Magnetic Impurity Doping Studies of the Cooper Pair Insulator State

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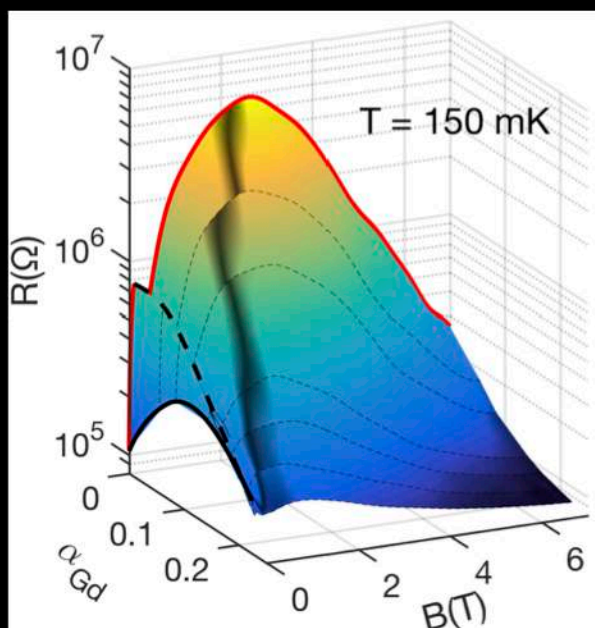

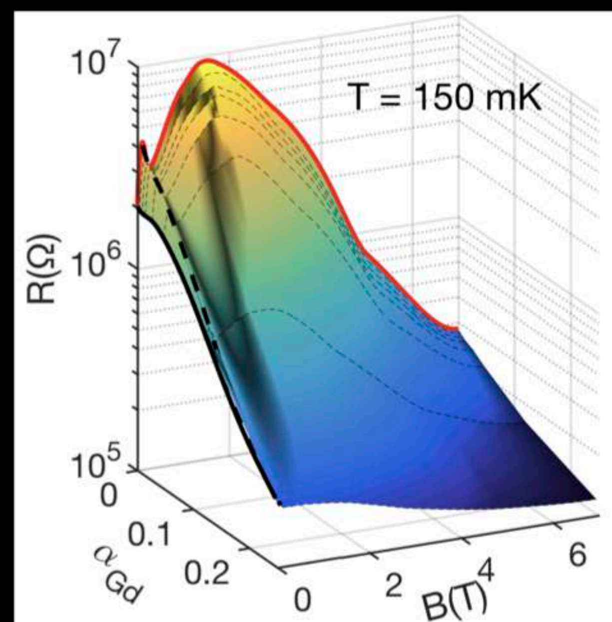

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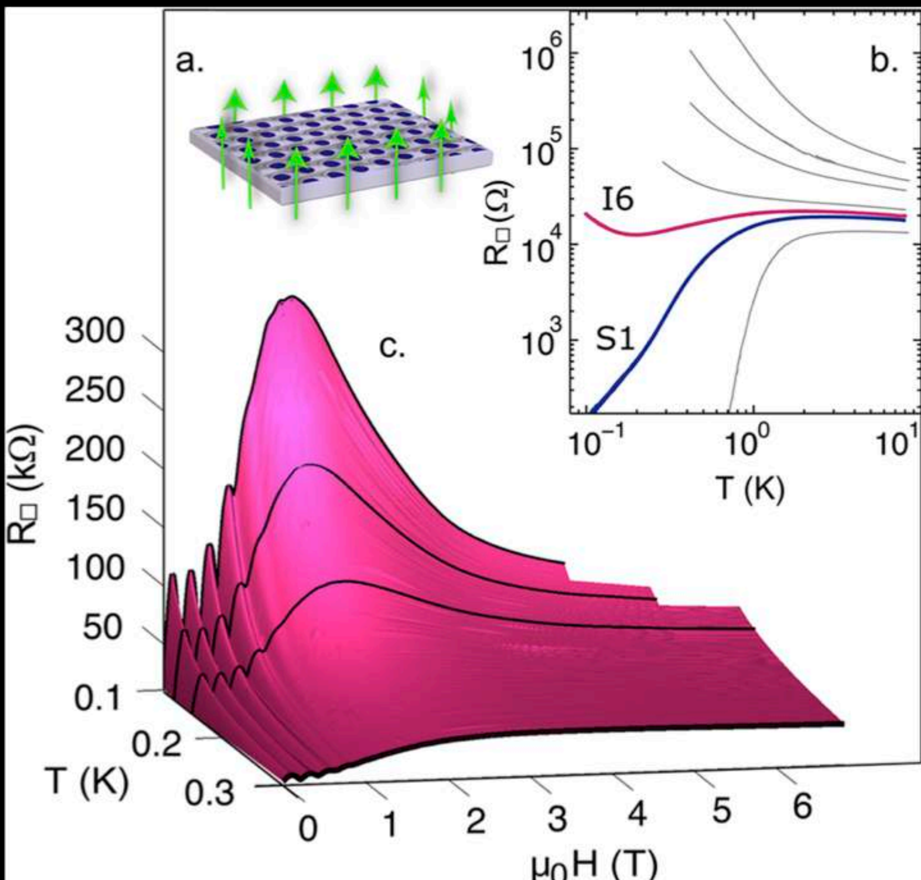
Road Map

- Cooper Pair Insulator phase
- Dope with magnetic impurities?
- Quench Condensed a-Bi films
- 2 studies of doping effects
  - Effects on Localization
    - (Mott insulator with virtual qp screening)
  - Effects on Giant Magnetoresistance Peak
    - (low field dephasing and high field pairbreaking)

Cooper Pair Insulator Phase



Near SIT

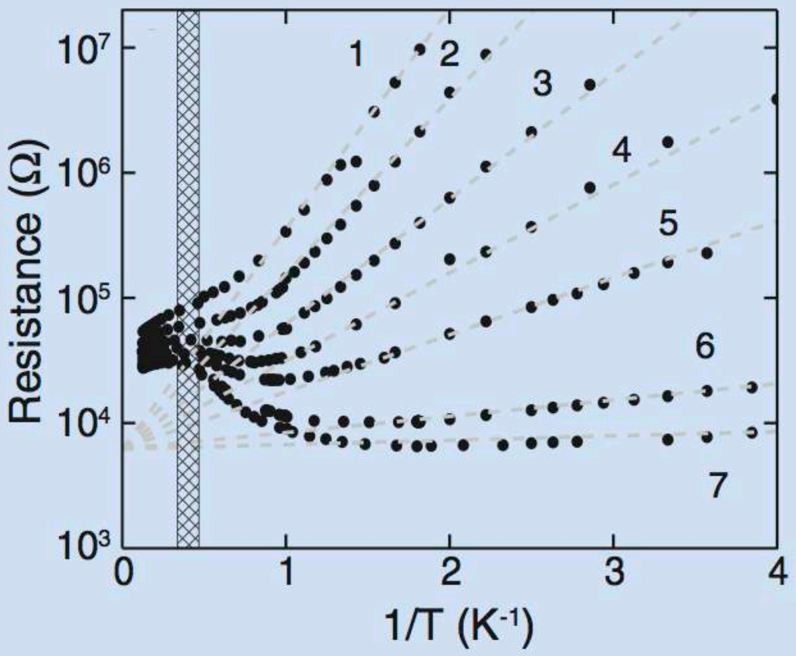
Cooper Pair transport –

MR oscillations

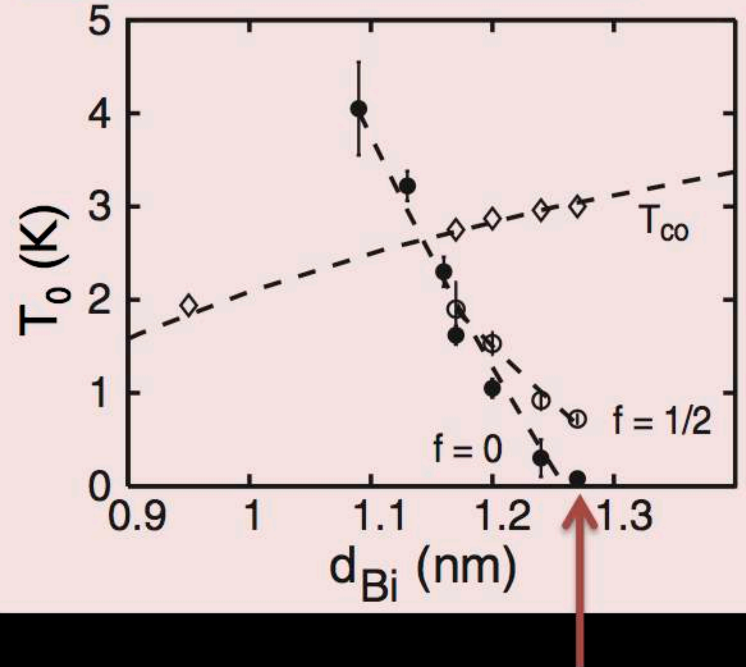
Giant MR Peak

Hard gap in qp DoS

$R(T) = R_0 e^{T_0/T}$



$T_0 \to 0$ at SIT

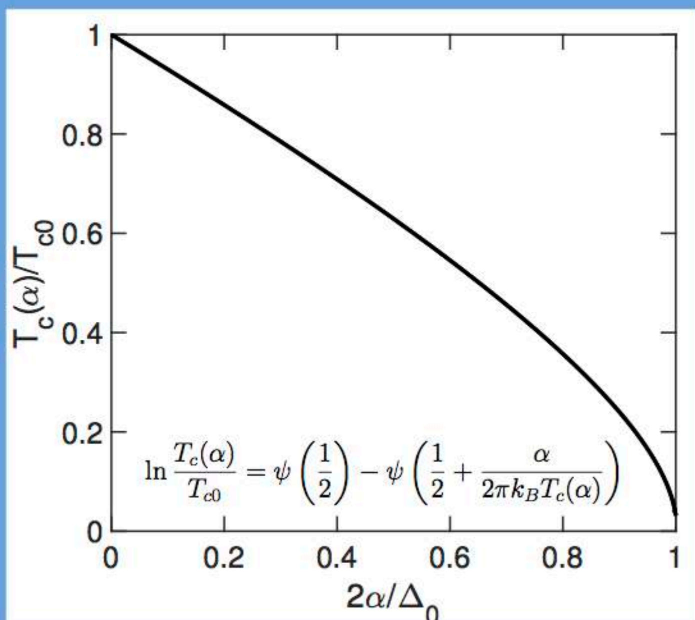


How do magnetic impurities affect…

Superconductor?

“pairbreaking”- α

reduce Δ, T_c



Cooper Pair Insulator?

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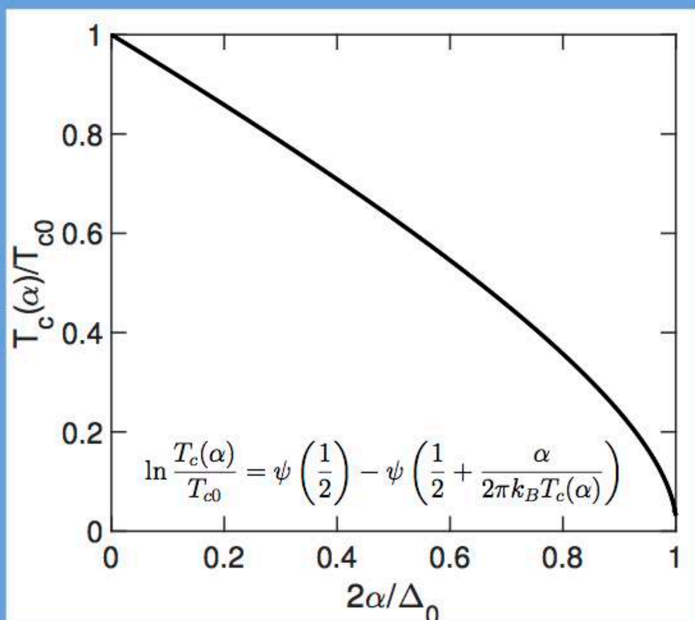

Cooper Pair Insulator?

“pairbreaking”- α

reduce Δ, E_J , or t

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Superconductor?

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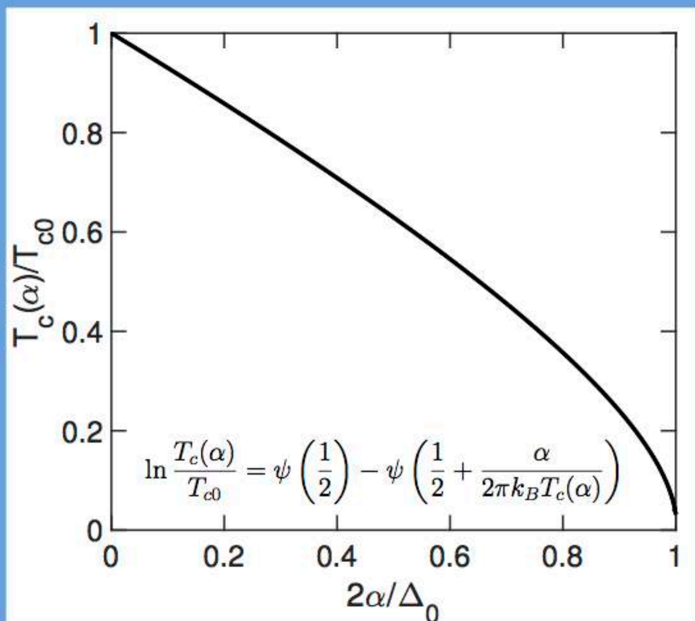
reduce Δ, T_c



Cooper Pair Insulator?

"pairbreaking"- α_{imp}

reduce Δ, E_J, or t

If

$$H = E_c \sum_i n_i^2 + E_J \sum_{i,j} \cos(\theta_i - \theta_j)$$

with $T_0 = E_c\left(1 - \alpha \frac{E_J}{E_c}\right)$

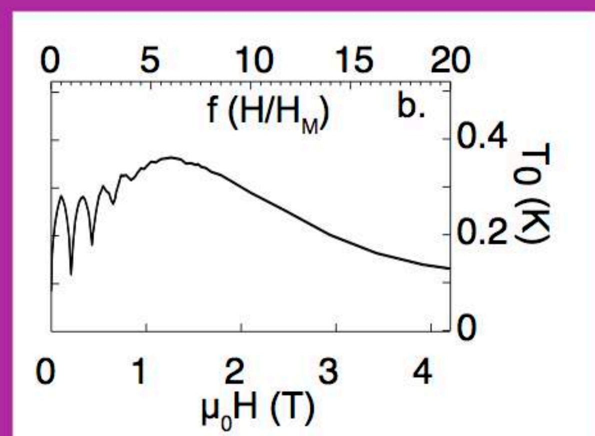
then doping leads to $T_0 \uparrow$

Major Questions

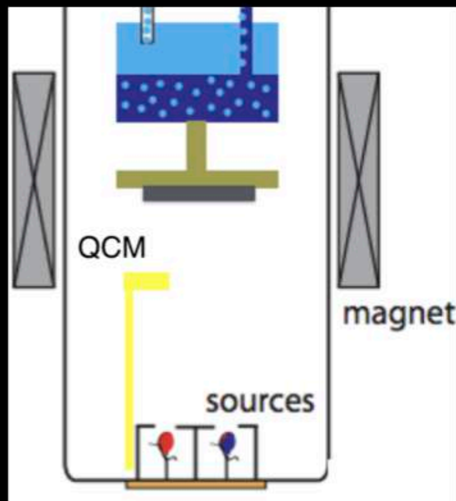
What gives rise to the activation energy?

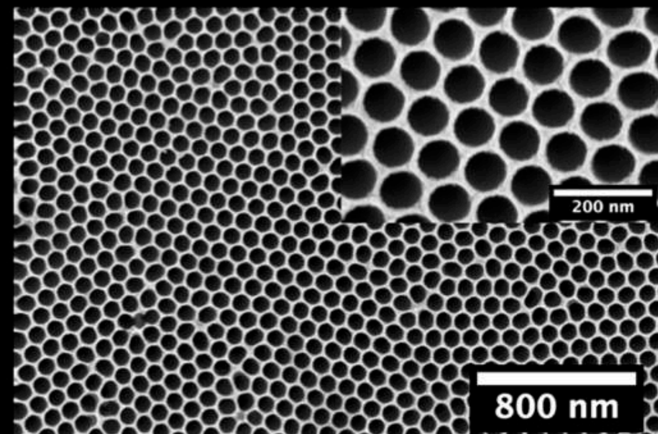
- Coulomb interactions?
- Mobility edge?

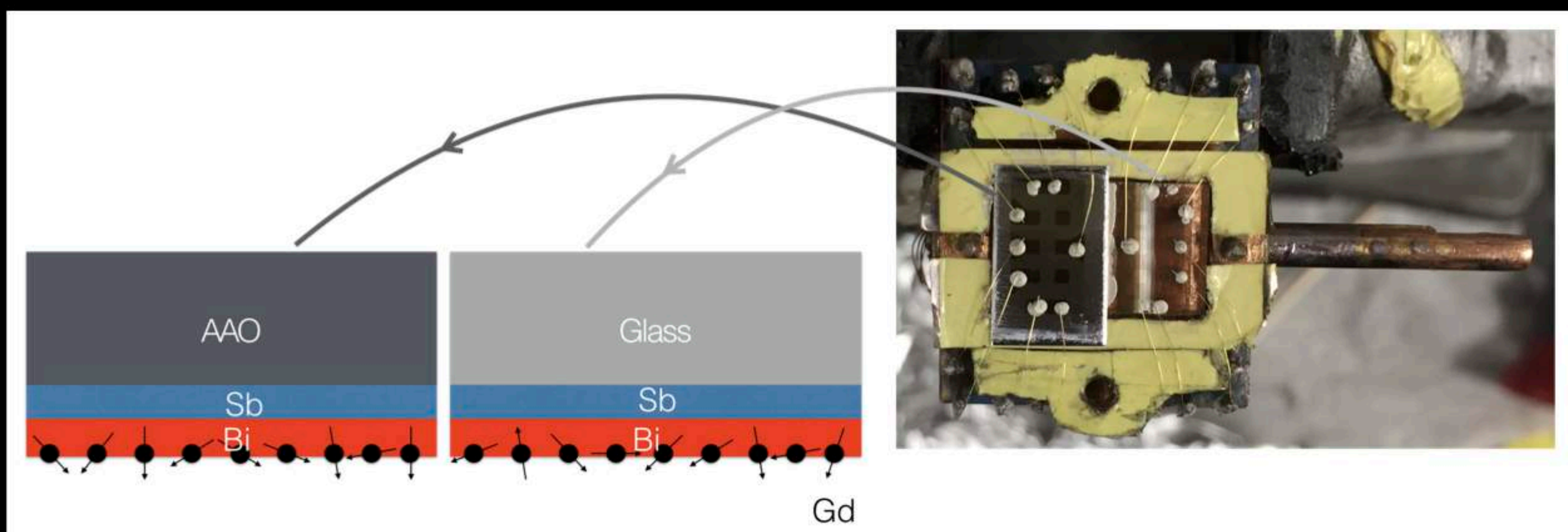
What is the giant MR peak?



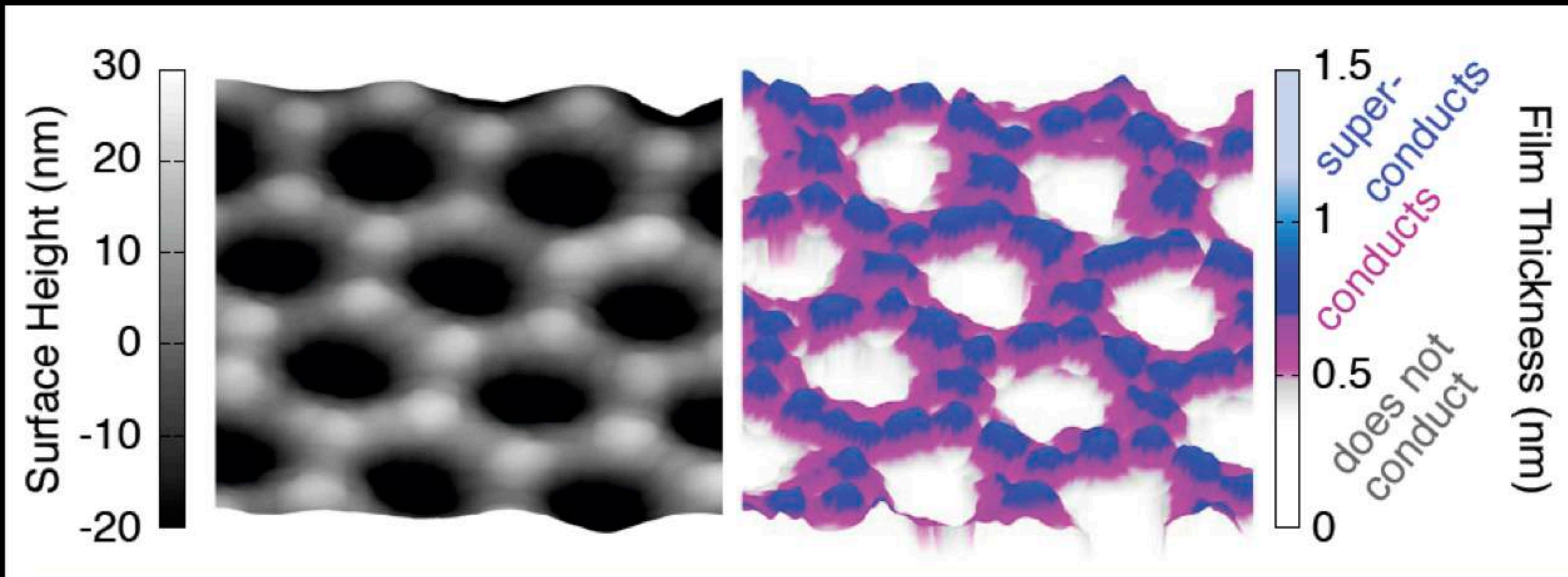
Quench Condensed a-Bi Films on porous AAO



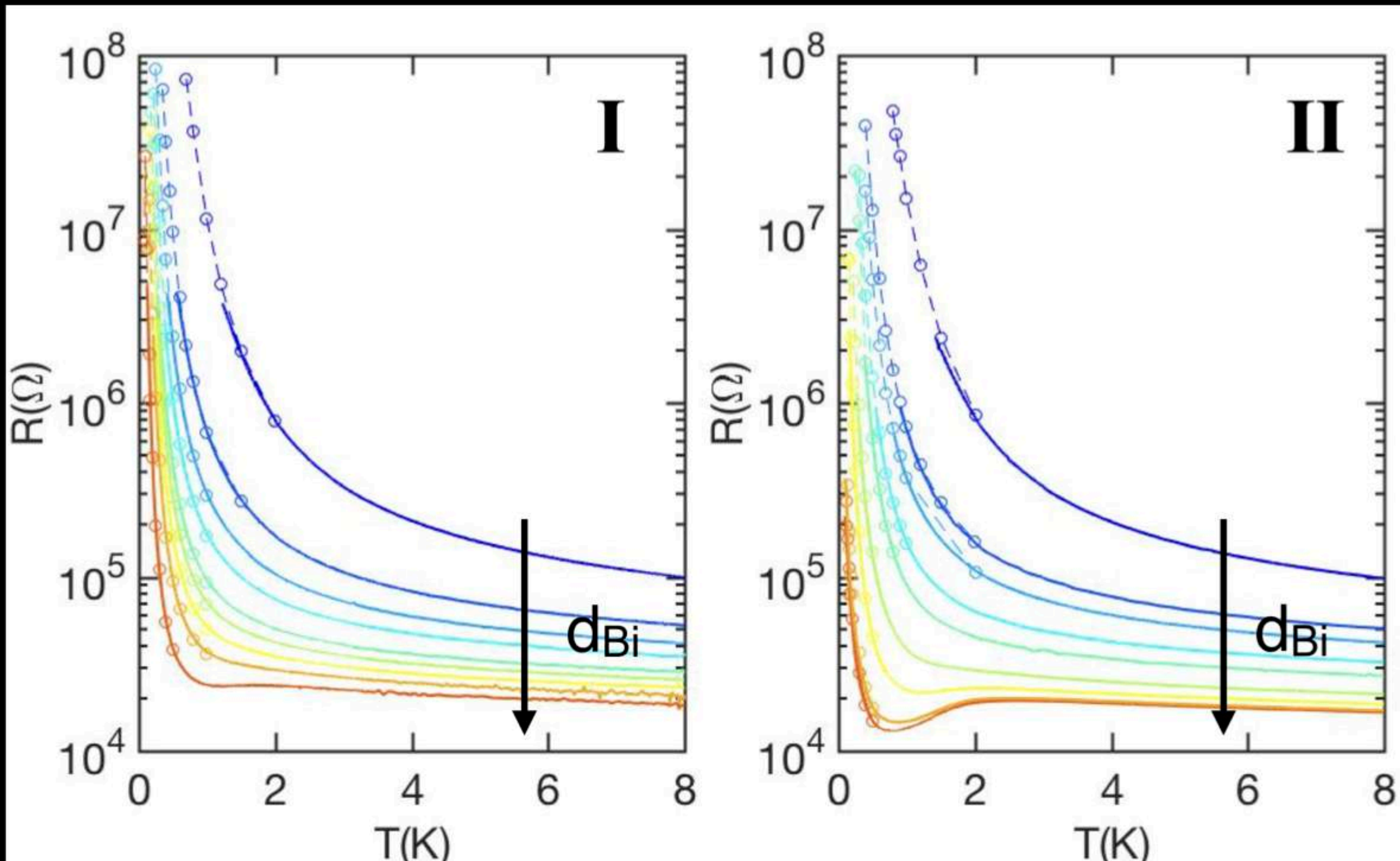




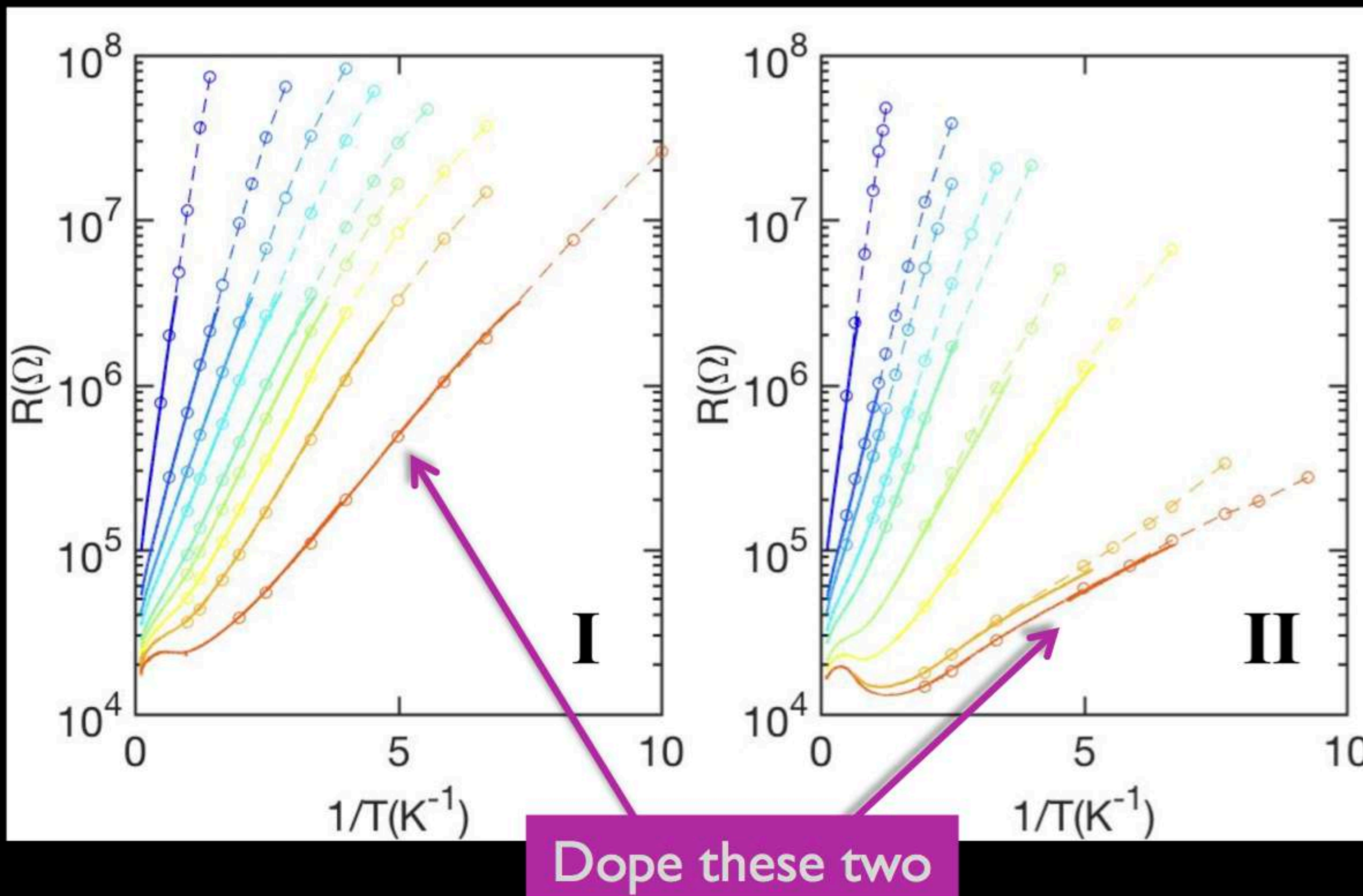
Films on AAO have nano-dots



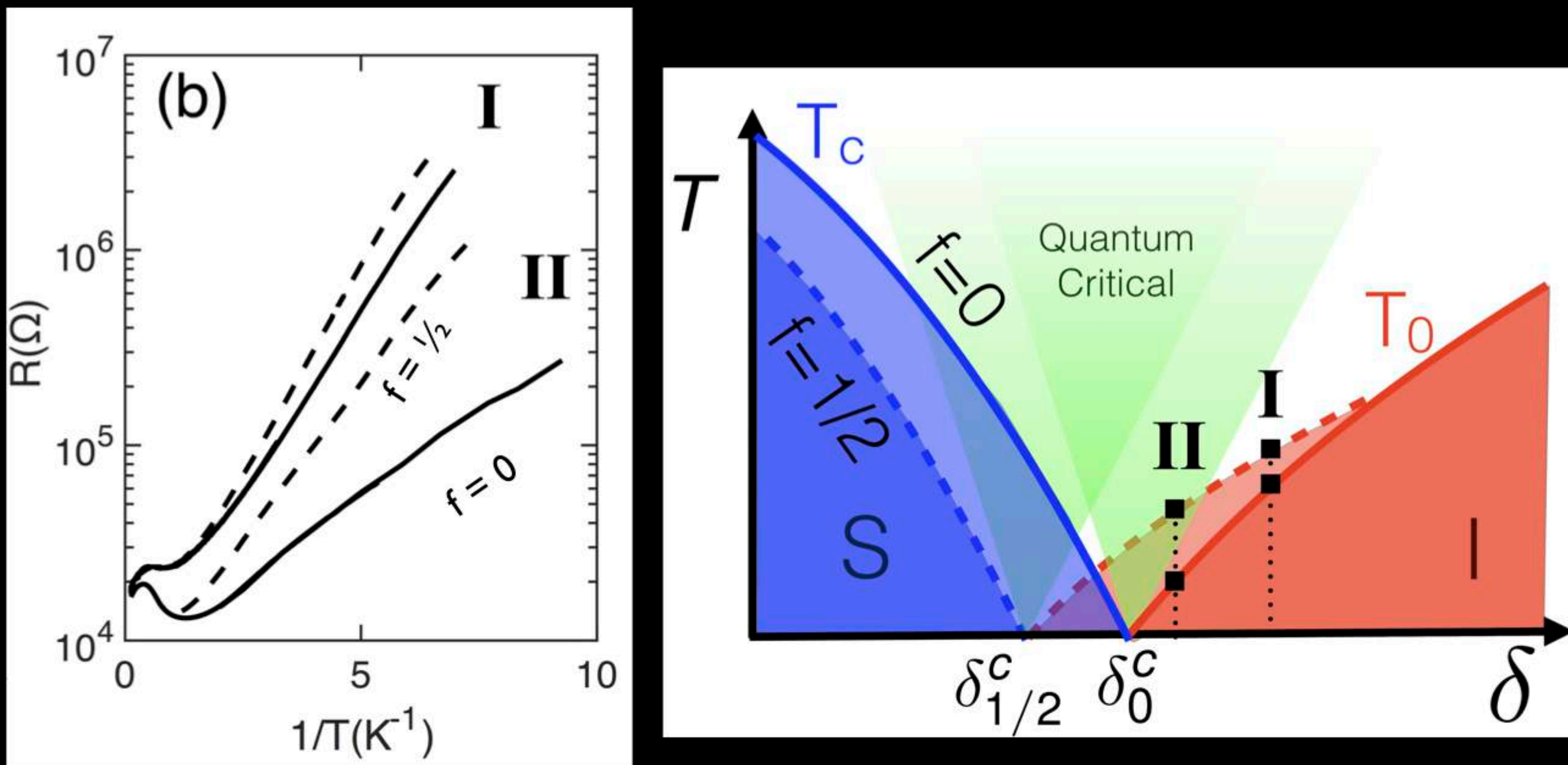
Experiments I and II



Activated Transport

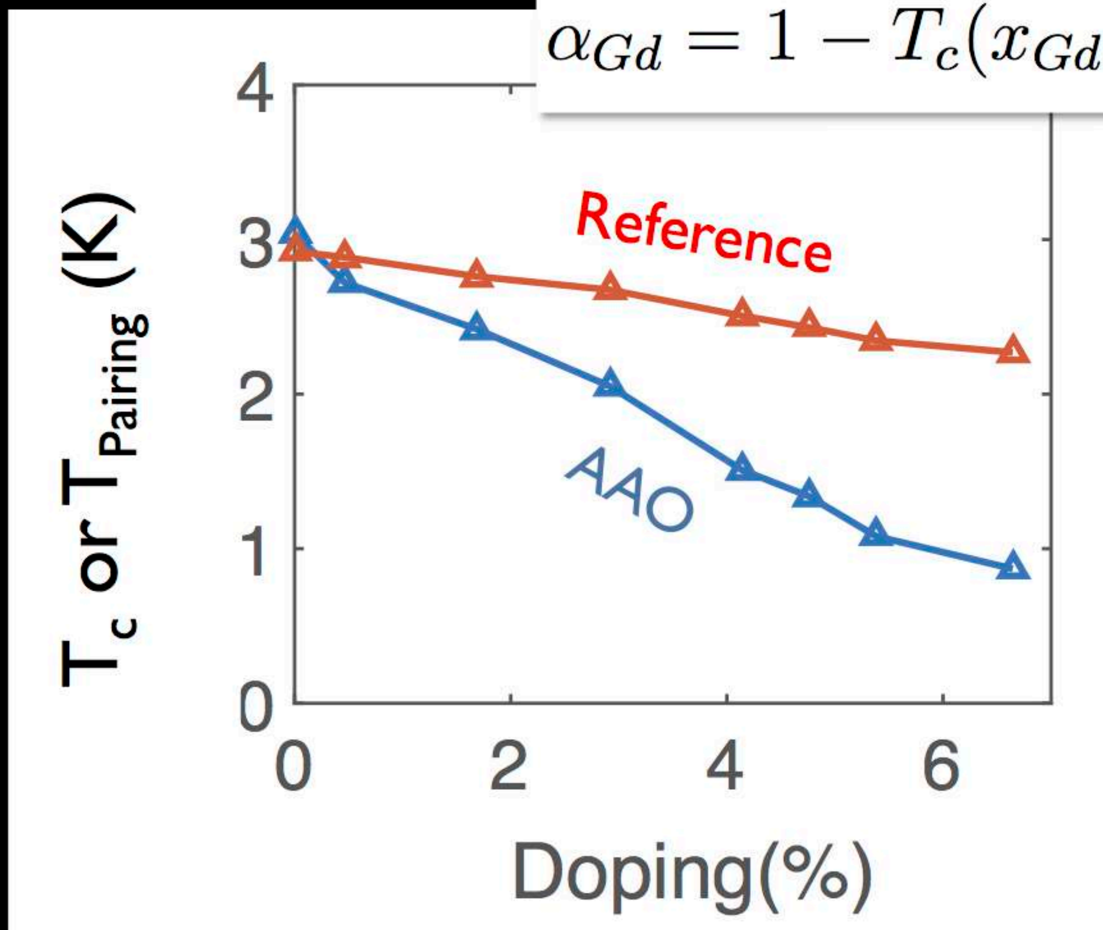


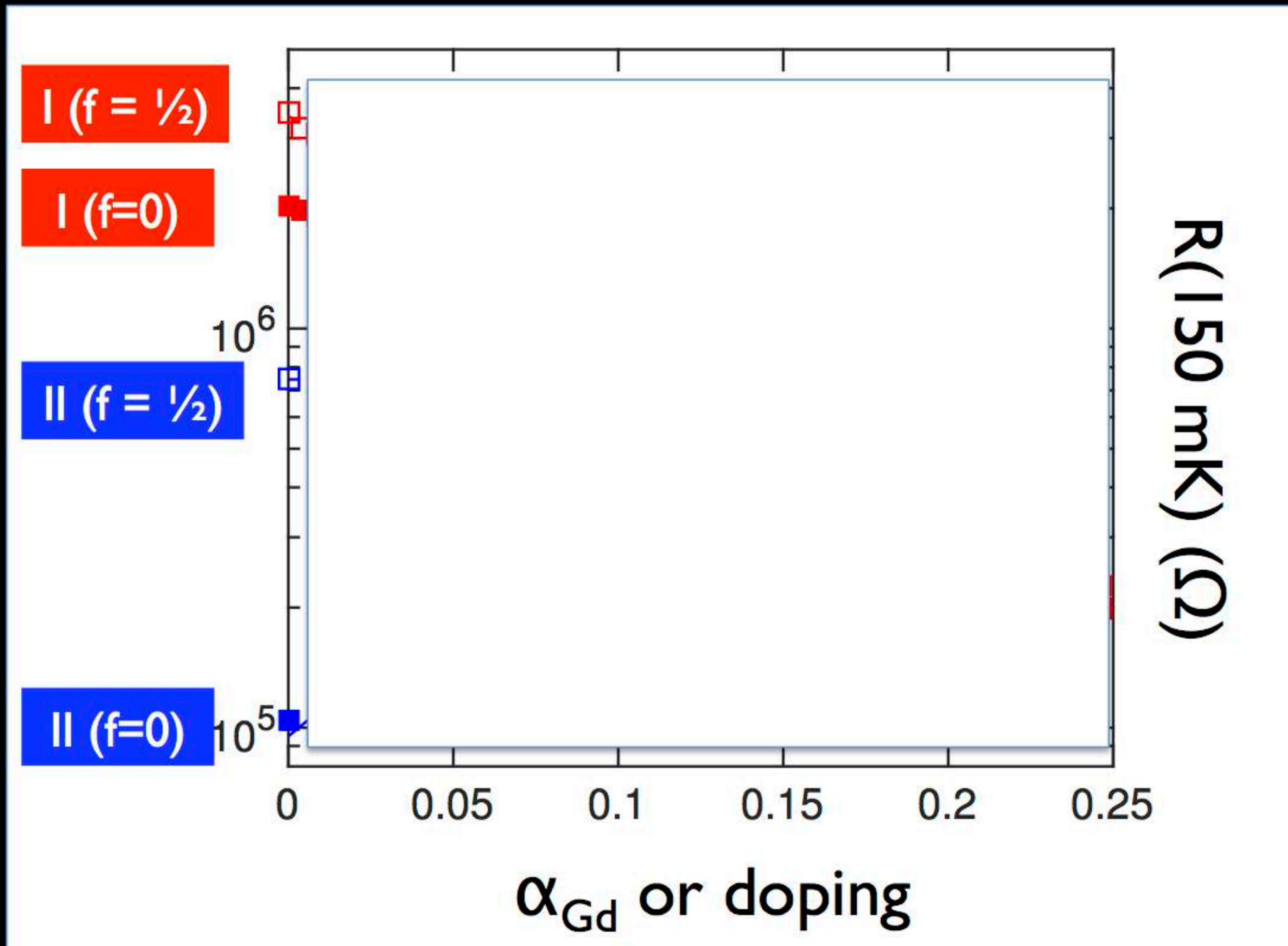
Films I and II on Phase Diagram



Doping and Pairbreaking

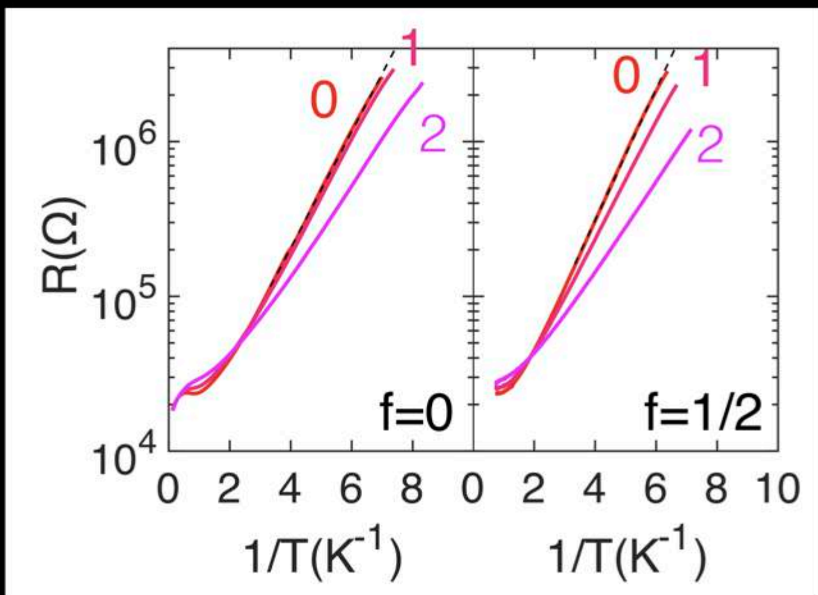
$$\alpha_{Gd} = 1 - T_c(x_{Gd})/T_c(0)$$

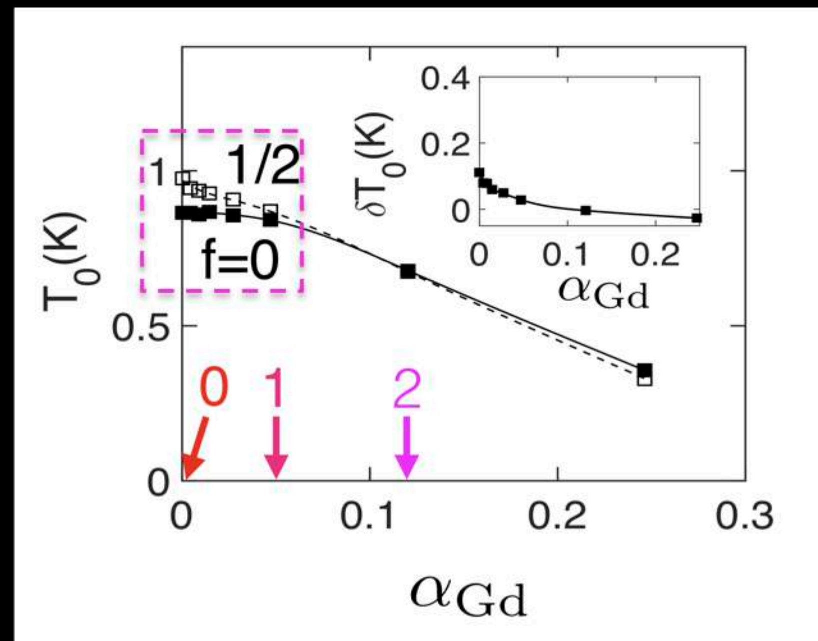




I (f = ½)
I (f=0)
II (f = ½)
II (f=0)
10^6
10^5
0
0.05
0.1
0.15
0.2
0.25
R(150 mK) (Ω)
α_{Gd} or doping

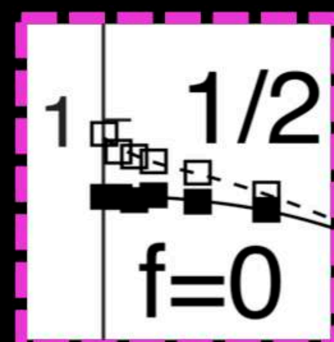
Doping Film I



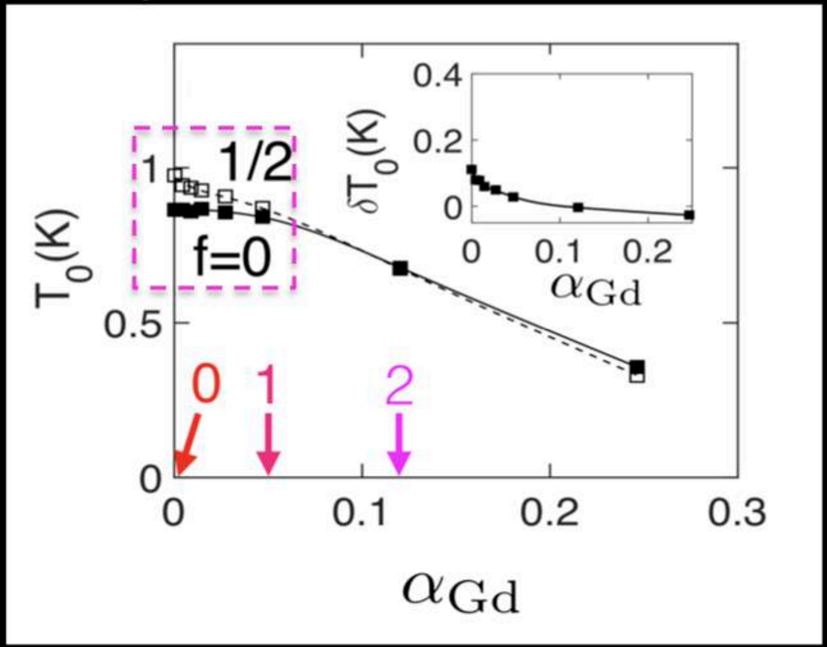


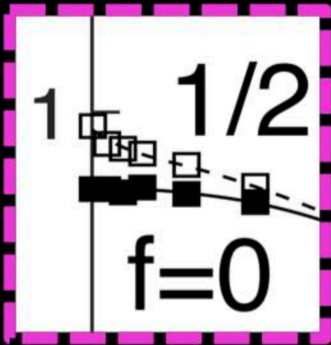
T_0 decreases at low doping

⇒ doping delocalizes



Expected E_J to decrease to cause T_0 to increase...



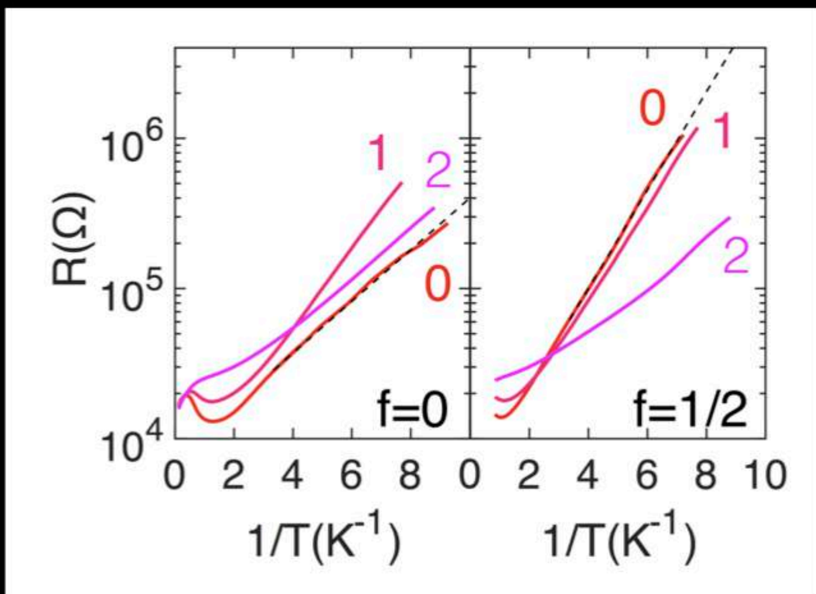


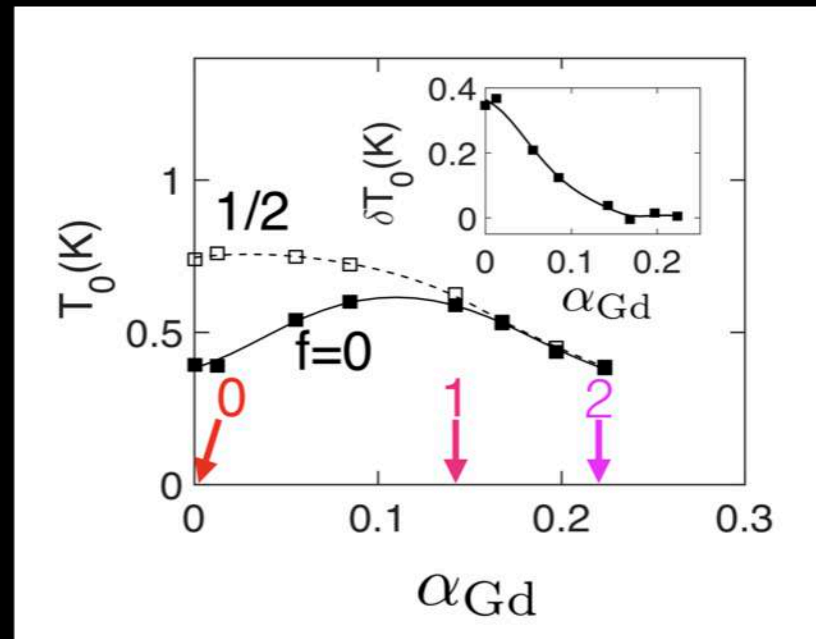
Need models different from the Quantum Rotor

$$H = \frac{e^2}{2C}\sum_i n_i^2 + E_J \sum_{i,j} \cos(\theta_i - \theta_j)$$

or Anderson Localization

But closer to the SIT
Doping Film II





Maximum in T_0 emerges closer to the SIT
⇒ doping enhances localization

Try a modified model

Start: quantum rotor model with CP screening

$$T_0 = E_c \left(1 - \alpha \frac{E_J}{E_c}\right)$$

Note for films with small Cooper pair puddles

$$E_c = \frac{e^2}{2C} >> \Delta$$

=> capacitance renormalization by virtual qp tunneling*

$$E_c \rightarrow \tilde{E}_c = \frac{2\Delta}{3\pi^2 g} \ln\left(\frac{gE_{c0}}{\Delta}\right)$$

* Larkin and Ovchinnikov, Ambegaokar, Eckern, Schon, Chakravarty, Kivelson, Zimanyi and Halpering, and Beloborov

Quantum Rotor with QP Screening*

$$T_0 = \frac{2\Delta}{3\pi^2 g} \ln\left(\frac{gE_{c0}}{\Delta}\right) - \beta g \Delta F(2\pi f)$$

g is interisland conductance, *F is a periodic function, β* depends on coordination

Renormalized E_c

- *depends more on Δ than geometry*
- *affected by pairbreaking*

*Beloborodov and coworkers RMP (2007), Chakravarty et al. (1987)

Quantum Rotor with QP Screening

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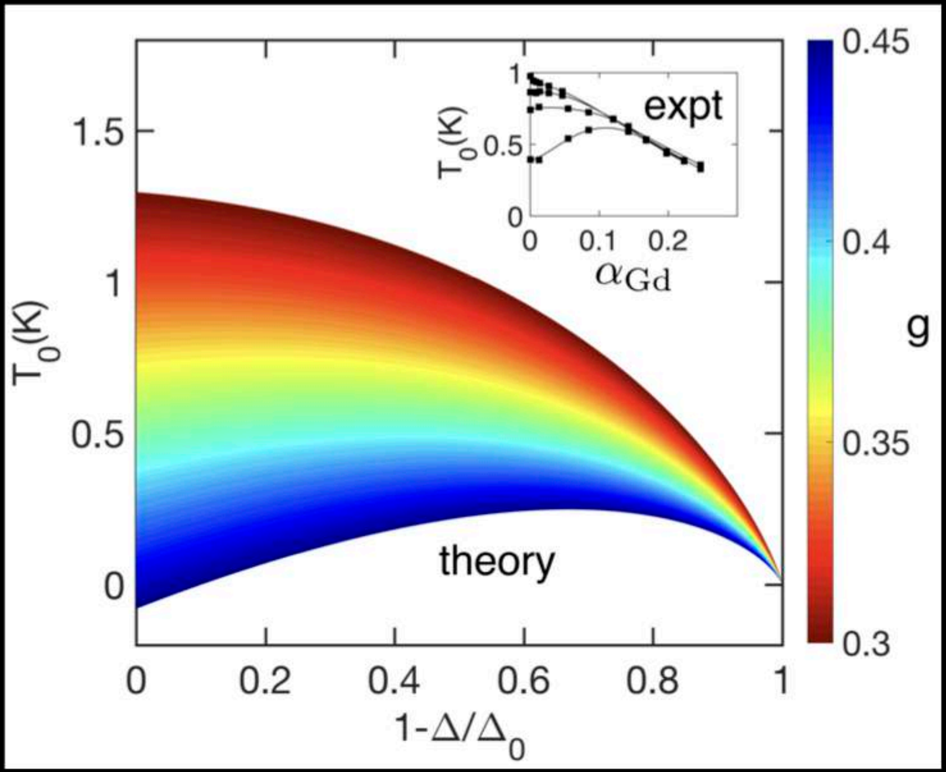
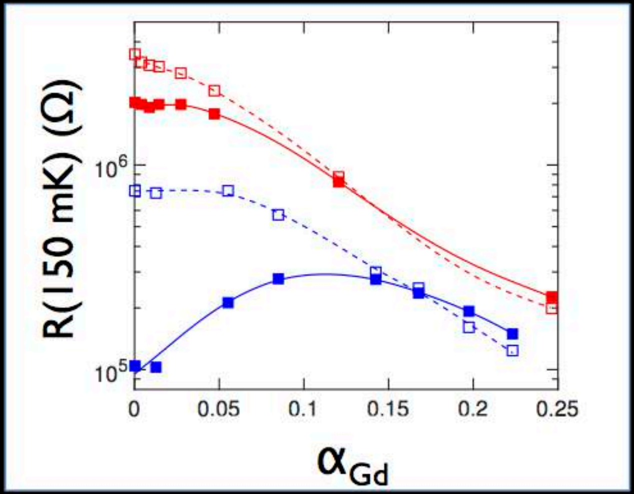
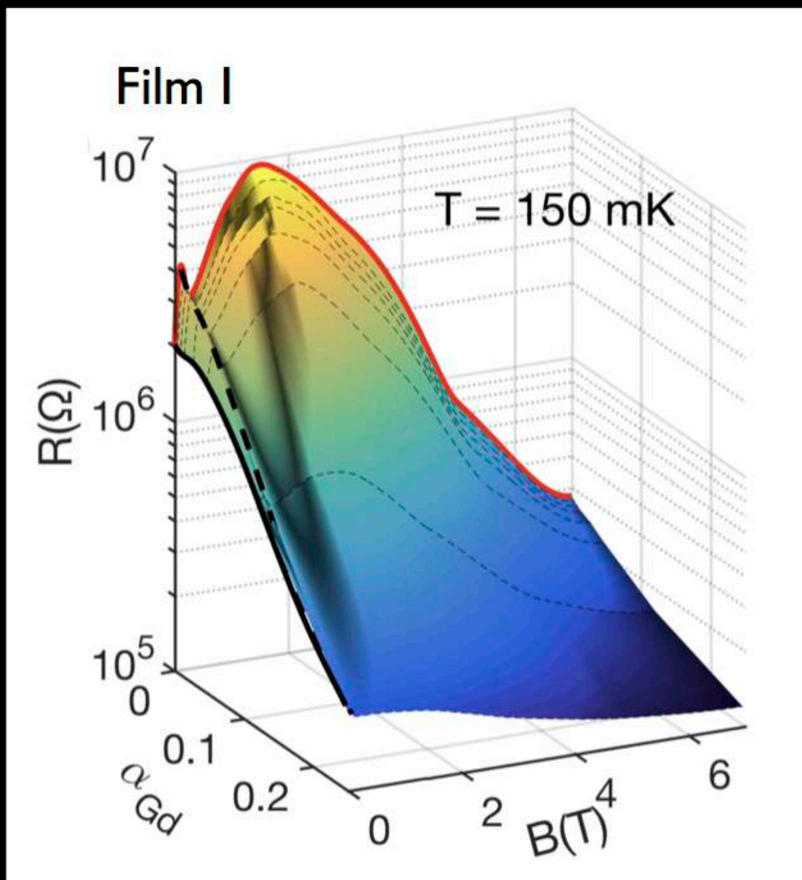


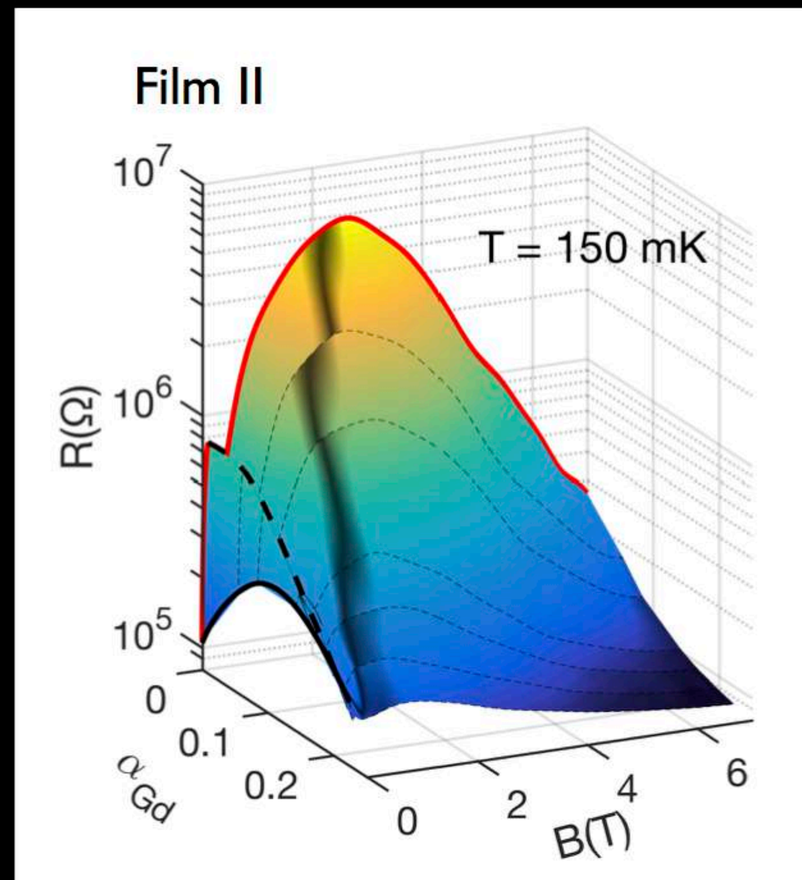
Magnetic Impurity Effects on CPI

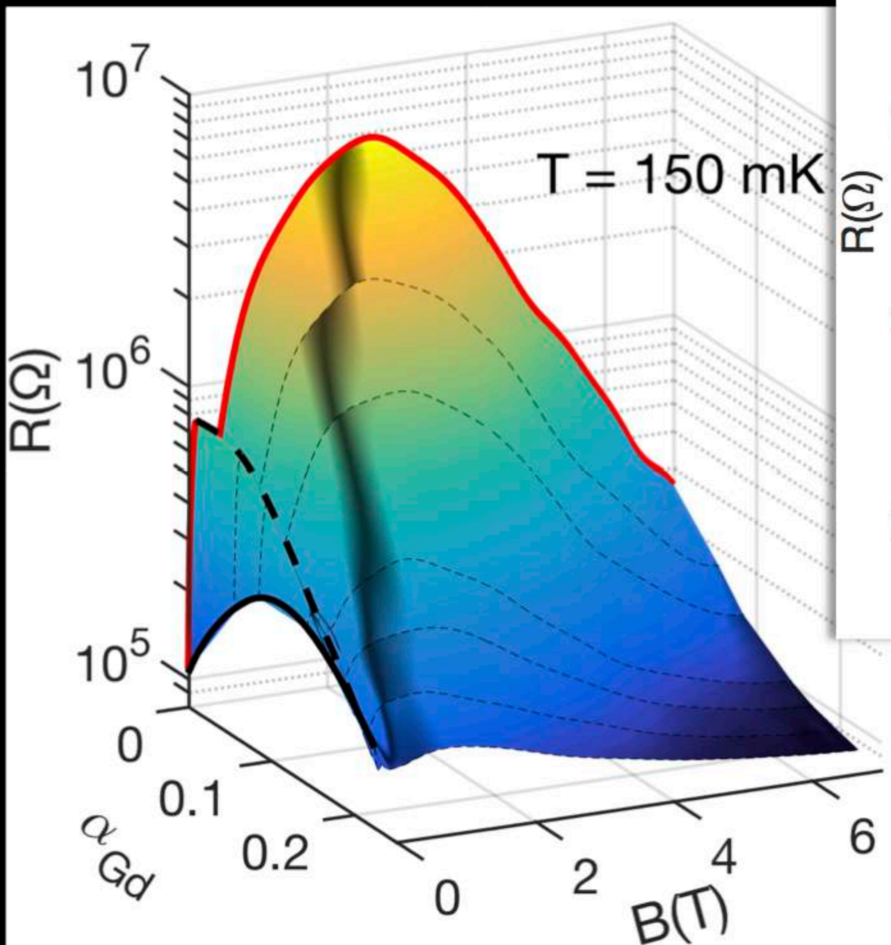


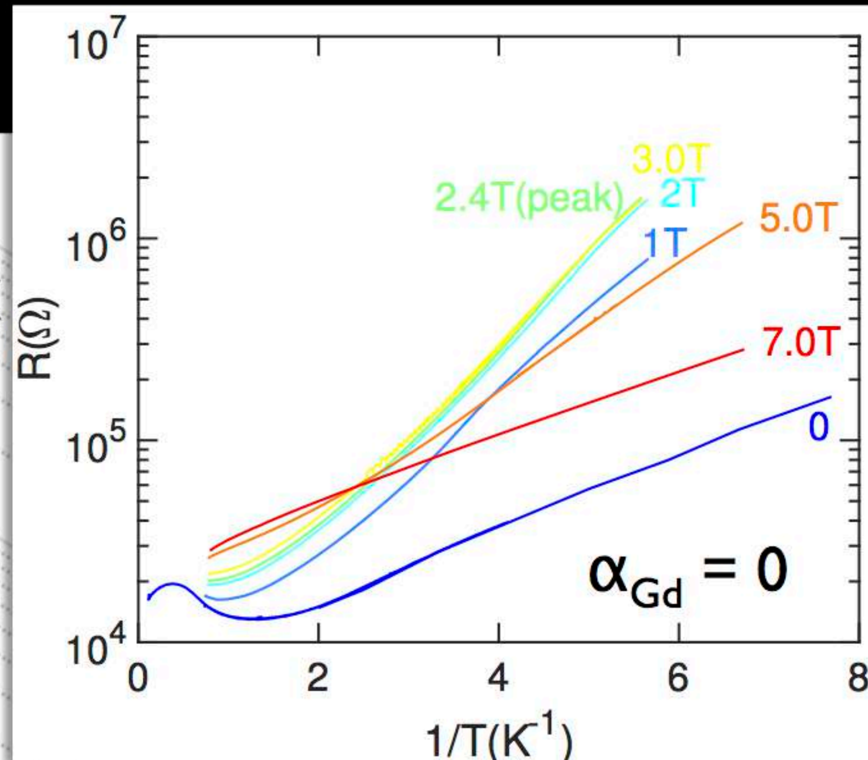
- Pairbreaking
  - Diminishes localization far from the SIT
  - Enhances localization close to the SIT
- Behavior of T_0 suggests
  - CPI is a Mott insulator
  - E_c depends on Δ
  - Maximum in T_0 implies long range Coulomb interactions

Giant MR Peak with Doping



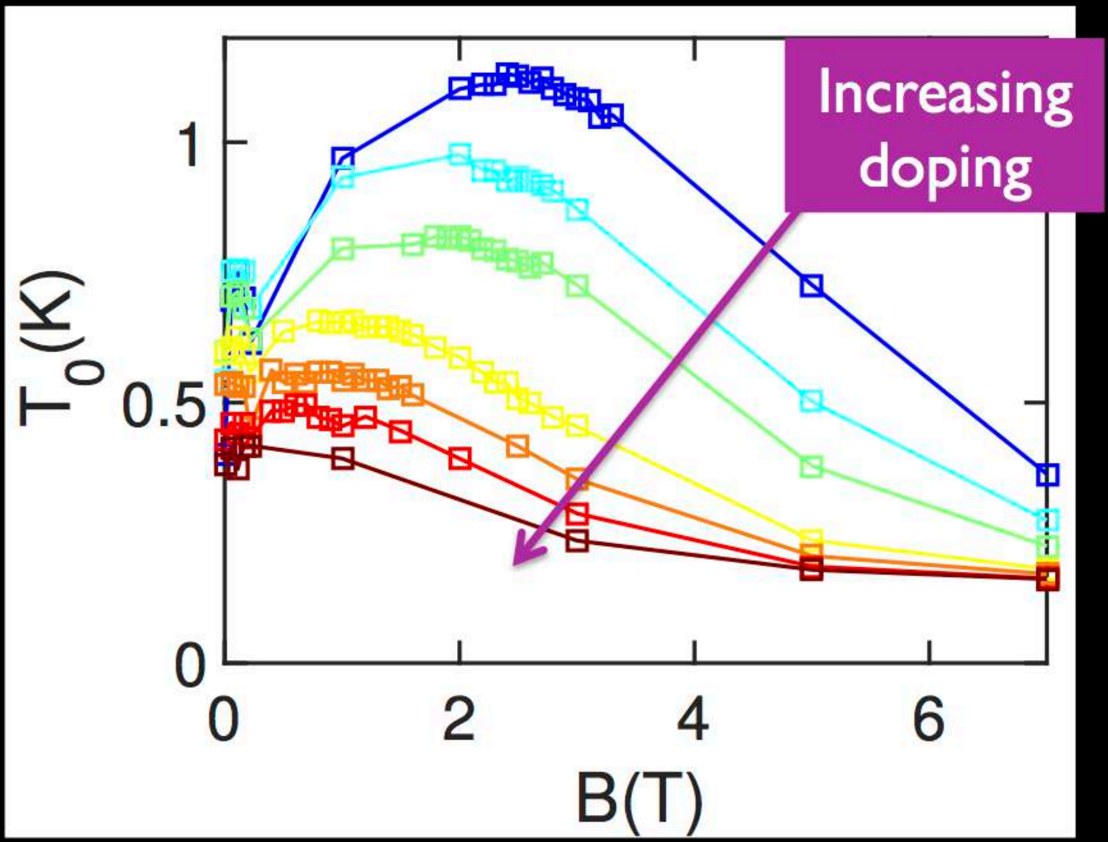




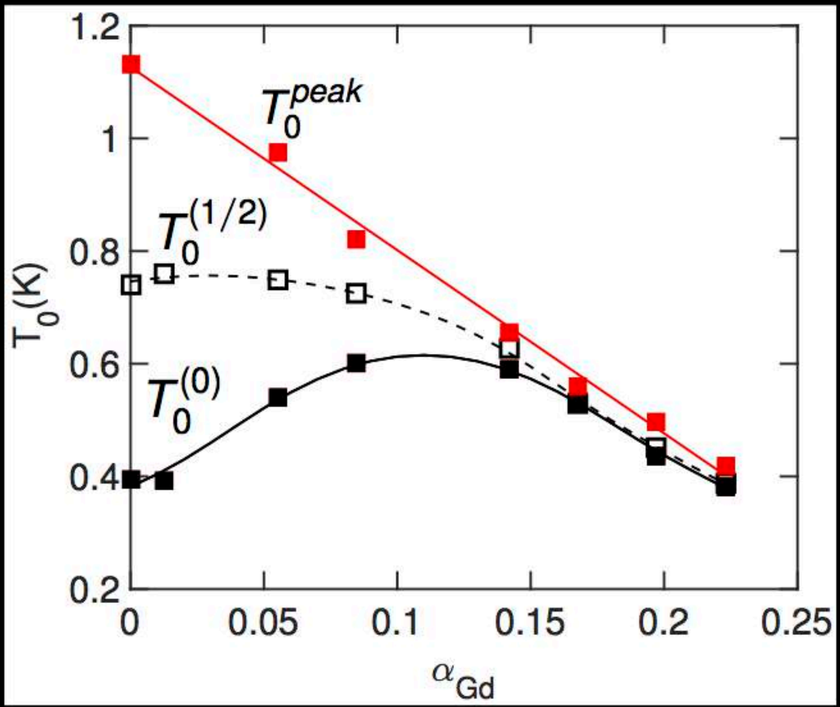


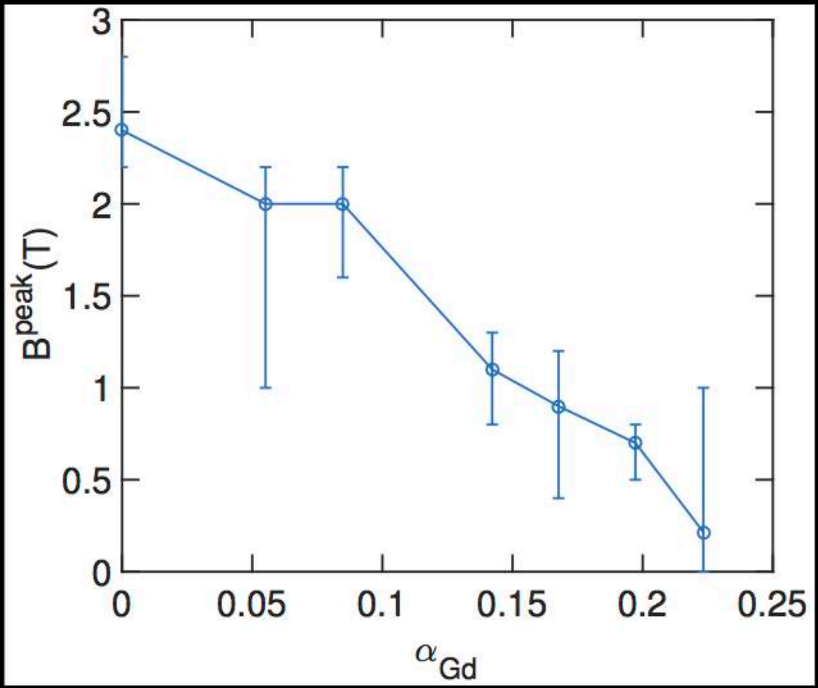
Activated up to high B fields

Peak in T_0 that evolves with doping



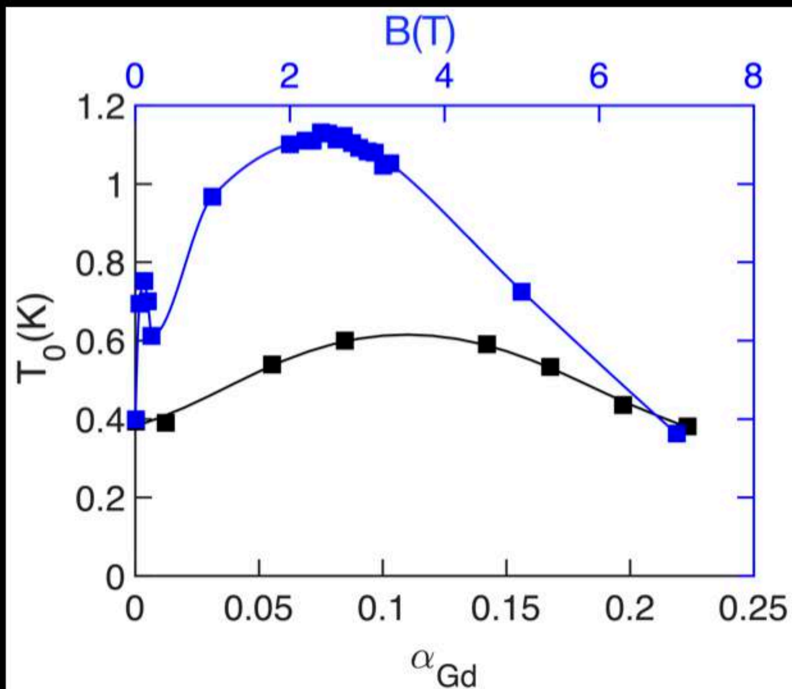
Peak Shrinks and Shifts to Low B with Doping

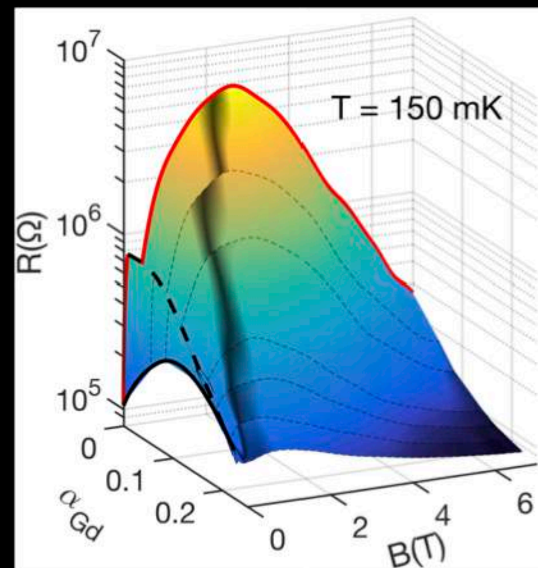




Nearly linear decrease of peak quantities

Magnetic Impurity Peak

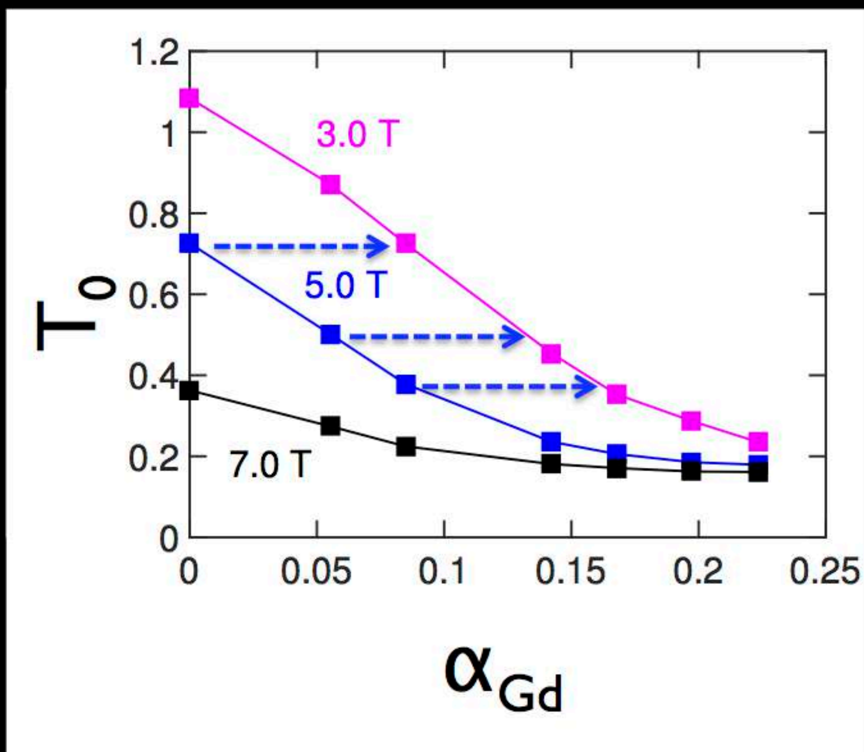


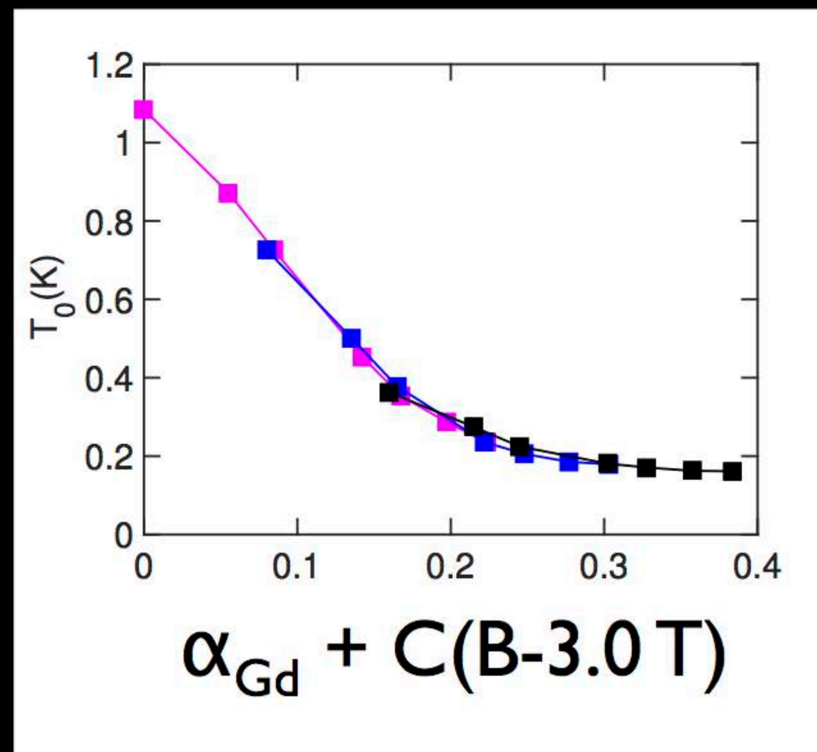


Gd peak much smaller than magnetic field peak
=> Orbital interference dominates peak

$B > B^{peak}$

Pairbreaking Together: B and α_{Gd}





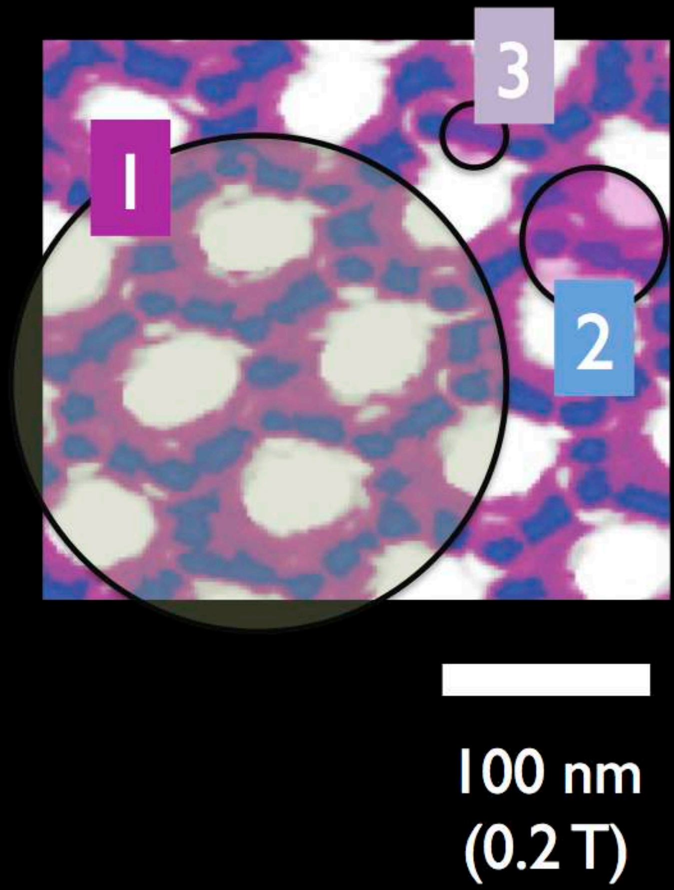
Modelling Positive MR

From low to high B:

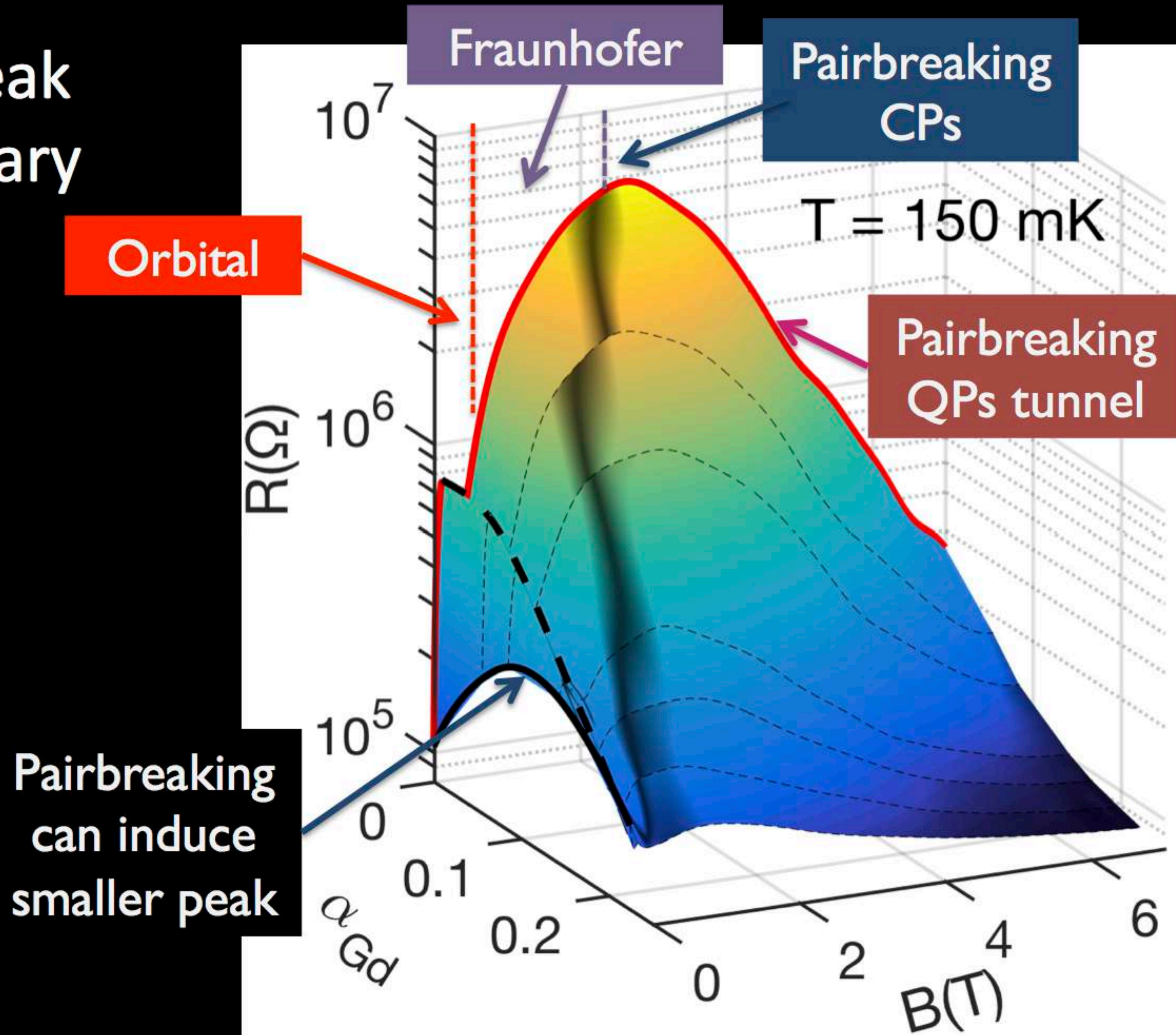
1) "Orbital Effect" or destructive interference in large loops

2) "Fraunhofer effect" or destructive interference in single junctions

3) "Pairbreaking" reduction of E_J by reducing Δ



MR Peak Summary



Doping the CPI

- Gd impurities change the activation energy
- Response suggests that CPI is a Mott Insulator with a gap that depends on the pair binding
  - Differentiates CPI from other Bose insulators
  - Suggests that a good CPI has a large Δ
  - Model agreement implies that the Coulomb interaction is long ranged in these films
- Giant Positive MR mostly an orbital effect
- Pair breaking alone can create resistance peak