Superconductivity and quantum phase transition at oxides interface

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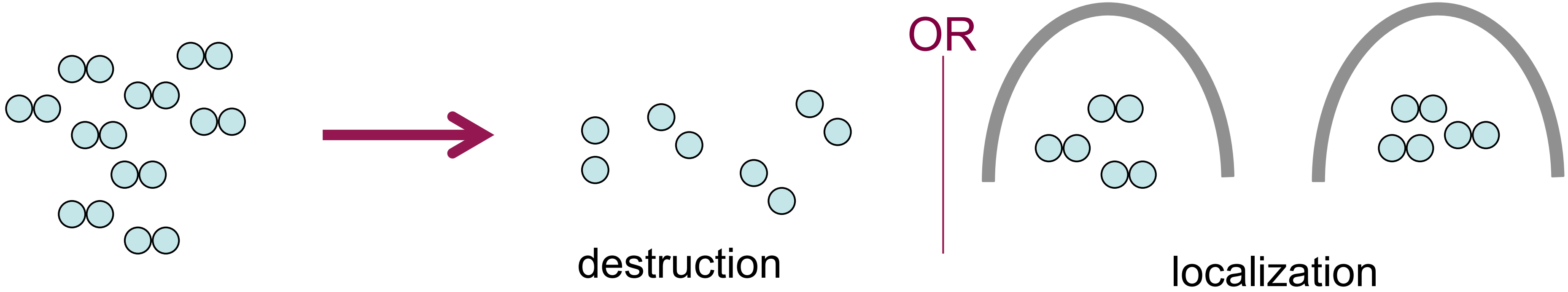
Quantum Phase Transition in a 2D superconductor

■ Superconductor-Insulator Quantum Phase Transition (QPT) in 2D

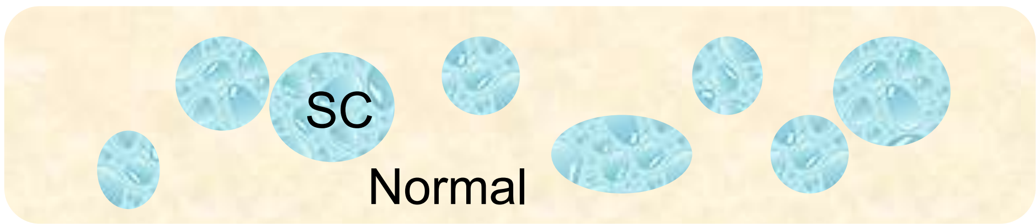
➡ Many experimental results

➡ Open questions

- Nature of the "Insulating State" : fermionic vs bosonic scenario



- Intrinsic mesoscopic disorder at the transition : homogeneous media ?



Mason et al, PRB 2001
Kapitulnik et al PRB 2001

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

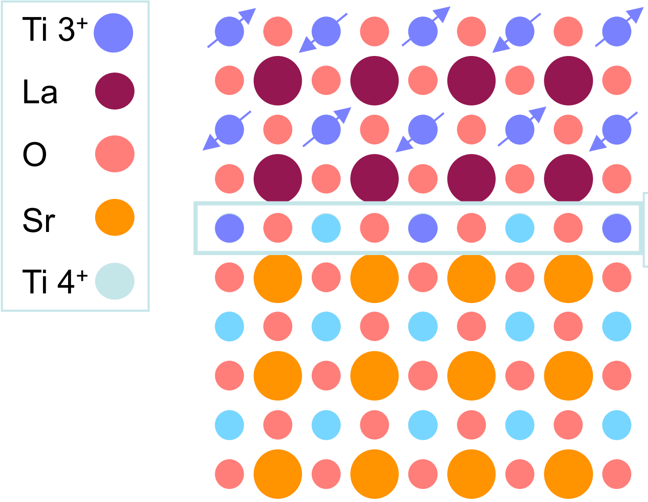
Multiple Quantum Criticalities ?

- Towards a 1D filamentary structure at the transition ?

Ioffe-Mezard PRL 2010, Goetz-Benfatto-Castellani PRL 2012 ⟵ cf Castellani's & Grilli's talks

2 DEG at oxides interfaces

$LaTiO_3$ / $SrTiO_3$



$LaTiO_3$

Mott Insulator

2 DEG $3. 10^{14}$ /cm^2

$SrTiO_3$

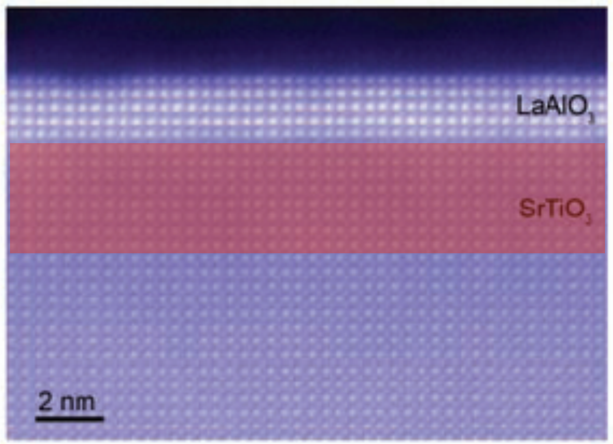
Band Insulator

Ohtomo et al Nature 2002

Hwang et al Physica E 2004

2 DEG at the interface

$LaAlO_3$ / $SrTiO_3$



1-10 nm

Mannhart et al, Science 2010

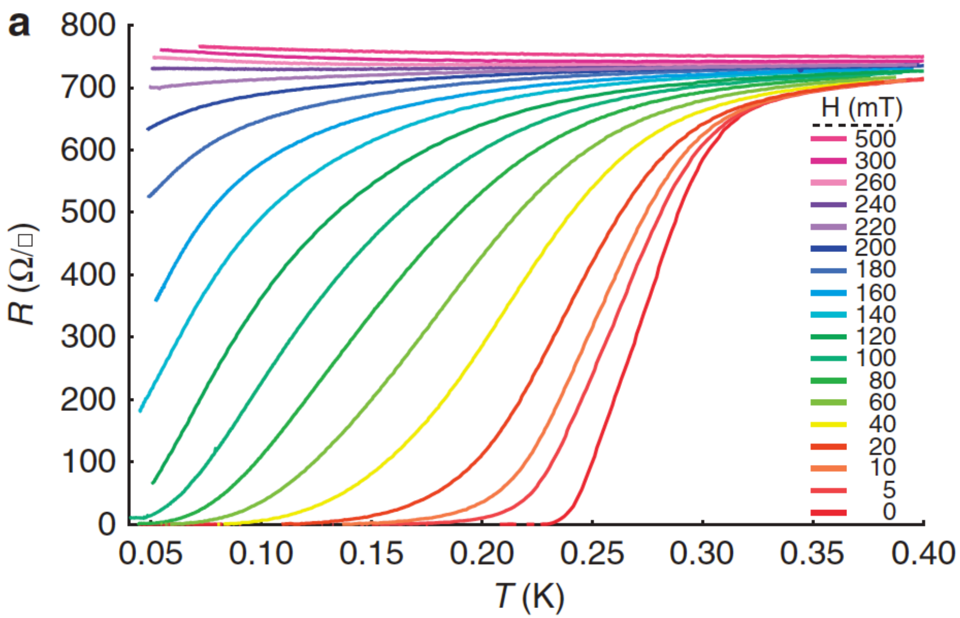
- High mobility (10^4 cm^2/Vs)
- Tunable electron density
- Superconductivity

↓

2D SC Physics

An extreme two-dimensional superconductor

- Size smaller than the coherence length



$$H_{\perp}(T) = \frac{\phi_0}{2\pi\xi_{//}^2(T)}$$

$$H_{//}(T) = \frac{\sqrt{3}\phi_0}{\pi d \xi_{//}(T)}$$

➡ ξ_0 ~ 36 nm

ξ_0 > d

2D SC

➡ d < 10 nm

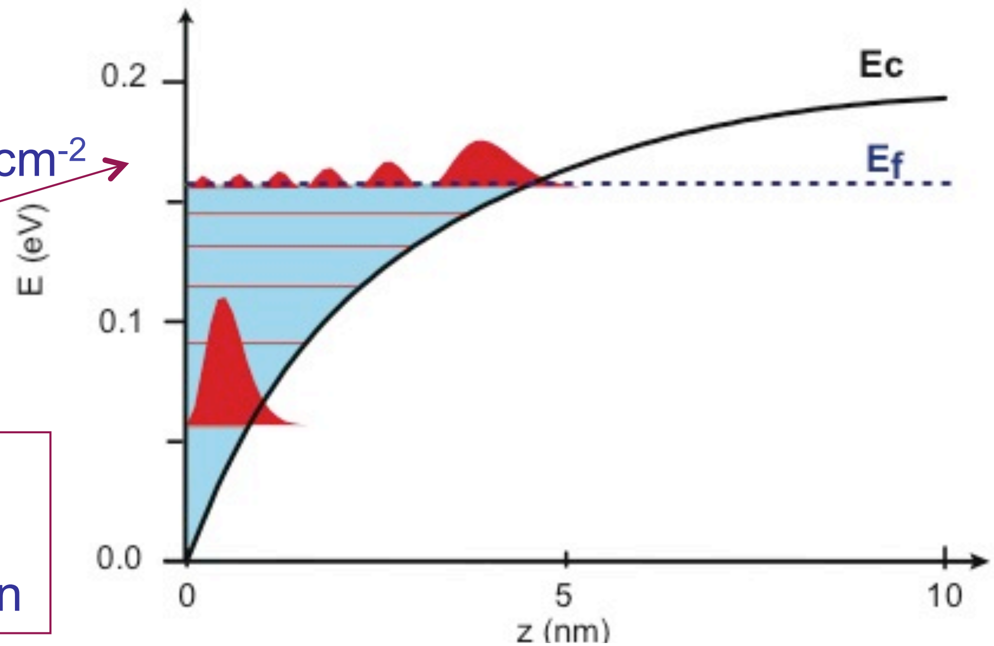
- A true two-dimensional system

Low electron density n = 10^{13}-10^{14} cm^{-2}

$$\lambda_F = \sqrt{\frac{2\pi}{n}} \qquad E_F = \frac{\hbar^2 \pi n}{m_e}$$

- λ_F > well size d

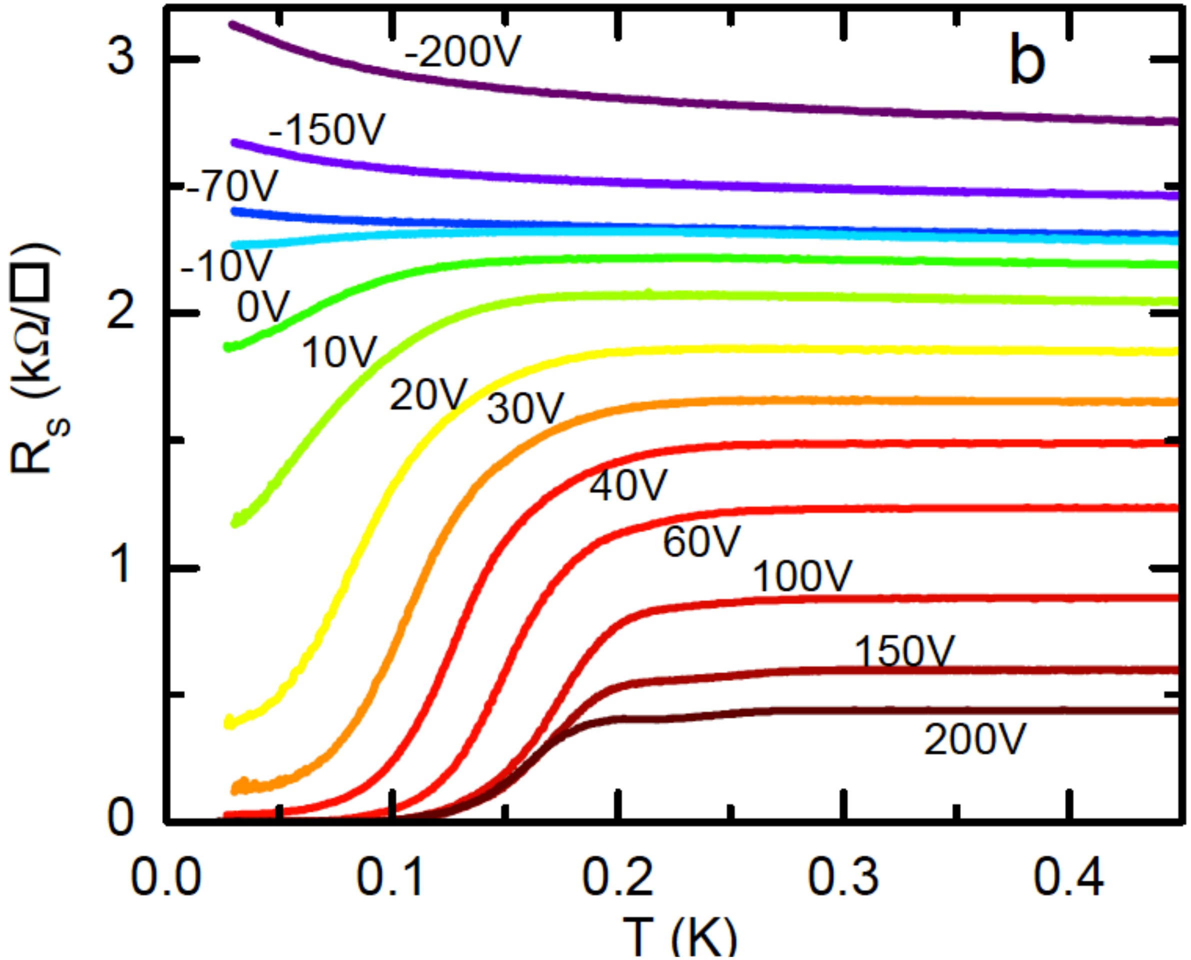
- quantized levels in the z-direction

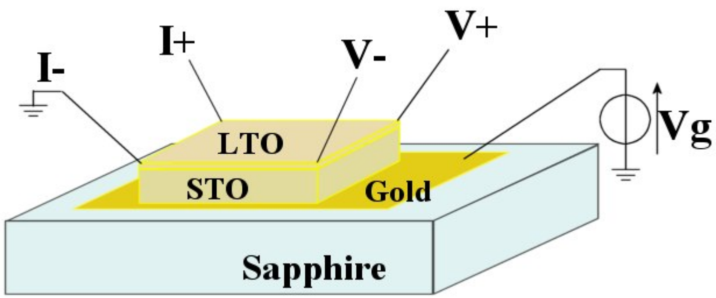


Electric field effect

- 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

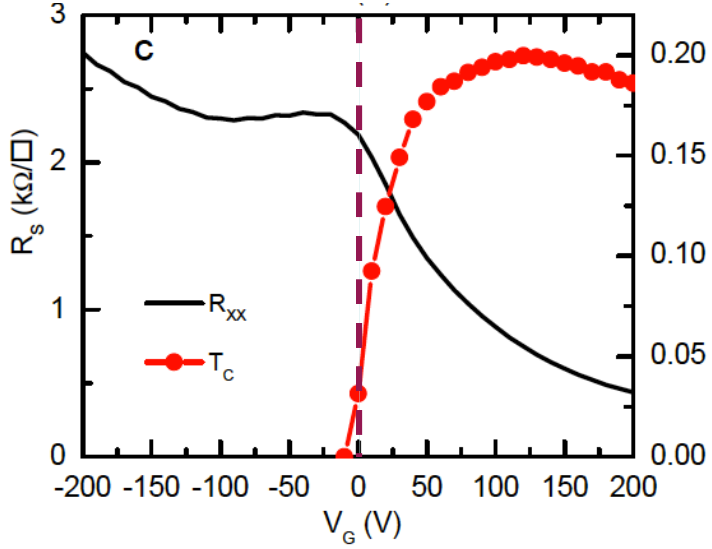
add e^-

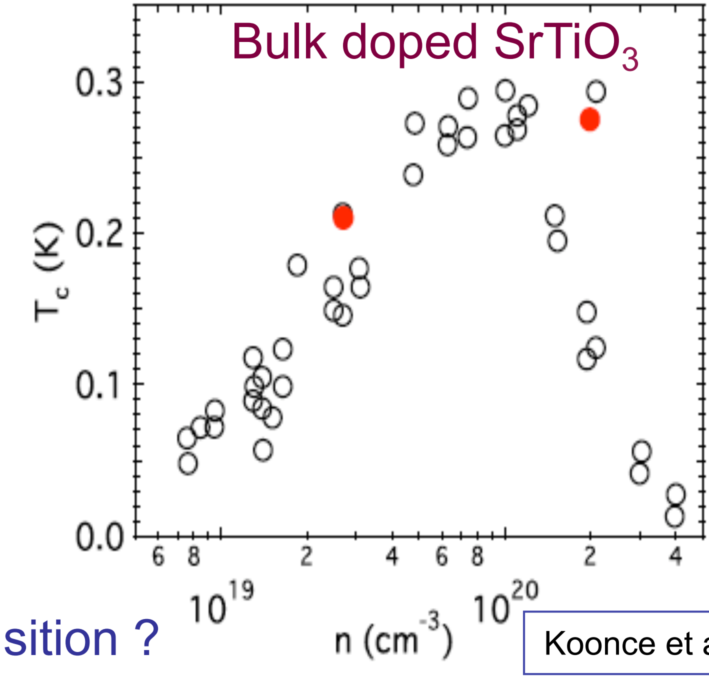
Biscaras et al, PRL 108, 247004 (2012)

- Superconductor-insulator transition induced by field effect

Two main questions

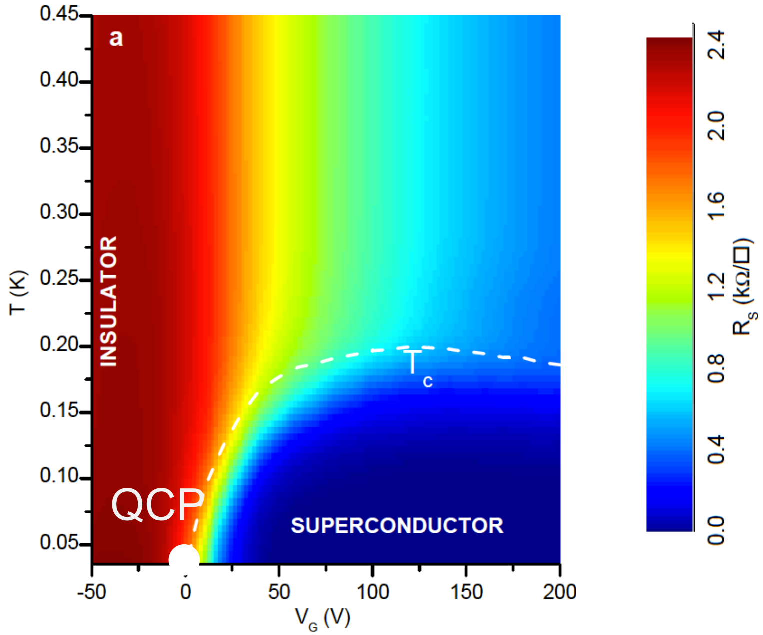
- What is the origin of superconductivity ?





Koonce et al, PRB (1967)

- What type of Superconductor-Insulator transition ?



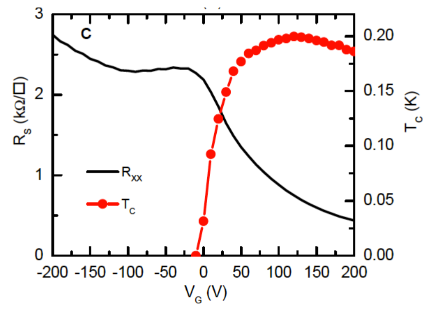
➡ Quantum phase transition ?

➡ Disorder driven phase transition ?

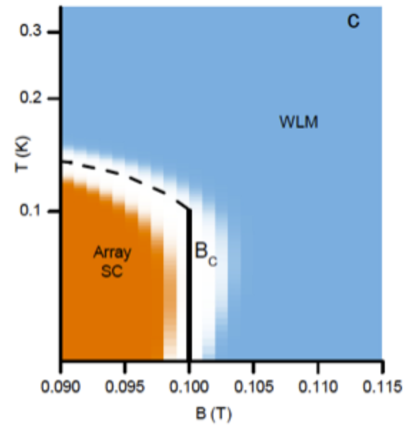
➡ Universality class ?

Outline

Tunable superconductivity in oxide 2DEG



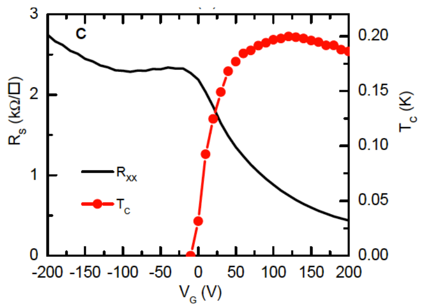
Quantum phase transition under magnetic field



Conclusions

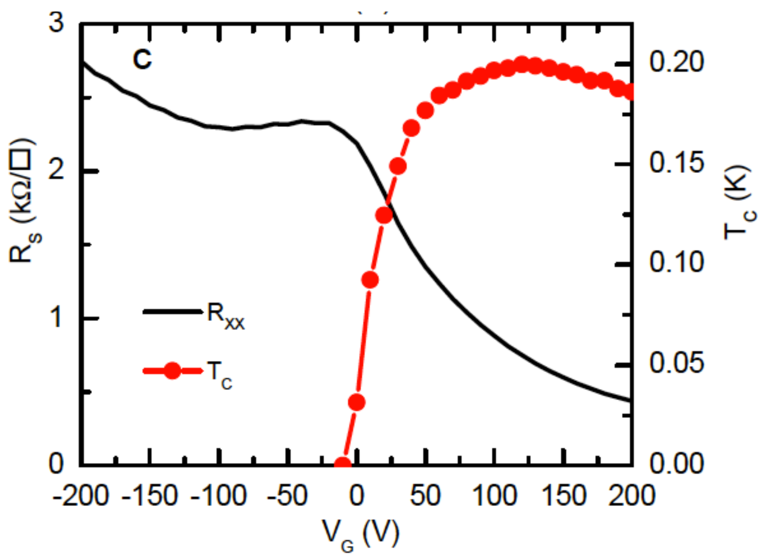
Outline

Tunable superconductivity in oxide 2DEG

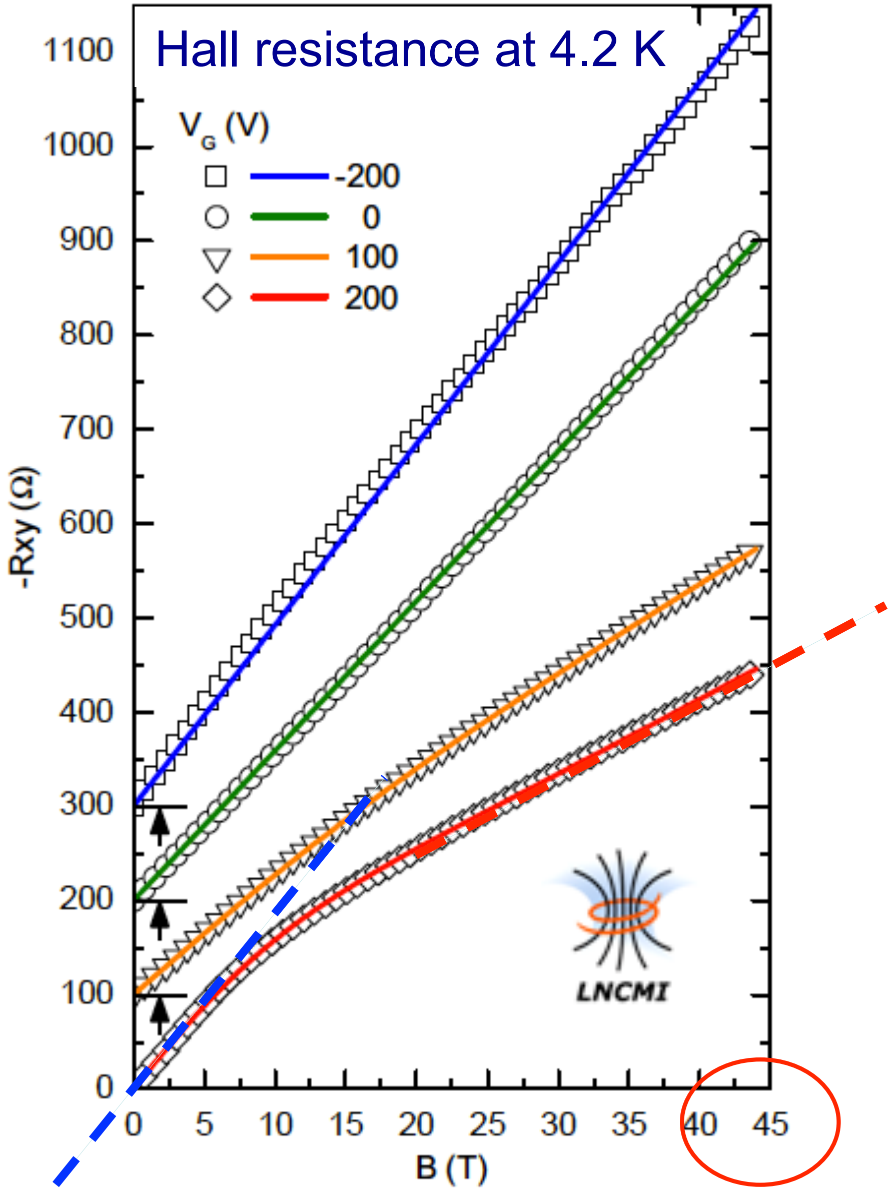


Quantum phase transition under magnetic field

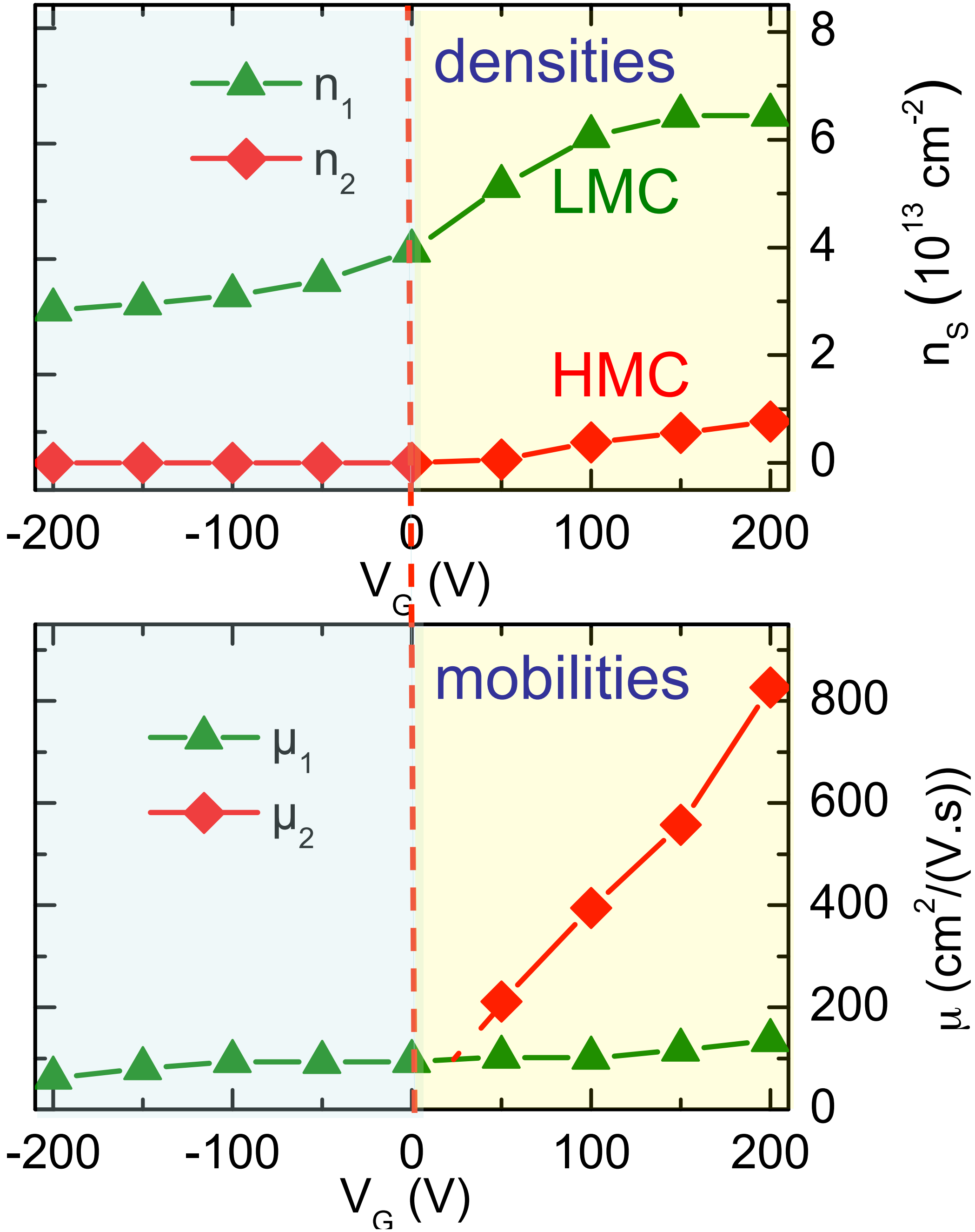
Conclusions



Two types of carriers for positive gate voltage

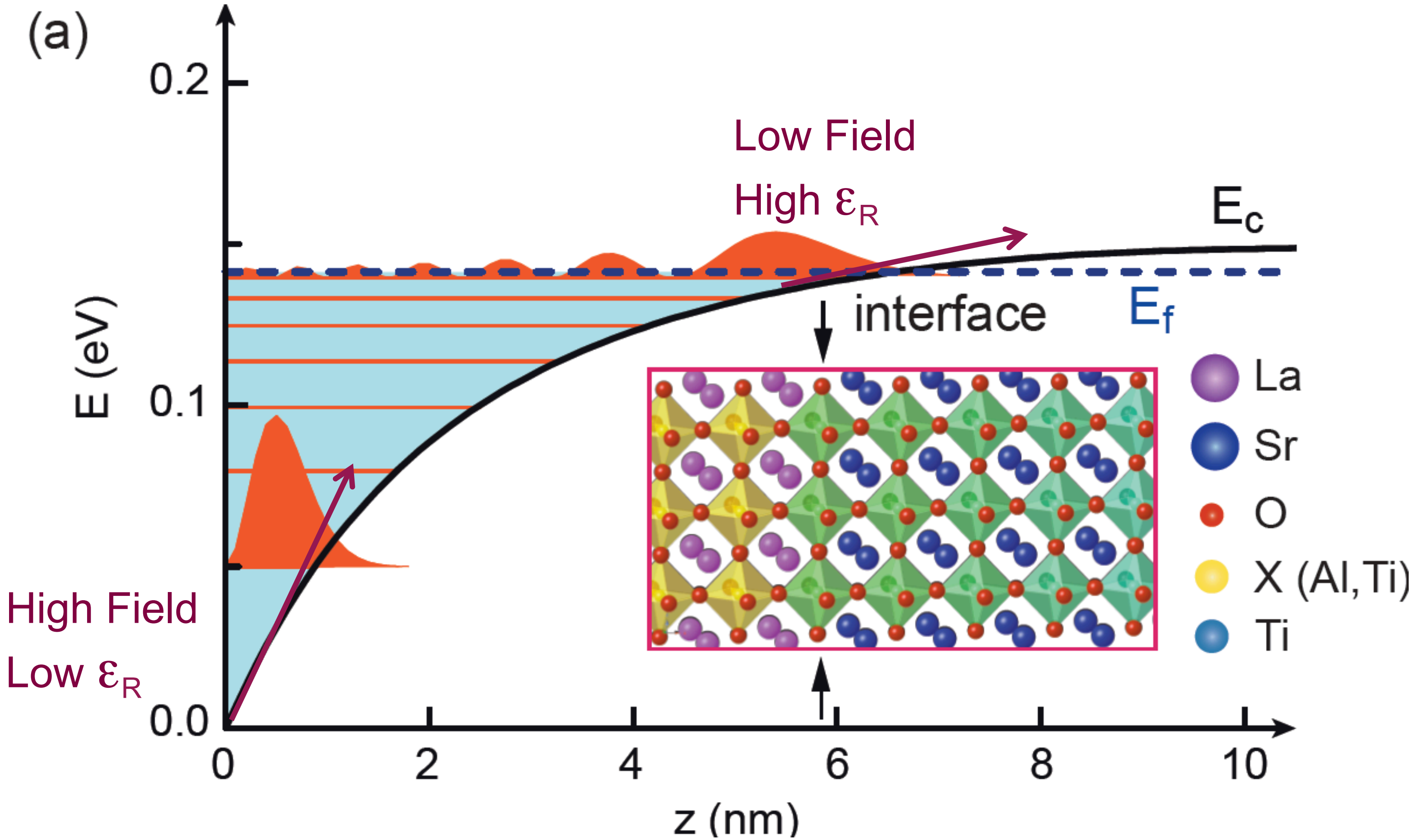


Biscaras et al, PRL 108, 247004 (2012)



Self consistent calculation : band bending model

- Confinement at the interface : $SrTiO_3$ conduction band bending



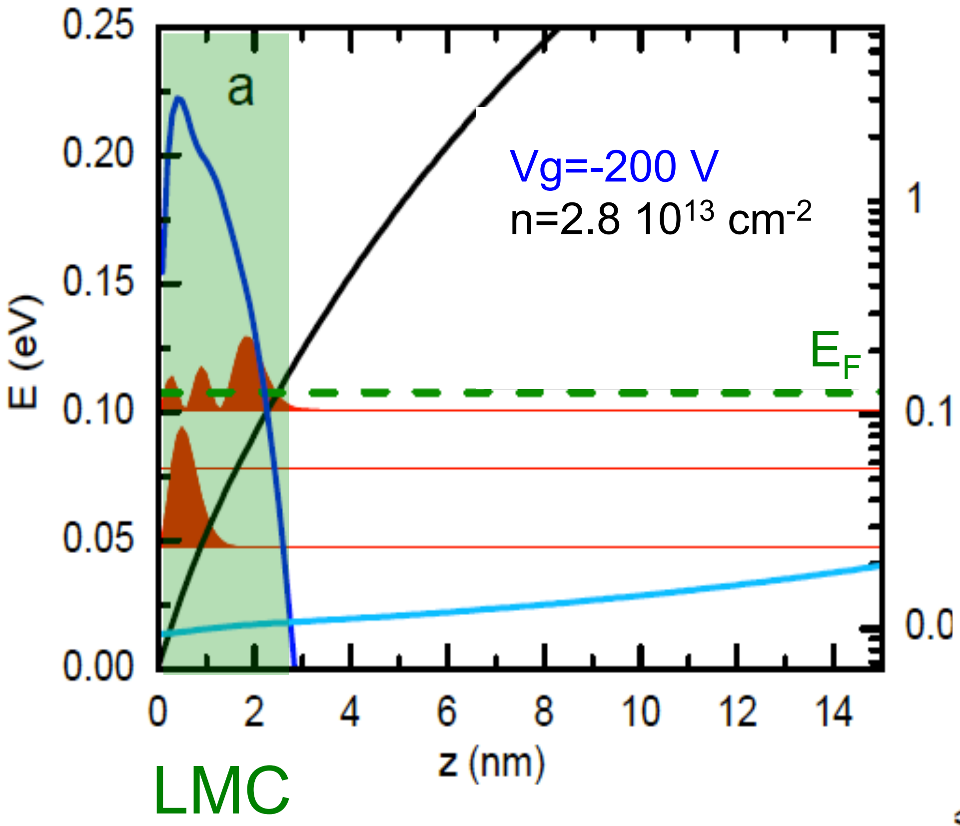
➡ Schrödinger Equation

➡ Poisson Equation

➡ Non linear $SrTiO_3$ Epsilon

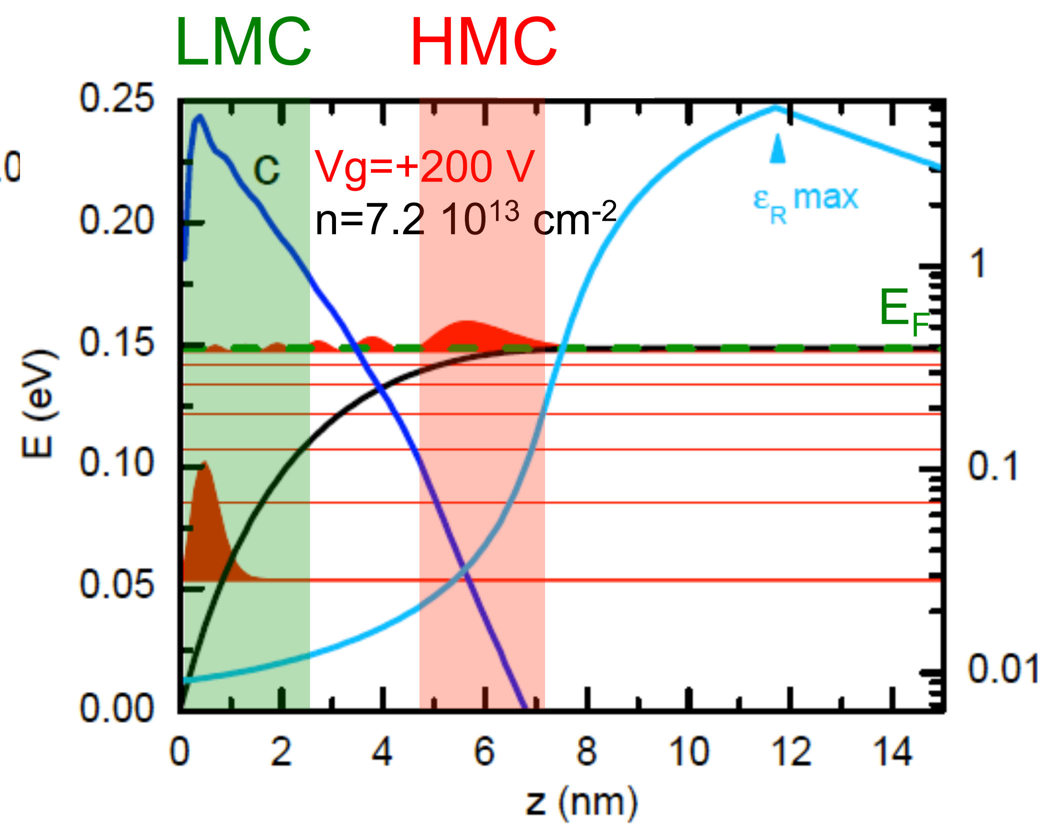
$$\epsilon_R(F) = \epsilon_R(\infty) + \frac{1}{(A+BF)}$$

Solutions of the model ($V_G \neq 0$)



■ Vg<0 carriers are confined at the interface

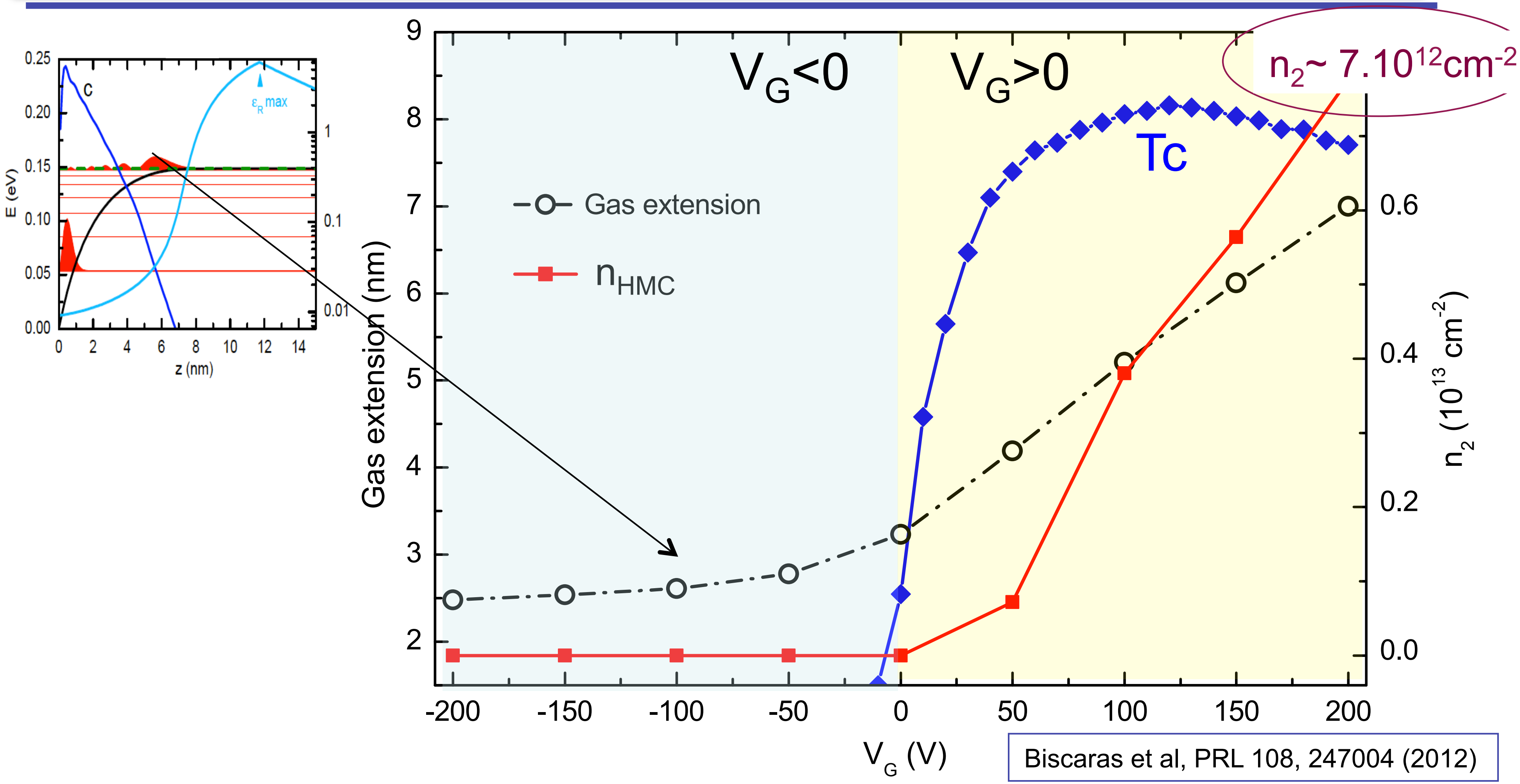
➡ Low mobility



■ Vg>0 carriers extends in $SrTiO_3$

➡ Mobility increases

High Mobility Carriers at the edge : Superconductivity

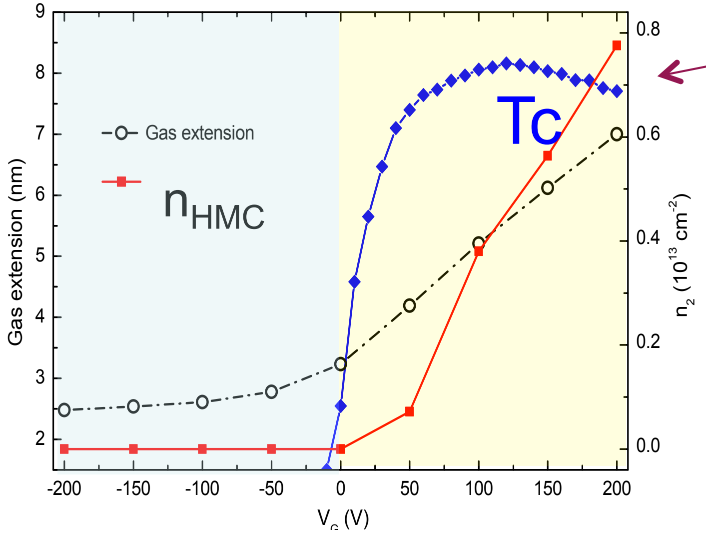


Biscaras et al, PRL 108, 247004 (2012)

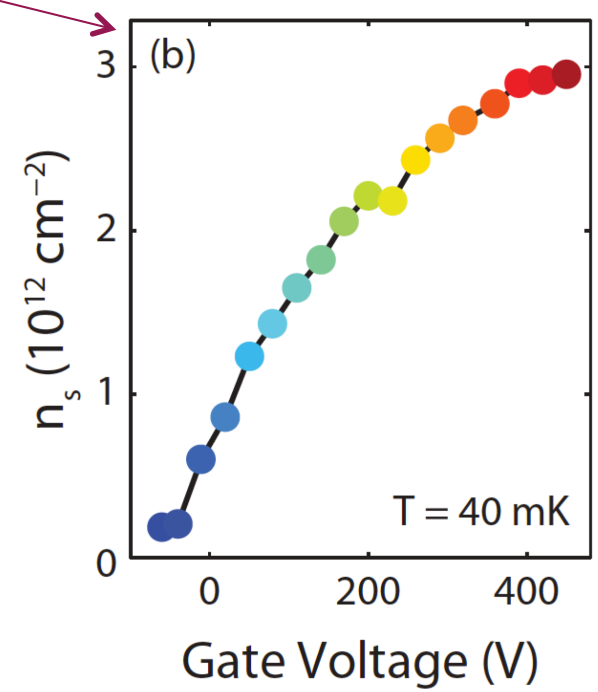
➡ Superconductivity is triggered by minority mobile carriers that extend in $SrTiO_3$

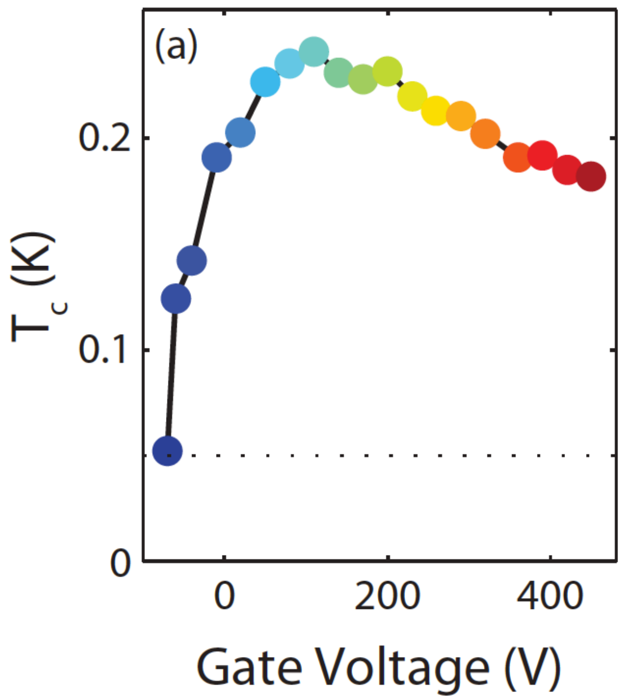
➡ Superfluid density measured by scanning probe : n_S ~ 5.10^{12}cm^{-2} Bert et al, PRB (2012)

Superconductivity related to mobile carriers ?



$n_2 \sim 7.10^{12} cm^{-2}$





Superfluid density measured by scanning probe

➡ $n_S \sim 5.10^{12} cm^{-2}$ for VG ~200 V

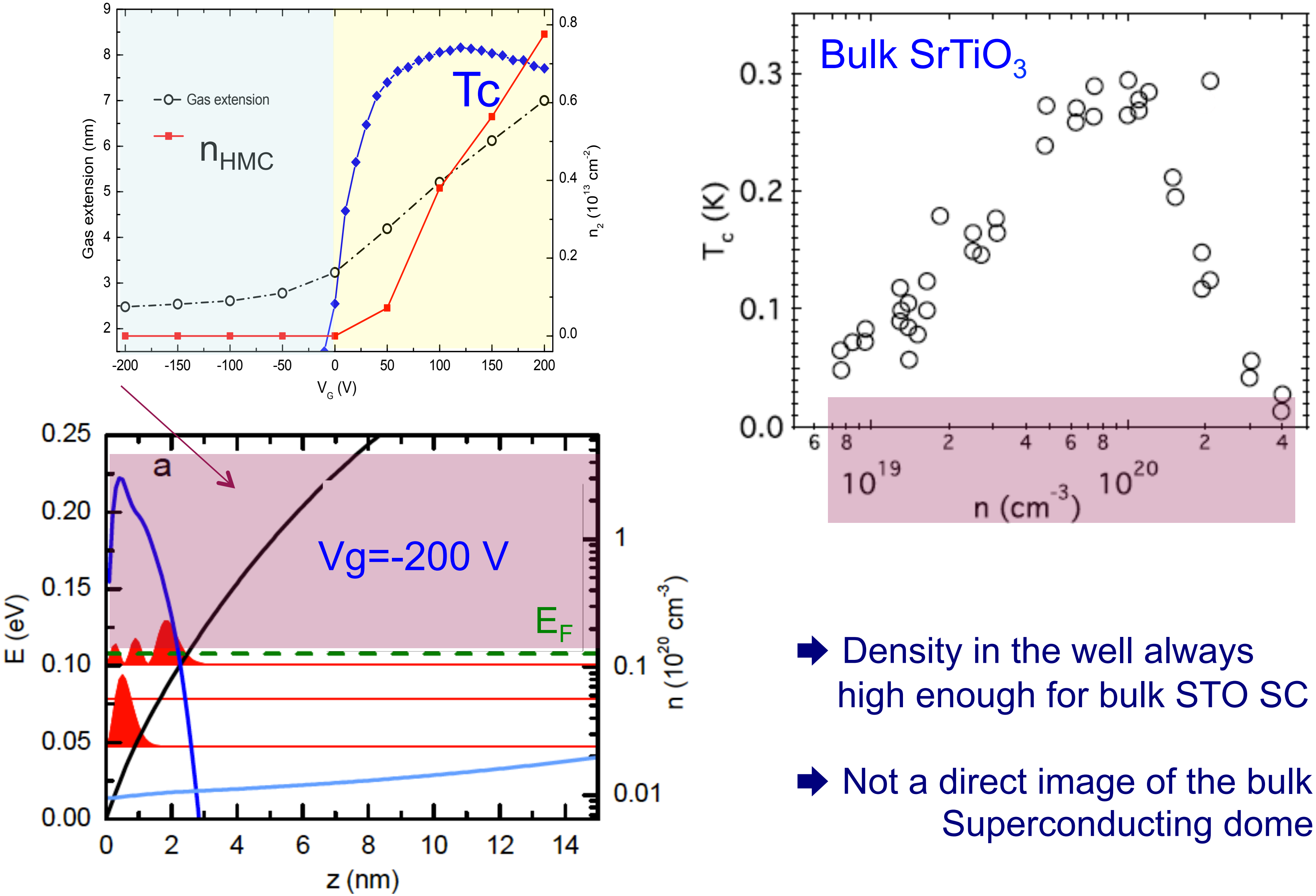
➡ $n_S/n_{total} \sim 0.1$ ($n_{HMC}/n_{total} \sim 0.1$)

➡ Inhomogeneous superfluid density

Bert et al, PRB (2012)

$$n_s/n = 2\Delta_0/(\hbar/\tau)$$

Superconductivity : not simply the bulk ...

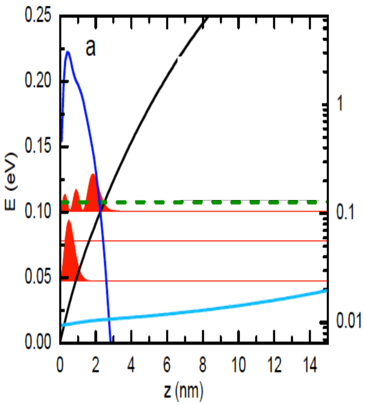


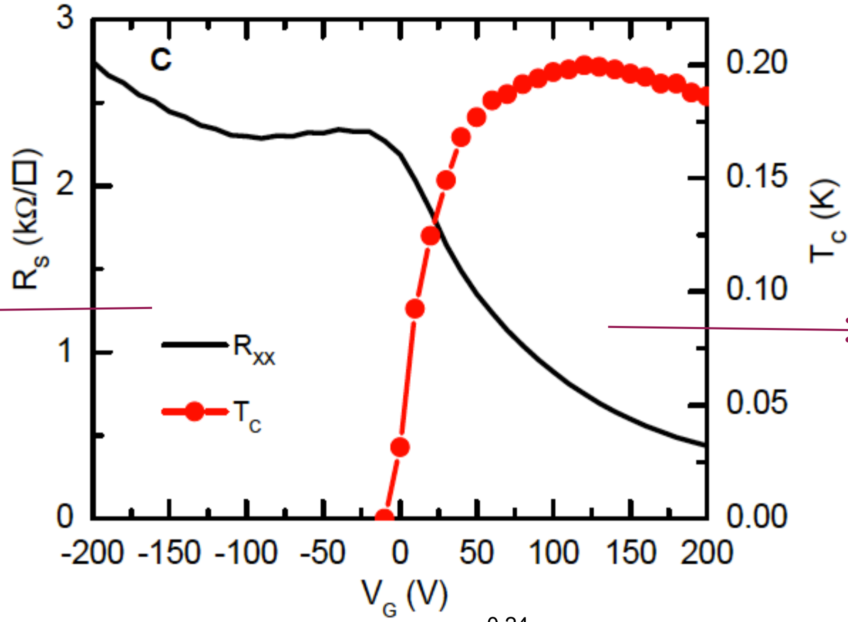
➡ Density in the well always high enough for bulk STO SC

➡ Not a direct image of the bulk Superconducting dome

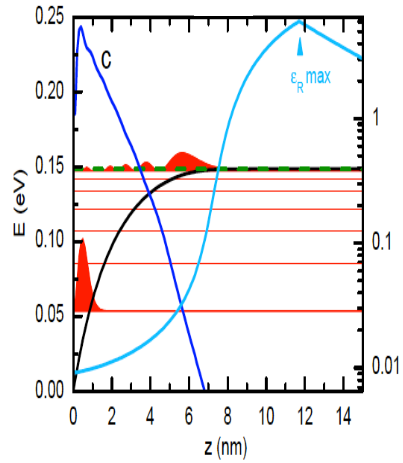
Superconductivity ... and disorder ?

Confined

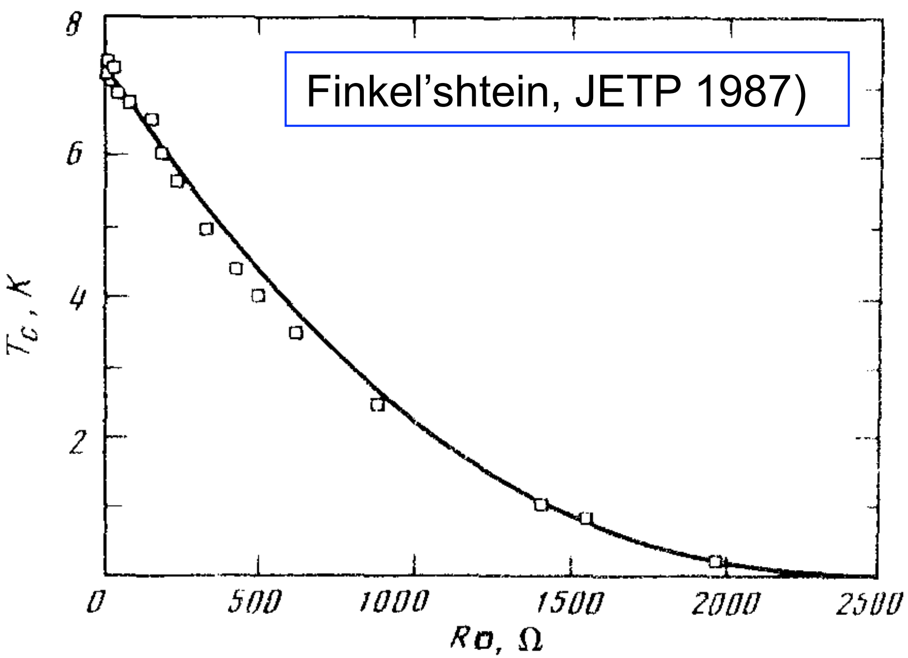


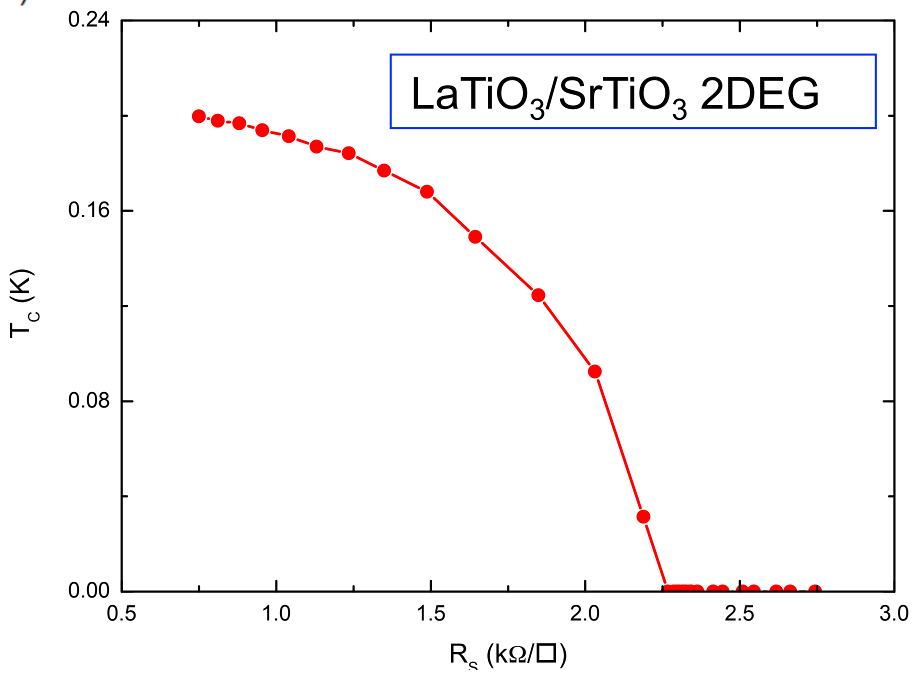


Deconfined

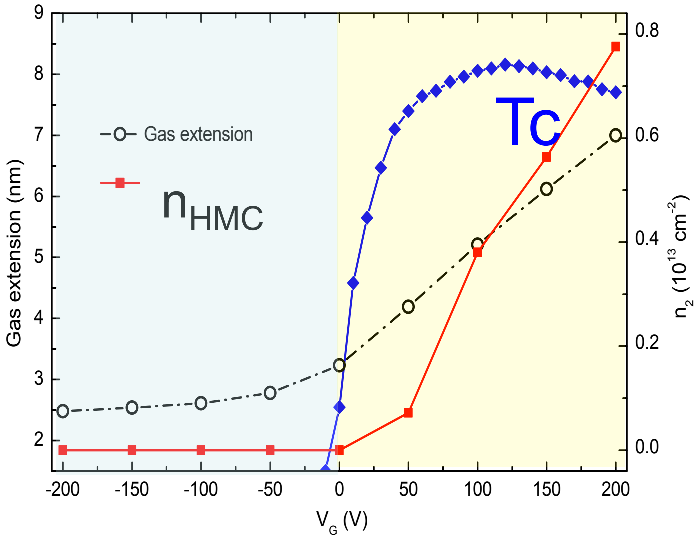


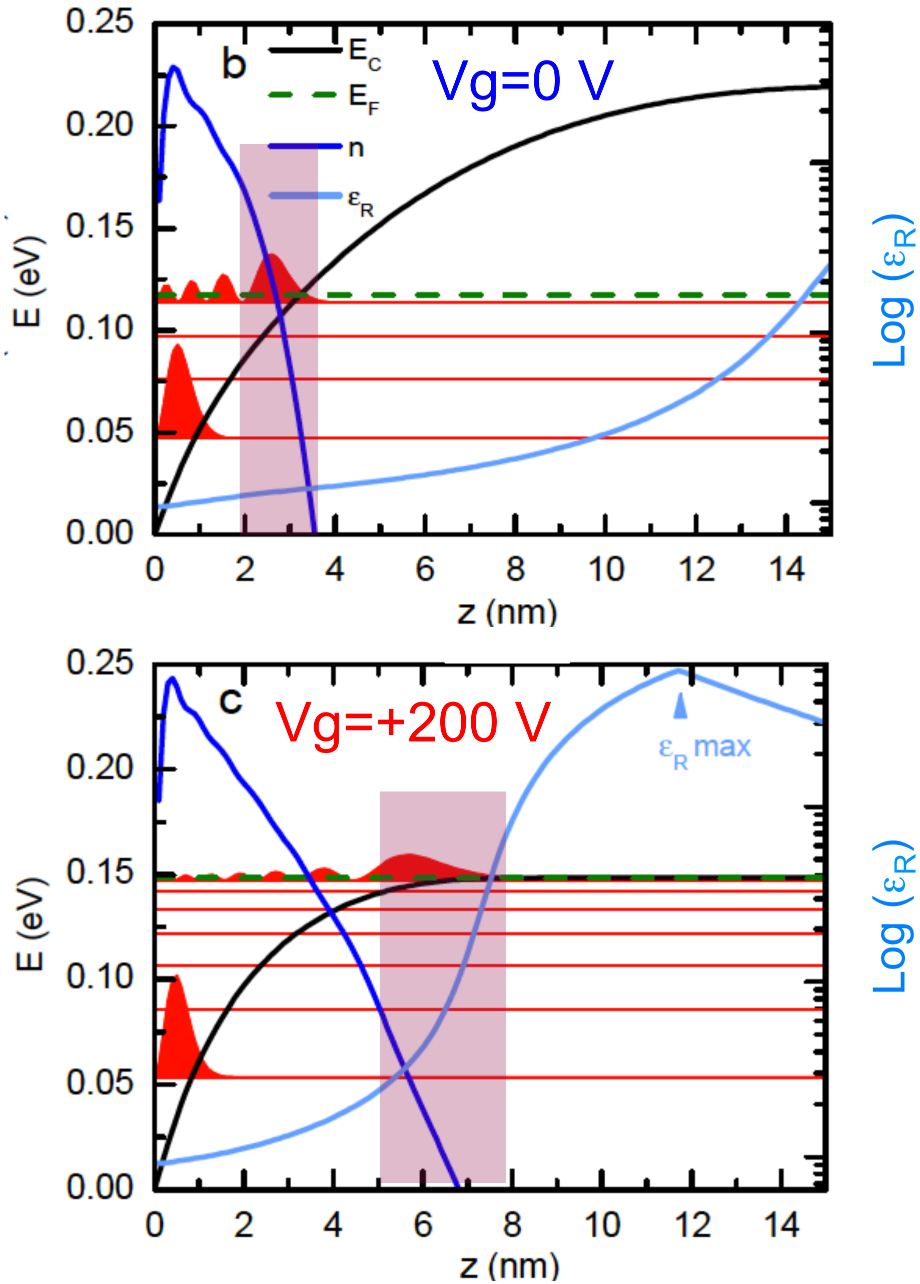
Disordered





Superconductivity ... and ε_R ?



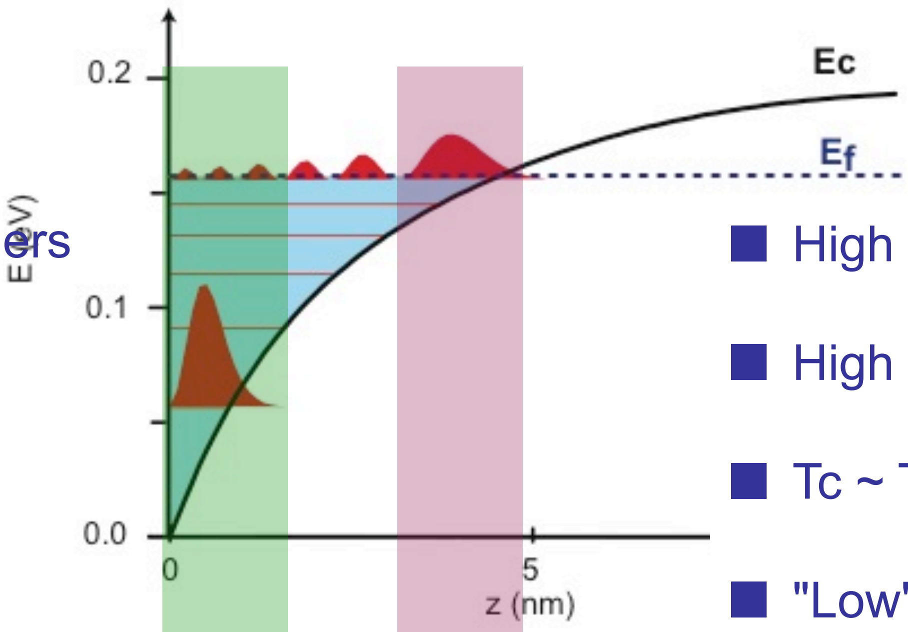


- Bulk STO dielectric constant restored
- STO Superconductivity ???
- Polar properties of STO
- cf Koonce, Appel, Takada ...

Superconductivity ... a possible scenario

Two bands approximation for $V_G > 0$

- Low mobility carriers
- Localization
- Tc ~ 0
- "High" density



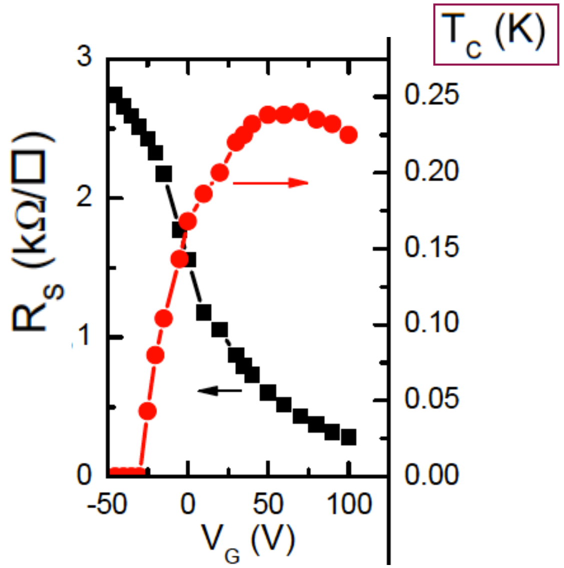
- High mobility carriers
- High ε_R (bulk value)
- Tc ~ Tcmax ~ 200 mK
- "Low" density

coupling $g_{11}=0$ coupling $g_{22}\neq 0$

coupling g_{12}
filling the second band

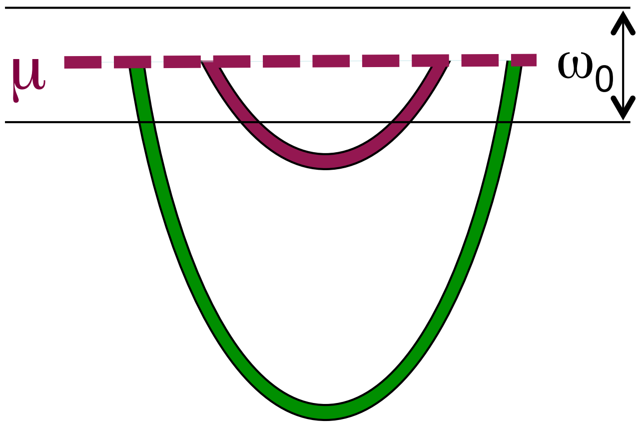
Multiband calculation : Tc (chemical potential) ~ Tc (V_G)

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

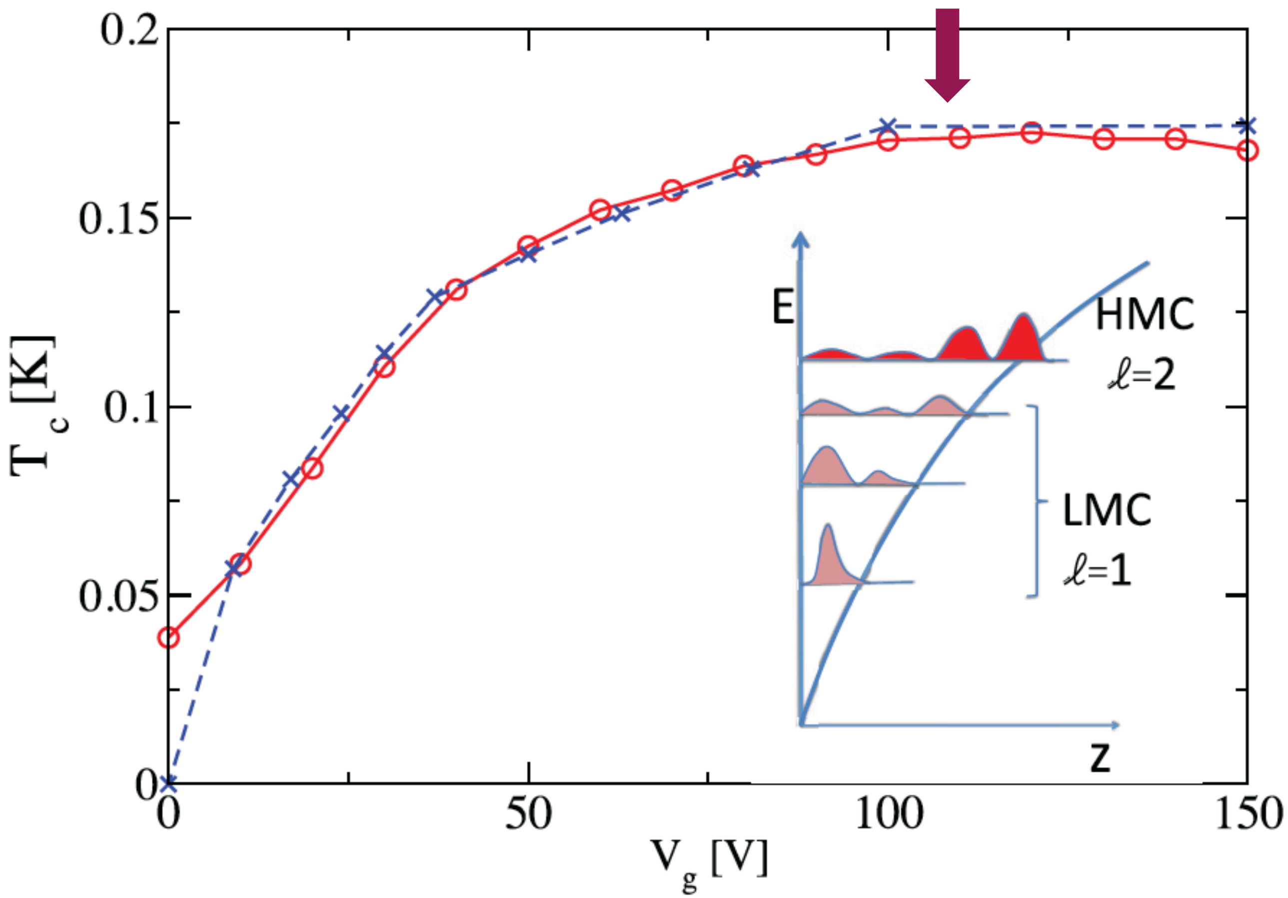


Superconductivity ... a simple model

Coupling of two bands progressively filled



$$T_c \approx 1.14\sqrt{\hbar\omega_0\mu}\, e^{-1/\lambda_2}$$



- Good agreement
- $\omega_0 \approx 23$ meV
- $\lambda_2 \approx 0.25$

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

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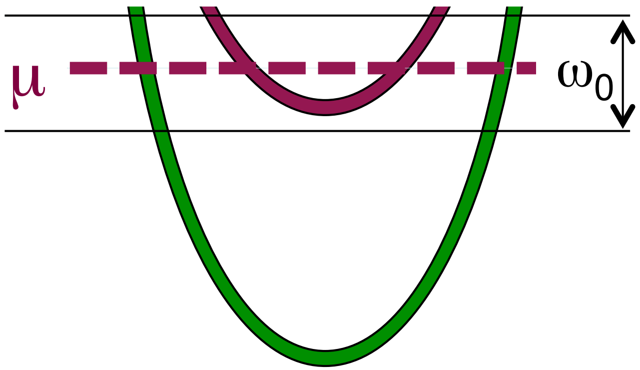

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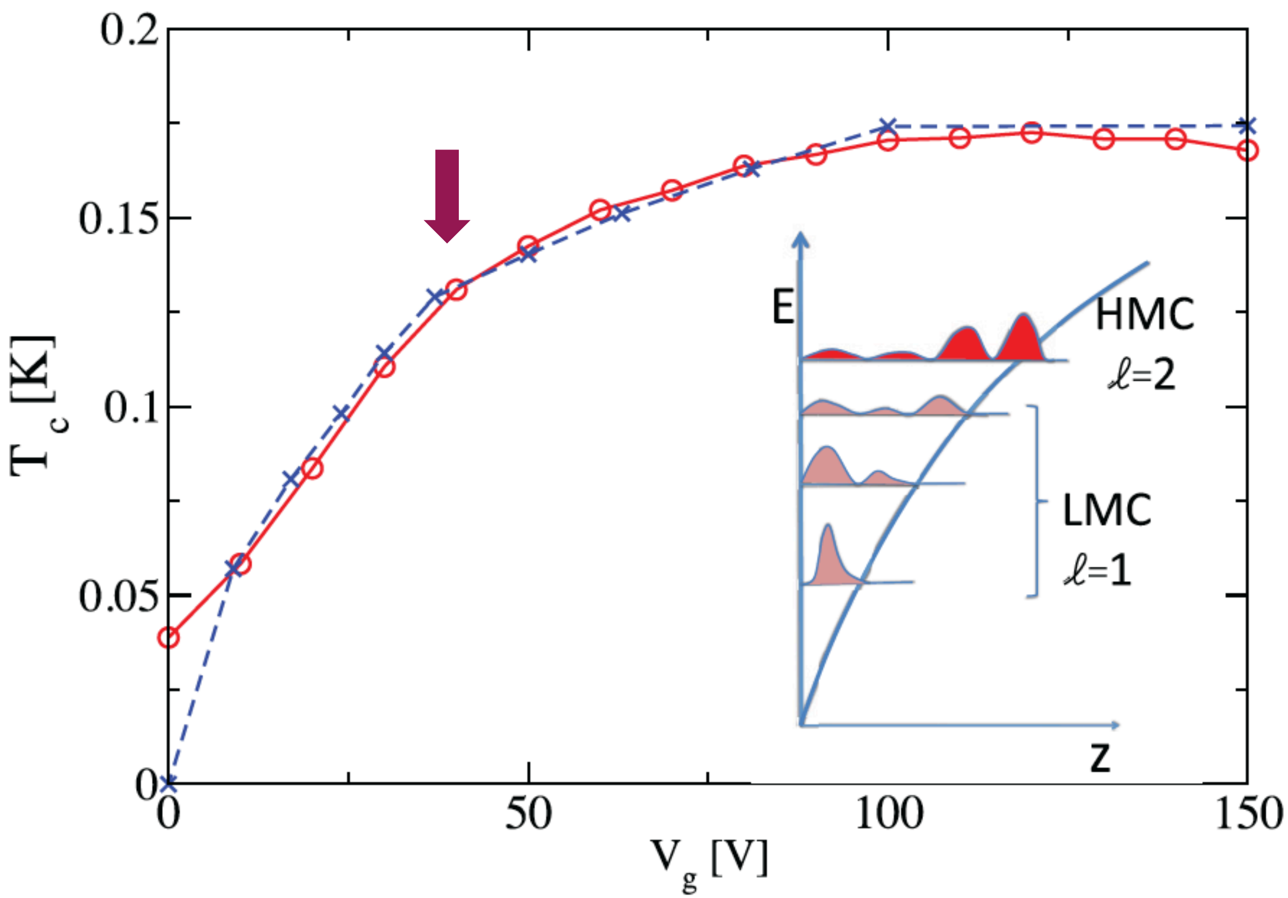

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Superconductivity ... a simple model

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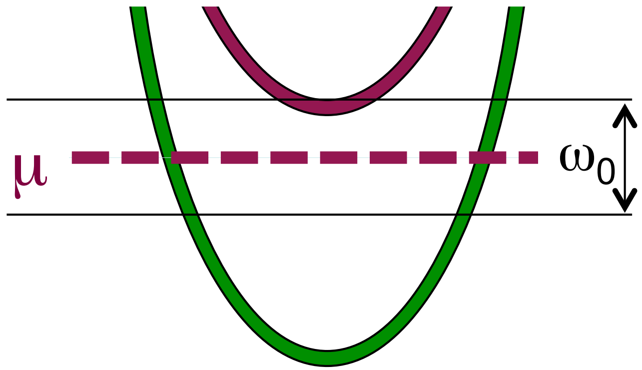

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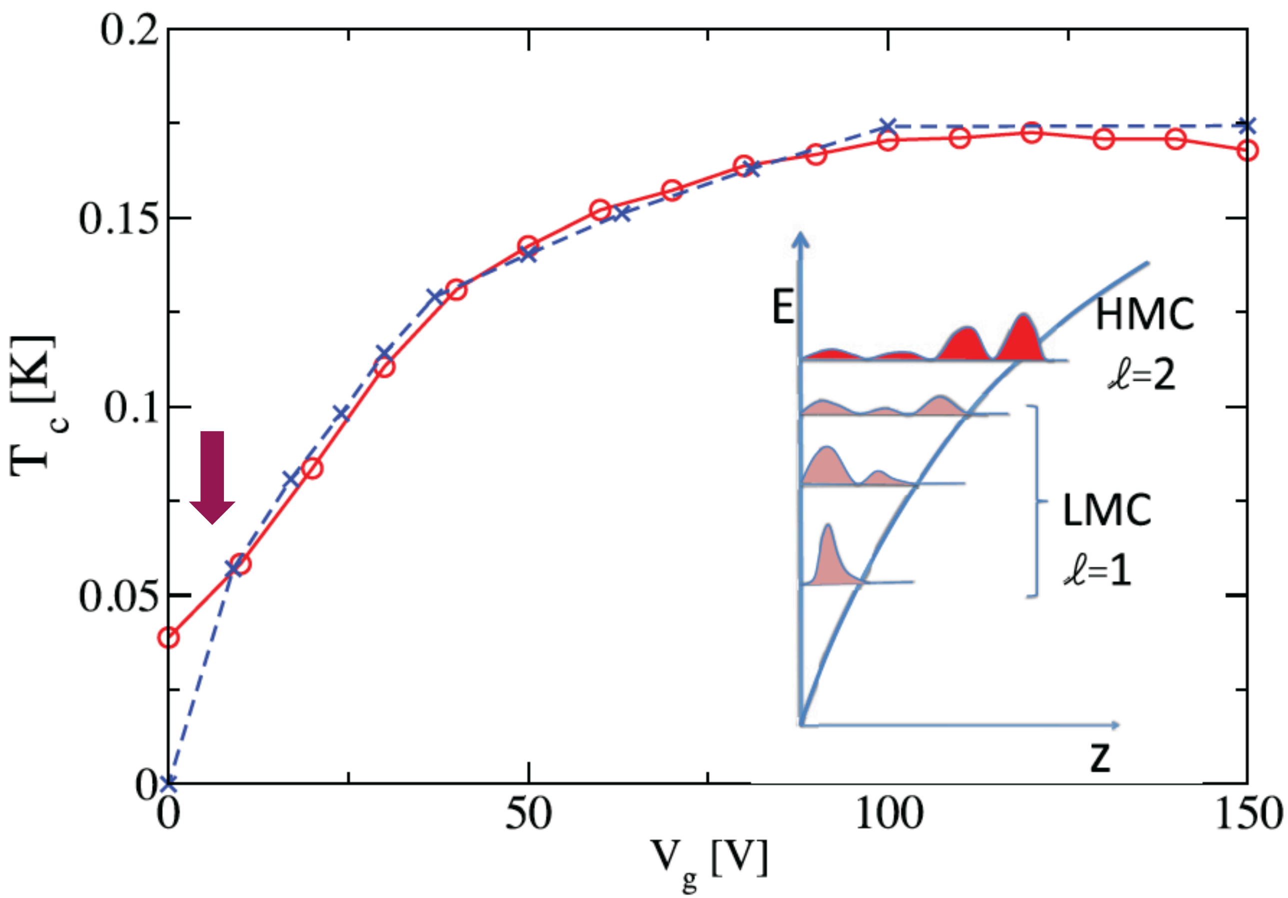

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- $\omega_0 \approx 23$ meV
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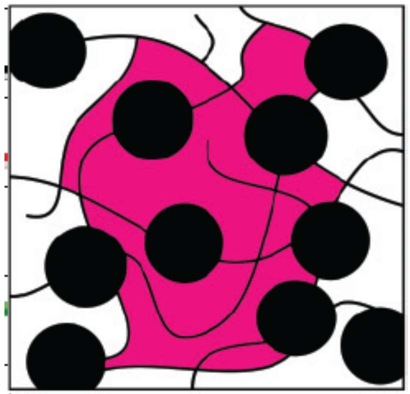
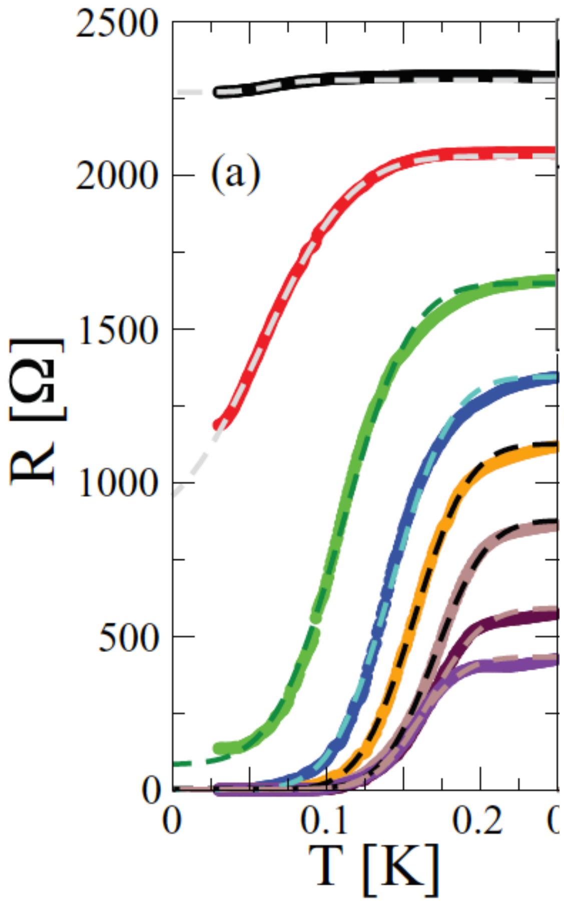
S. Caprara et al, Phys Rev B (R) 88, 020504 (2013)

Superconductivity ... inhomogeneous medium

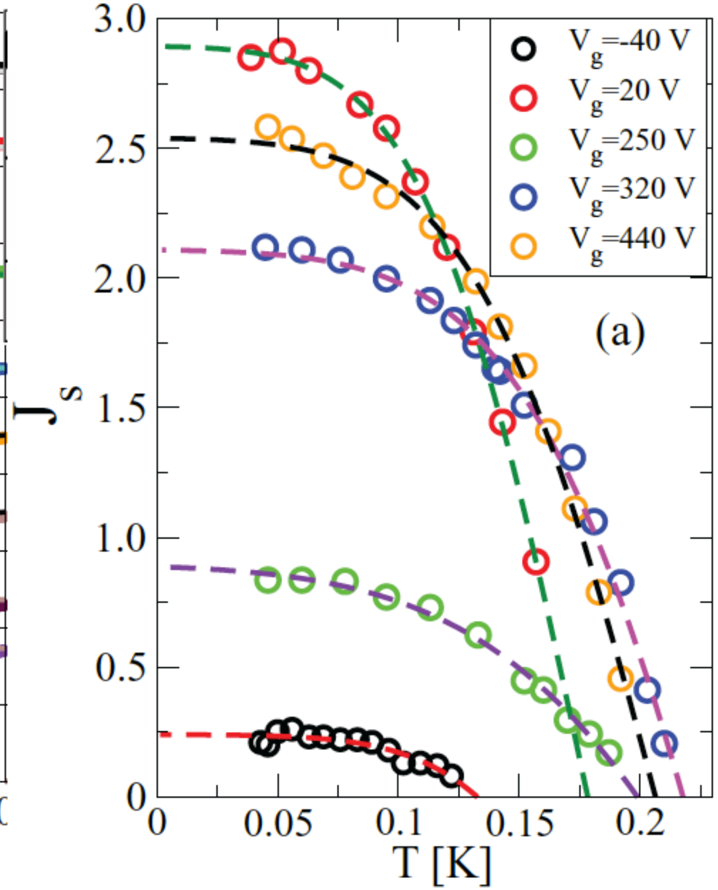
- Effective Medium Theory
- Random Resistance Network
- Filamentary structure



Resistance



Superfluid density



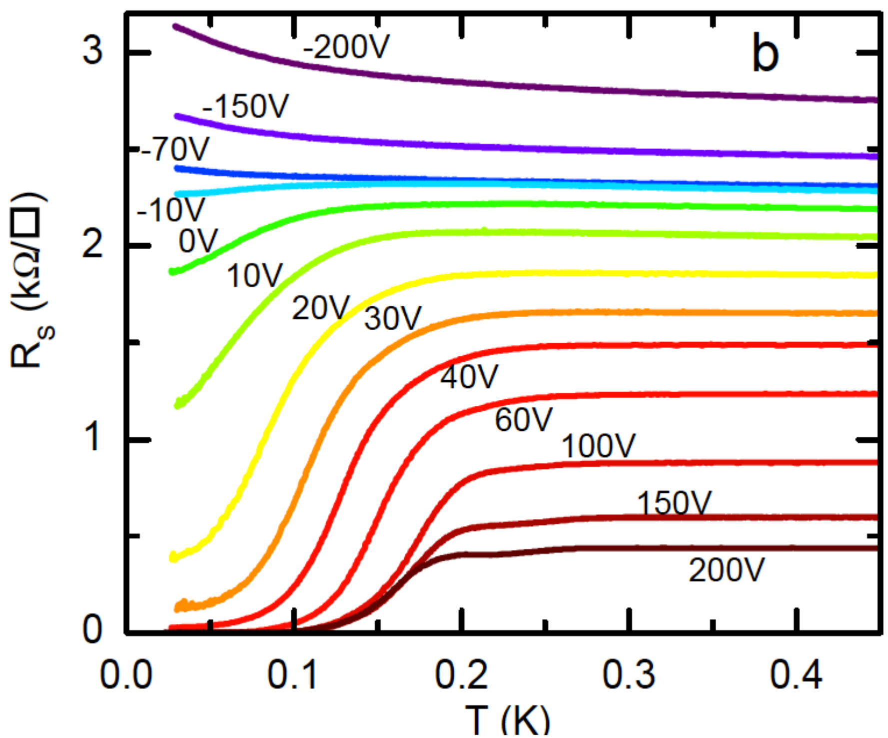
S. Caprara et al, Phys Rev B (R) 88, 020504 (2013)

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

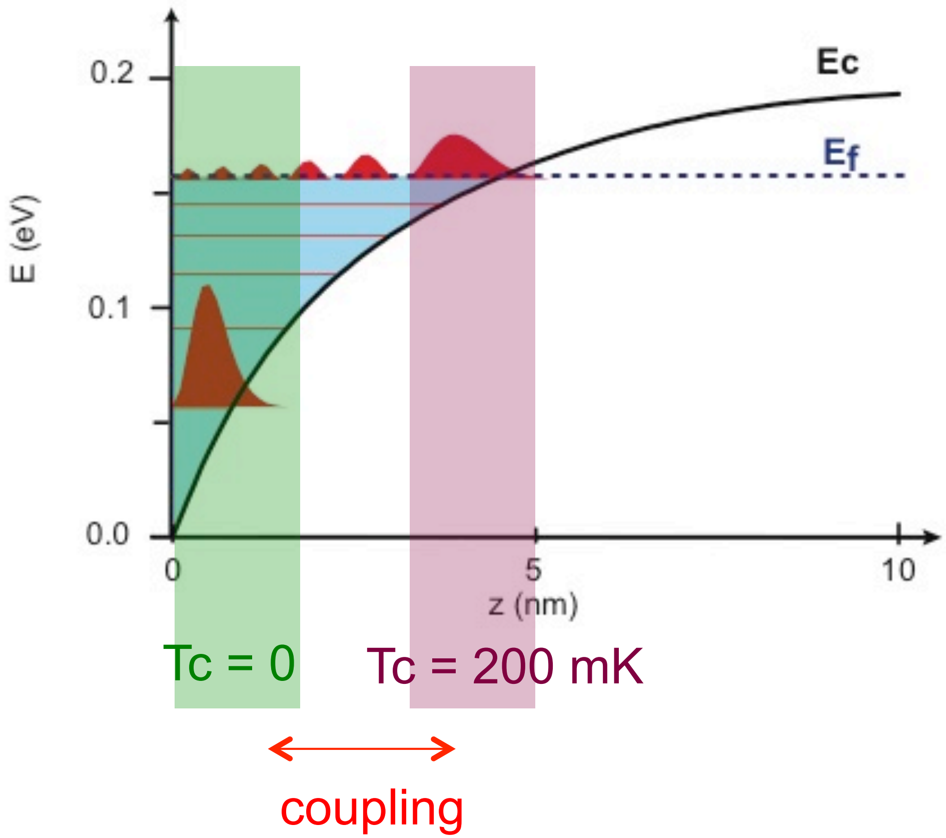
cf M. Grilli's talk

First conclusions about superconductivity

- Control of the 2-DEG SC by V_G



- Two types of carriers (one with Tc ≠ 0)



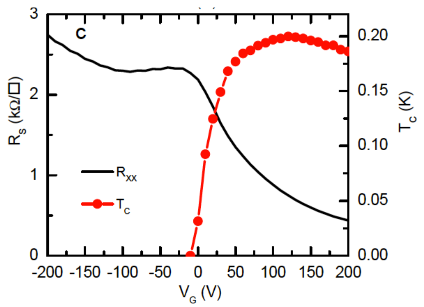
Biscaras et al, PRL 108, 247004 (2012)

- Presence of inhomogeneous superconducting behavior

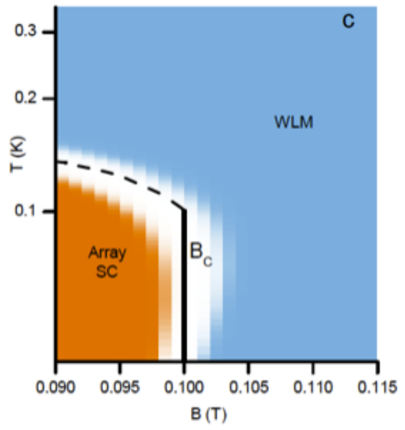
S. Caprara et al, Phys Rev B (R) 88, 020504 (2013)

Outline

Tunable superconductivity in oxide 2DEG



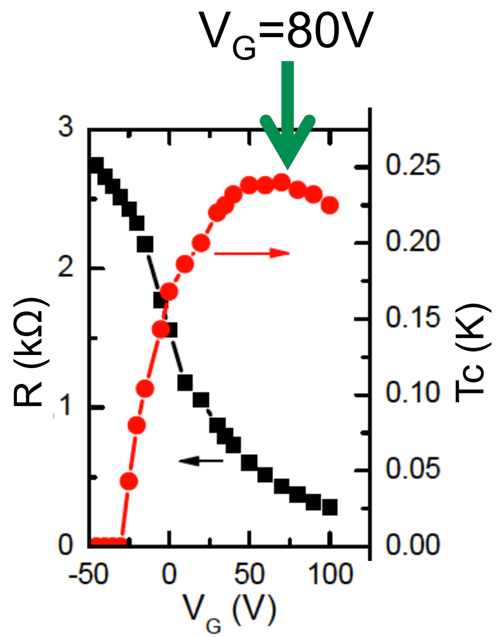
Quantum phase transition under magnetic field

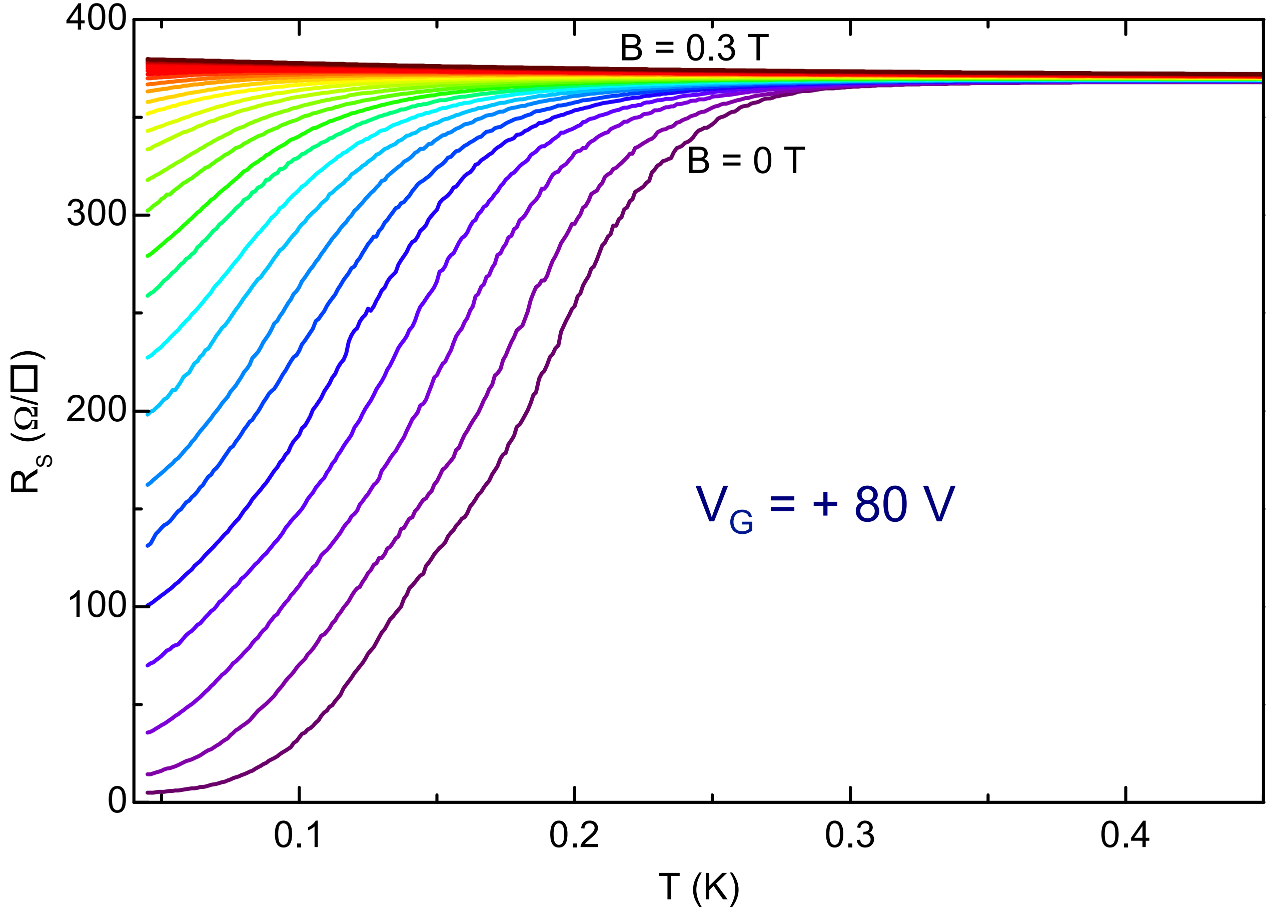


Conclusions

Magnetic field driven quantum phase transition

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

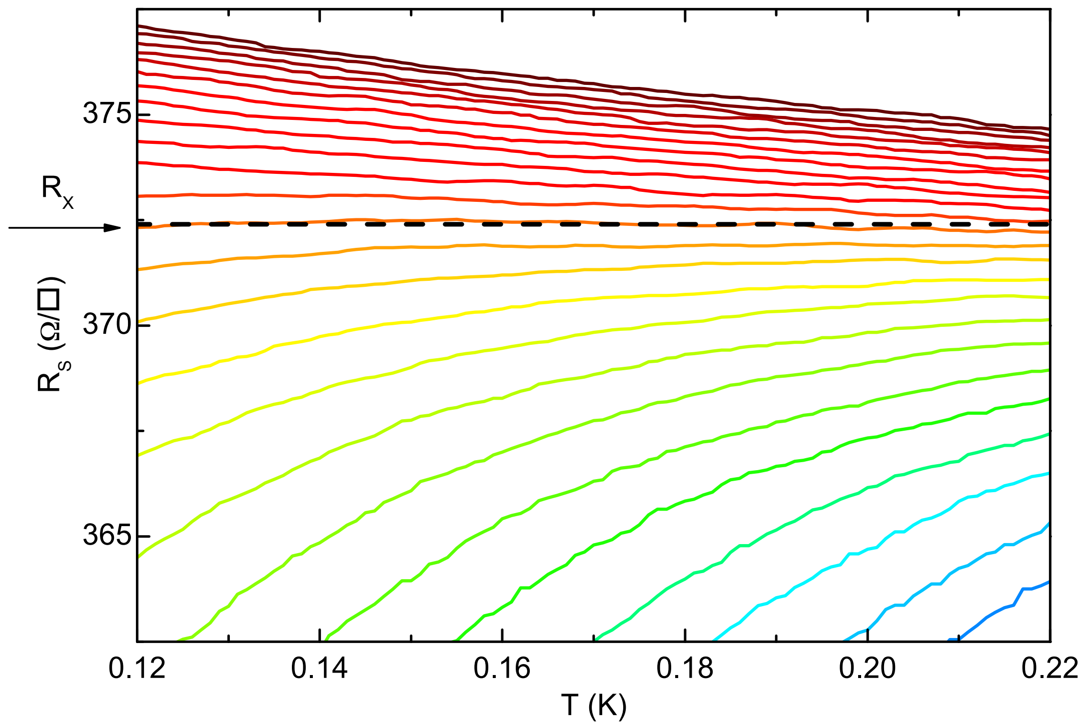


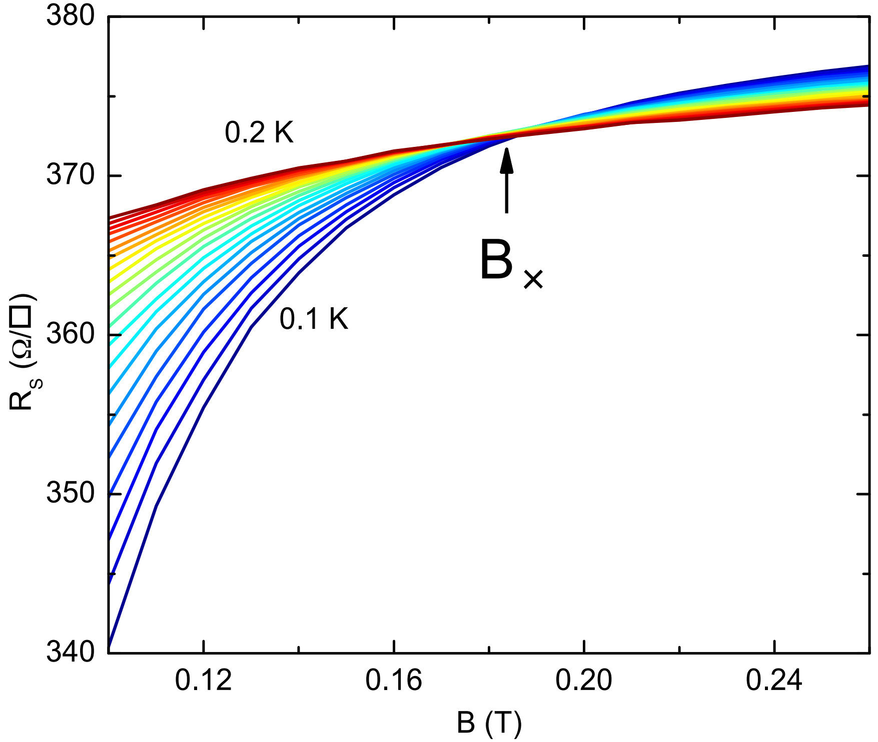


➡ Transition from superconducting to weakly localized metallic state

Magnetic field driven quantum phase transition

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

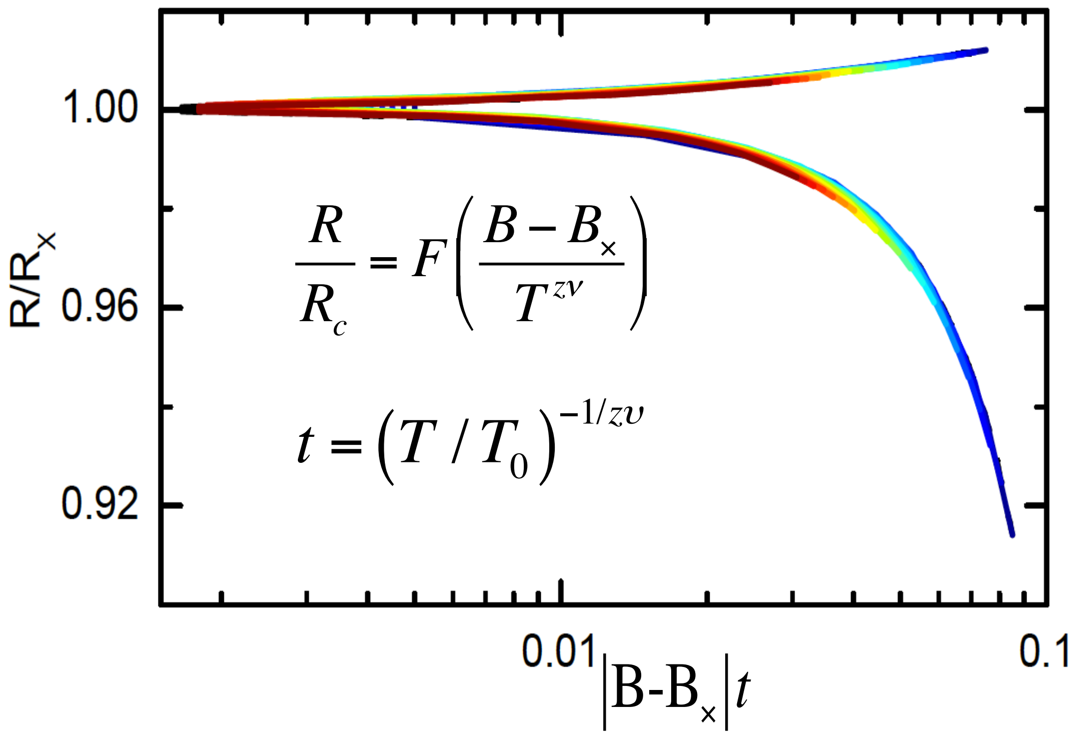




➡ Crossing point at $B_\times$: a first signature of a quantum phase transition

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, …)

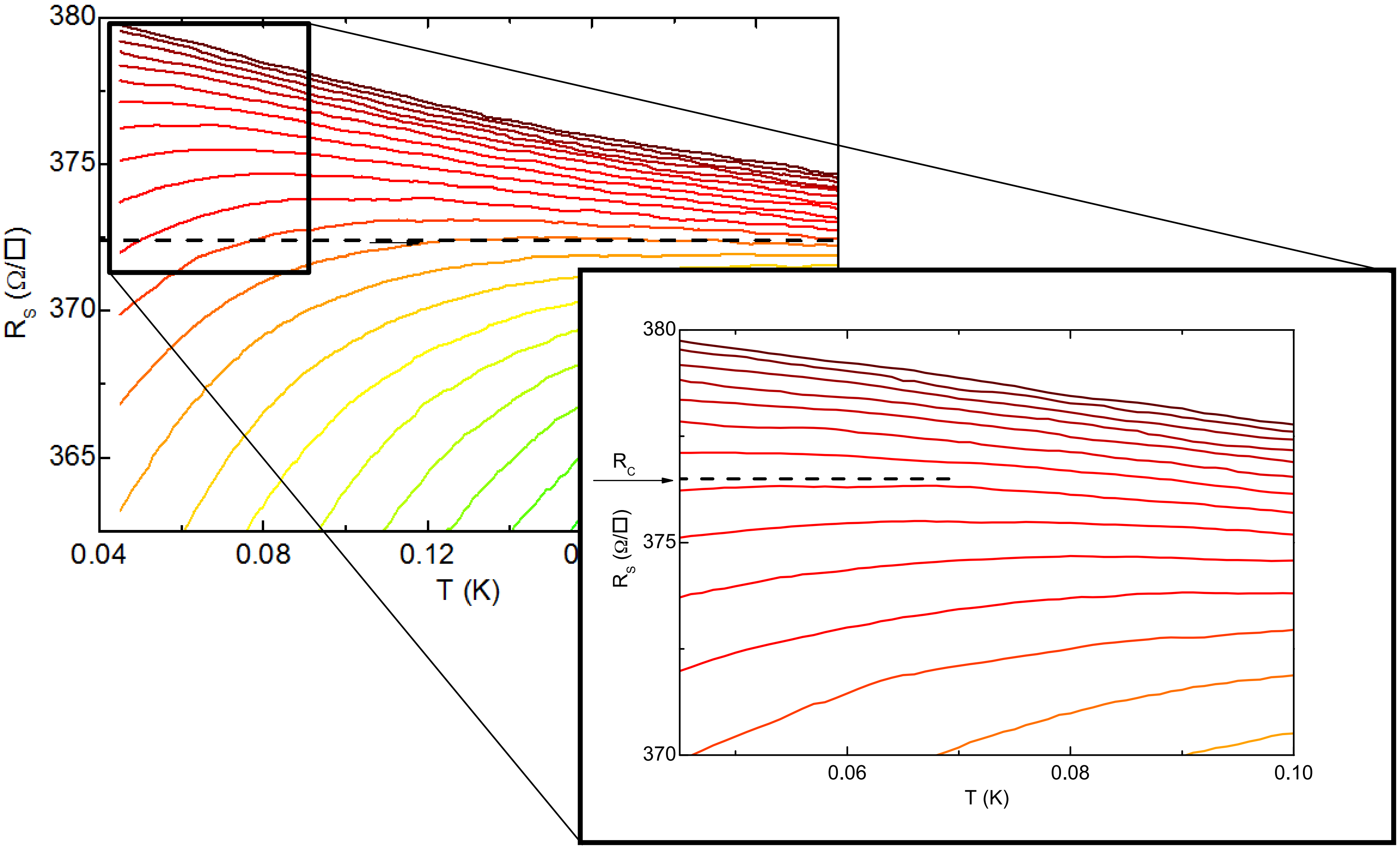
Superfluid transition in charged system : z=1

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

Disordered systems : Harris criteria sets $\nu > 1$

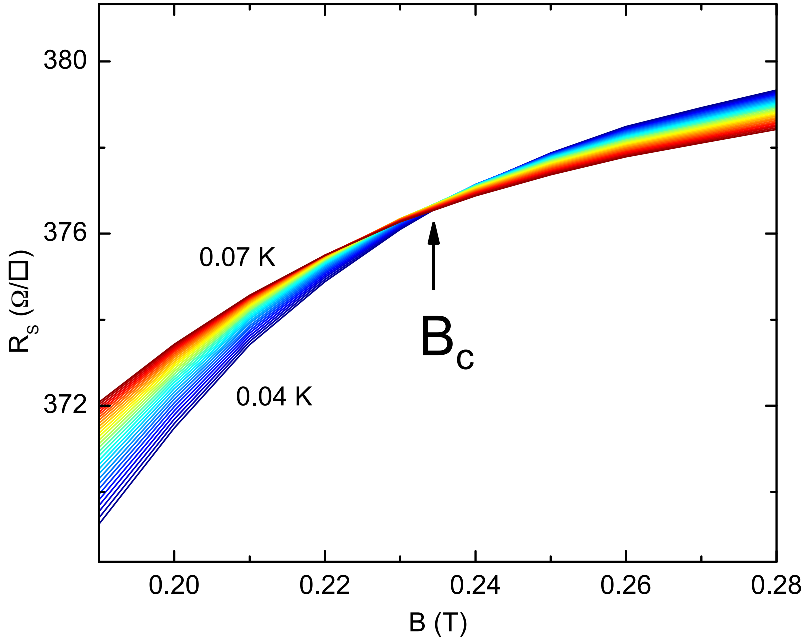
Harris, J Phys. C Solid State, 1974

A true quantum Phase Transition ?



➡ Scaling does not work at low temperature !

Scaling at lower temperature



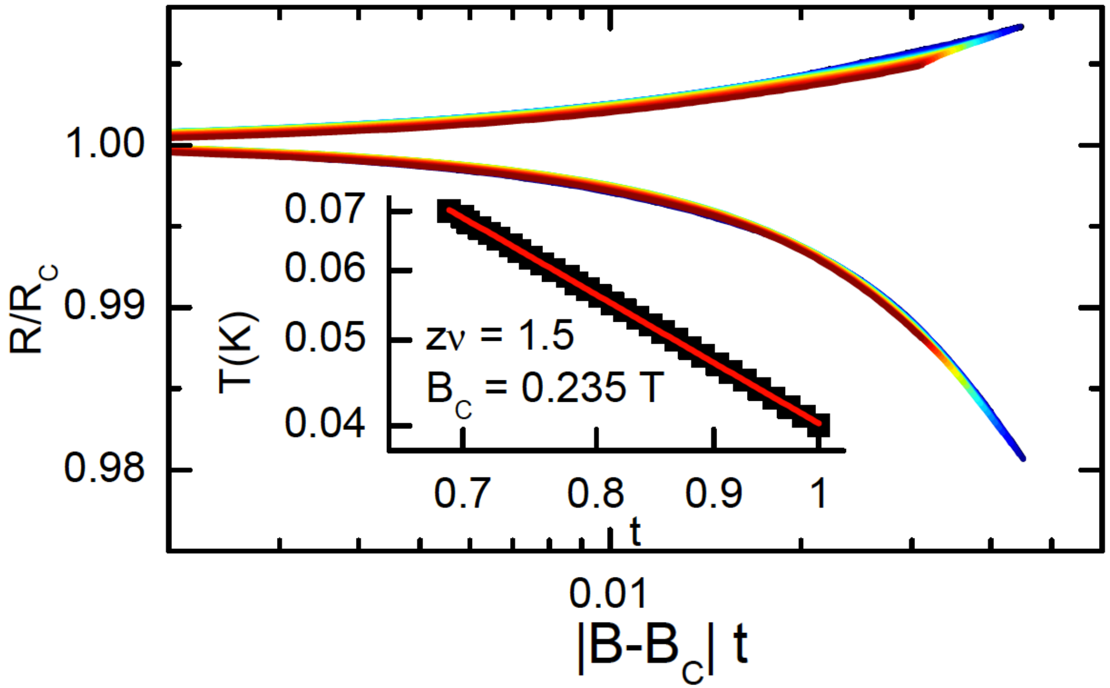
■ Crossing point at B_c

$$B_c > B_\times$$

■ Finite size scaling analysis

$$t = (T/T_0)^{-1/z\nu}$$

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

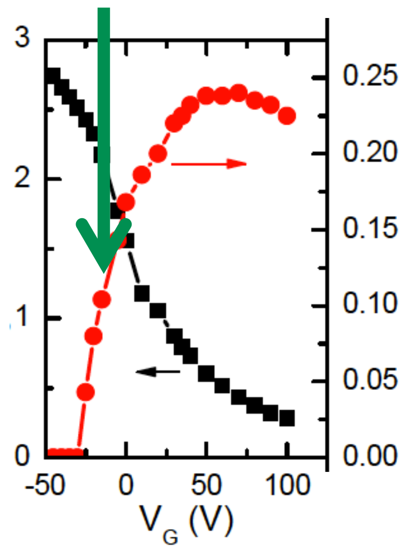


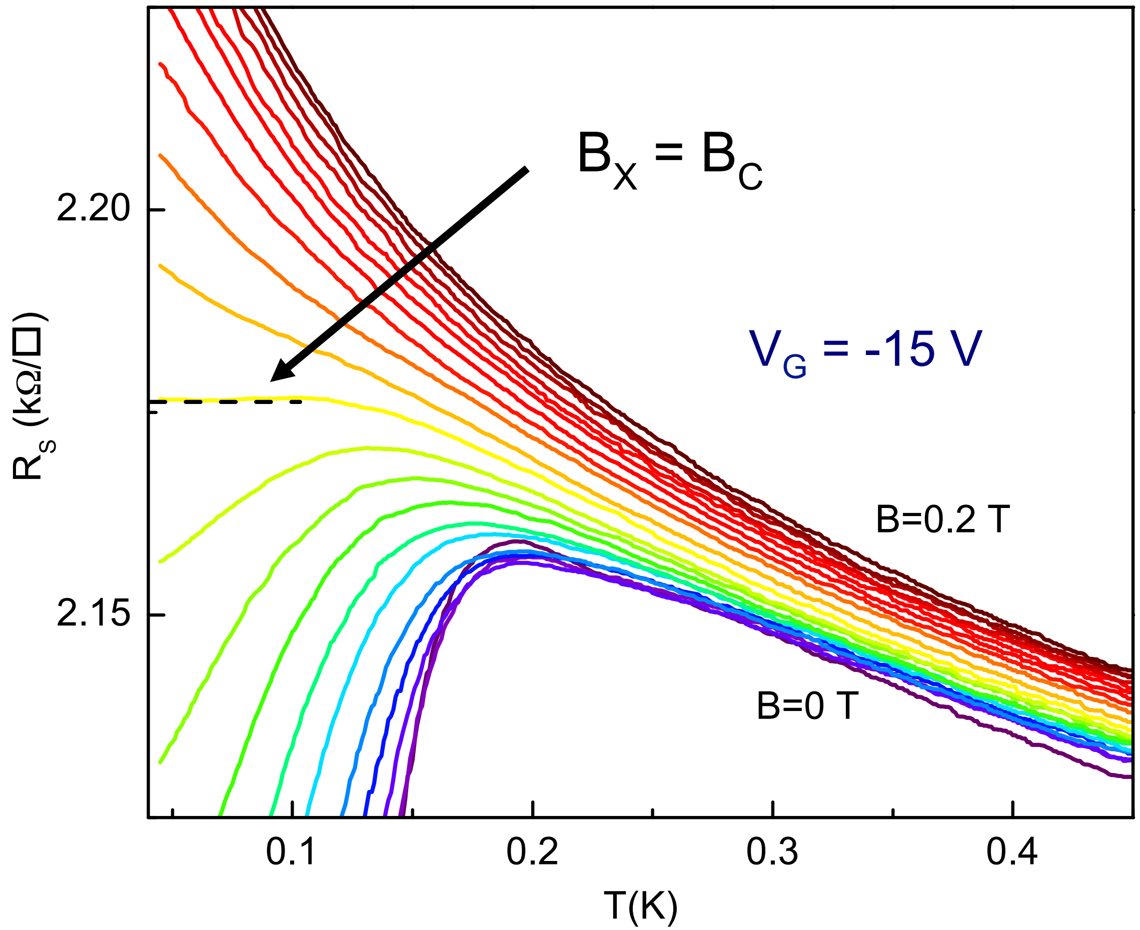
Biscaras et al, Nature Mat. 12, 542 (2013)

Magnetic field driven quantum phase transition

- Suppression of superconductivity by a perpendicular magnetic field at V_G=-15V

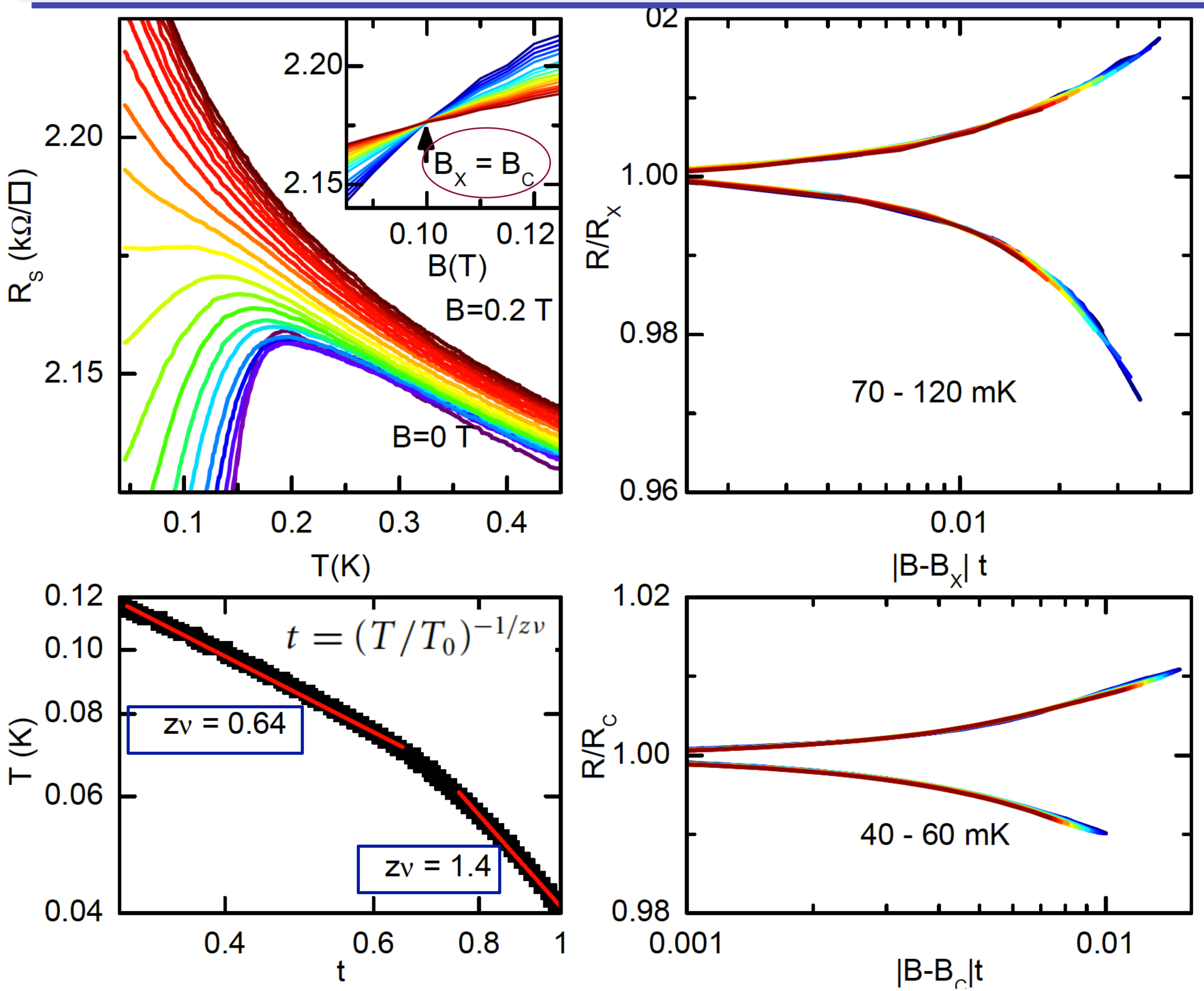
V_G=-15V





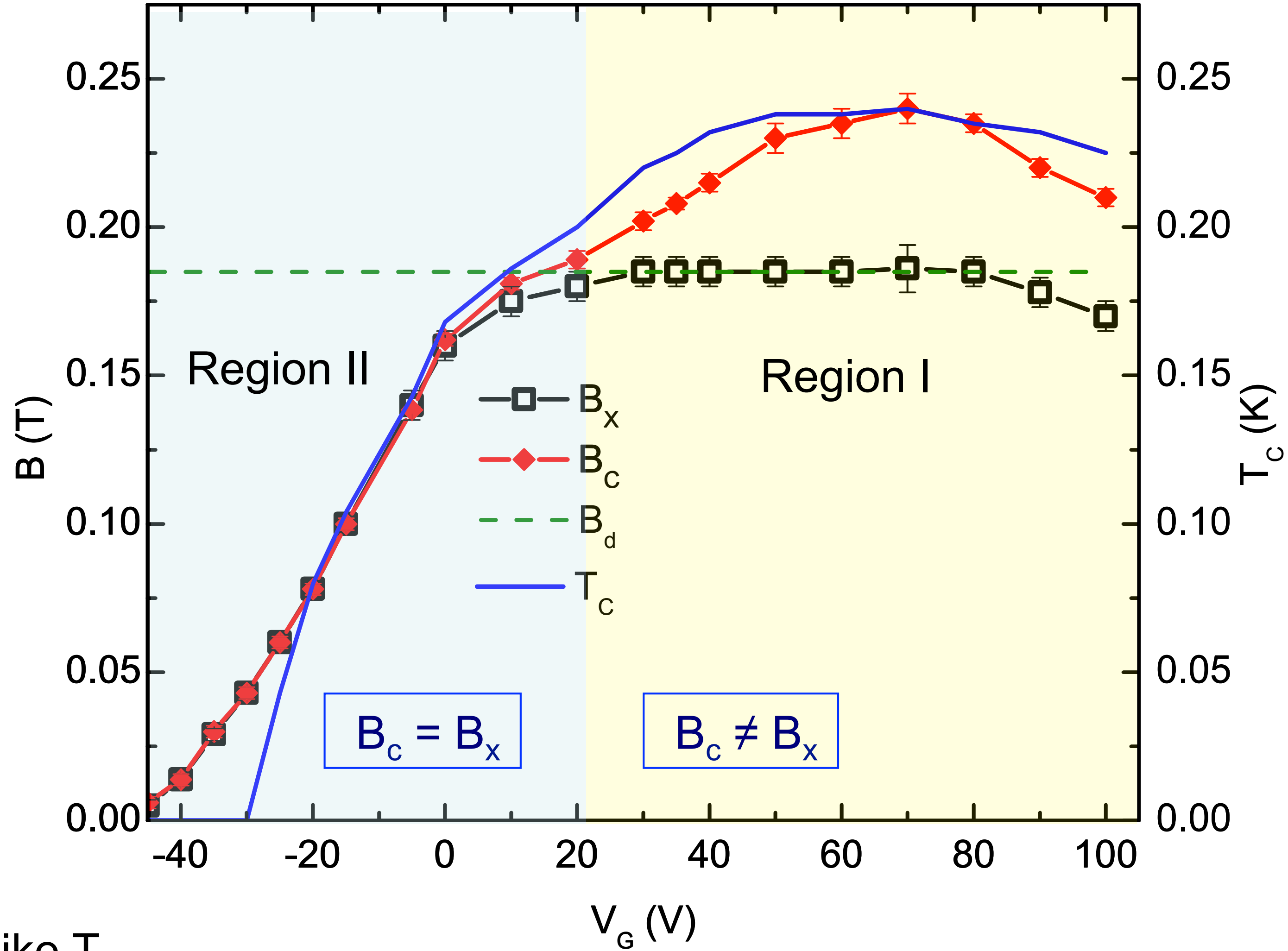
➡ Plateau in the resistance down to the lowest temperature !

Scaling and critical exponents



- "High" T
- zν ≈ 2/3
- "Low" T
- zν ≈ 3/2

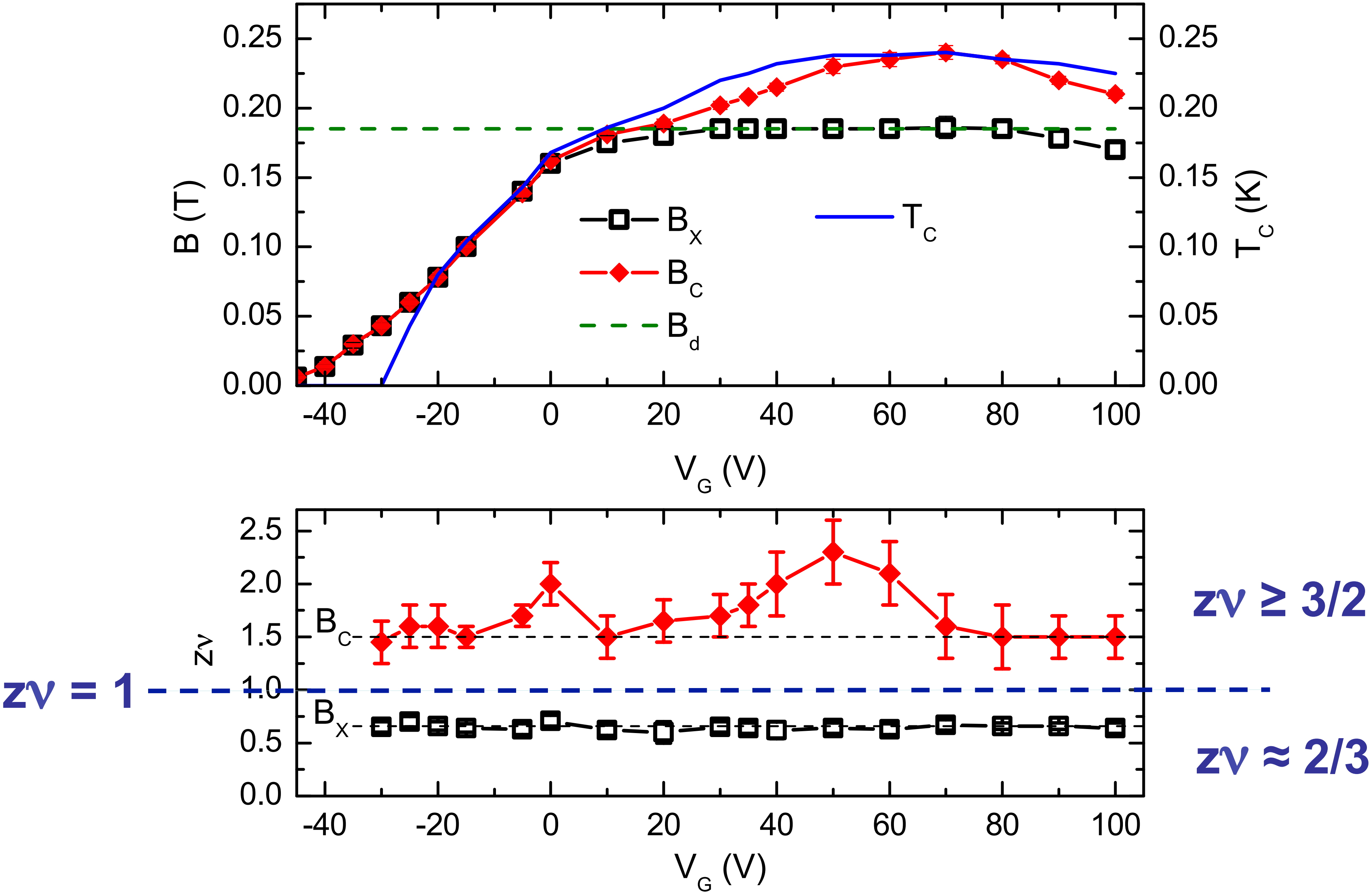
Critical fields as a function of V_G



- B_c scales like T_c
- Two different regions ($B_x = B_c$ & $B_x \neq B_c$)
- B_x is constant in Region I

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

Critical exponents as a function V_G

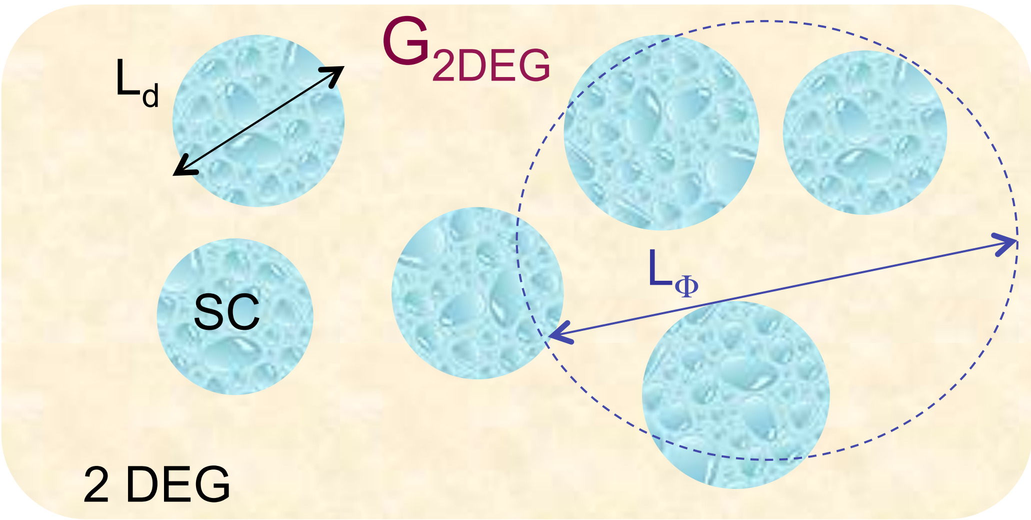


➡ Multiple Critical Behavior (B_x & B_c) associated to different critical exponents

Multiple Quantum Critical Behaviors in 2D SC

Disordered array of SC puddles

Spivak et al, PRB 2008

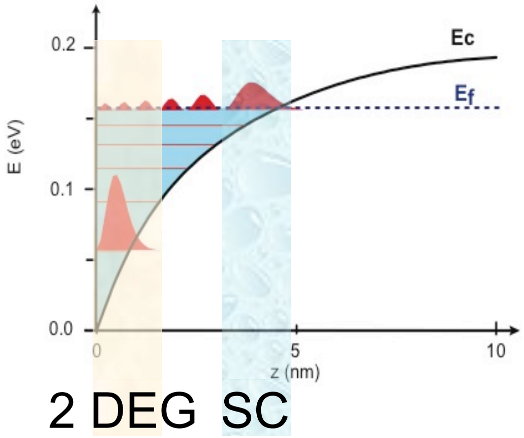


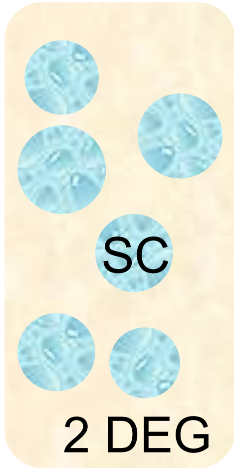
- Characteristic puddle size L_d
- Puddles coupled by Josephson through G_{2DEG}
- Phase length $L_\Phi \sim T^{-1/z}$

- Phase fluctuations in the puddles and between puddles : two critical fields
- Puddles may be not SC if the coupling is too weak : two regimes (G_{2DEG})
- The critical field B_c scales like T_c

Towards a scenario ...

■ Superconducting puddles in a 2DEG matrix



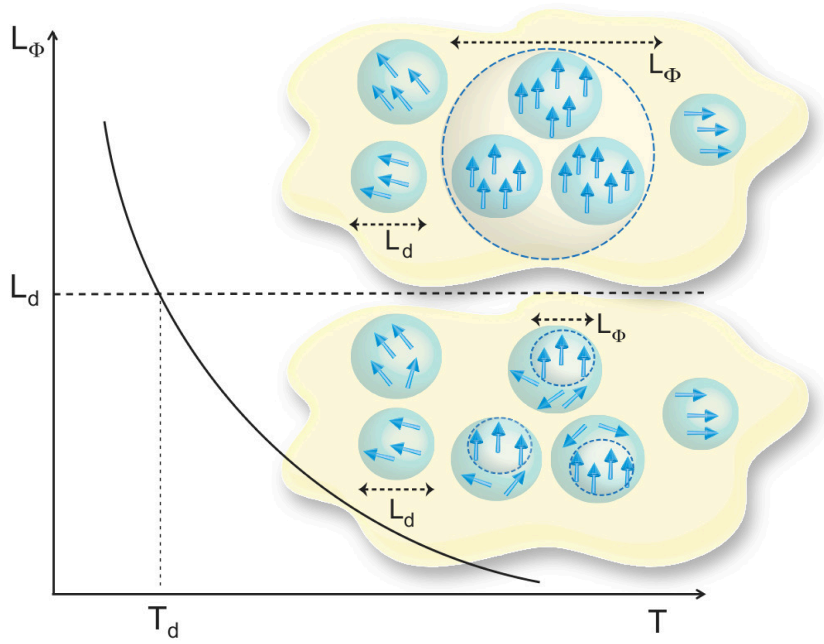


V_G controls G_{2DEG}

Strong coupling
i.e high G_{2DEG}

Small coupling
i.e low G_{2DEG}

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



➡ Low temperature $T < T_d$

$L_\Phi > L_d$ "disordered" system

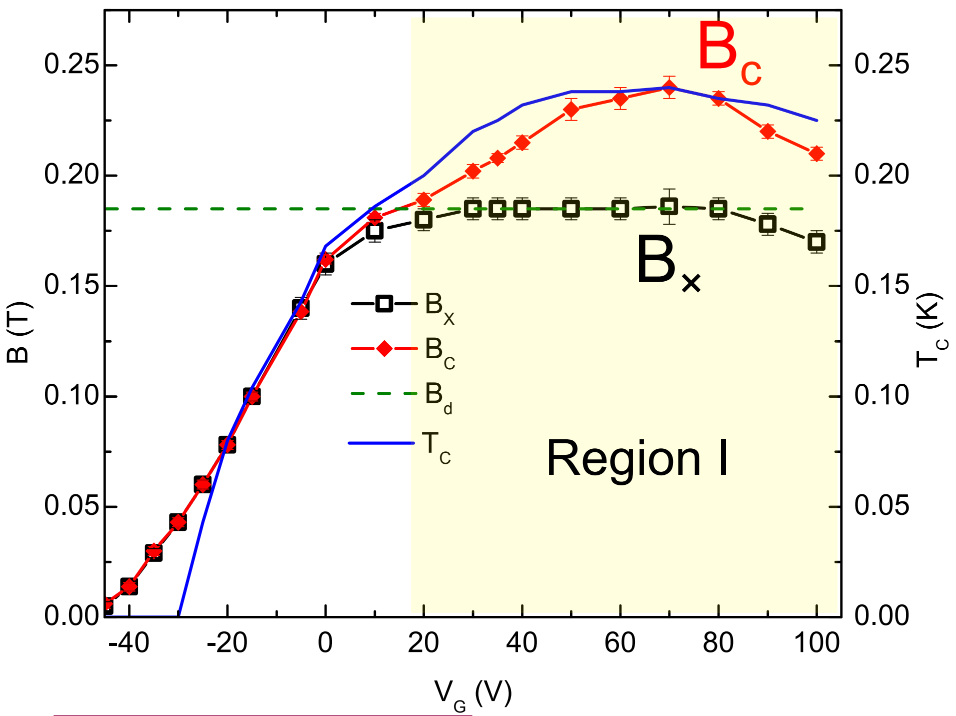
$\nu > 1$ (Harris criteria)

➡ High temperature $T > T_d$

$L_\Phi < L_d$ "clean" system

The puddles scenario

- High G_{2DEG} regime for V_G> 20V



High temperature

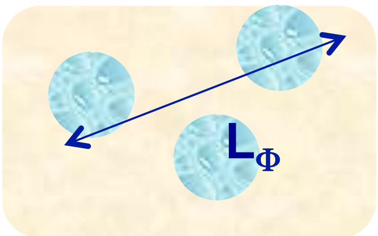
"clean"

$z\nu = 2/3$

- $B_\times$ destroys superconductivity inside puddles
- Typical size of a puddle

$$L_d = \sqrt{\Phi_0 / B_\times} \approx 100nm$$

Low temperature



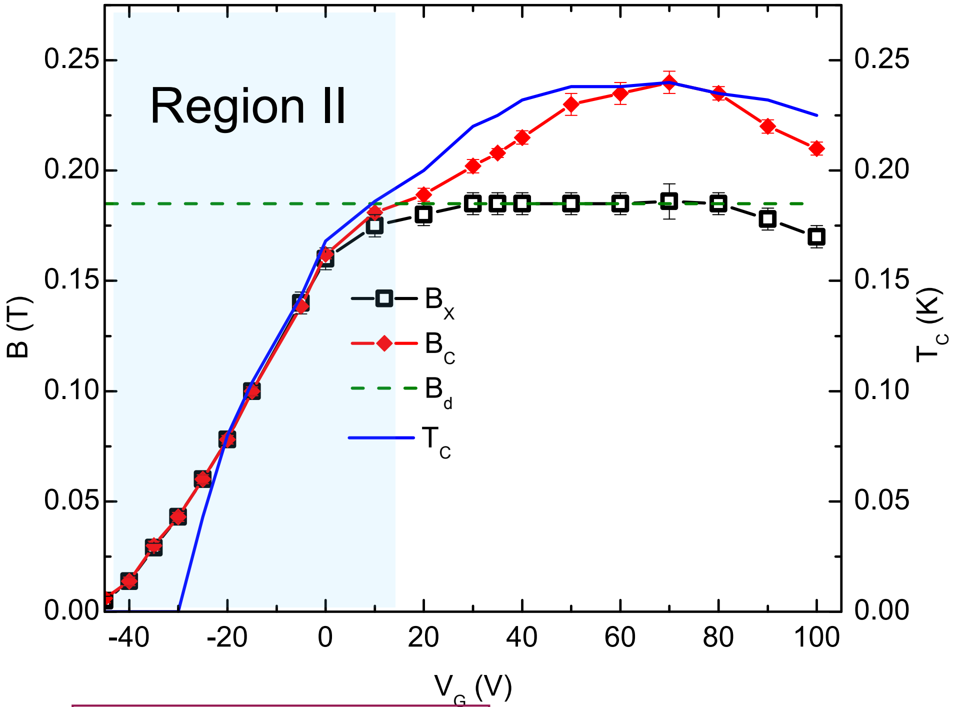
"disordered"

$z\nu$ ~ 3/2 > 1

- B_c destroys superconductivity of the array

The puddles scenario

- Low G_{2DEG} regime for $V_G < 20V$

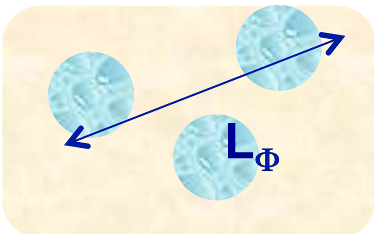


➡ a single critical field $B_c = B_x$

➡ Puddles are always fluctuating

➡ B_c destroys superconductivity of the array

Low temperature



"disordered"

$z\nu \sim 3/2 > 1$

High temperature

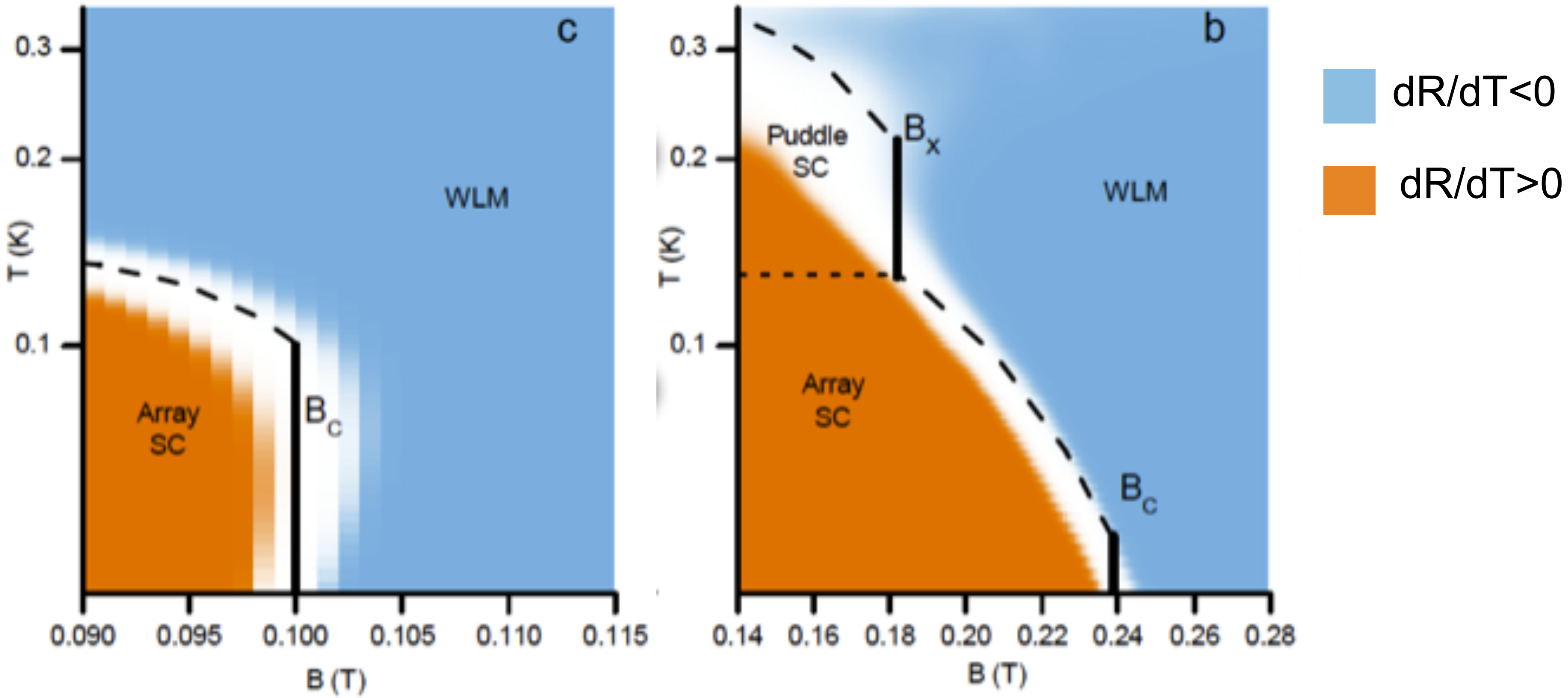
"clean"

$z\nu = 2/3$

B-T phase diagrammes

Region II

Region I



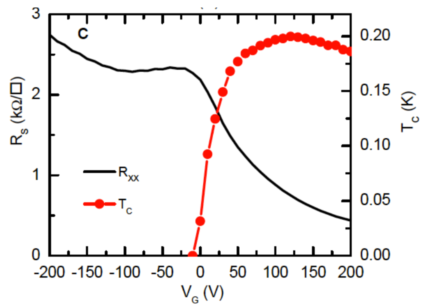
V_G=-15 V

V_G=80 V

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

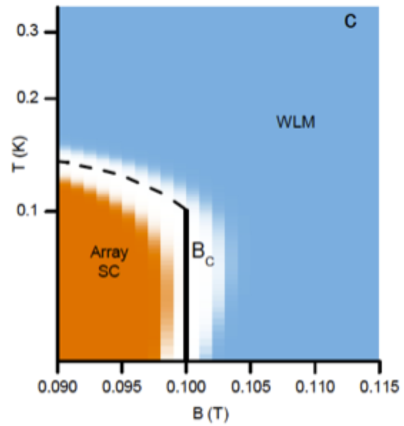
Outline

Tunable superconductivity in oxide 2DEG



Quantum phase transition under magnetic field

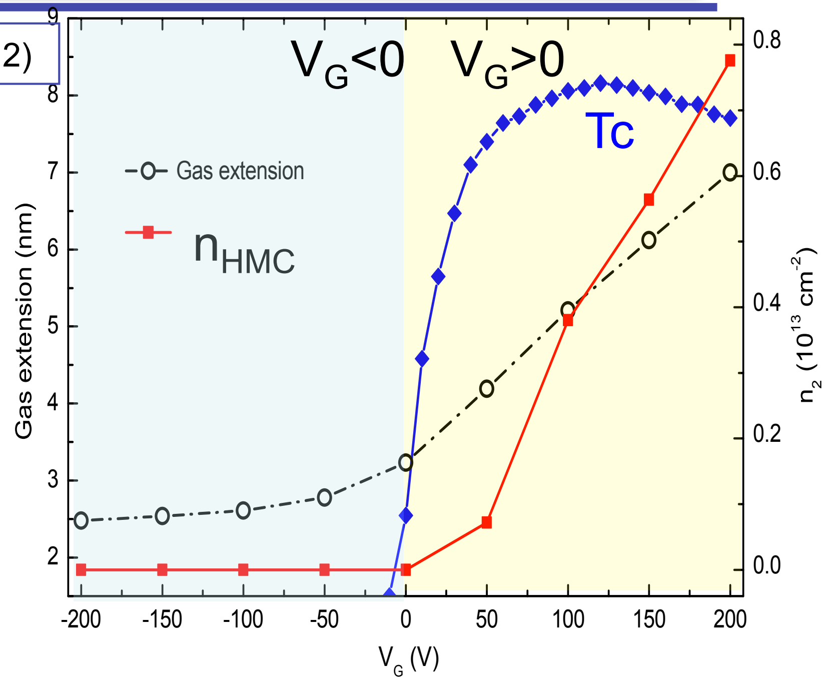
Conclusions



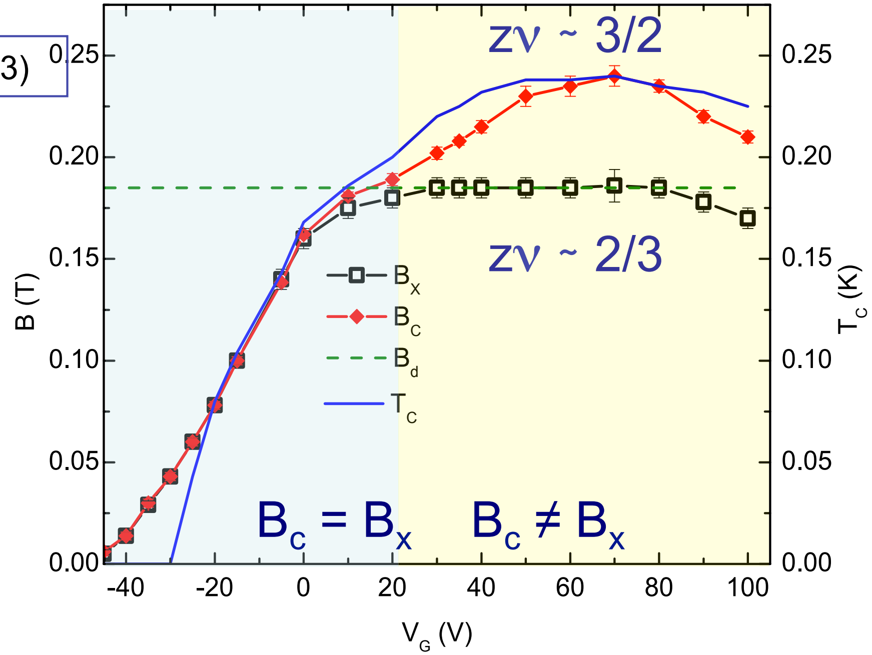
Conclusions

Biscaras et al, PRL 108, 247004 (2012)

- Two types of carriers
- Highly Mobile Carriers & Superconductivity
- Inhomogeneous behavior



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



- SC puddles coupled by a 2DEG
- (2+1)D XY quantum phase transition
- Two Critical Behaviors
- Cross over the "Harris criteria"
- ? Intrinsic filamentary inhomogeneity ?

People

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

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C. Proust, D LeBoeuf, LNMCI Toulouse (France)

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

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

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

Biscaras et al, PRL 108, 247004 (2012)

Caprara et al, PRB(R) 88, 020504 (2013)

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