Entering the Quantum Griffiths Phase of a Disordered Superconductor

Jérôme Lesueur

Physics and Materials Laboratory (LPEM)
ESPCI – CNRS – UPMC
Paris

People

PhD & PDF : **A. Jouan** – **G. Singh** - J. Biscaras – S. Hurand

Collaborators : N. Bergeal, C. Feuillet-Palma, LPEM (Paris)

A. Rastogi, ITT Kanpur (India)

R. C. Budhani, A. Dogra, NPL Dehli (India)

A. Barthelemy, M. Bibes, J. Villegas, N. Reyren, E Lesne
UMR Thales-CNRS (Palaiseau)

M. Grilli, S. Caprara, L. Benfatto, La Sapienza (Rome)

Quantum Phase Transition and fluctuations

Spatial correlation length

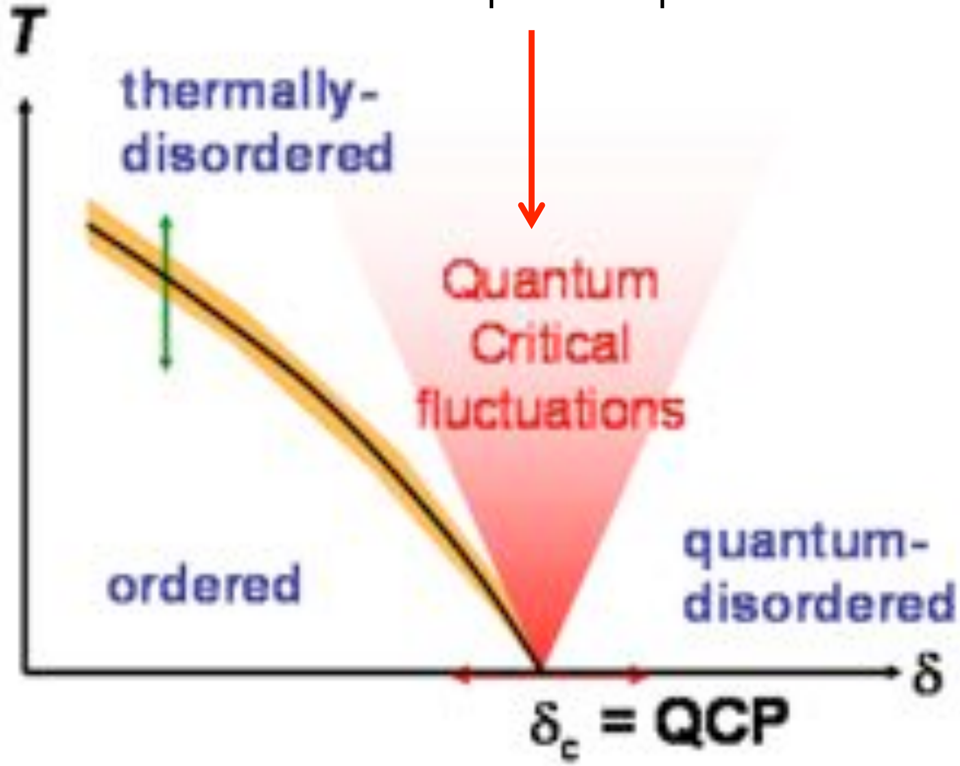
$$\xi \approx |\delta - \delta_c|^{-\nu}$$

Dynamical correlation length

$$\xi_\tau \approx |\delta - \delta_c|^{-z\nu}$$

Critical exponents

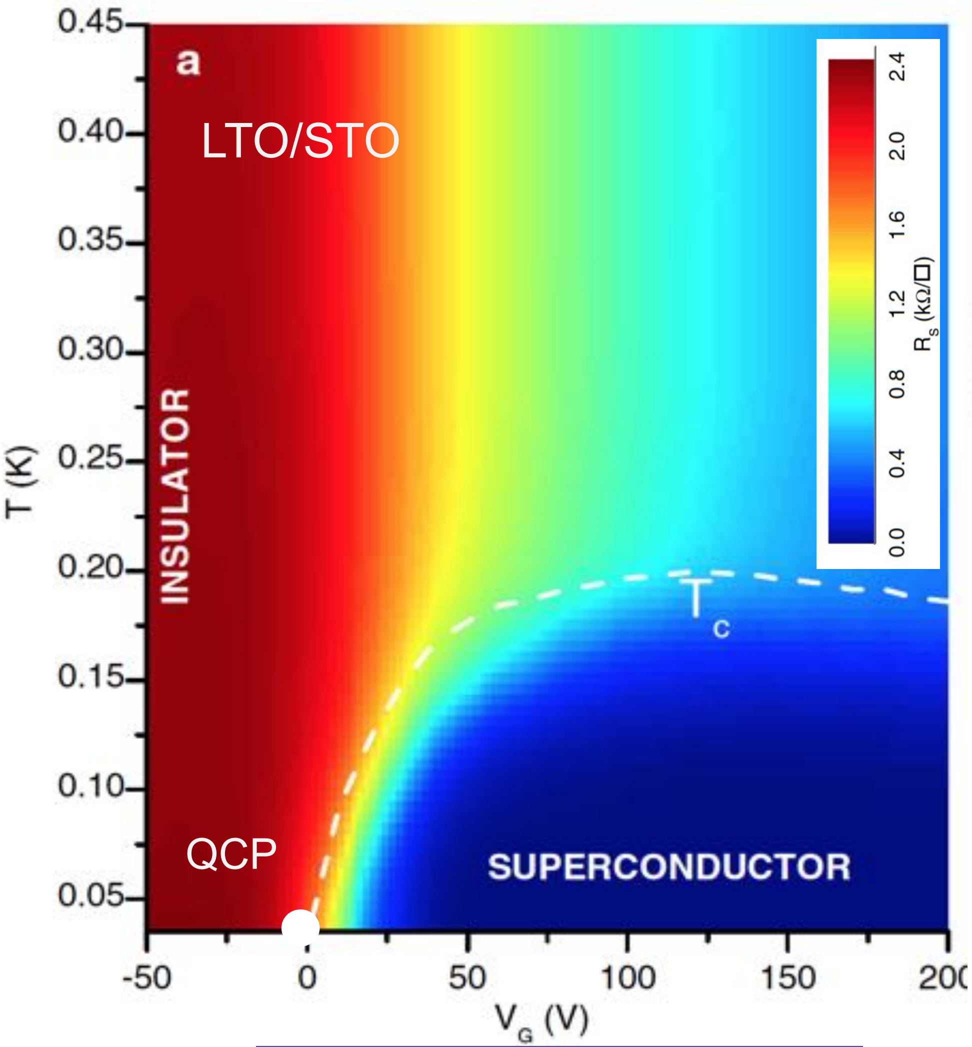
Universality class



Parameter in the Hamiltonian

Quantum Phase Transition and fluctuations in 2D

■ Phase diagram



Caviglia et al, Nature 2008

Biscaras et al, PRL 108, 247004 (2012)

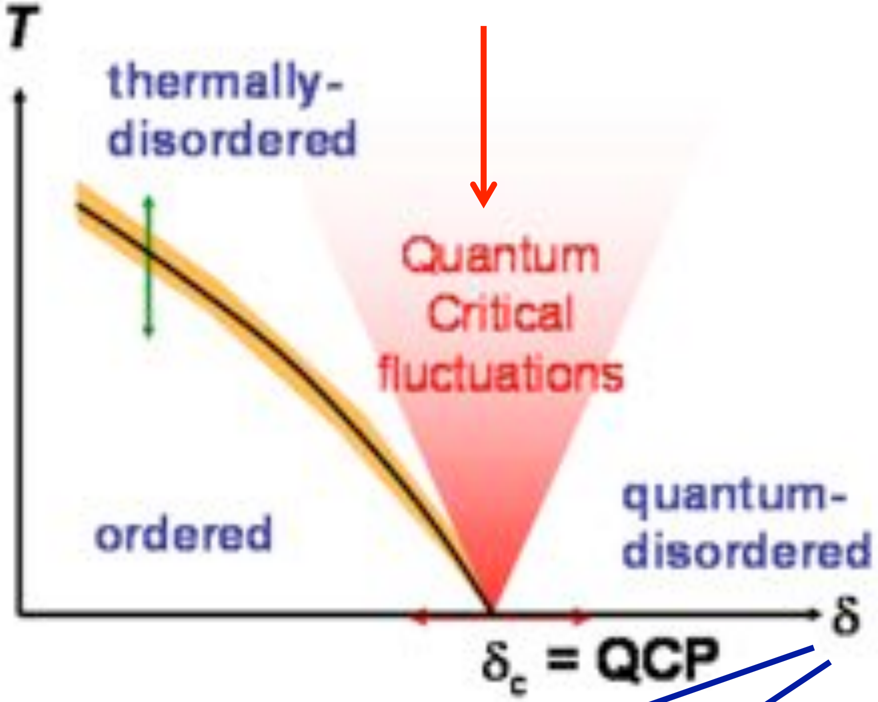
Correlation length

$$\xi \approx |B - B_\times|^{-\nu}$$

Dynamical correlation length

$$\xi_\tau \approx |B - B_\times|^{-z\nu}$$

Critical exponents

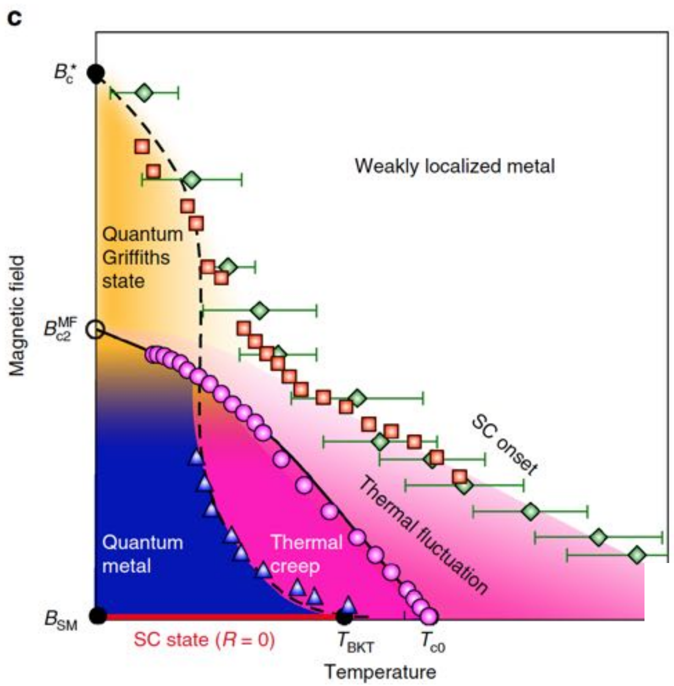


Perpendicular magnetic field B

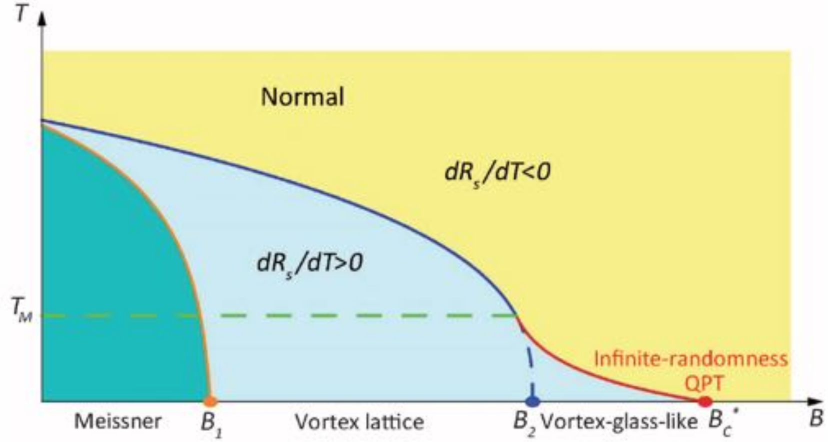
Gate Voltage V_G

Complex phase diagrams

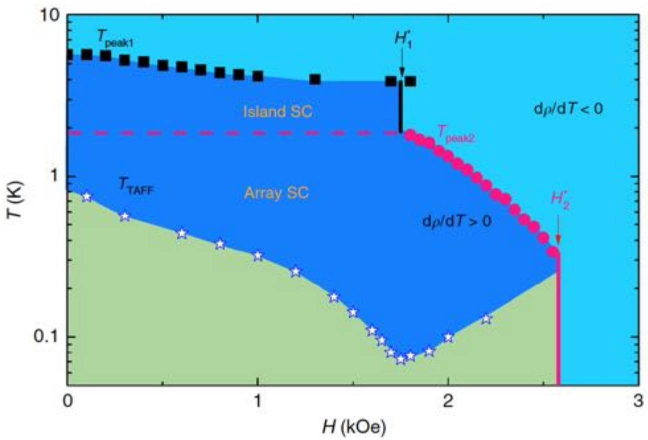
- Large varieties



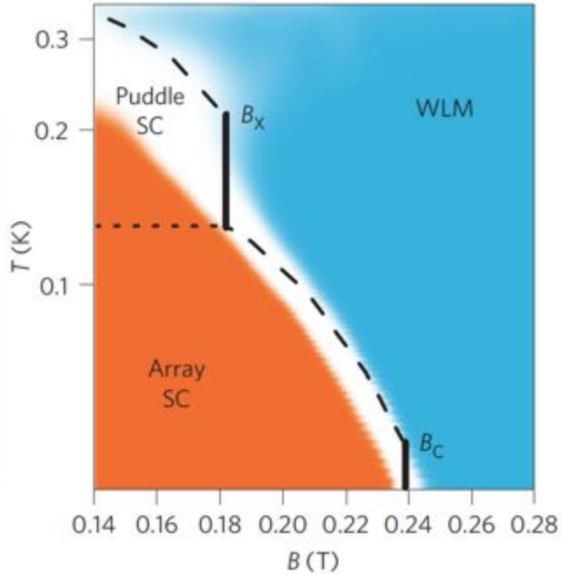
Saito et al, Nat Com (2018)



Xing et al, Science (2015)



Sun et al, Nat Com (2018)



Biscaras et al, Nat Mat (2013)

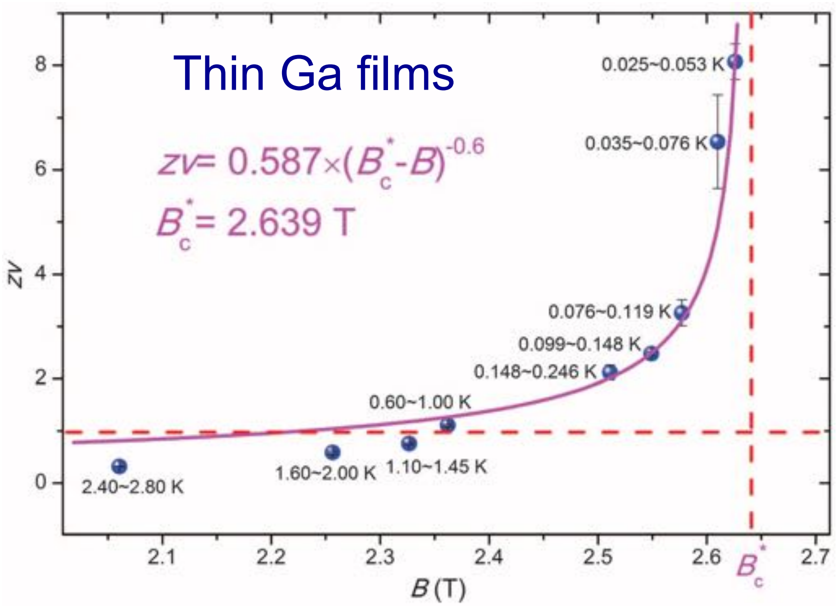
Critical exponents

- Large varieties

$z = 1$ $\nu = 0.66$ $\nu = 7/4$

$\nu = 3/2$ $\nu = 4/3$ $\nu = \ldots$

- Non universal exponents



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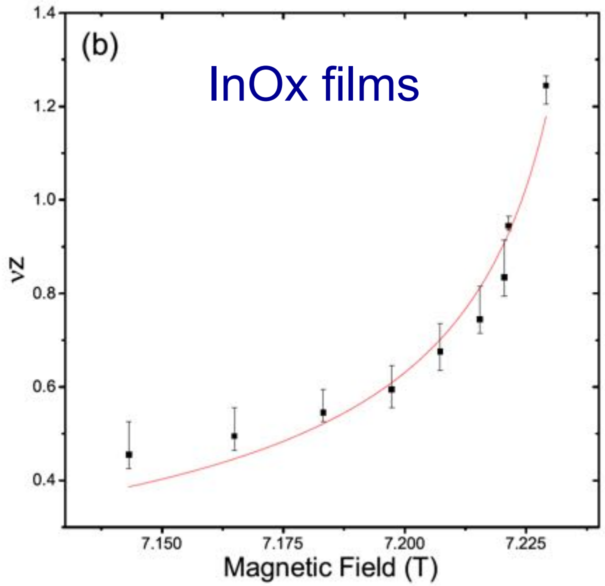


Lewellyn et al, arXiv 2018

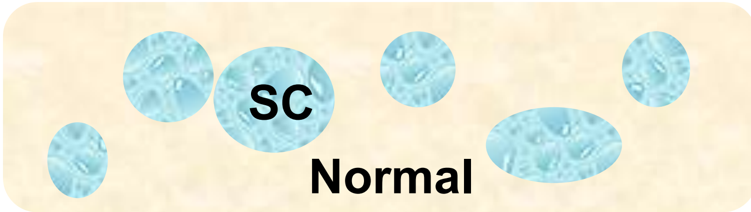
Quantum Phase Transition in oxide interfaces

Point #1

- Role of the mesoscopic disorder ...

  - Intrinsic inhomogeneity builts up
  - Quasi-1D filamentary structure appears

Multiple Quantum Criticalities ?



Feigel'man et al, PRL 2001
Spivak et al, PRB 2008

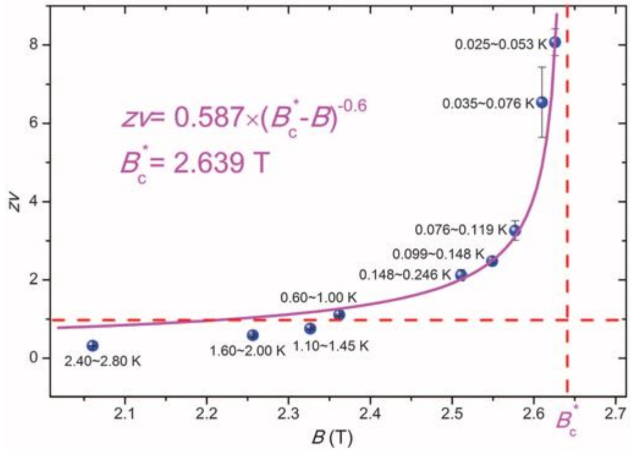
Ioffe-Mezard PRL 2010,
Goetz-Benfatto-Castellani PRL 2012

Point #2

- Role of the Griffiths singularities ?

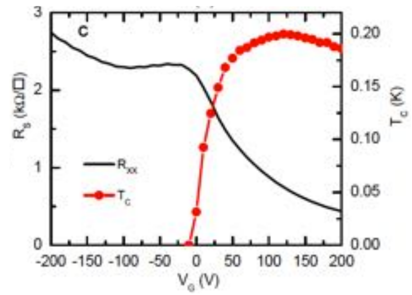
  - Rare events matter
  - Consequence on the observables

Evidence for a Griffiths phase ?



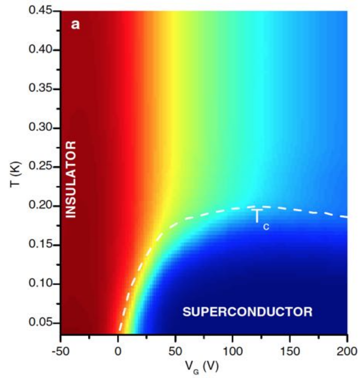
Outline

Tunable superconductivity in oxide 2DEG



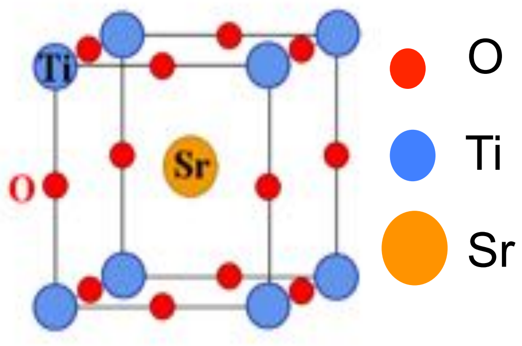
Quantum phase transition in magnetic field

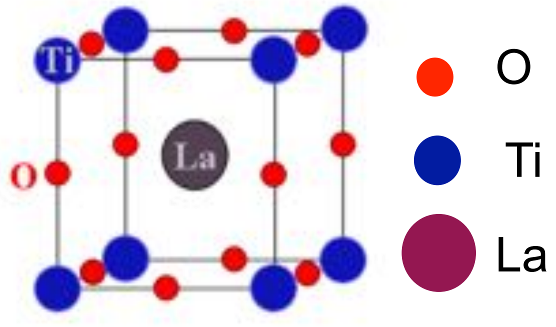
Quantum phase transition in gate voltage



2 DEG at oxides interfaces $LaXO_3/SrTiO_3$ (X=Al or Ti)

- Thin layer of $LaAlO_3$ or $LaTiO_3$ deposited by PLD on a $SrTiO_3$ substrate



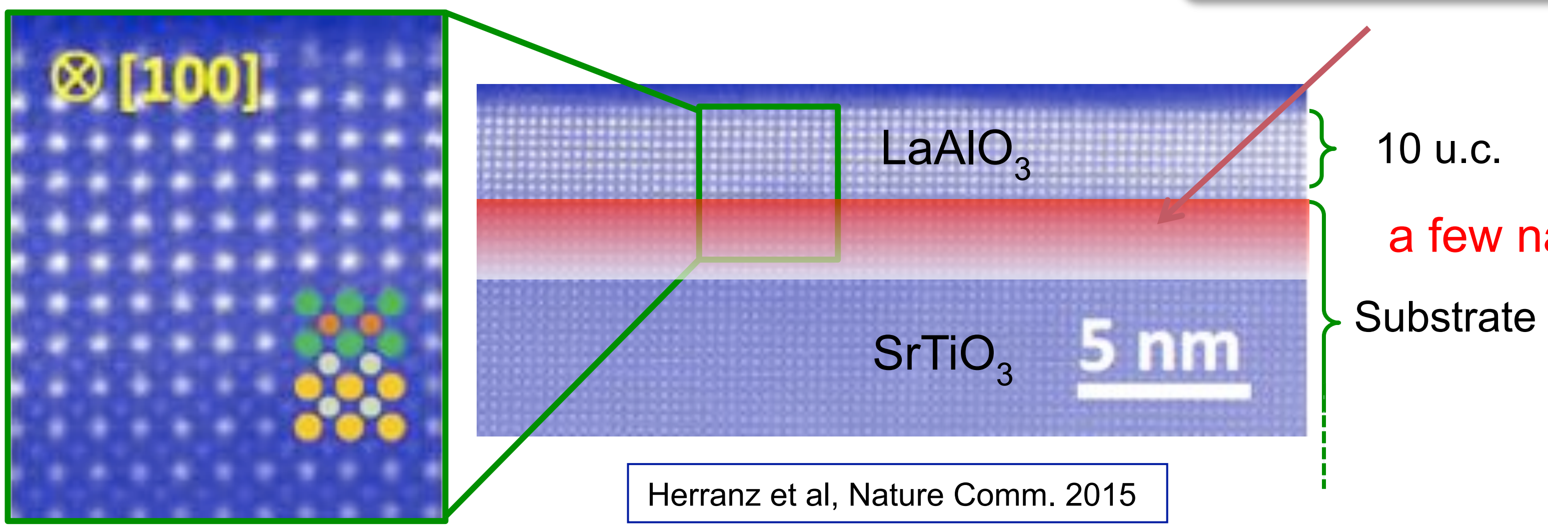


Ohtomo et al, Nature 2002

Hwang et al, Physica E 2004

2 DEG at the interface

$n_S \sim 10^{14}$ e/cm^2



Herranz et al, Nature Comm. 2015

Reyren et al, Science 2007

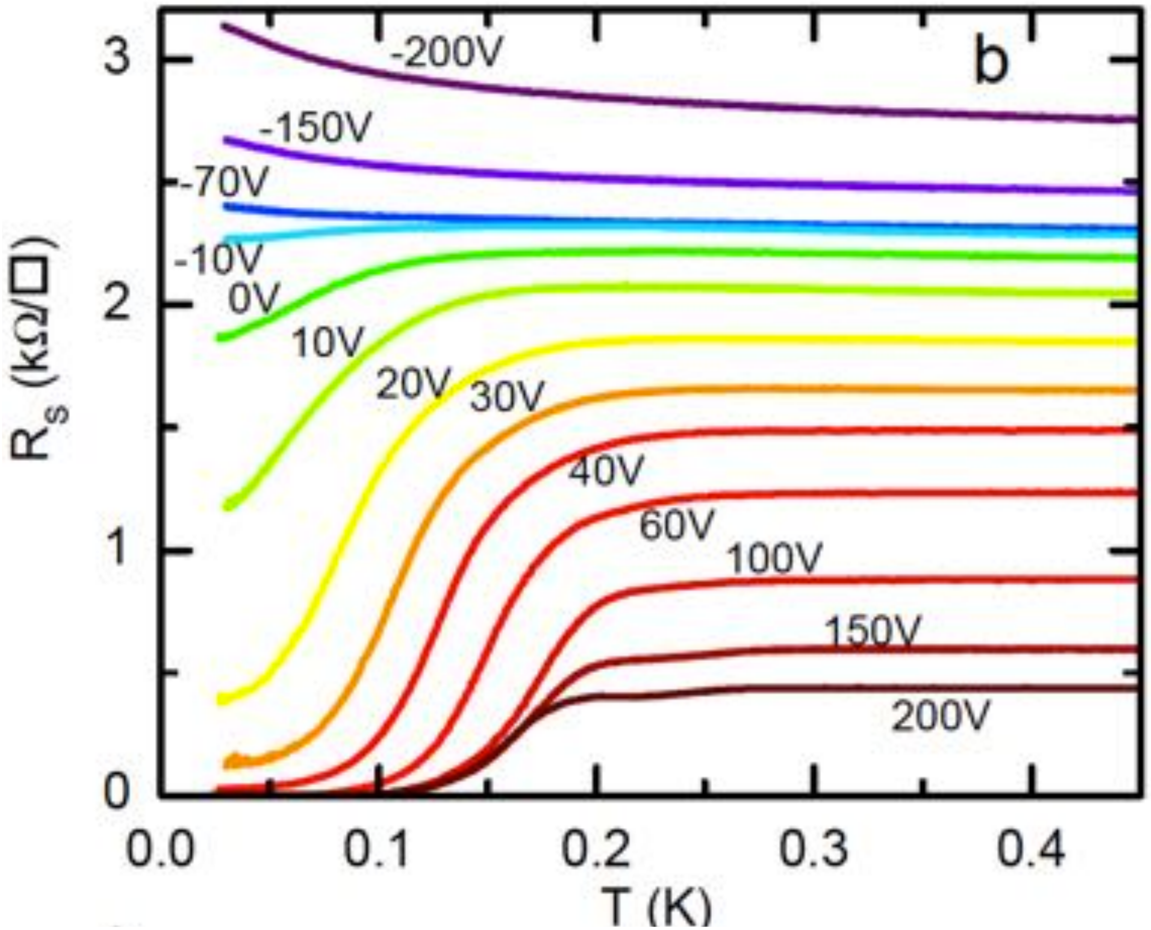
Biscaras et al, Nature Com. 1, 89 (2010)

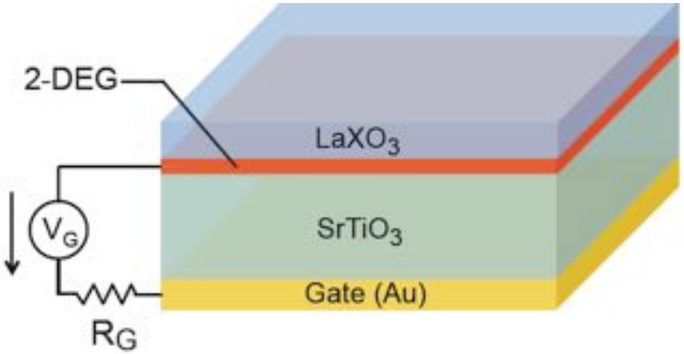
Superconductivity → **2D SC Physics**

Electric field effect

- Control of the 2-DEG by **electrostatic back gate**

$LaTiO_3/SrTiO_3$





remove e-

R_s decrease with Vg

T_c goes through a maximum

add e^-

Caviglia et al, Nature 2008

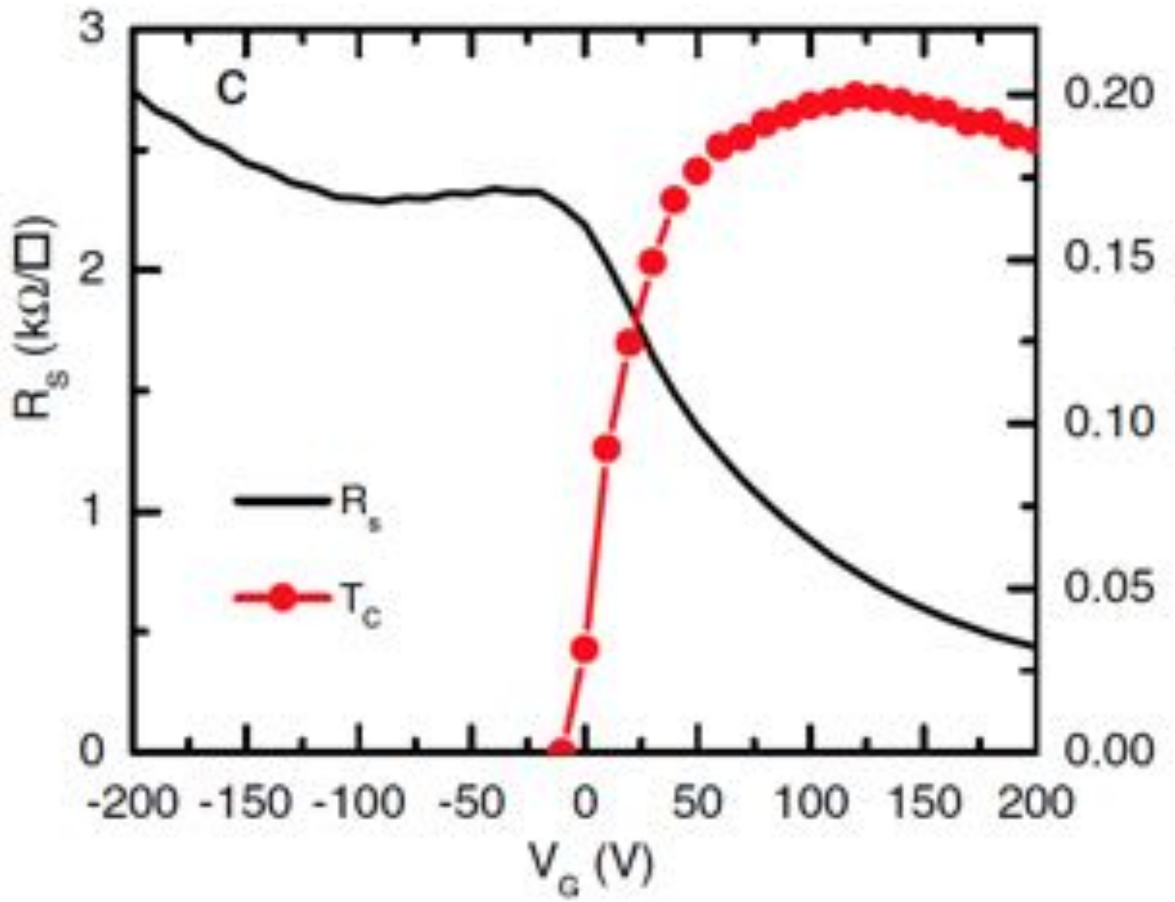
Biscaras et al, PRL 108, 247004 (2012)

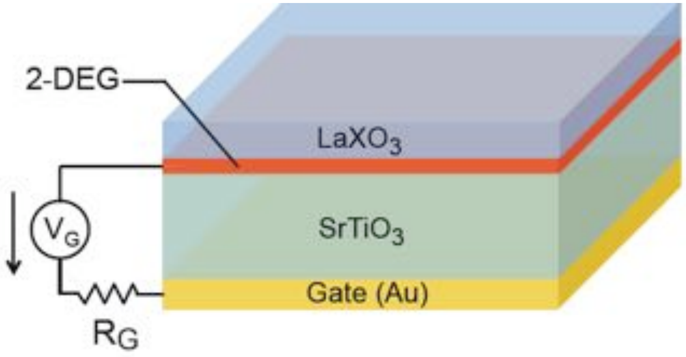
- Superconductor-insulator transition induced by field effect

Electric field effect

- Control of the 2-DEG by **electrostatic back gate**

$LaTiO_3/SrTiO_3$





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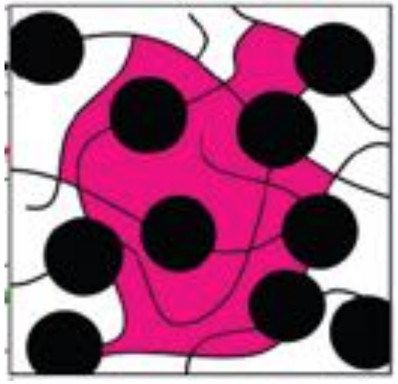
Biscaras et al, PRL 108, 247004 (2012)

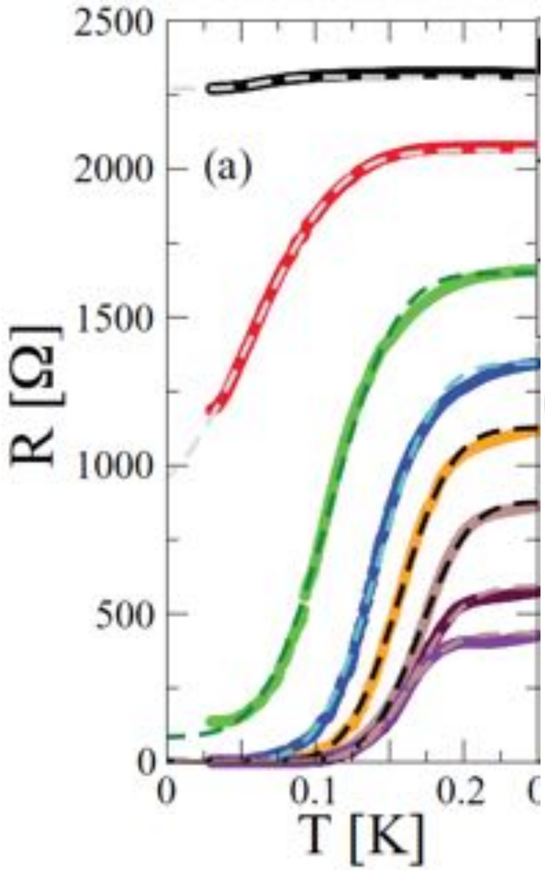
- Superconductor-insulator transition induced by field effect

Superconductivity ... inhomogeneous medium

- Effective Medium Theory
- Random Resistance Network
- Filamentary structure

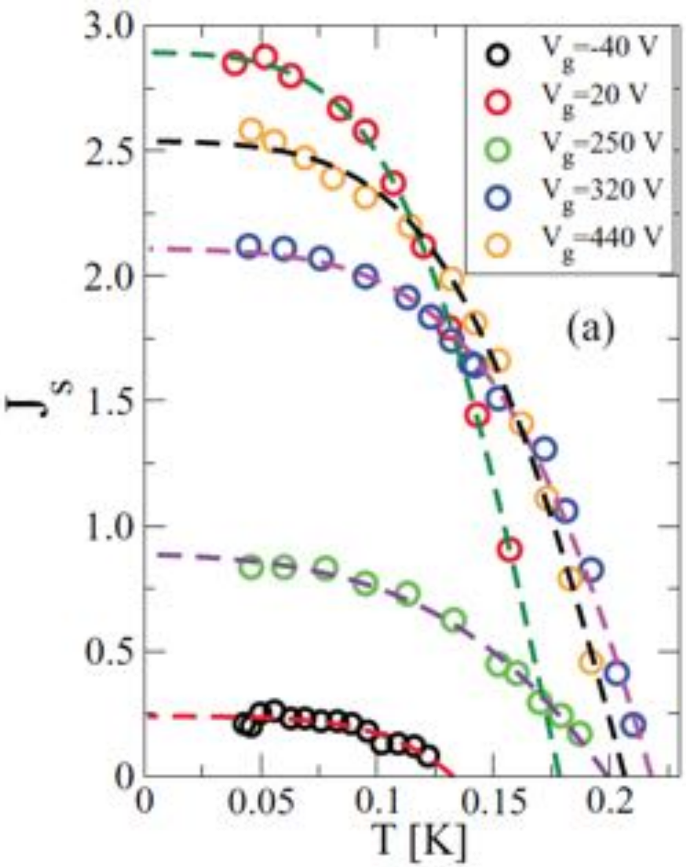


Resistance



Bert et al, PRB (2012)

Superfluid density



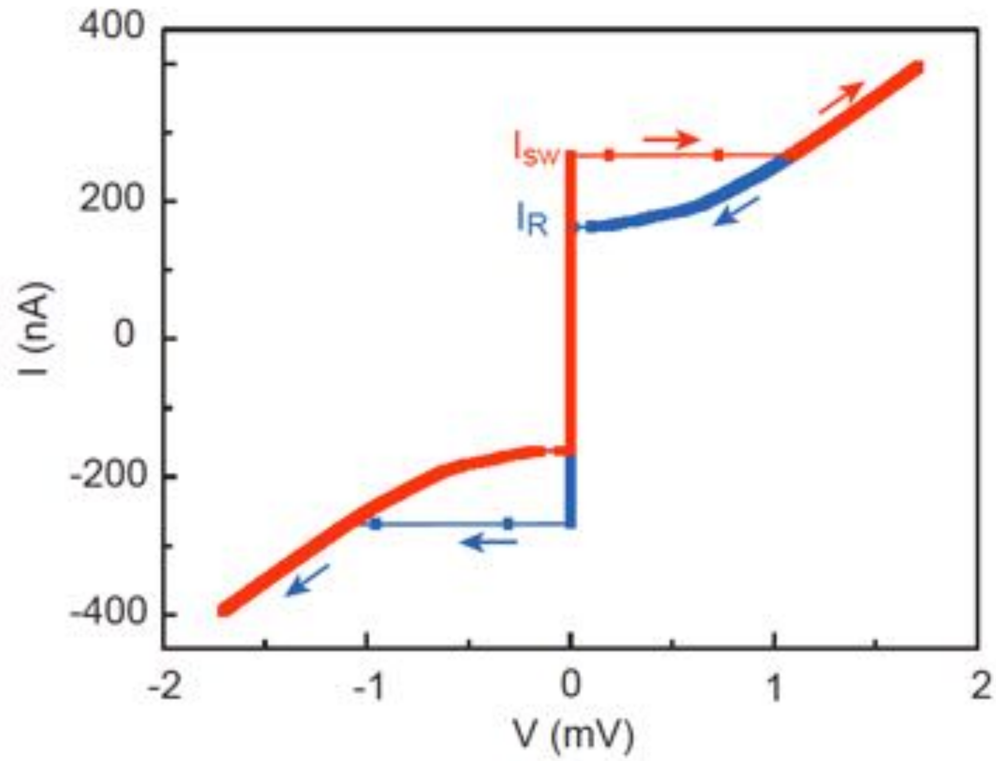
S. Caprara et al, Phys Rev B (R) 88, 020504 (2013)

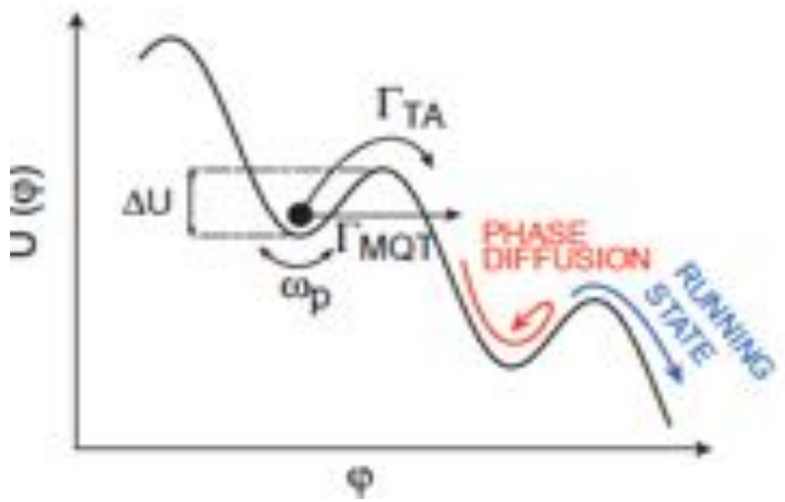
D. Bucheli et al, New J. of Phys. 15, 023014 (2013)

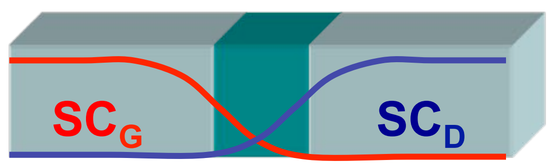
Ioffe-Mezard PRL 2010, Goetz-Benfatto-Castellani PRL 2012

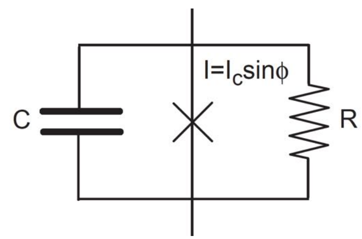
Superconductivity ... inhomogeneous medium

- **Josephson Junctions (JJ)**
- Hysteretic characteristics
- Stochastic Critical Current
- RCSJ model for the JJ
- Thermal vs Quantum





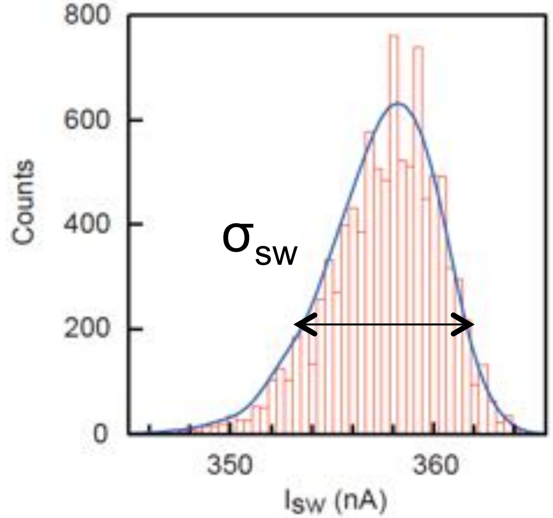


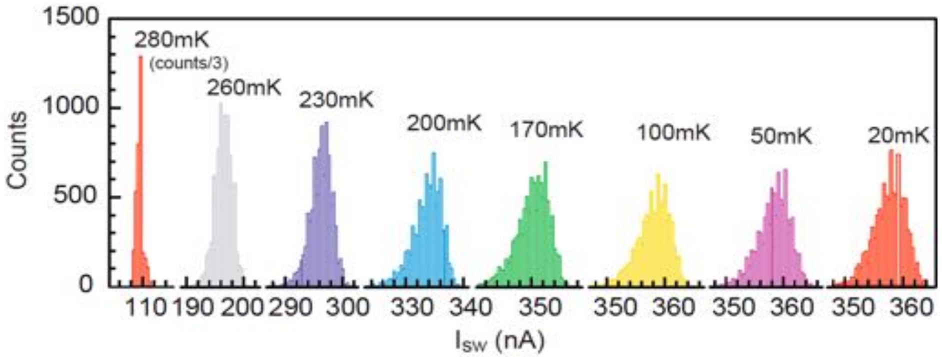


S. Hurand *et al.* unpublished results

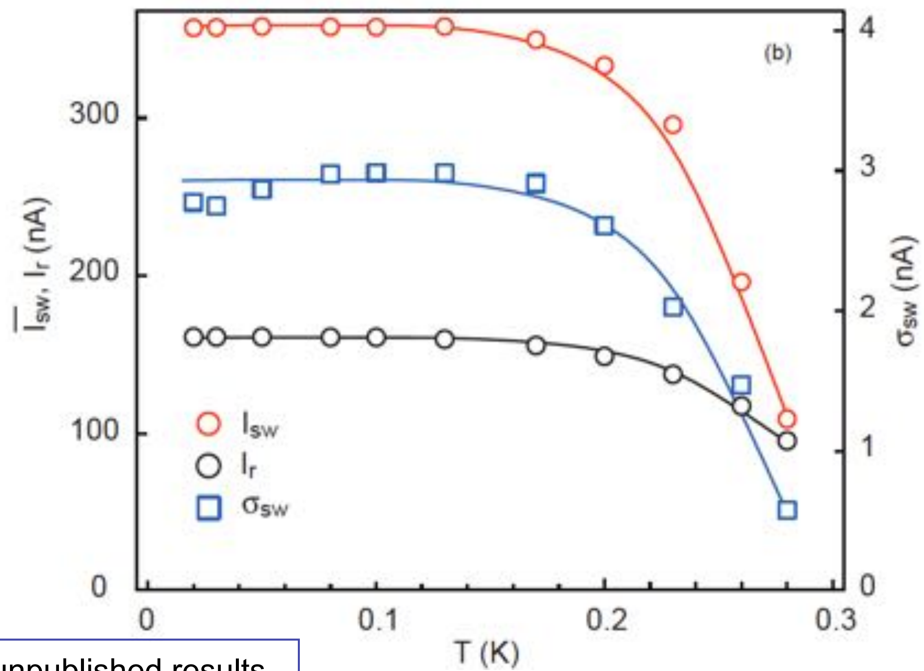
Superconductivity ... inhomogeneous medium

- **Statistical analysis : 10 000 switching events**
- Evolution with temperature
- Compatible with MQT behavior





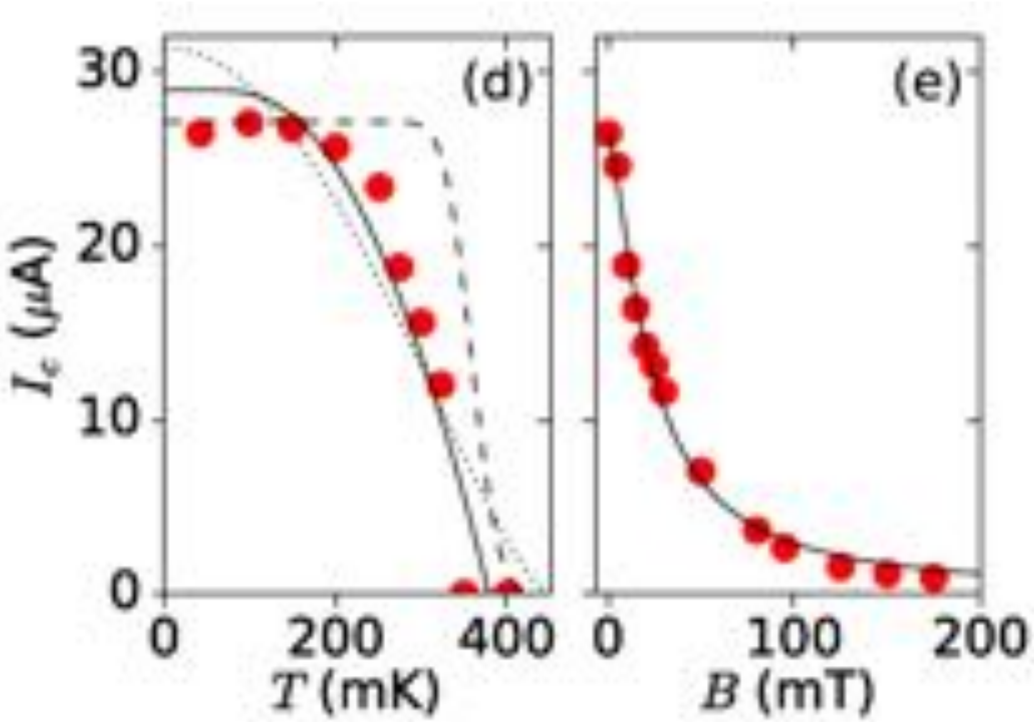
- σ_{sw} saturates at low temperature
- σ_{sw} follows Ic at high temperature
- $\sigma_{sw} \sim I_c^{2/3}$
- RCSJ model $T_{cr} \approx 478$mK

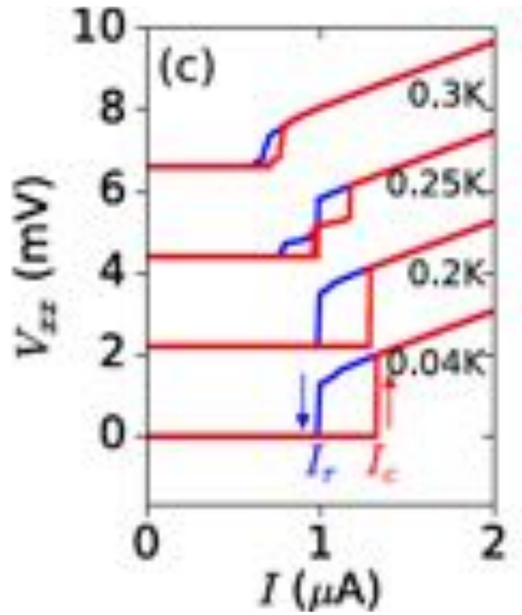


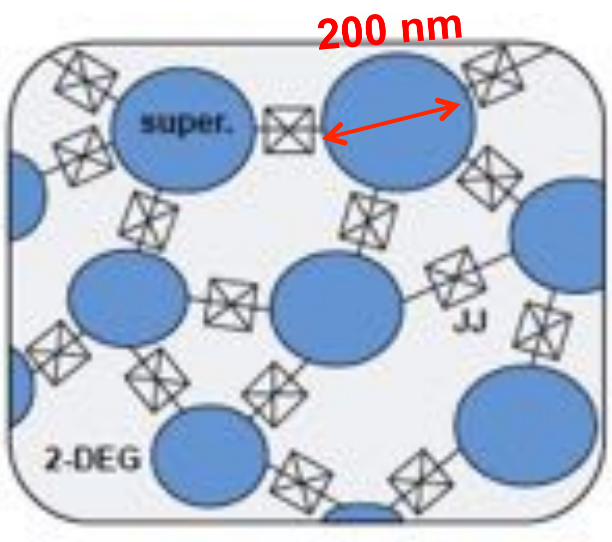
S. Hurand *et al.* unpublished results

Superconductivity ... inhomogeneous medium

- **Josephson Junctions (JJ) network**
- Typical scale : **200 nm**



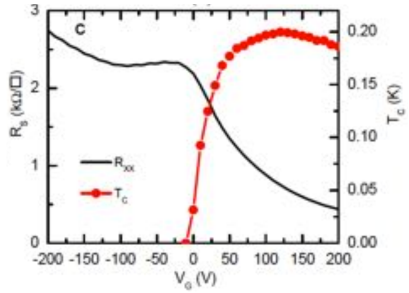




Prawiroatmodjo *et al.* Phys Rev B **93**, 184504 (2016)

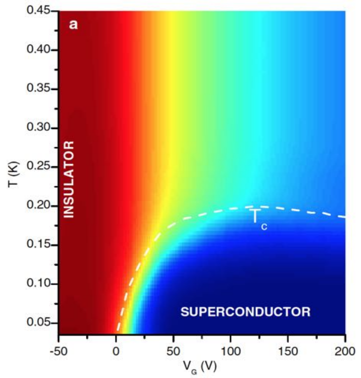
Outline

Tunable superconductivity in oxide 2DEG



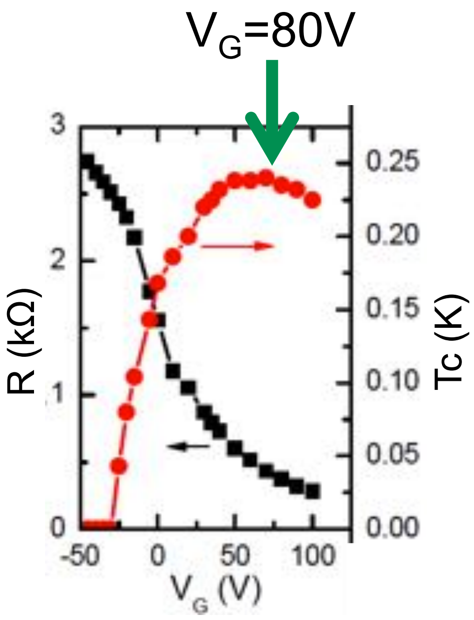
Quantum phase transition in magnetic field

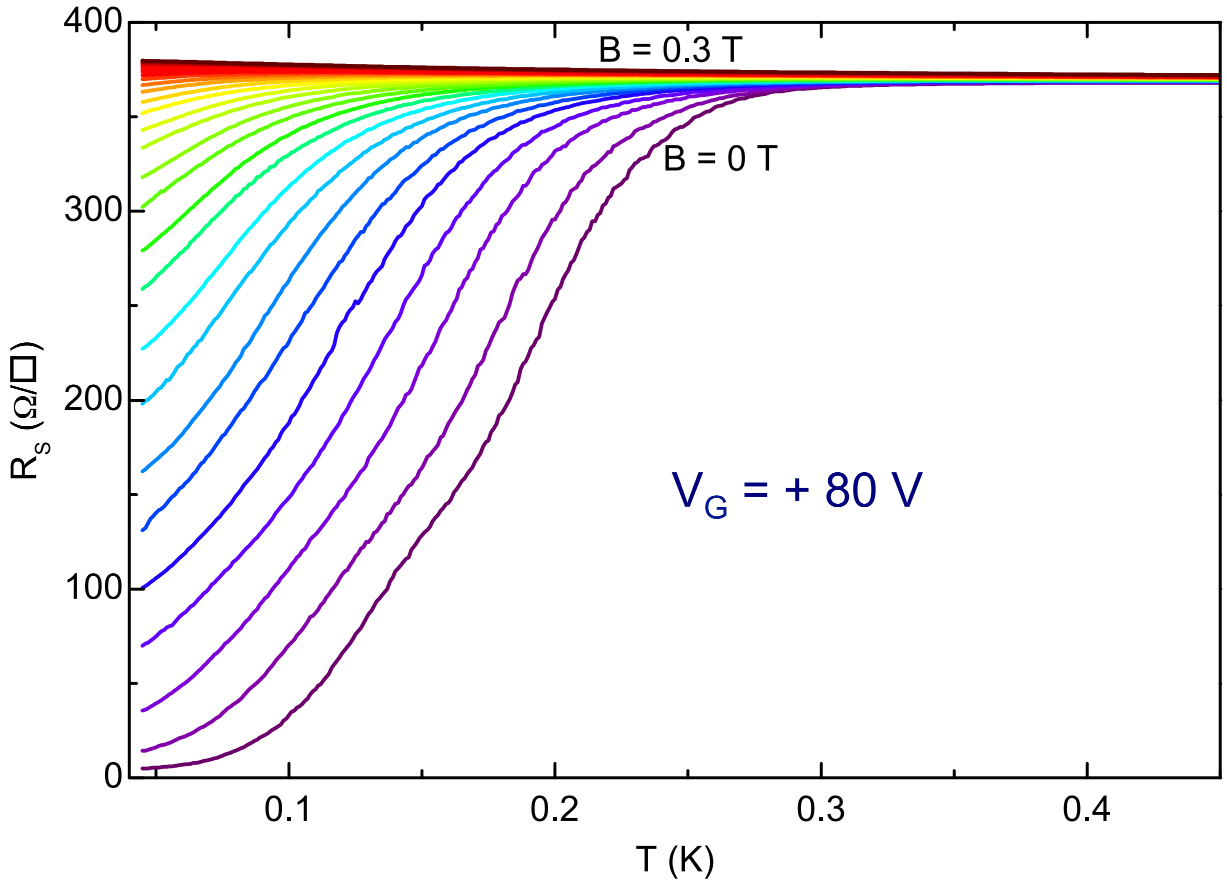
Quantum phase transition in gate voltage



Magnetic field driven Quantum Phase Transition

- Suppression of superconductivity by a perpendicular magnetic field at V_G=80V





➡ Transition from superconducting to weakly localized metallic state

Magnetic field driven Quantum Phase Transition

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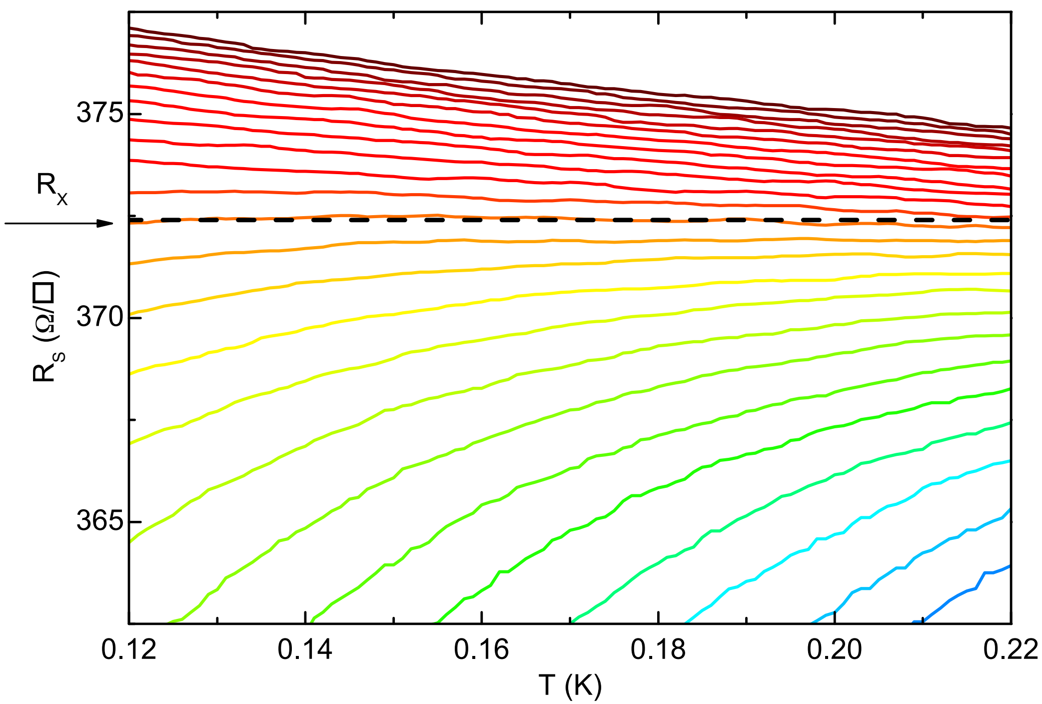
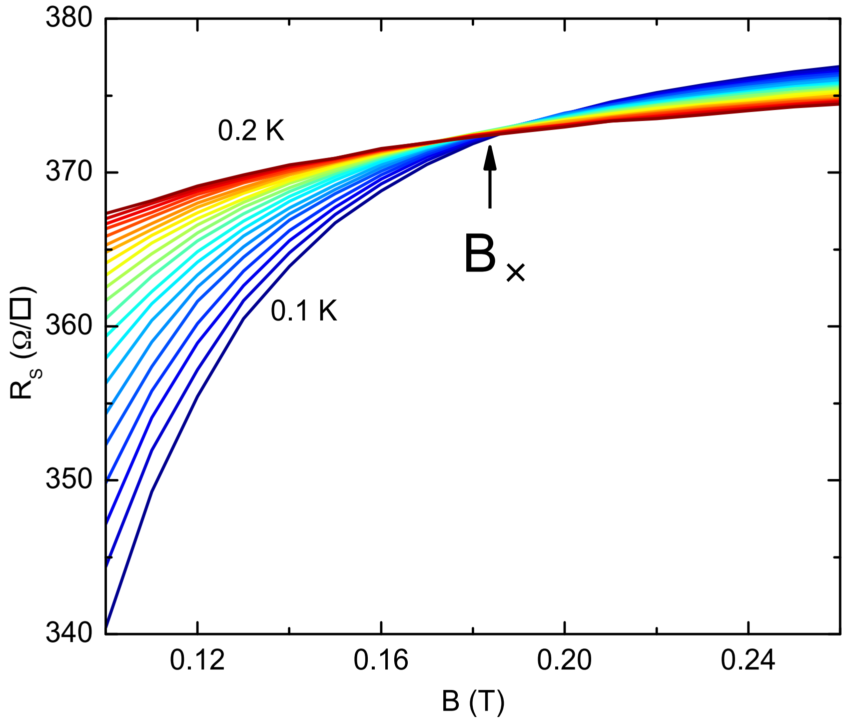
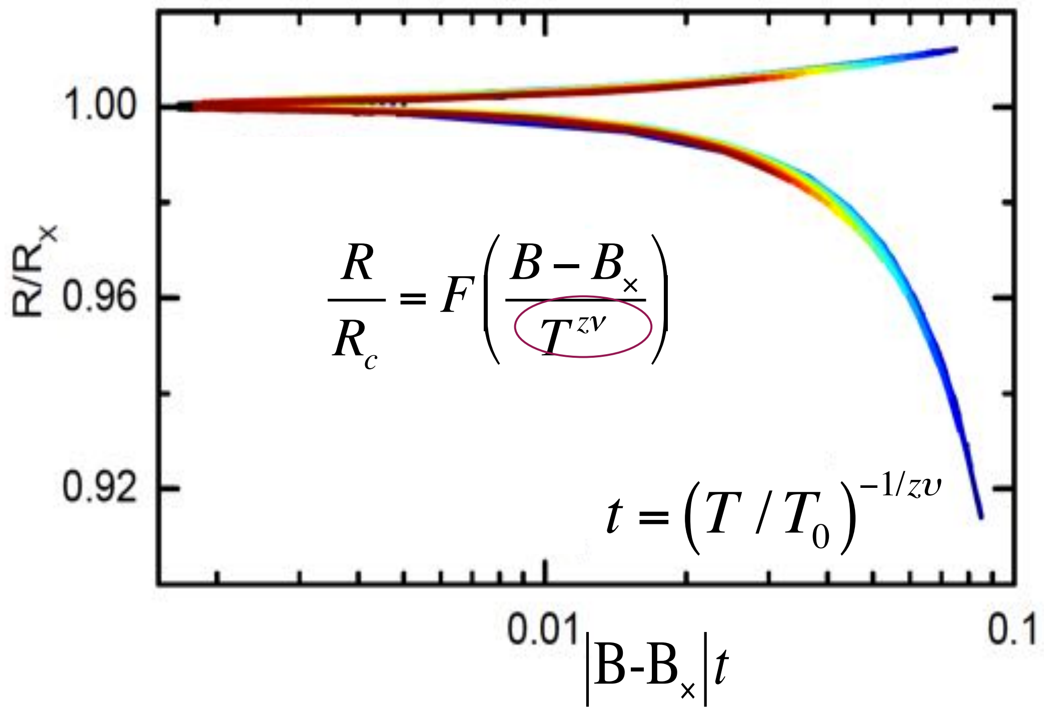




➡ Crossing point at $B_\times$: a first signature of a quantum phase transition

Scaling and critical exponents

- Finite size scaling analysis



Correlation length

$$\xi \approx |B - B_\times|^{-\nu}$$

Dynamical correlation length

$$\xi_\tau \approx |B - B_\times|^{-z\nu}$$

Biscaras et al, Nature Mat. 12, 542 (2013)

Scaling Behaviour with $z\nu$ = 2/3 (as in a-Bi, NbSi, …)

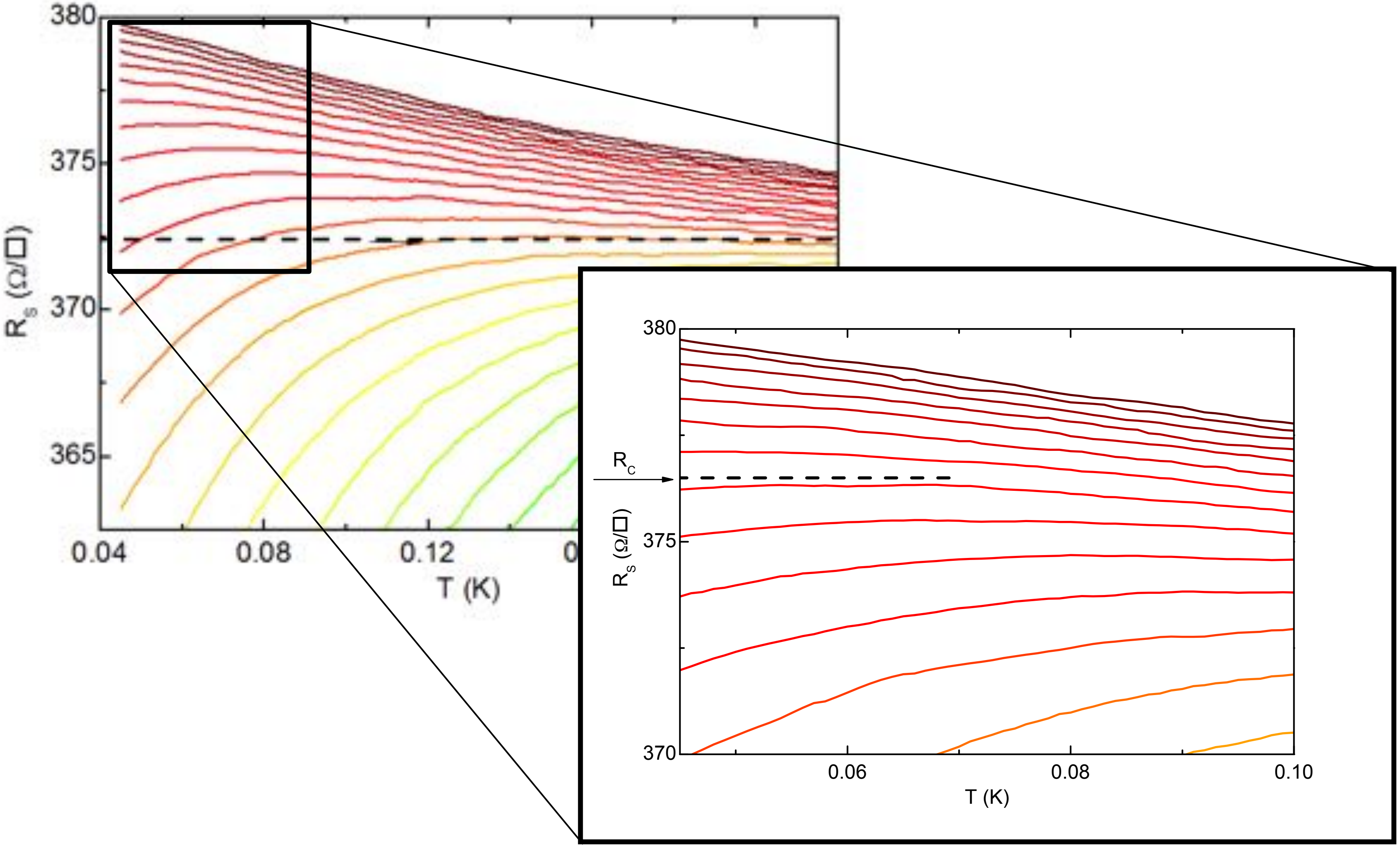
N. Markovic et al. PRL 1998
H. Aubin et al. PRB 2006

Superfluid transition in charged system : z=1

M Fisher PRL 1990
I F Herbut et al. PRL 2001

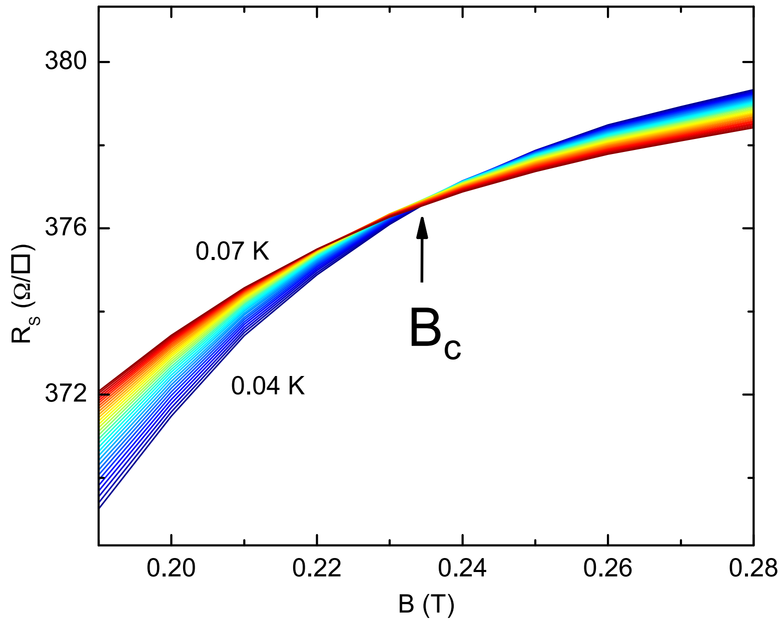
Universality Class : (2+1)D *XY* in the clean limit : ν = 2/3 (Quantum Phase Fluctuations)

A true quantum Phase Transition ?



➡ Scaling does not work at low temperature !

Scaling at lower temperature

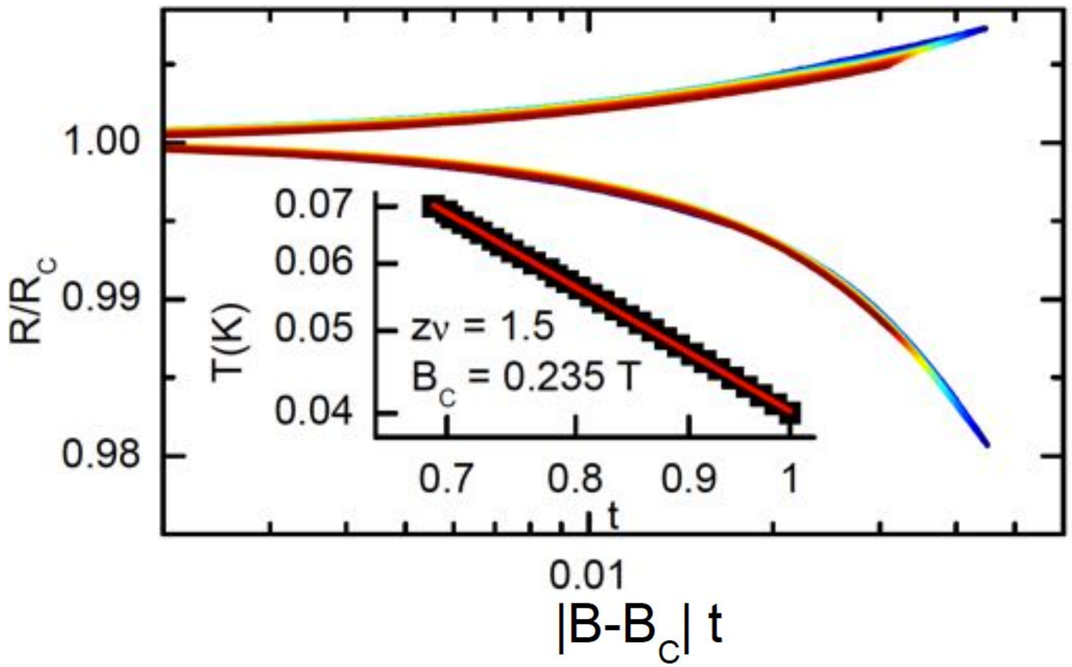


- Crossing point at B_c

$B_c > B_\times$

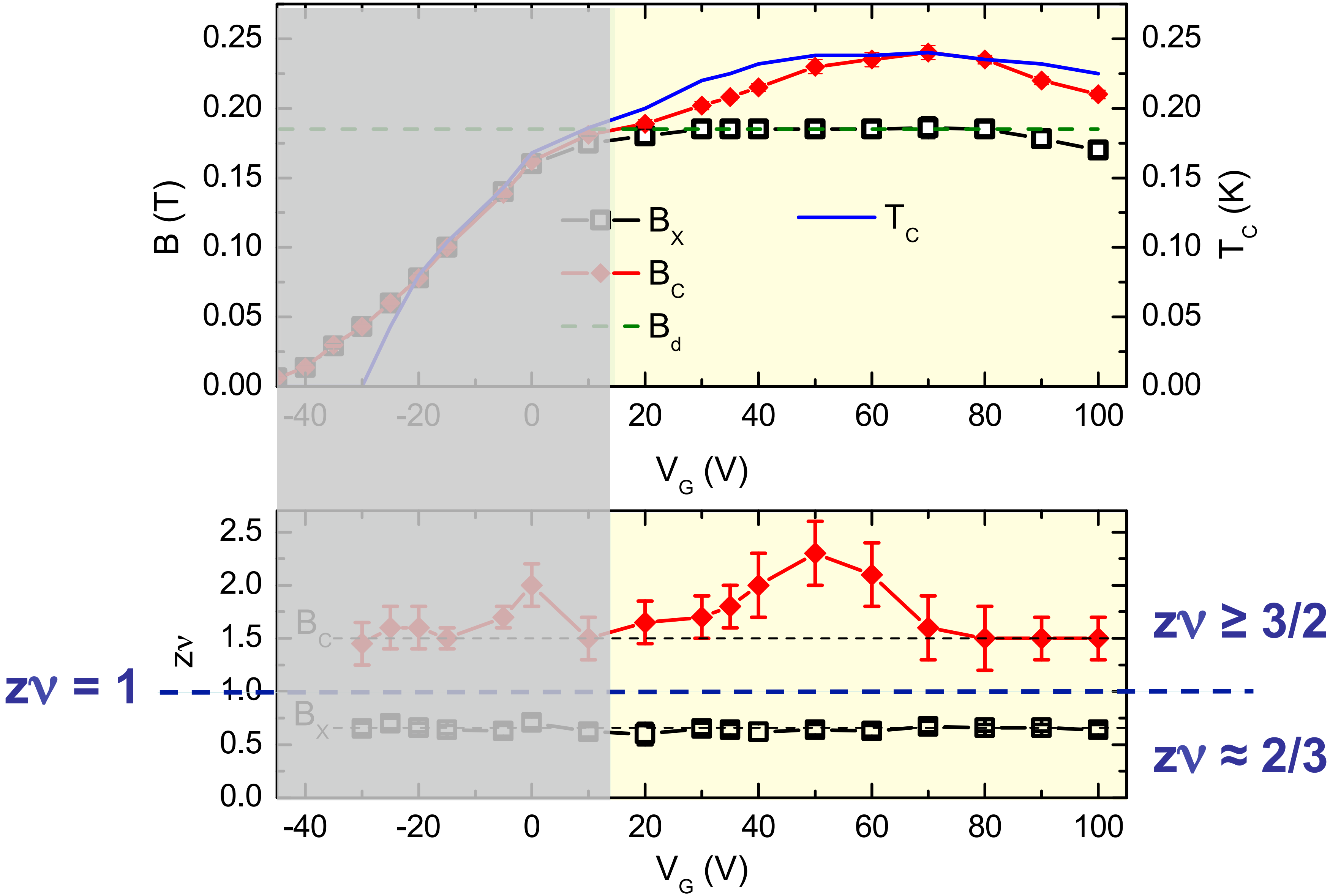
- Finite size scaling analysis

➡ Critical exponent $z\nu \approx 3/2$



Biscaras et al, Nature Mat. 12, 542 (2013)

Critical exponents as a function V_G

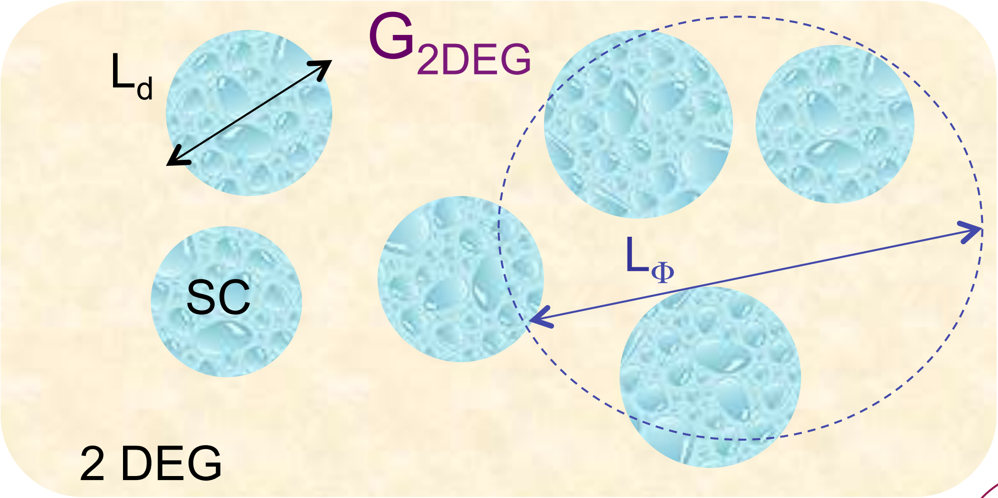


➡ Multiple Critical Behavior (B_x & B_c) associated to different critical exponents

Multiple Quantum Critical Behaviors in 2D SC

■ Superconducting puddles in a 2DEG matrix

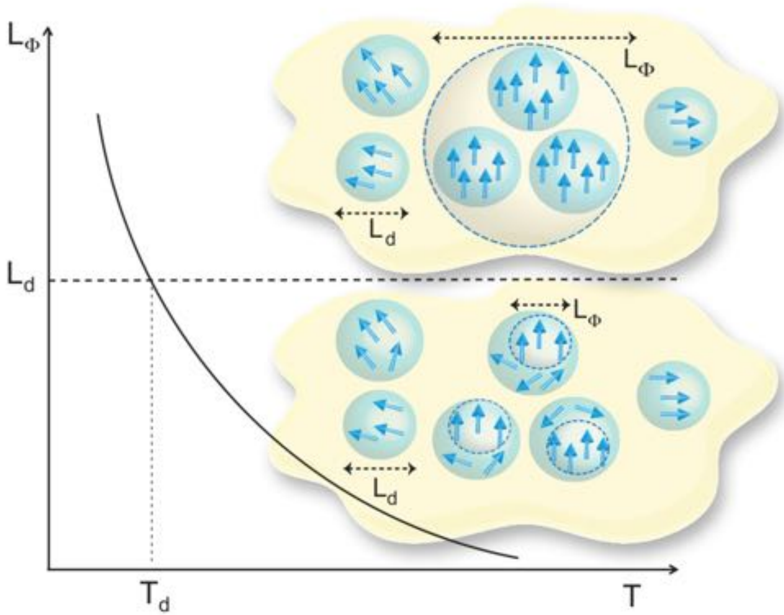
Spivak et al, PRB 2008



- Characteristic puddle size L_d ~200 nm
- Puddles coupled by Josephson through G_{2DEG}
- Phases fluctuations in the puddles AND between puddles : two critical fields

■ Divergence of the thermal dephasing length $L_\Phi \sim T^{-1/z}$

if z=1



➡ Low temperature $T < T_d$

$L_\Phi > L_d$ "disordered" system

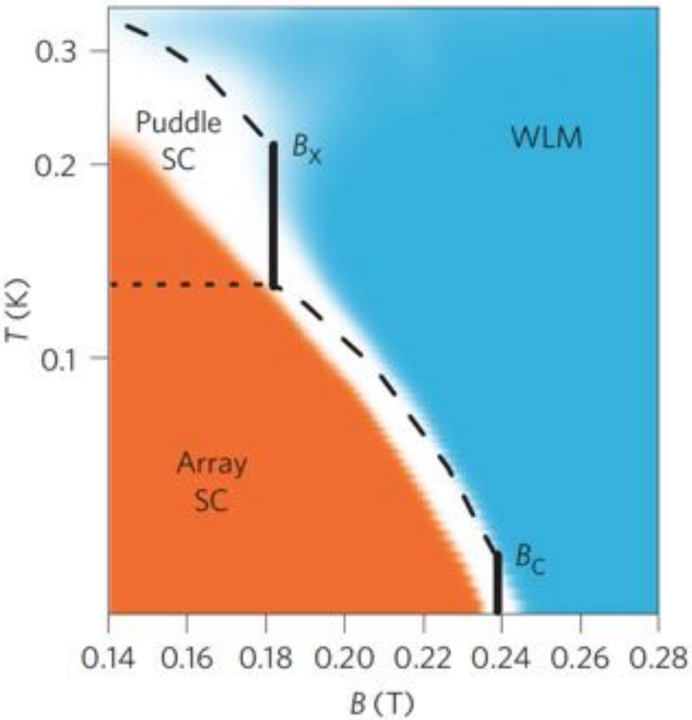
$\nu \geq 3/2$ Harris criteria

➡ High temperature $T > T_d$

$L_\Phi < L_d$ "clean" system

$\nu \approx 2/3$

Multiple Quantum Critical Behaviors in 2D SC

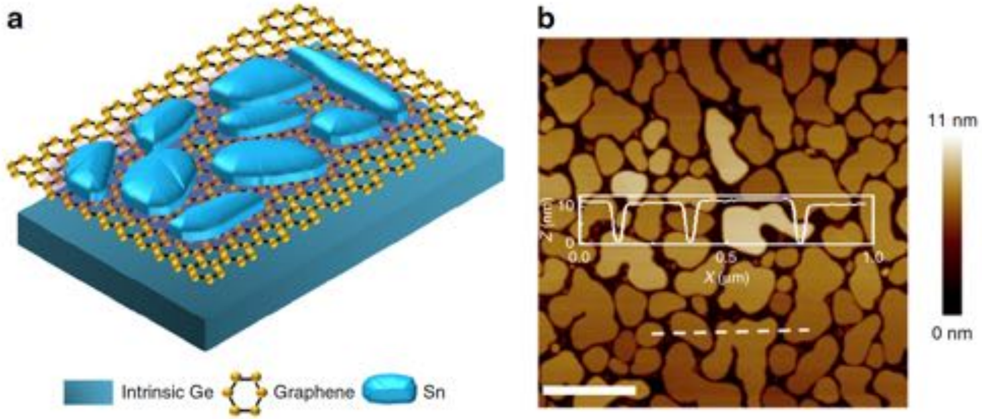


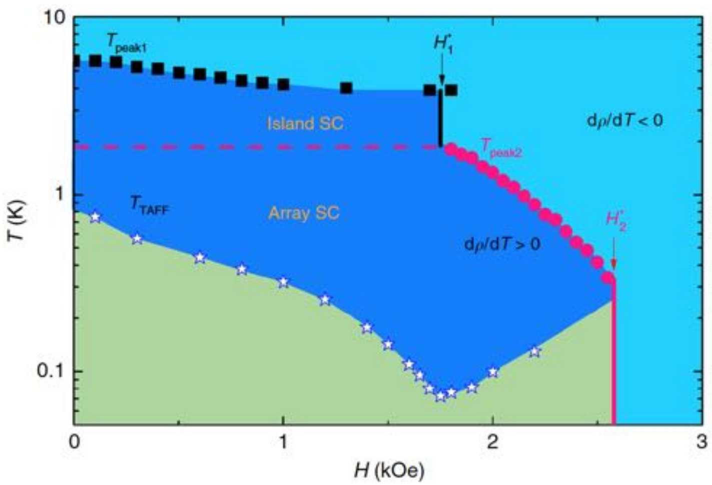
Biscaras et al, Nat Mat (2013)

ARTICLE

DOI: 10.1038/s41467-018-04606-w OPEN

Double quantum criticality in superconducting tin arrays-graphene hybrid

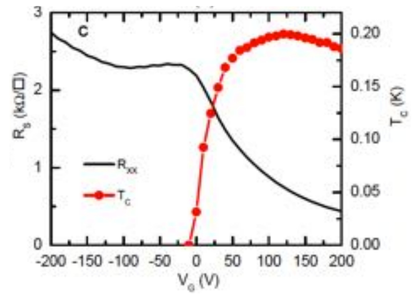




Sun et al, Nat Com (2018)

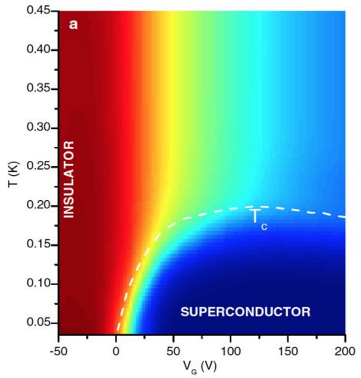
Outline

Tunable superconductivity in oxide 2DEG



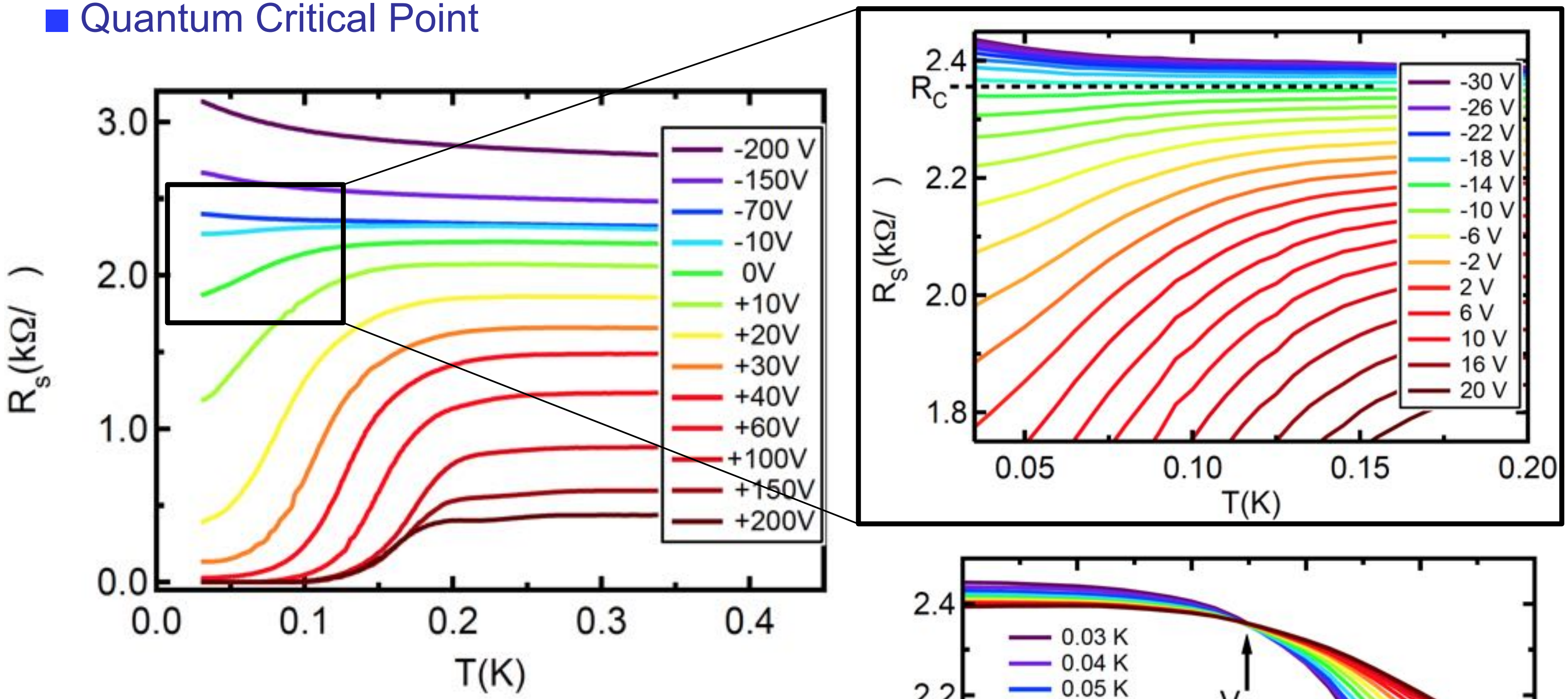
Quantum phase transition in magnetic field

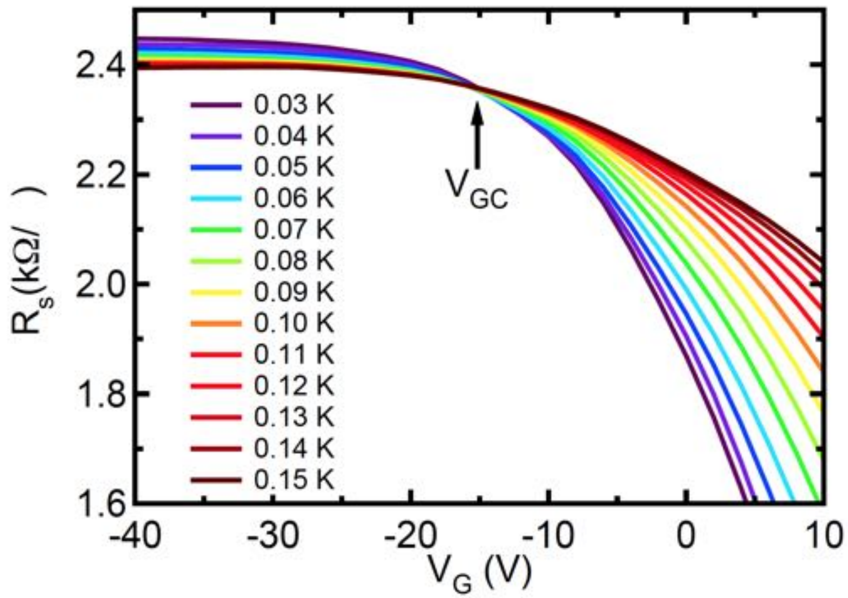
Quantum phase transition in gate voltage



Gate voltage driven Quantum Phase Transition

■ Quantum Critical Point

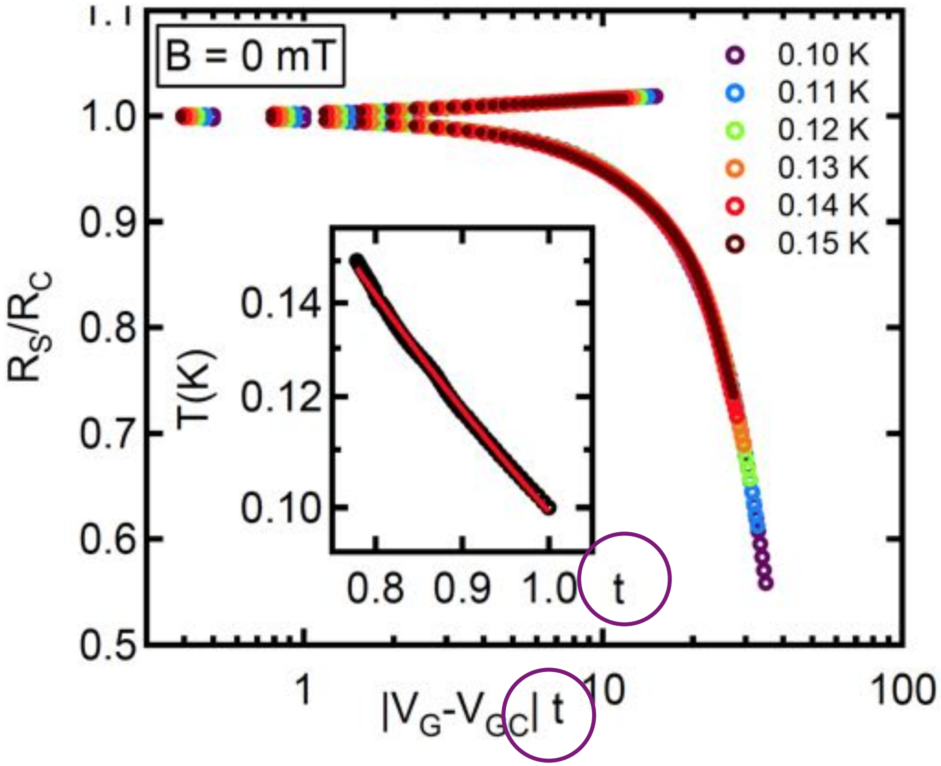




Critical resistance R_c and Voltage V_{GC}

Gate voltage driven Quantum Phase Transition

■ Finite size scaling analysis



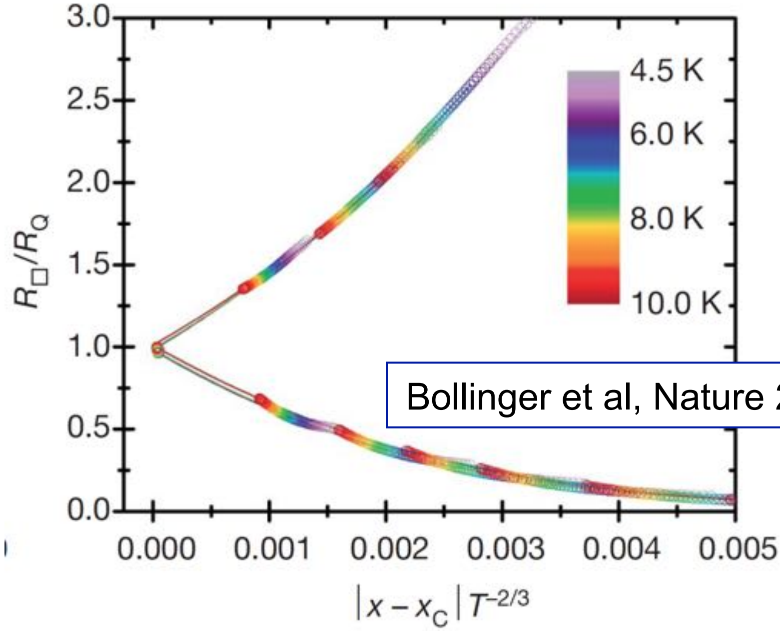
■ Scaling function and parameters

$$\frac{R_S}{R_c} = F\left(\frac{V_G - VGc}{T^{z\nu}}\right) \qquad t = \left(\frac{T}{T_0}\right)^{\left(-1/z\nu\right)}$$

■ Critical exponents

$z\nu \approx 3/2$

➡ also observed in LSCO



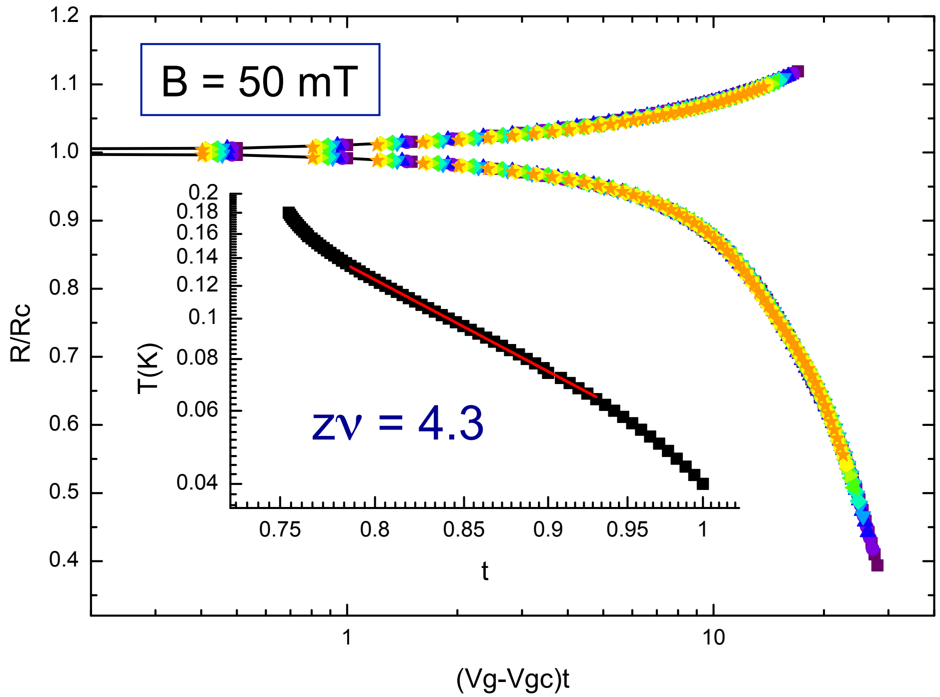
➡ if z = 1, ν = 3/2

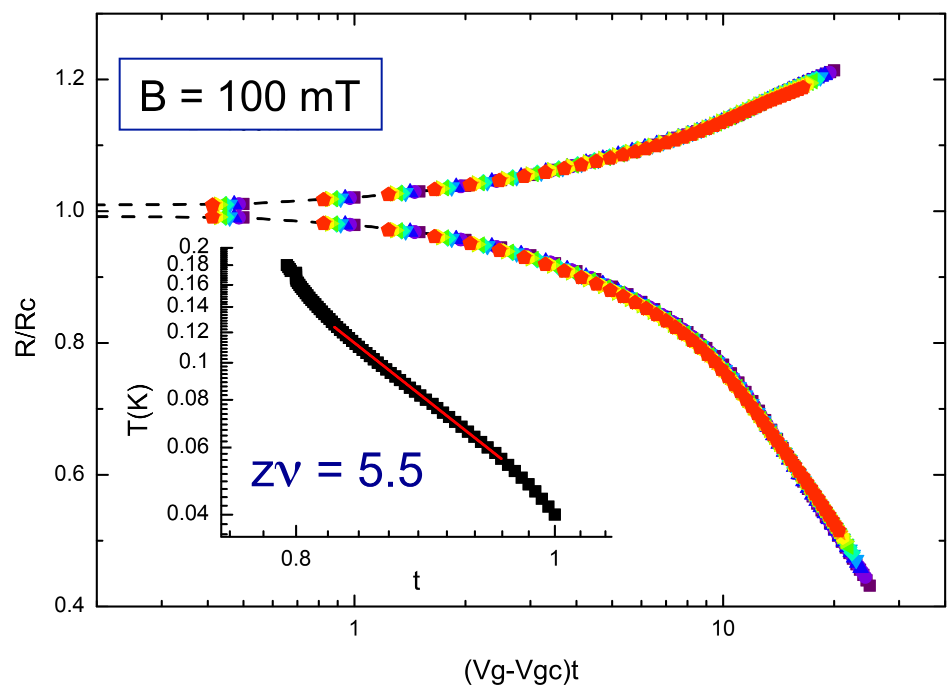
➡ **not classical (ν = 4/3) nor quantum (ν = 7/4) percolation**

➡ **possible electronic phase separation**

Scaling for different magnetic fields

■ Conventional scaling

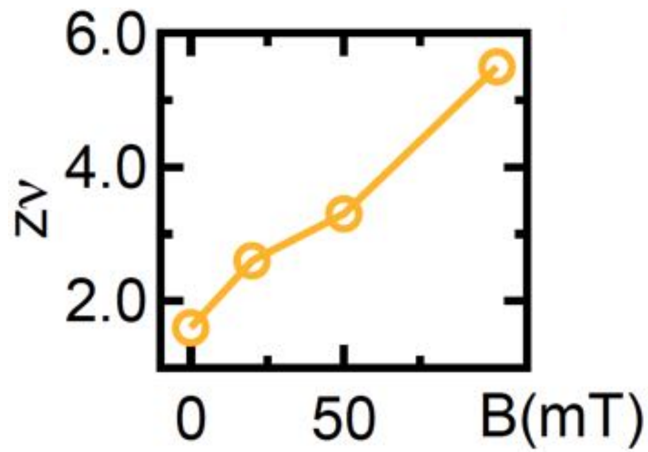




■ Problems

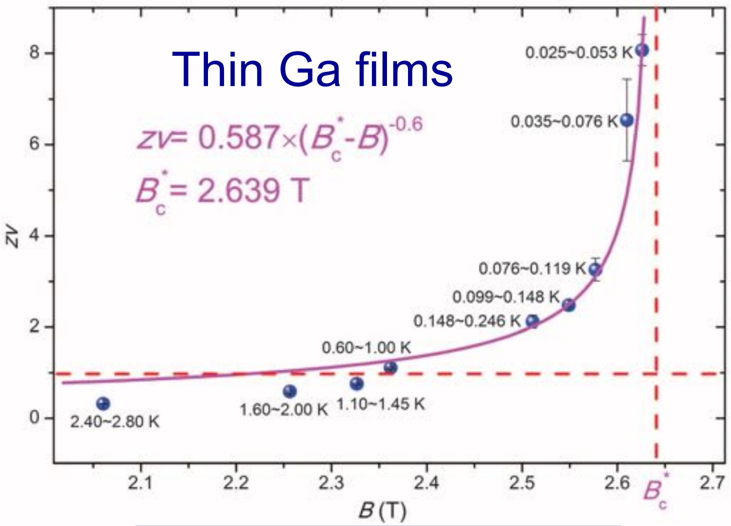
➡ zν varies with magnetic field

➡ Difficult to extract a single zν value

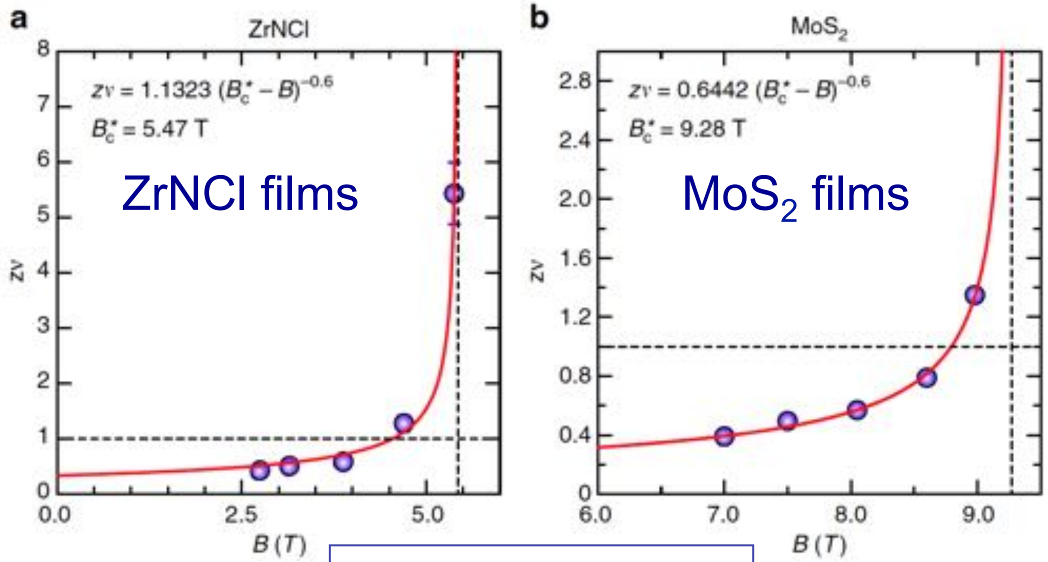


Quantum Griffiths phase transition

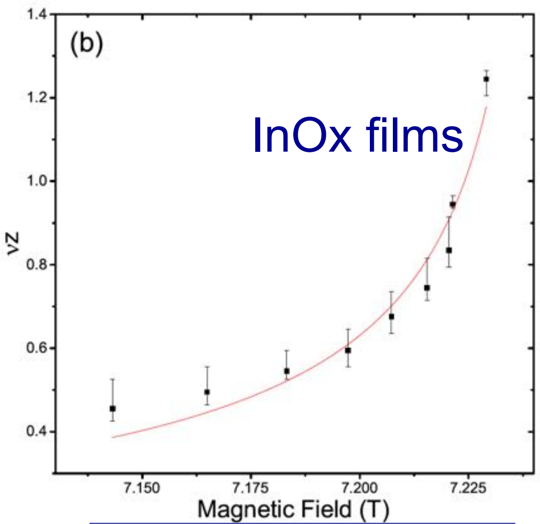
- Recent results in **magnetic field** driven transition



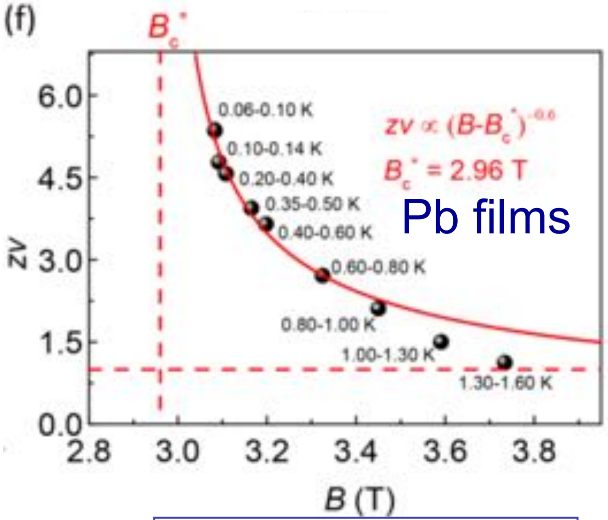
Ying Xing et al. Science (2015)



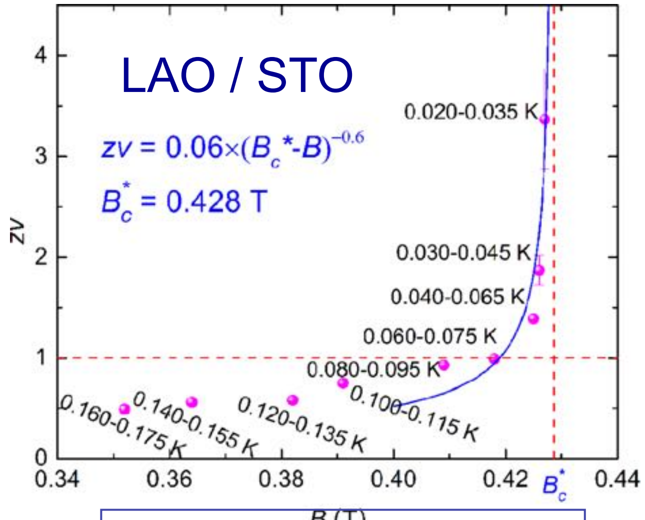
Saito et al, Nat Com 2018



Lewellyn et al, arXiv 2018



Liu et al, arXiv 2018



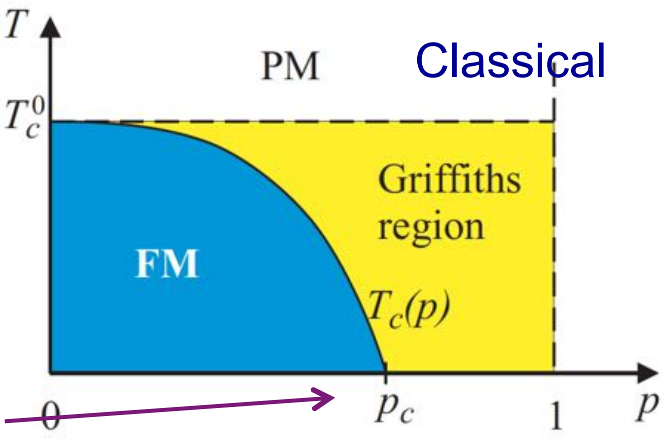
Ying Xing et al. PRB (2016)

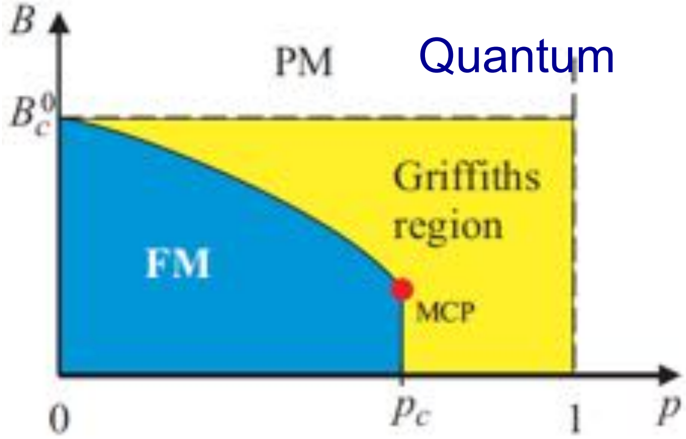
Quantum Griffiths Phase

Vojta AIP Proceedings (2013)

- Rare events and the Griffiths phase

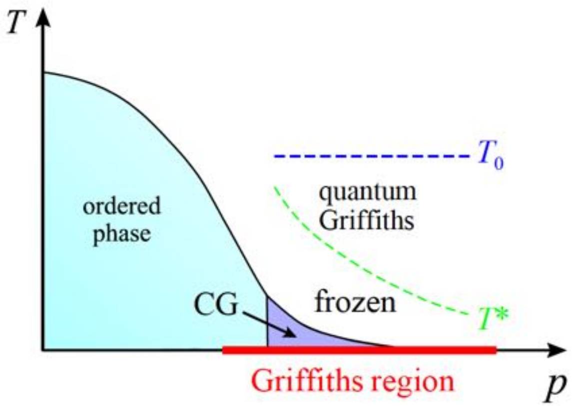
Mixing FM & non FM



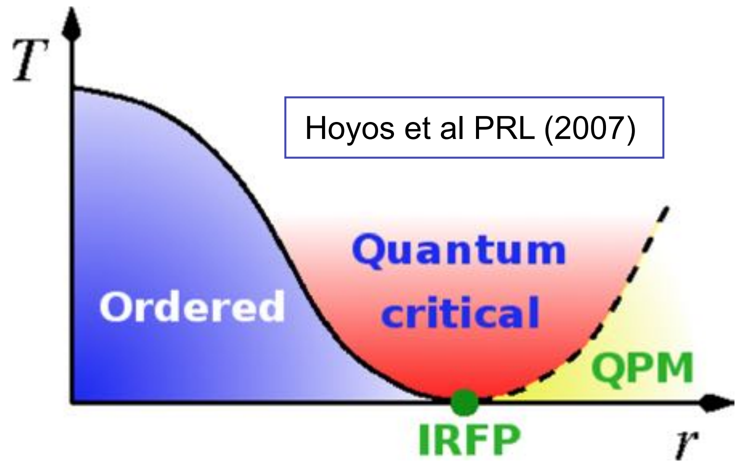


Random transverse field Ising chain

- Smeared transition



Hoyos et al PRL (2007)

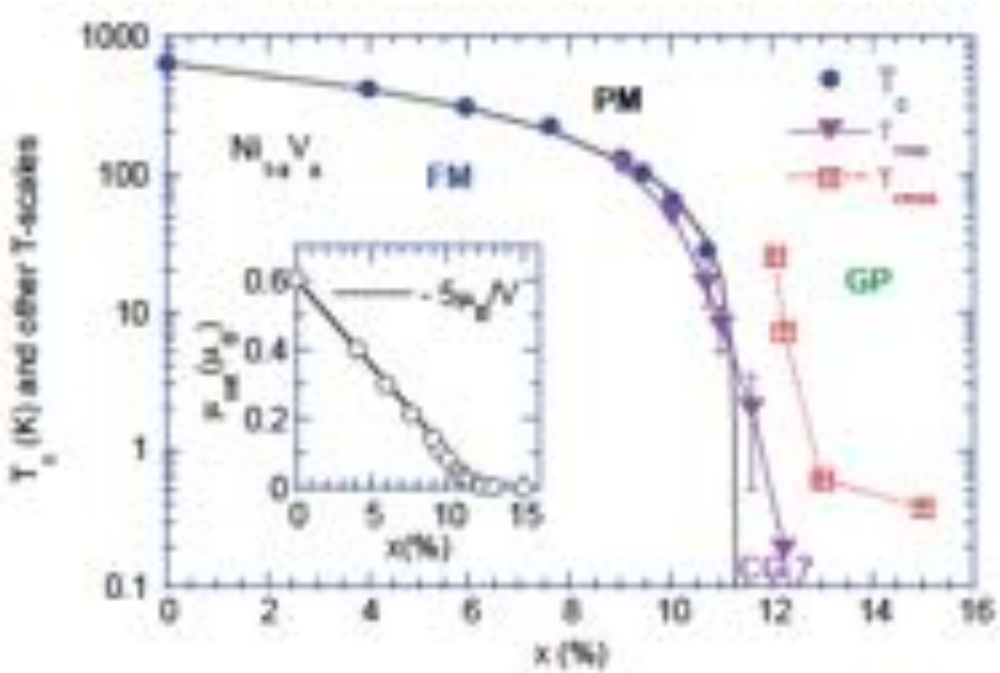


- Critical exponents vary : infinite randomness

$$z' \approx |V_G - V_{GC}|^{-\nu\psi}$$

Griffiths Phases

- Magnetic systems



Ubaid-Kassis et al PRL (2010)

- Biological systems

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Griffiths phase and long-range correlations in a biologically motivated visual cortex model

Received: 30 January 2016

M. Girardi-Schappo[1], G. S. Bortolotto[1], J. J. Gonsalves[1], L. T. Pinto[2] & M. H. R. Tragtenberg[1]

ARTICLE

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DOI: 10.1038/ncomms3521

Griffiths phases and the stretching of criticality in brain networks

Paolo Moretti[1] & Miguel A. Muñoz[1]

- Superconducting systems

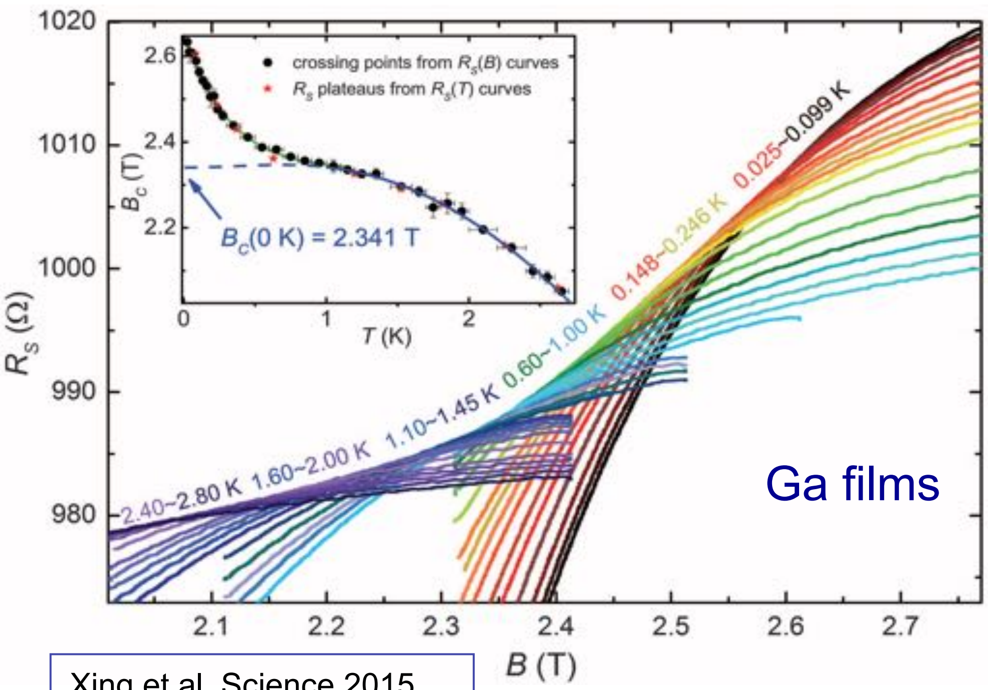
PRL **101**, 035701 (2008) PHYSICAL REVIEW LETTERS week ending 18 JULY 2008

Infinite Randomness Fixed Point of the Superconductor-Metal Quantum Phase Transition

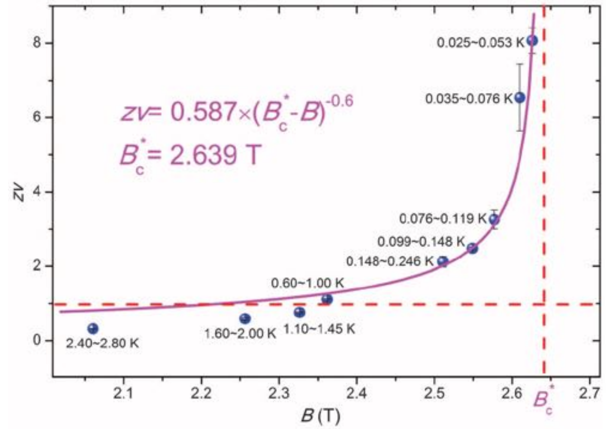
Adrian Del Maestro, Bernd Rosenow, Markus Müller, and Subir Sachdev

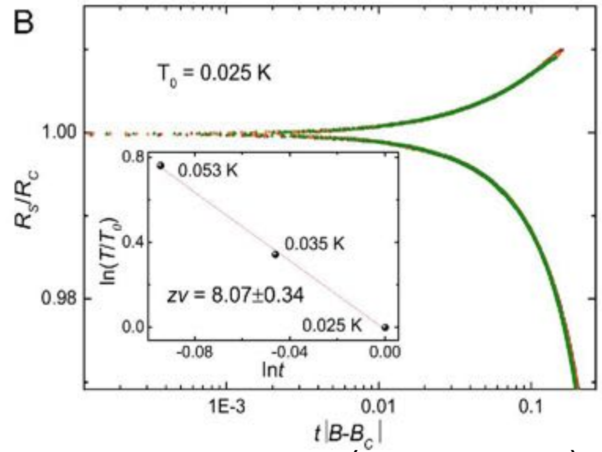
Quantum Griffiths phase transition

■ Crossing points ?



Xing et al, Science 2015





$$\frac{R_S}{R_c} = F\left(\frac{V_G - V_{GC}}{T^{z'\nu}}\right)$$

➡ Temperature range for each crossing point ?

➡ The critical exponent depends on the distance to the QCP

$$z' \approx \left|V_G - V_{GC}\right|^{-\nu\psi}$$

$$\psi \approx 0.6$$

Quantum Griffiths phase transition

■ Diverging dynamical exponent

$$z' = \frac{A}{|V_G - V_{GC}(B_i)|^{\psi\nu}} + z_\infty.$$

B_i is the magnetic field

z_∞ is the "clean" value of z

■ New scaling function

$$\tilde{R} = \frac{R_S}{R_C}$$ is a scaling function of $\Delta V \left(\frac{T}{T_0}\right)^{-1/z'\nu}$

$$\Delta V = |V_G - V_G^c(B_i)|$$

New scaling function

$$\tilde{\tilde{R}}\left(\left(\frac{\Delta V}{\Delta V_0}\right)^{z'\nu}\frac{1}{T}\right)$$

Rescaling procedure

$$\tilde{V}(\Delta V) = \left(\frac{\Delta V}{\Delta V_0}\right)^{z'(\Delta V)\nu} = \left(\frac{\Delta V}{\Delta V_0}\right)^{\frac{A\nu}{(\Delta V/\Delta V_0)^{\nu\psi}}+\nu z_\infty}$$

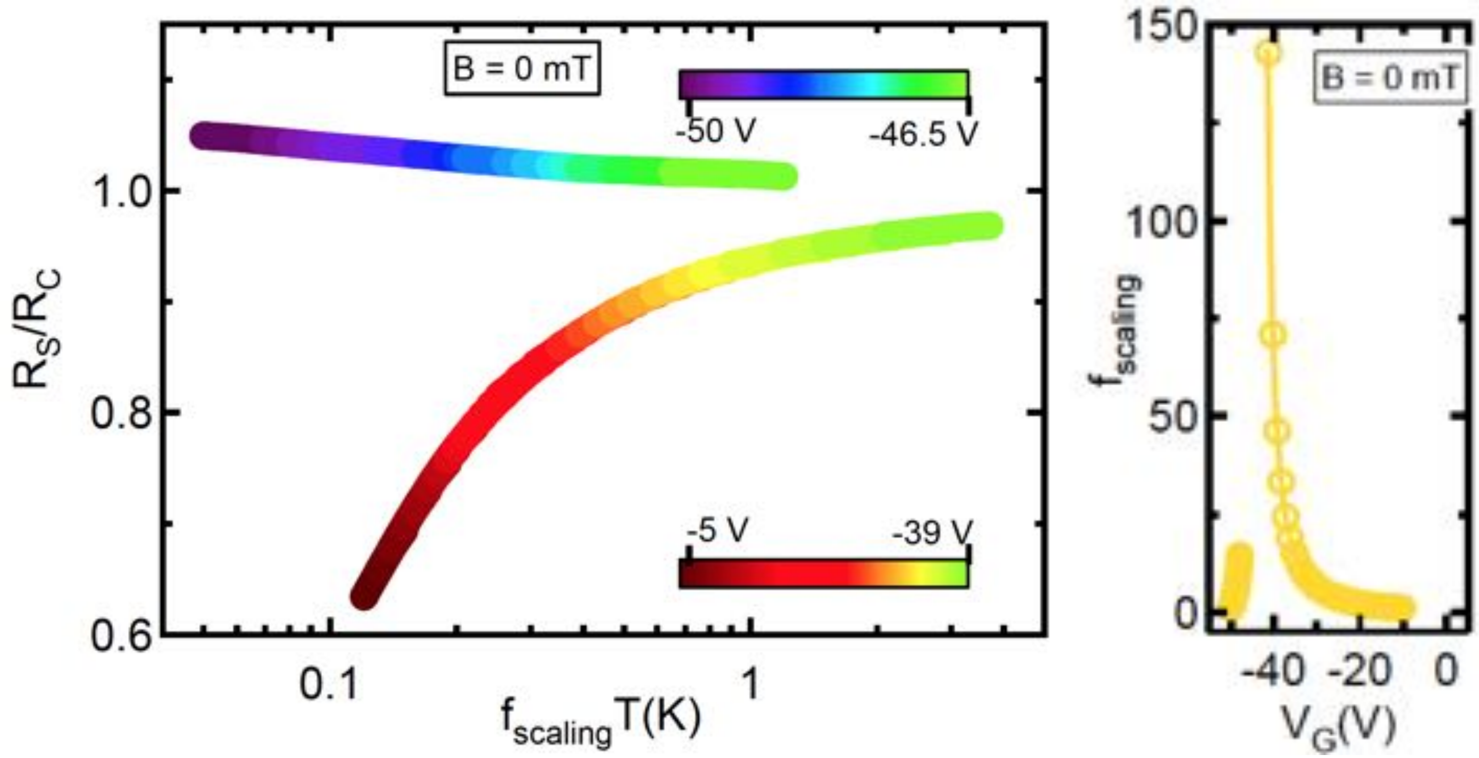
$$\tilde{V}(\Delta V_0) = \left(\frac{\Delta V_0}{\Delta V_0}\right)^{z'(\Delta V)\nu} = 1$$

■ Rescaling the data

$$\ln \tilde{V} = \nu\left(\frac{A}{(\Delta V/\Delta V_0)^{\nu\psi}} + z_\infty\right)(\ln \Delta V - \ln \Delta V_0)$$

Quantum Griffiths phase transition

- Rescaling the data



- Two branches

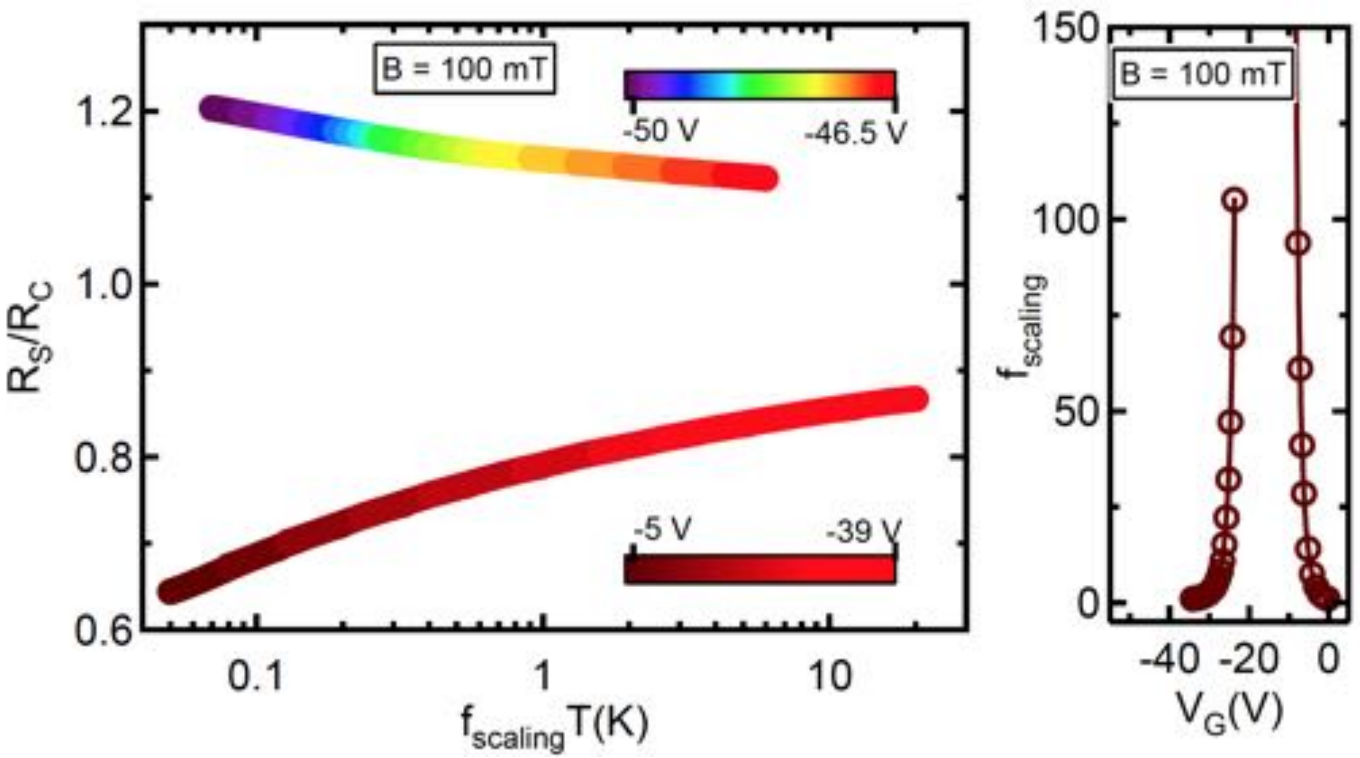
$$z'_{\pm} = A_{\pm}/\Delta V^{\psi\nu} + z_{\infty}$$

$$z_{\infty}\nu = \frac{3}{2}$$

$$\psi = 0.5$$

Quantum Griffiths phase transition

- Scaling for different magnetic fields



- Two branches

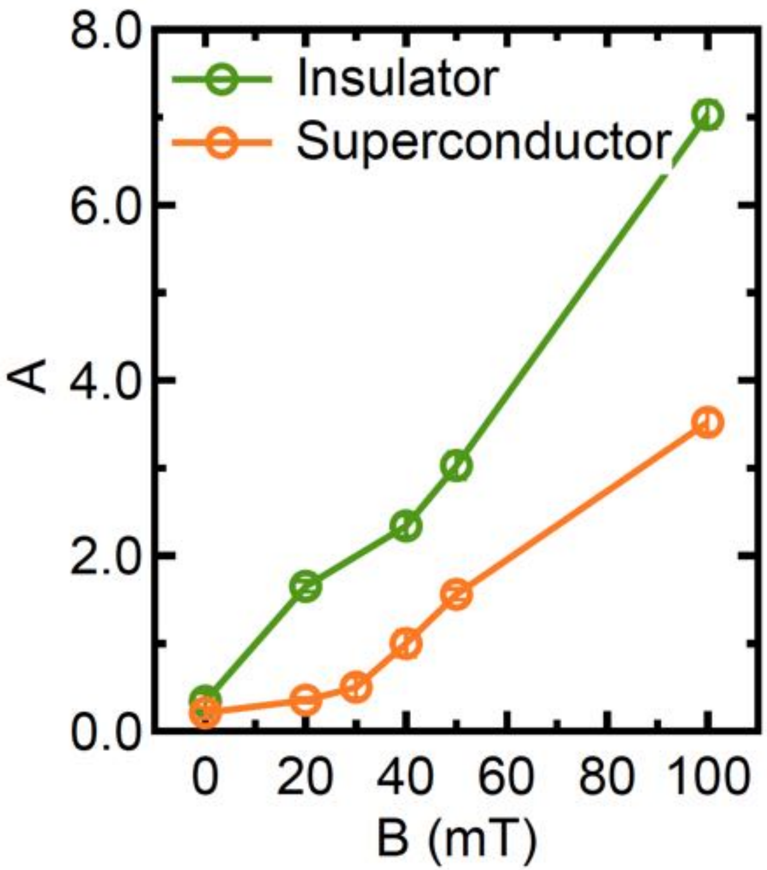
$$z'_{\pm} = A_{\pm}/\Delta V^{\psi\nu} + z_{\infty}$$

$$z_{\infty}\nu = \frac{3}{2}$$

$$\psi = 0.5$$

Quantum Griffiths phase transition

- Entering the Giffiths phase in magnetic field



$$z'_{\pm} = A_{\pm}/\Delta V^{\psi\nu} + z_{\infty}$$

$$z_{\infty}\nu = \frac{3}{2}$$

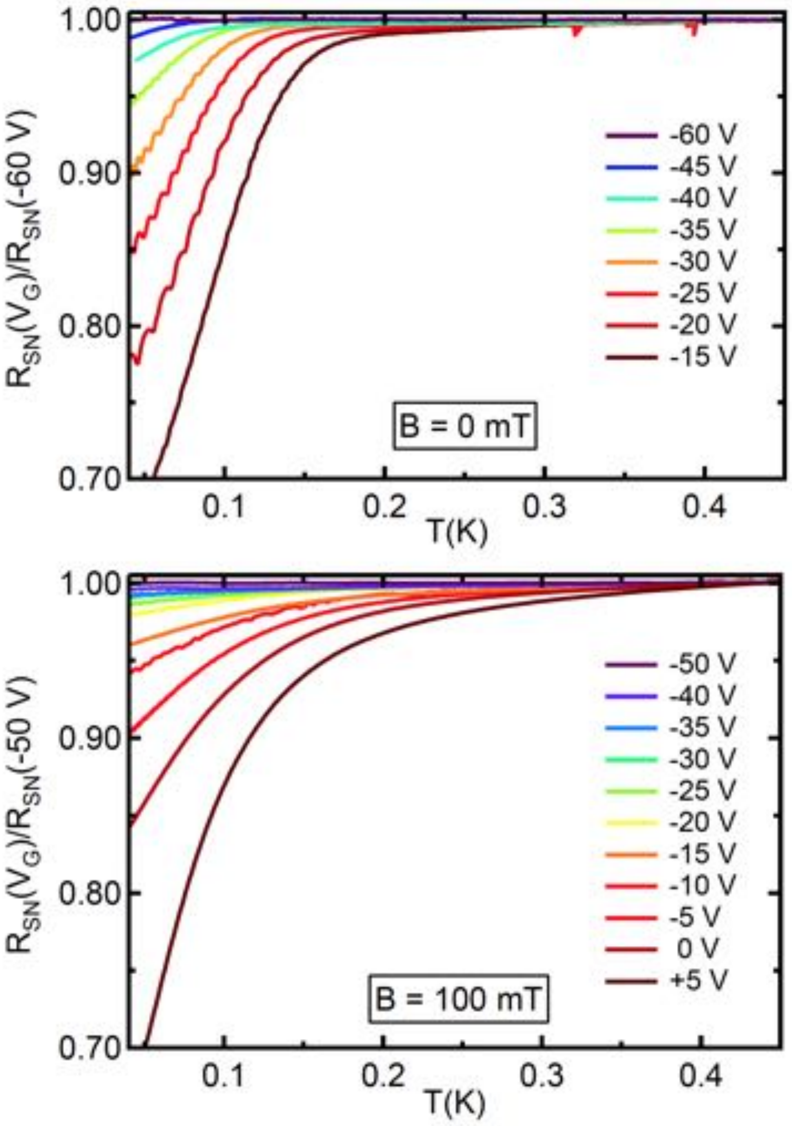
$$\psi = 0.5$$

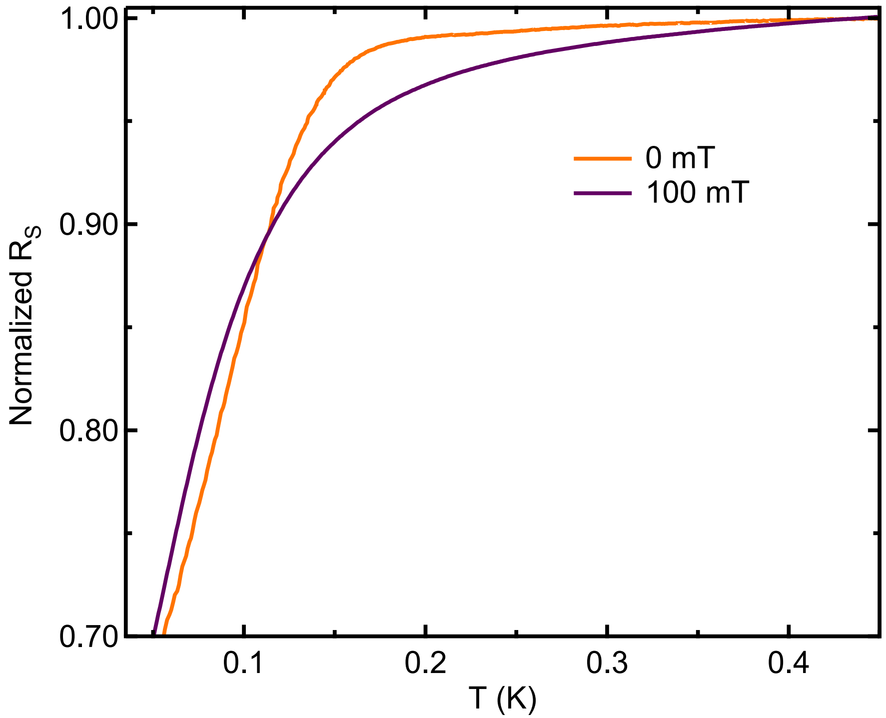
- Other signature of the Griffiths phase ?

Looking for rare events

Quantum Griffiths phase transition

■ Resistive transition in a magnetic field





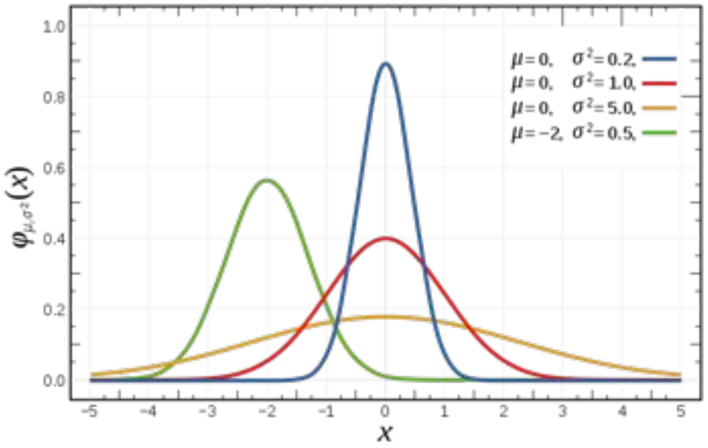
➡ Lower resistance in a magnetic field B

➡ SC contributions revealed under B

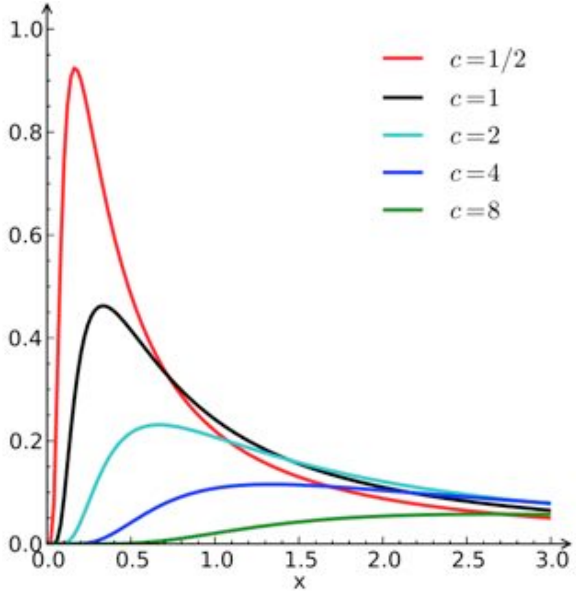
Levy statistics of rare events

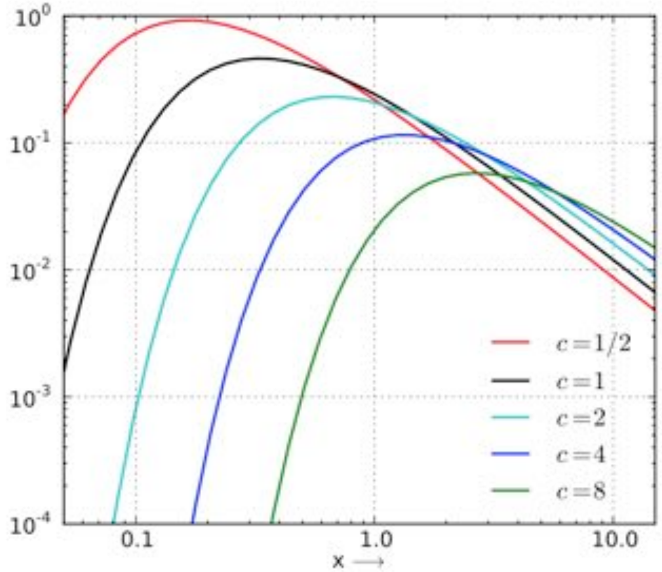
- Gaussian distributions

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



- Levy distributions





$$f(x; \mu, c) = \sqrt{\frac{c}{2\pi}} \frac{e^{-\frac{c}{2(x-\mu)}}}{(x-\mu)^{3/2}}$$

$$f(x; \mu, c) \sim \sqrt{\frac{c}{2\pi}} \frac{1}{x^{3/2}}$$

➡ Long tails

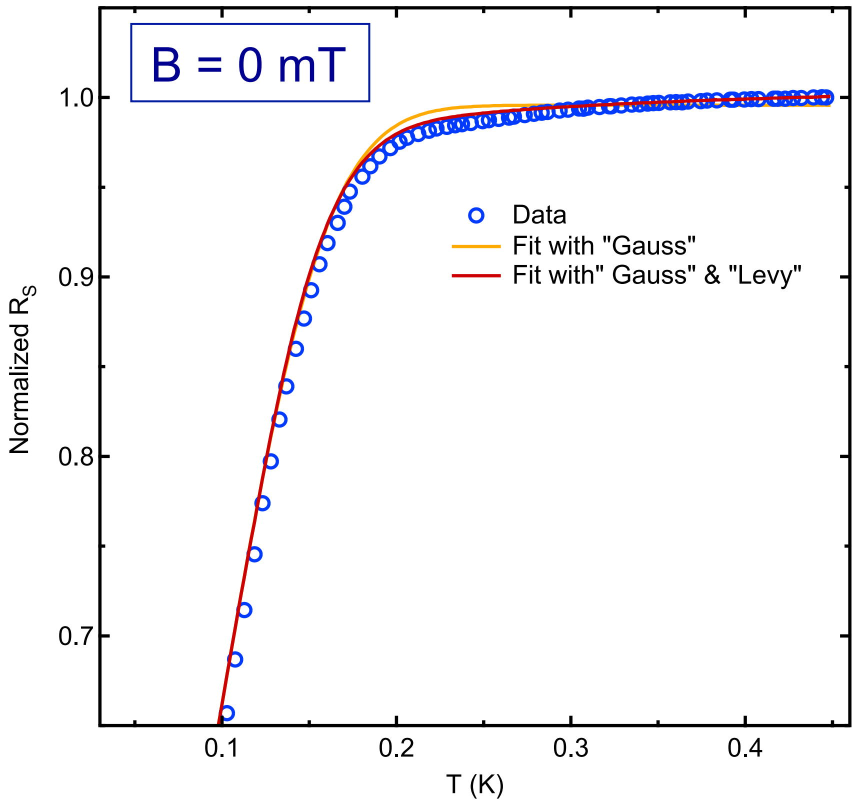
➡ Rare events

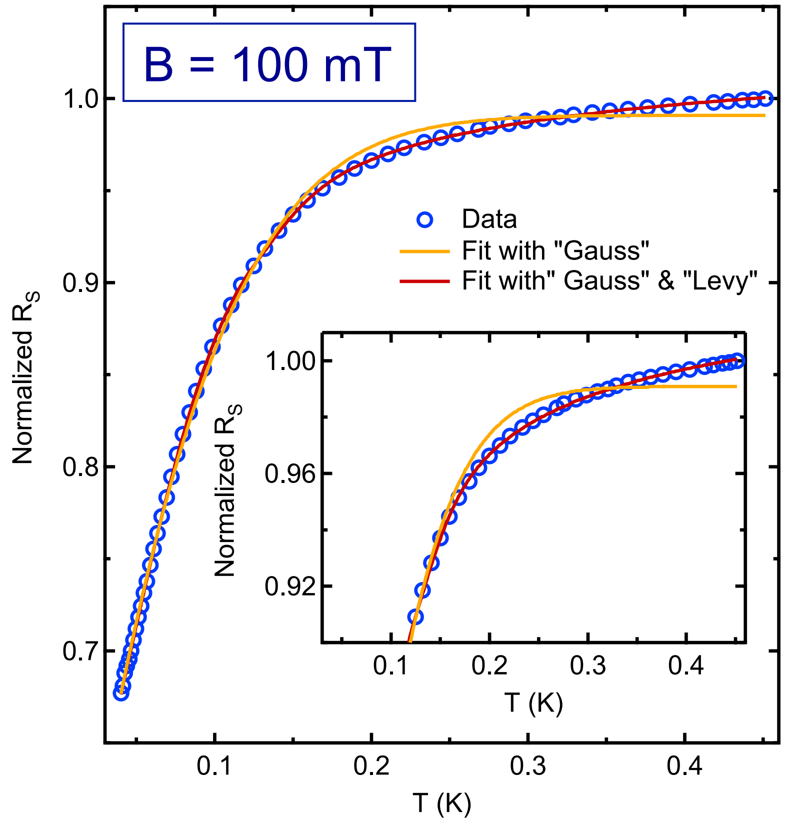
Effective medium theory

- Mixing between normal and superconducting phase

Gaussian distribution of Tc within a normal matrix : W_G, T_{CG}, ΔT_{CG}

Additional Levy distribution of Tc : W_l, T_{CL}, ΔT_{CL} for $B \neq 0$

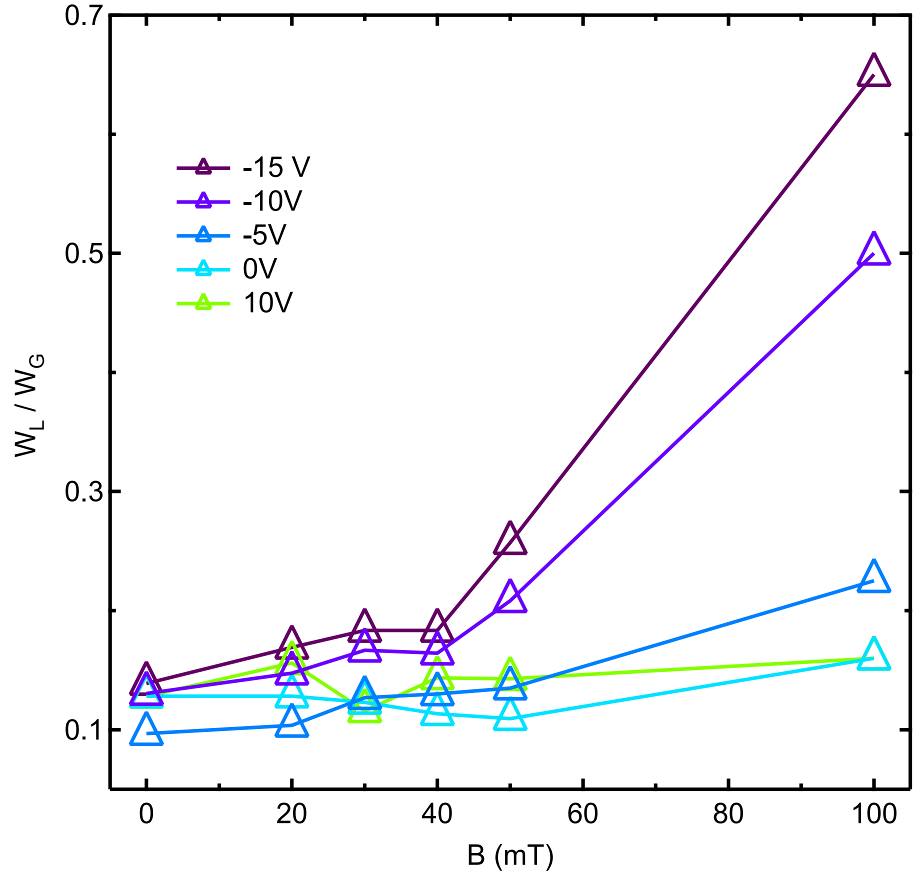




Effective medium theory

■ Relative weights : Levy vs Gauss

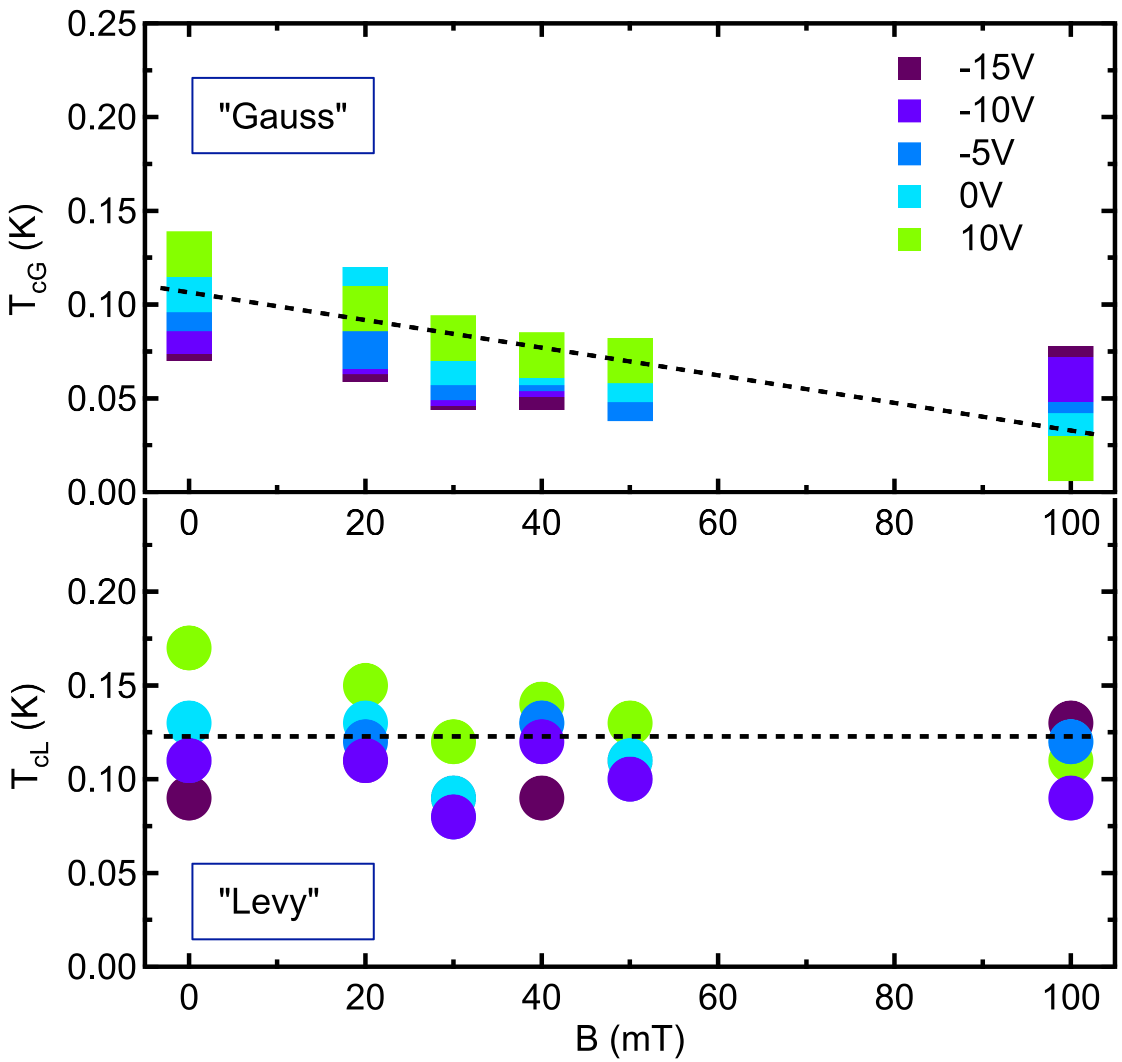
Levy (**rare events**) contribution increases with magnetic field

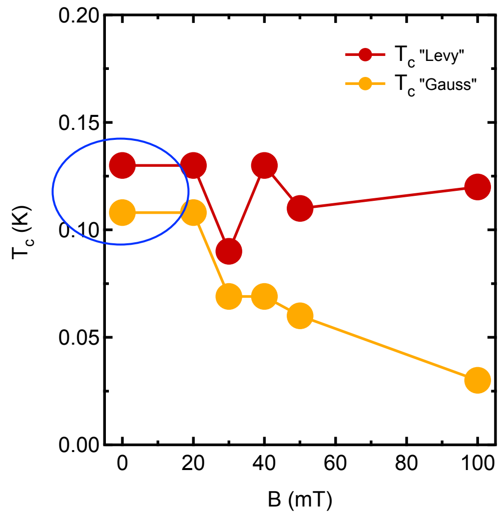


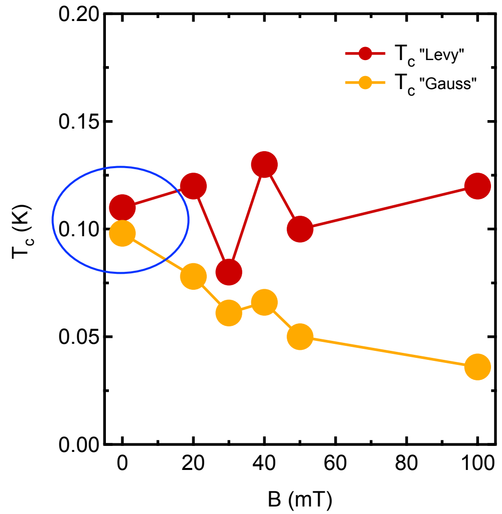
Effective medium theory

Evolution of Tc with magnetic field : Levy vs Gauss

Tc Gauss decreases but Tc Levy stays constant (roughly the $T_{CG}(B=0)$ value)







Griffiths phase and magnetic field

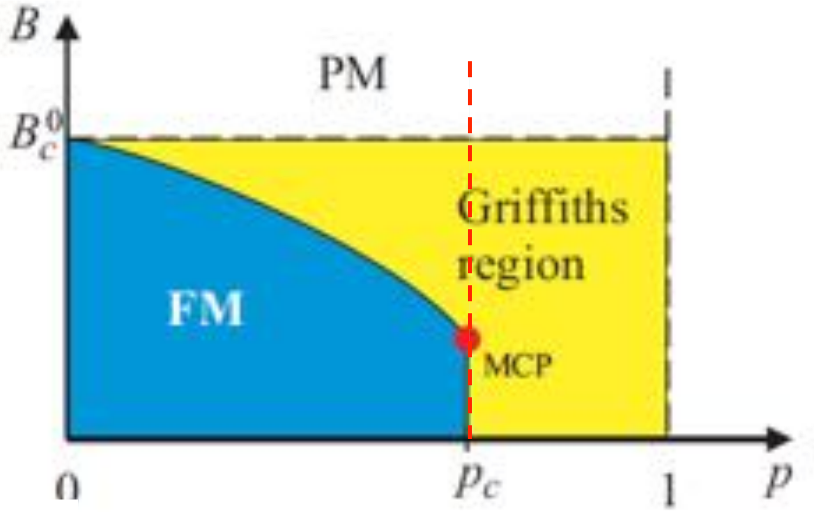
- Entering the Griffiths phase

➡ Enhanced Griffiths signature in magnetic field

➡ What phase ? Role of the magnetic field ?

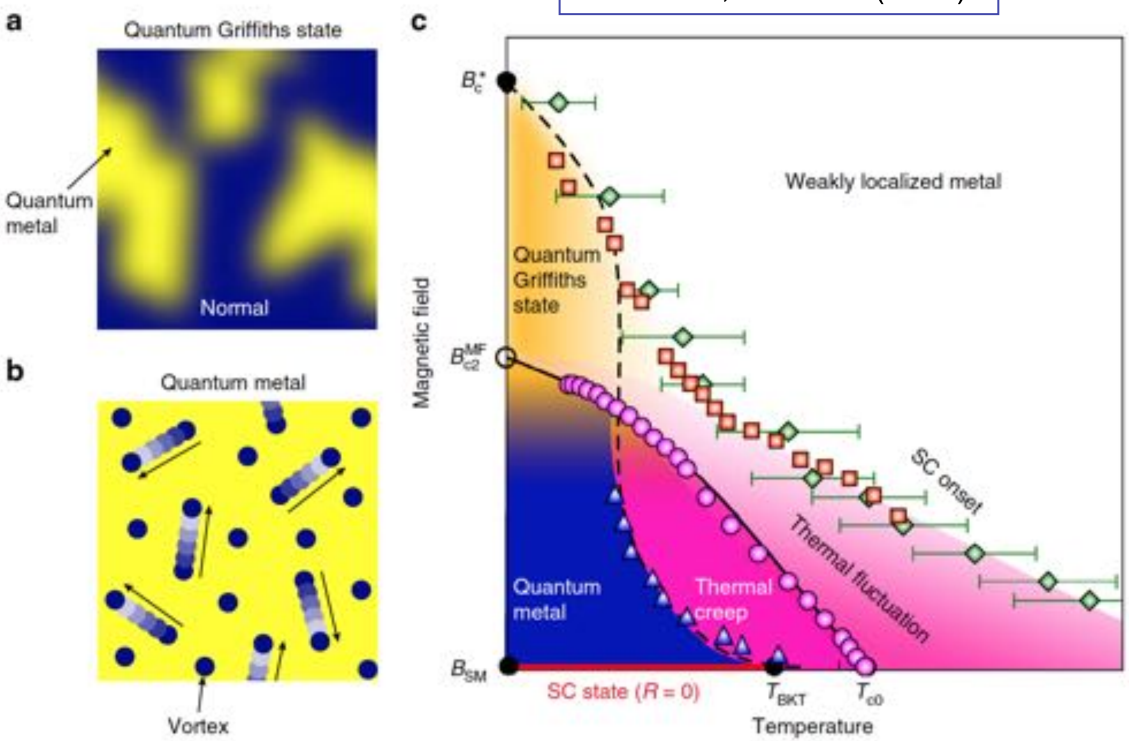
➡ Specific to LTO/STO ?

- Scenario in MoS_2



Vojta AIP Proceedings (2013)

Saito et al, Nat Com (2018)



Conclusions

- Tunable superconductivity
- Inhomogeneous superconductivity (meso scale)
- **Multiple criticalities**
- **Evidence of a Griffiths phase**
- **? Role of the magnetic field**