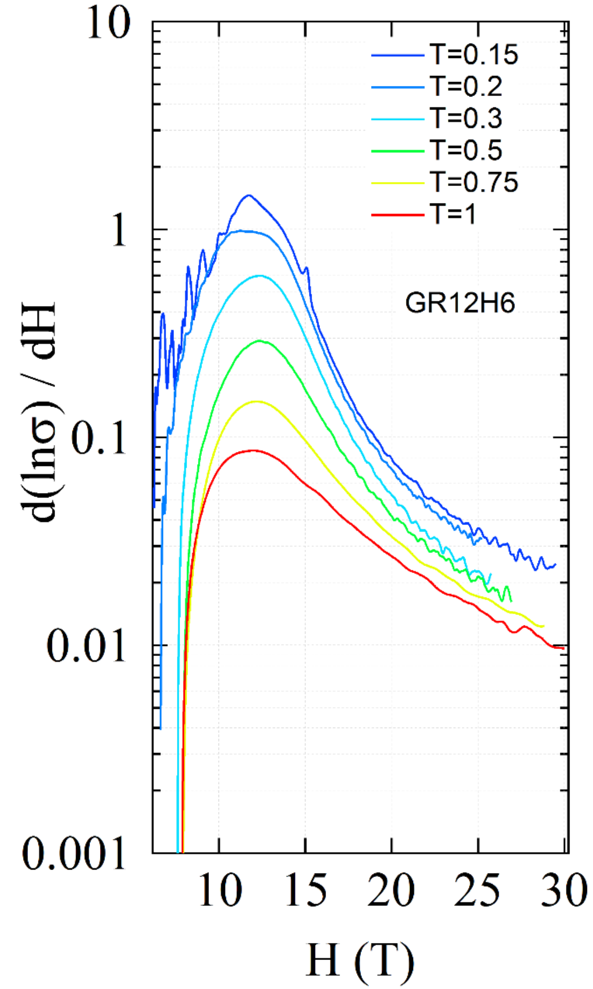
From superconductor to Cooper-pair insulator



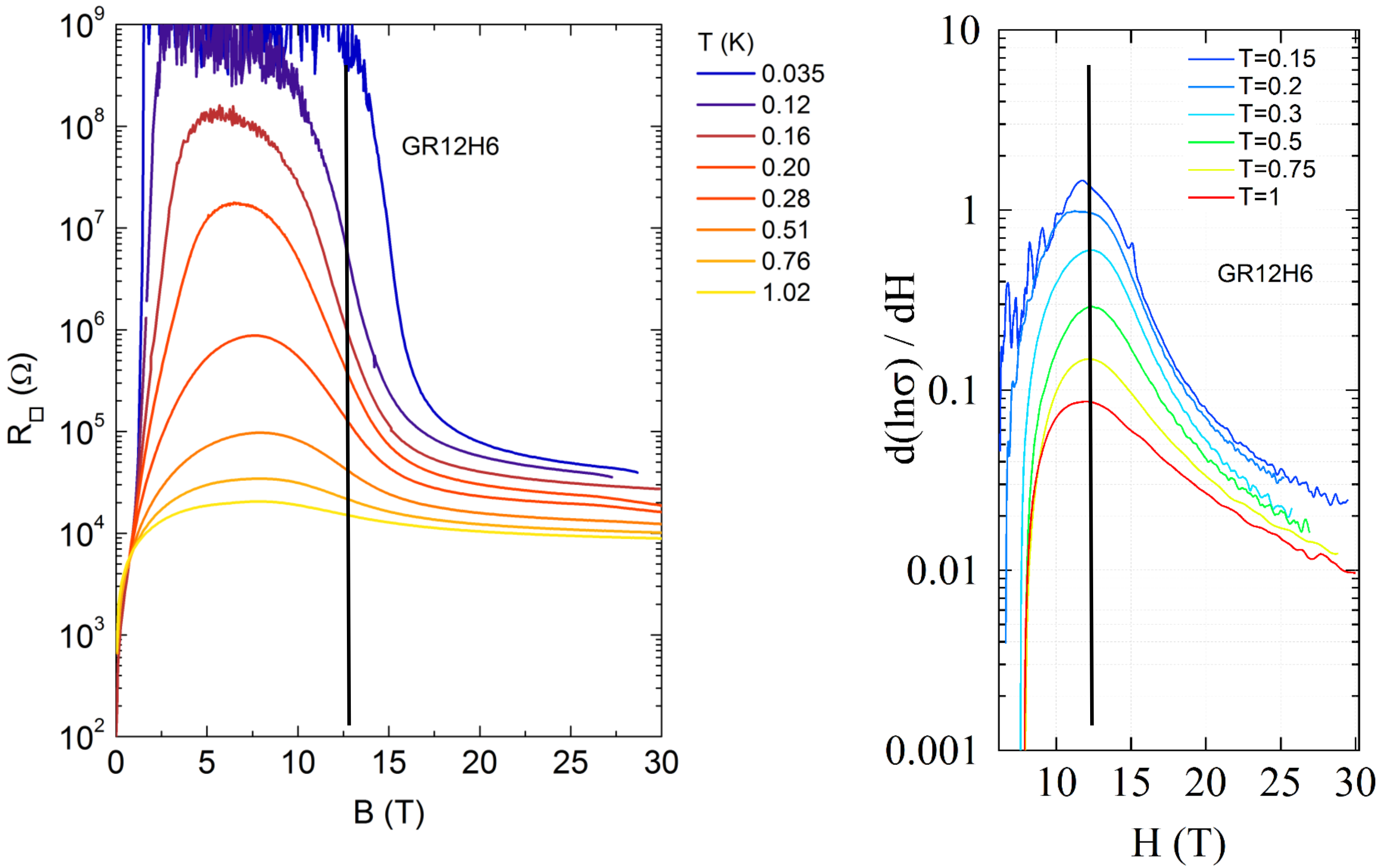
$H_{c2}(0)$ in low disorder samples coincides with Cooper-pair to fermionic insulator transition

Insulator-to-insulator transition ?

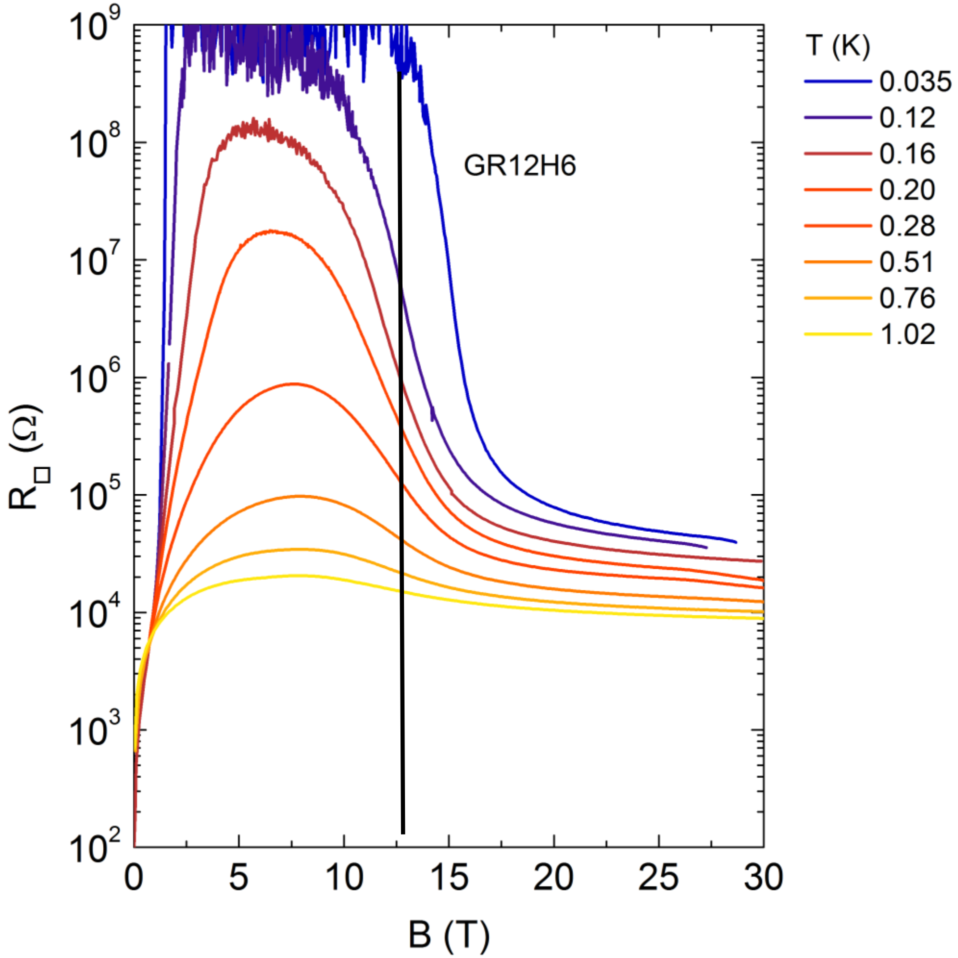


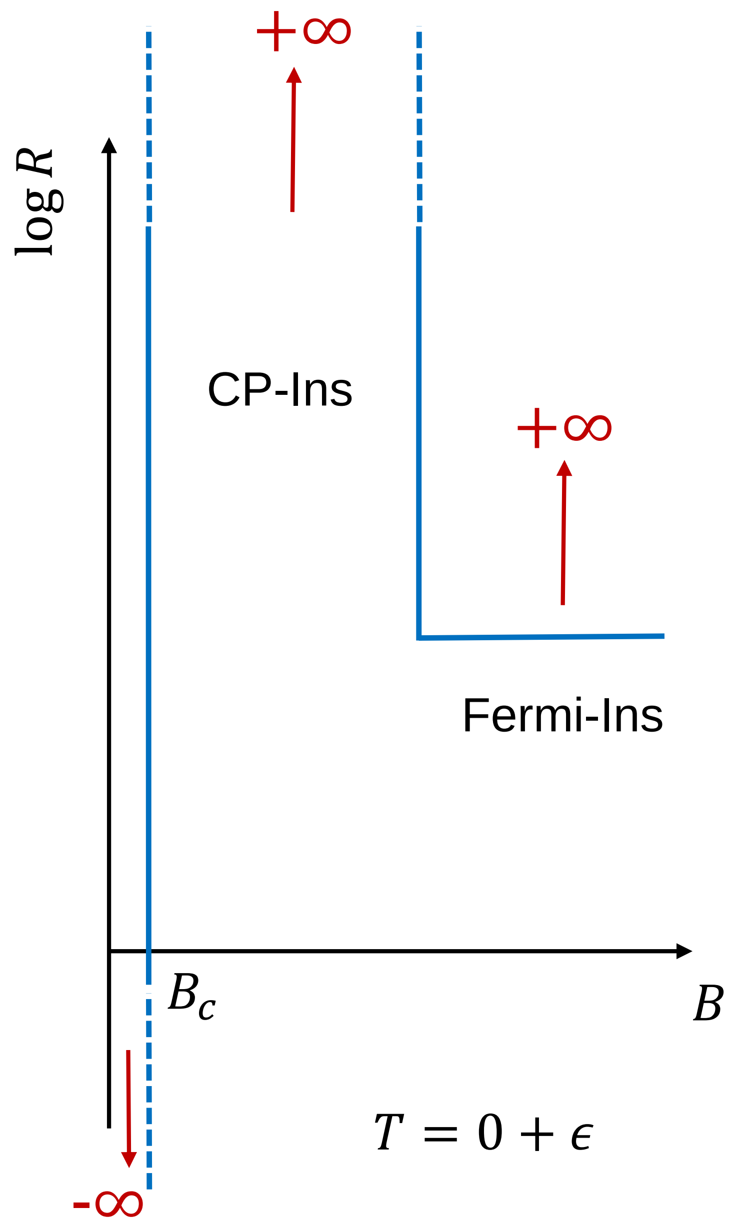


Insulator-to-insulator transition ?



Insulator-to-insulator transition ?

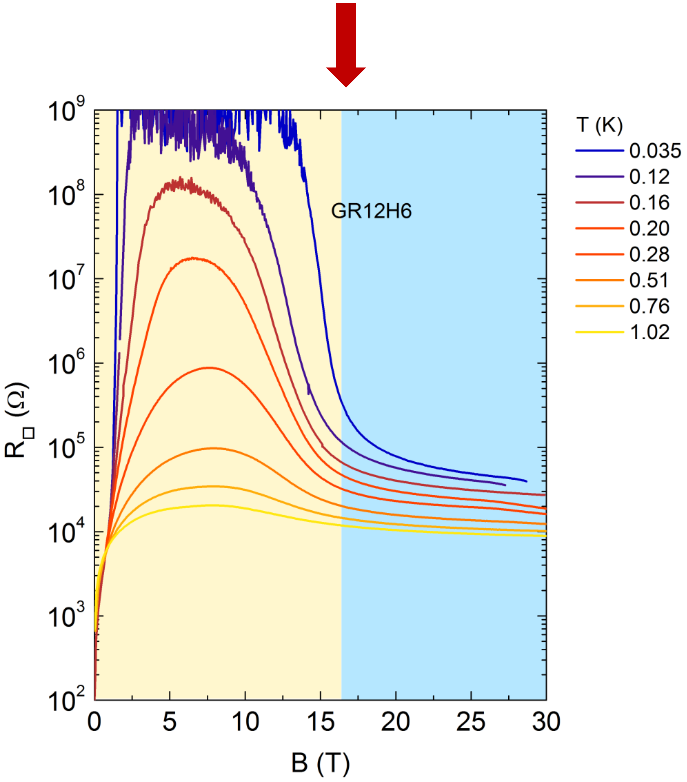




High-B termination of the magnetoresistance peak

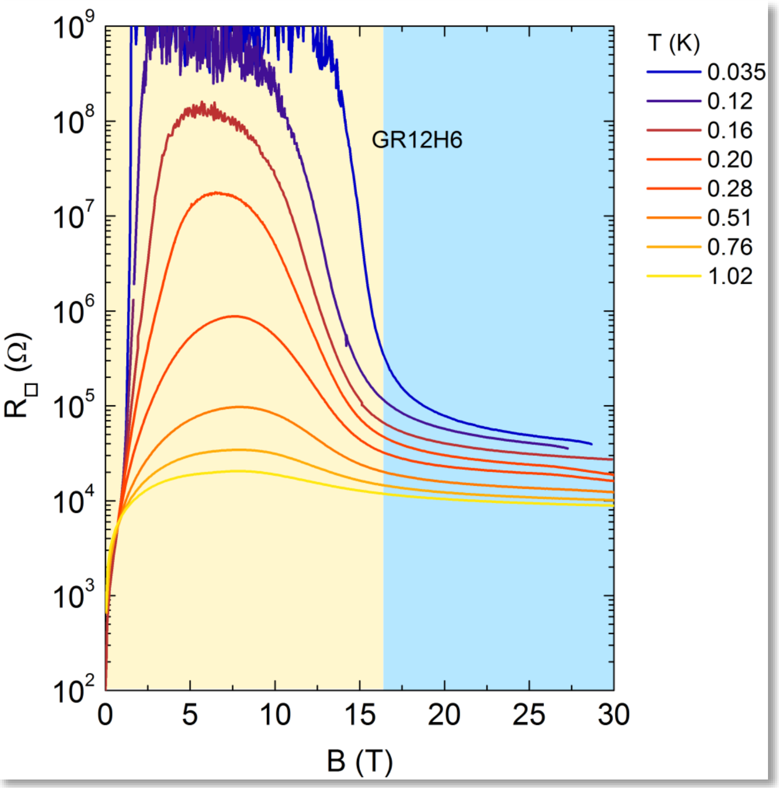
Cooper-pair insulator | fermionic insulator

$B \sim 15\ T$



New insulator-to-insulator quantum phase transition or crossover ?

Conclusions



Low disorder films:

- $H_{c2}(0) \sim 12 - 15\ T$
- $\xi_s \sim 4$ nm $\Rightarrow$ $3D$ SC state
- No Pauli limit due to SOI

High disorder films

- VRH in the high-B state
- Bose insulator to Fermi insulator transition/crossover

B. Sacépé *et al*. PRB 91, 220508(R) (2015)