Quantum critical collapse of the pinned vortex glass at the superconductor-insulator transition

arXiv:2605.23838

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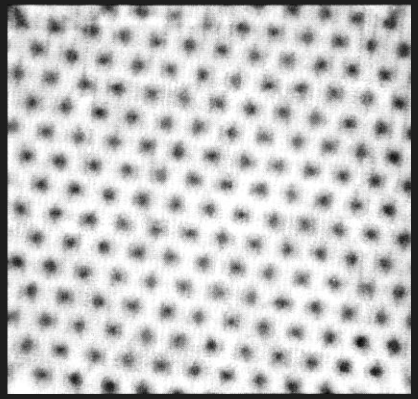
Néel Institute, CNRS & Univ. Grenoble Alpes

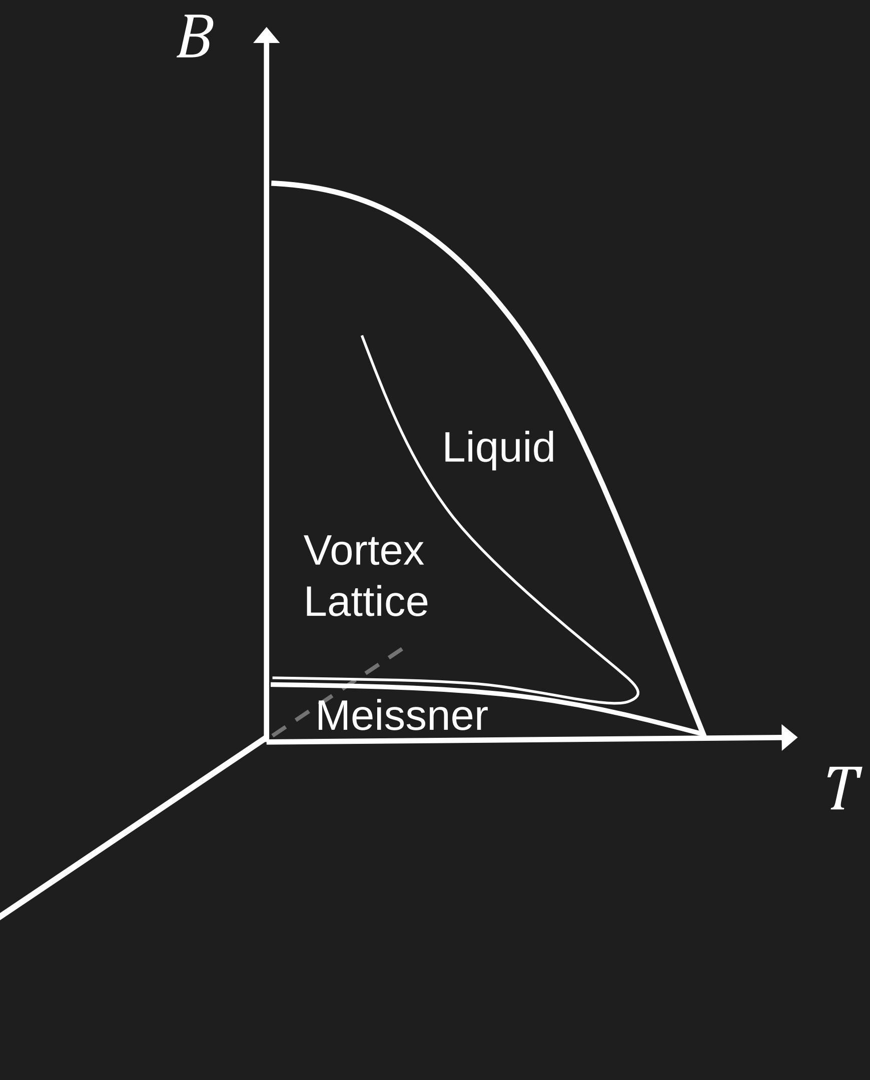
TIDES
Two-dimensional & Disordered Superconductors

July 6–17, 2026

Vortex matter

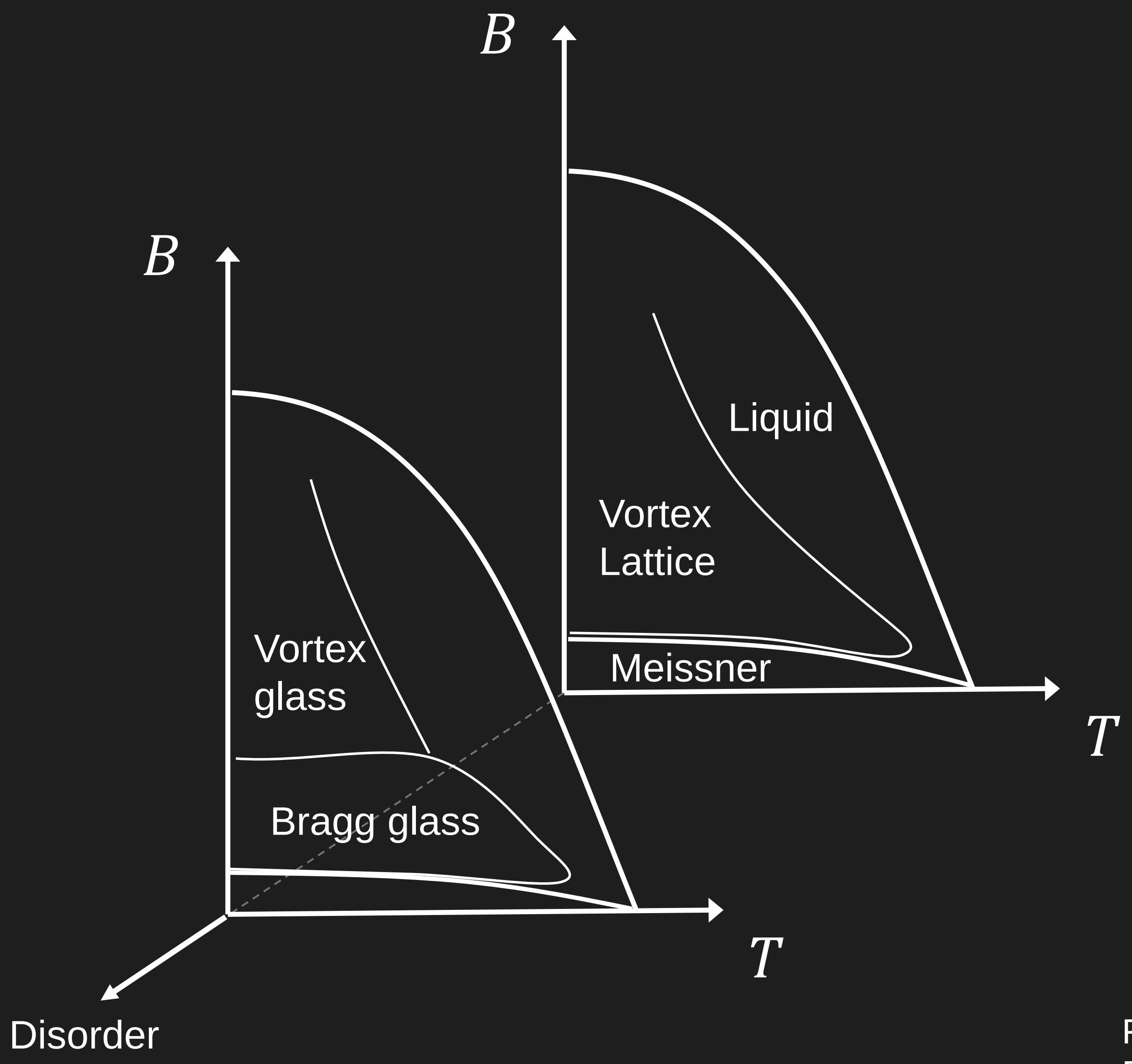
STM on NbSe2





Fisher, Fisher, Huse PRB (‘ 91)
Blatter, et al. RMP (’94)
T. Giamarchi, P. Le Doussal PRB (‘95)
Kwok, et al. Rep. Prog. Phys. (‘16)

Vortex matter



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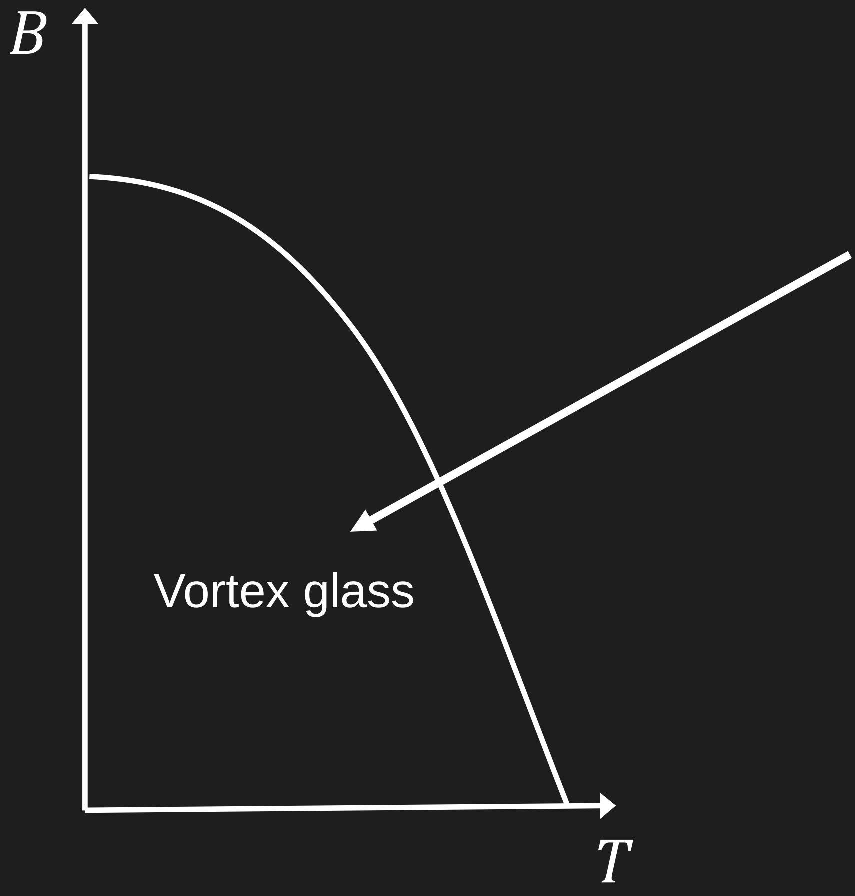
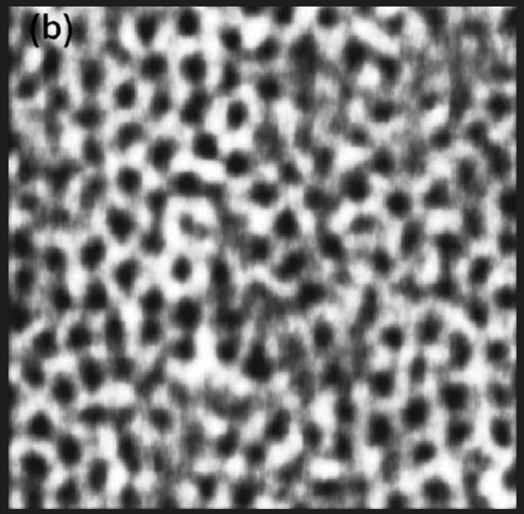
Strong disorder

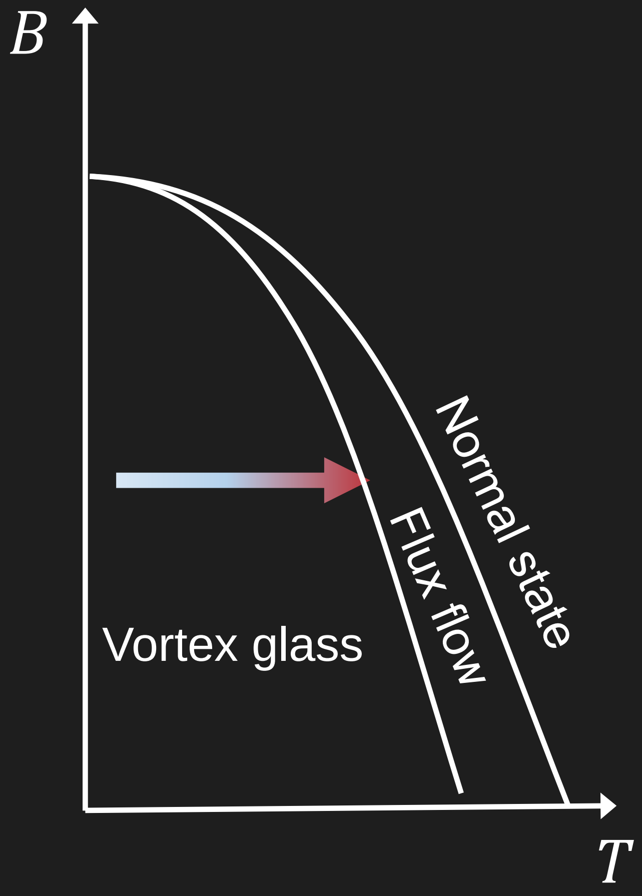


B.S. et al. PRL ('06)

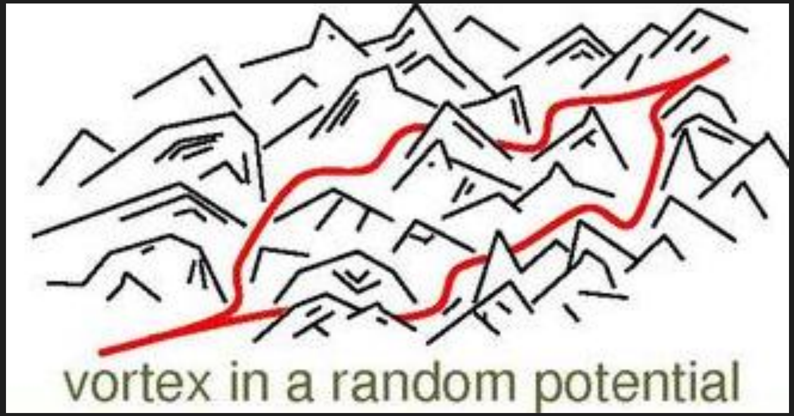


- Many metastable states: glass!
- No translational order
- Topological defects

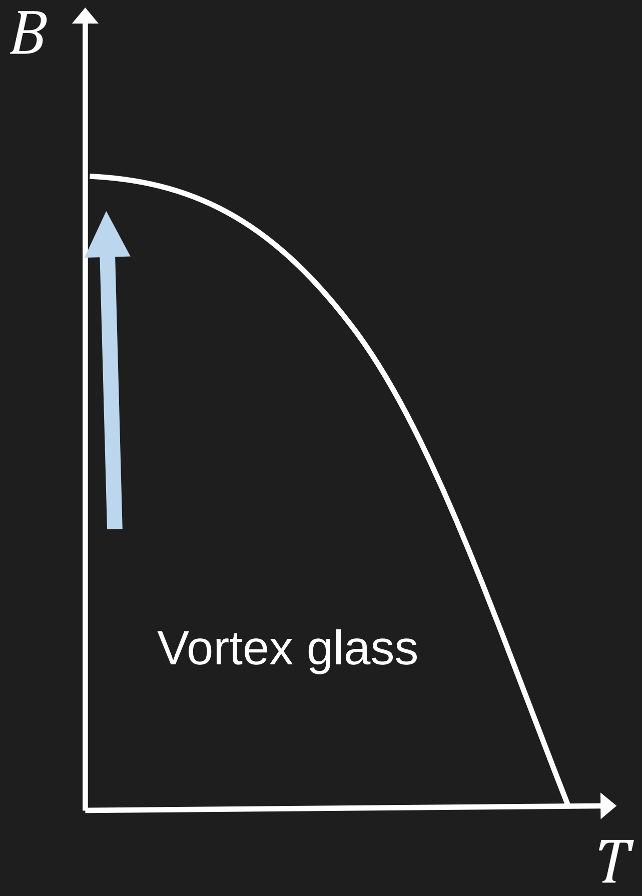
Thermally assisted flux flow/creep



$$R = R_0 exp\left(-\frac{U(B,T,j)}{k_B T}\right)$$



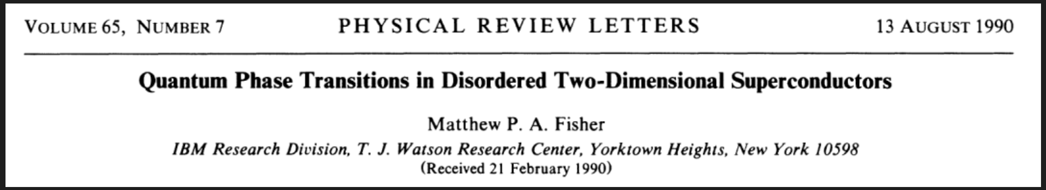
Open questions:



1. **Superfluid stiffness at T=0 ?**
2. ***B*-suppression of superfluid stiffness ?**

Superglass Phase of Interacting Bosons:

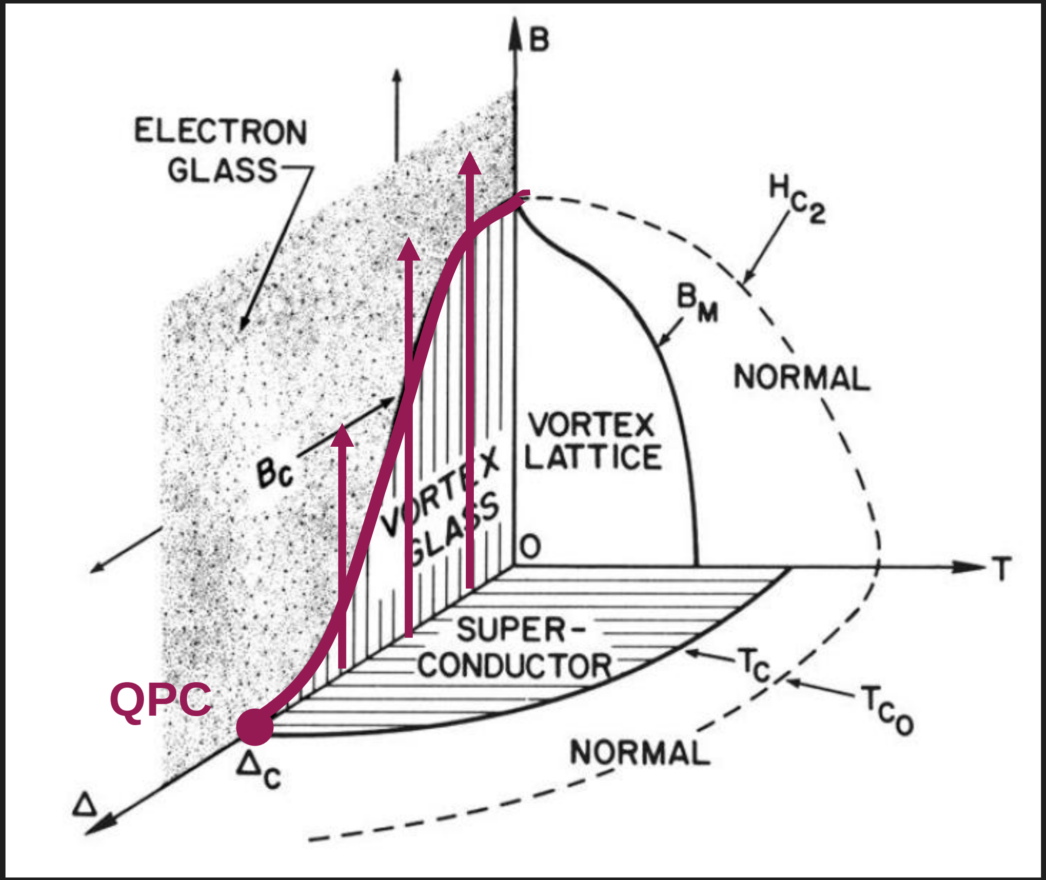
Tam, Geraerdts, Inglis, Gingras, Melko PRL (’10)
Yu, Müller, PRB (‘12)



VOLUME 65, NUMBER 7 PHYSICAL REVIEW LETTERS 13 AUGUST 1990

Quantum Phase Transitions in Disordered Two-Dimensional Superconductors

Matthew P. A. Fisher
IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598
(Received 21 February 1990)

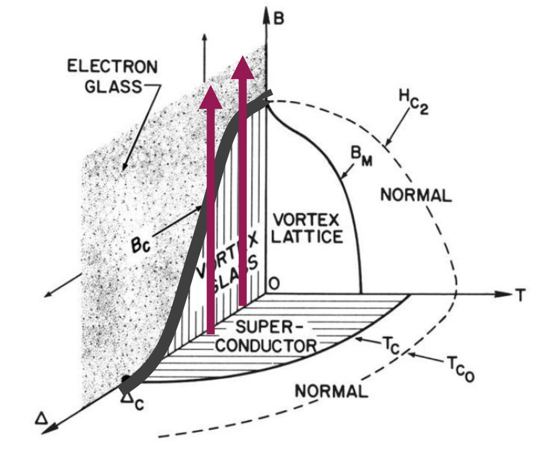


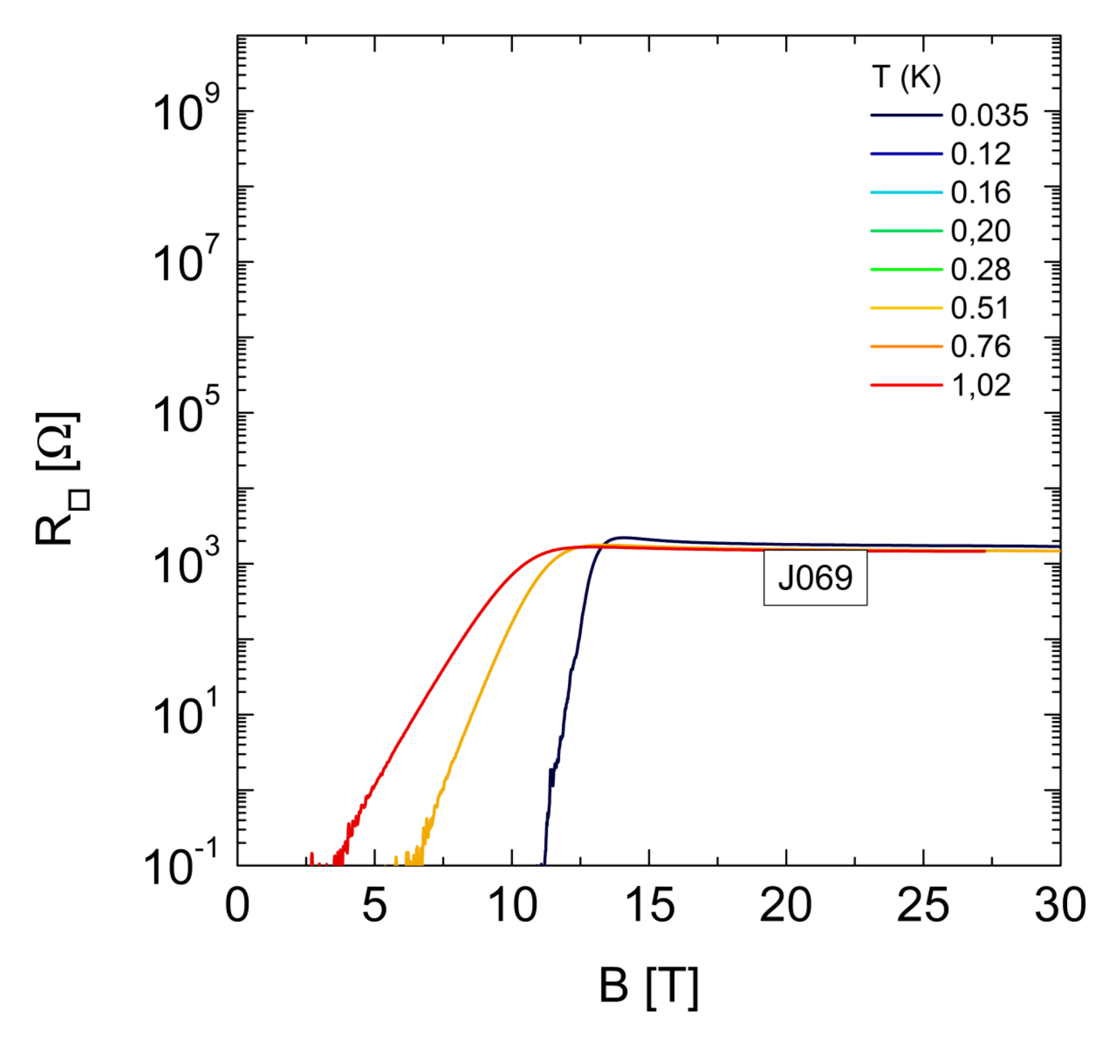
Open questions:

1. Superfluid stiffness at T=0 ?
2. B-suppression of superfluid stiffness ?
3. **Disorder dependence ?**

Superconductor-Insulator Transition

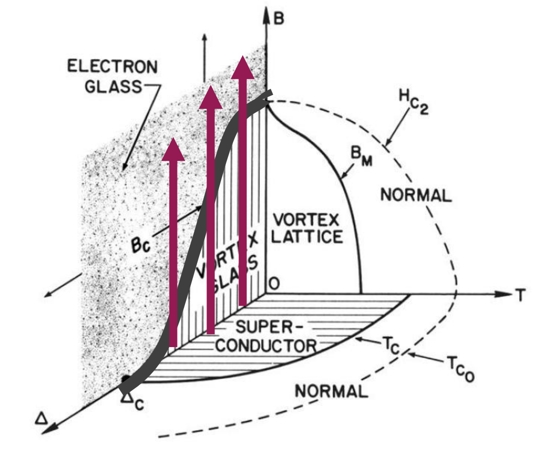
Low disorder

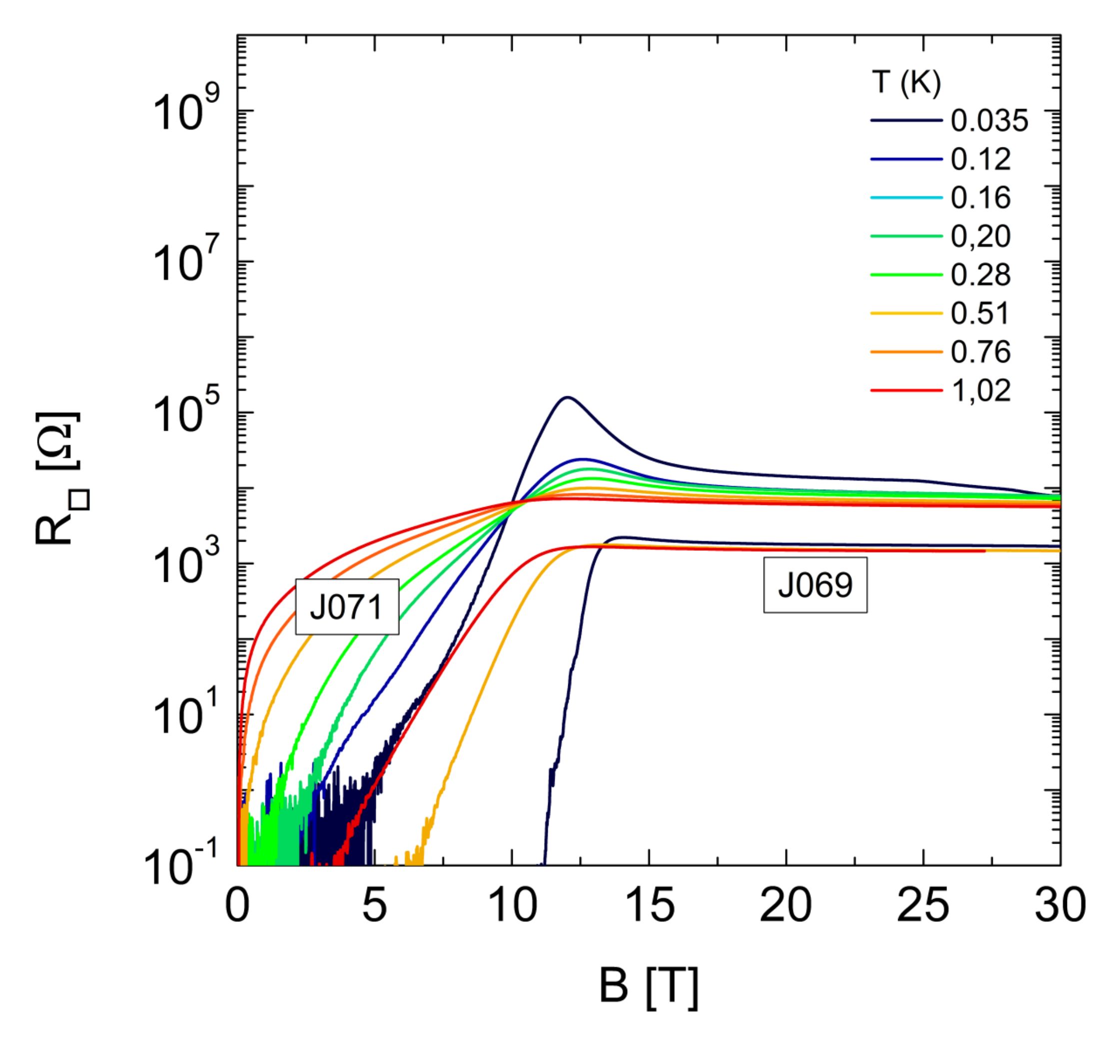




B.S. et al. *PRB* (‘15)

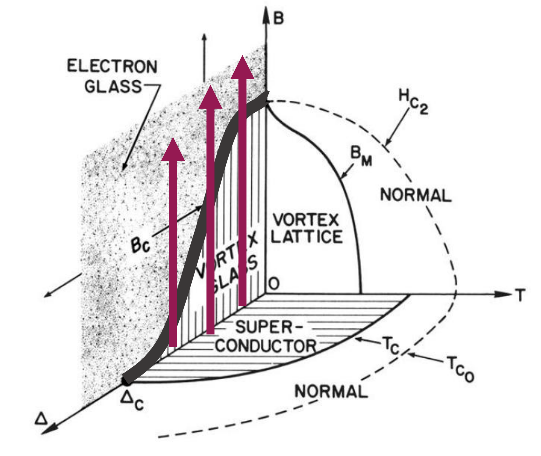
Medium disorder

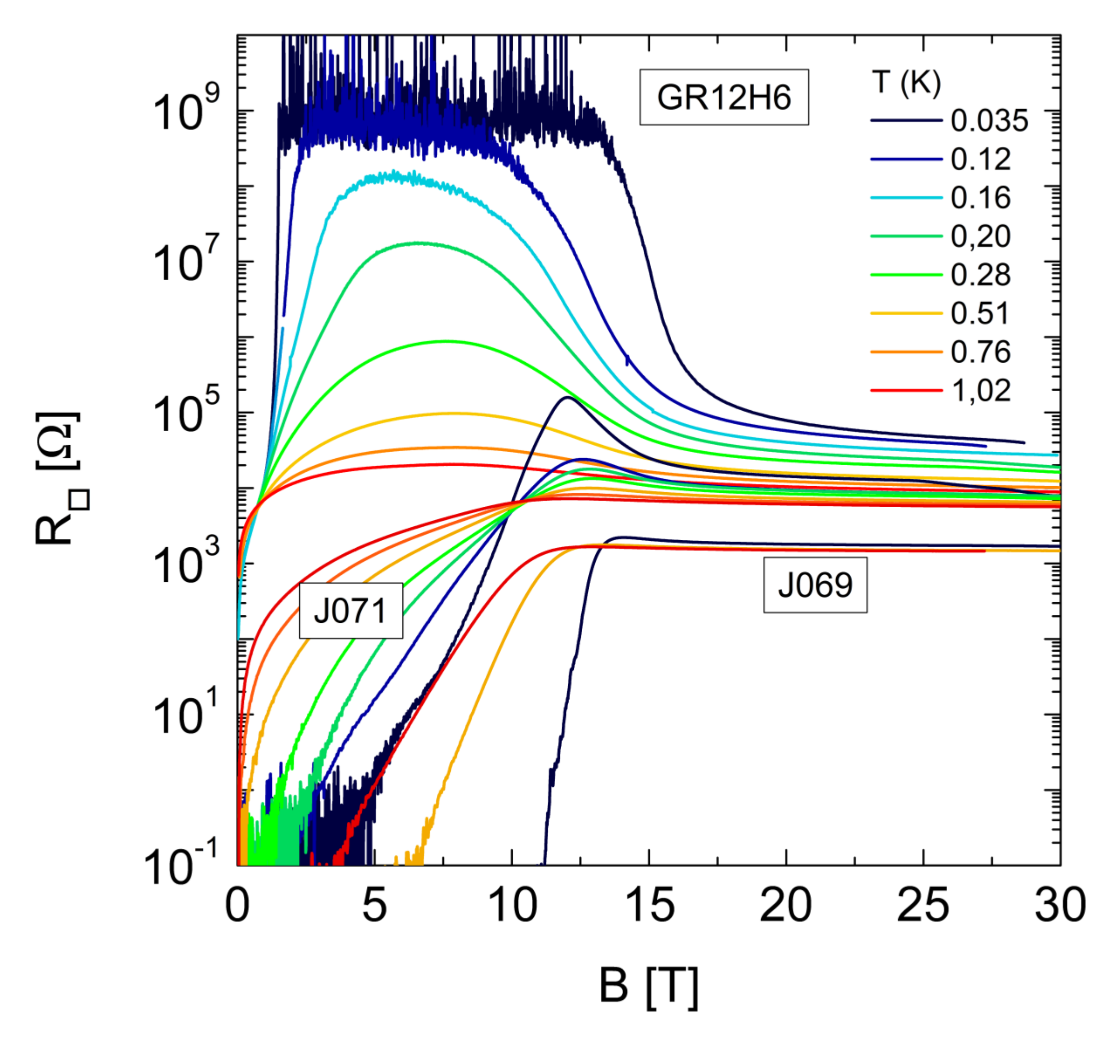




B.S. et al. *PRB* (‘15)

High disorder: Cooper pair insulator



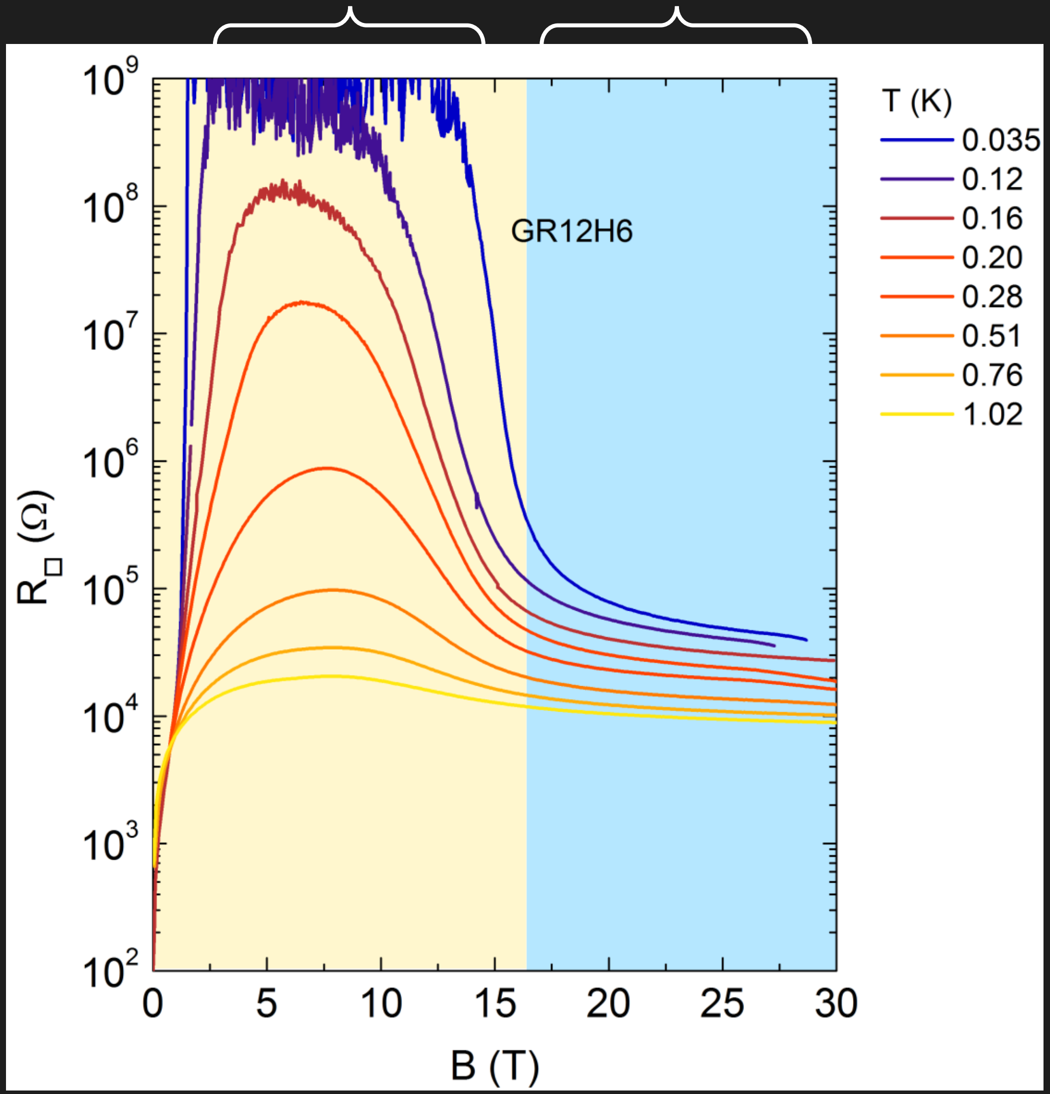


B.S. et al. *PRB* ('15)

See also:
Gantmakher et al ('98)
Shahar et al ('04)
Steiner & Kapitulnik ('05)

Cooper-pair insulator | Fermionic insulator

$\rho \to +\infty$

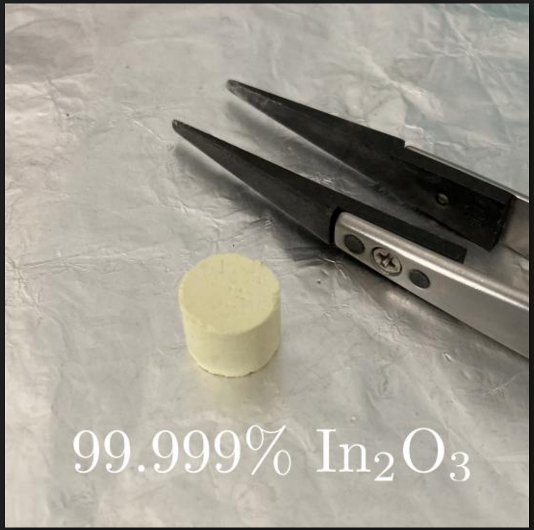


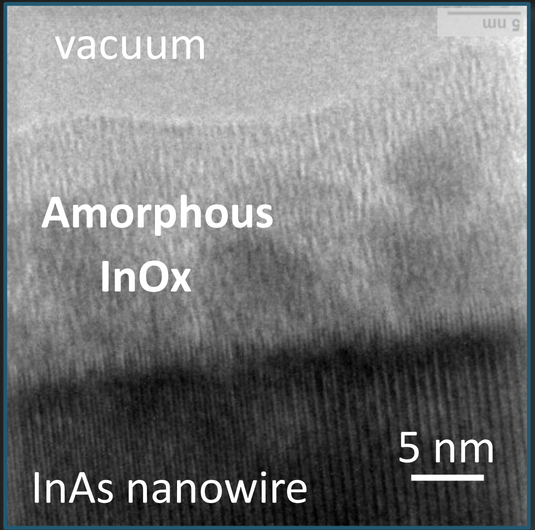
$\sigma \to +\infty$

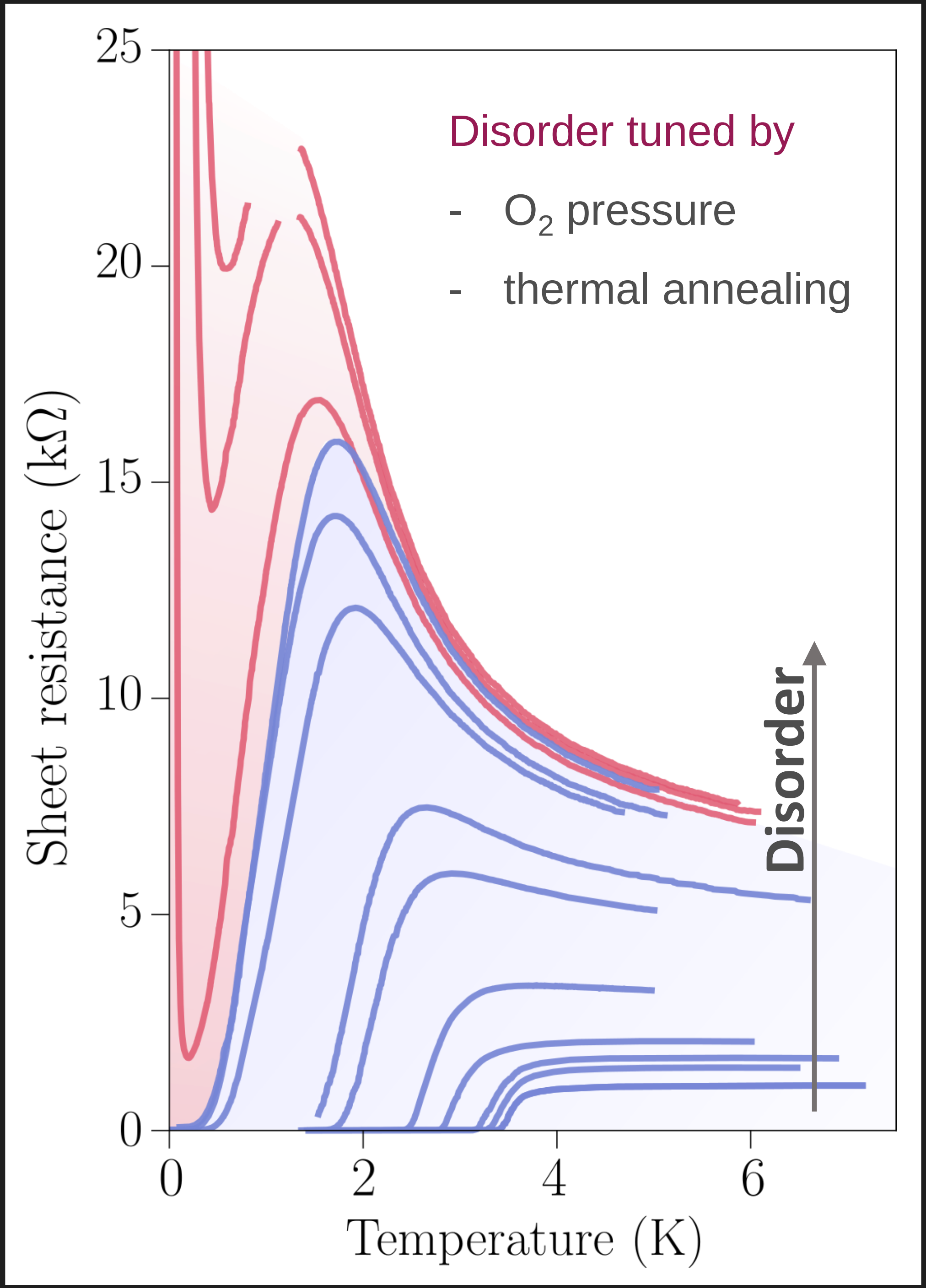
B.S. et al. *PRB* ('15)

Amorphous indium oxide

E-gun evaporation under O_2 pressure





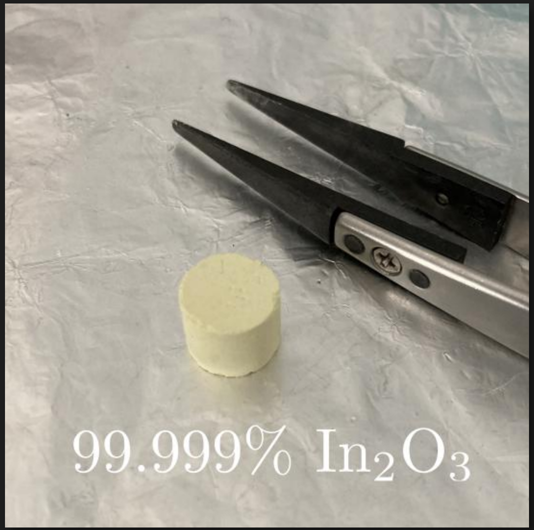


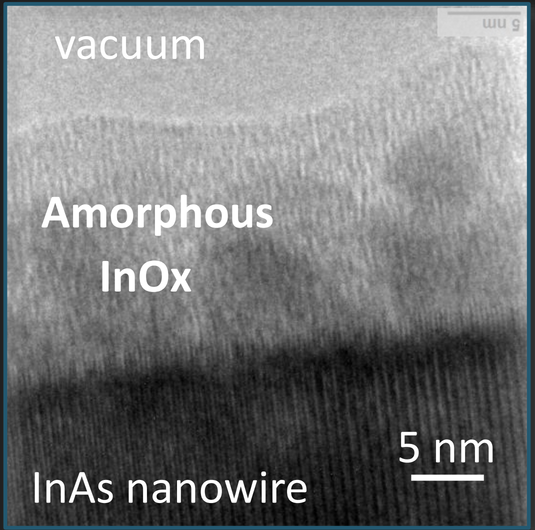
Parameters

- 40 nm thick
- e-density : $n \sim 10^{21}\ \mathrm{cm}^{-3}$
- Resistivity : $\mathbf{1 - 20\ m\Omega.cm}$
- Disorder : $\boldsymbol{k_F l_e \sim 0.3 - 0.4}$
- SC coherence length : $\xi = 5\ \mathrm{nm}$

Amorphous indium oxide

E-gun evaporation under O_2 pressure





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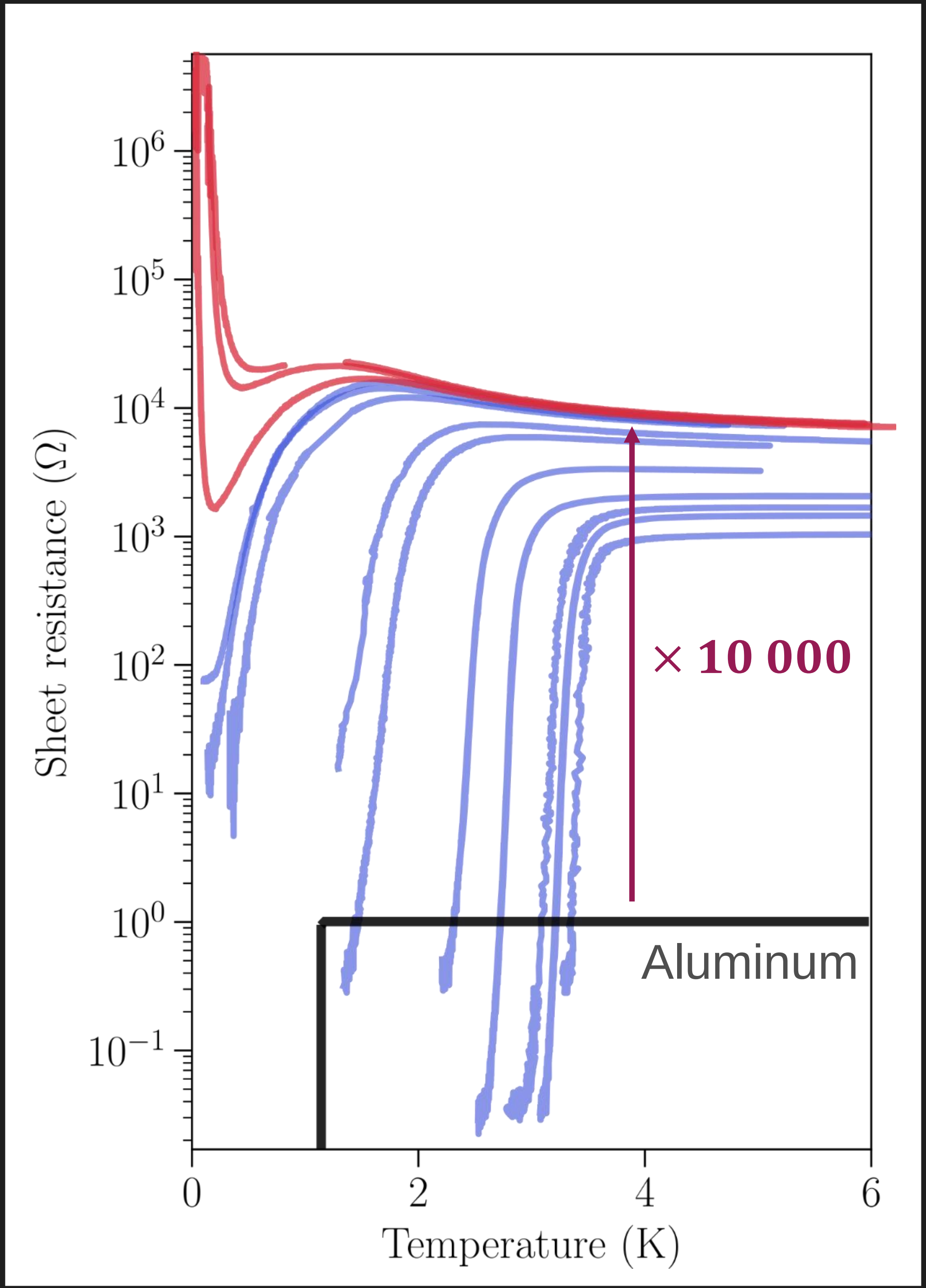
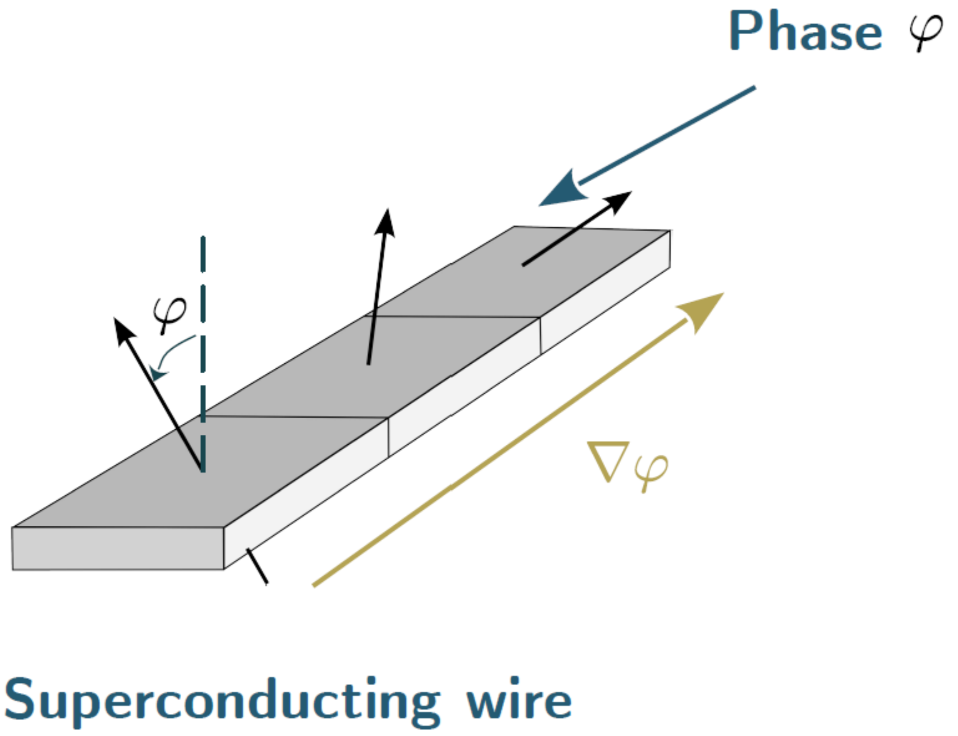


Vortex glass superfluid stiffness ?

Superfluid stiffness $\boldsymbol{\Theta}$

$$E = \int d\boldsymbol{r} \frac{1}{2} \boldsymbol{\Theta} (\nabla\varphi)^2$$

Energy cost to twist the phase



Superfluid stiffness

$$\boldsymbol{\Theta} = \left(\frac{\hbar}{2e}\right)^2 \frac{1}{L_K^{\square}}$$

Superfluid stiffness $\boldsymbol{\Theta}$

$$E = \int d\boldsymbol{r}\, \frac{1}{2} \boldsymbol{\Theta} (\nabla\varphi)^2$$

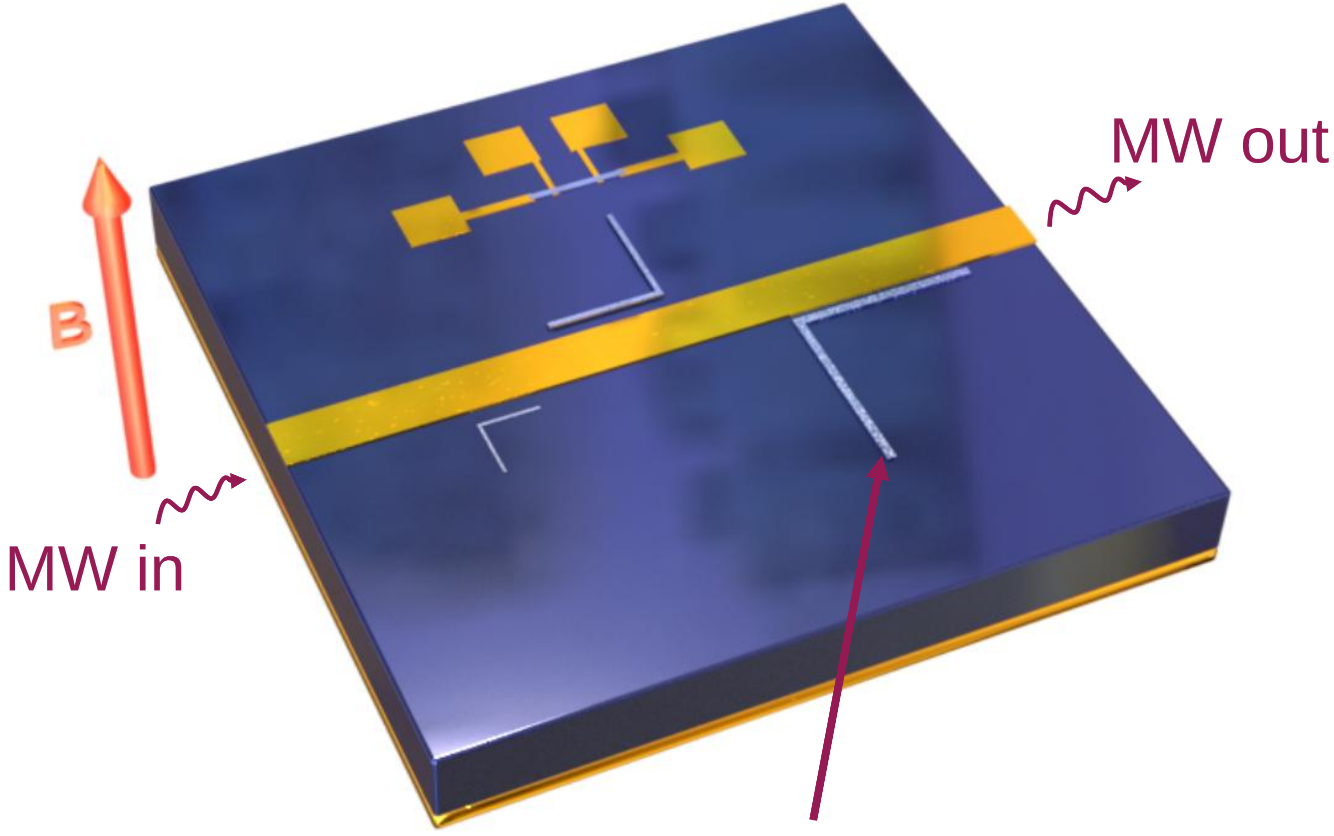
Energy cost to twist the phase

Kinetic inductance $L_K^{\square} = \dfrac{\hbar R_{\square}}{\pi\Delta}$

$$E = \frac{1}{2} N m v_s^2 \quad \text{where} \quad v_s = \frac{\hbar\nabla\varphi}{m}$$

$$E = \frac{1}{2} \boldsymbol{L_K^{\square}} I^2$$

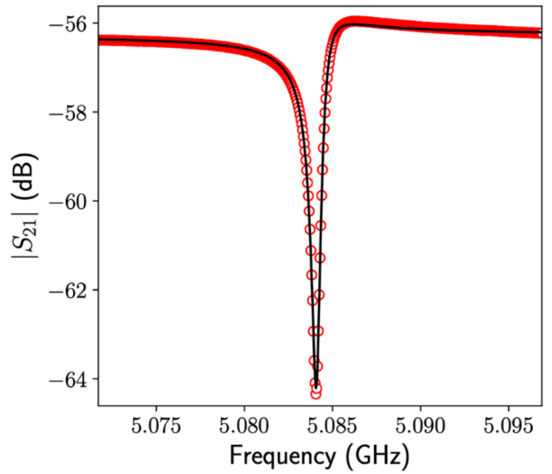
Measurement of superfluid stiffness (Kinetic inductance)



$\lambda/2$ microstrip
resonators

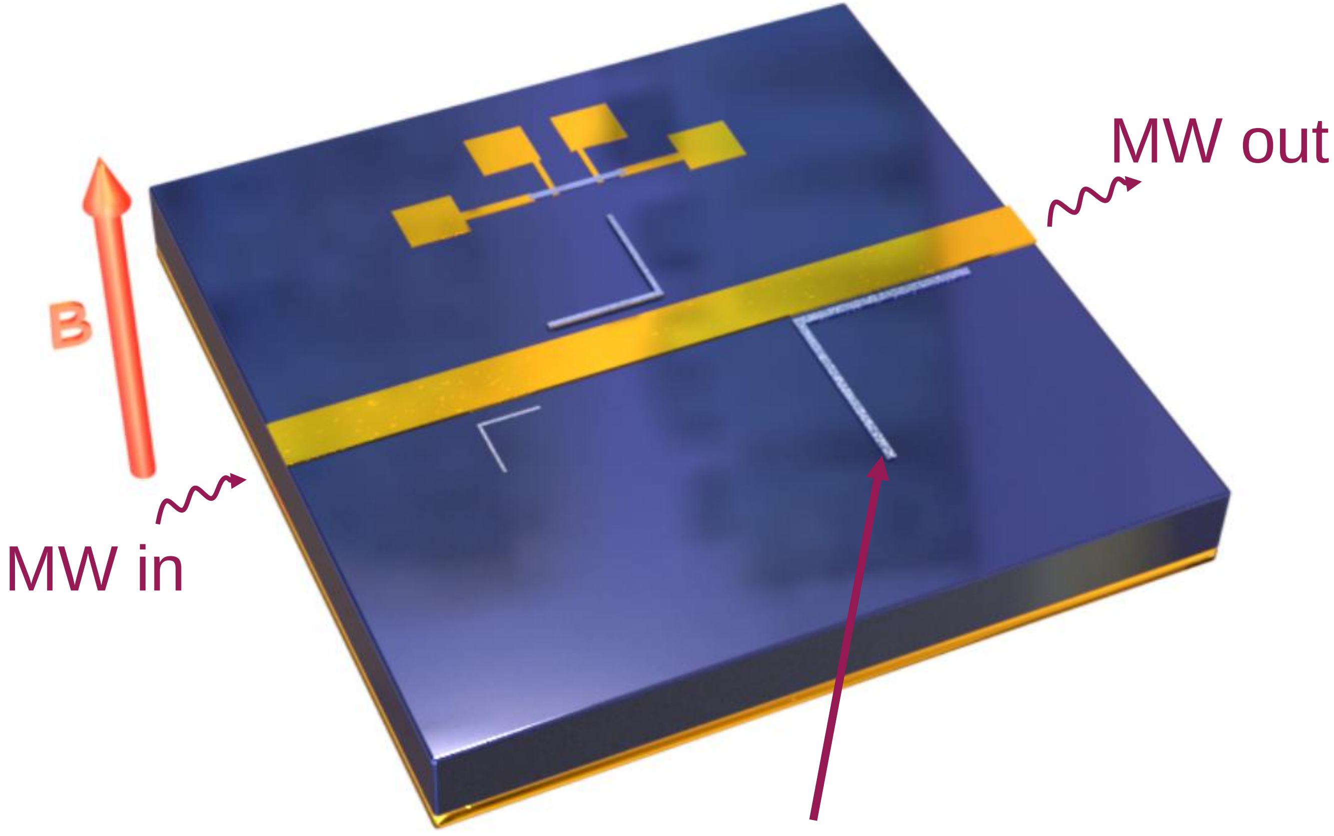
Standing wave plasma modes

$$f = \frac{1}{2\pi\sqrt{L_K C}}$$



Transmission $S_{21} = \frac{a_{out}}{a_{in}}$

Measurement of superfluid stiffness (Kinetic inductance)



$\lambda/2$ microstrip resonators

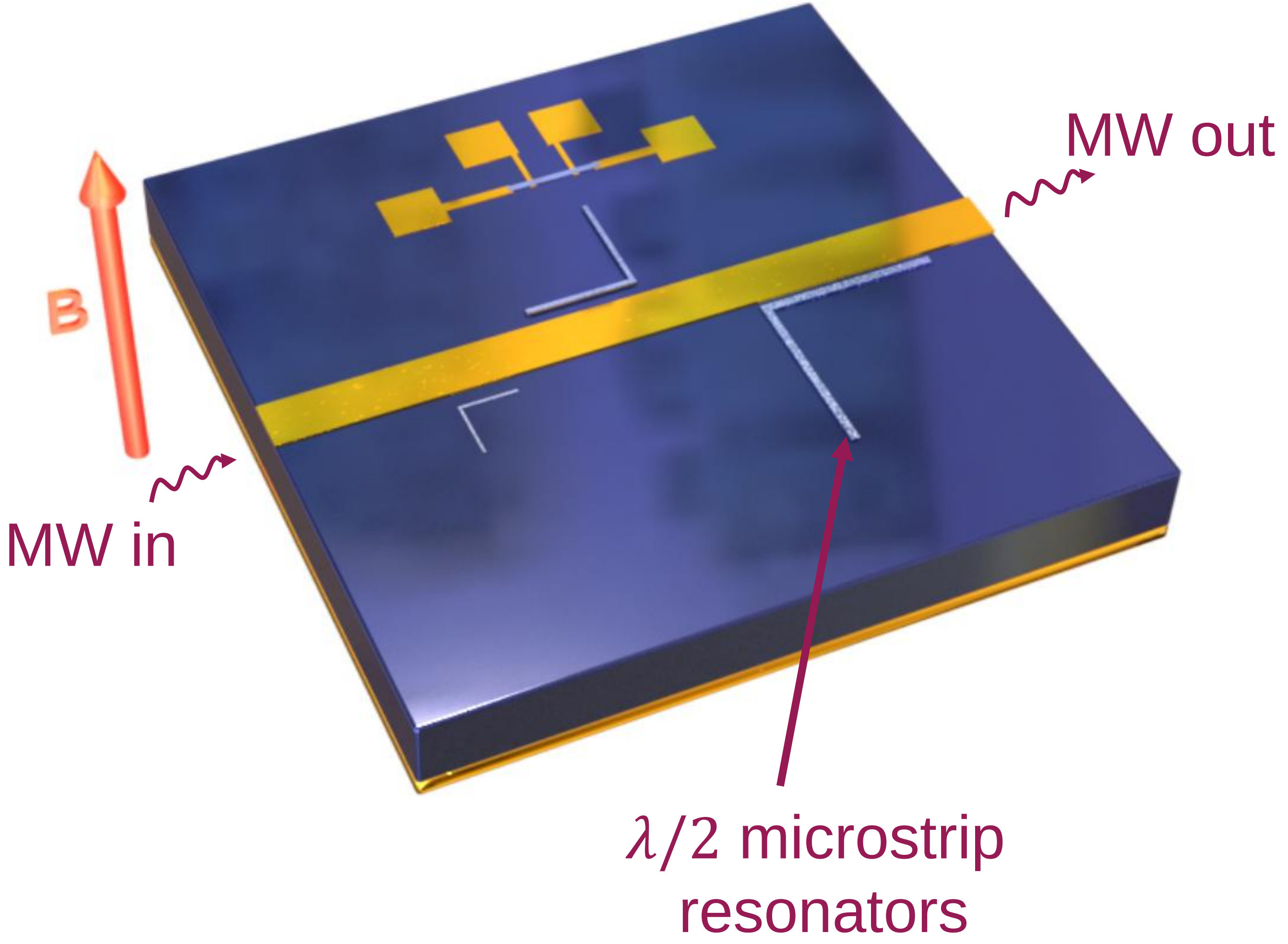
Standing wave plasma modes

$$f(B) = \frac{1}{2\pi\sqrt{L_K(B)C}}$$

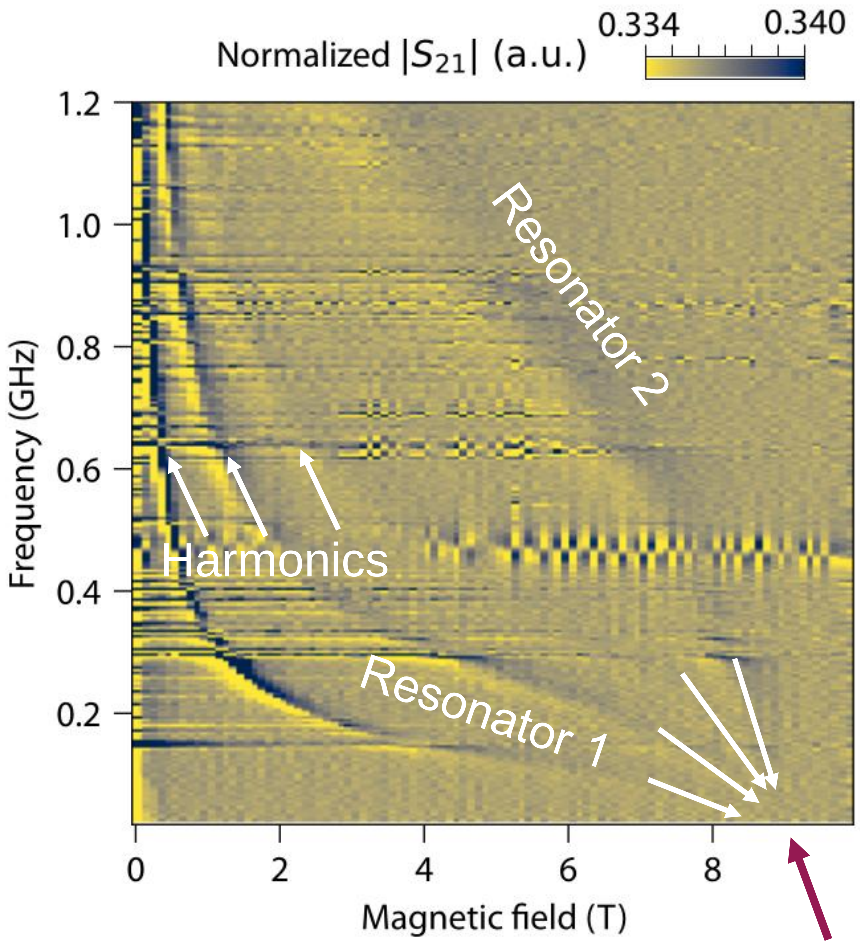
B-dependence of superfluid stiffness

$$\frac{\Theta(B)}{\Theta(0)} = \left(\frac{f(B)}{f(0)}\right)^2$$

Control experiment: low disorder MoGe film (R ~ 170 Ω)

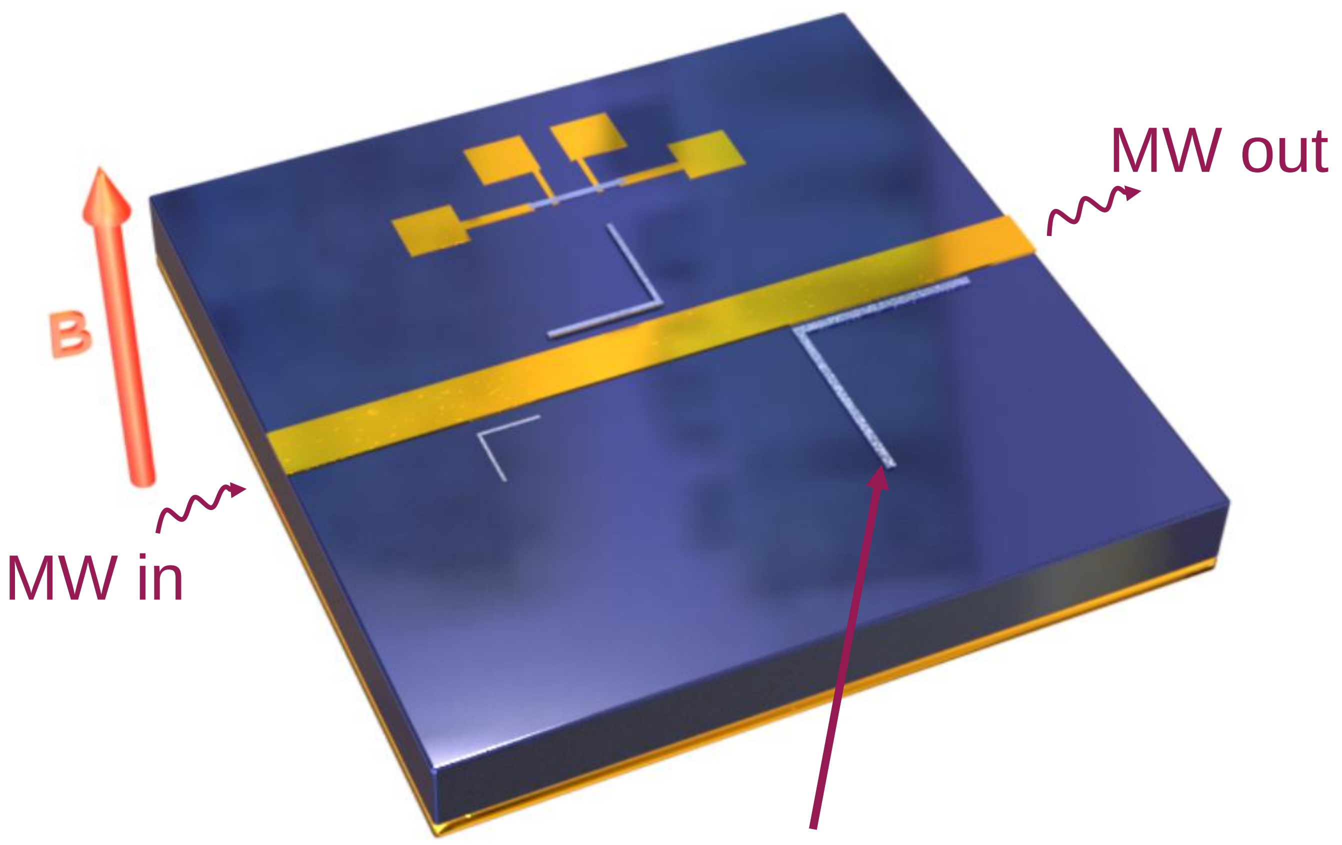


MoGe inductance $L_K = 70\, pH/\square$

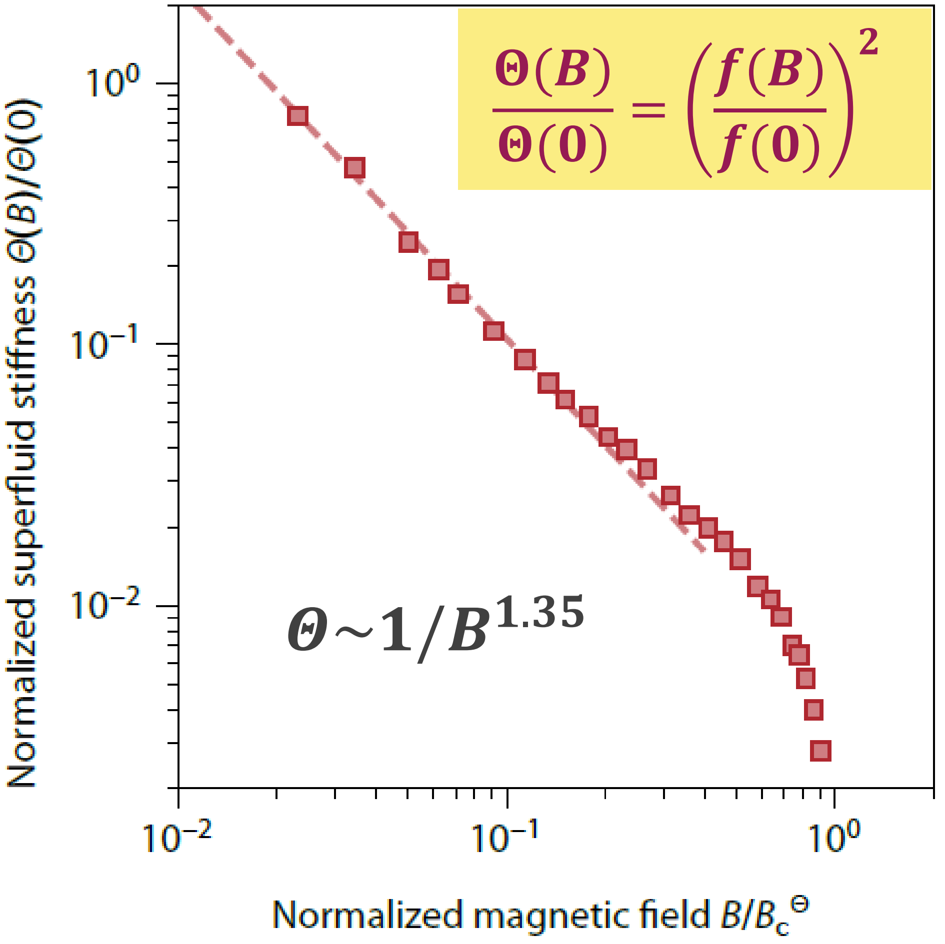


$H_{c2} \simeq 9T$

Control experiment: low disorder MoGe film (R ~ 170 Ω)



MoGe inductance $L_K = 70\ pH/\square$



High frequency response of a vortex lattice

1. Individual pinning of vortices: interaction between them is irrelevant

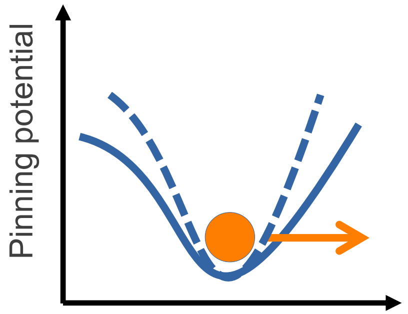
$$\Theta(B) = \frac{\Phi_0^2}{L_K(B)}$$

$$L_K(B) = L_K(0) + \frac{\Phi_0 B}{\tilde{k}}$$

$$\boldsymbol{\Theta \sim 1/B}$$

$$L_K(B) = \mu_0 \frac{\lambda^2(B)}{d}$$

$\boldsymbol{\tilde{k}}$ **:** effective curvature of the pinning potential



$\boldsymbol{\tilde{k} = 0}$ ⇔ no pinning ⇔ no superconducting response ⇔ $\boldsymbol{\Theta = 0}$

High frequency response of a vortex lattice

1. Individual pinning of vortices: interaction between them is irrelevant

$$\Theta(B) = \frac{\Phi_0^2}{L_K(B)} \qquad L_K(B) = L_K(0) + \frac{\Phi_0 B}{\tilde{k}} \quad \Rightarrow \quad \boldsymbol{\Theta \sim 1/B}$$

$\tilde{\boldsymbol{k}}$ **:** effective curvature of the pinning potential

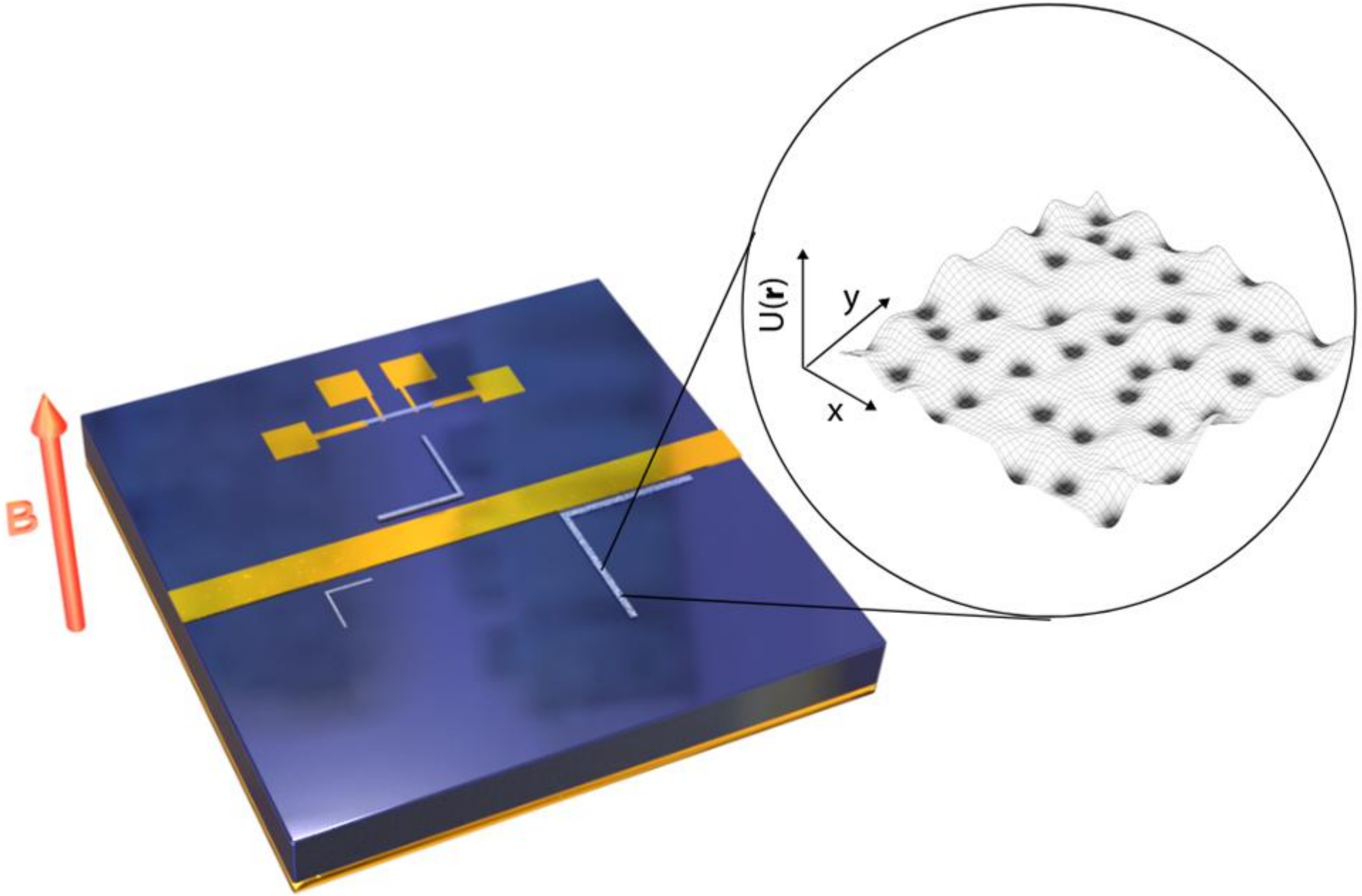
2. Collective pinning of elastic lattice (Bragg glass)

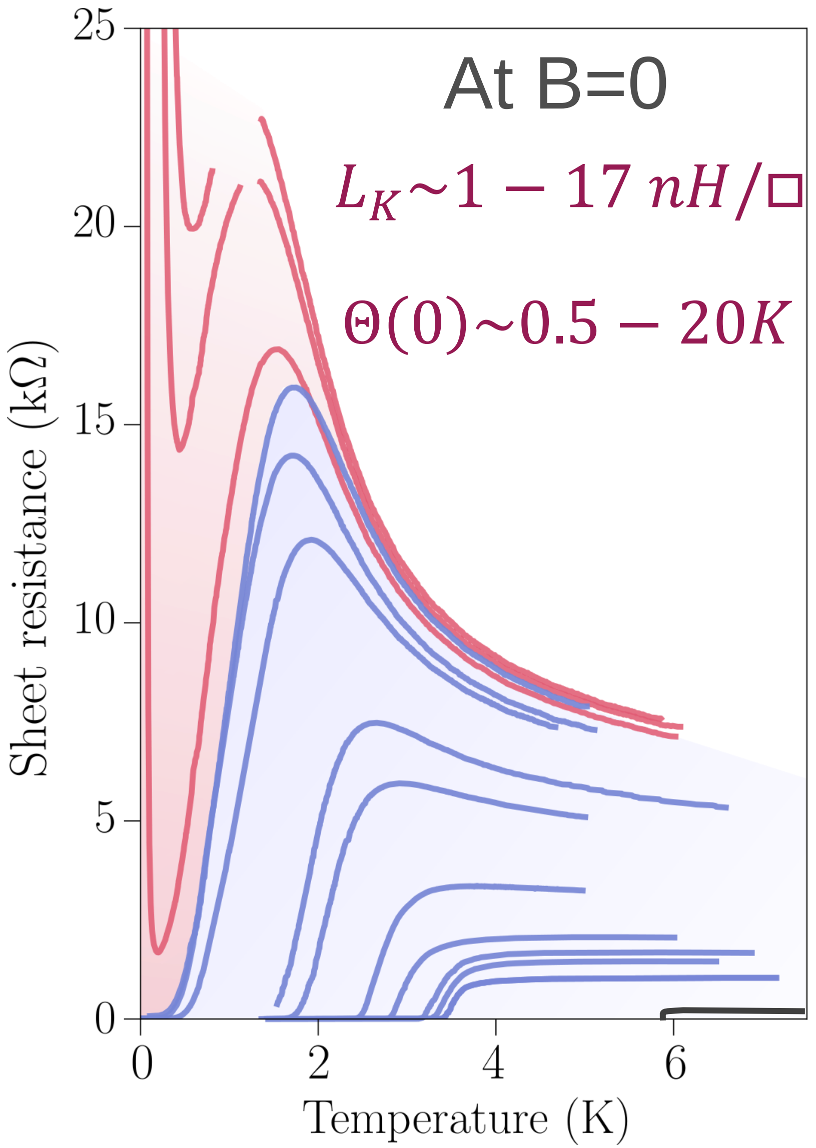
Giamarchi, Le Doussal ('95)
Feigelman, Geshkenbein, Larkin ('90)

$$\tilde{k} \sim \frac{\Phi_0}{B} \quad \Rightarrow \quad \boldsymbol{\Theta \sim 1/B^2}$$

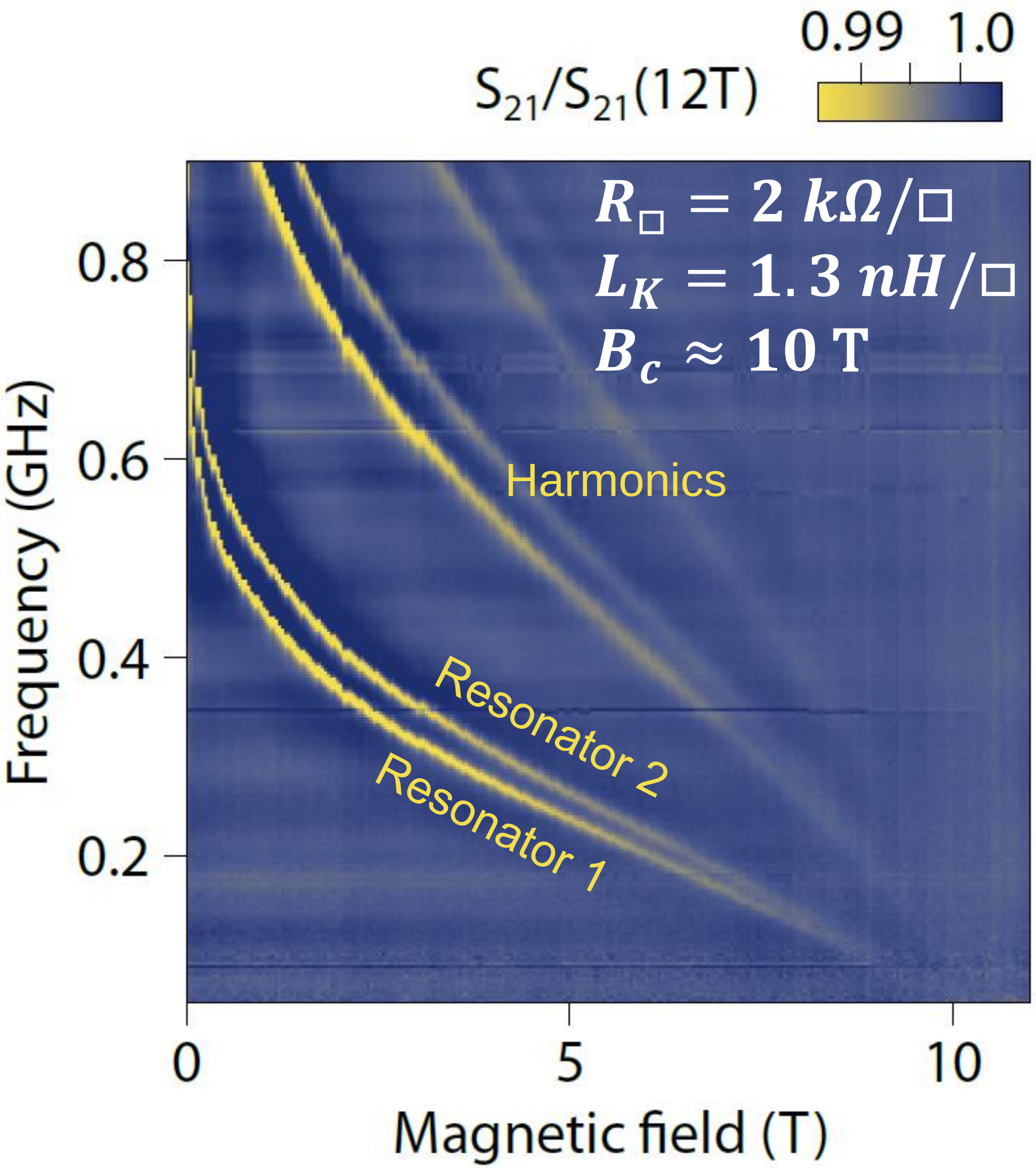
MoGe $\Theta \sim 1/B^{1.35}$: ok!

Strongly disordered InOx: vortex glass

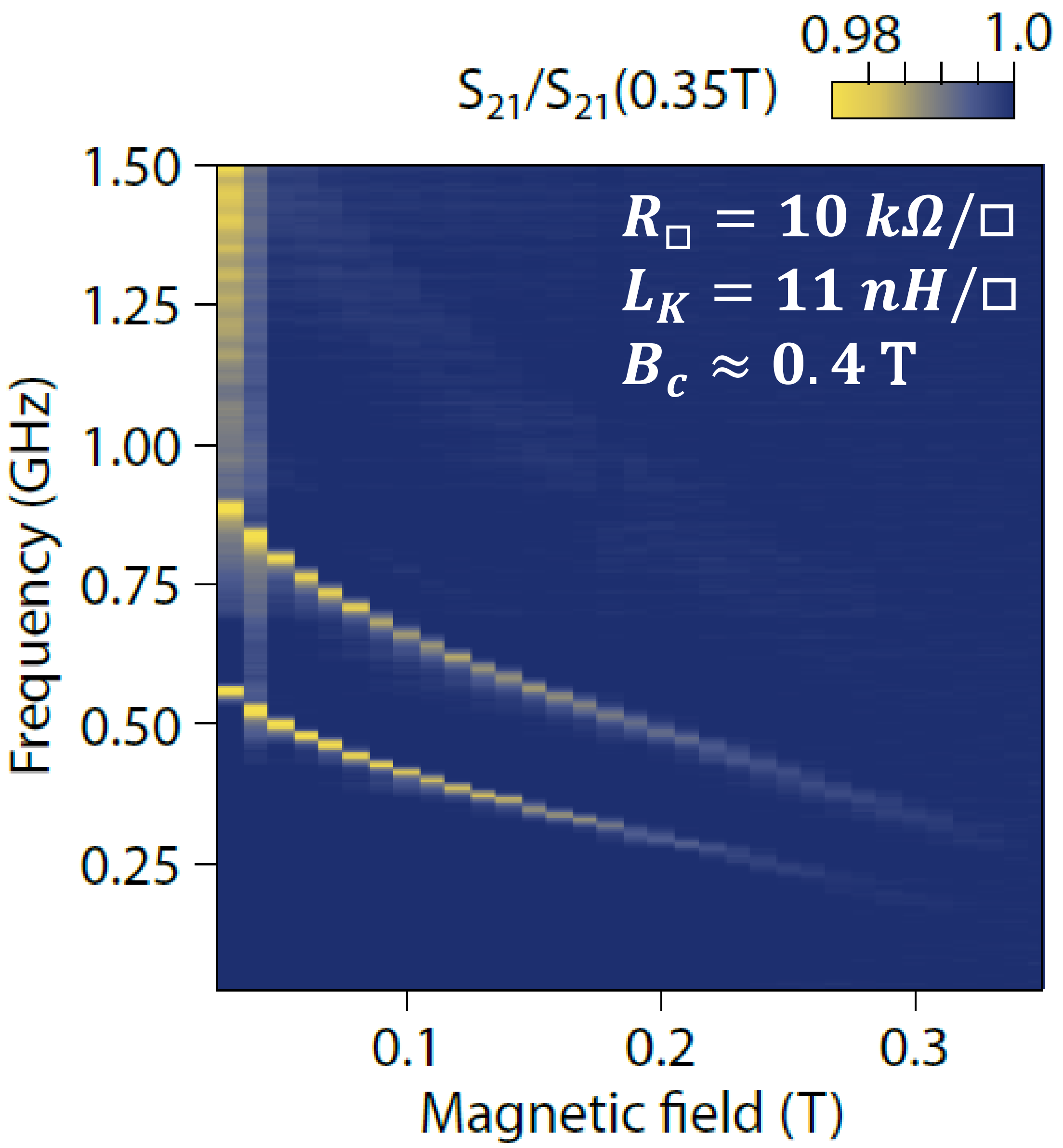




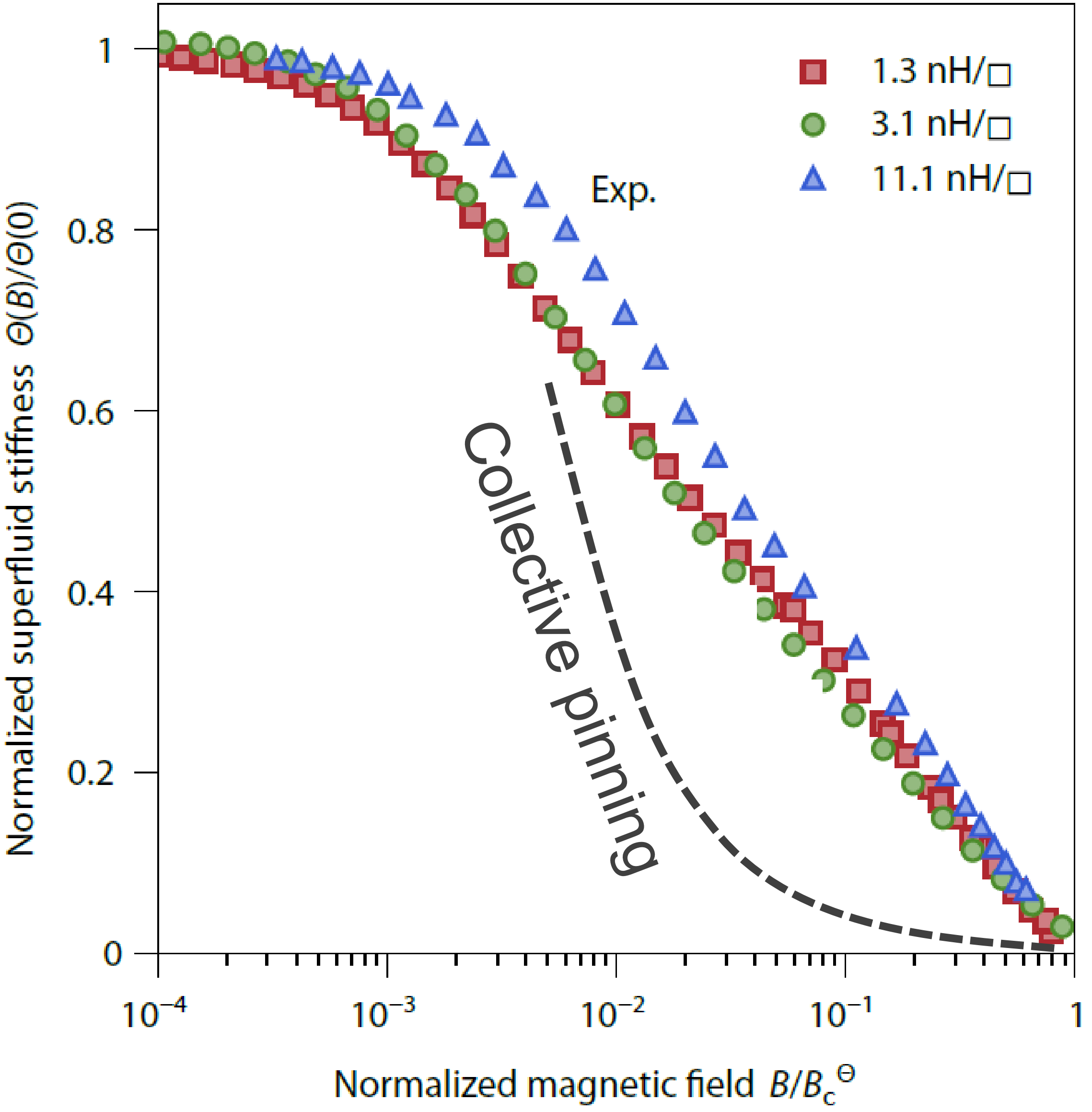
Moderate disorder



Strong disorder



Superfluid stiffness $\mathbf{\Theta(B)}$



$$\frac{\Theta(B)}{\Theta(0)} = \left(\frac{f(B)}{f(0)}\right)^2$$

Much slower decay than expected !

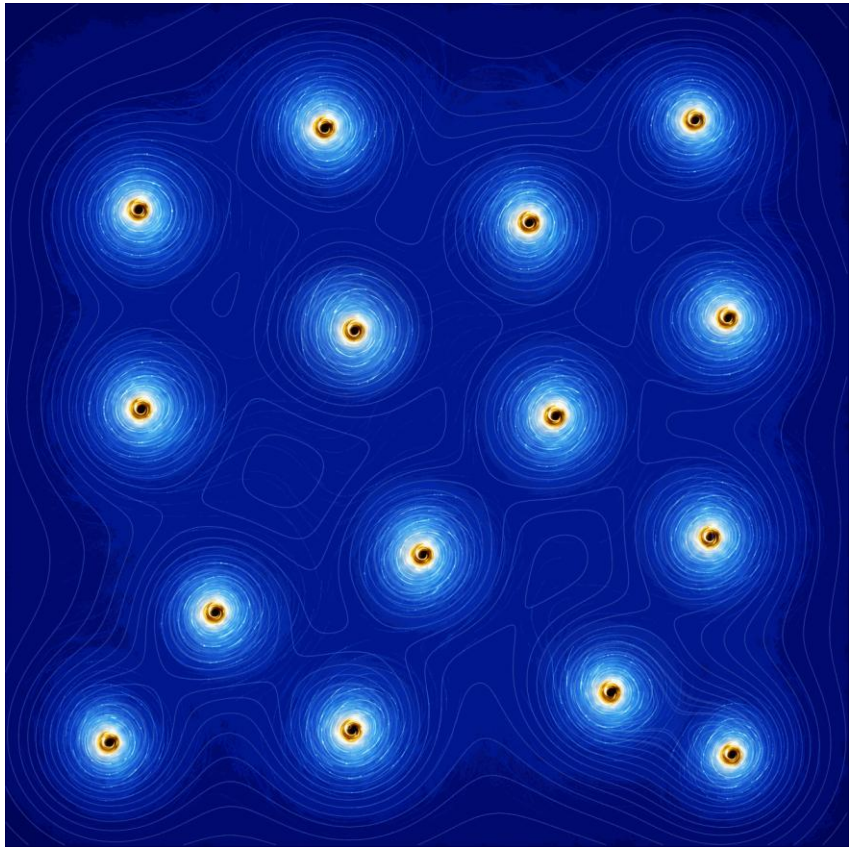
$$\boldsymbol{\Theta(B) \propto -log(B/B_c)}$$

Third scenario: Interaction-enhanced pinning

Feigelman & Kabanov (2026)

Cage model:

- Uncorrelated movement of vortices
- single vortex pinned by interactions with the neighbors



Pair-wise vortex repulsion : $U(r) = -2\pi\Theta_0 \ln(r)$

$$\tilde{k}(B) = \beta(B) \left.\frac{\partial^2 U}{\partial r^2}\right|_{a_B} = 2\pi\beta(B)\frac{\Theta_0 B}{\Phi_0} \gg \frac{W}{\xi_0^2}$$

$a_B = \sqrt{\phi_0/B}$

Major effective contribution comes from **interactions between vortices** and **not pinning potential**

$\Theta \sim \tilde{k}(B)/B$ ➡ $\boldsymbol{\Theta \sim \beta(B)}$

Third scenario: Interaction-enhanced pinning

Feigelman & Kabanov (2026)

Cage model:

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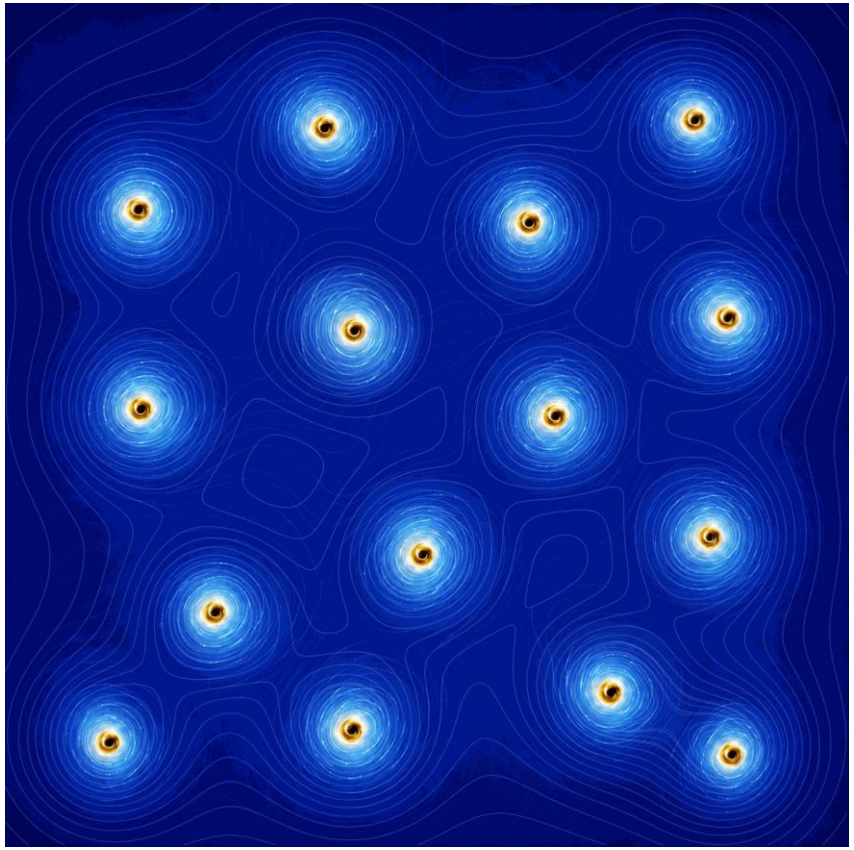


Pair-wise vortex repulsion : $U(r) = -2\pi\Theta_0 \ln(r)$

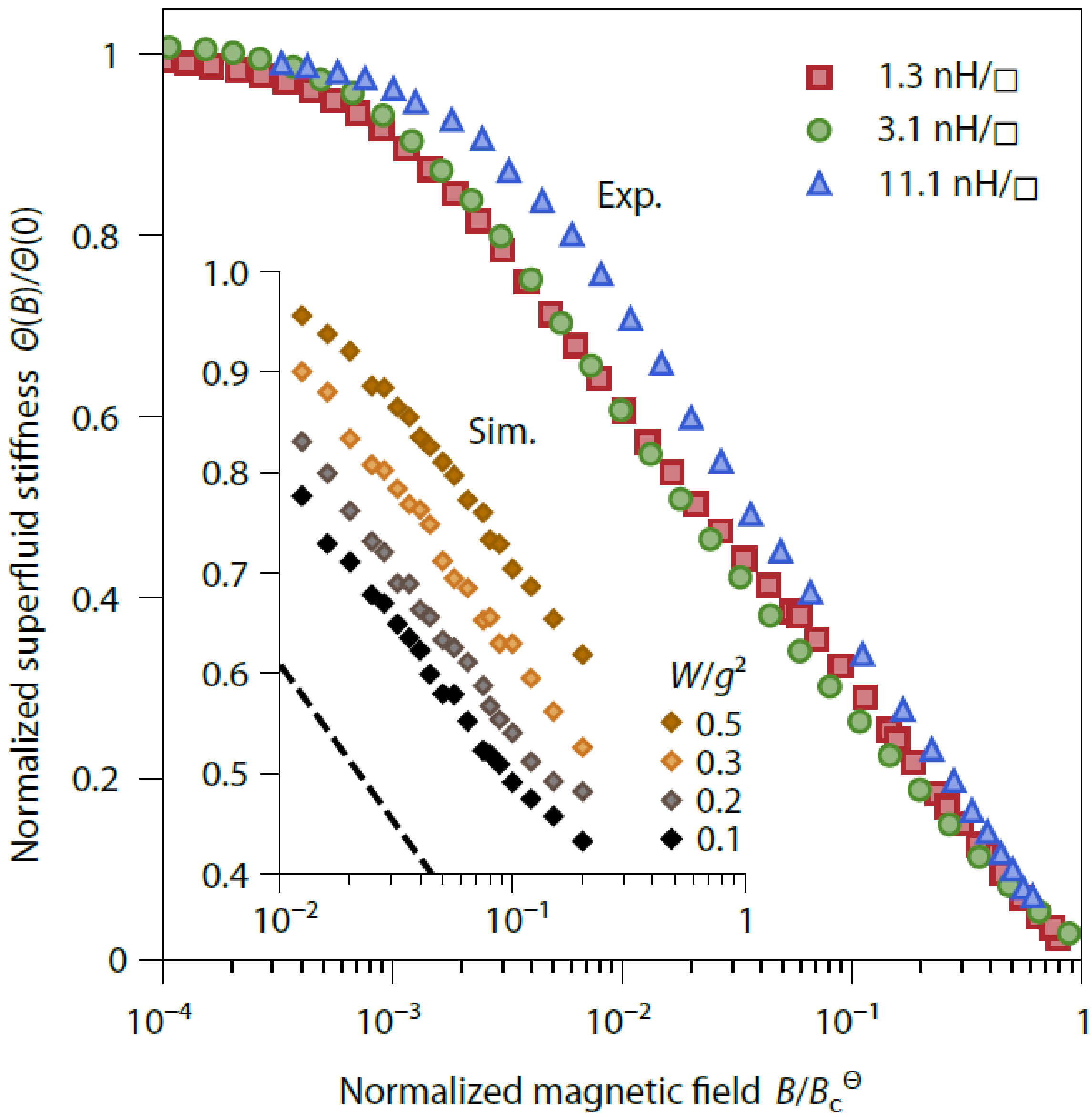
2D Coulomb gaz in a random potential

- Self consistent numerics: increasing B reduces interaction
- Superfluid response ⇔ dielectric response

$$\boldsymbol{D}_v = \epsilon_v \boldsymbol{E}_v = (1 + 2\pi\chi_v)\boldsymbol{E}_v$$

$$\frac{\Theta(B)}{\Theta(0)} = \left\langle \frac{1}{\epsilon_v} \right\rangle = \left\langle \frac{1}{1 + 2\pi\chi_v} \right\rangle$$

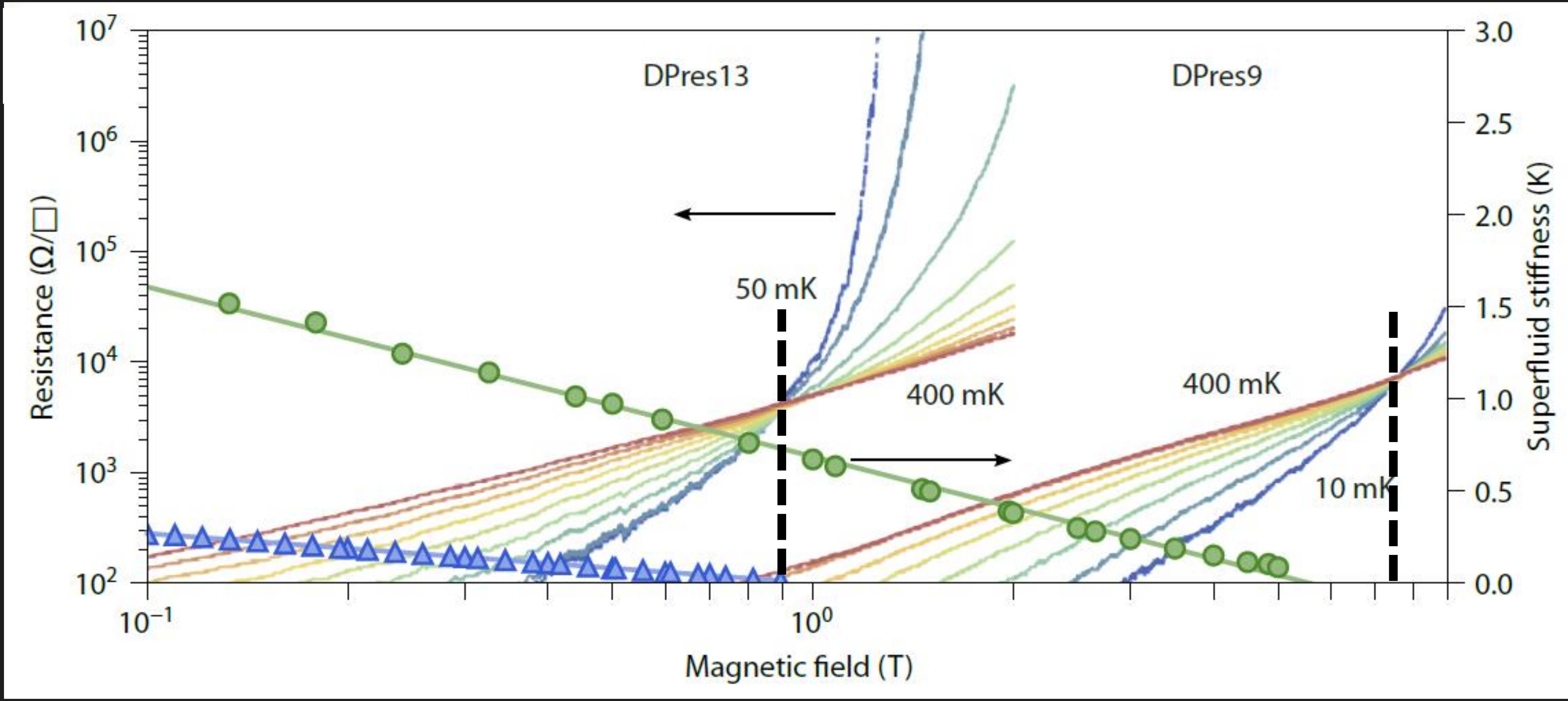
Pinned Vortex Glass: $\Theta(B) \propto -log(B/B_c)$



Exp. $W/g^2 = 0.016$

Consequences

Consequence 1 : mean-field suppression

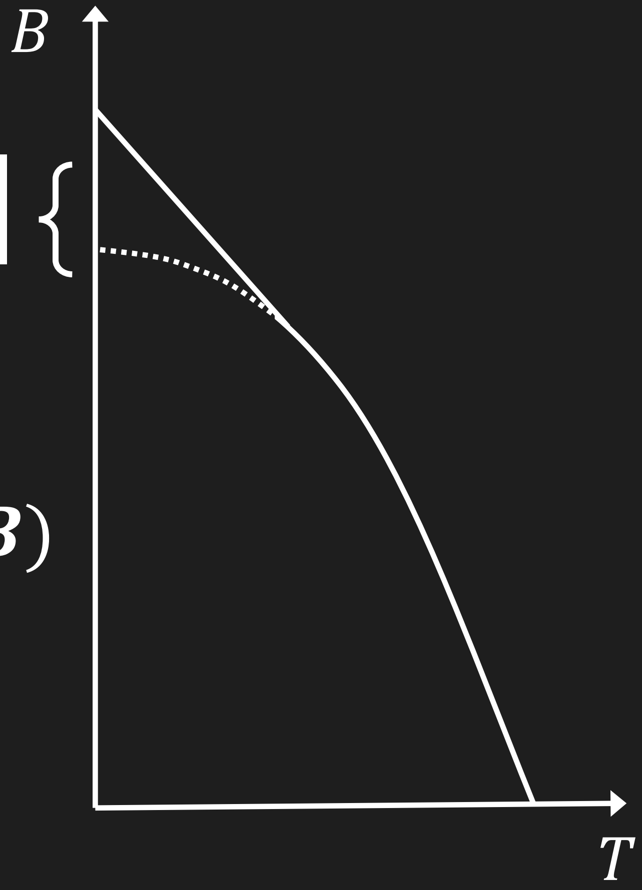


Superfluid density vanishes linearly at B_c

Consequence 1 : mean-field suppression

$\boldsymbol{\rho_s \sim B_c - B}$

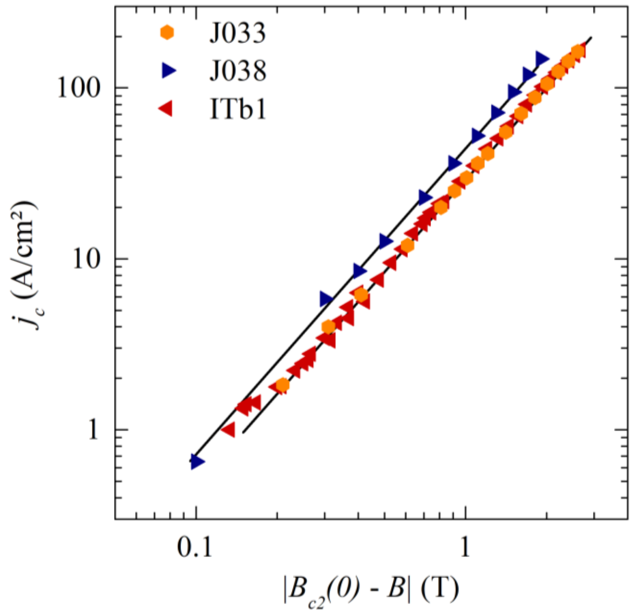
$\boldsymbol{\rho_s \sim \log(B_c/B)}$



ARTICLES
https://doi.org/10.1038/s41567-018-0294-6
nature physics
Corrected: Author Correction

Low-temperature anomaly in disordered superconductors near B_{c2} as a vortex-glass property

Benjamin Sacépé[1]*, Johanna Seidemann[1], Frédéric Gay[1], Kevin Davenport[2], Andrey Rogachev[2], Maoz Ovadia[3], Karen Michaeli[3] and Mikhail V. Feigel'man[4,5]



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

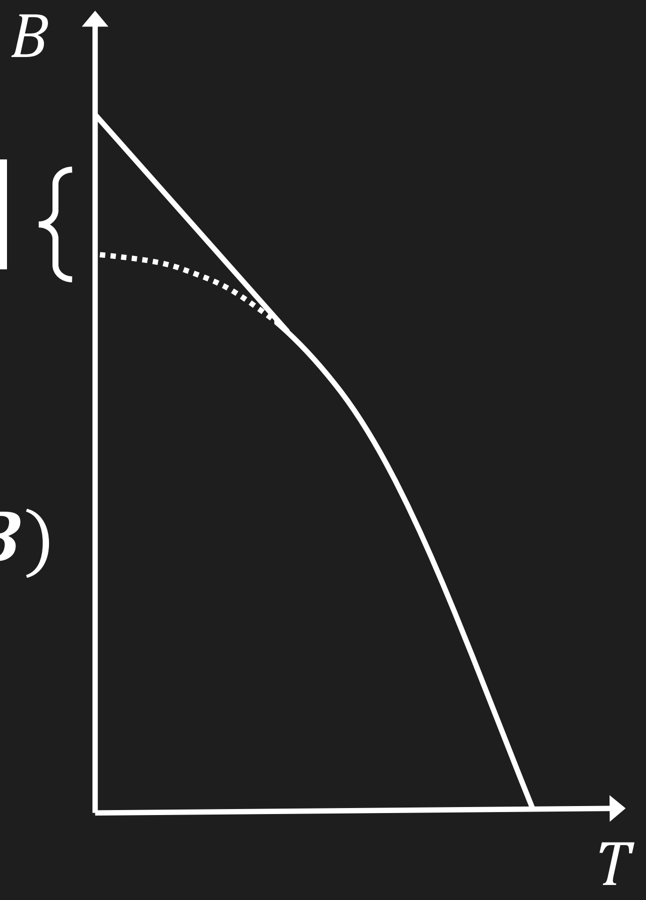
$$\begin{cases} \xi_{GL} \propto |B - B_{c2}|^{-1/2} \\ \boldsymbol{\rho_s \propto |B - B_{c2}|} \end{cases}$$

Consequence 1 : mean-field suppression

$$\boxed{\rho_s \sim B_c - B}$$

$$\uparrow$$

$$\rho_s \sim \log(B_c/B)$$



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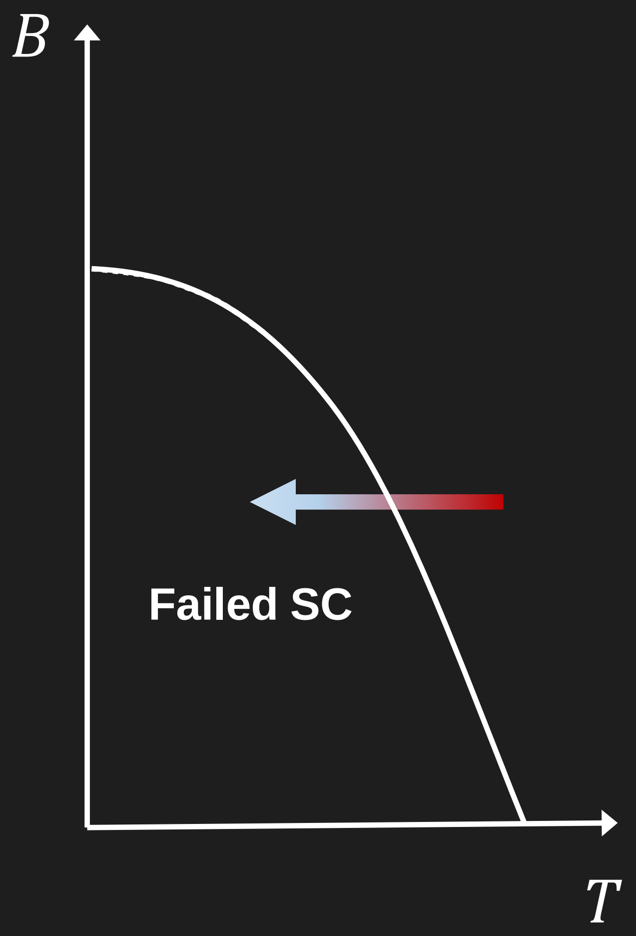
Quantum critical scaling ?

$$\cancel{\rho_s \propto \left(\frac{|B - B_c|}{B_c}\right)^{(z+d-2)\nu}}$$

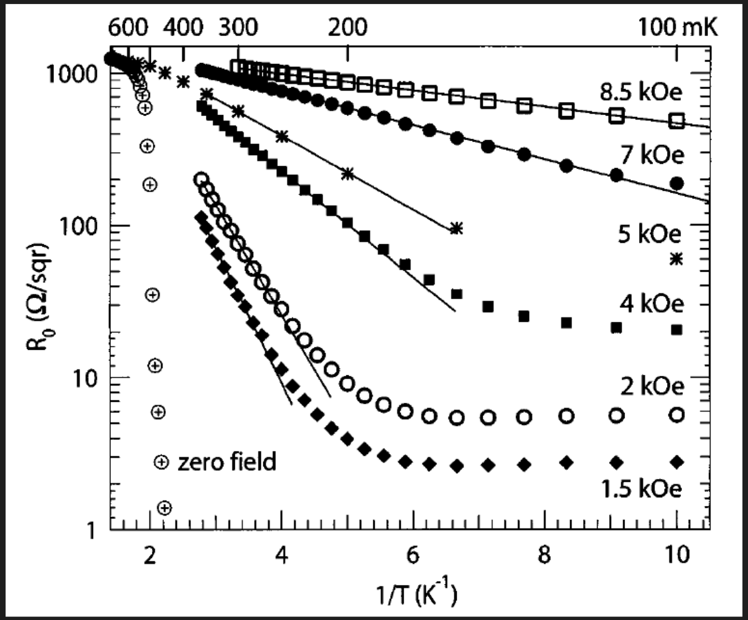
Fisher, Weichman, Grinstein, Fisher ('89)

Consequence 2 : Failed superconductivity

Kapitulnik, Spivak, Kivelson RMP ('19)



MoGe films



Ephron et al. PRL ('96)

Thermally assisted flux flow/creep $R = R_0 exp\left(-\frac{U(B,T,j)}{k_B T}\right)$

Consequence 2 : Failed superconductivity

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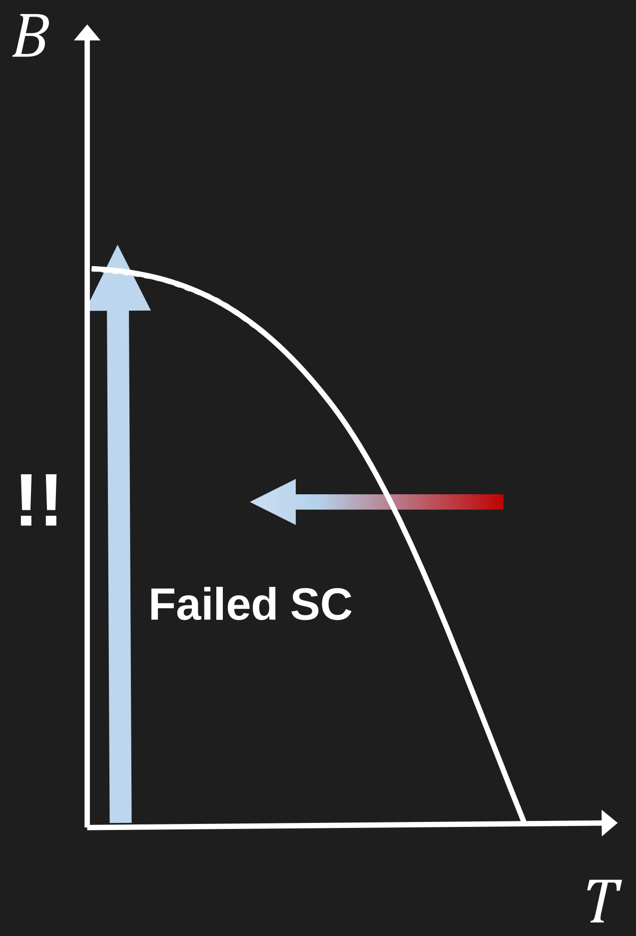
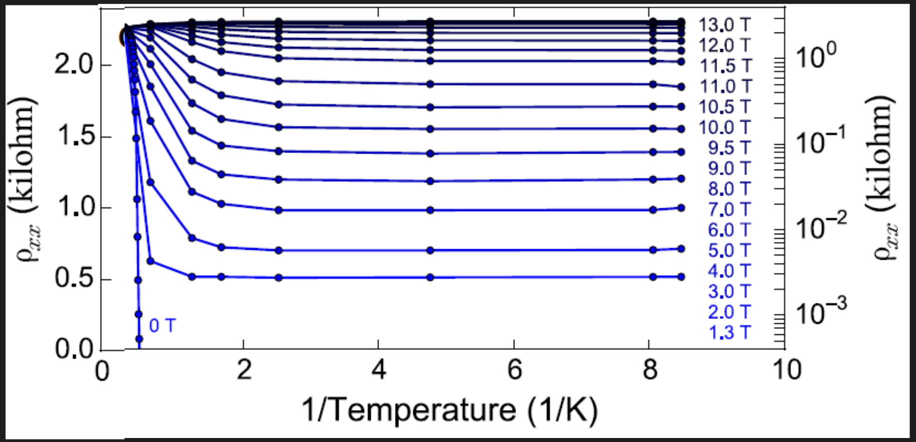


!! $\rho_s \neq 0$!!

InOx films



Breznay, Kapitulnik Sci. Adv. ('17)

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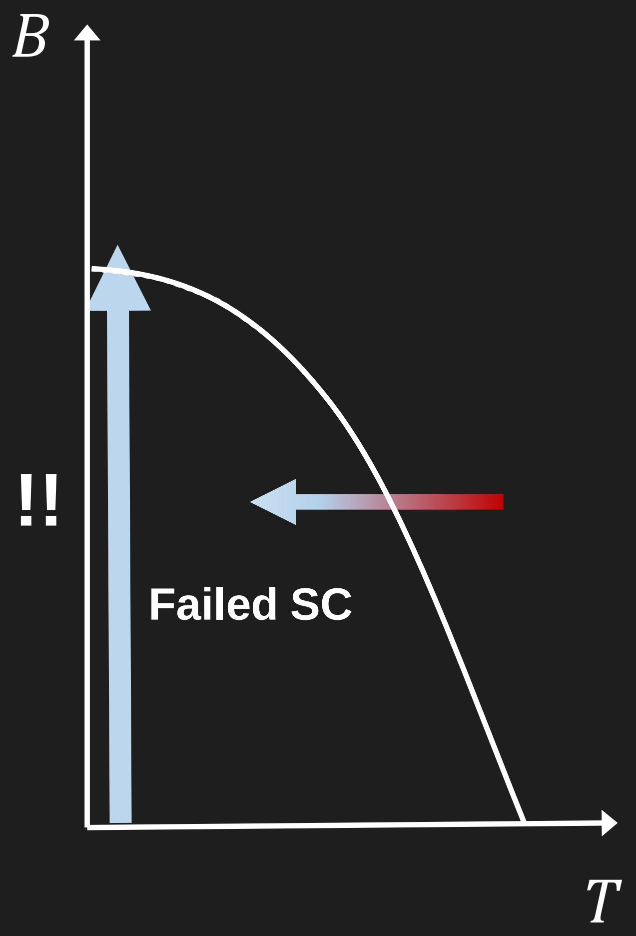
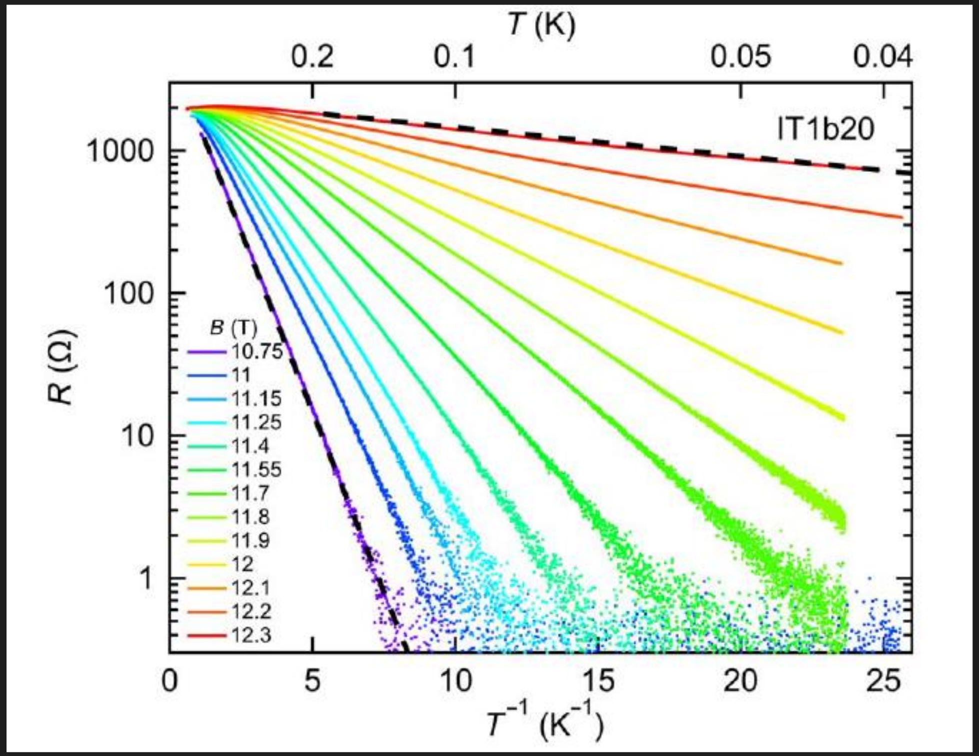


$!!\ \rho_s \neq 0\ !!$

InOx films



Tamir et al. Sci. Adv. ('19)

Acknowledgements

David Perconte (Postdoc)

Thibault Charpentier (PhD)

Nadjib Benchabane (PhD)

Nikolaos Koutsopoulos (PhD)

Kalpajit Roy (PhD)

Xiaoli Peng (Postdoc)

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Conclusion

Pinned vortex glass

1. Non zero superfluid density near $T \approx \mathbf{0}$
2. Interaction-induced pinning strengthen $\Theta(B)$
3. Meanfield-like transition at the *B-tuned* SIT

D. Perconte, *et al.* arXiv:2605.23838