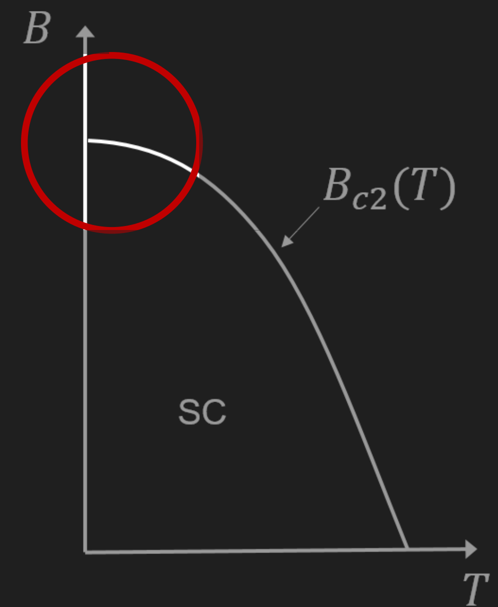
Quantum meets classical phase transition: Low-T anomaly in disordered superconductors near B_{c2}

Benjamin Sacépé

Néel Institute, CNRS & Univ. Grenoble Alpes



Villard de Lans, October 8-12, 2018

Experiments

Johanna Seidemann
Néel Institute

Fédéric Gay
Néel Institute

Maoz Ovadia
Weizmann Institute

MoGe samples

Kevin Davenport
Univ. of Utah

Andrey Rogachev
Univ. of Utah

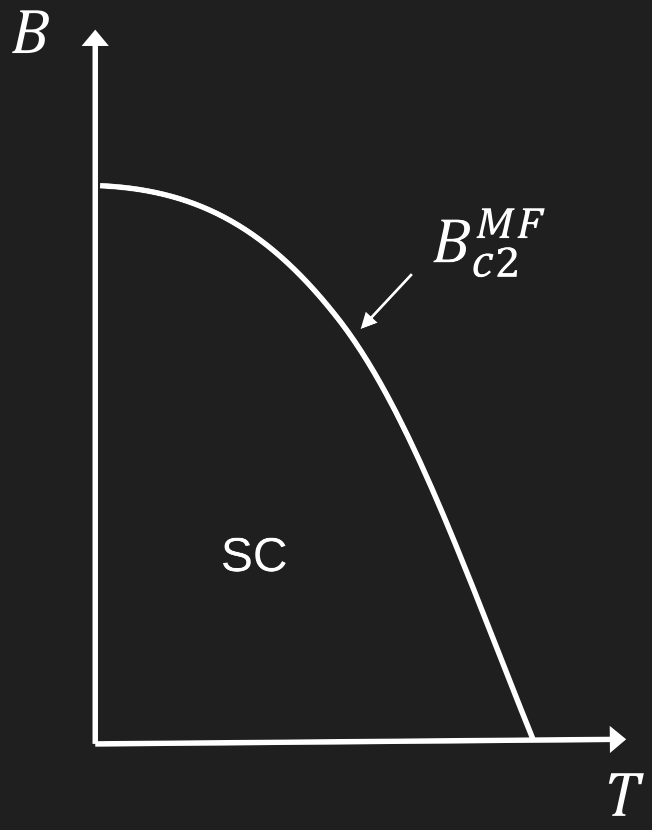
Theory

Karen Michaeli
Weizmann Institute

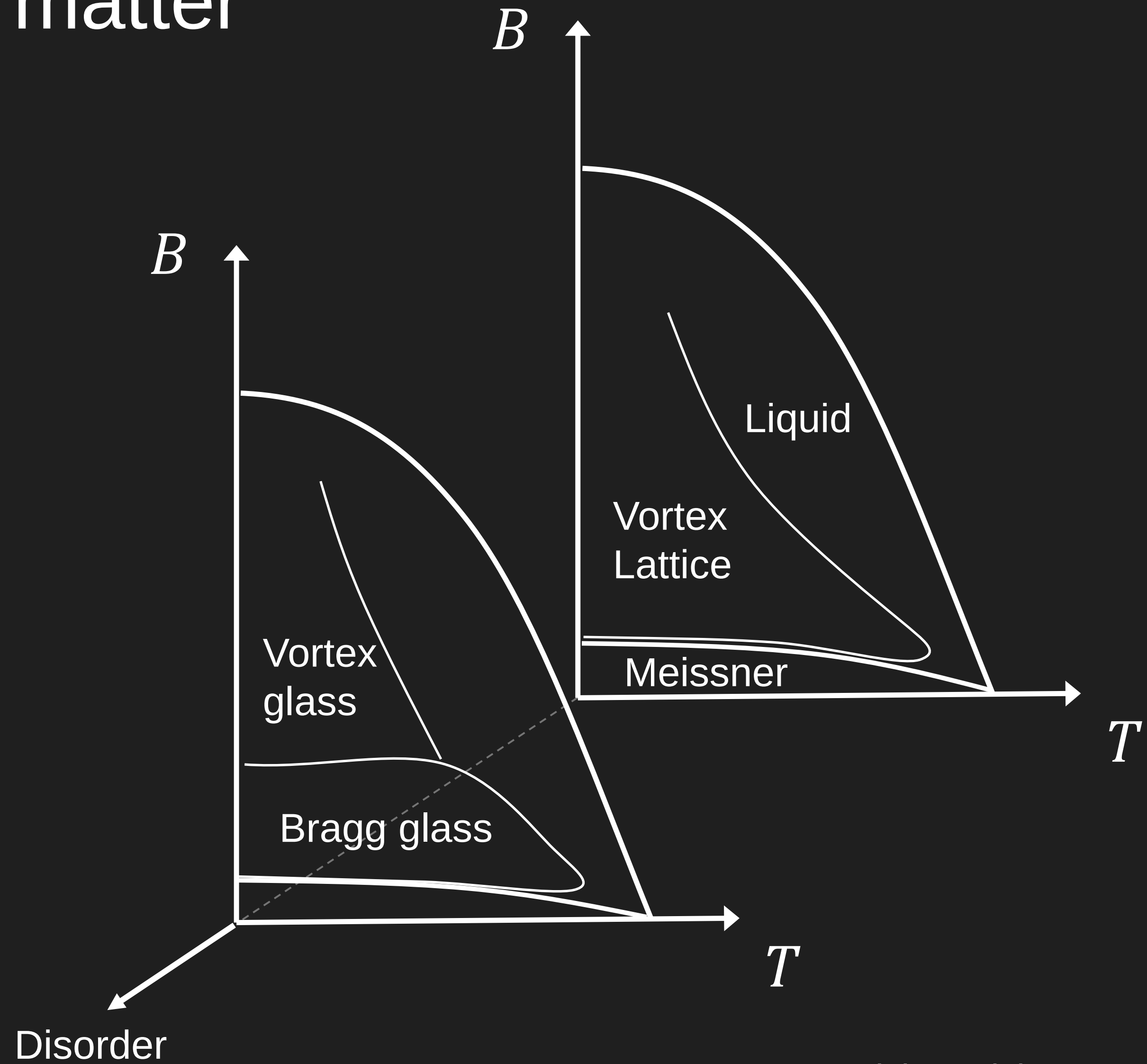
Mikhail Feigel’man
(And the cat)
Landau Institute

+ Many fruitful discussions with Shahar’s group

B-T phase diagram

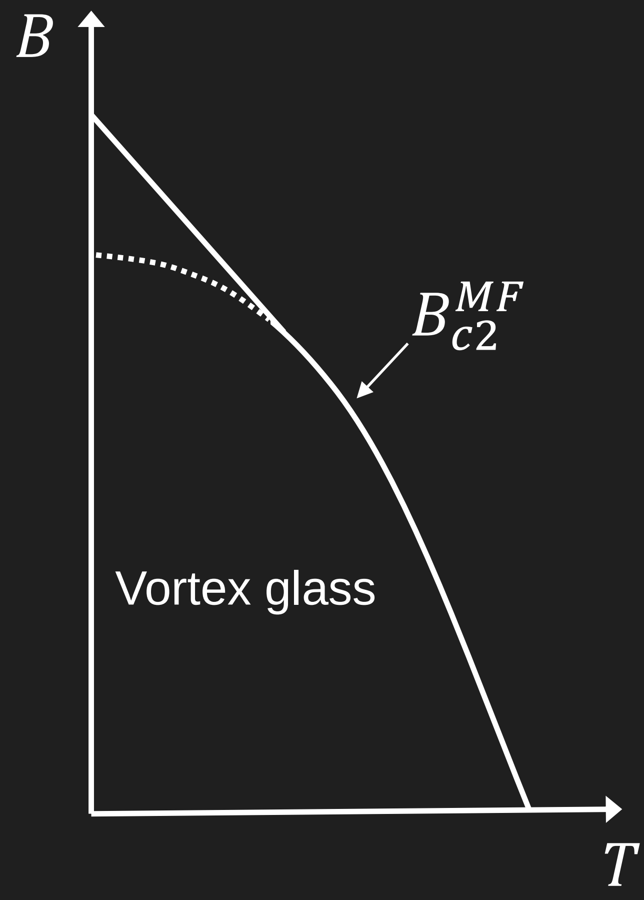


Vortex matter



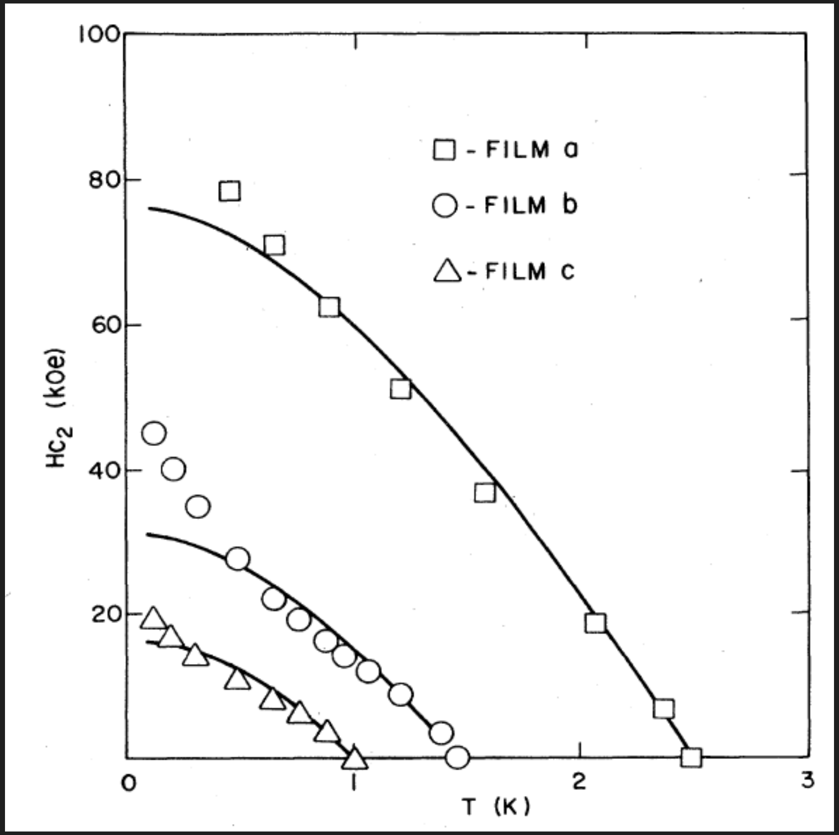
Fisher, Fisher, Huse PRB (‘ 91)
Blatter, et al. RMP (’94)
Kwok, et al. Rep. Prog. Phys. (‘16)

(Very) dirty superconductors



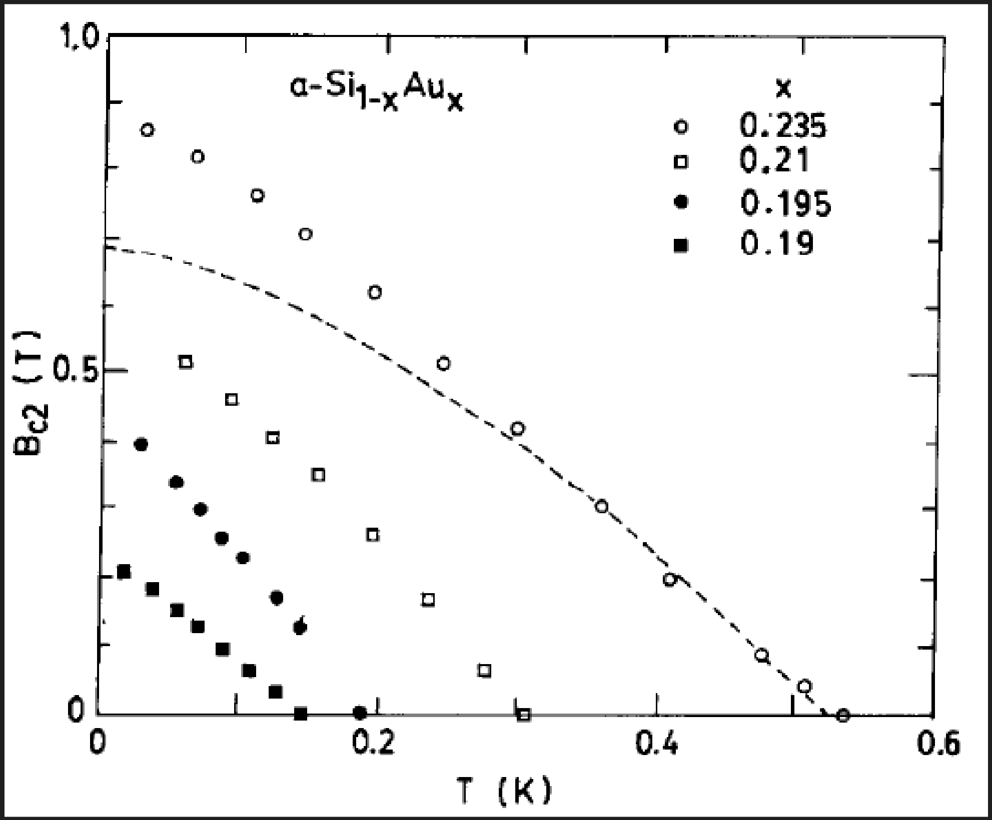
Fisher, Fisher, Huse PRB (‘ 91)
Blatter, et al. RMP (’94)
Kwok, et al. Rep. Prog. Phys. (‘16)

In/InO_x composite films (10 nm thick)



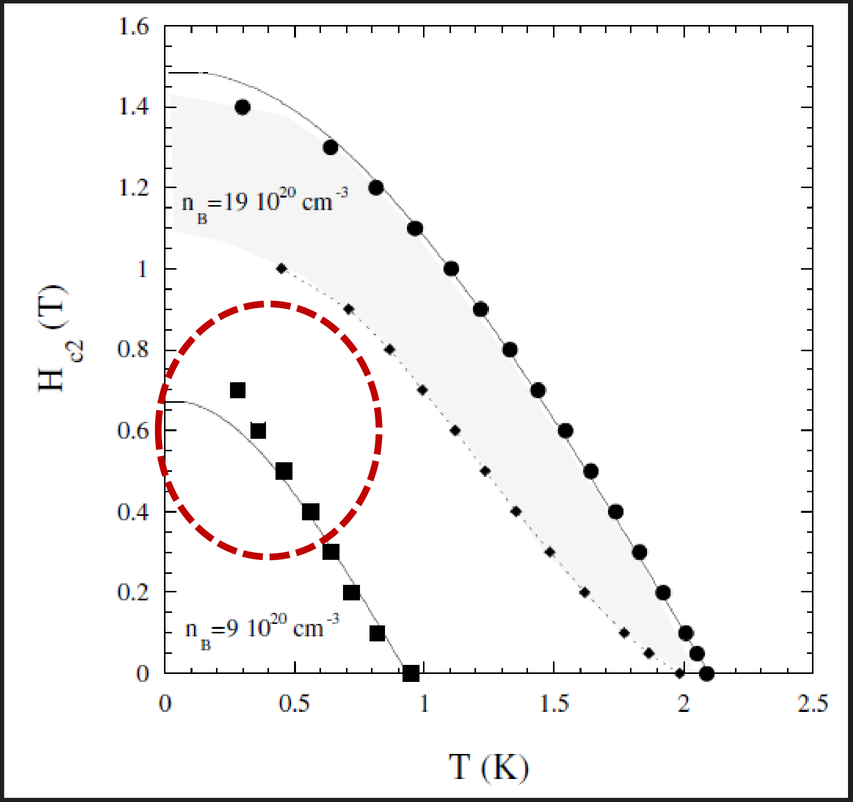
Hebard, Paalanen PRB ('84)

a-$Si_{1-x}Au_x$ films (100-200nm)



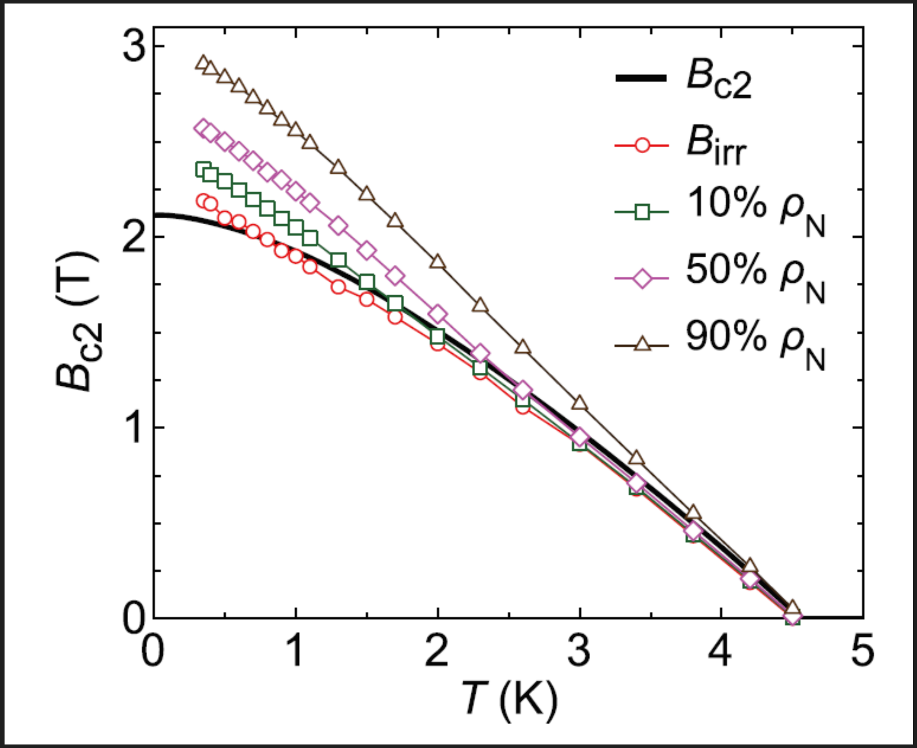
Furubayashi, Nishida, Yamagushi, Morigaki, Ishimot (‘85)

B-doped diamond (bulk)



Bustarret et al. PRL (‘04)

$AgSnS_2$ (bulk)



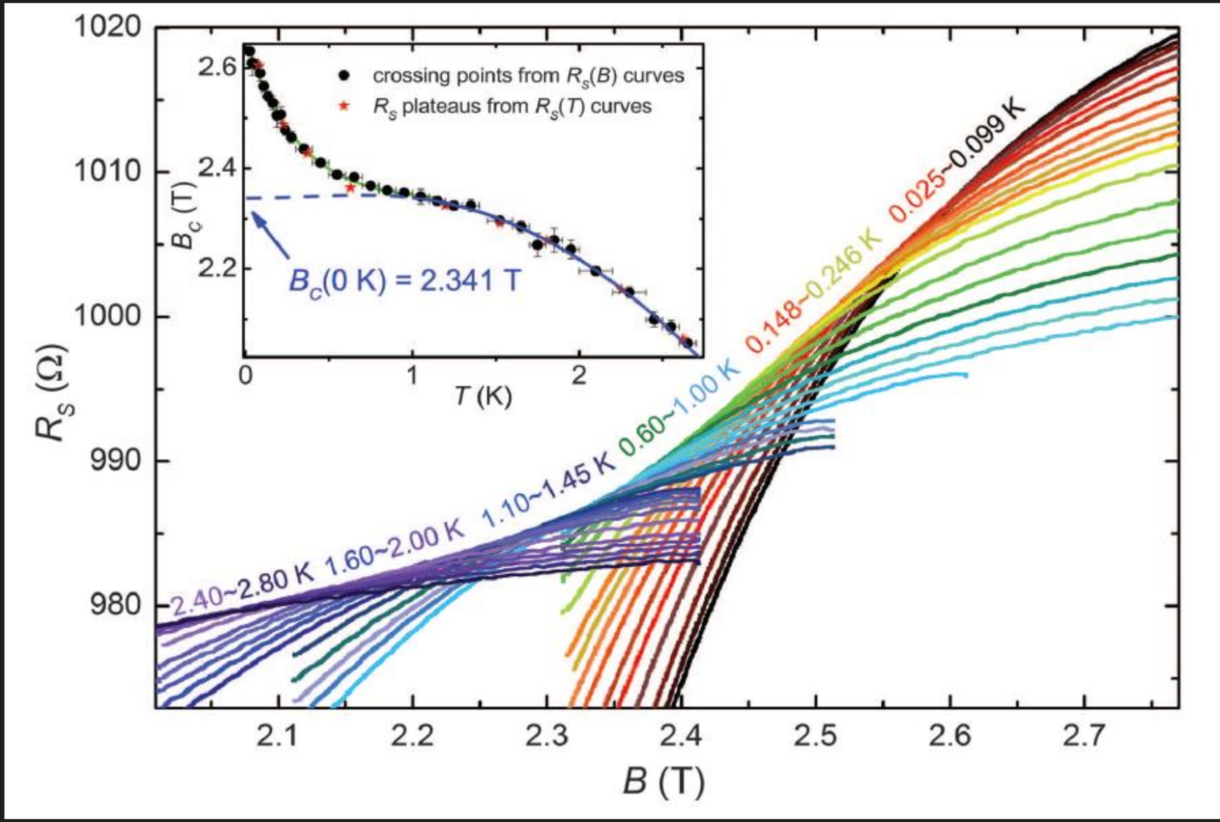
Y. Ando PRB ('13)

SUPERCONDUCTIVITY

Quantum Griffiths singularity of superconductor-metal transition in Ga thin films

Ying Xing,[1*] Hui-Min Zhang,[2*] Hai-Long Fu,[1*] Haiwen Liu,[1,4*] Yi Sun,[1] Jun-Ping Peng,[2] Fa Wang,[1,4] Xi Lin,[1,4†] Xu-Cun Ma,[2,3,4†] Qi-Kun Xue,[3,4] Jian Wang,[1,4†] X. C. Xie[1,4]

Science 350, 542 (2015)



Low-T anomaly of $B_{c2}(T)$

Tenhover et al. (‘ 81)

Okuma et al. (‘83)

Hebard, Paalanen (‘84)

Graybeal, Beasley (‘84)

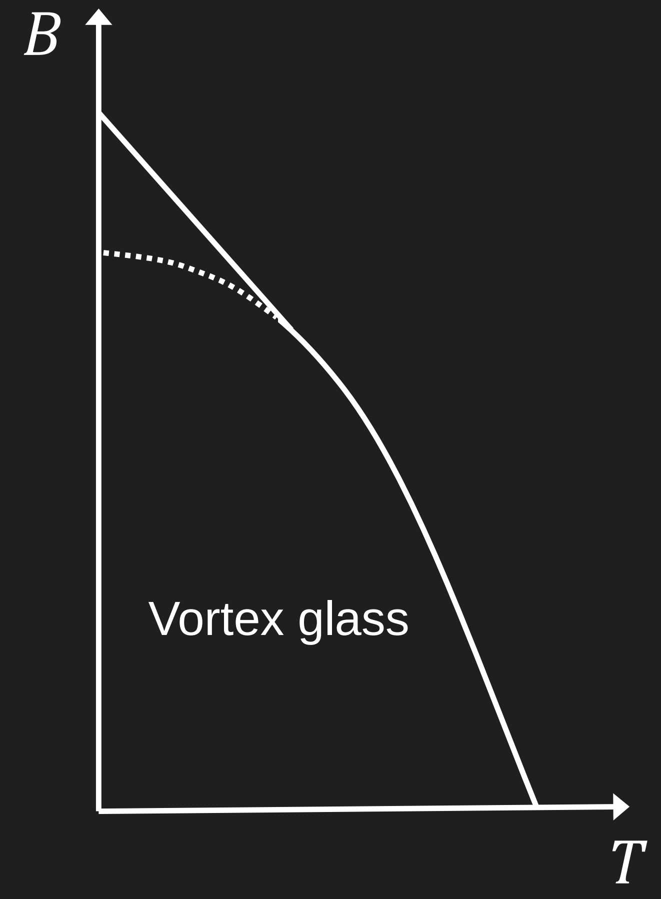
Furubayashi et al. (‘85)

Nordström et al. (‘ 93)

Bustarret et al. (‘04)

Ren et al. (‘13)

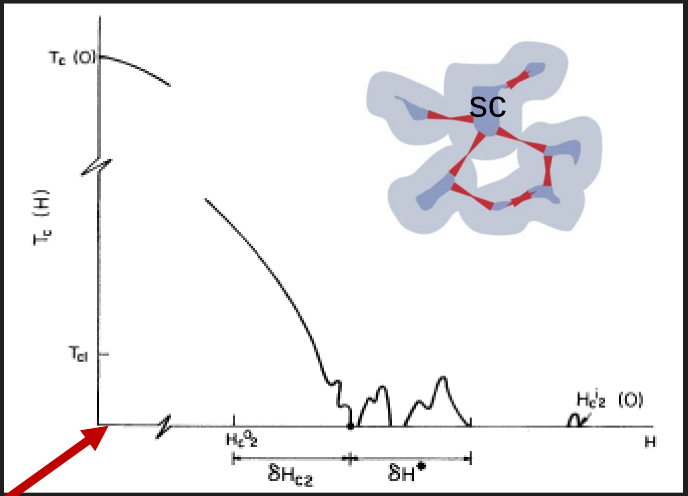
Xing et al. (‘15)



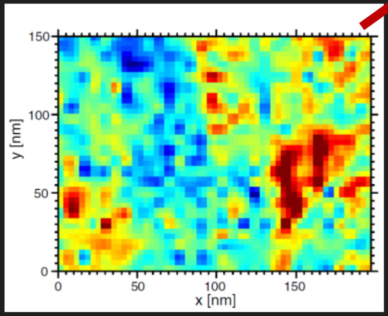
Mesoscopic fluctuations scenario

Spivak & Zhou, PRL ('95)

Mesoscopic sample



STM map of $\Delta(r)$



B.S. et al, PRL ('08)

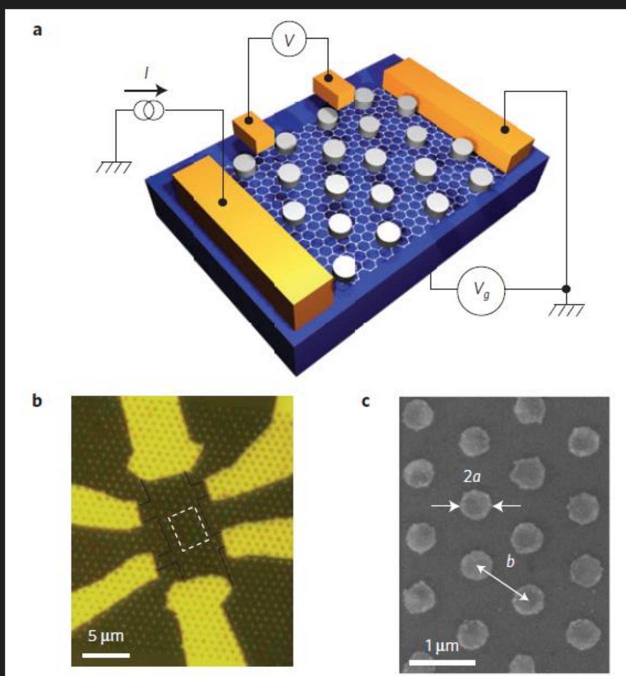
nature physics

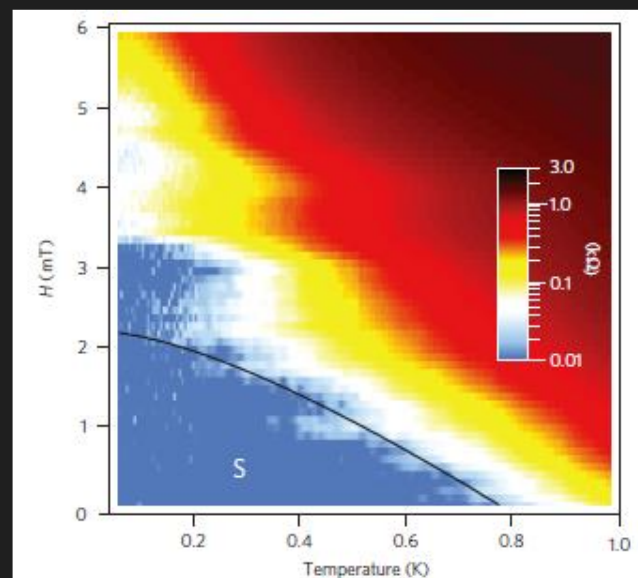
ARTICLES

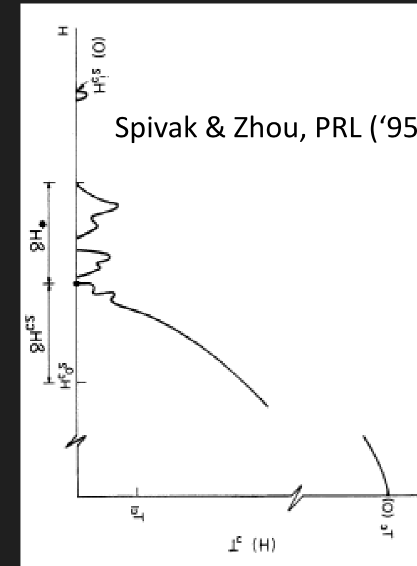
PUBLISHED ONLINE: 30 MARCH 2014 | DOI: 10.1038/NPHYS2929

Collapse of superconductivity in a hybrid tin–graphene Josephson junction array

Zheng Han[1,2], Adrien Allain[1,2], Hadi Arjmandi-Tash[1,2], Konstantin Tikhonov[3,4], Mikhail Feigel'man[3,5], Benjamin Sacépé[1,2] and Vincent Bouchiat[1,2]*





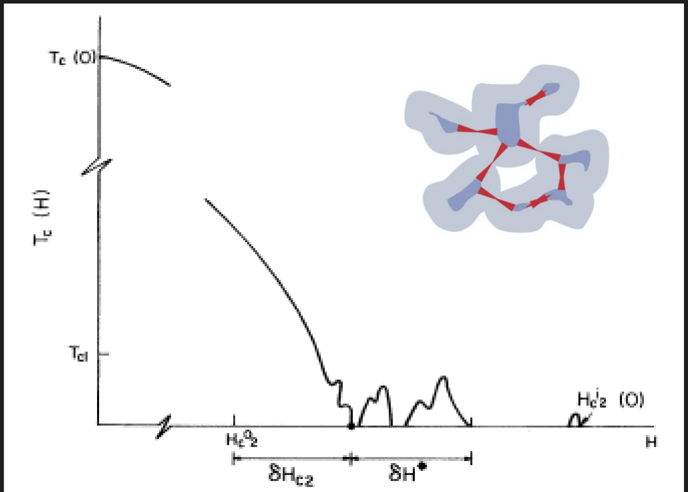


Spivak & Zhou, PRL ('95)

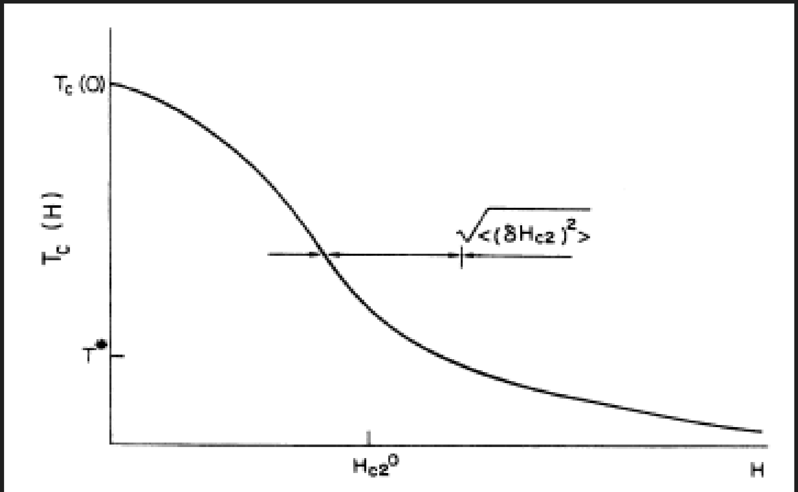
Mesoscopic fluctuations scenario

Spivak & Zhou, PRL ('95)

Mesoscopic sample



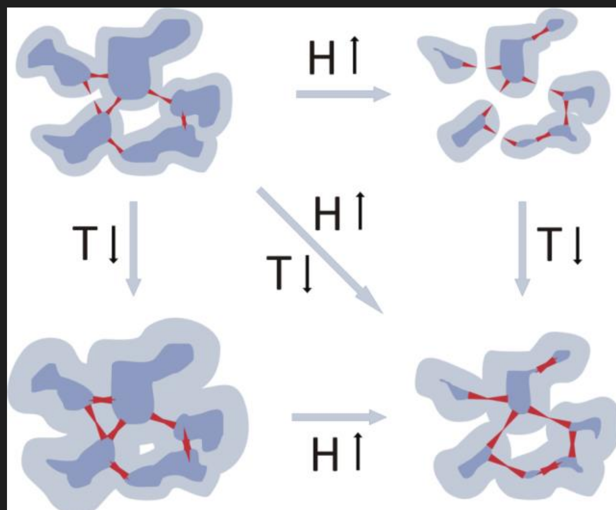
Bulk sample

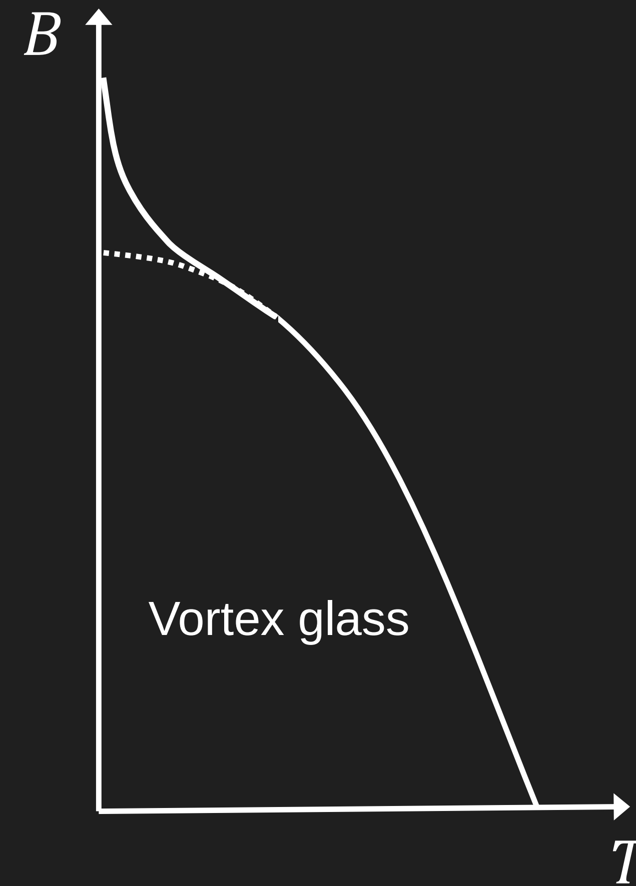


Predict exponential decrease of $\langle j_c \rangle \sim exp\left(-\frac{R_0}{L_H} - \frac{R_0}{L_T}\right)$

Mesoscopic fluctuations scenario

Galitski & Larkin, PRL ('01)



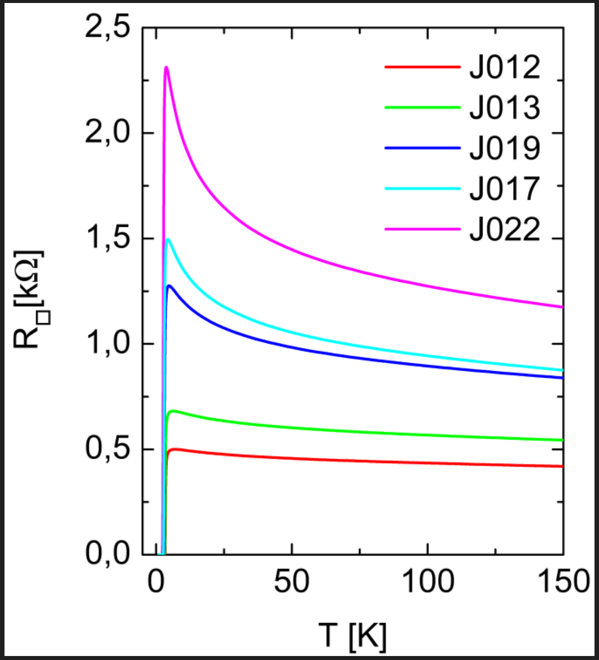


- $B \nearrow$: decrease of SC island size
- $T \searrow$: increase of SC proximity effect

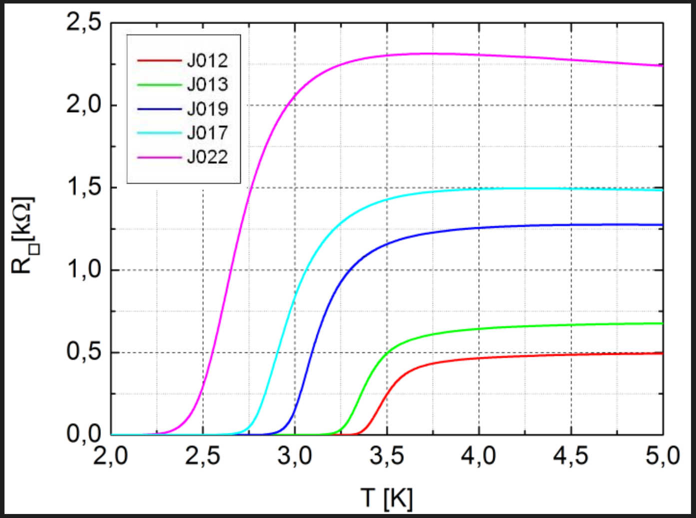
Predict exponential increase of $B_{c2}(T)$ and exp. suppression of $j_c(B)$!

Critical current

Moderetely disordered amorphous indium oxide (InO)



- 30-60 nm thick
- *e*-density : $n \sim 10^{21}\ cm^{-3}$
- Disorder : $k_F l_e \sim 0.3 - 0.4$



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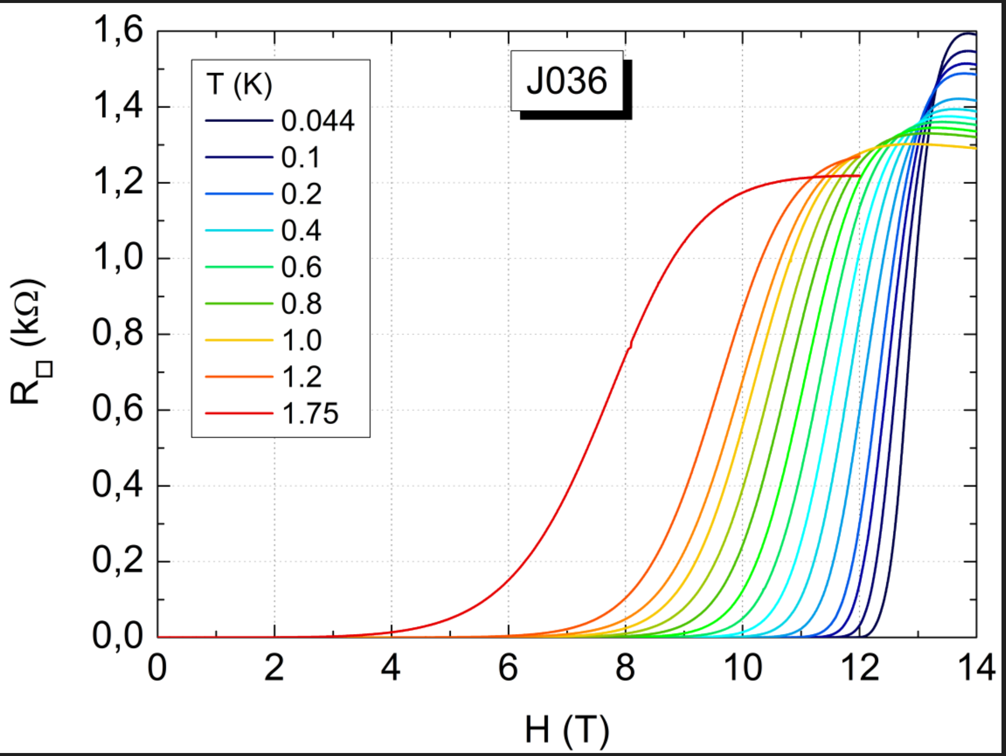

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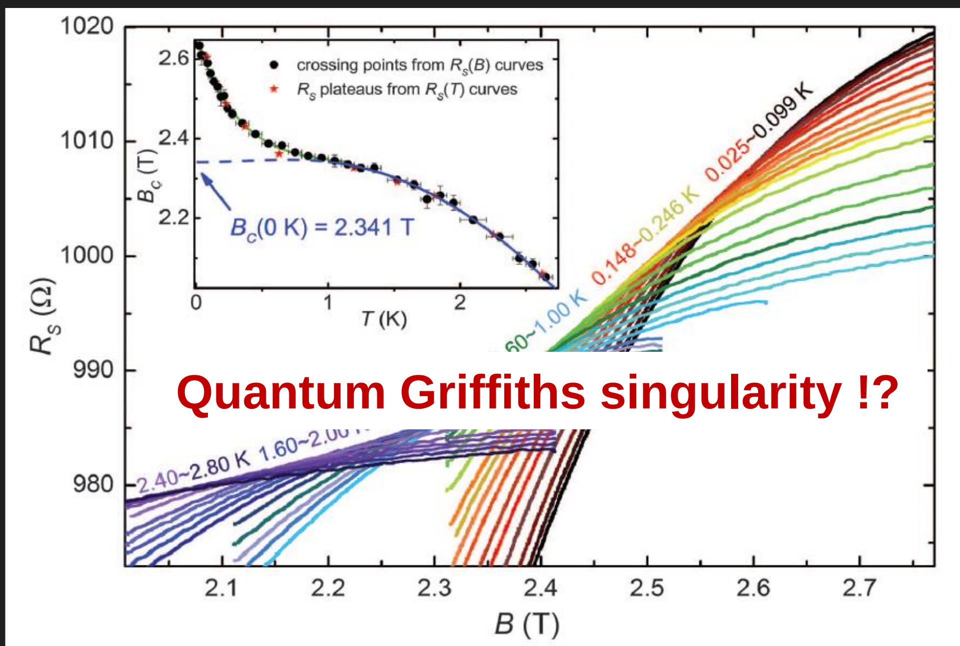
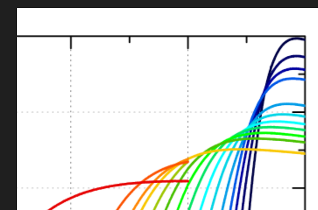
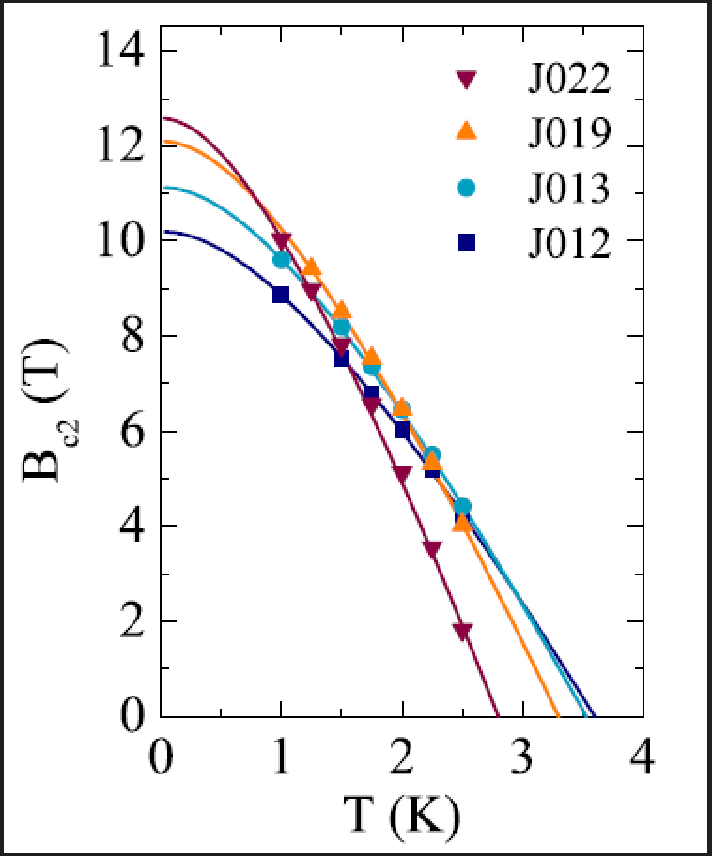




Science 350, 542 (2015)

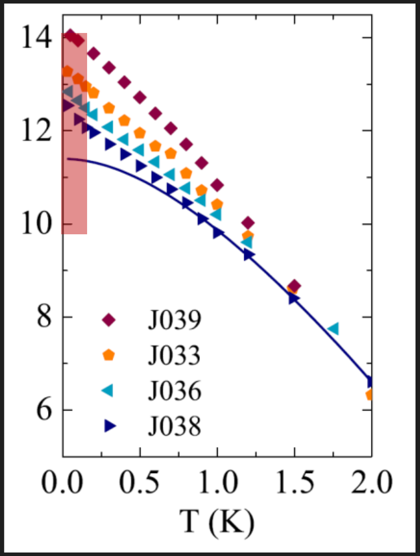
Linear *T*-dependence of $B_{c2}(T)$

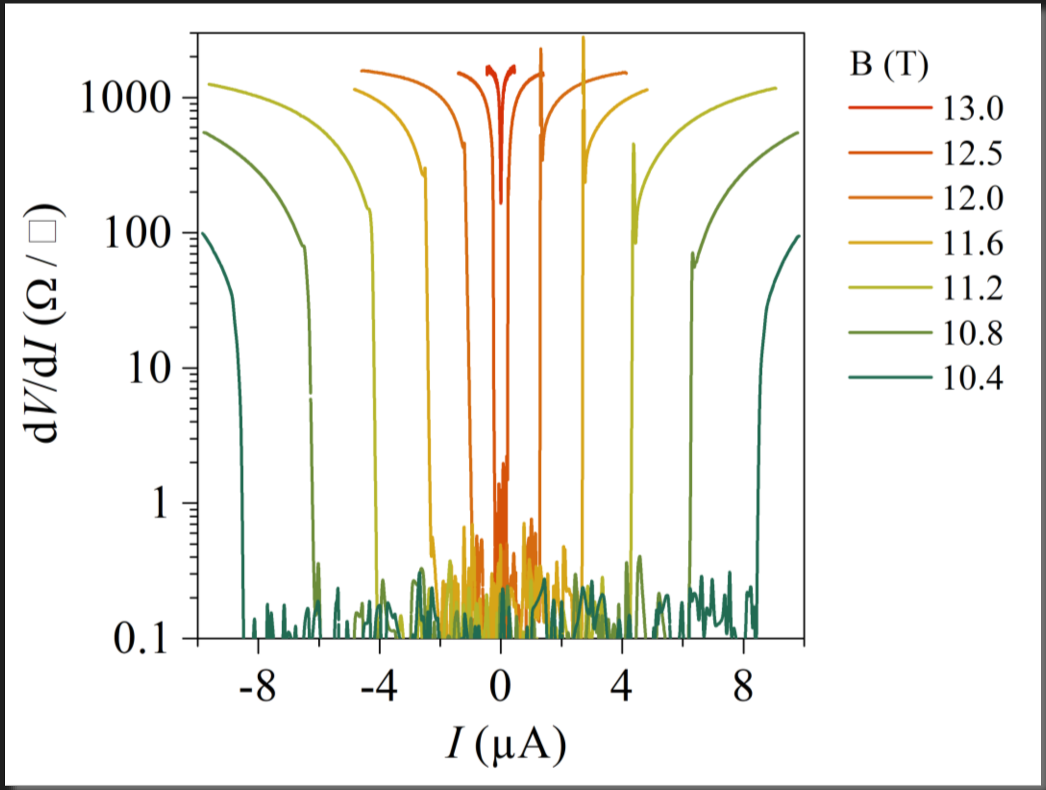


B.S. et al. *PRB* ('15)

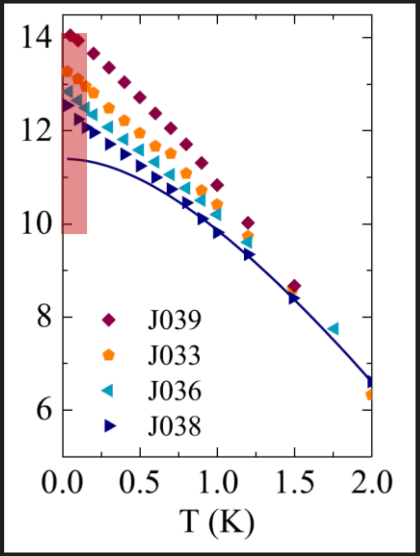
Critical current measurements

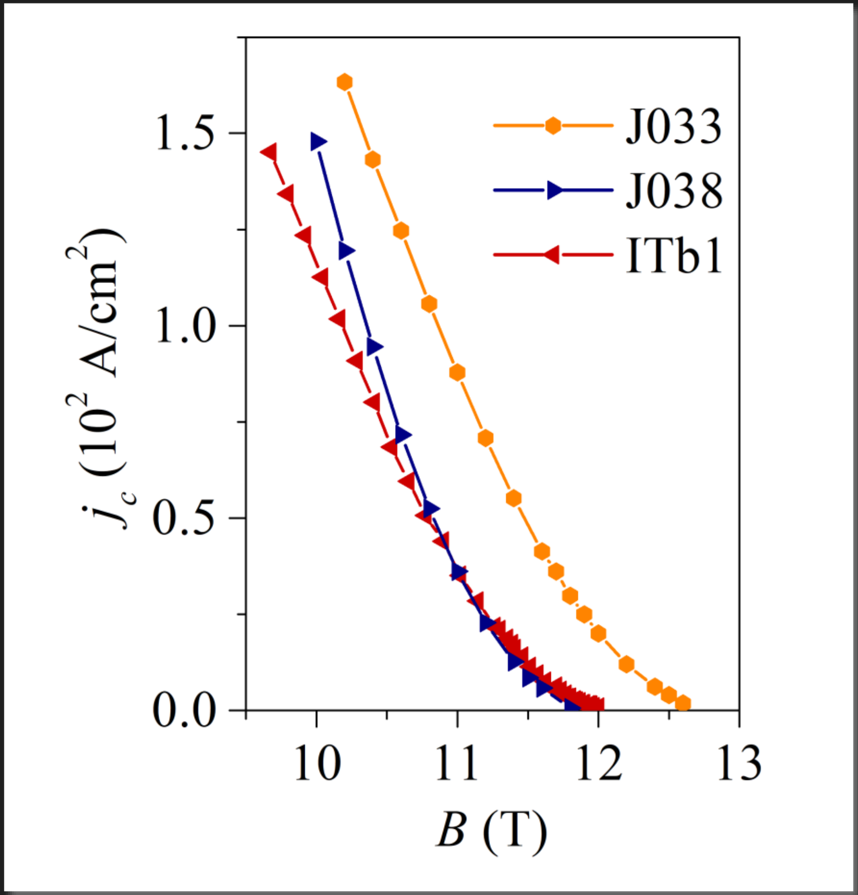
$T \simeq 0.03\ K$





Critical current measurements





Critical current measurements

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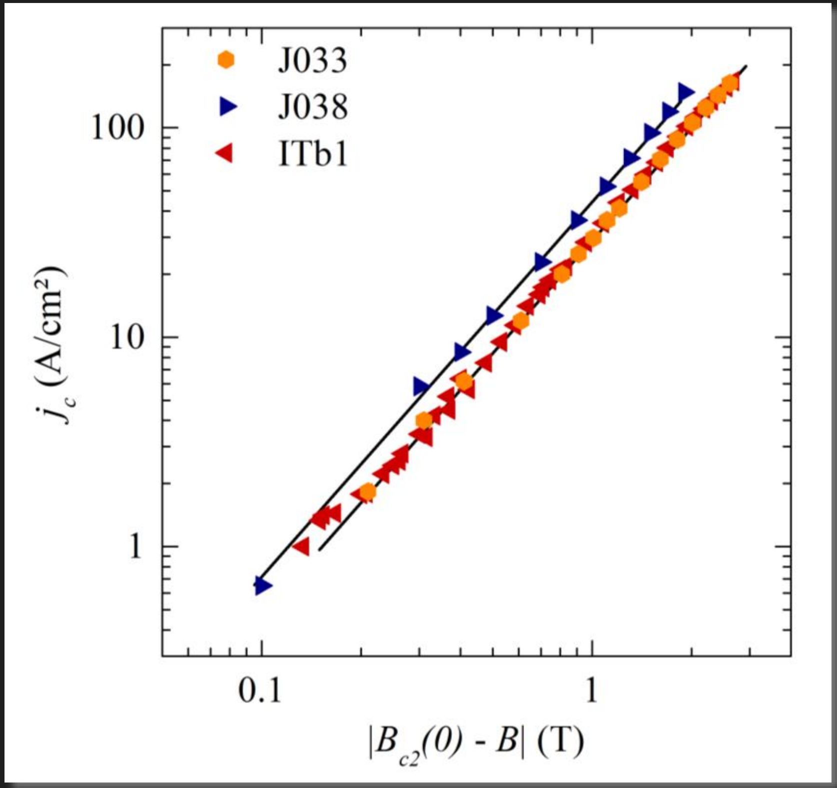
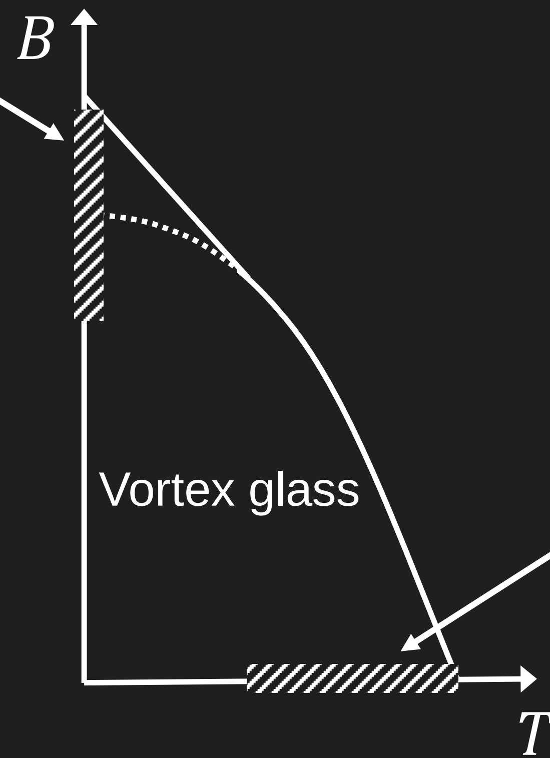


$$J_c(T{\sim}0) \propto (B_{c2}(0) - B)^{\alpha} \qquad \alpha \simeq 1.5 - 1.6$$

Mean-field depairing current ?

Near quantum transition:

$$J_c \propto |B - B_{c2}|^{3/2} \propto \frac{\rho_s}{\xi_{GL}}$$



$$\begin{cases} \rho_s \propto |B - B_{c2}| \\ \xi_{GL} \propto |B - B_{c2}|^{-1/2} \end{cases}$$

?

Near thermal transition:

$$\begin{cases} \rho_s \propto |T - T_c| \\ \xi_{GL} \propto |T - T_c|^{-1/2} \end{cases}$$

$$J_c \propto \frac{\rho_s}{\xi_{GL}} \propto |T - T_c|^{3/2}$$

Ginzburg-Landau

$$F = \alpha|\Delta(\boldsymbol{r})|^2 + \beta|\Delta(\boldsymbol{r})|^4 + \gamma\left|\left(-i\boldsymbol{\nabla} - \frac{2e}{\hbar c}\boldsymbol{A}(\boldsymbol{r})\right)\Delta(\boldsymbol{r})\right|^2$$

$$j_c \propto \rho_s/\xi_{GL}$$

From the free energy

$$\boldsymbol{j} = -c\frac{\partial F}{\partial \boldsymbol{A}}$$

$$\boldsymbol{j} = \gamma\frac{2e}{\hbar}|\Delta(\boldsymbol{r})|^2\boldsymbol{A}$$

From London equation

$$\boldsymbol{j} = -4\rho_s\frac{e^2\boldsymbol{A}}{\hbar^2 c}$$

$$\rho_s = \frac{\hbar c}{2e}\gamma|\Delta(\boldsymbol{r})|^2$$

Ginzburg-Landau

$$F = \alpha|\Delta(\boldsymbol{r})|^2 + \beta|\Delta(\boldsymbol{r})|^4 + \gamma\left|\left(-i\boldsymbol{\nabla} - \frac{2e}{\hbar c}\boldsymbol{A}(\boldsymbol{r})\right)\Delta(\boldsymbol{r})\right|^2$$

$$|\Delta|^2 = \frac{\alpha}{2\beta}$$

$$\alpha = \nu\left[\ln\frac{T}{T_{c0}} + \psi\left(\frac{1}{2} + \frac{eDB}{2\pi cT}\right) - \psi\left(\frac{1}{2}\right)\right]$$

$$\alpha = \xrightarrow[T\to 0]{} \nu\left(1 - \frac{B}{B_c}\right)$$

$$\rho_s = \frac{\hbar c}{2e}\gamma|\Delta(\boldsymbol{r})|^2 = \frac{12}{\pi}\rho_{s0}\left(1 - \frac{B}{B_{c2}(0)}\right)$$

Critical current

$$j_c \propto \rho_s / \xi_{GL}$$

Superfluid stiffness

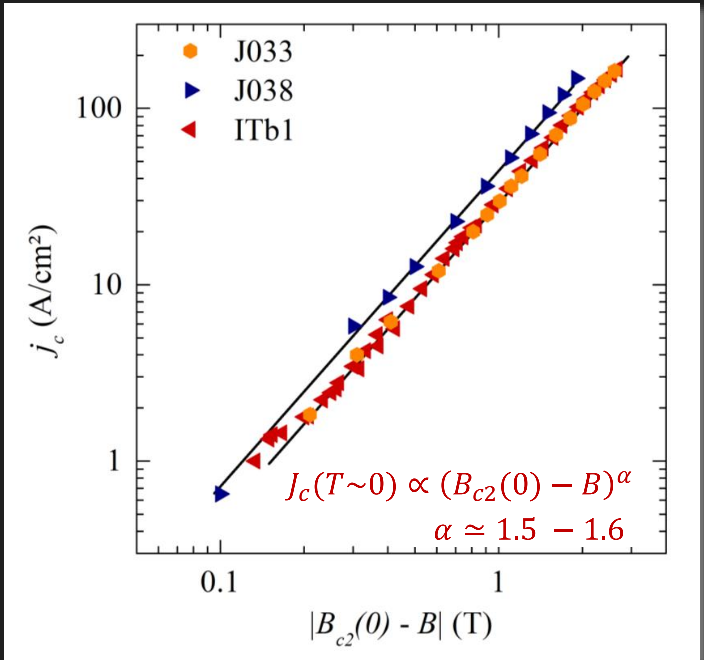
$$\rho_s \propto |\Delta|^2 \sim \left(1 - \frac{B}{B_{c2}(0)}\right)$$

Coherence length

$$\xi_{GL} \sim \frac{v_F}{\Delta}$$

$$\boldsymbol{J_c \propto \frac{\rho_s}{\xi_{GL}} \sim \left(1 - \frac{B}{B_{c2}(0)}\right)^{3/2}}$$

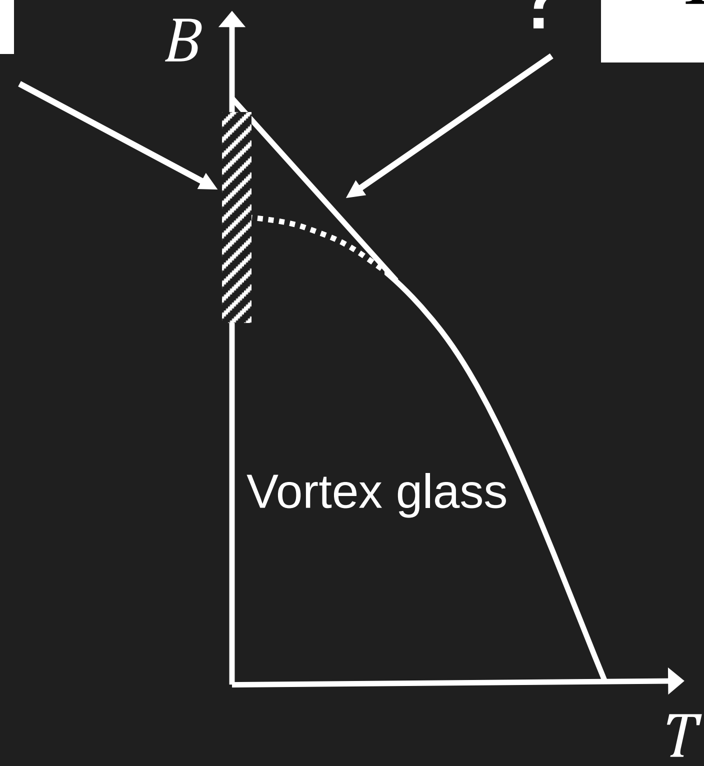
Mean-field scaling of the critical current



$$J_c \propto \frac{\rho_s}{\xi_{GL}} \sim \left(1 - \frac{B}{B_{c2}(0)}\right)^{3/2}$$

$$\rho_s \sim \left(1 - \frac{B}{B_{c2}(0)}\right)$$

? $$1 - \frac{B_{c2}(T)}{B_{c2}(0)} \sim T$$?



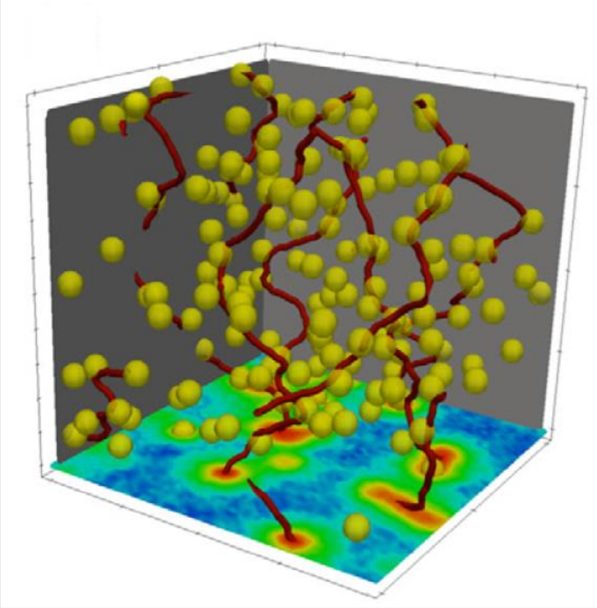
Low-T anomaly of B_{c2}

For bulk crystal $T_c(B)$ is given by :

$$\delta\rho_s(B, T_c) = \epsilon\rho_s(B, 0)$$

Similar to the Lindemann criterion for the melting of bulk cristal

Low-*T* thermal fluctuations of the vortex glass



Kwok et al. Rep. Prog. Phys. ('16)

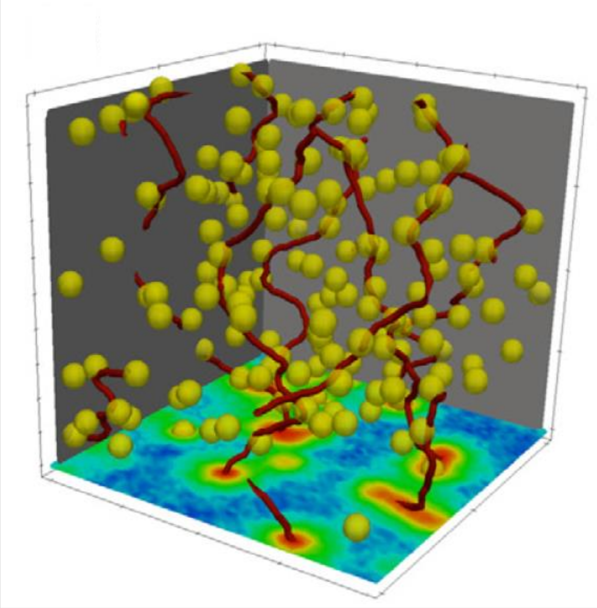
Correction to the superfluid density :

$$\delta\rho_s(T,B) = -C\,\frac{\hbar\sigma_n}{e^2}\,\frac{T^2}{3\pi\rho_s(B)a_0}$$

Valid for $T \ll T_c$ and $\delta\rho_s(T,B) \ll \rho_s(0,B)$

For details see Feigel'man talk

Low-*T* thermal fluctuations of the vortex glass



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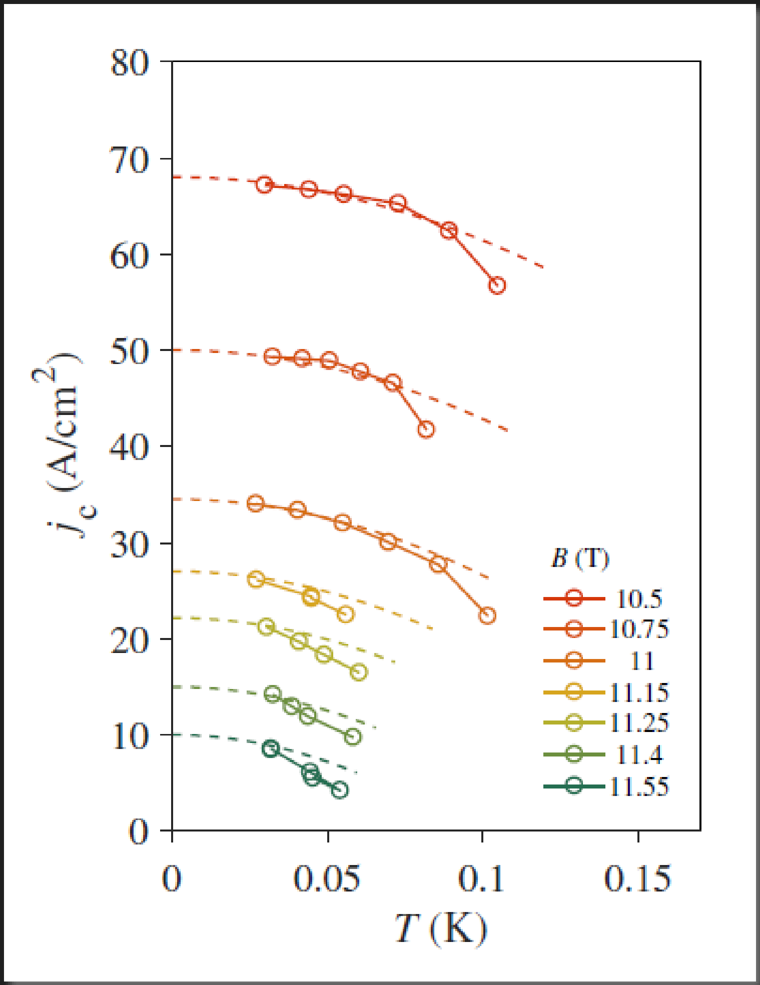
Valid for $T \ll T_c$ and $\delta\rho_s(T,B) \ll \rho_s(0,B)$

→ correction to critical current :

$$\delta j_c^{GL}(T,B) \propto \frac{\delta\rho_s(T,B)}{\xi_{GL}} \propto \frac{T^2}{\sqrt{B_{c2}(0)-B}}$$

Low-*T* thermal fluctuations of the vortex glass



Correction to the superfluid density :

$$\delta\rho_s(T,B) = -C\,\frac{\hbar\sigma_n}{e^2}\,\frac{T^2}{3\pi\rho_s(B)a_0}$$

Valid for $T \ll T_c$ and $\delta\rho_s(T,B) \ll \rho_s(0,B)$

➡ correction to critical current :

$$\delta j_c^{GL}(T,B) \propto \frac{\delta\rho_s(T,B)}{\xi_{GL}} \propto \frac{T^2}{\sqrt{B_{c2}(0)-B}}$$

Low-T anomaly of B_{c2}

☑ **Bulk crystal :** $T_c(B)$ is given by $\delta\rho_s(B, T_c) = \epsilon\rho_s(B, 0)$

Similar to the Lindemann criterion for the melting of bulk cristal

$$\delta\rho_s(T, B) = -C\frac{\hbar\sigma_n}{e^2}\frac{T^2}{3\pi\rho_s(B)a_0} = \epsilon\rho_s(B)$$

$$\rho_s(B) \propto \left(1 - \frac{B_{c2}(T)}{B_{c2}(0)}\right) \propto T$$

☑ **Thin films :** Generalized BKT transtion $\rho_s(B, T_{BKT}) = \frac{\chi}{d}T_{BKT}$

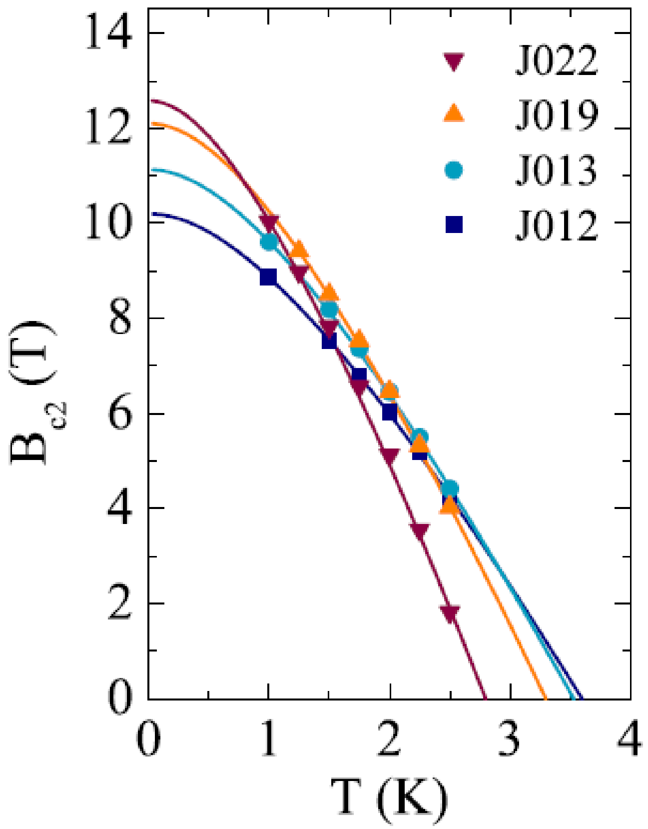
$\chi^{-1} \sim 1.5 - 2$

T. Schneider, and A. Schmidt ('92)

$$1 - \frac{B_{c2}(T)}{B_{c2}(0)} \propto \frac{T}{d}$$

Thickness

Linear T-dependence of $B_{c2}(T)$



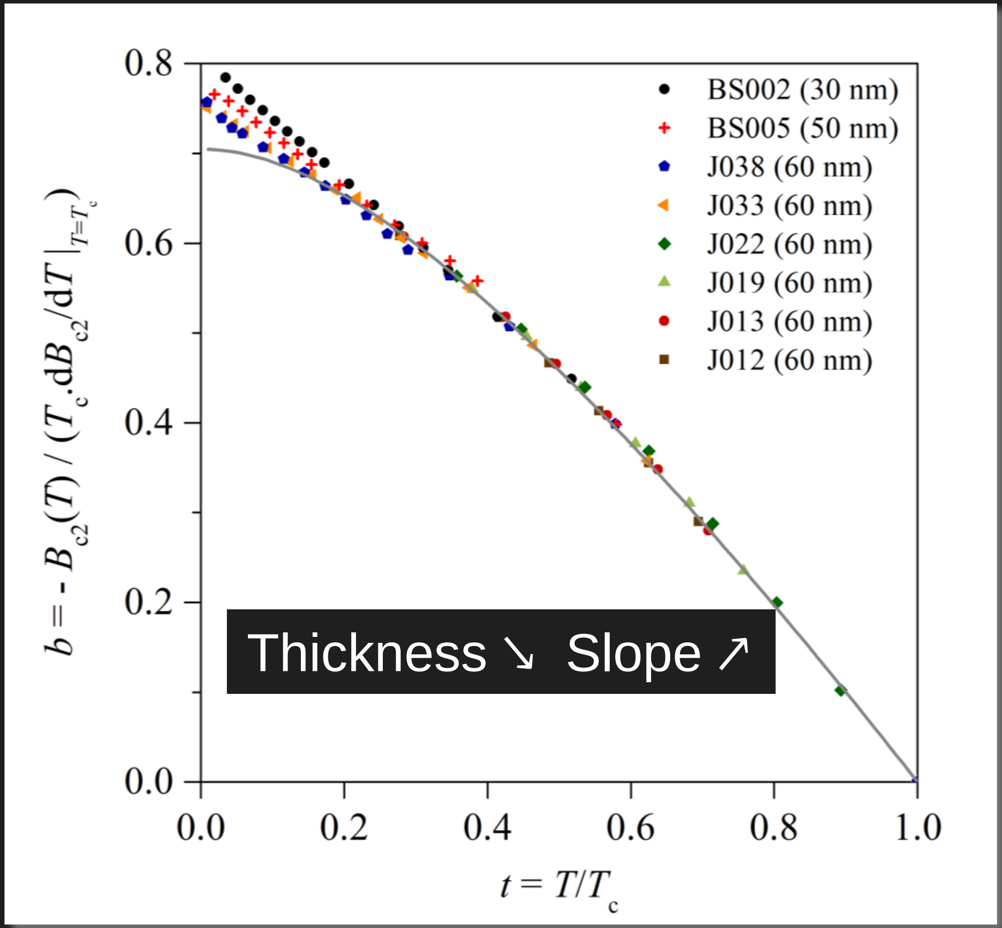
$$\left.\frac{dB_{c2}}{dT}\right|_{T\to T_c} \propto -\frac{1}{D}$$

$$B_{c2}(0) = \frac{\phi_0}{2\pi\xi^2} \propto \frac{1}{D}$$

B.S. et al. *PRB* (‘15)

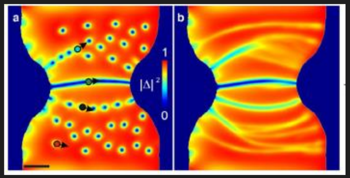
$$b = -\frac{B_{c2}(T)}{\left(T_c \left.\frac{dB_{c2}}{dT}\right|_{T\to T_c}\right)} \quad \text{versus} \quad T/T_c$$

WHH ('66)



De-pairing vs. de-pinning

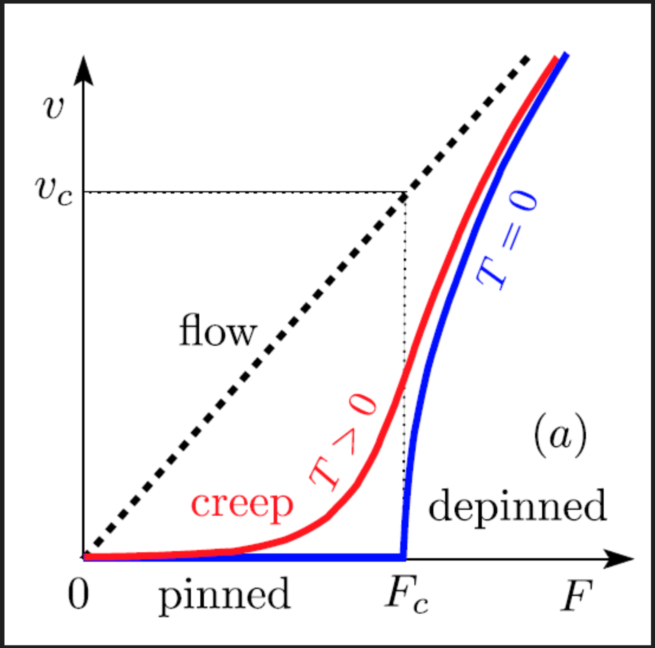
$$J_c \propto \frac{\rho_s}{\xi_{GL}}$$



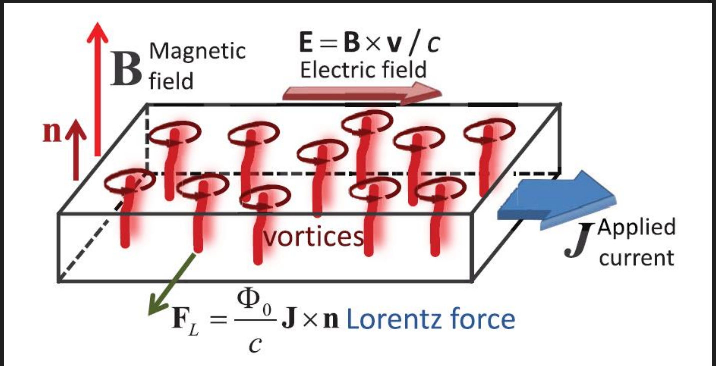
E. Zeldov (‘17)

Weak vs strong pinning

WEAK pinning



Pinning collapses beyond F_c

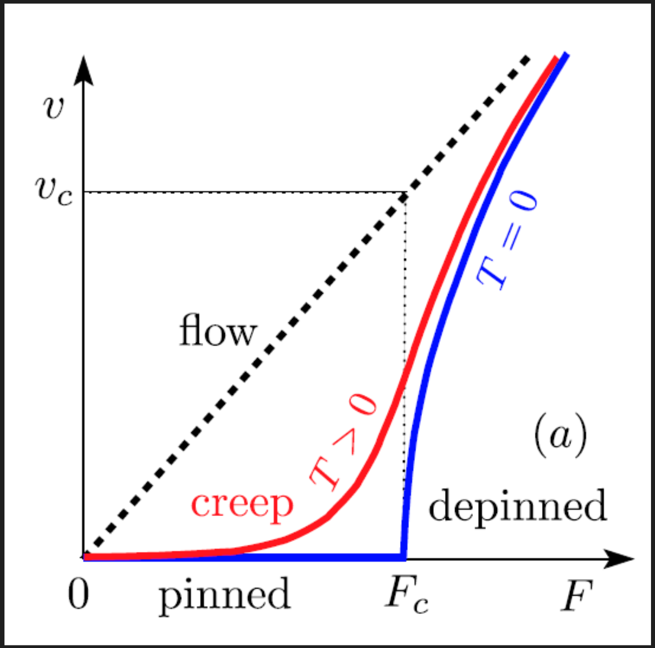


Kwok et al. Rep. Prog. Phys. ('16)

Buchacek, Willa, Geshkenbein, Blatter (2018)

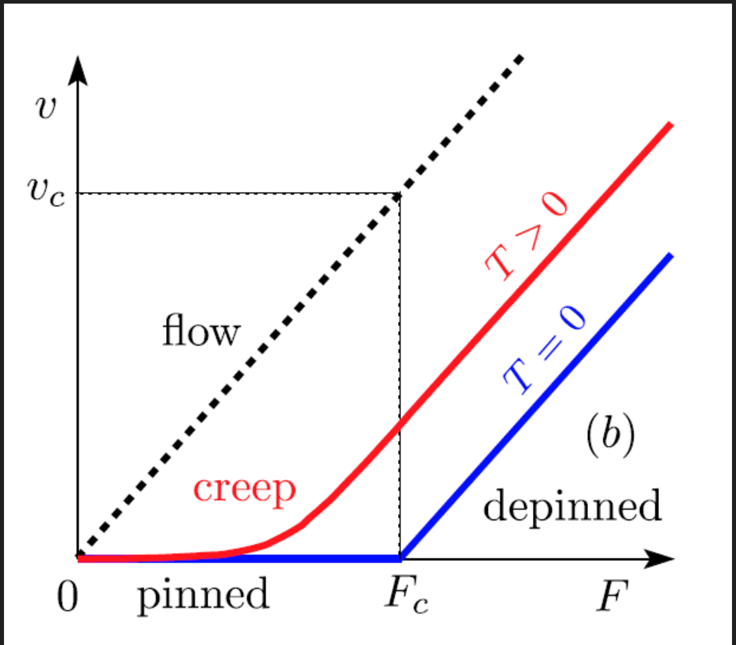
Weak vs strong pinning

WEAK pinning



Pinning collapses beyond F_c

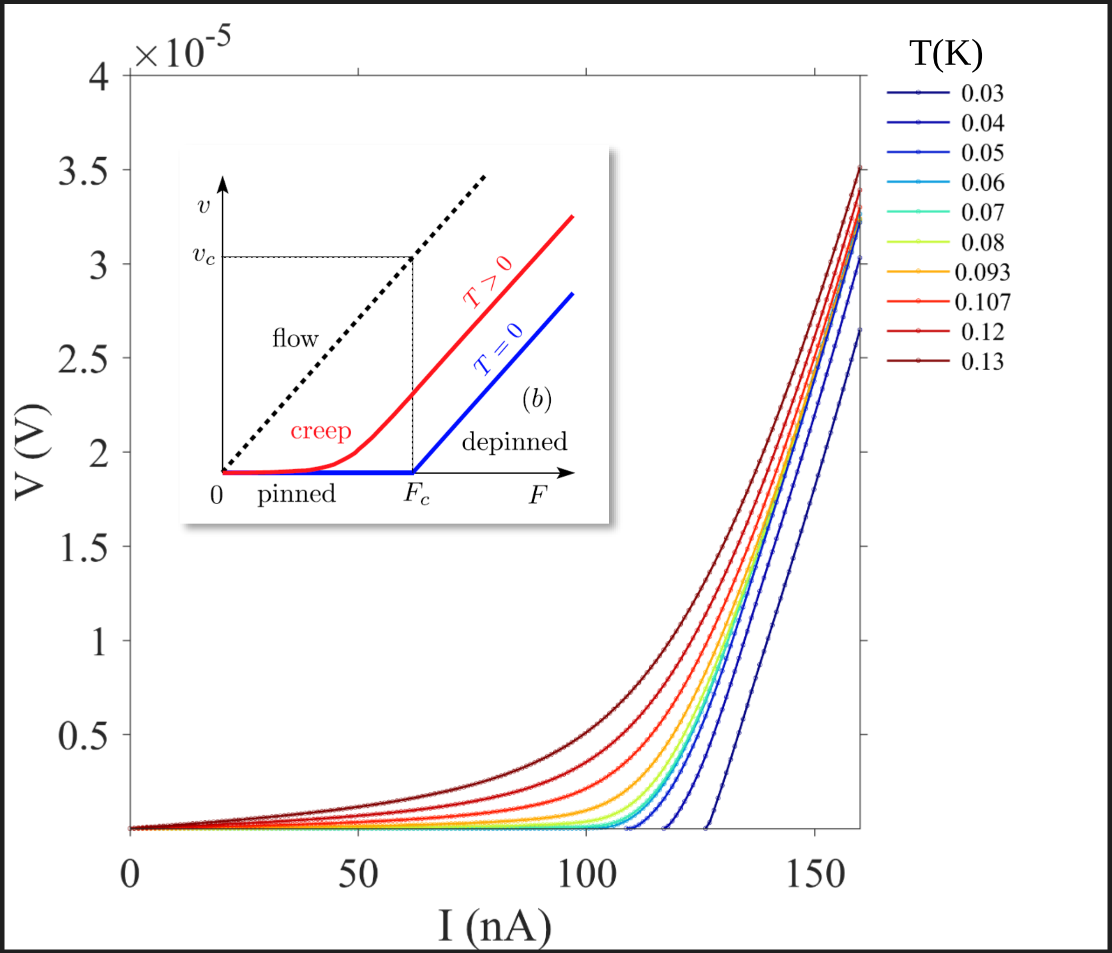
STRONG pinning



Vortex creep above F_c

Buchacek, Willa, Geshkenbein, Blatter (2018)

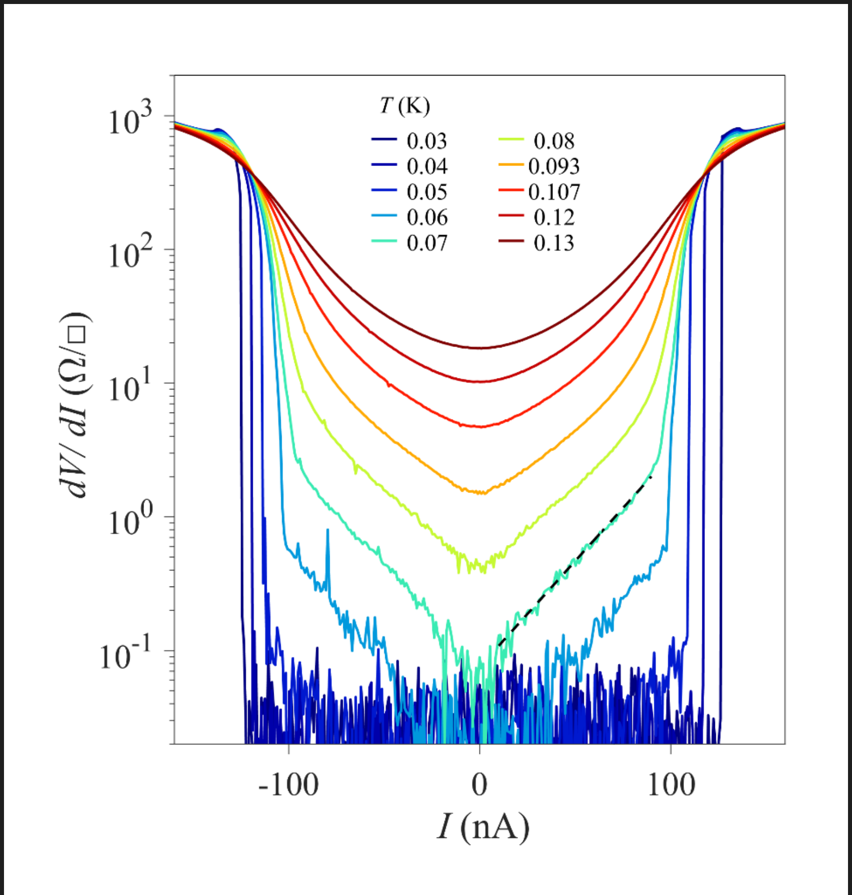
Strong pinning !



Strnad, Hempstead, Kim ('64-'65)
Xiao, Andrei, Paltiel, Zeldov, Shuk, Greenblatt ('02)

De-pinning transition

B = 11.25 T

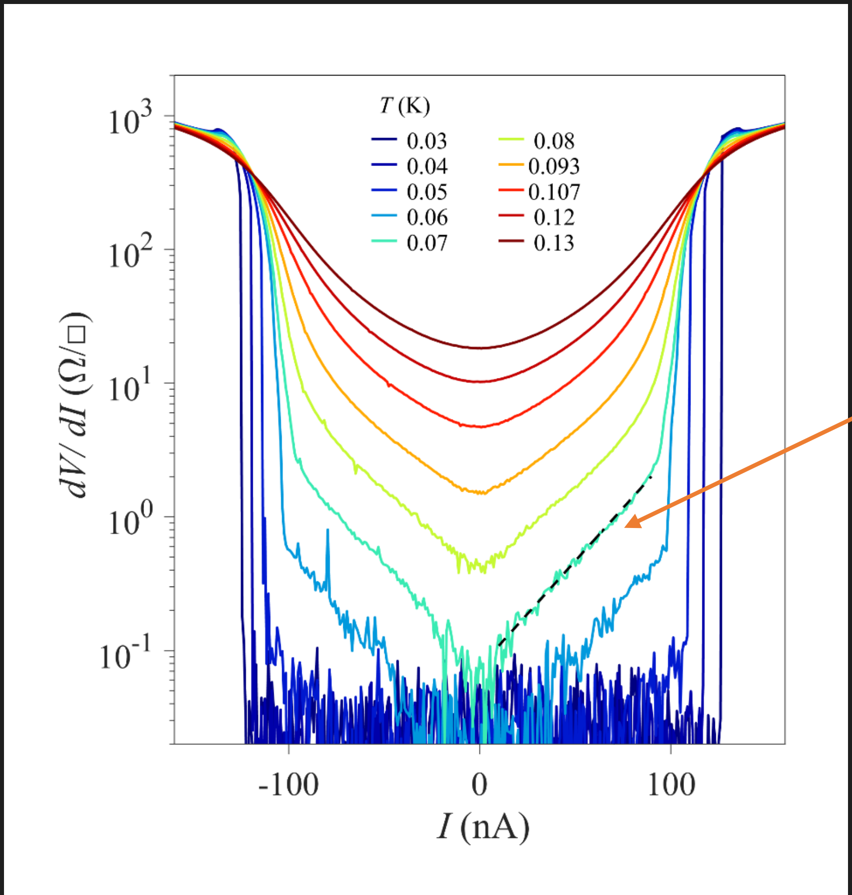


☑ Jump of several orders of dV/dI:

➡ **collective de-pinning !?**

De-pinning transition

B = 11.25 T



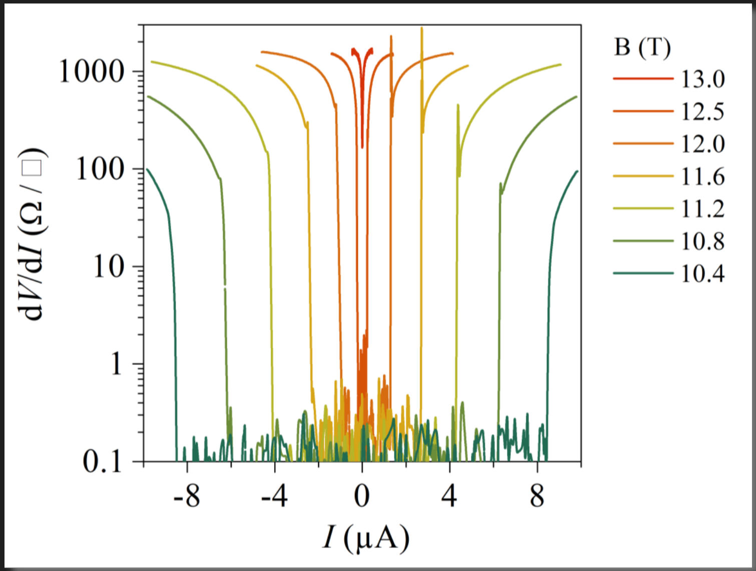
☑ Exponential increase of dV/dI

$$R(T,B,j) = R_0 e^{-U(B,j)/T}$$

$$\mathrm{U}(B,j) = U(B)\left(1 - \frac{j}{j_1}\right)$$

De-pairing vs. de-pinning

- ☑ **Large resistance (~ kOhms / □)**
- ☑ **Signatures of strong pinning in IV's** → $j_c^{de-pinning}$
- ☑ **Collective depinning**



De-pairing vs. de-pinning

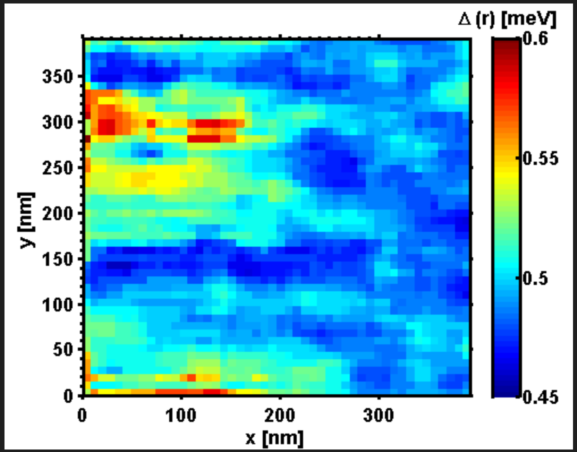
☑ **Mean-field scaling** $j_c \sim |B - B_{c2}|^{3/2}$

De-pairing vs. de-pinning

☑ **Mean-field scaling** $j_c \sim |B - B_{c2}|^{3/2}$

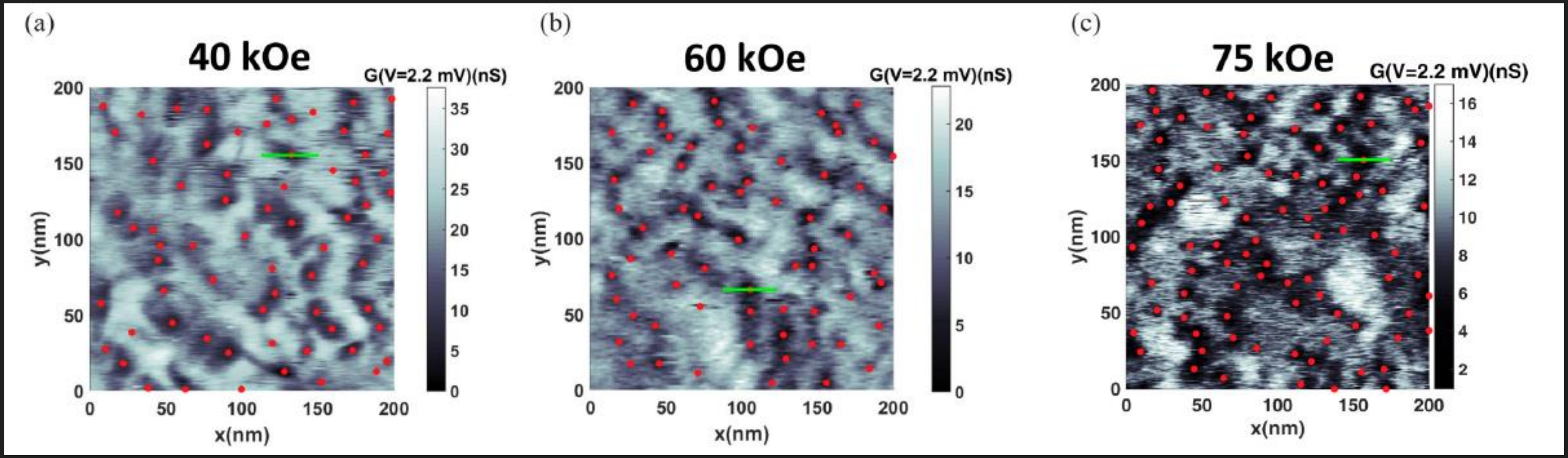
☑ **Strong spatial fluctuations of** $\Delta(r)$

InOx films (B=0)



B. Sacépé, *et al., Nat. Phys. ('11)*

NbN films



P. Raychaudhuri PRB ('17)

De-pairing vs. de-pinning

- ☑ **Mean-field scaling** $j_c \sim |B - B_{c2}|^{3/2}$
- ☑ **Strong spatial fluctuations of $\Delta(r)$**
- ☑ **Similar to columnar defects**

Mkrtchyan & Schmidt JETP (‘72)

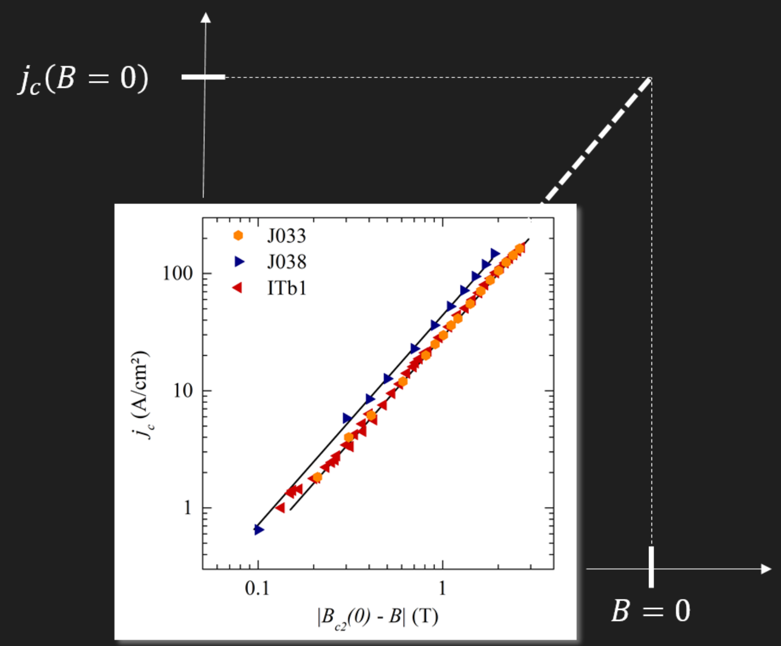
⟹ $$j_c^{de-pinning} = \Gamma\, j_c^{GL}$$ $(\Gamma < 1)$

$$J_c^{GL}(B) = J_c^{GL}(0)\left(1 - \frac{B}{B_{c2}(0)}\right)^{3/2}$$

$$J_c^{GL}(0) = \frac{4e\rho_{s0}}{3\sqrt{3}\pi\hbar\xi_{GL}}$$

ρ_{s0} from Yazdani PRL ('13)

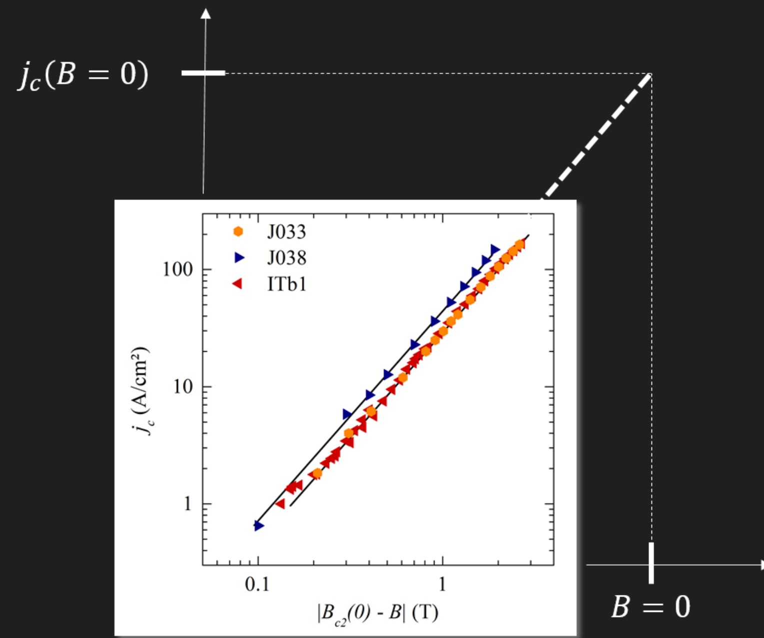
$\xi_{GL} \sim 5$ nm from B.S. PRB ('15)



$$J_c^{GL}(B) = J_c^{GL}(0)\left(1-\frac{B}{B_{c2}(0)}\right)^{3/2}$$

$$J_c^{GL}(0) \sim 10^4 A/cm^2$$

$$J_c(0) \approx (2.5-4).10^3 A/cm^{-2}$$



$$\Rightarrow \quad J_c^{de-pinning} = \Gamma J_c^{GL}$$

$$\Gamma^{-1} \sim 2-4$$

Conclusion

- **Mean-field scaling** $J_c \sim |B - B_{c2}|^{3/2}$
- $J_c^{de-pinning} = \Gamma \, J_c^{GL}$

$$\rho_s \sim \left(1 - \frac{B}{B_{c2}(0)}\right)$$

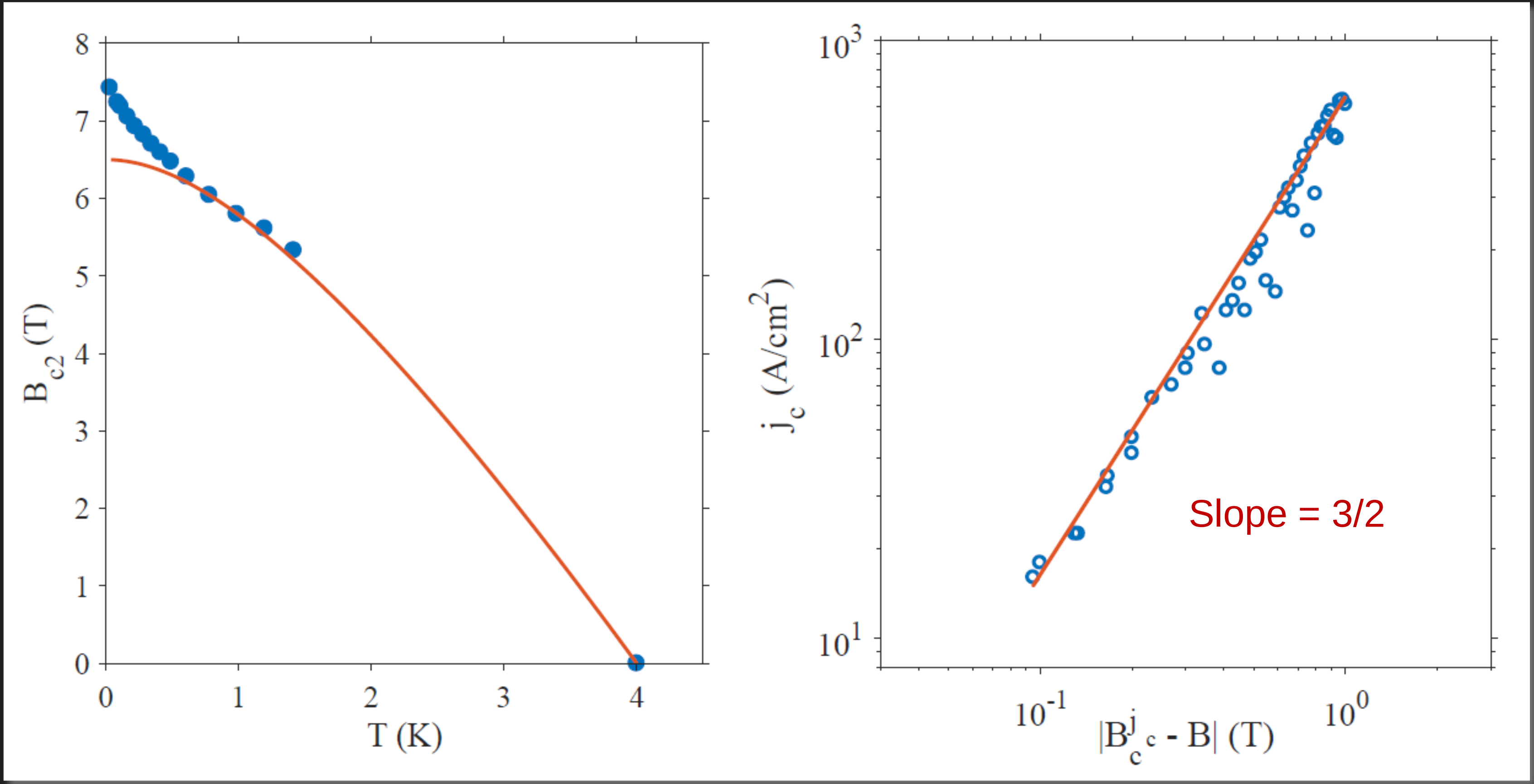
Thermal fluctuations of vortex glass

$$1 - \frac{B_{c2}(T)}{B_{c2}(0)} \sim T$$

Sacépé, Seidemann, Gay, Davenport, Rogachev, Ovadia, Michaeli, Feigel’man, *Nature Physics,* today

Universality

MoGe film : $3\ nm$ thick $R_{sq} = 700\ \Omega$ $T_c = 4\ K$



Thank you!