First-order quantum breakdown of a superconductor ruled by phase fluctuations

Thibault Charpentier

Néel Institute, Grenoble, France

Les Houches, June 5 2023

In this talk

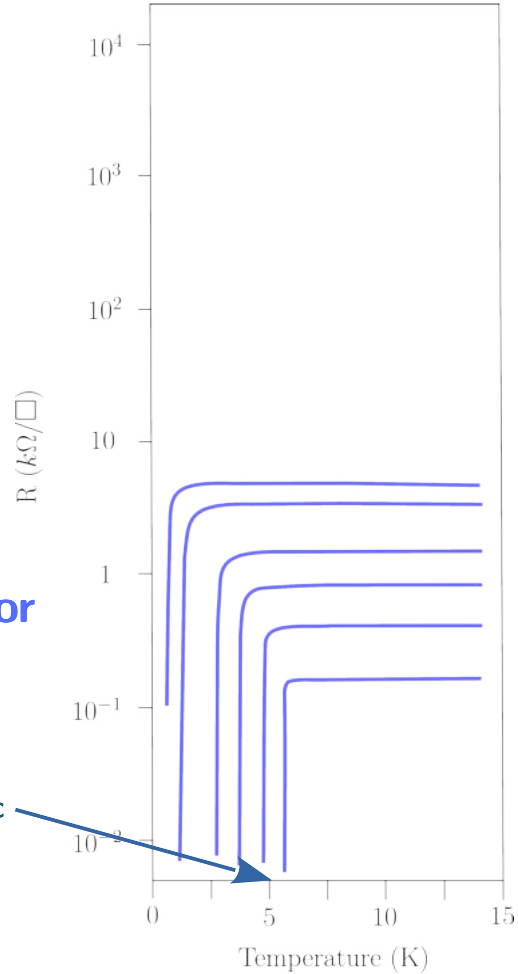
Study of strongly disordered amorphous indium oxide film (aInO) across the Superconductor-Insulator Transition at microwave frequencies.

PhD supervised by

N. Roch

B. Sacépé

Superconductor-Insulator Transition



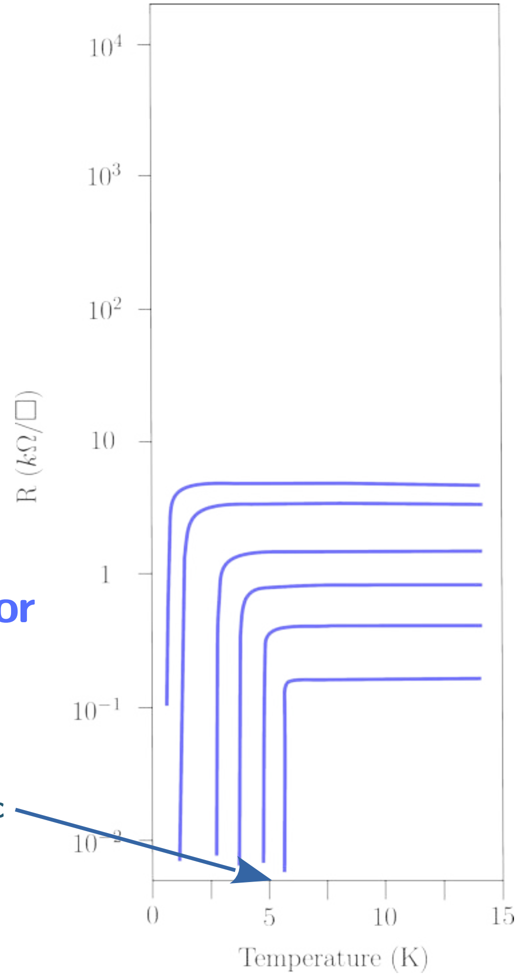
Superconductor

Critical temperature T_c

Example : Bismuth thin films

Adapted from Haviland et al, PRL (1989)

Superconductor-Insulator Transition



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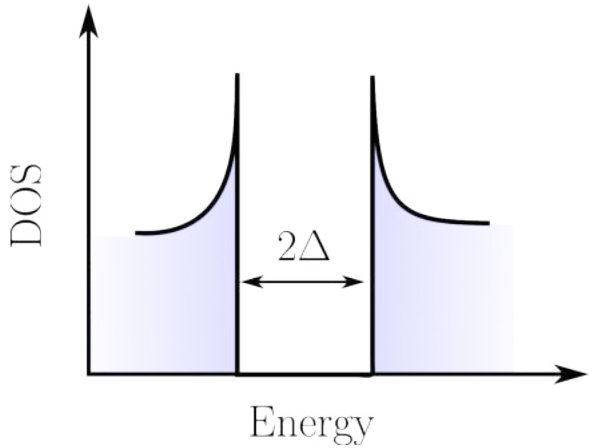
Superconducting gap Δ

Pairing energy between electrons of a CP



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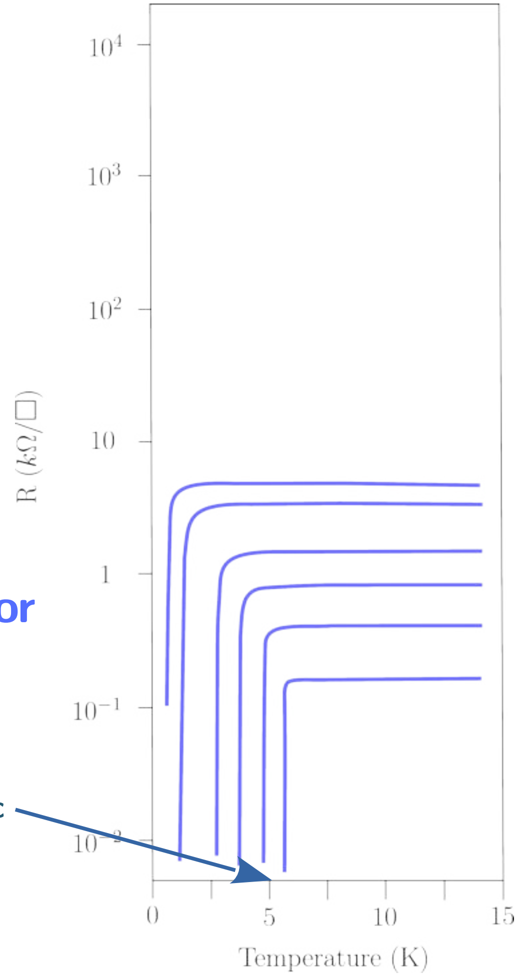
Superconductor-Insulator Transition



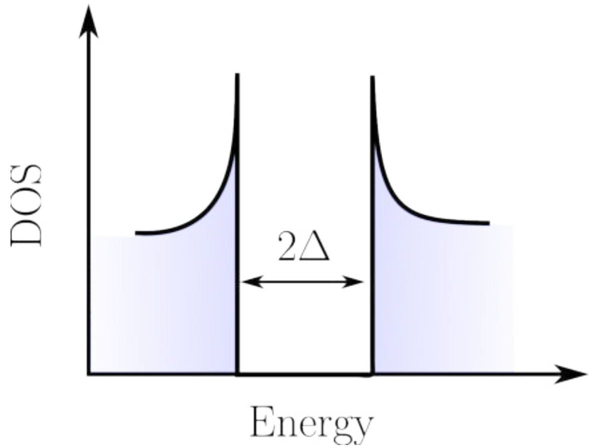
Superconductor

Critical temperature T_c

Example : Bismuth thin films

Superconducting gap $\Delta \sim 1.76\, k_B T_c$

Pairing energy between electrons of a CP



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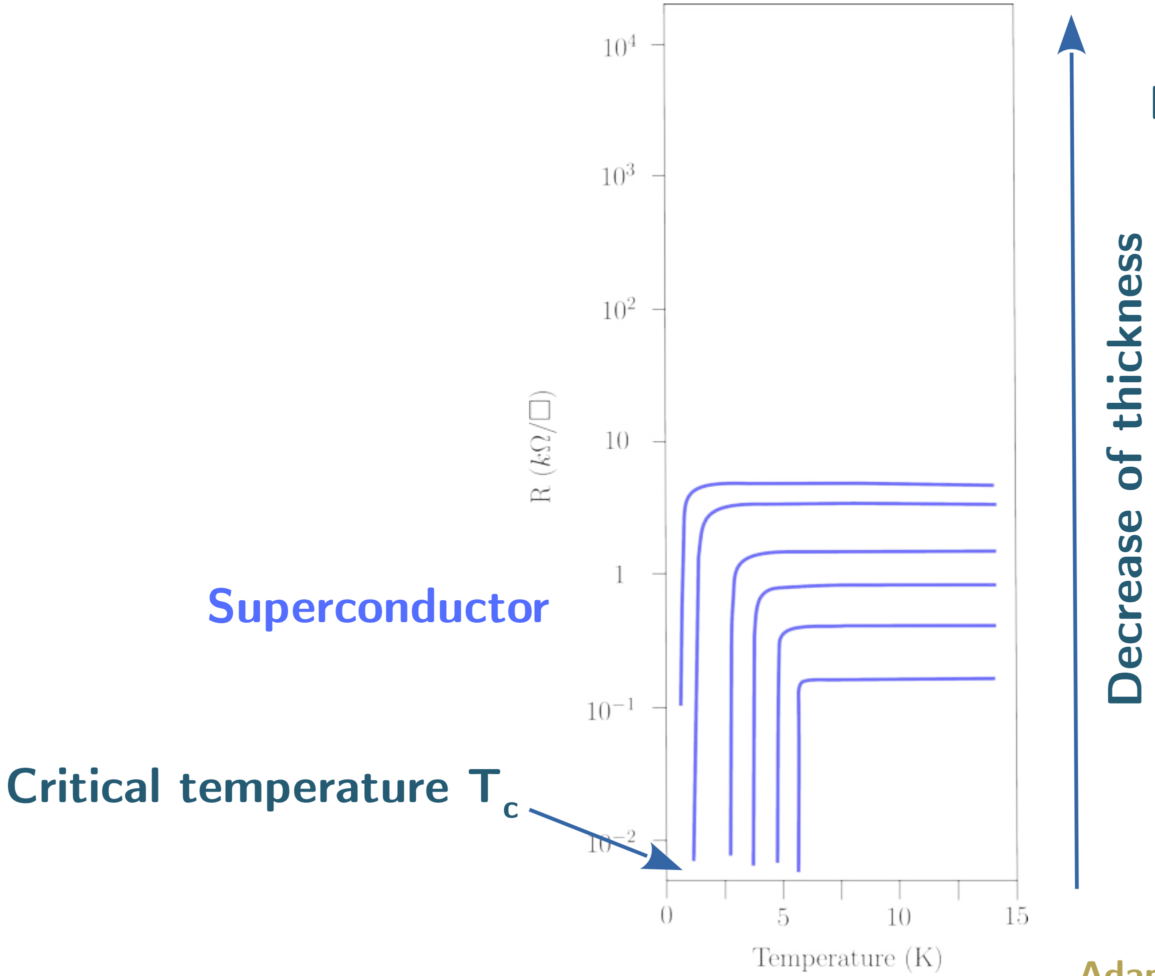
Superconductor-Insulator Transition



Example : Bismuth thin films

With some driving parameter (thickness, disorder, B-field ...)

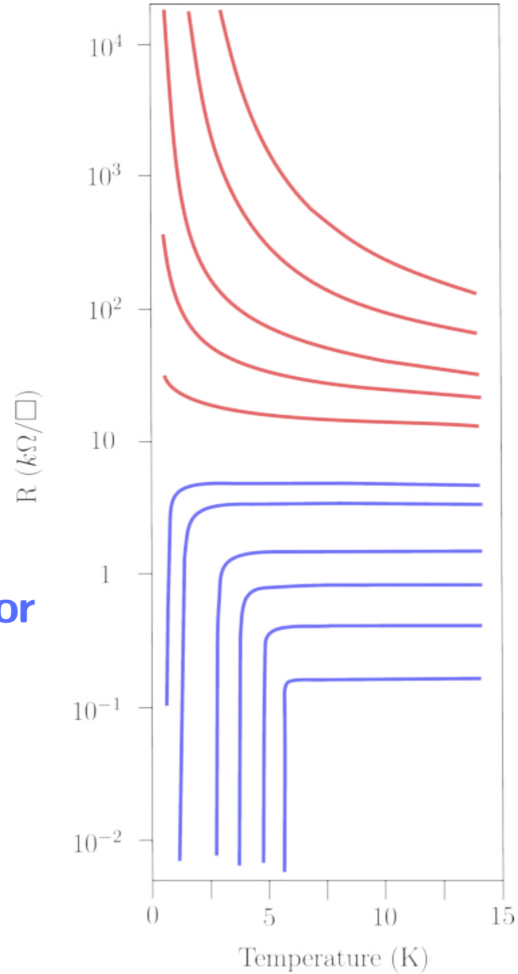
Suppression of T_c

Adapted from Haviland et al, PRL (1989)

Superconductor-Insulator Transition

Insulator

Superconductor



Decrease of thickness

Example : Bismuth thin films

With some driving parameter (thickness, disorder, B-field ...)

Suppression of T_c

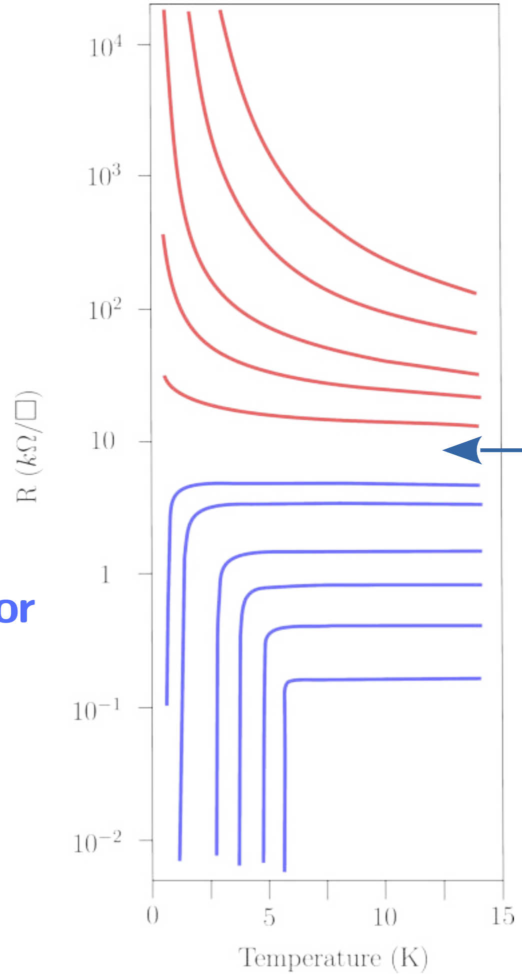
Superconductor-Insulator Transition

Adapted from Haviland et al, PRL (1989)

Superconductor-Insulator Transition

Insulator

Superconductor



Order parameter of the transition

$$\Psi = \Delta e^{i\varphi}$$

$$\Psi \to 0$$

Superconductor-Insulator Transition

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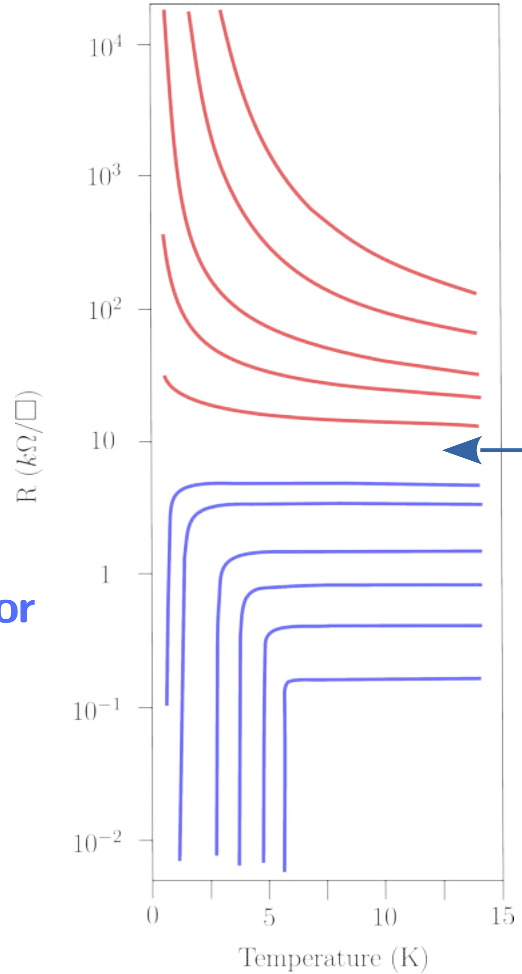
Superconductor-Insulator Transition

Insulator

Superconductor



Order parameter of the transition

$$\Psi = \Delta e^{i\varphi}$$

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Evolution of Δ with disorder ?

Adapted from Haviland et al, PRL (1989)

Superconductor-Insulator Transition

Fermionic mechanism

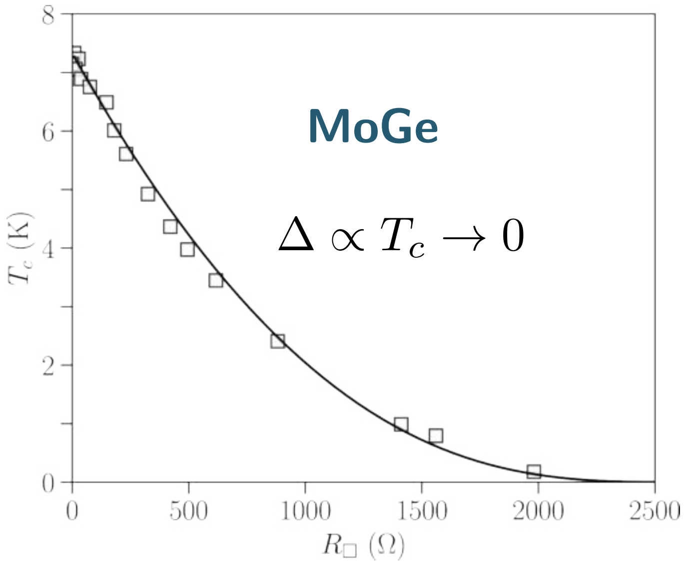
Disorder-enhanced Coulomb repulsion between electrons of a Cooper pair opposes to pairing attraction

Cooper pairing dies out at the SIT

$$\Delta \to 0$$

Order parameter of the transition

$$\Psi = \cancel{\Delta} e^{i\varphi}$$



Finkel'stein, Physica B (1994)

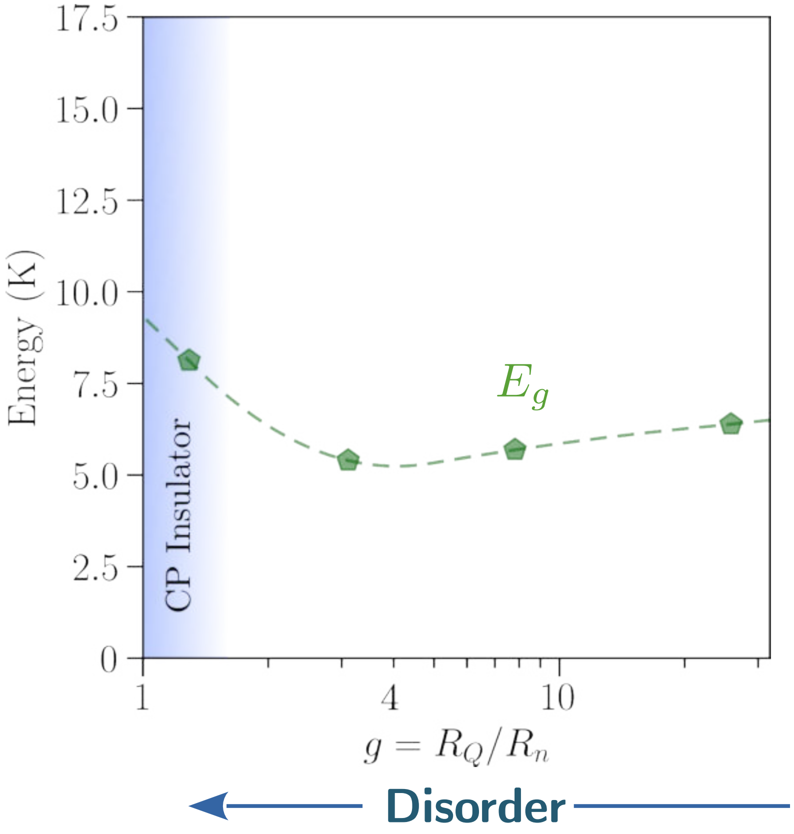
Superconductor-Insulator Transition

Is it the full picture ?

Let us see indium oxide data

Superconductor-Insulator Transition

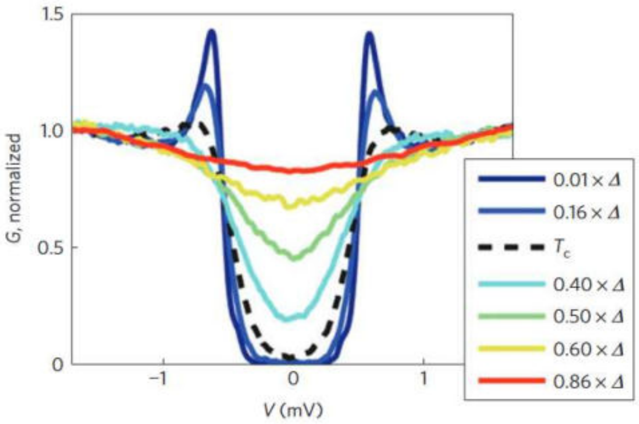
Indium oxide



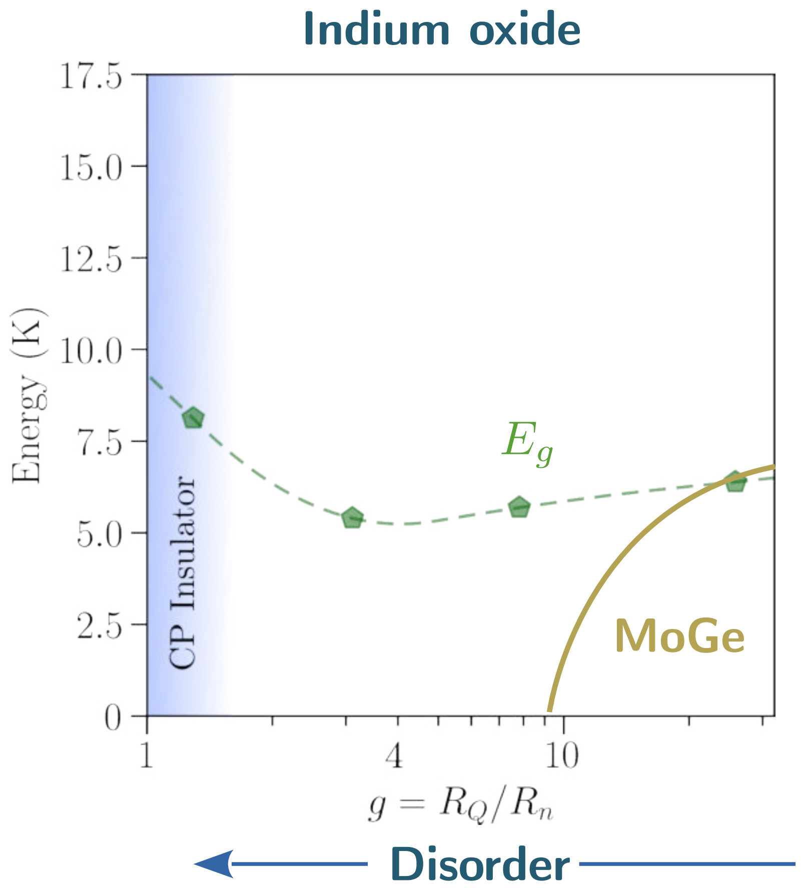
Superconducting gap E_g

Sacépé et al, Nature Physics (2011)
Sacépé et al, PRB (2015)
Sherman et al, PRB (2014)

Tunneling spectroscopy



Superconductor-Insulator Transition



Comparison with fermionic scenario

Gap in MoGe is strongly suppressed

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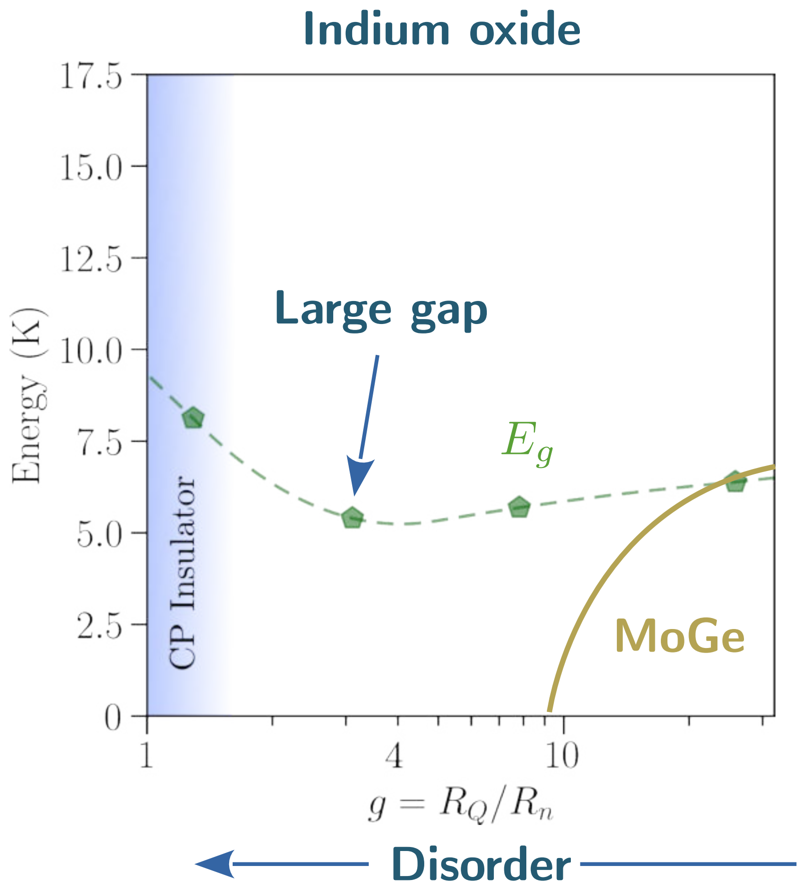
Superconductor-Insulator Transition



Comparison with fermionic scenario

Gap in MoGe is strongly suppressed

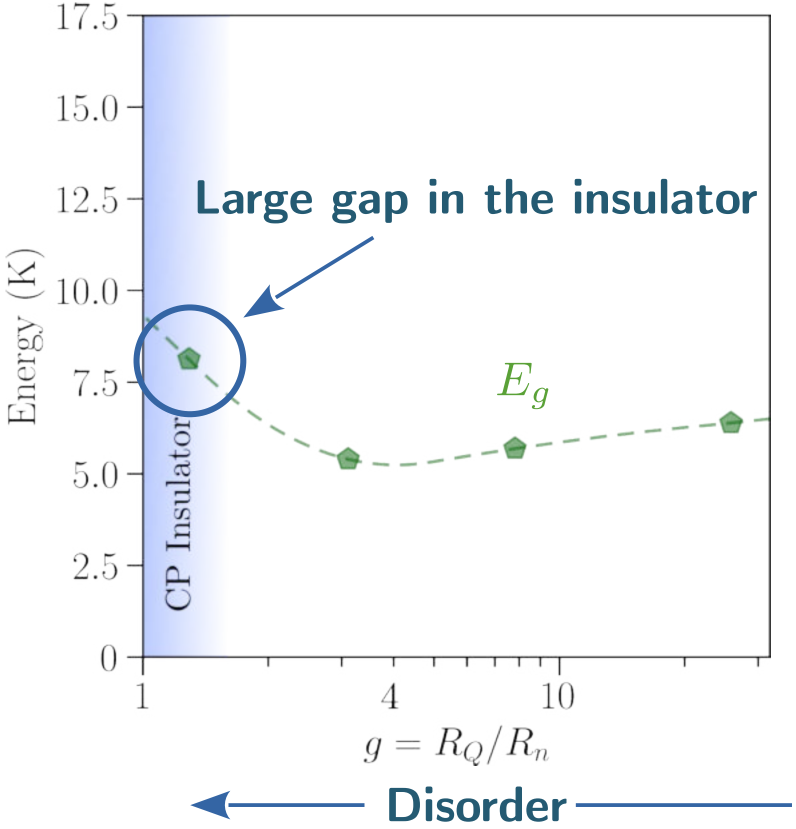
Finkel'stein, Physica B (1994)

But gap in InO remains large

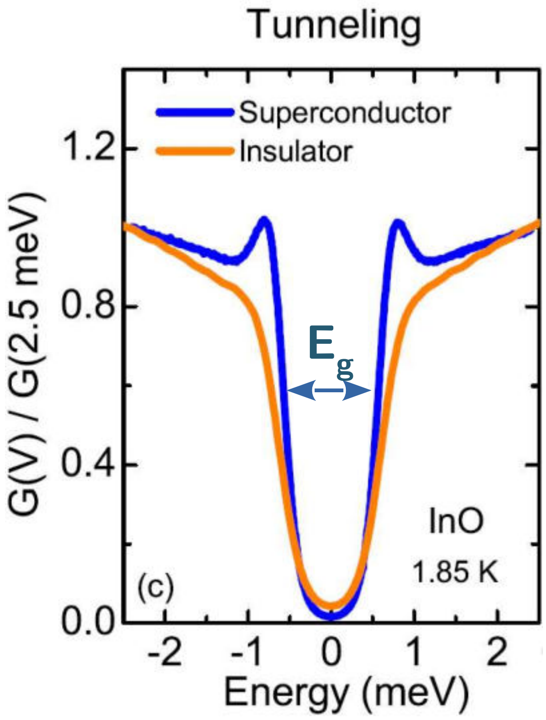
Fermionic scenario does not apply for InO

Pseudogap in indium oxide

Indium oxide



Gap remains in insulating state



Sherman et al, PRB (2014)

Pseudogap in indium oxide

Superconducting gap does not vanish in the insulator (pseudogap)

Other mechanism for the breakdown of superconductivity :

Bosonic mechanism

$$\Psi = \Delta e^{i\cancel{\varphi}}$$

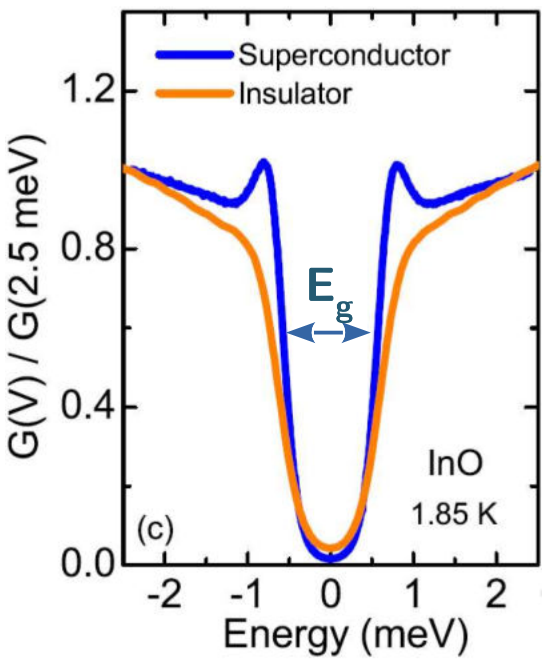
Phase fluctuations suppress superconductivity

Insulator of incoherent Cooper pairs

Fisher et al, PRB (1989)

Gap remains in insulating state

Tunneling

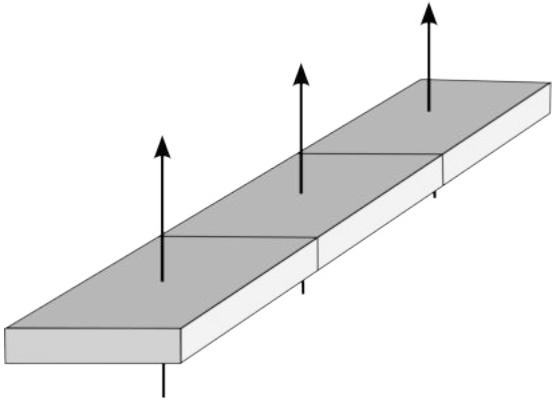


Sherman et al, PRB (2014)

On phase fluctuations

Superconducting order parameter

$$\Psi(\mathbf{r}) = \Delta(\mathbf{r})e^{i\varphi(\mathbf{r})}$$



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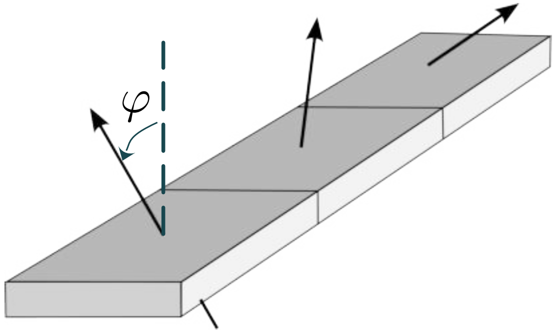

Elastic energy cost to twist the phase :

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

where Θ is the superfluid stiffness $\approx E_J$

On phase fluctuations

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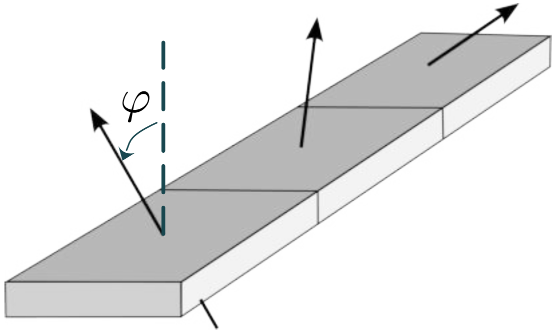

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where Θ is the superfluid stiffness $\approx E_J$

Θ describes the resilience of a superconductor against phase fluctuations : SIT for $\Theta \to 0$

On phase fluctuations

Elastic energy cost to twist the phase

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

Kinetic energy of the condensate

$$E = \int \frac{1}{2} n_s m v_s^2 \, d\mathbf{r} \quad \textbf{where} \quad v_s = \frac{\hbar}{m}\nabla\varphi$$

$$= \frac{1}{2} L_K I^2$$

L_K **is the kinetic inductance**

On phase fluctuations

Elastic energy cost to twist the phase

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

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

Kinetic energy of the condensate

$$E = \int \frac{1}{2} n_s m v_s^2 \, d\mathbf{r} \quad \textbf{where} \quad v_s = \frac{\hbar}{m} \nabla \varphi$$

$$= \frac{1}{2} L_K I^2$$

L_K is the kinetic inductance

Θ can be obtained experimentally through the measurement of L_K

Phase stiffness versus gap

Elastic energy cost to twist the phase

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

Amplitude of pairing strength E_g

Two possibilities

$\Theta \gg E_g$ Phase fluctuations do no affect superconductivity

Phase stiffness versus gap

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Amplitude of pairing strength E_g

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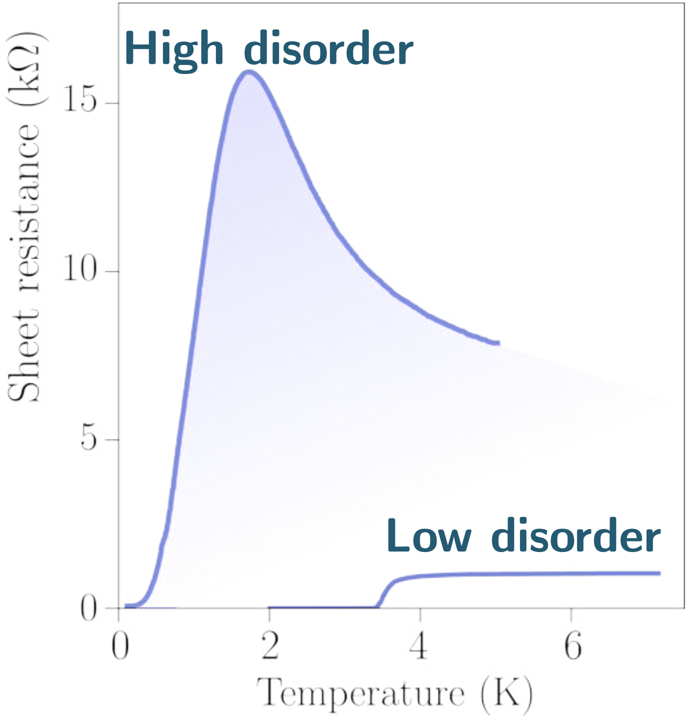
$\Theta \gg E_g$ Phase fluctuations do no affect superconductivity

$\Theta \leq E_g$ Phase fluctuations suppress superconductivity (bosonic scenario)

In which system ?

$\Theta \leq E_g$ can be achieved in strongly disordered superconductors



Strong electron scattering $k_F l \sim 1$

Enhanced normal state resistance R_n

Low superfluid density

In which system ?

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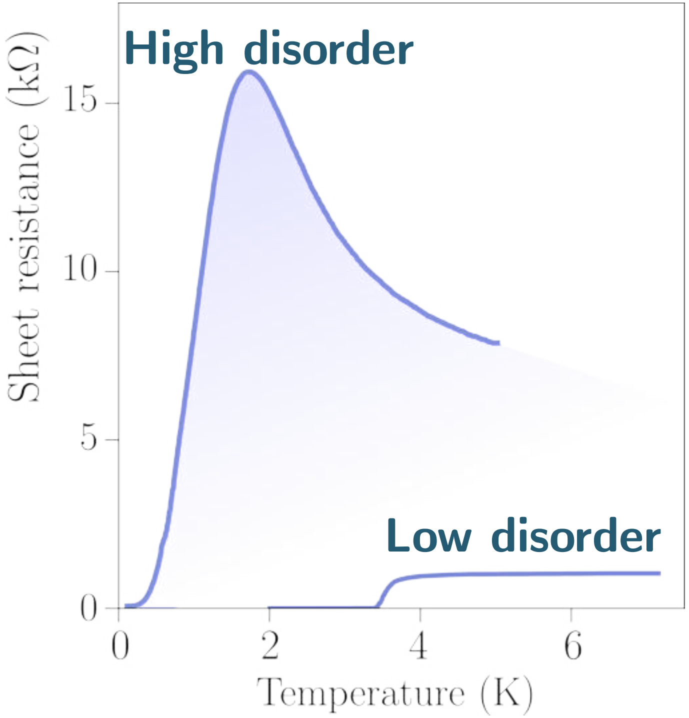


Strong electron scattering $k_F l \sim 1$

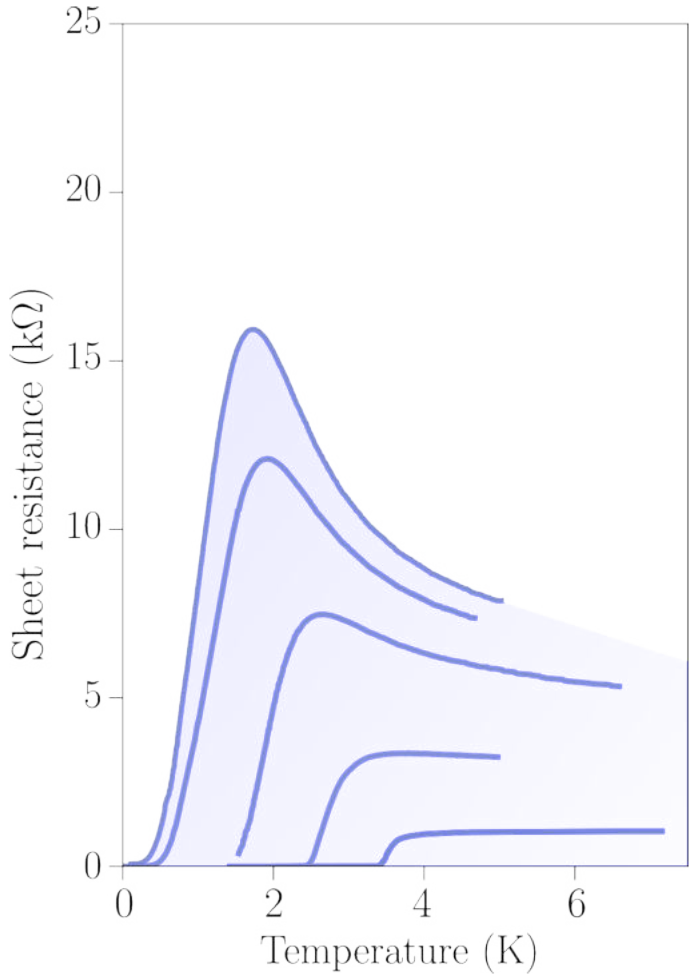
Enhanced normal state resistance R_n

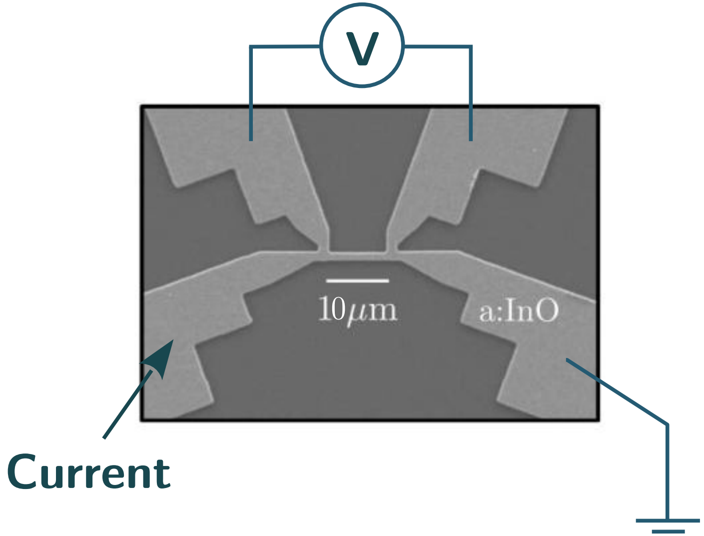
Low superfluid density

$$L_K = \frac{\hbar R_n}{\pi \Delta} \longrightarrow \Theta \propto \frac{1}{R_n} \text{ is small}$$

large phase fluctuations

Amorphous indium oxide

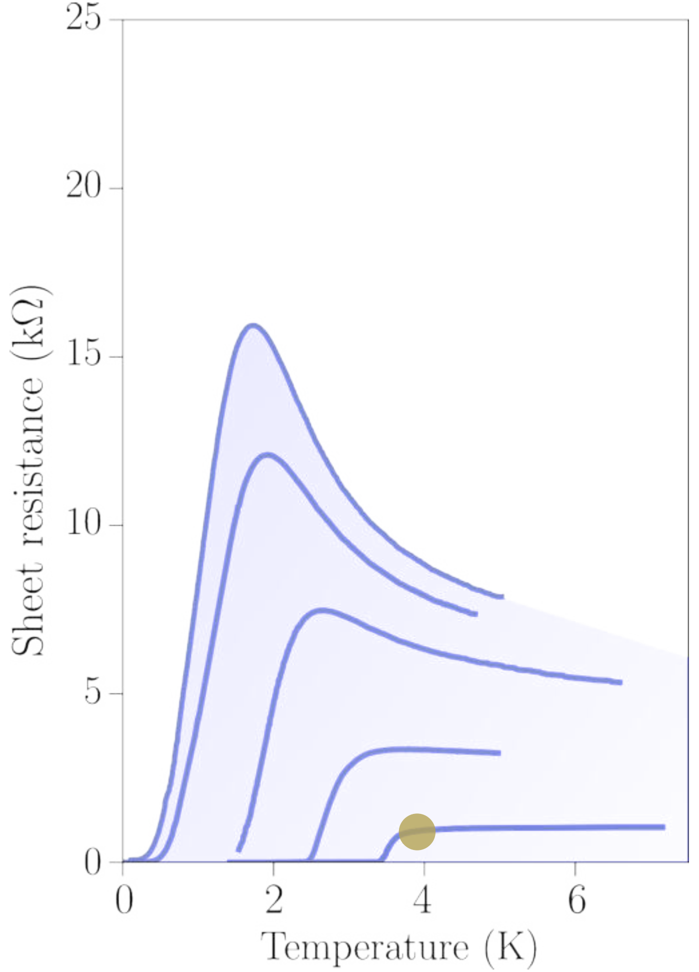




Sheet resistance $R_\square = \frac{\rho}{d}$

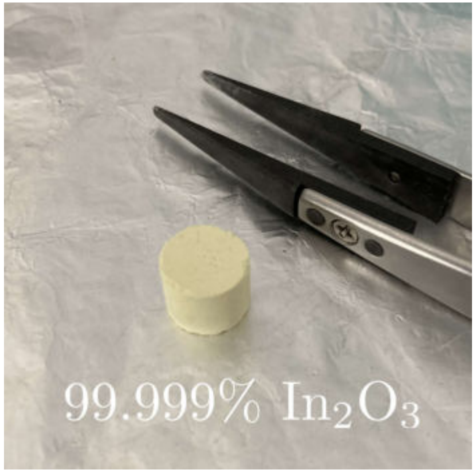
Thickness $d = 40$ nm

Amorphous indium oxide



Resistance increases with disorder

Disorder tuned by oxygen pressure during evaporation



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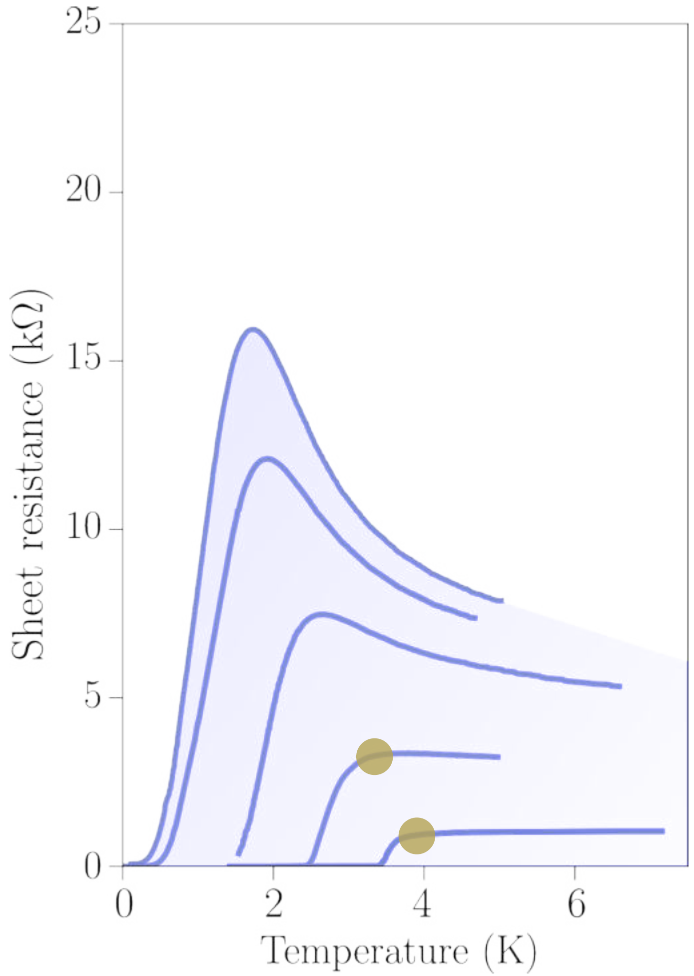

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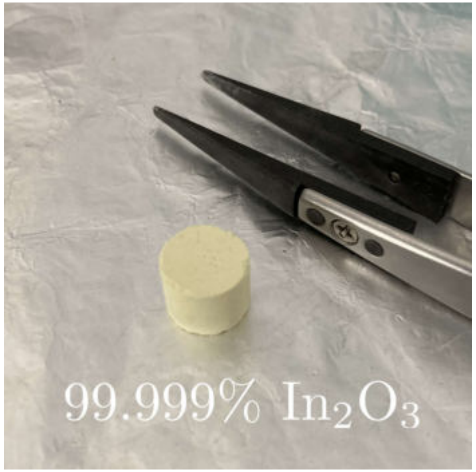

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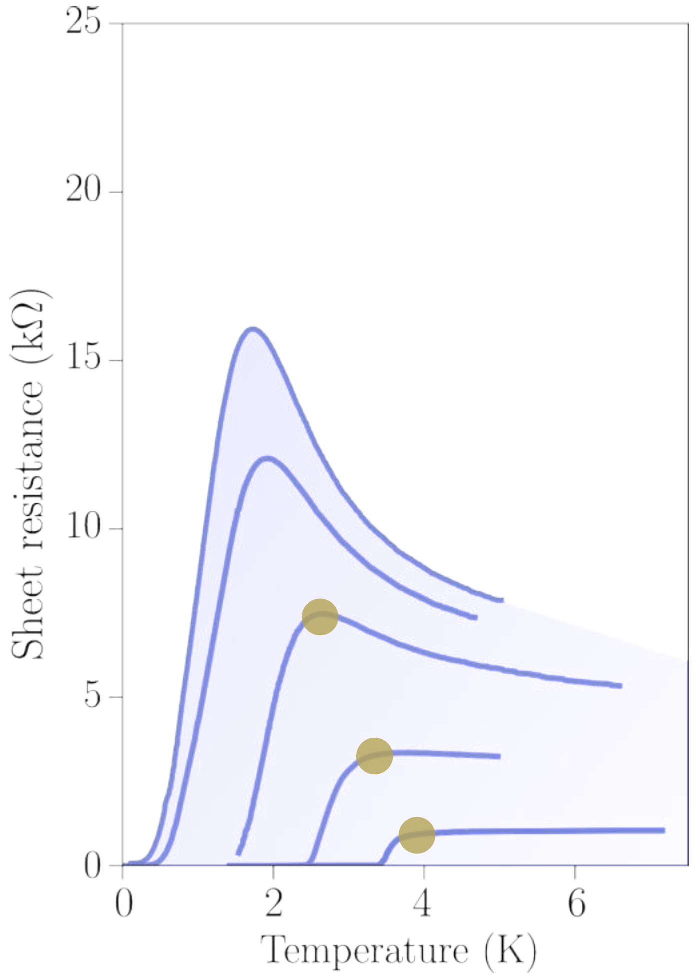

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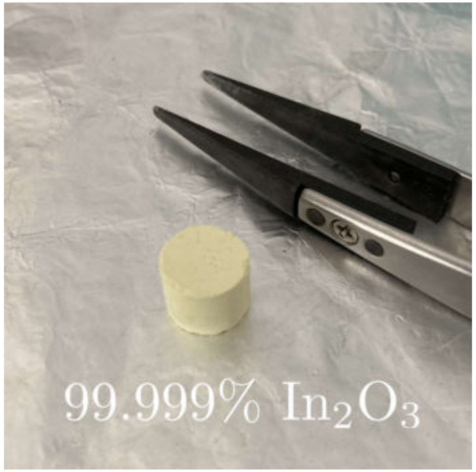

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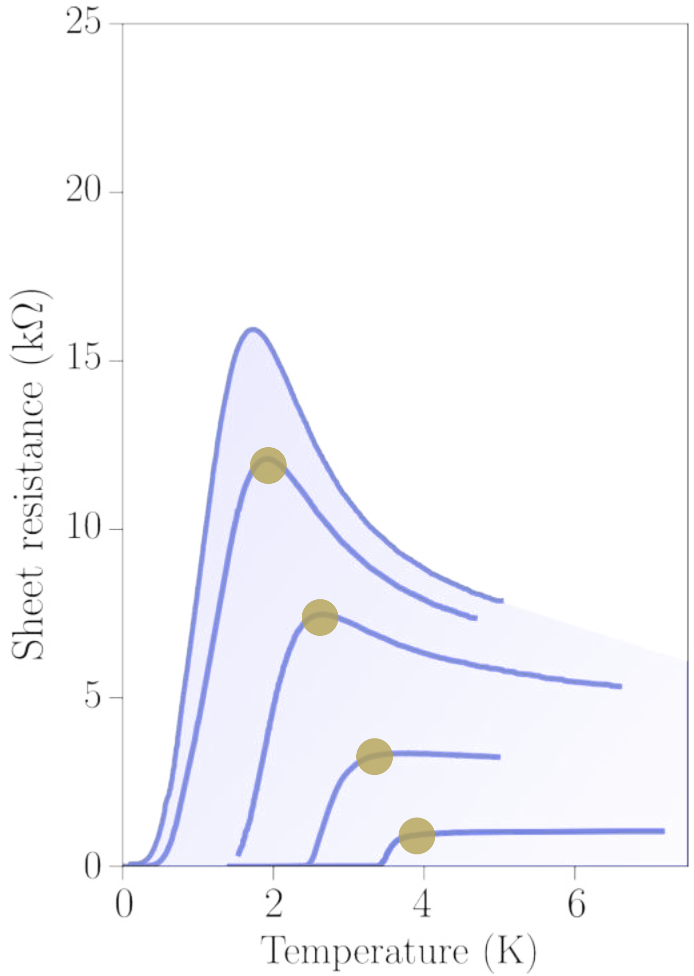

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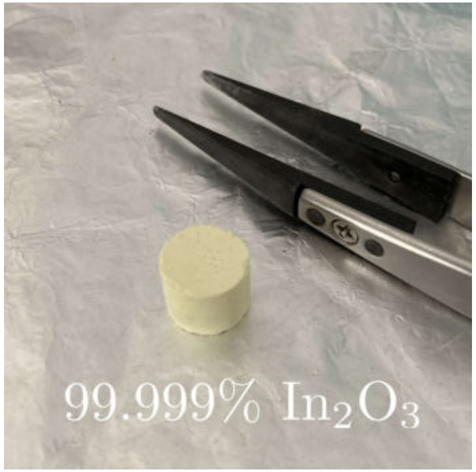

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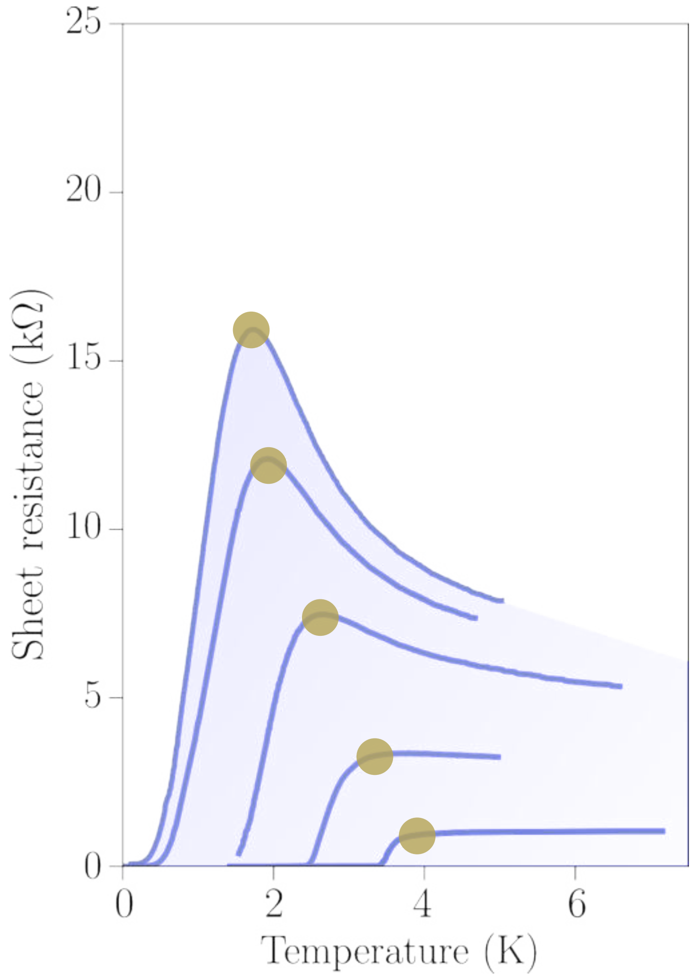
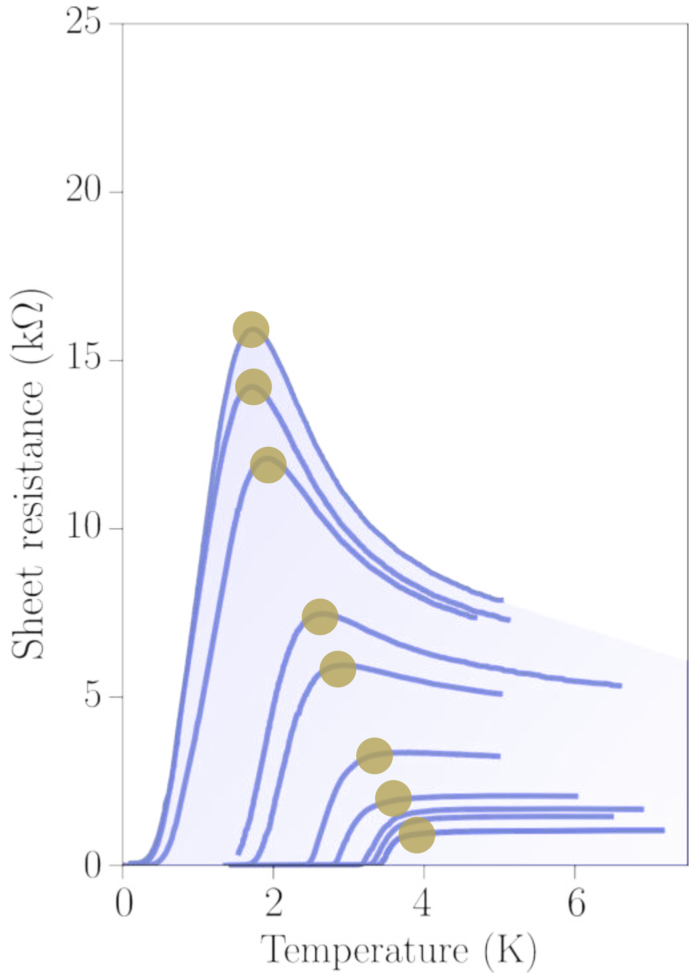


Resistance increases with disorder

Strongly disordered superconductor :

- **Short coherence length** $\xi \sim 5$ nm
- **Strong electron localization** $k_F l < 1$

Amorphous indium oxide

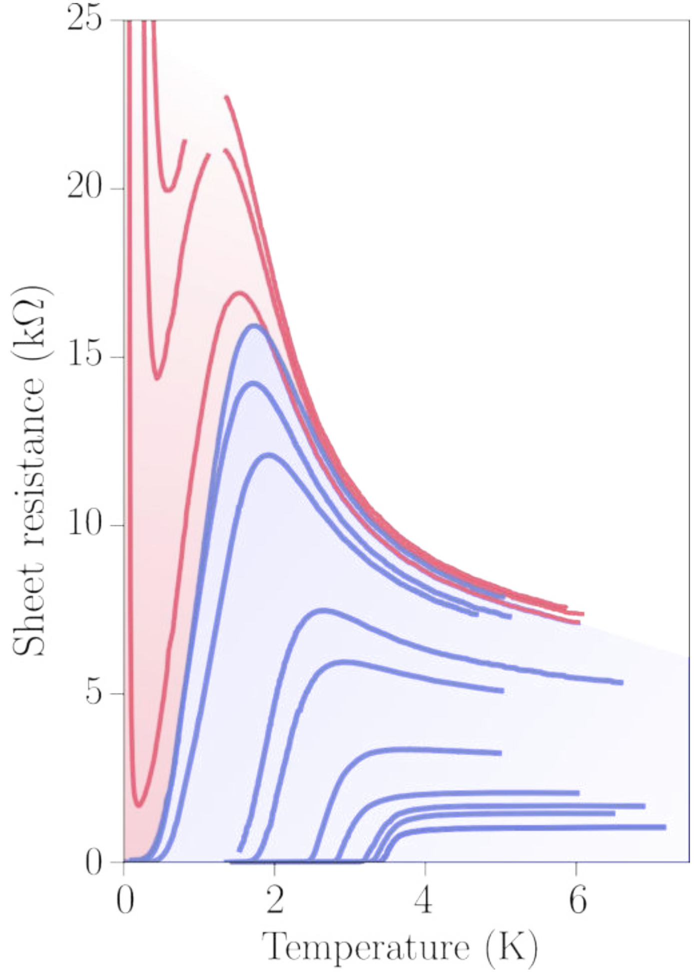


Anderson's theorem (conventional SCs are robust against disorder) does not apply here

Superconductivity is weakened by strong disorder

T_c decreases

Amorphous indium oxide



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Superconductivity is weakened by strong disorder

Above a critical disorder :
Superconductor-Insulator Transition

Review article : Sacépé, Feigel'man and Klapwijk, Nature Physics (2020)

The sample

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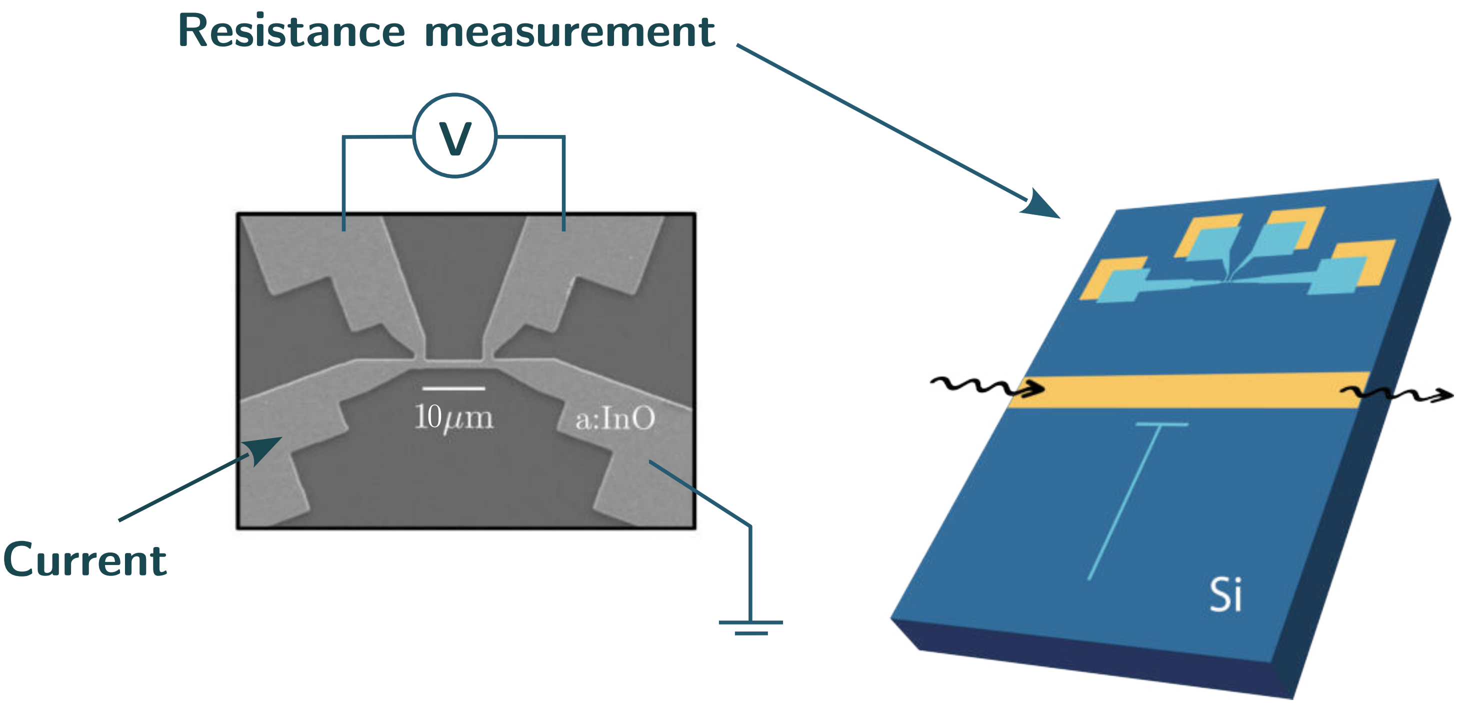
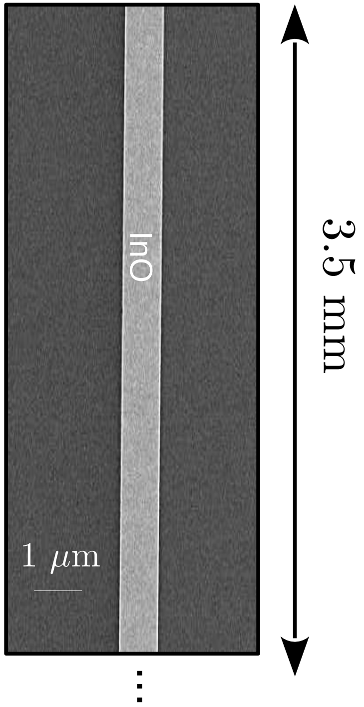


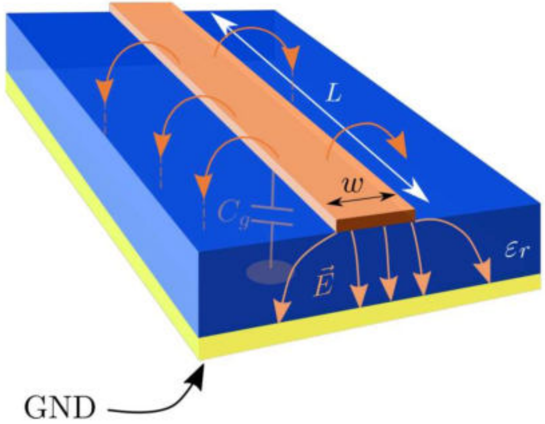
Microwave resonator

Long aInO resonator

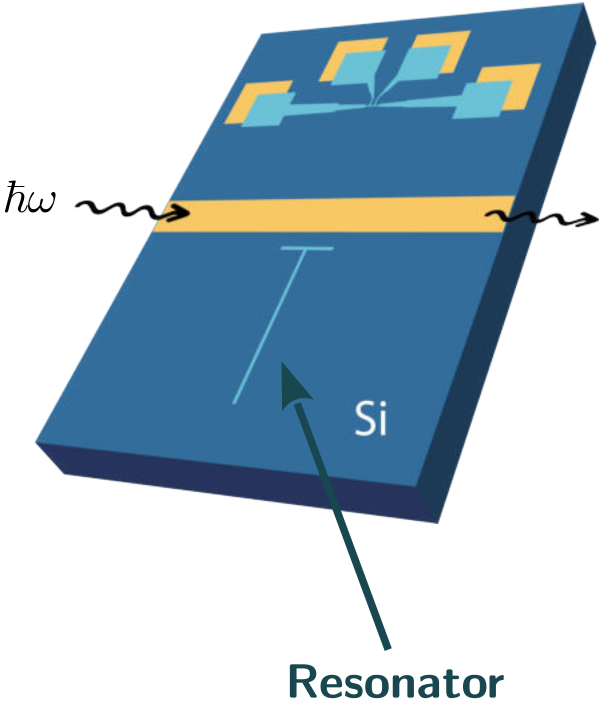


Kinetic inductance L_K

Microstrip geometry



Capacitance to ground C



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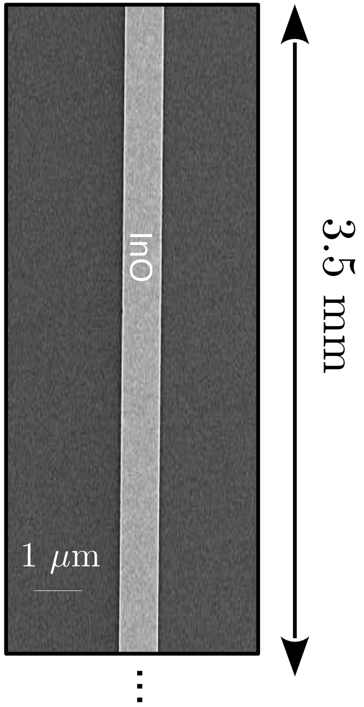

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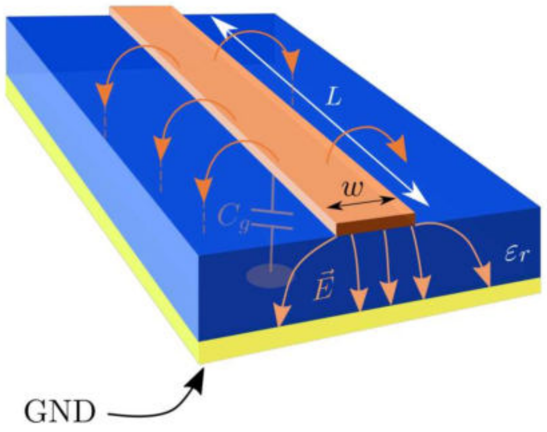


Capacitance to ground C

Plasmon standing wave resonances given by

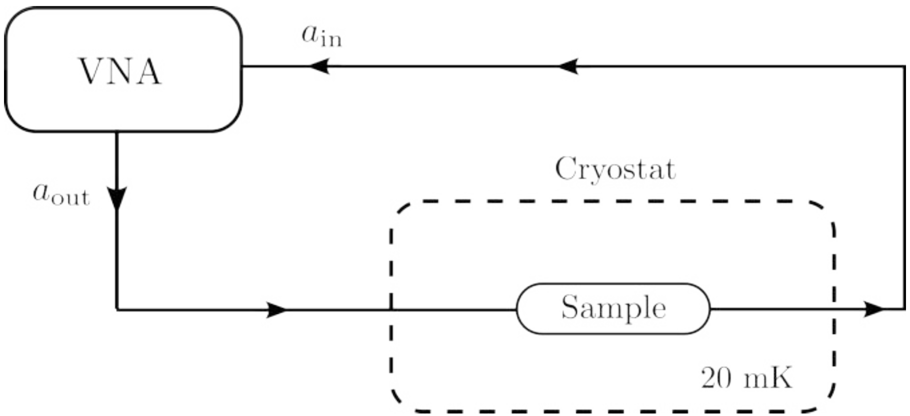
$$\omega_n = v|k_n| = \frac{|k_n|}{\sqrt{L_K C}}$$

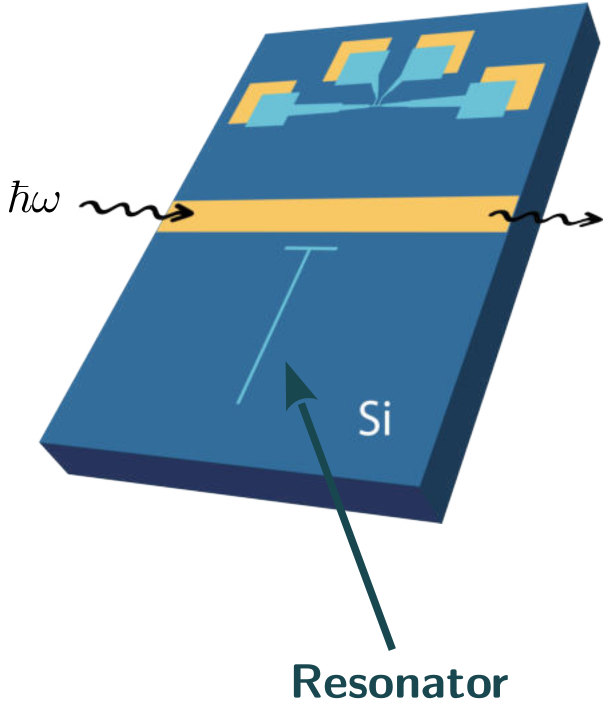
Kulik, ZETF (1973)
Mooij and Schön, PRL (1985)
Camarota et al, PRL (2001)

Microwave spectroscopy

Single-tone measurement (at T = 20 mK)

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





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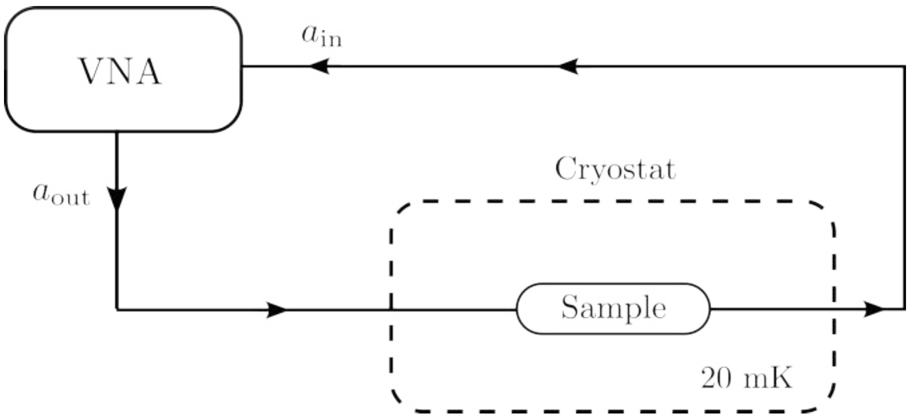

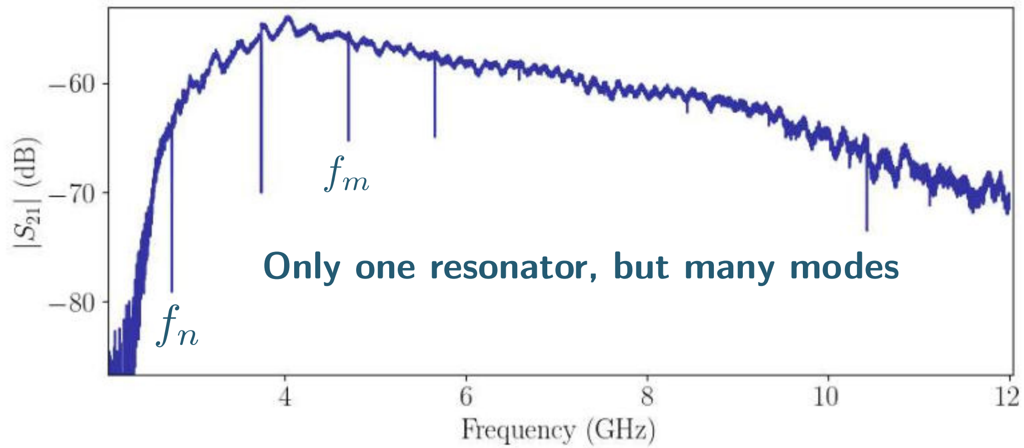

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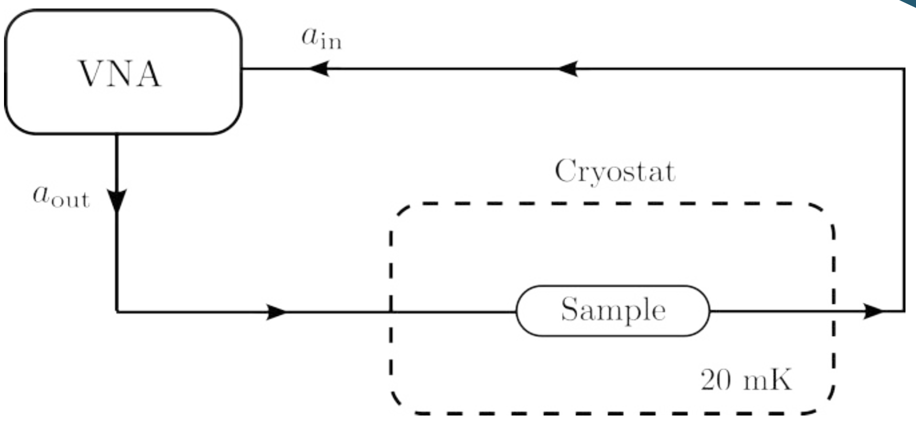
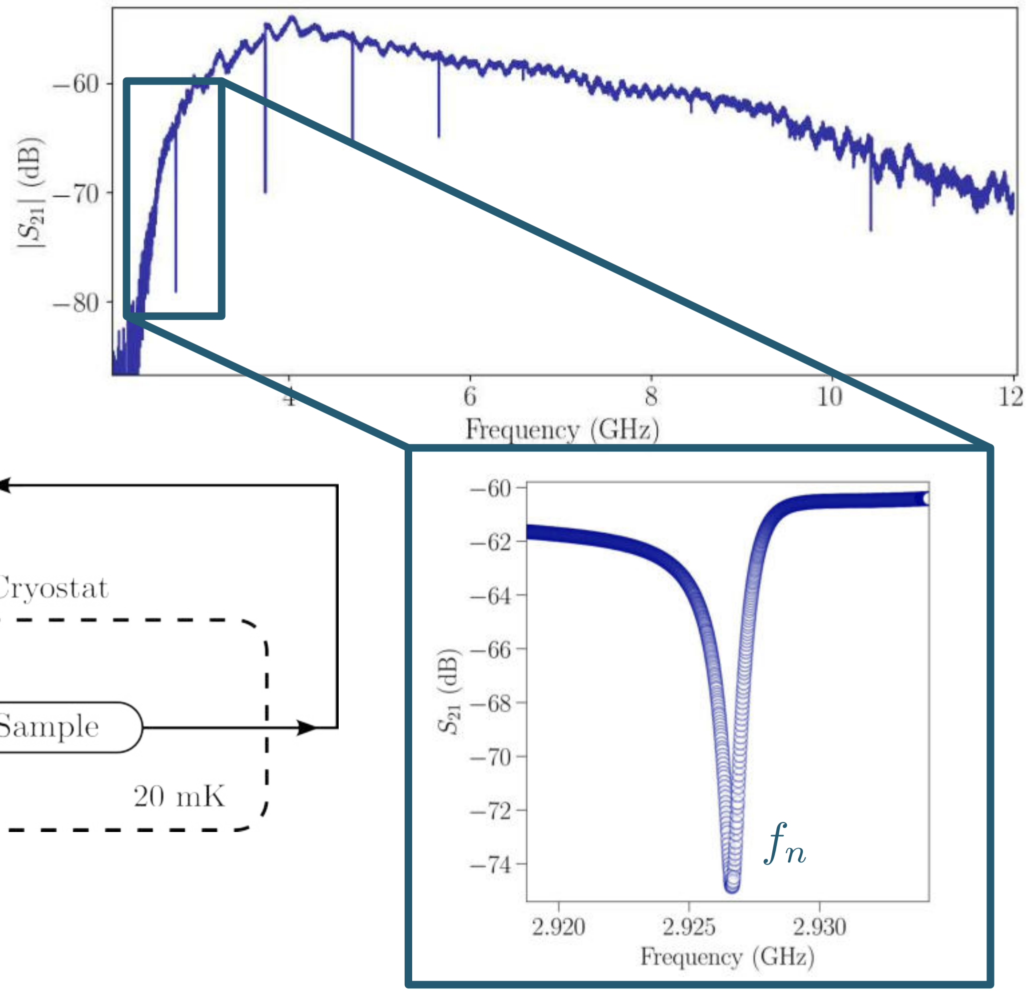
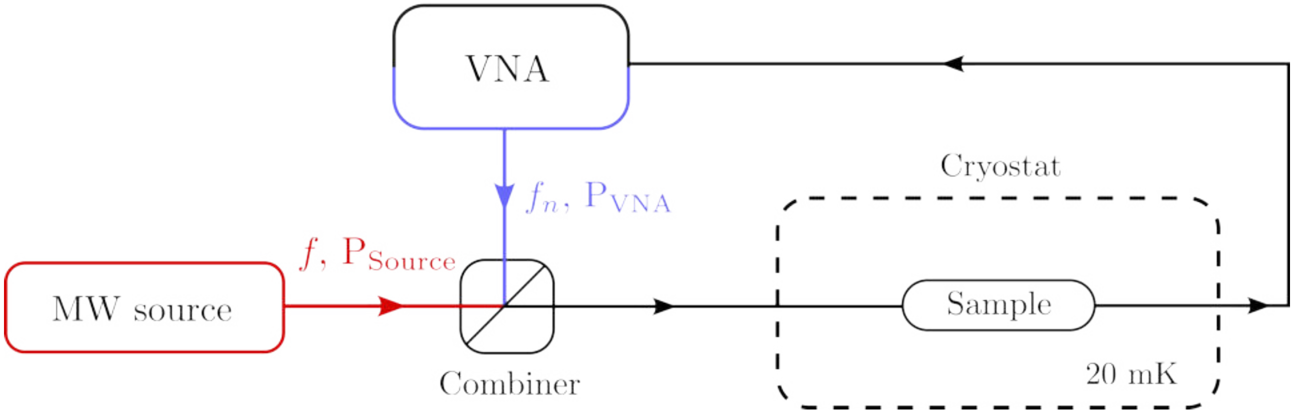




Two-tones spectroscopy

To measure modes between 0-30 GHz we perform a two-tones spectroscopy

We add a second tone to the VNA signal and exploit the resonator's non-linearities



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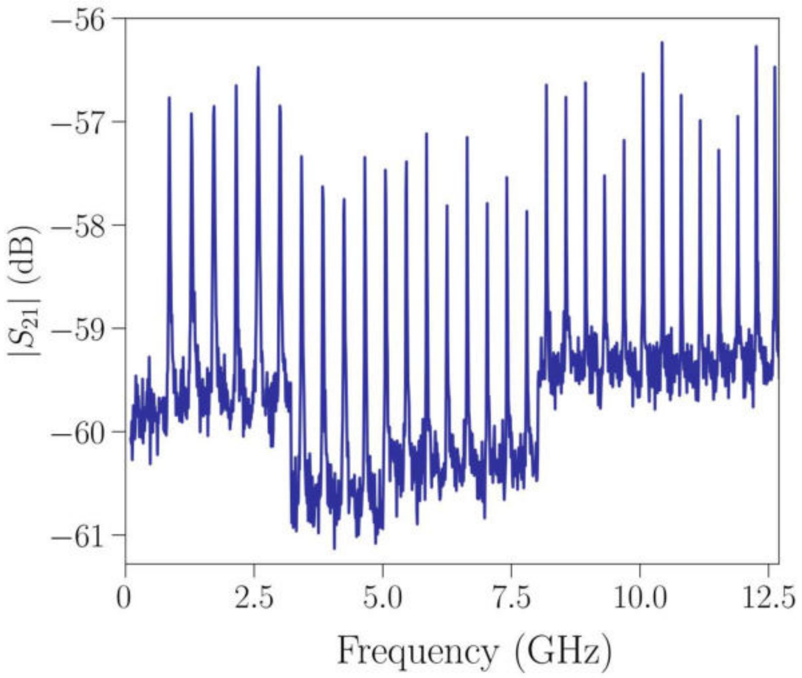
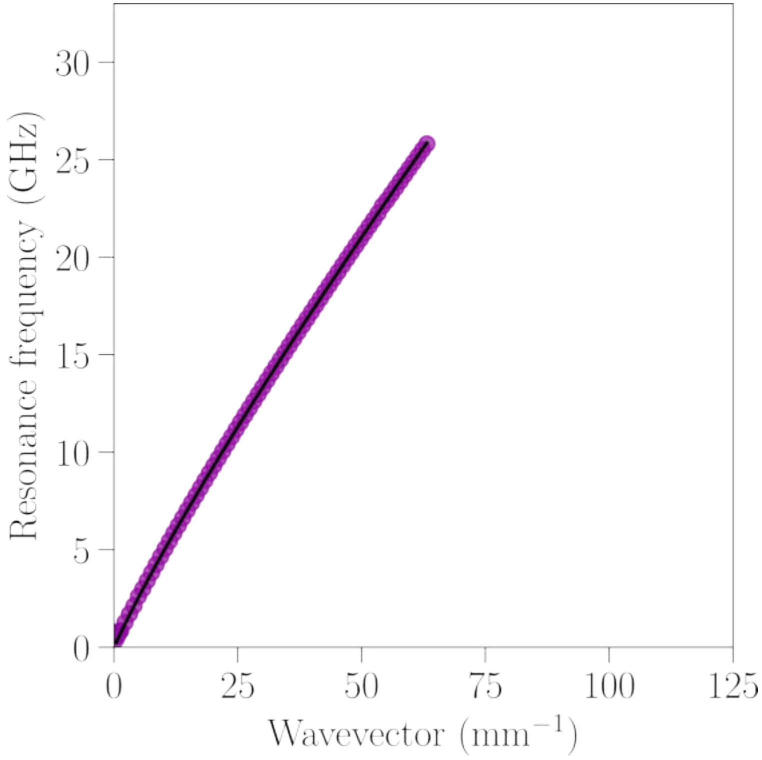


Each peak corresponds to a resonant mode of the Indium oxide resonator

$$\omega_n = \frac{|k_n|}{\sqrt{L_K C}} \quad , n \in \mathbb{N}$$

Plasmon dispersion relation

Dispersion relation $\omega(k)$



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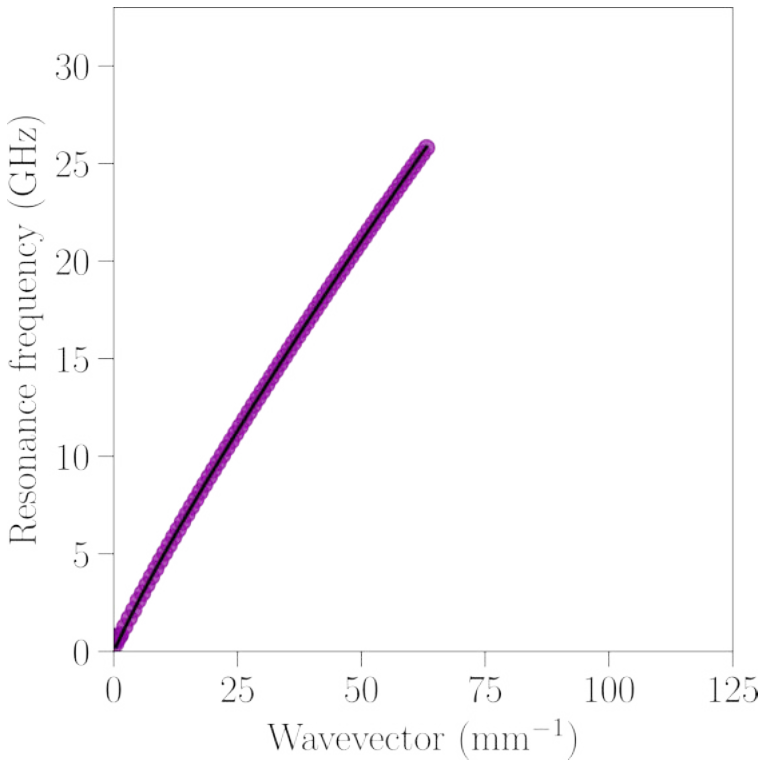
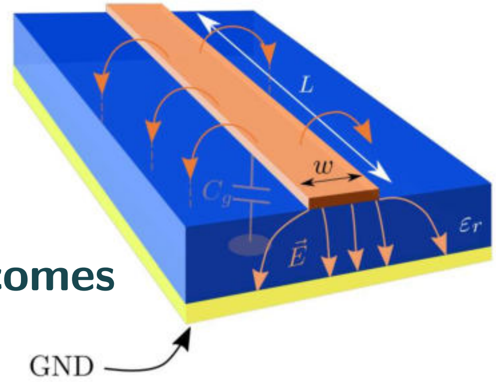


Remote ground plane :

Capacitance to ground becomes frequency-dependent $C(k)$



D. Basko, Private communications

Plasmon dispersion relation

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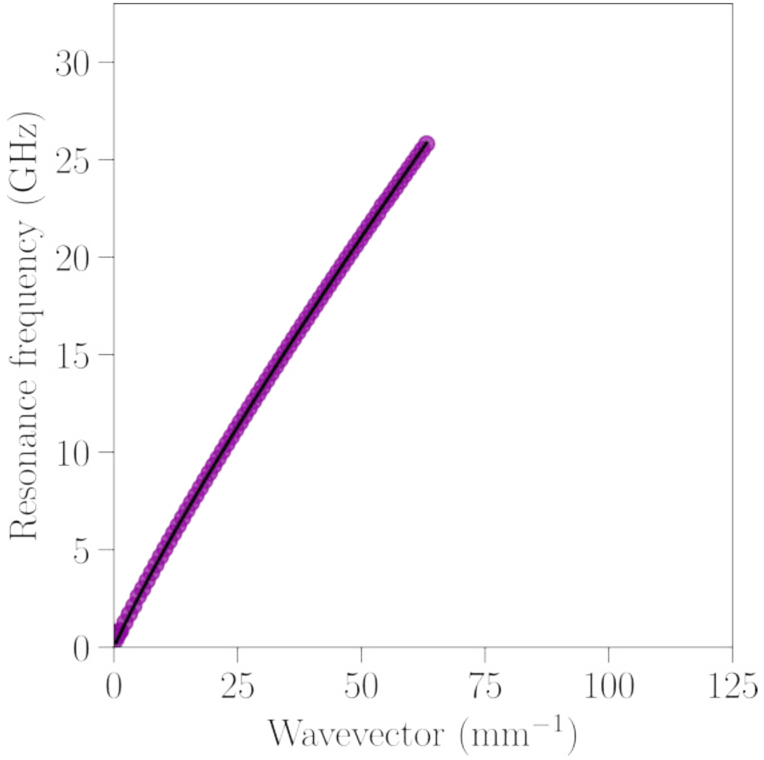
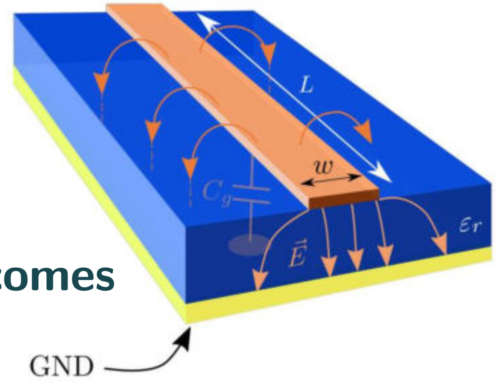


Remote ground plane :



Capacitance to ground becomes frequency-dependent $C(k)$

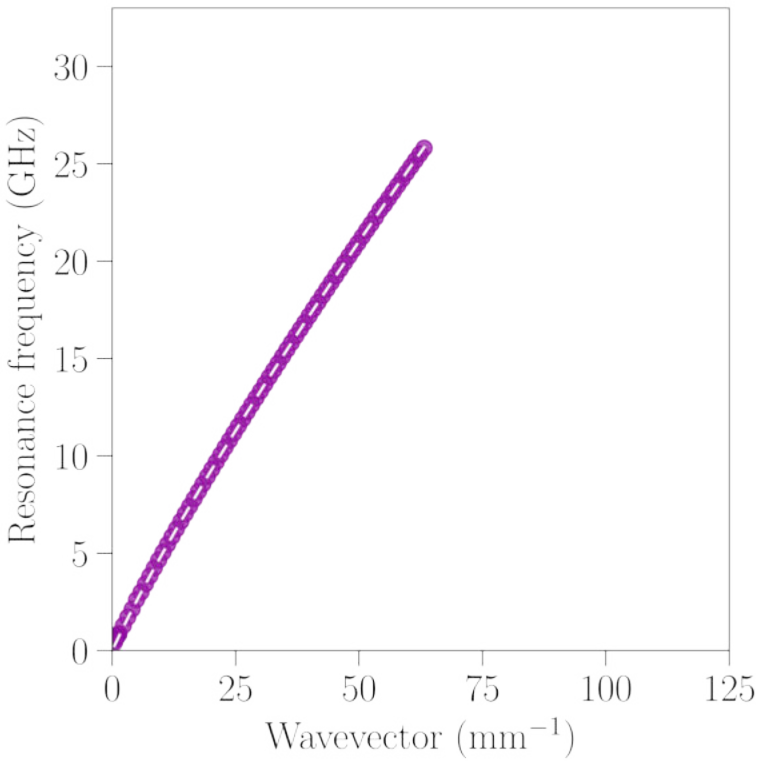
D. Basko, Private communications

Plasmon velocity slightly k-dependent

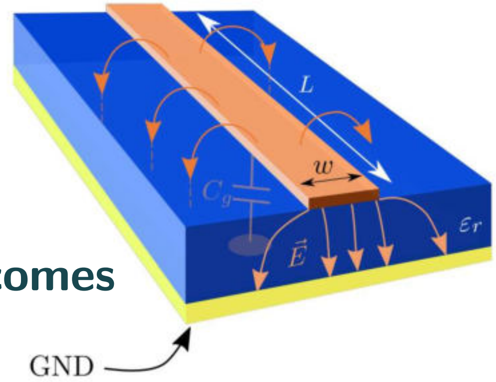
$$\omega(k) = \frac{|k|}{\sqrt{L_K C(k)}} = v(k)|k|$$

Plasmon dispersion relation

Dispersion relation $\omega(k)$



Remote ground plane :



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D. Basko, Private communications

Plasmon velocity slightly k-dependent

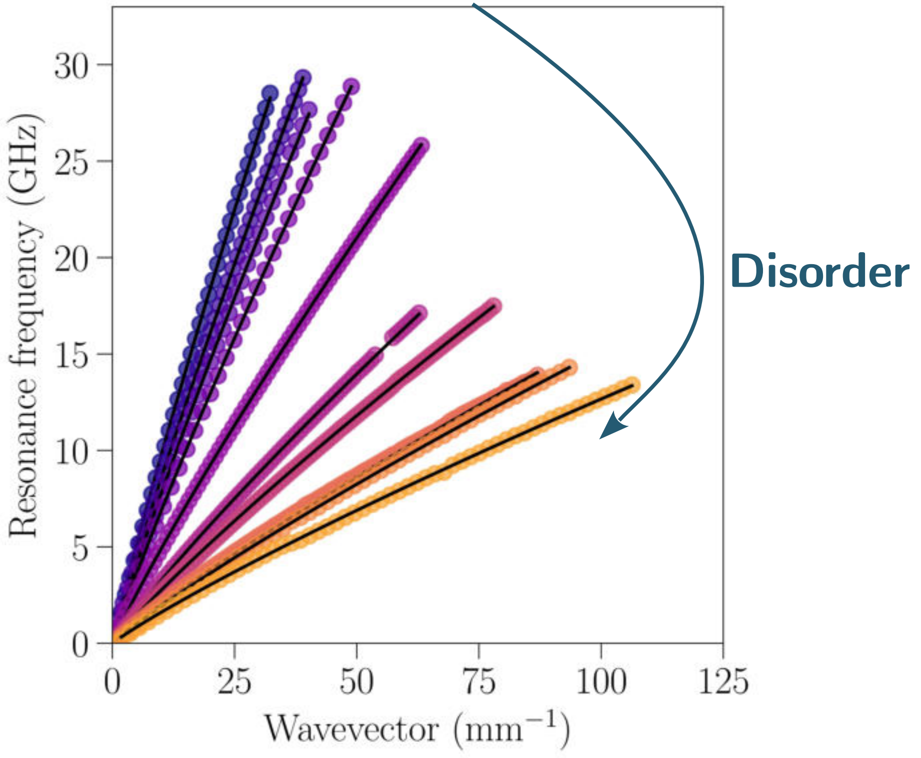
$$\omega(k) = \frac{|k|}{\sqrt{L_K C(k)}} = v(k)|k|$$

Only fitting parameter is L_K

Accurate determination of kinetic inductance

Plasmon dispersion relation

Dispersion relation $\omega(k)$

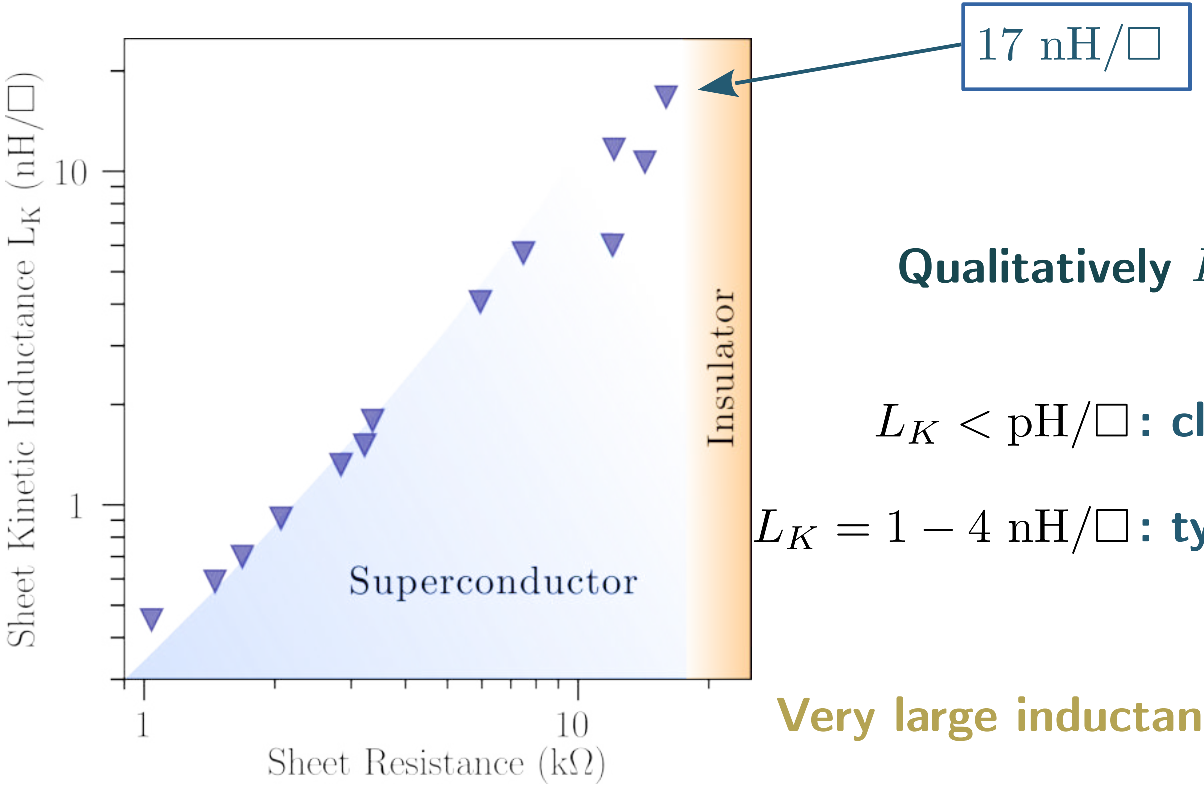


Extraction of kinetic inductance for increasing disorder

$$\omega(k) \propto \frac{1}{\sqrt{L_K}}$$

Slope decreases with disorder

Kinetic inductance



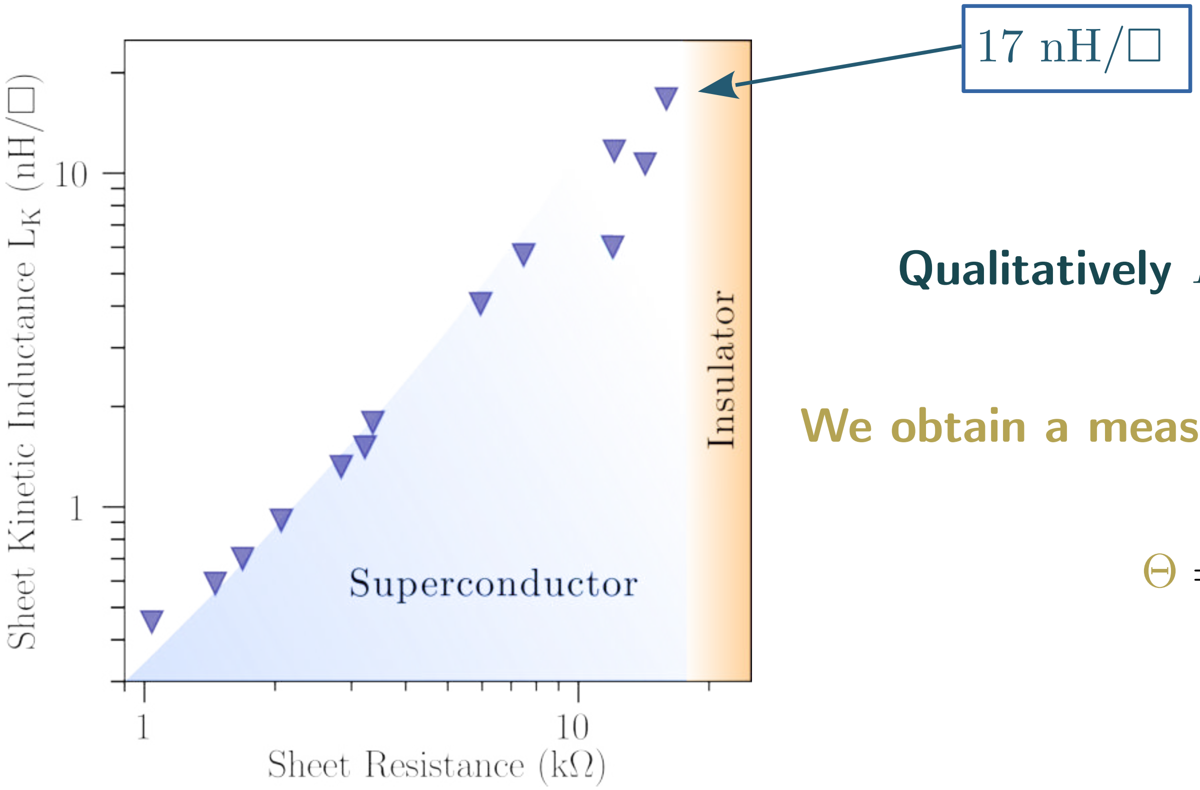
Qualitatively $L_K \approx \dfrac{\hbar R_n}{\pi \Delta}$

$L_K < \mathrm{pH}/\square$: **clean Aluminum films**

$L_K = 1 - 4\ \mathrm{nH}/\square$: **typical granular Al used for cQED**

Very large inductance : potential applications to cQED

Kinetic inductance

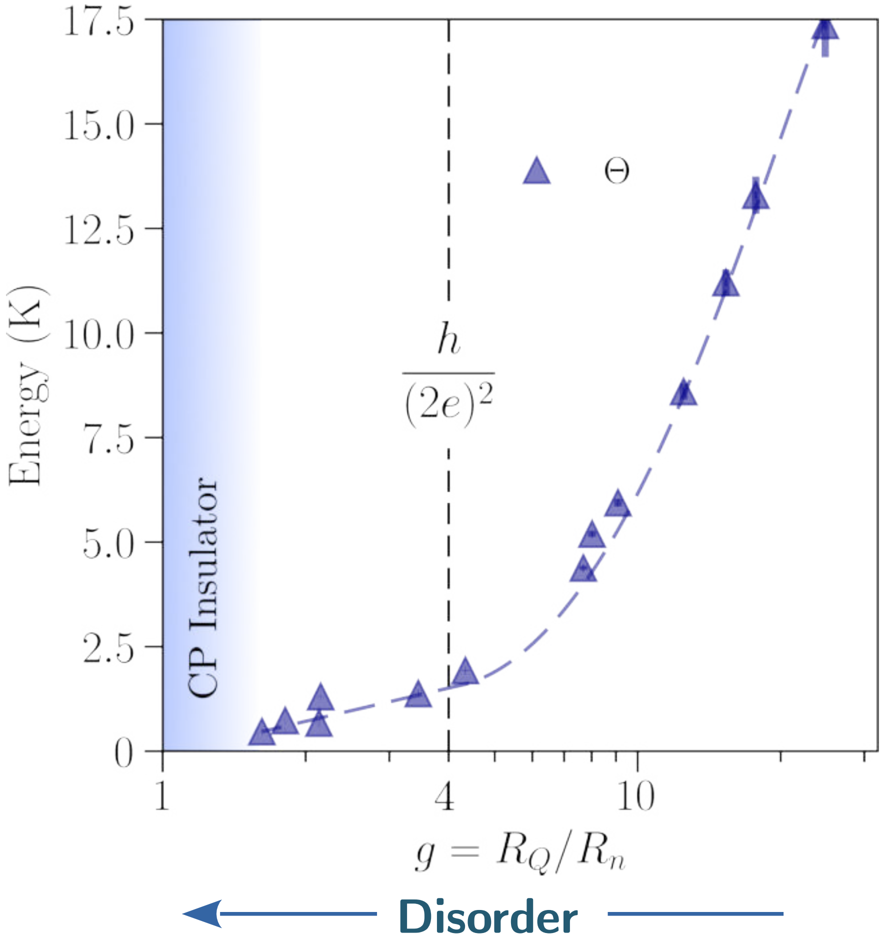


Qualitatively $L_K \approx \frac{\hbar R_n}{\pi \Delta}$

We obtain a measurement of the superfluid stiffness

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

Superconductor ruled by phase fluctuations

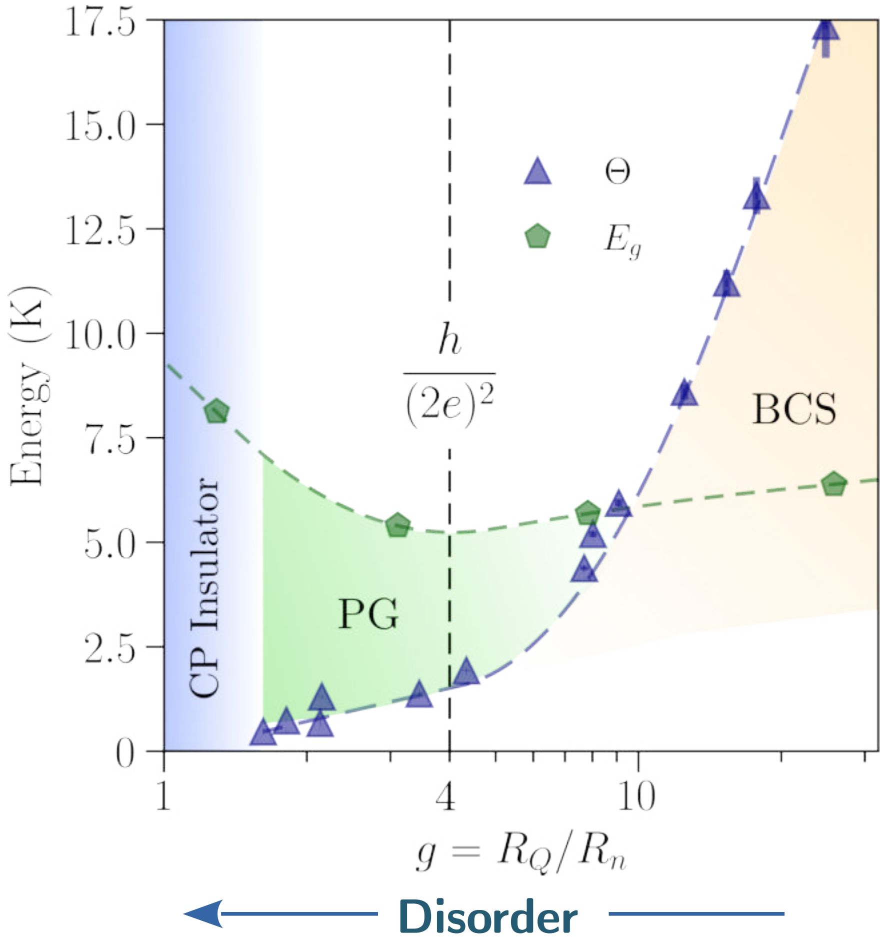


2D Superfluid stiffness

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

BCS theory : $\Theta = \frac{1}{8} g\Delta$

Superconductor ruled by phase fluctuations



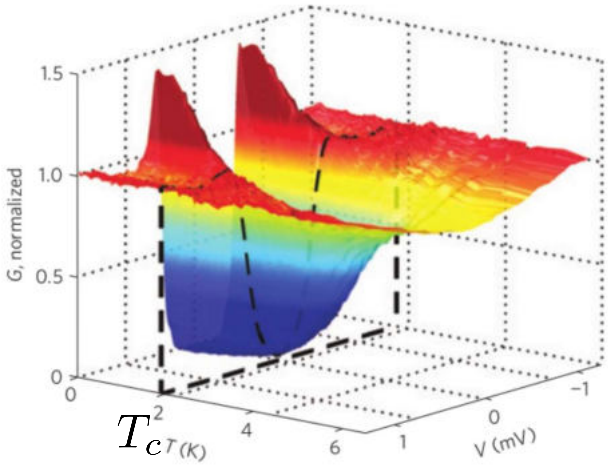
E_g = single particle gap

from tunneling measurement

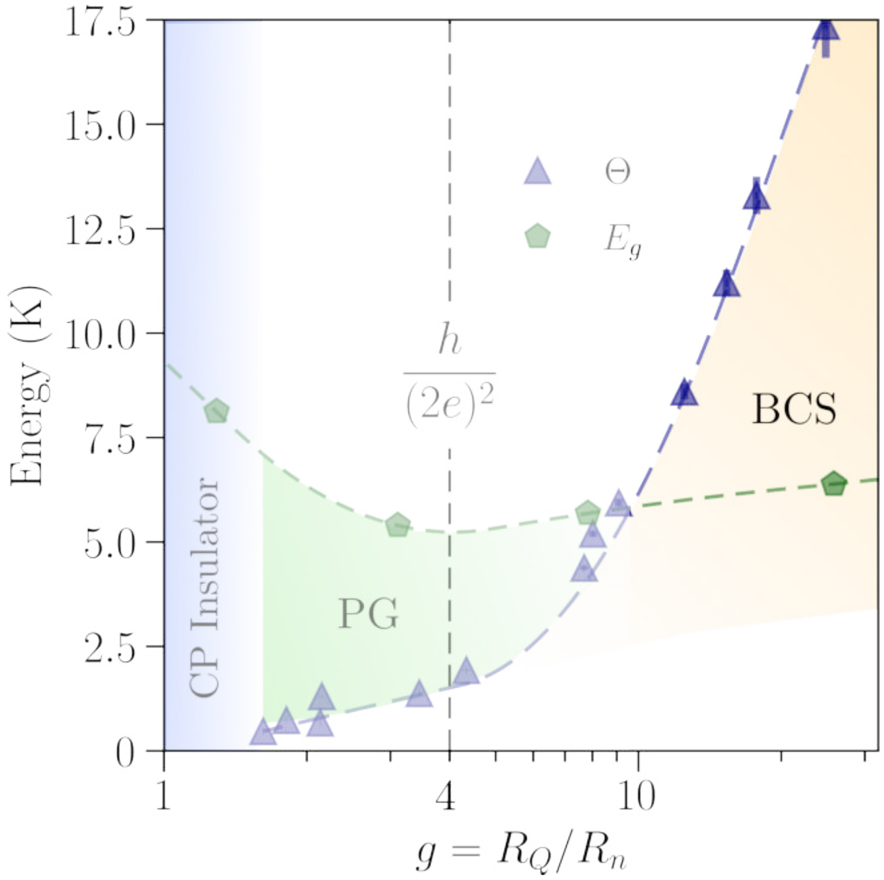
Sacépé et al, Nature Physics (2011)

Sherman et al, PRB (2014)

Sacépé et al, PRB (2015)



Superconductor ruled by phase fluctuations



Disorder

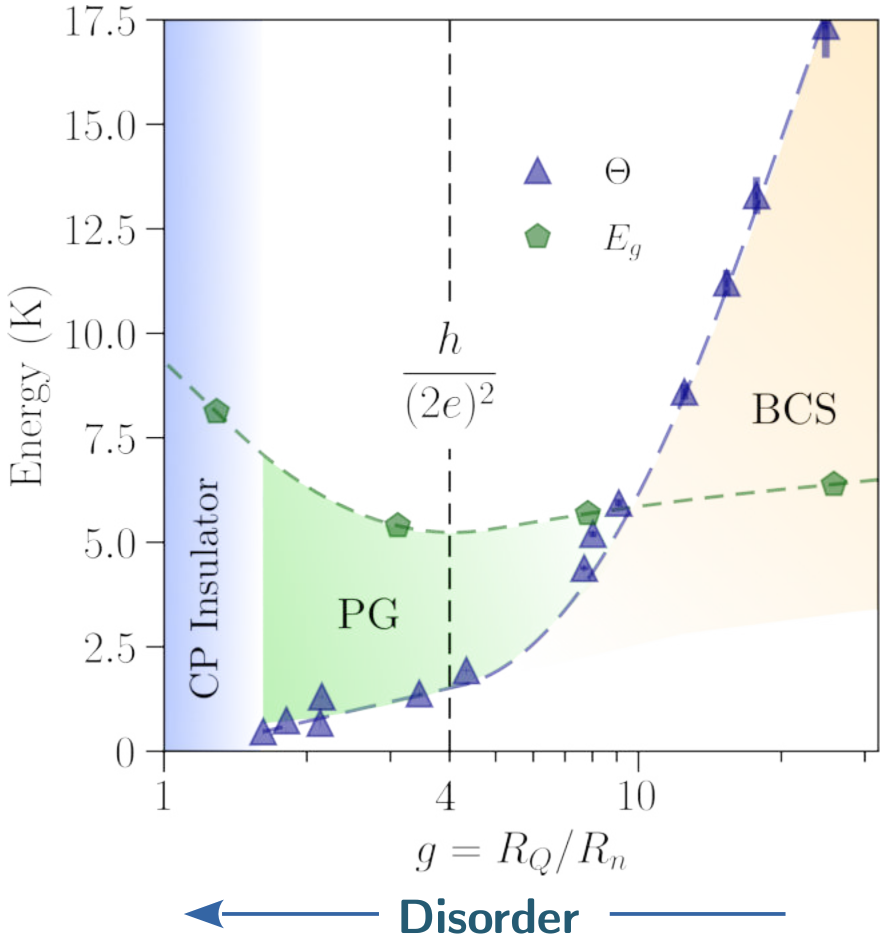
E_g = single particle gap from tunneling measurement

Sacépé et al, Nature Physics (2011)
Sherman et al, PRB (2014)
Sacépé et al, PRB (2015)

$\Theta \gg E_g = \Delta$: BCS superconductor

Phase fluctuations can be neglected

Superconductor ruled by phase fluctuations



E_g = single particle gap
from tunneling measurement

Sacépé et al, Nature Physics (2011)
Sherman et al, PRB (2014)
Sacépé et al, PRB (2015)

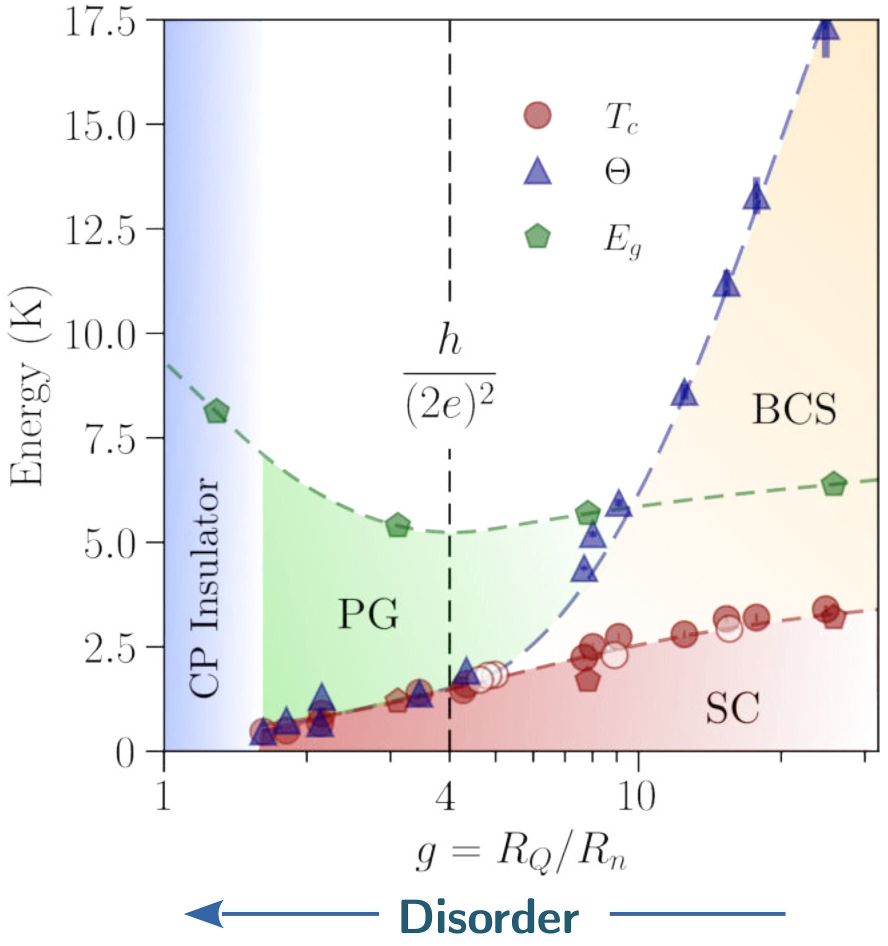
$\Theta \gg E_g = \Delta$: BCS superconductor

Phase fluctuations can be neglected

$\Theta \leq E_g$: Pseudo-gap superconductor

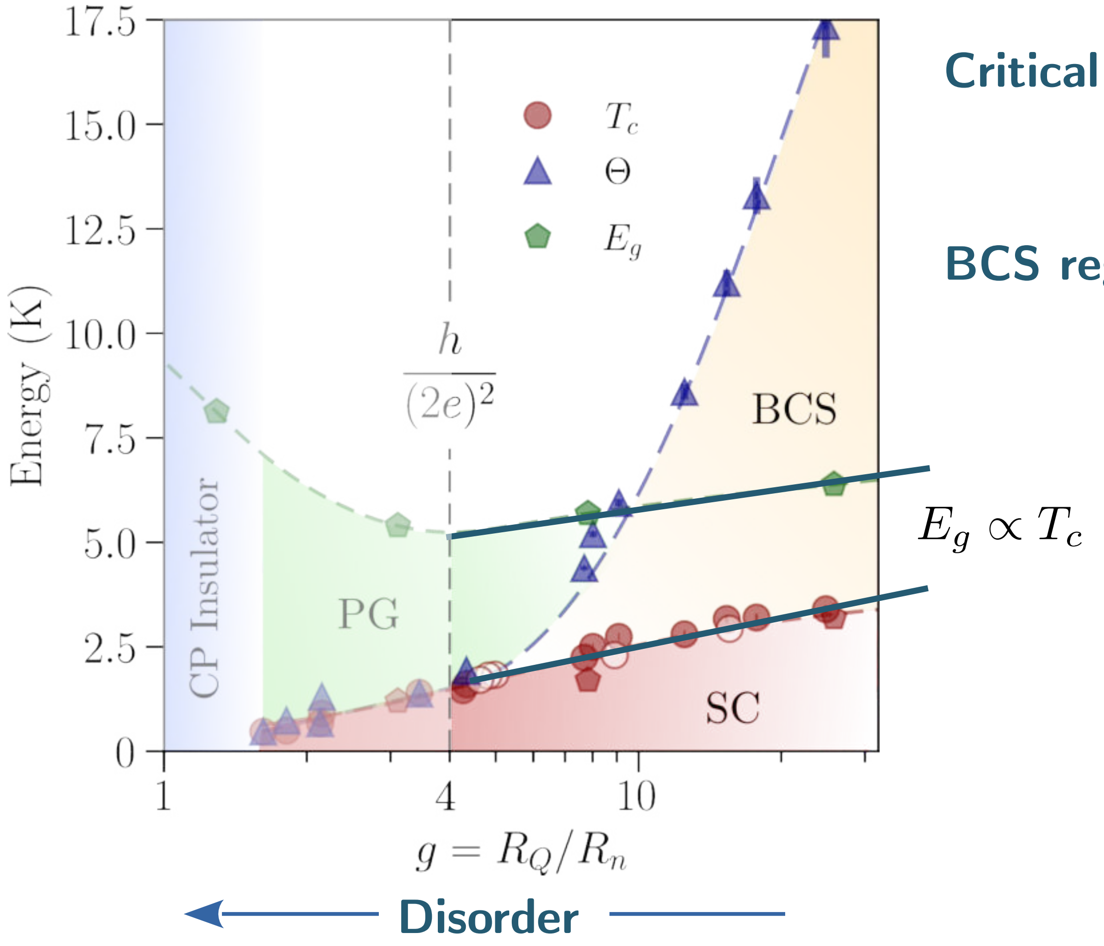
Phase fluctuations become predominant

Superconductor ruled by phase fluctuations



Critical temperature T_c from DC measurements

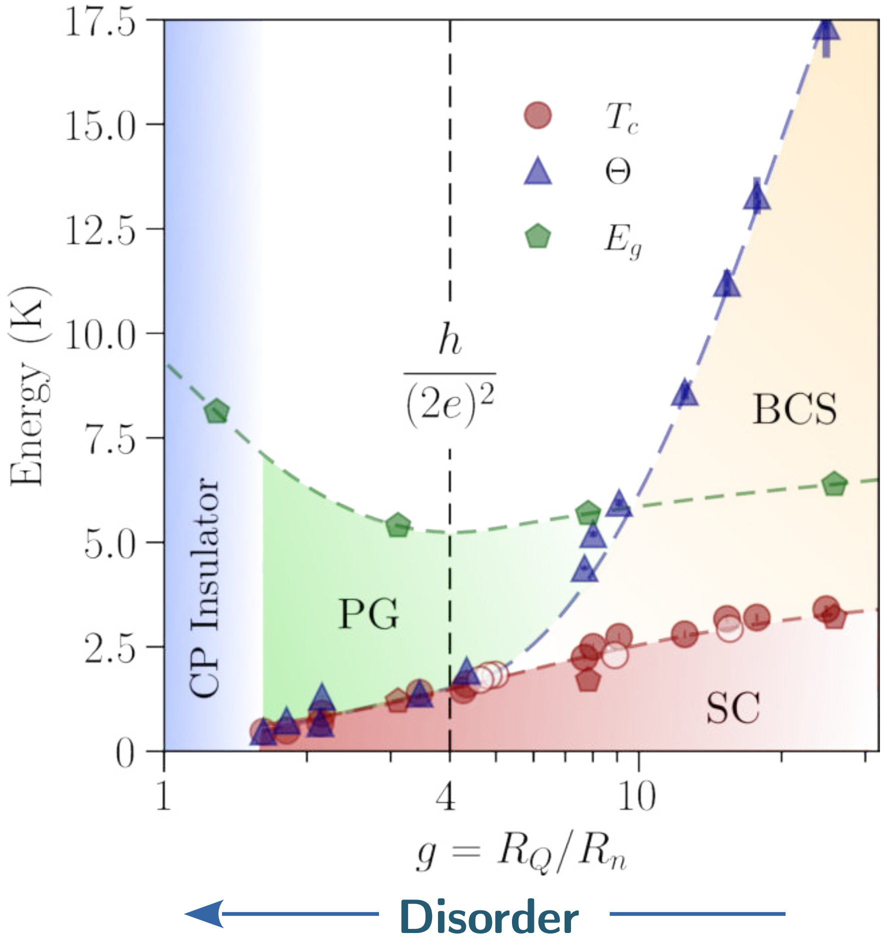
Superconductor ruled by phase fluctuations



Critical temperature T_c from DC measurements

BCS region : T_c defined by pairing $E_g \sim 2k_BT_c$

Superconductor ruled by phase fluctuations



Critical temperature T_c from DC measurements

BCS region : T_c defined by pairing $E_g \sim 2k_BT_c$

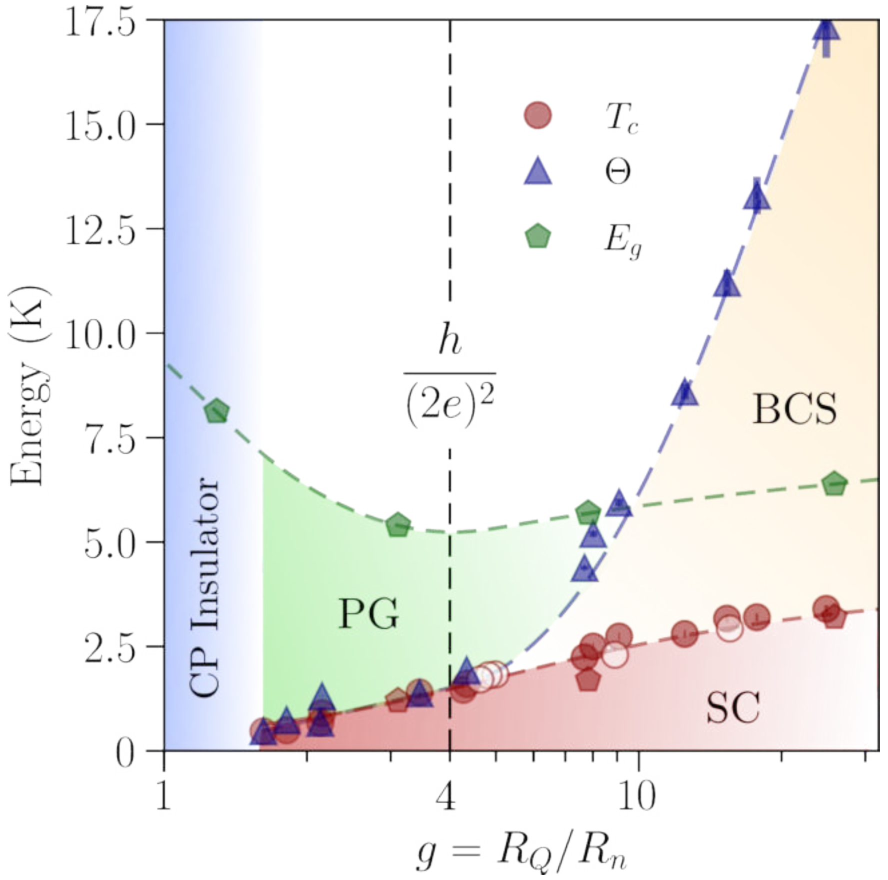
Pseudo-gap region : T_c defined by Θ

$$T_c = \Theta$$

Superconductivity ruled by phase fluctuations

Emery and Kivelson, Nature (1995)

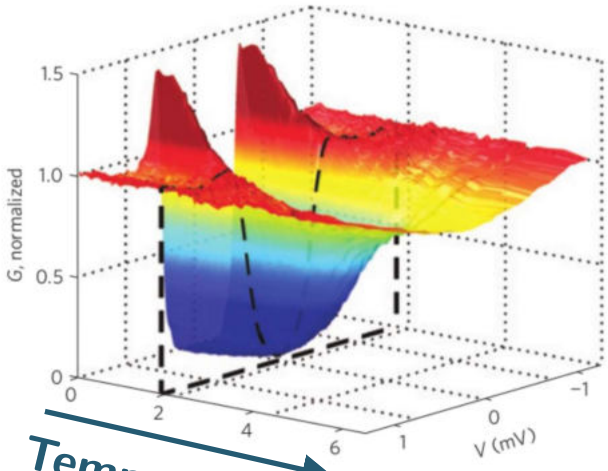
Superconductor ruled by phase fluctuations



Disorder

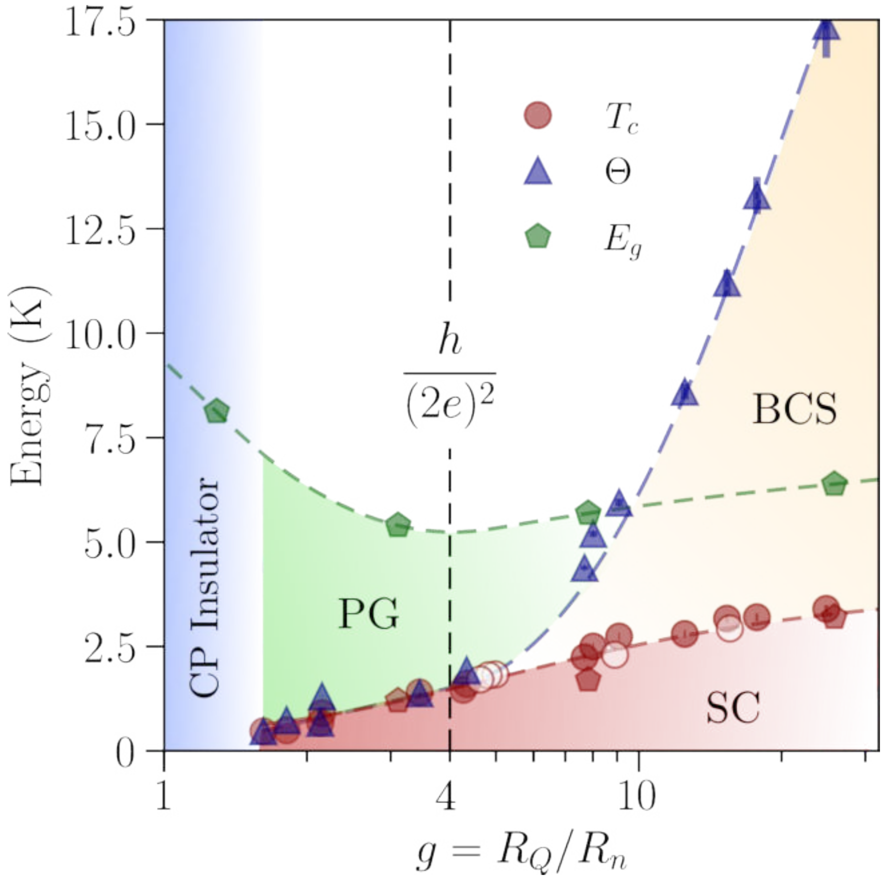
In the pseudo-gap region $T_c = \Theta$

DOS versus temperature



Temperature

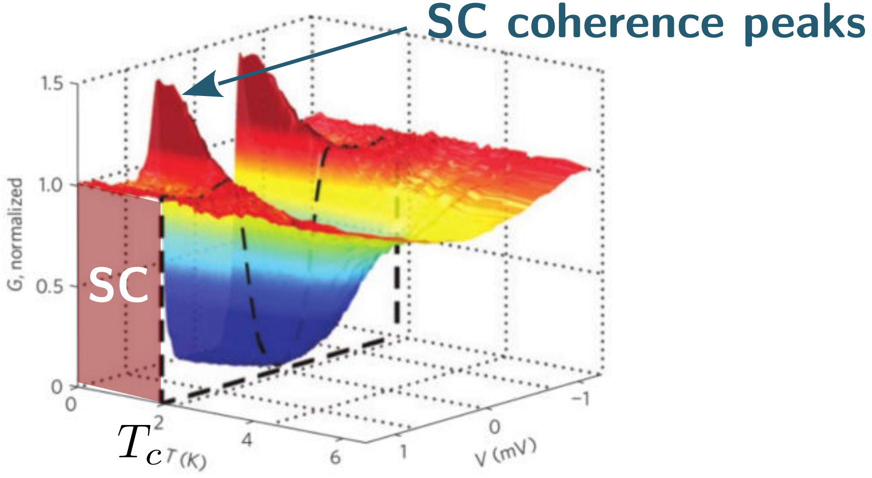
Superconductor ruled by phase fluctuations



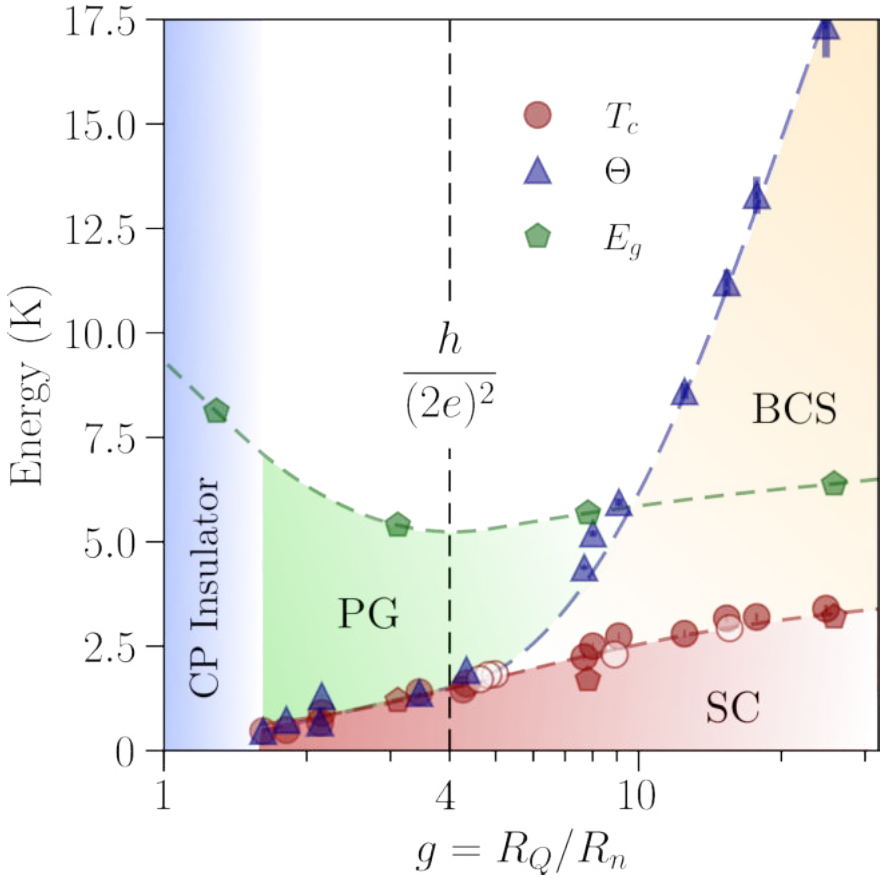
← Disorder

In the pseudo-gap region $T_c = \Theta$

DOS versus temperature



Superconductor ruled by phase fluctuations



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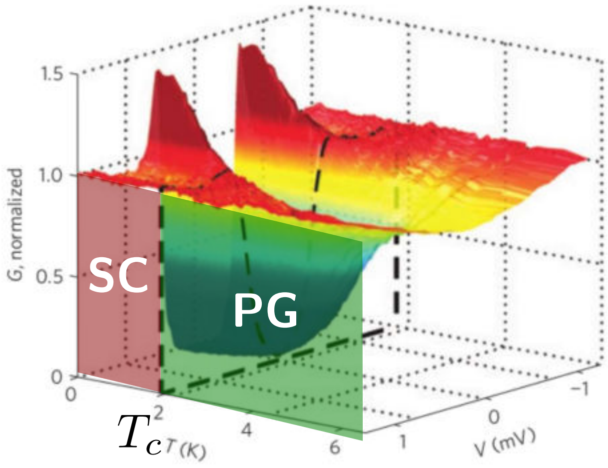
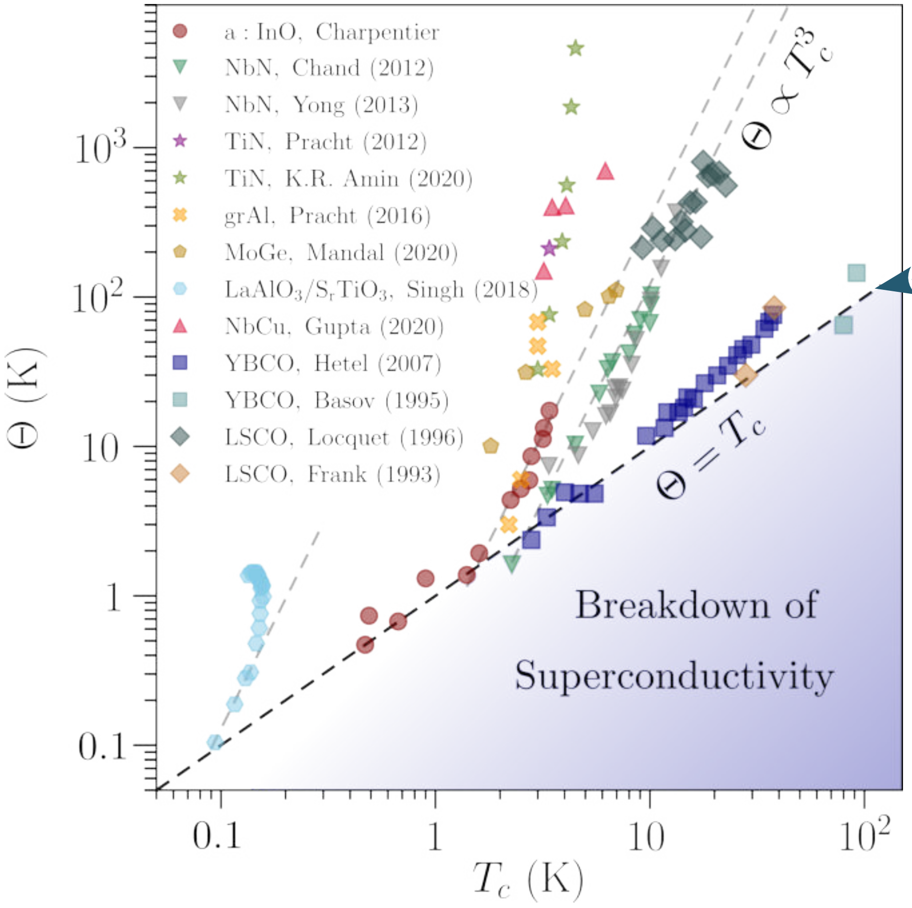


Pseudogap

Role of phase fluctuations in low-density SCs



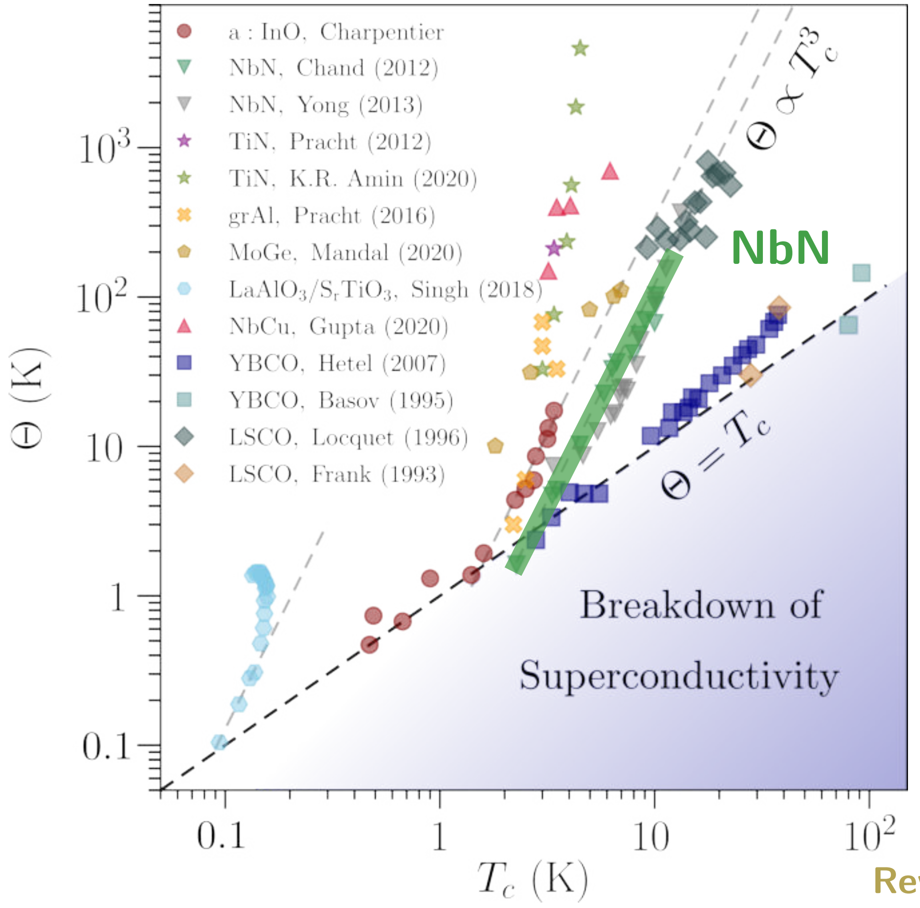
Critical line $\Theta = T_c$

Emery and Kivelson, Nature (1995)

Review article :

Raychaudhuri and Dutta, Journal of Physics: Cond. Mat. (2021)

Role of phase fluctuations in low-density SCs



PHYSICAL REVIEW B **85**, 014508 (2012)

NbN

Phase diagram of the strongly disordered *s*-wave superconductor NbN close to the metal-insulator transition

Madhavi Chand,[1] Garima Saraswat,[1] Anand Kamlapure,[1] Mintu Mondal,[1] Sanjeev Kumar,[1] John Jesudasan,[1] Vivas Bagwe,[1] Lara Benfatto,[2] Vikram Tripathi,[1] and Pratap Raychaudhuri[1,*]

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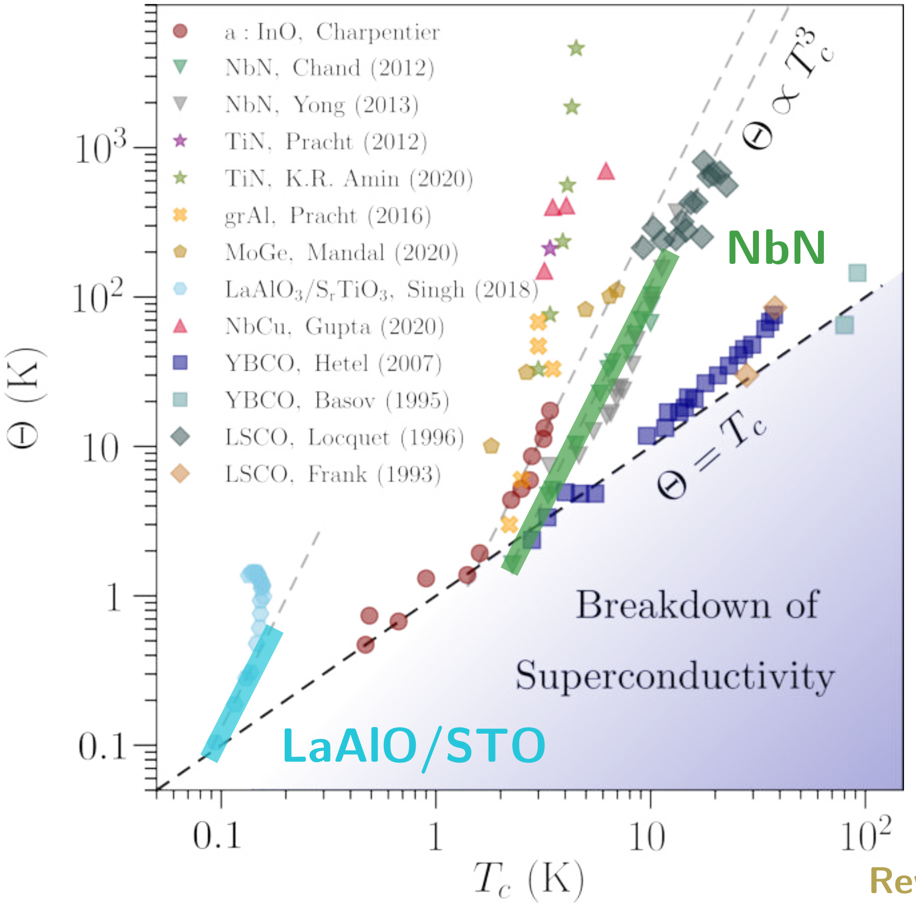

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nature COMMUNICATIONS

LaAlO/STO

ARTICLE

DOI: 10.1038/s41467-018-02907-8 OPEN

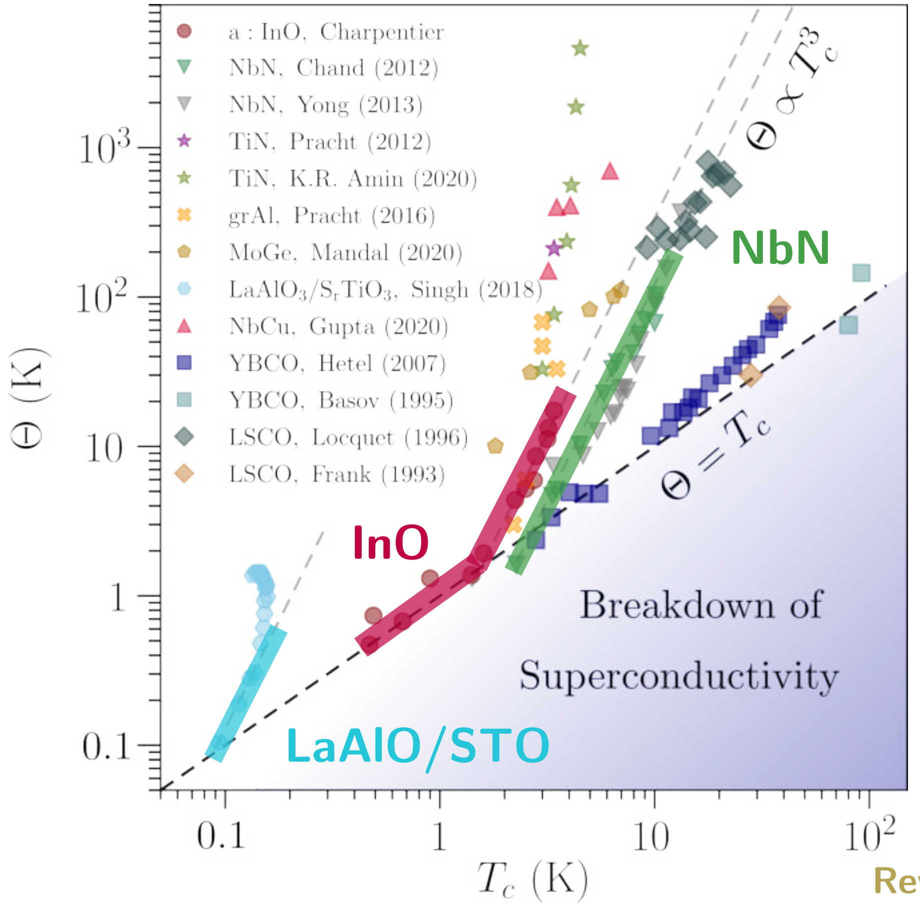
Competition between electron pairing and phase coherence in superconducting interfaces

G. Singh[1,2], A. Jouan[1,2], L. Benfatto[3,4], F. Couëdo[1,2], P. Kumar[5], A. Dogra[5], R.C. Budhani[6], S. Caprara[3,4] M. Grilli[3,4], E. Lesne[7], A. Barthélémy[7], M. Bibes[7], C. Feuillet-Palma[1,2], J. Lesueur[1,2] & N. Bergeal[1,2]

But also grAl, high-T_c superconductors ...

Review article :
Raychaudhuri and Dutta, Journal of Physics: Cond. Mat. (2021)

Role of phase fluctuations in low-density SCs



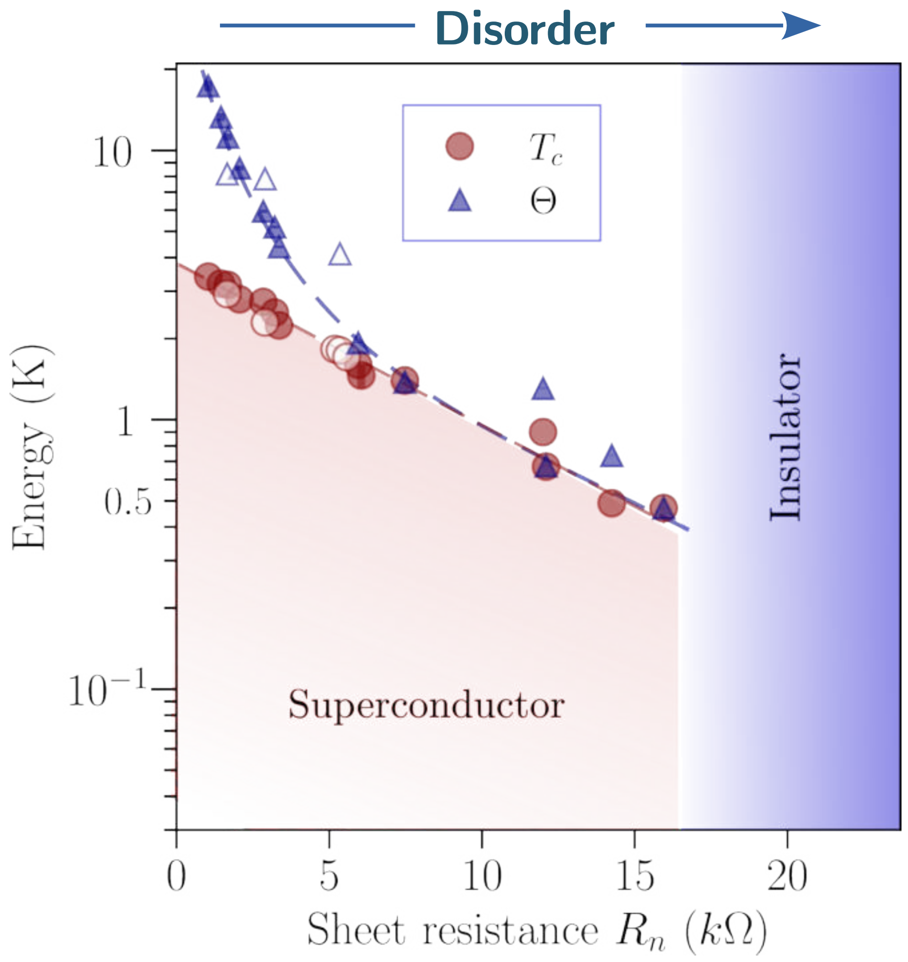
And Indium oxide

Review article :
Raychaudhuri and Dutta, Journal of Physics: Cond. Mat. (2021)

Nature of the T=0 phase transition ?

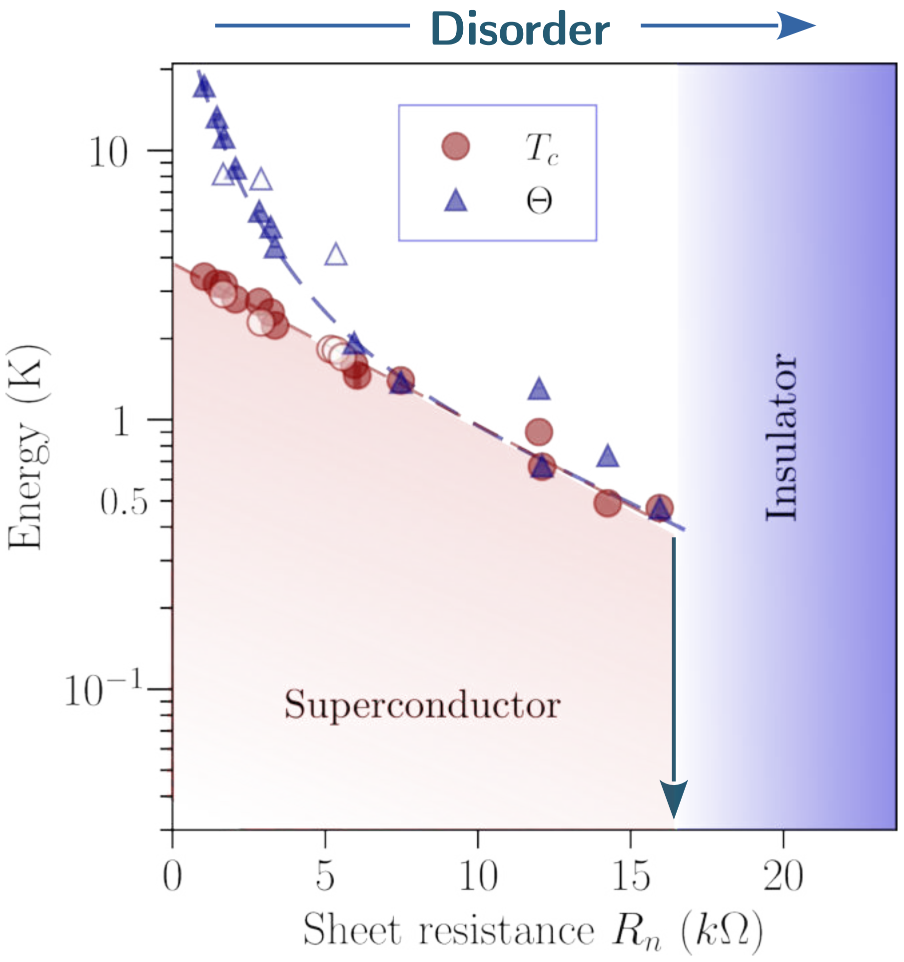
Superconductor-Insulator quantum phase transition driven by disorder

Nature of the T=0 phase transition



T_c and Θ versus R in log scale

Nature of the T=0 phase transition

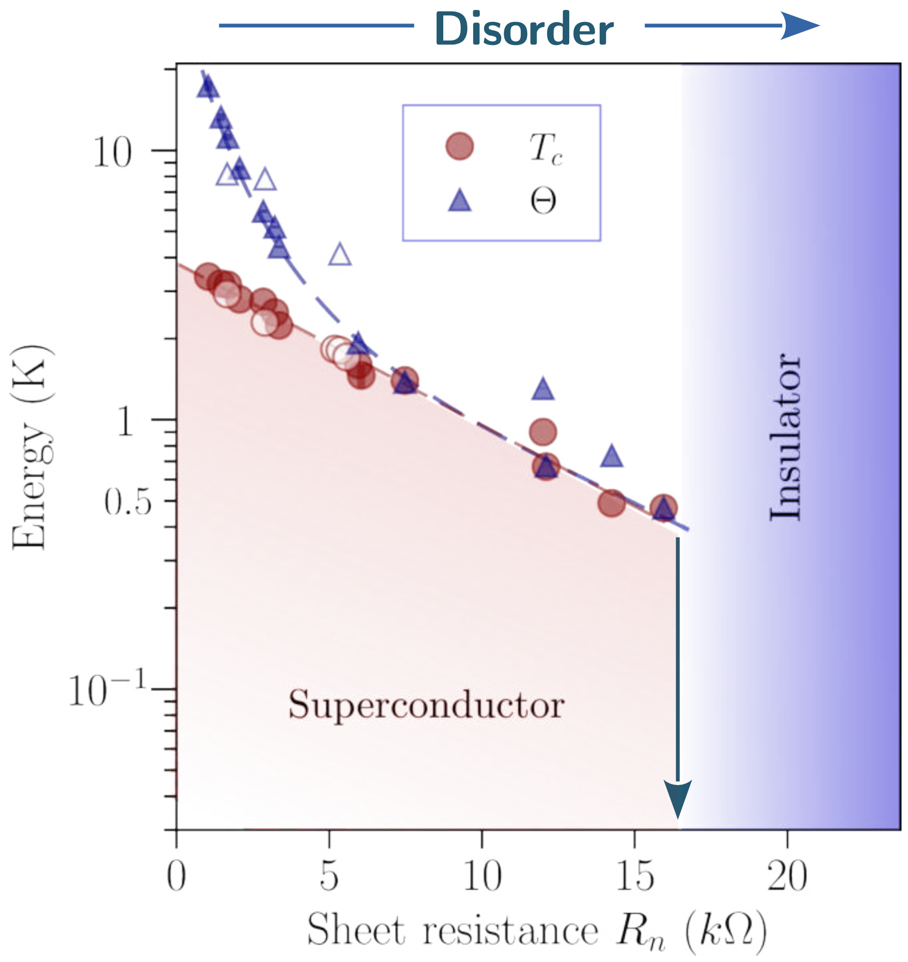


Θ and T_c are finite at SIT

$$T_c \sim \Theta \sim 0.5 \text{ K}$$

Abrupt drop of T_c and Θ at the critical disorder

Nature of the T=0 phase transition



Θ and T_c are finite at SIT

$$T_c \sim \Theta \sim 0.5\ \mathrm{K}$$

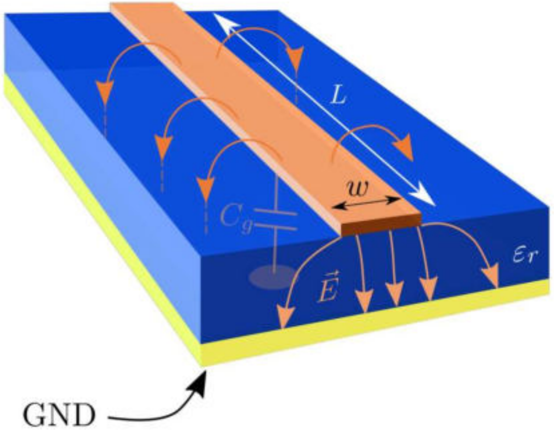
Abrupt drop of T_c and Θ at the critical disorder

Why this jump ?

First idea : quantum BKT transition in (1+1)D

(1+1)D BKT transition

1D plasmons



Our wires are 1D with respect to plasmon modes

$w = 1\ \mu\text{m}$

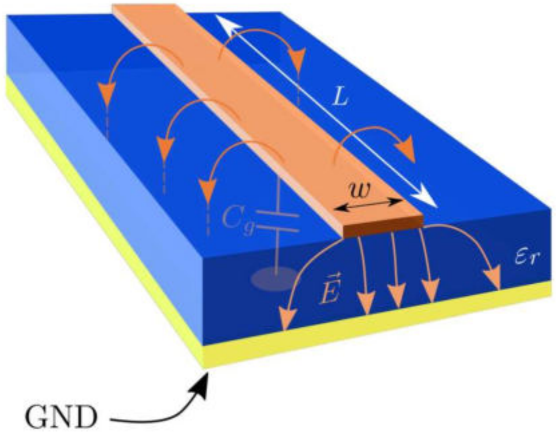
$d = 40\ \text{nm}$ → $\lambda_L \gg wd$

$L = 3.5\ \text{mm}$

1D Coulomb potential

(1+1)D BKT transition

1D plasmons



$w = 1\ \mu\mathrm{m}$

$d = 40$ nm → $\lambda_L \gg wd$

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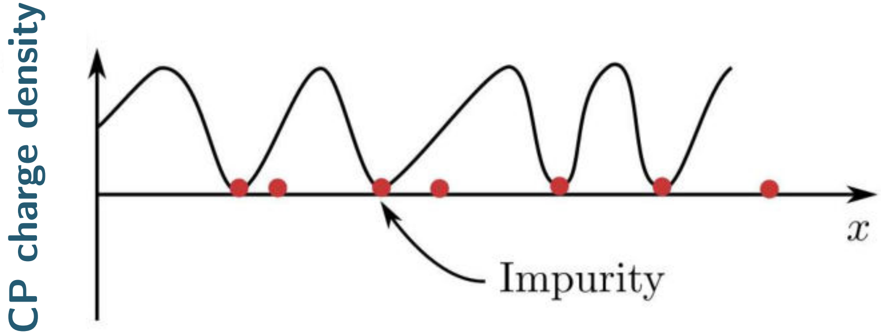
1D Coulomb potential

Pinning of plasmons by disorder



Giamarchi and Schulz, PRB (1988)

(1+1)D BKT transition

Wave impedance

$$Z = \sqrt{\frac{L_K^{\square}}{wC'}}$$

Superfluid to Bose glass transition (1+1)D BKT

$$\boxed{Z_c = \frac{R_Q^S}{3}} \quad \text{where} \quad R_Q^S = \frac{h}{(2e)^2}$$

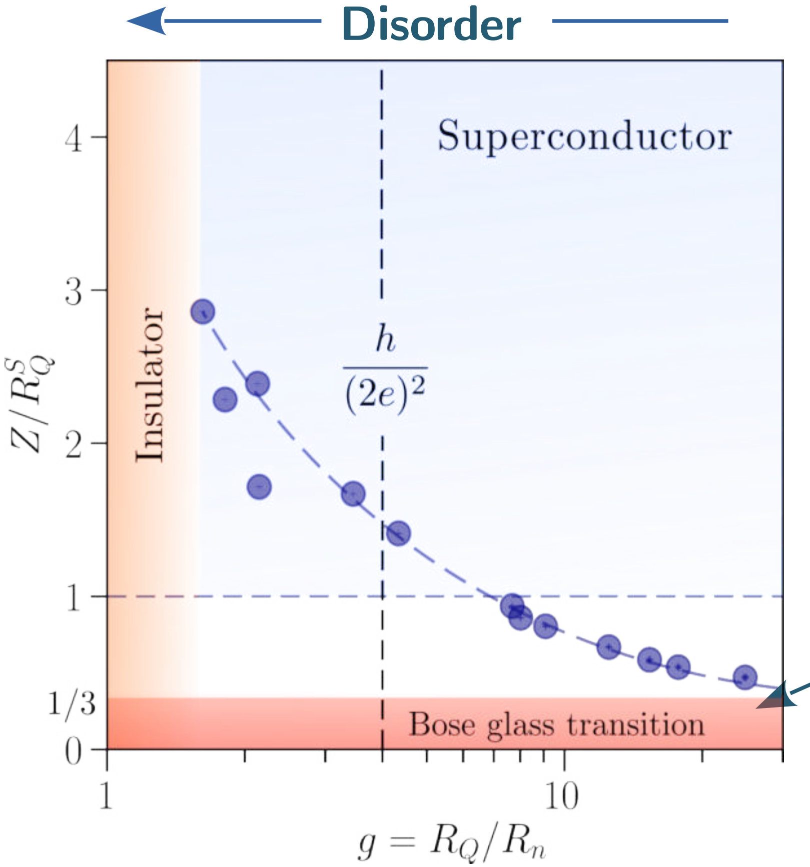
Giamarchi and Schulz, PRB (1988)
Bard et al, PRB (2017)
Houzet and Glazman, PRL (2019)

See also in JJ arrays :
Cedergren et al, PRL (2017)
Kuzmin et al, Nature Physics (2019)
Mukhopadhyay et al, arXiv (2022)

(1+1)D BKT transition

Wave impedance

$$Z = \sqrt{\frac{L_K^{\square}}{wC'}}$$



Transition to Bose glass

$$Z_c = \frac{R_Q^S}{3}$$

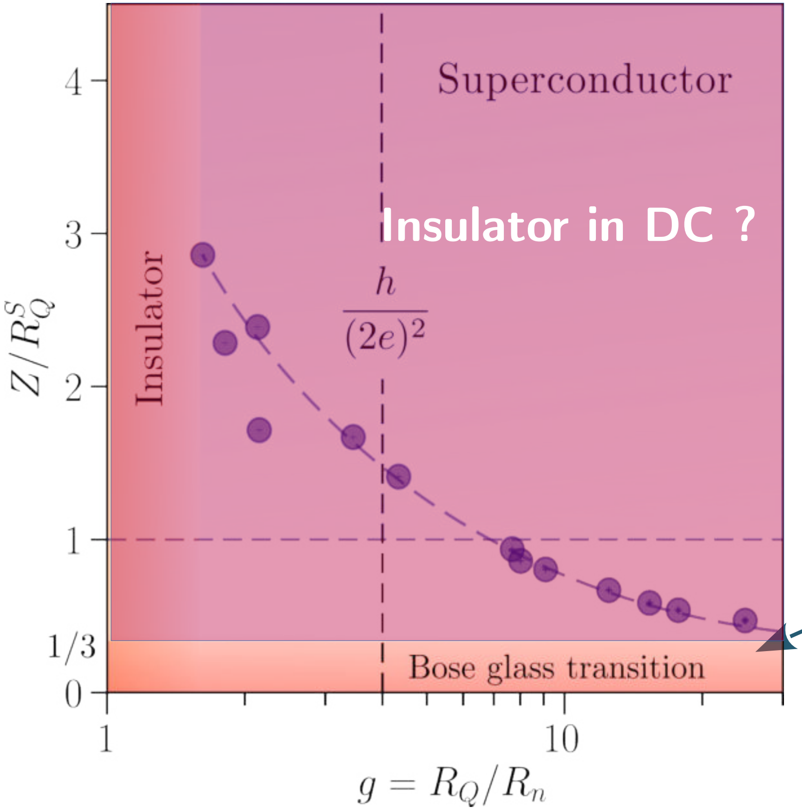
All samples would be insulating in DC !!

(1+1)D BKT transition

Disorder

Wave impedance

$$Z = \sqrt{\frac{L_K^{\square}}{wC'}}$$



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(1+1)D BKT transition

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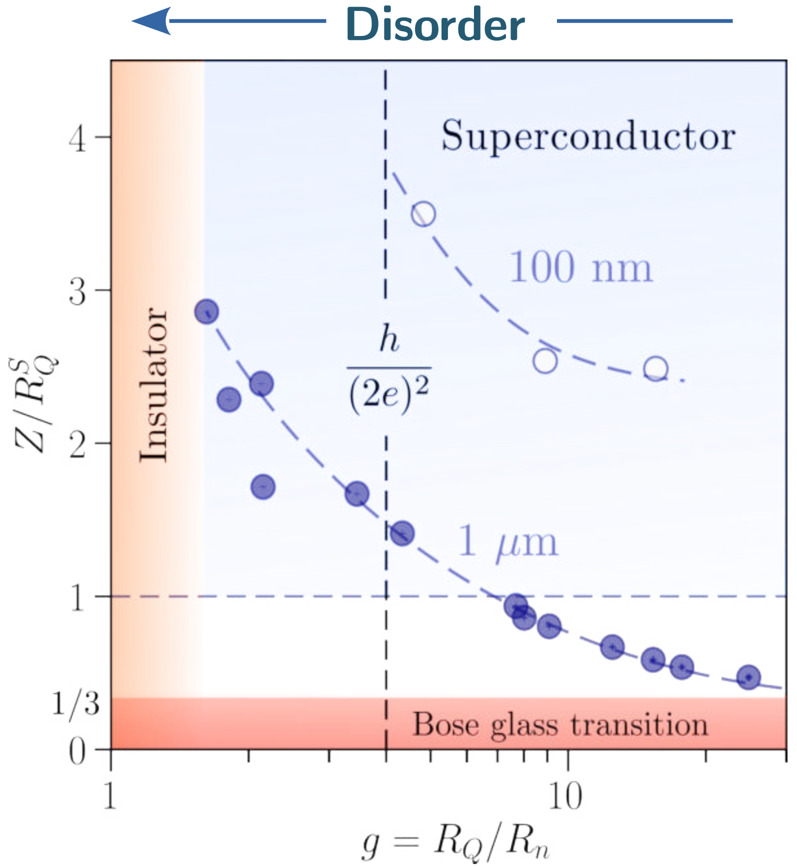
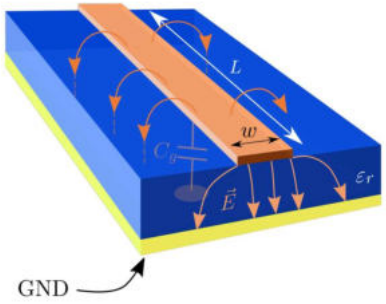


Nanowires



$w = 0.1\ \mu\text{m}$

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(1+1)D BKT transition

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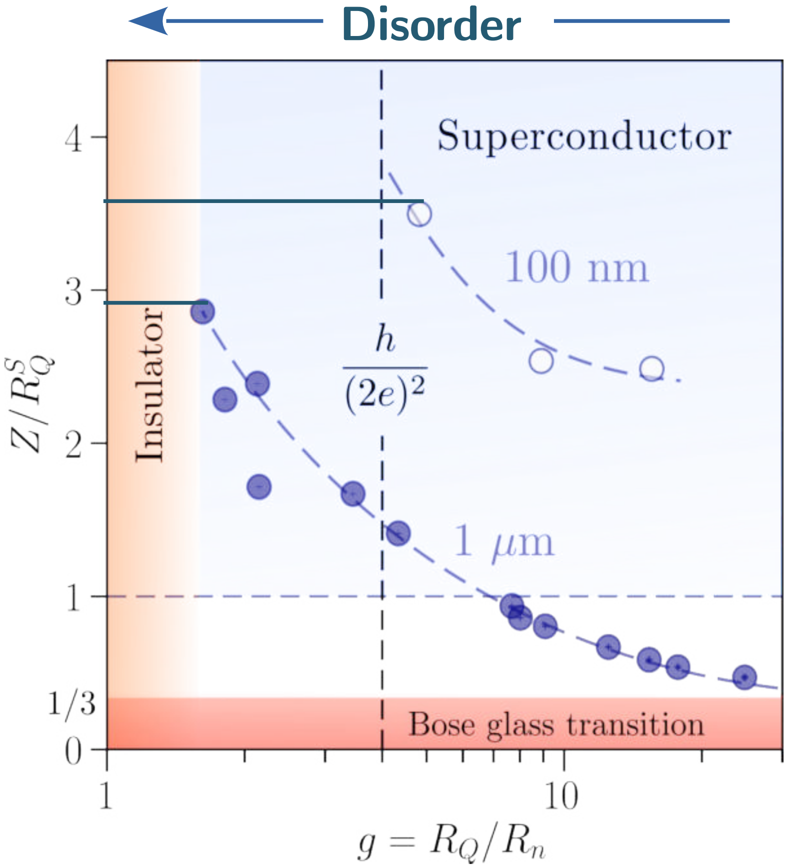

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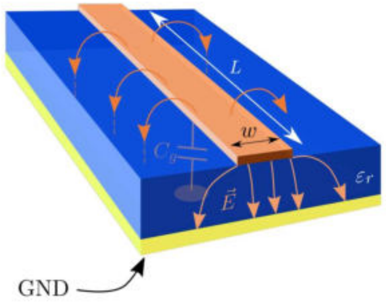

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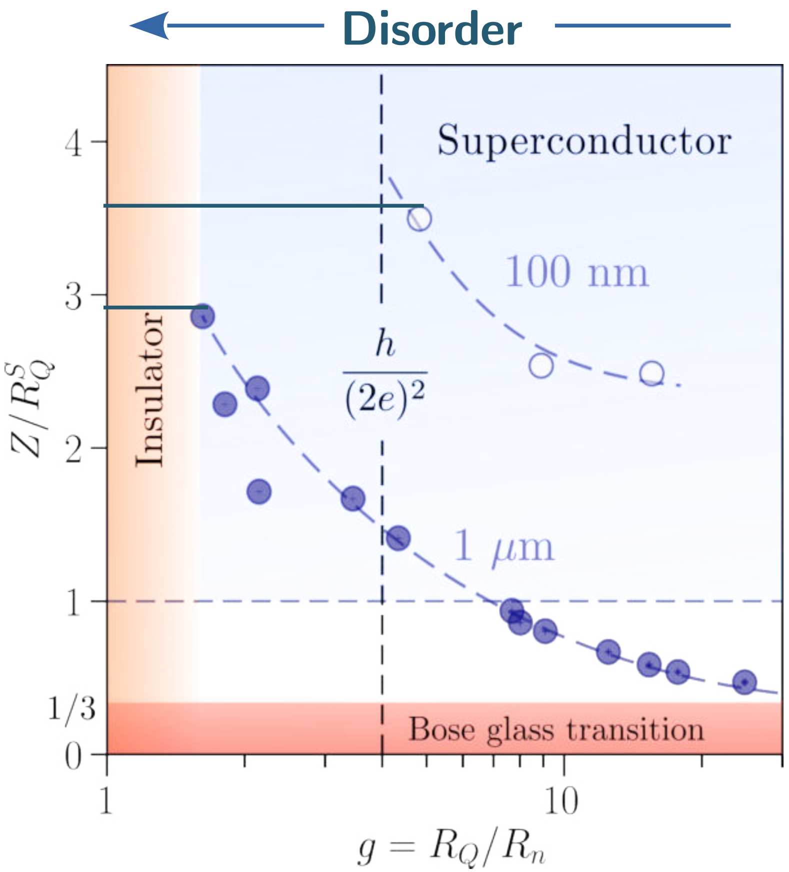
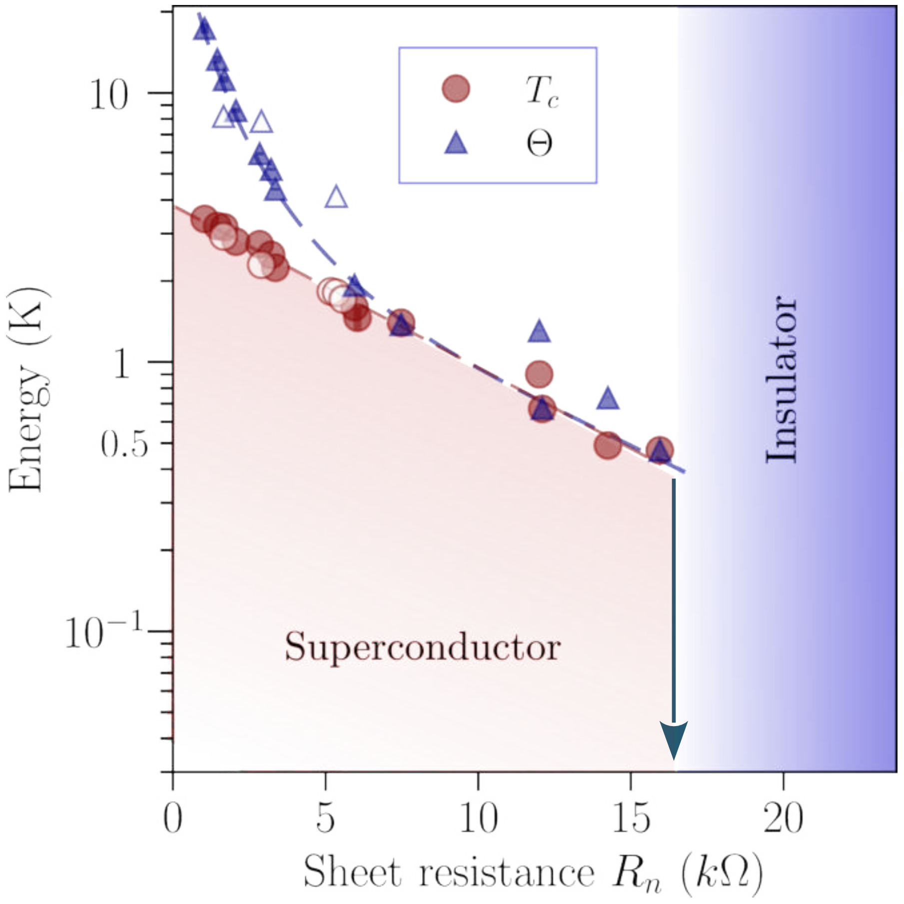


Conclusion

Bose glass transition seems incompatible with indium oxide data

All samples would be insulating in DC !!

Nature of the T=0 phase transition

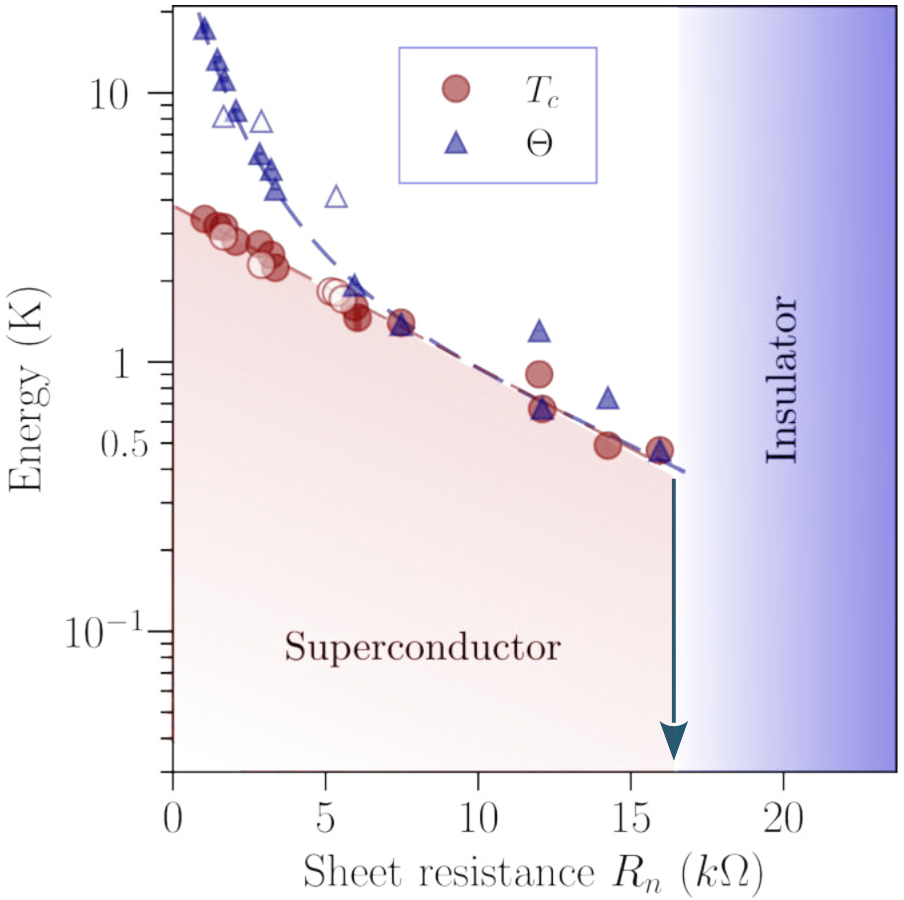


Θ and T_c are finite at SIT

Next scenario :

First-order quantum phase transition ?

Nature of the T=0 phase transition



Θ and T_c are finite at SIT

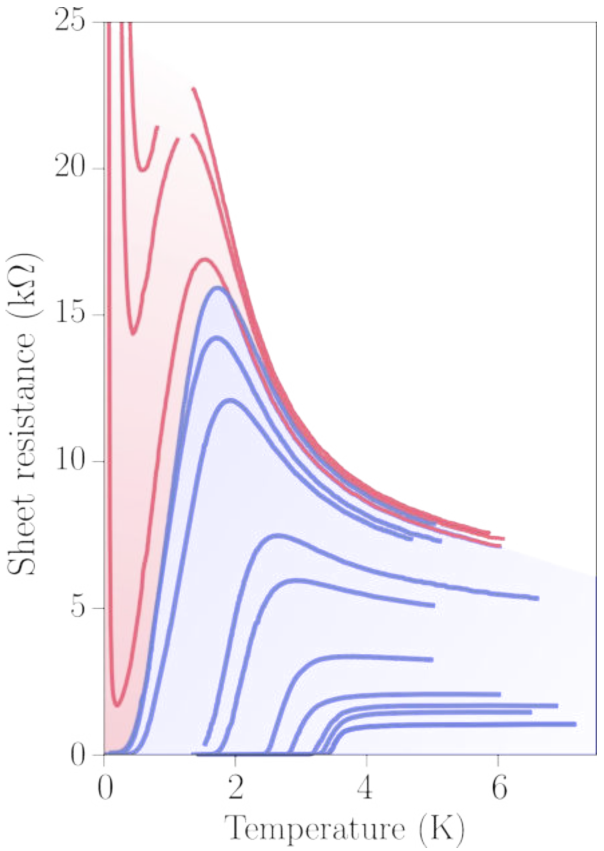
Next scenario :

First-order quantum phase transition ?

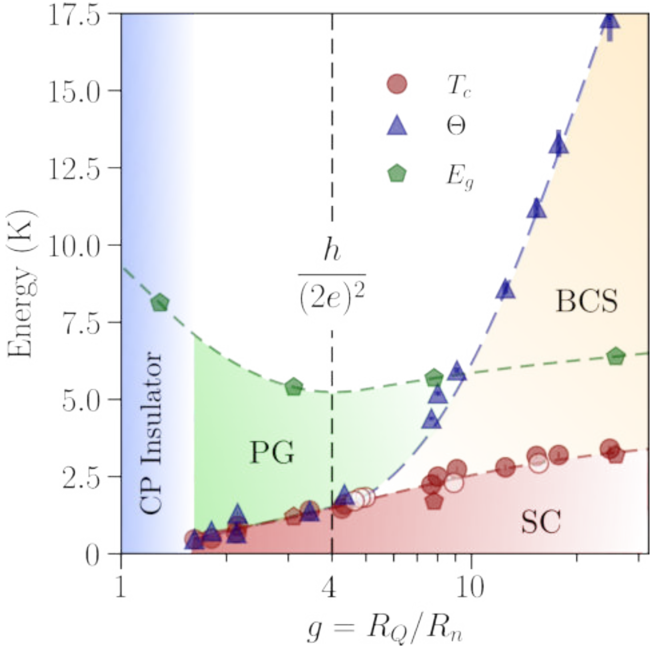
New theories needed

Conclusion

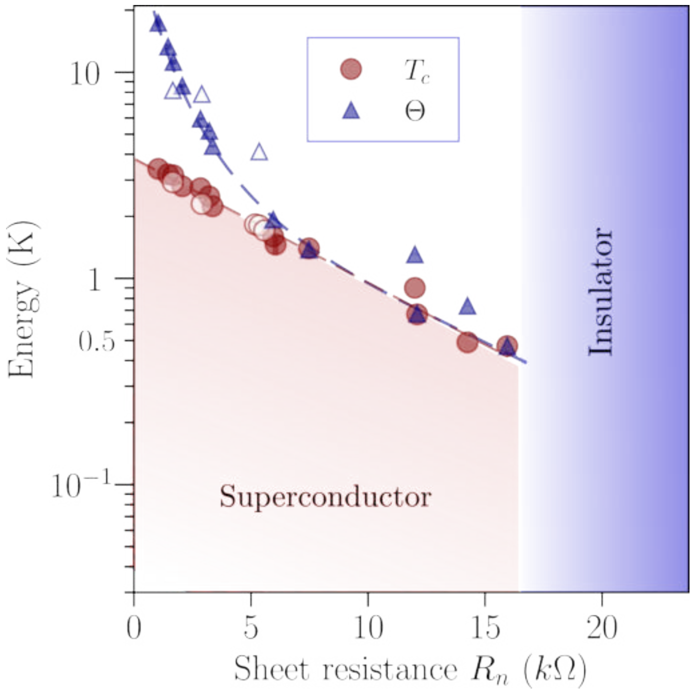
Superconductor-Insulator Transition



DC and cQED study of phase fluctuations

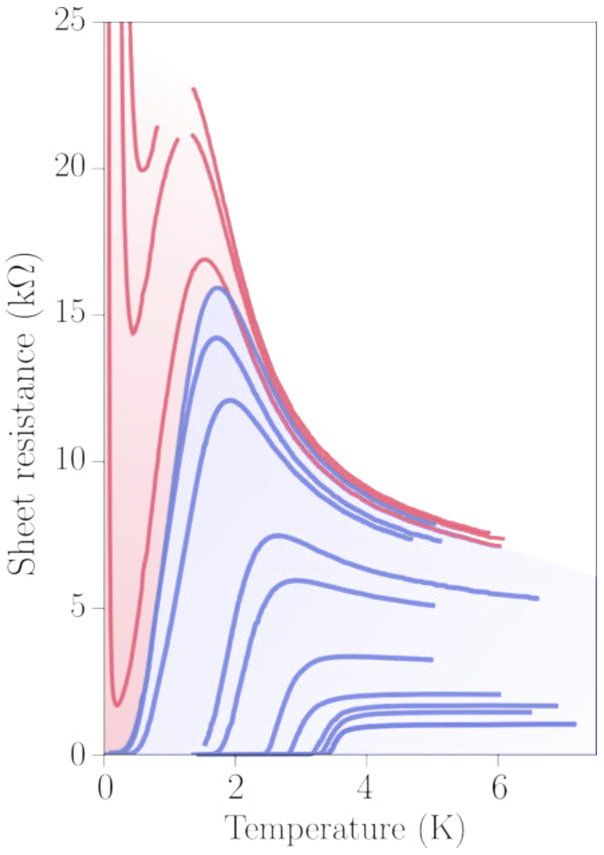


First-order quantum phase transition ?

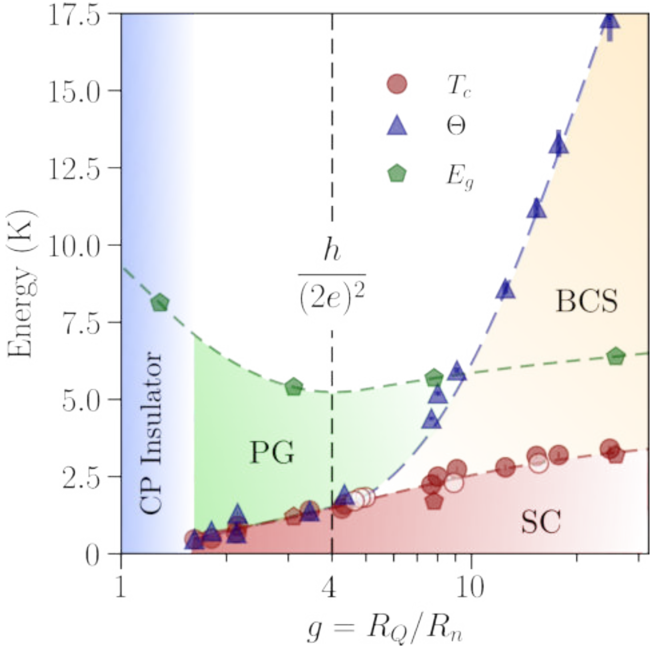


Conclusion

Superconductor-Insulator Transition



DC and cQED study of phase fluctuations



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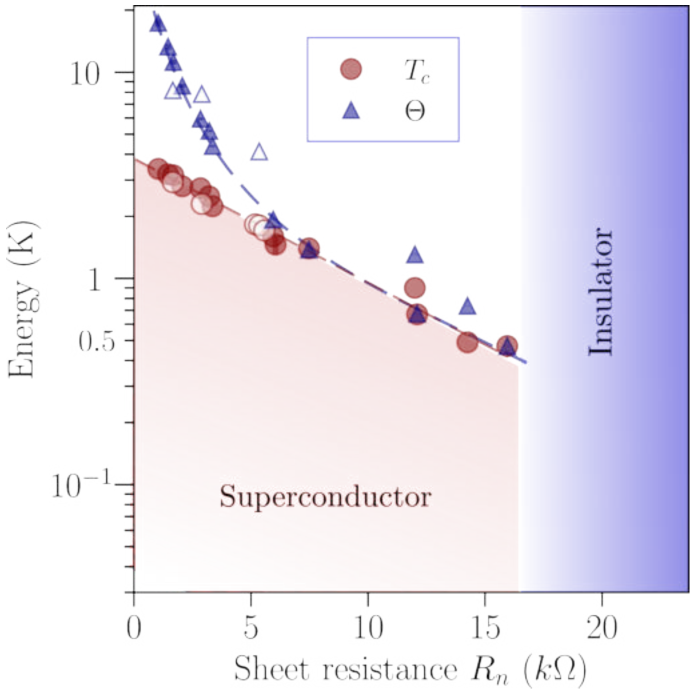
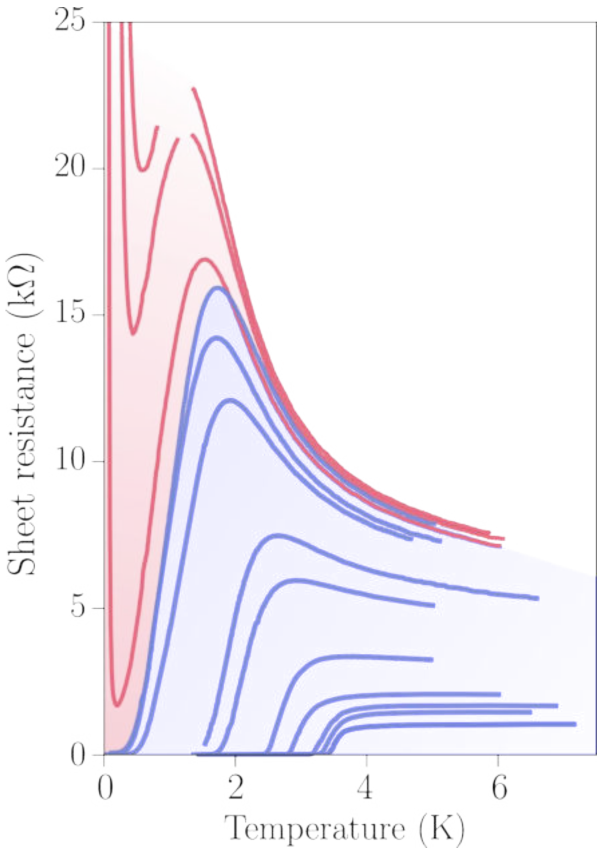
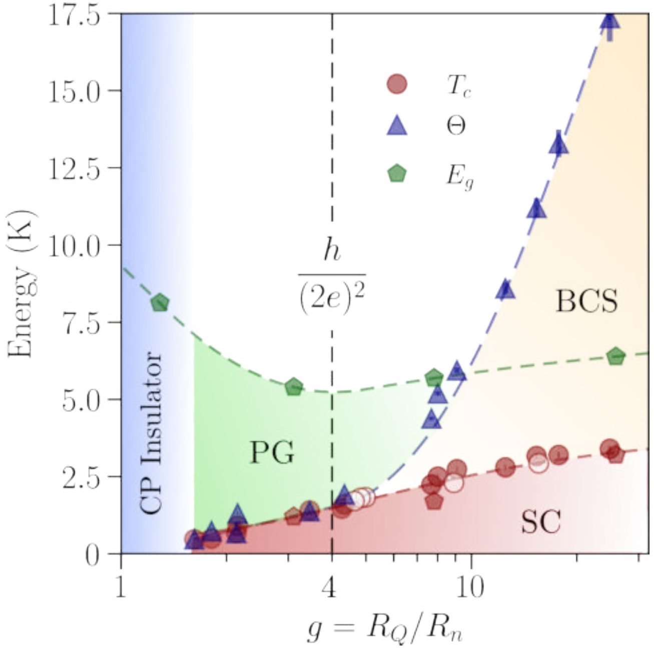


Conclusion

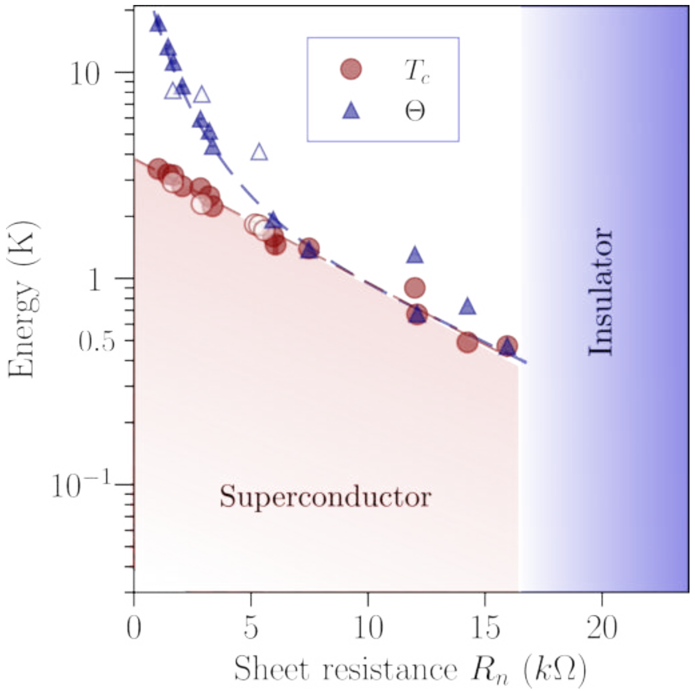
Superconductor-Insulator Transition



DC and cQED study of phase fluctuations

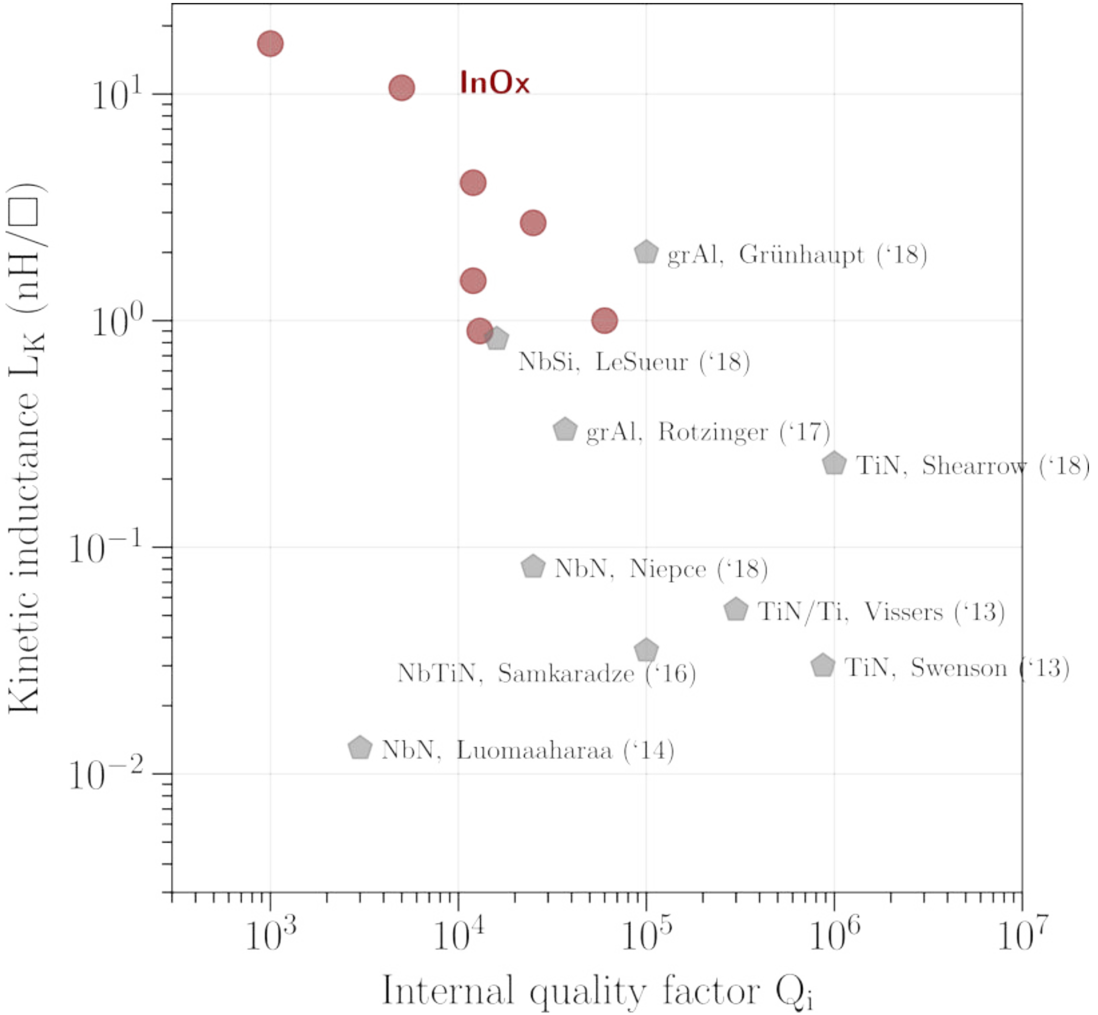


First-order quantum phase transition ?

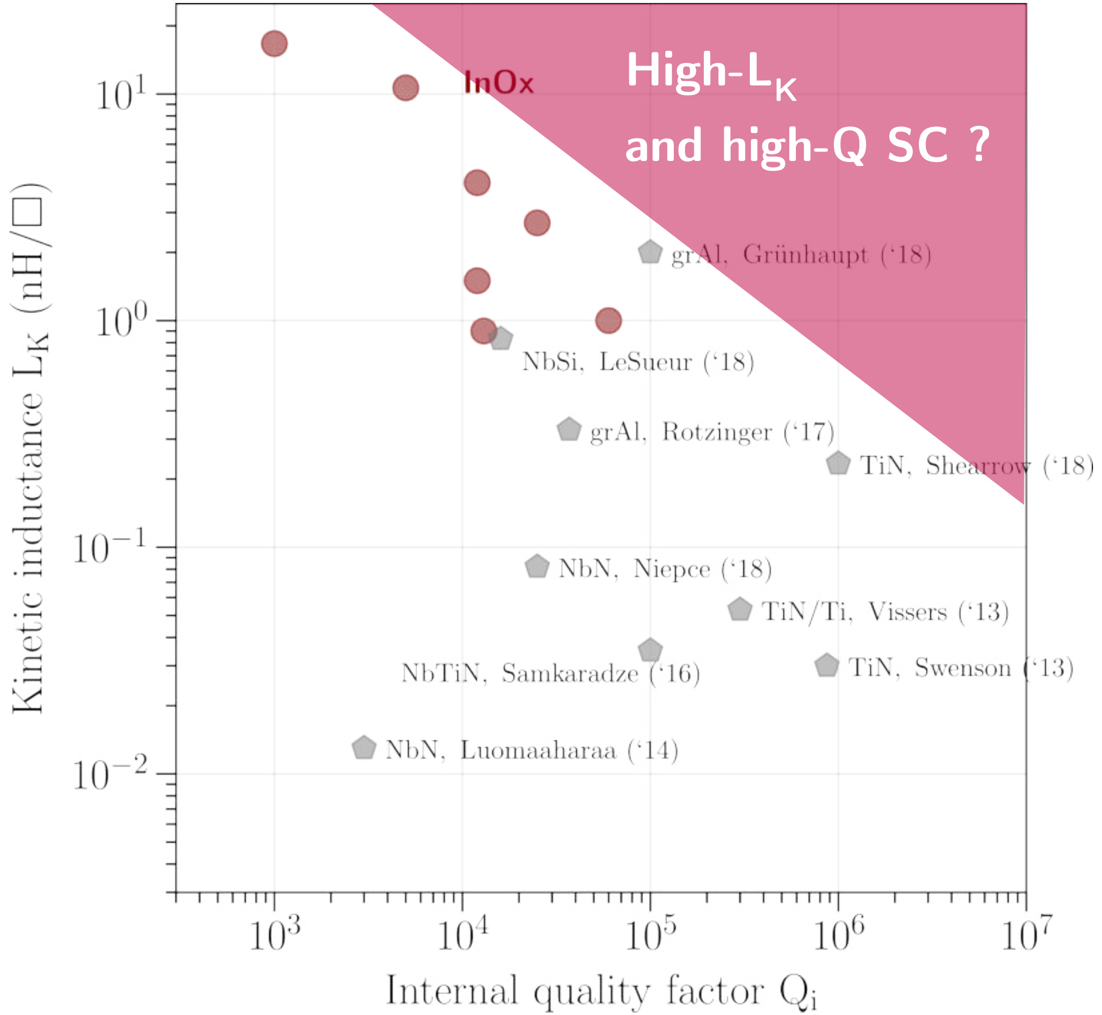


Applications of aInO resonators

Perspectives for cQED : understand losses



Perspectives for cQED : understand losses



Acknowledgments

Supervisors


N. Roch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Experimental


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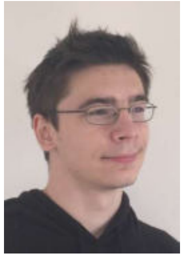
M. Feigel'man


L. Ioffe


A. Khvalyuk

Thank you !