Laboratoire de Physique des Solides • UMR 8502 Université Paris sud bât 510 • 91405 Orsay cedex

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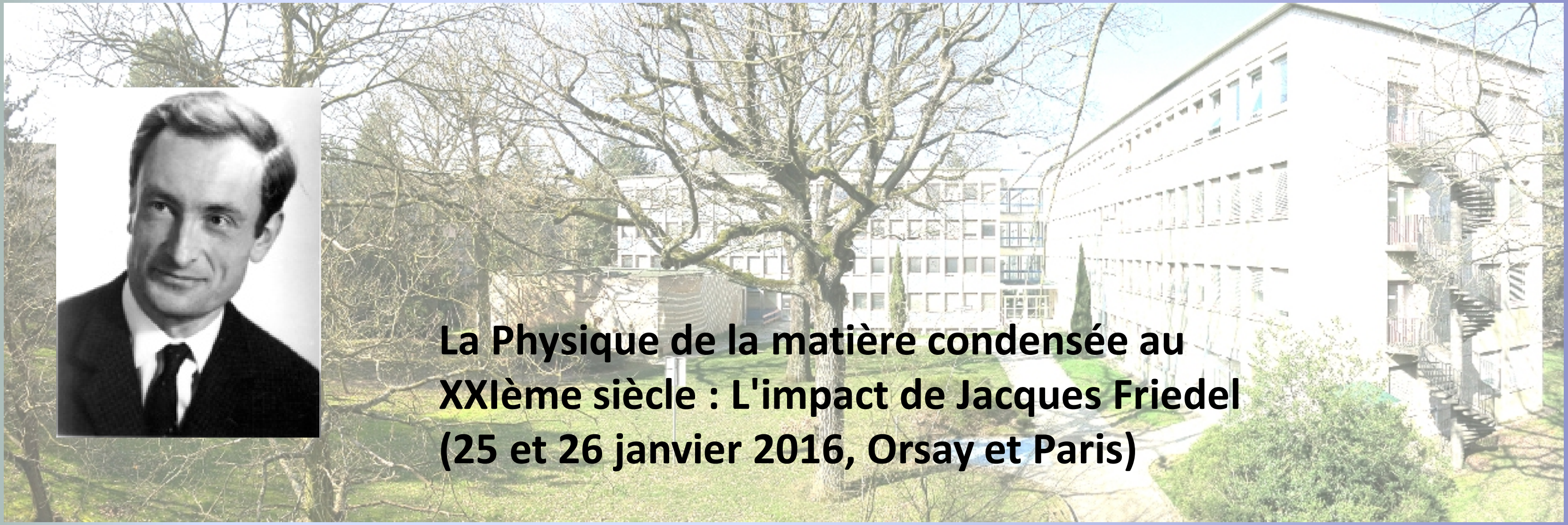
IUF

UNIVERSITÉ PARIS SUD



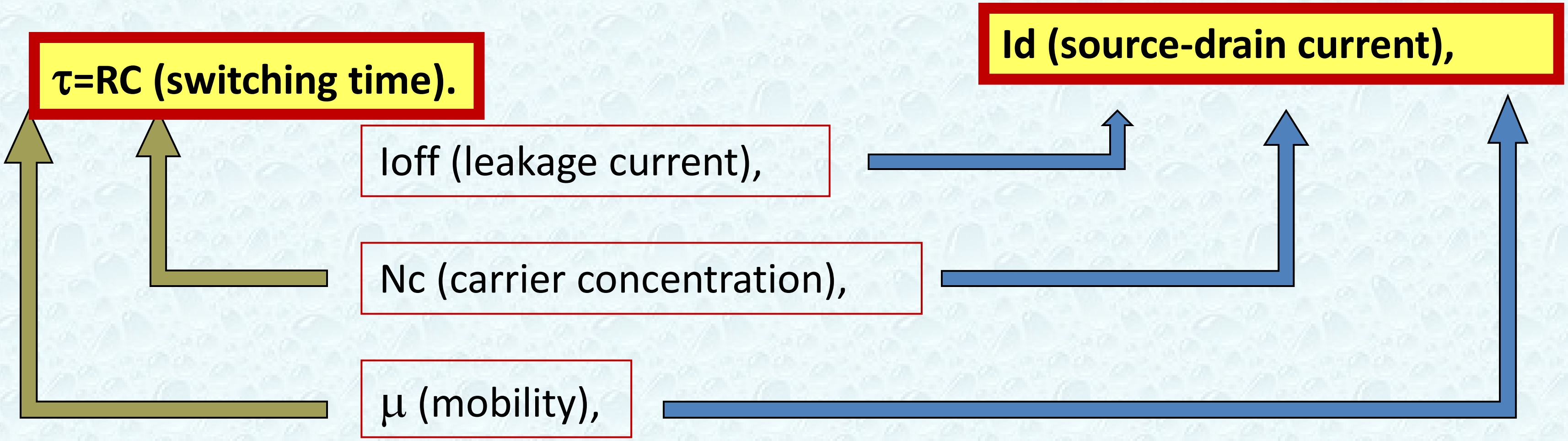
La Physique de la matière condensée au XXIème siècle : L'impact de Jacques Friedel (25 et 26 janvier 2016, Orsay et Paris)

L'oxytronique : une (r)évolution technologique?

M. Gabay

I. Down the rabbit hole

Scaling down impacts critical parameters of a transistor:



τ=RC (switching time).

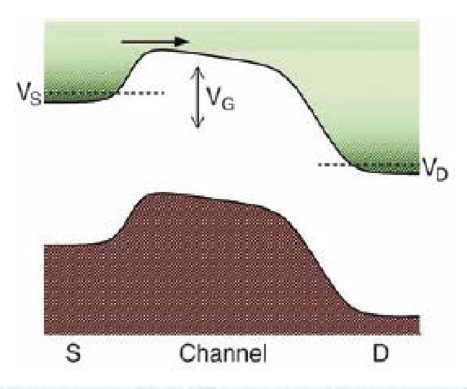
Id (source-drain current),

Ioff (leakage current),

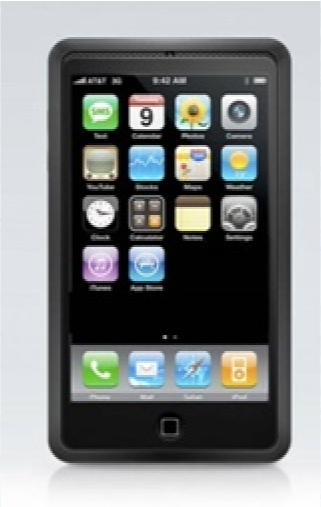
Nc (carrier concentration),

μ (mobility),

j=Nc e μ E



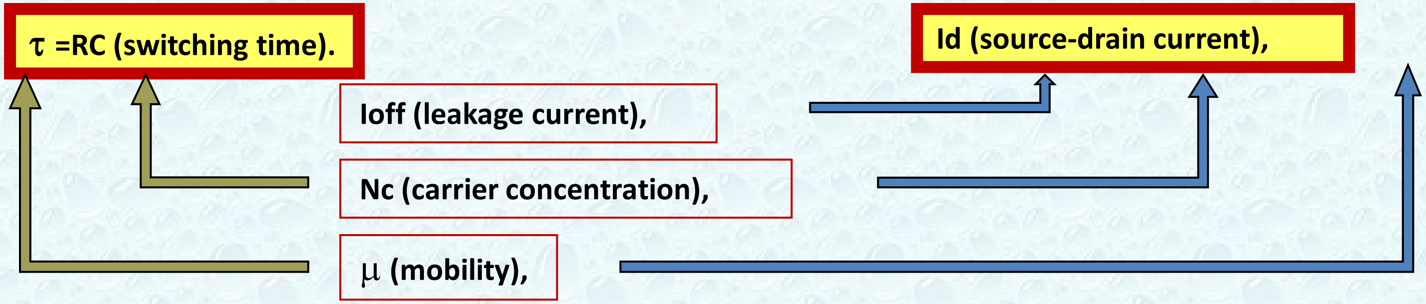
Thomas N. Theis *Science* **327**, 1600 (2010);



If Ioff/transistor~100nA @room T
→ Ileak~10A !!

Technological hurdles.

Scaling down impacts critical parameters of a transistor:



τ =RC (switching time).

Id (source-drain current),

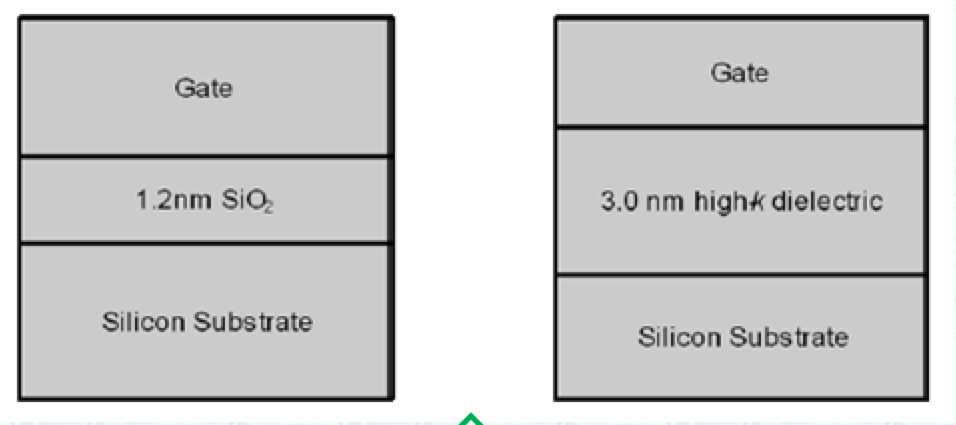
Ioff (leakage current),

Nc (carrier concentration),

μ (mobility),

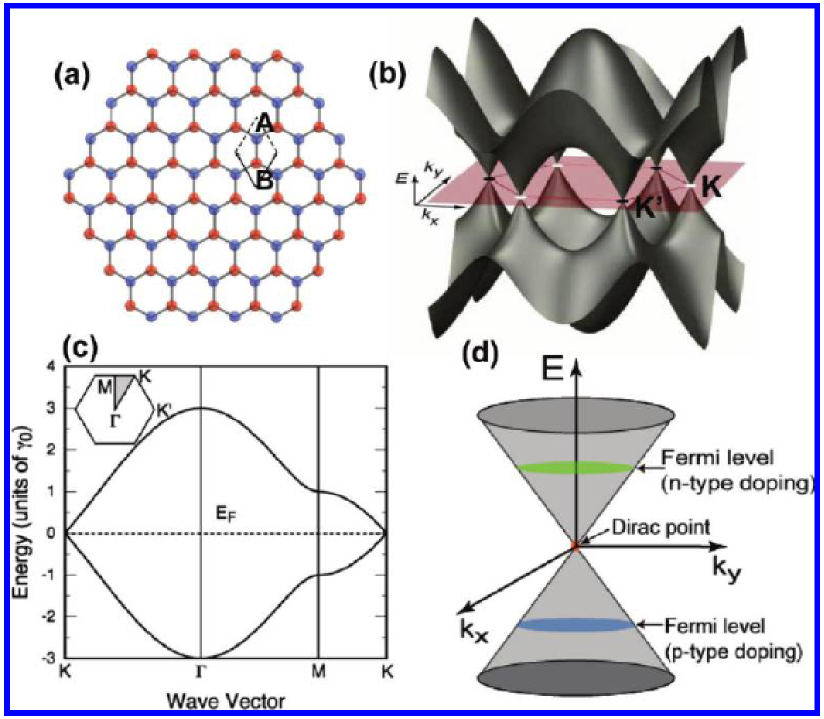
🙂 ☹

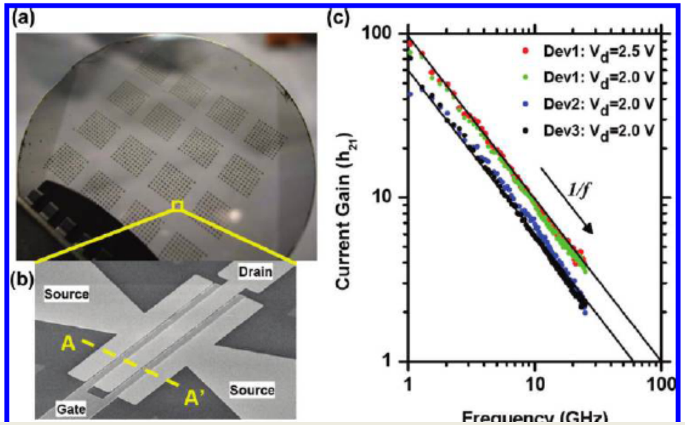
$\Leftarrow$ **Constant voltage scaling : good for leakage but… bad for $\mu \sim 1/E^{1/3}$**



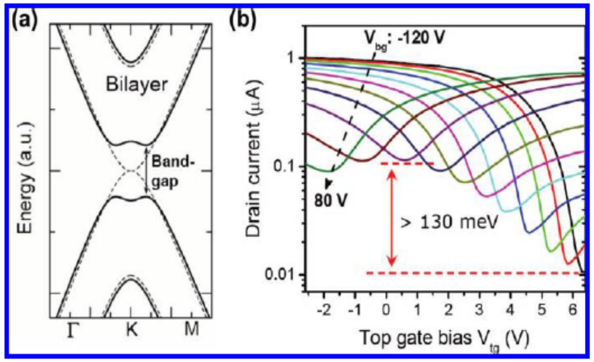
☹ **Bad for τ** $\Rightarrow$ **multicore**

Avouris, Nanoletters, 10, 4285, 2010

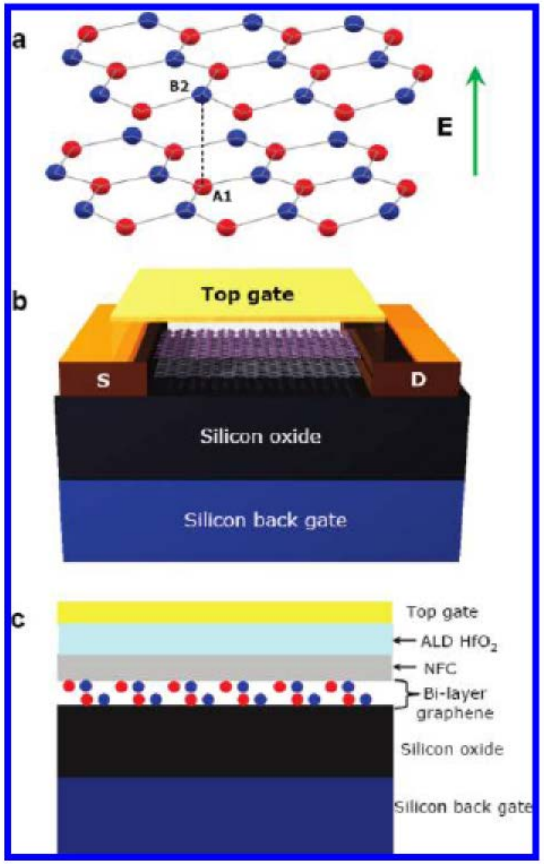




Avouris, Nanoletters, 10, 715, 2010



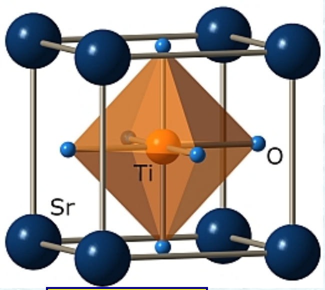
applied perpendicular electric field. The
bandstructure in the presence of a strong
current as a function of top-gate bias for
temperature and a gap >130 meV opens



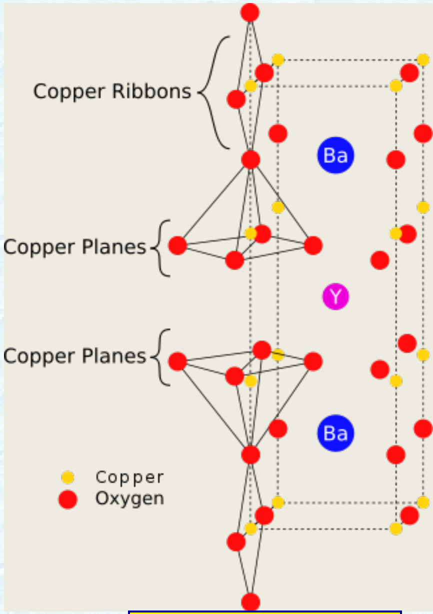
Plus: 100GHz vs 28 GHZ limit for ususal semiconductors, mobility@room T =10 times that of MOSFET

Minus: On/Off ratio of 100 vs 10^4 to 10^7 for MOSFET

Transition Metal oxide (TMO)

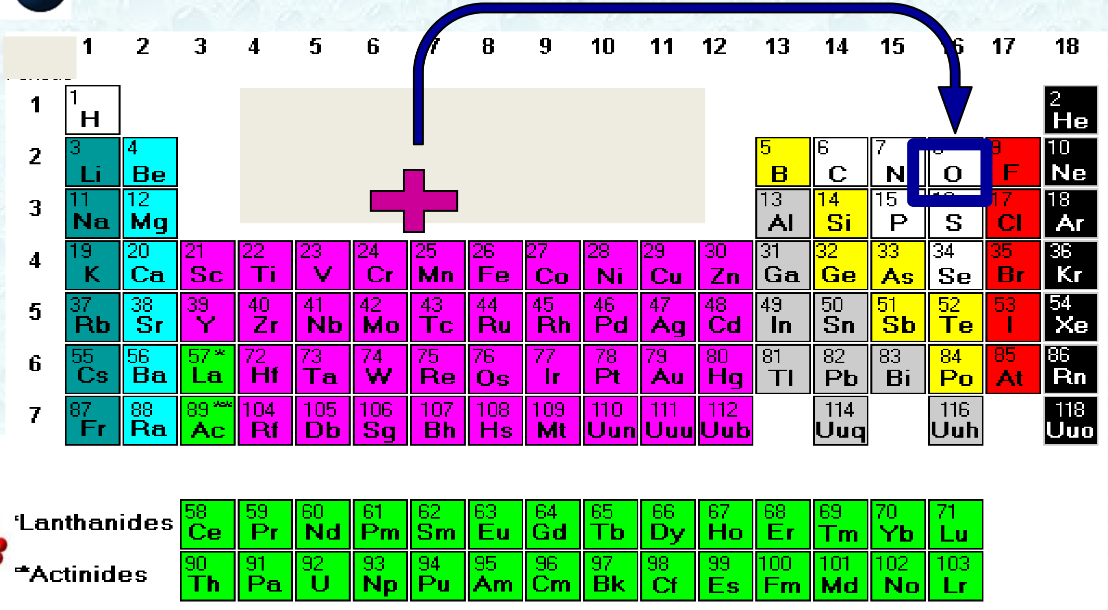


SrTiO$_3$



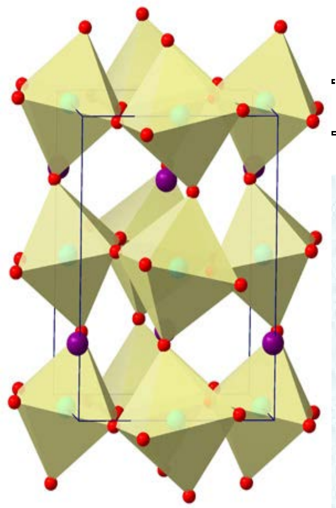
YBa$_2$Cu$_3$O$_{7-}$

♎

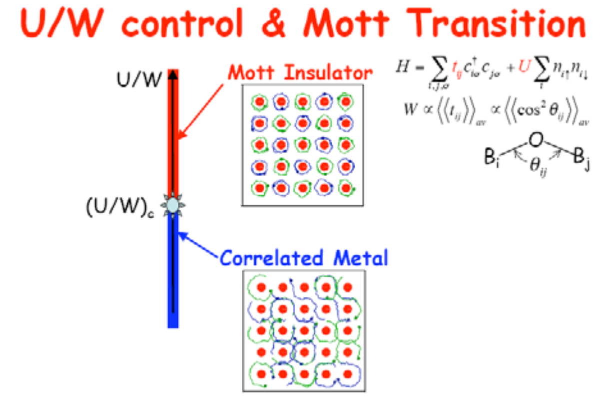


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 * La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 ** Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq		116 Uuh		118 Uuo

*Lanthanides	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
**Actinides	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



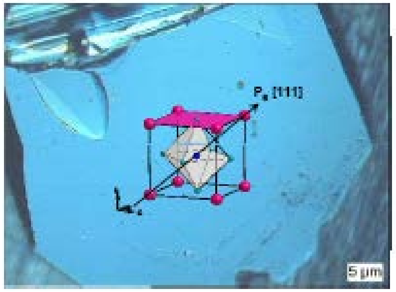
La$_{1-x}$Sr$_x$MnO$_3$



U/W control & Mott Transition

$$H = \sum_{i,j,\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

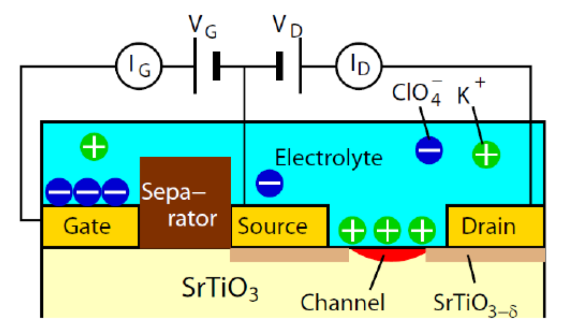
$$W \propto \langle\langle t_{ij} \rangle\rangle_{av} \propto \langle\langle \cos^2 \theta_{ij} \rangle\rangle_{av}$$



BiFeO$_3$

Large ε_r for oxides surface carrier doping and « built-in » insulating coating

μ (mobility) sensitive to the quality of the interface



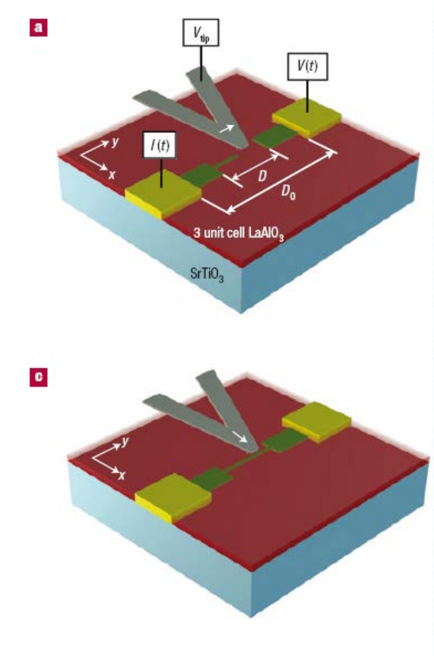
K Ueno et al, Applied physics Letters 96, 252107, 2010


PHYSICS

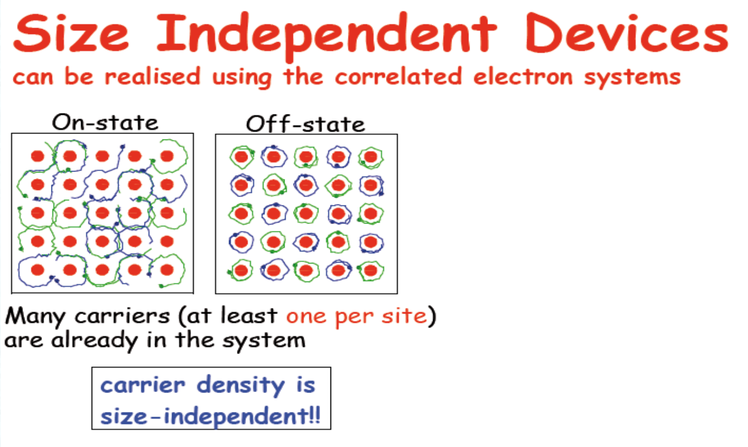
Metal oxide chips show promise

Materials that flip from insulator to conductor could make energy-efficient transistors.

E.S. Reich, Nature, 495, 17 (2013)



C. Cen et al, Nature Materials ,7 , 298. 2008


Size Independent Devices

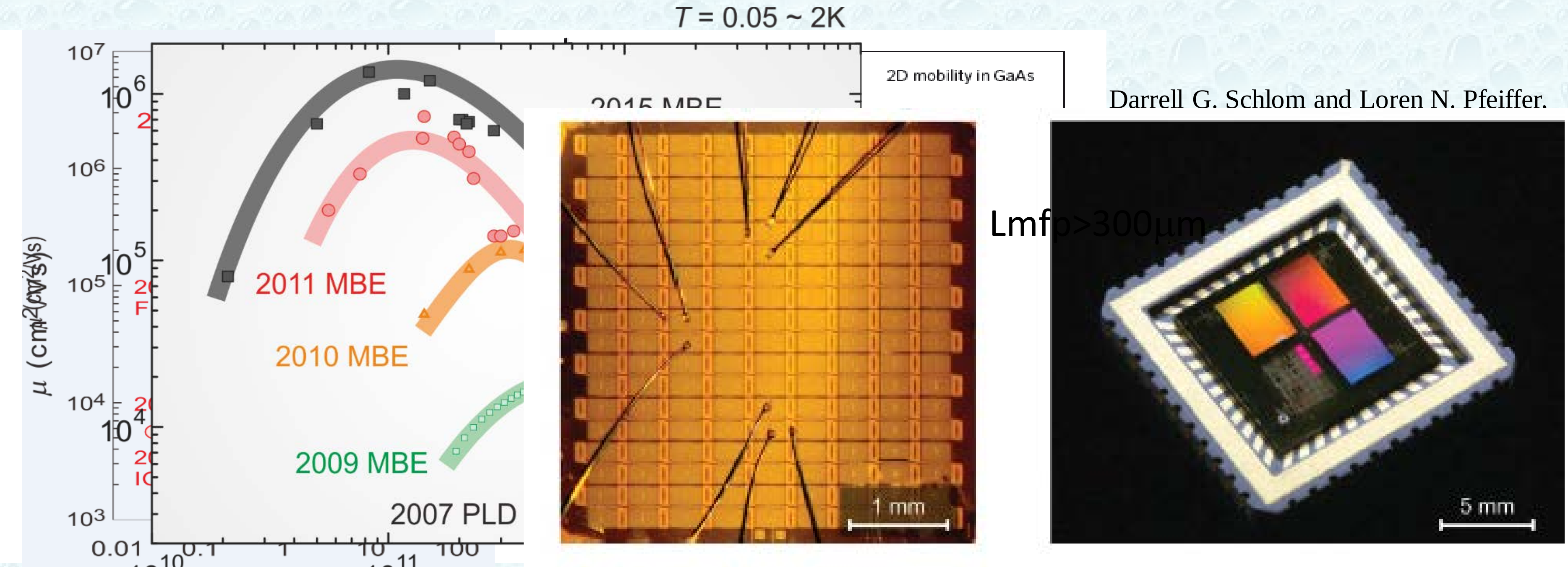
can be realised using the correlated electron systems

Many carriers (at least one per site) are already in the system

carrier density is size-independent!!

Large ε_r for oxides surface carrier doping and « built-in » insulating coating

μ (mobility) sensitive to the quality of the interface



Darrell G. Schlom and Loren N. Pfeiffer.

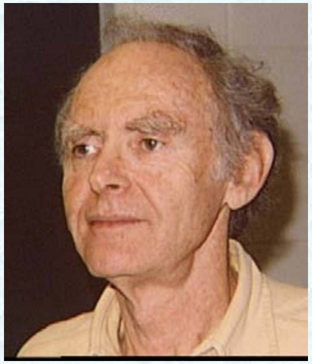
Lmfp>300μm

Figure 2. a) Photograph of an array of $LaAlO_3$–$SrTiO_3$ FETs with a design according to Figure 1a. Source (S), Drain (D), and Gate (G) of three FETs are contacted via wirebonding. b) Photograph of a $LaAlO_3$–$SrTiO_3$ chip carrying arrays with more than 700 000 FETs with a design as shown in Figure 1b with channel lengths as small as ≈350 nm. The colors are interference colors arising from the transistor patterns (see the Experimental Section).

Courtesy M. Kawasaki
μ= 1,200,000 cm2/Vs T=2K
Lmfp>10μm
(Mg,Zn)O/ZnO 2015 Ozone-MBE; $n=10^{11}cm^{-2}$

J. Mannhart et al. Advanced Materials Interfaces, DOI : 10.1002/admi.201300031, Wiley 2013

1.3. Quantum concept of transport (1979):

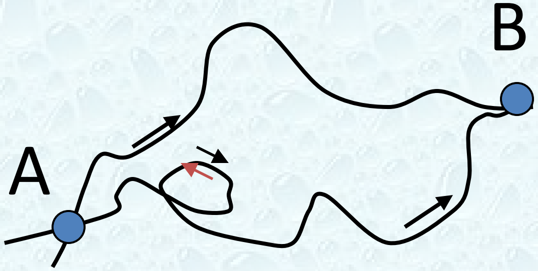


E.Abrahams

T.V. Ramakrishnan

P.W. Anderson

Competition between dimensionality and interferences



Interference of electron waves causes localization

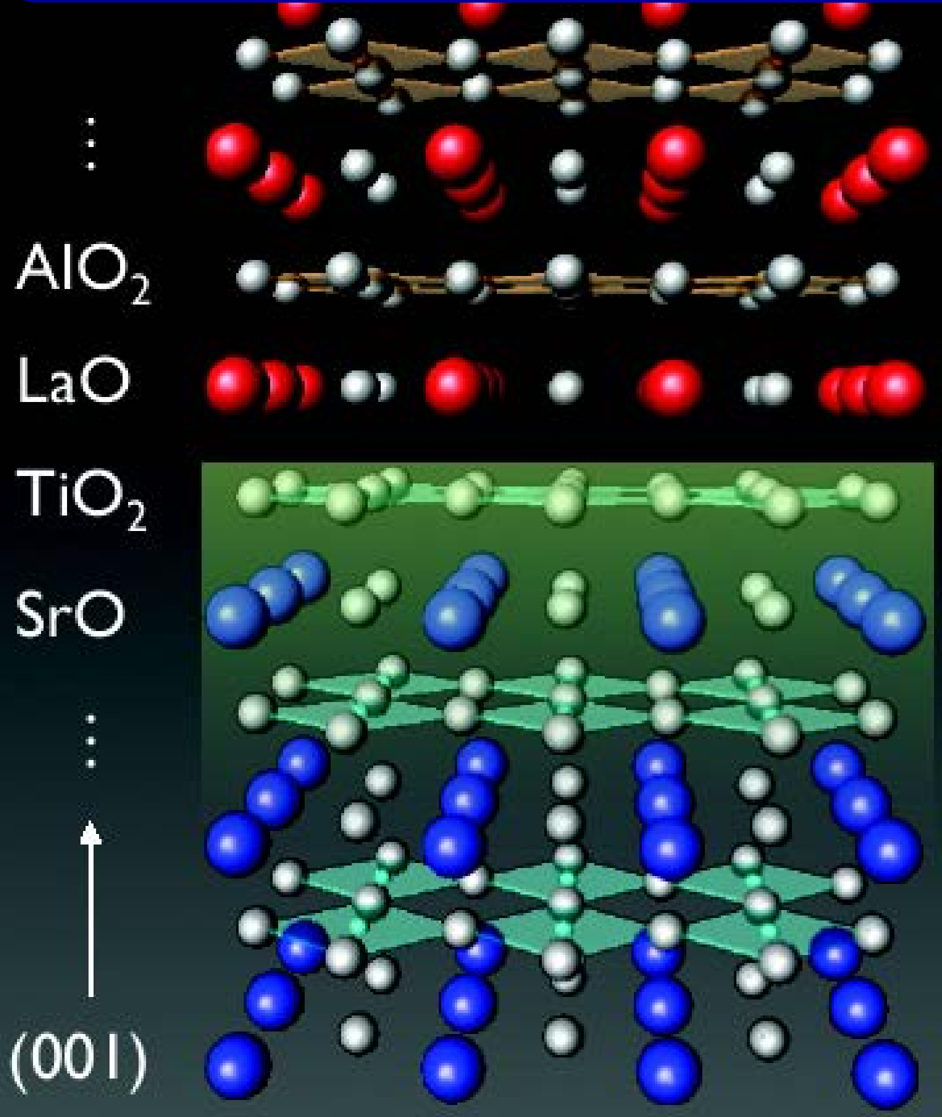
$$\sigma = \sigma_D + \frac{e^2}{\pi h}\ln(T\tau)$$

All electrons in 2D become localized at T → 0

for $\ln(1/T\tau) \geq \sigma$

D.C. Licciardello

V. Transport in an oxide heterostructure



$LaAlO_3$:

band insulator

$\Delta = 5.6\,\mathrm{eV},\ \ \kappa = 24$

$SrTiO_3$:

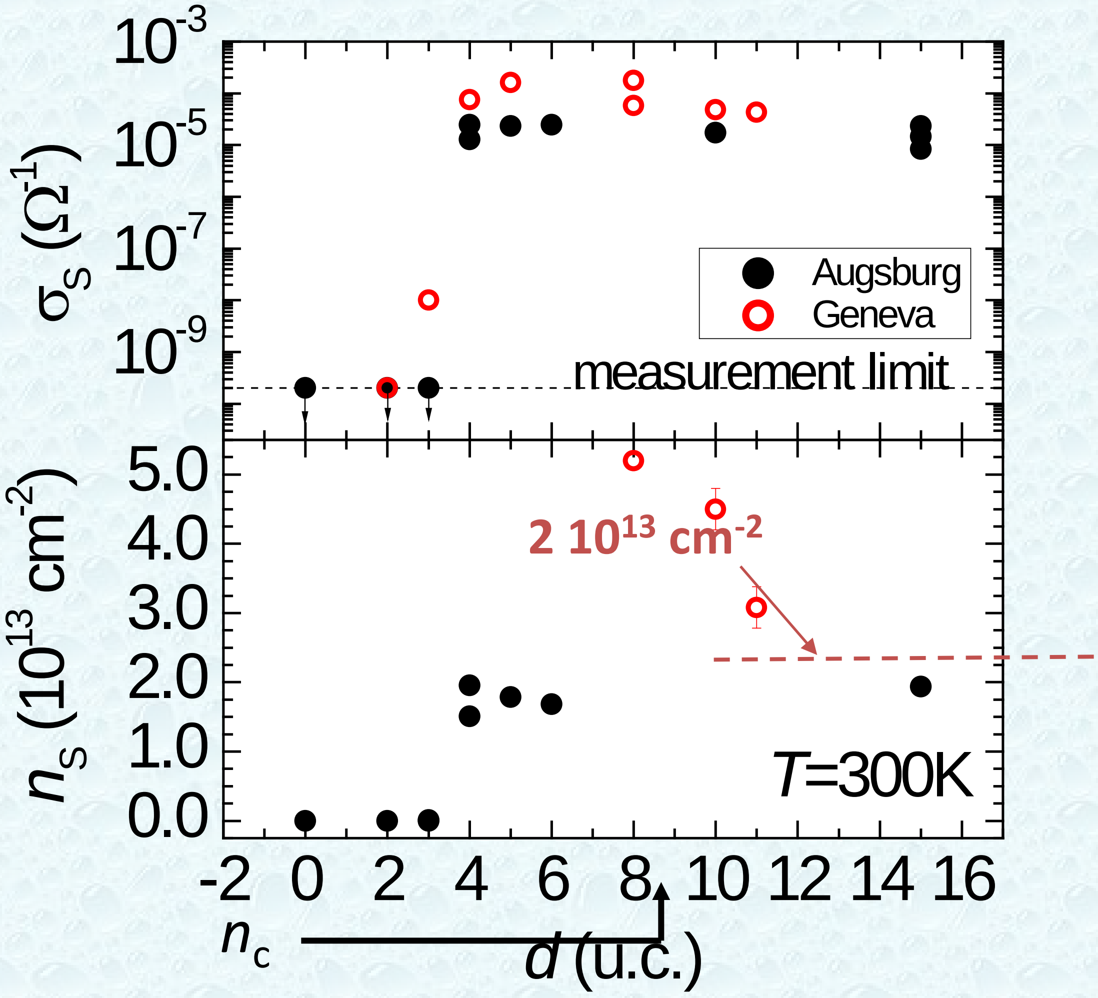
band insulator

$\Delta = 3.2\,\mathrm{eV},\ \ \kappa\,(300\,\mathrm{K}) = 300$

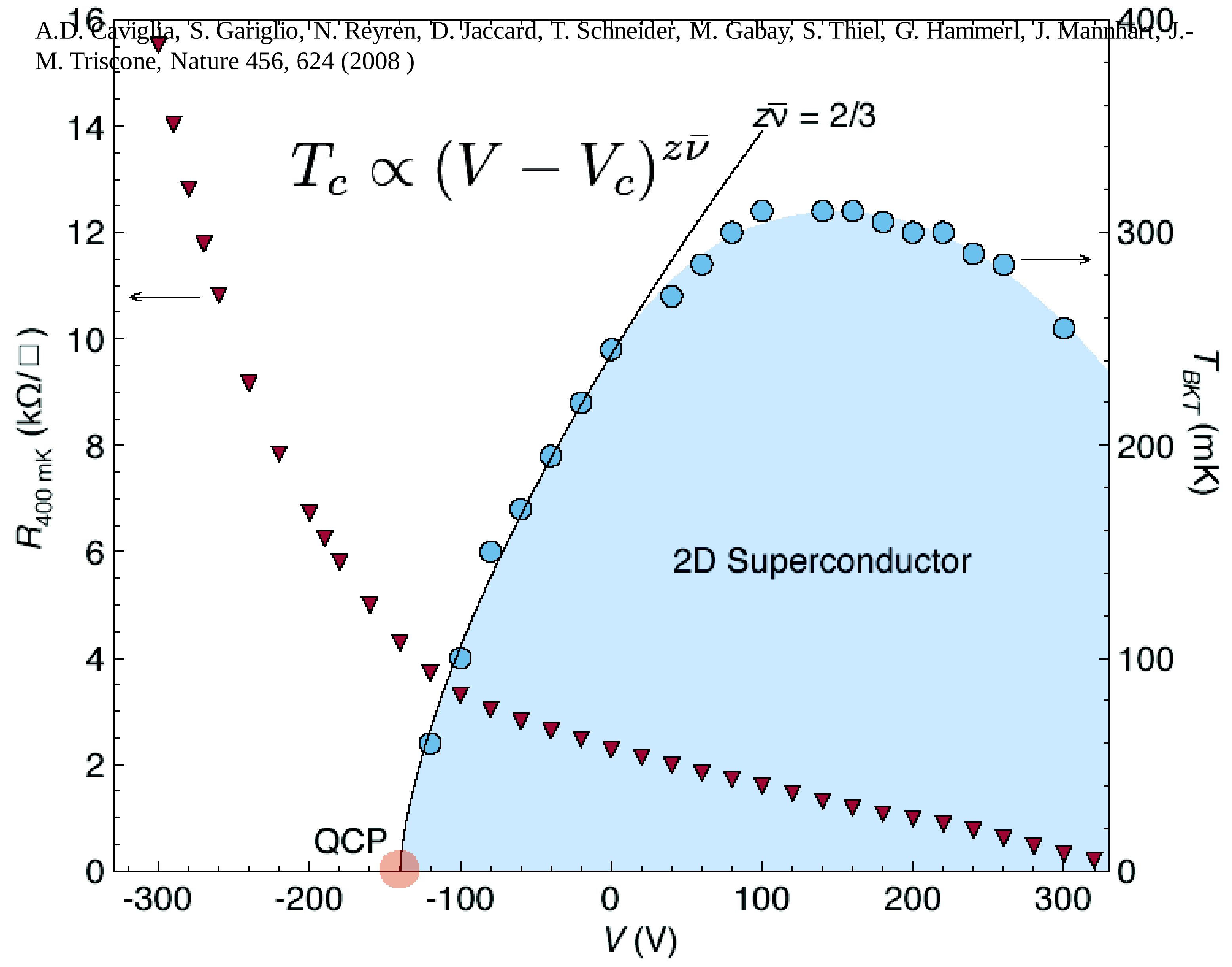
quantum paraelectric

A. Ohtomo and H.Y. Hwang, *Nature* **427**, 423 (2004)

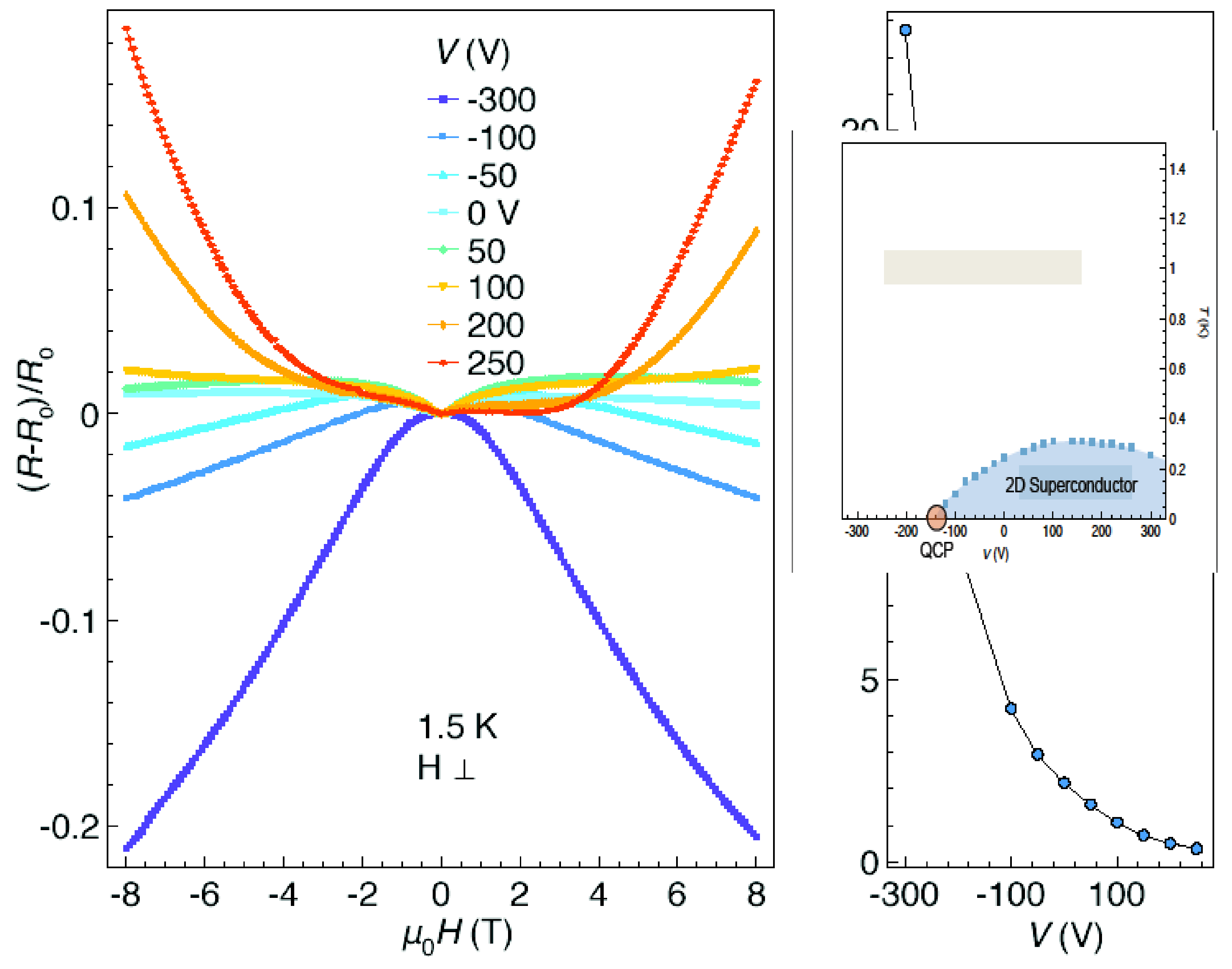
S. Thiel, *et al.*
Science **313**, 1942 (2006);

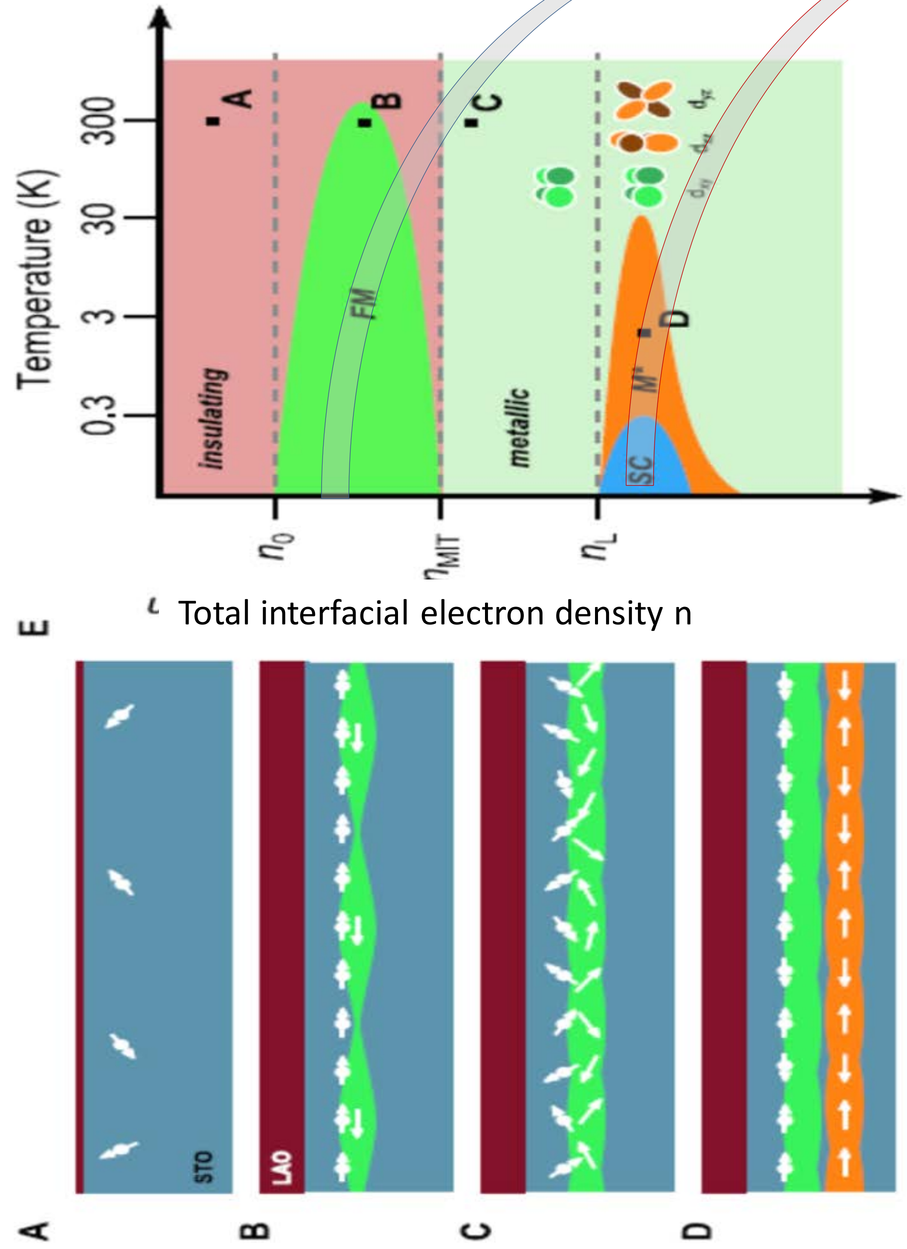


Phase diagram

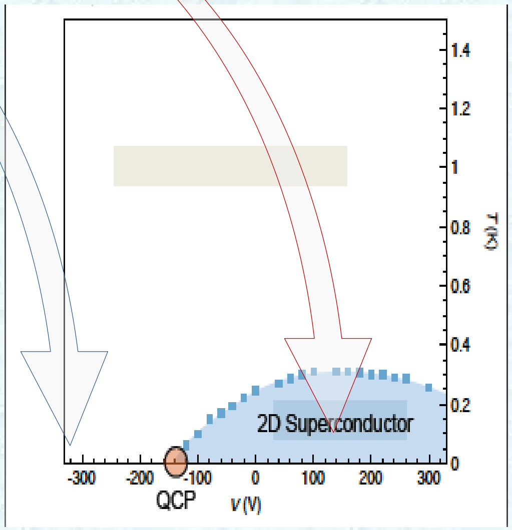

A.D. Caviglia, S. Gariglio, N. Reyren, D. Jaccard, T. Schneider, M. Gabay, S. Thiel, G. Hammerl, J. Mannhart, J.-M. Triscone, Nature 456, 624 (2008)

$$T_c \propto (V - V_c)^{z\bar{\nu}}$$

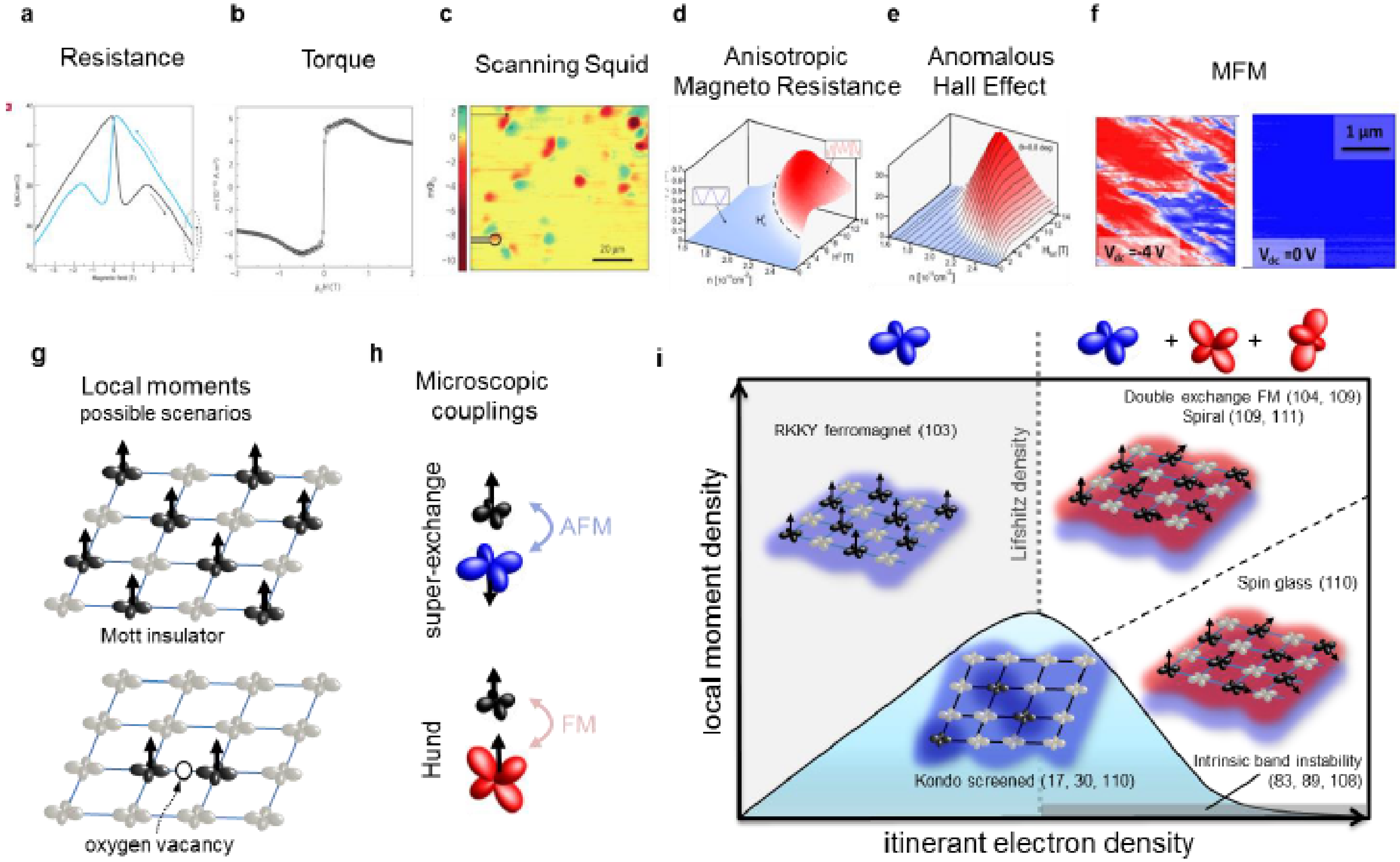

V (V)
-300
-100
-50
0 V
50
100
200
250
(R-R$_0$)/R$_0$
0.1
0
-0.1
-0.2
-8
-6
-4
-2
0
2
4
6
8
$\mu_0 H$ (T)
1.5 K
H ⊥
20
5
0
-300
-100
100
V (V)
2D Superconductor
QCP
-300
-200
-100
0
100
200
300
V (V)
T (K)
1.4
1.2
1
0.8
0.6
0.4
0.2
0



Total interfacial electron density n



Feng Bi et al. Nature Communications 5, 5019 (2014)



J. Sulpizio et al. Annual Review of Materials Research
Vol. 44: 117-149 (Volume publication date July 2014)

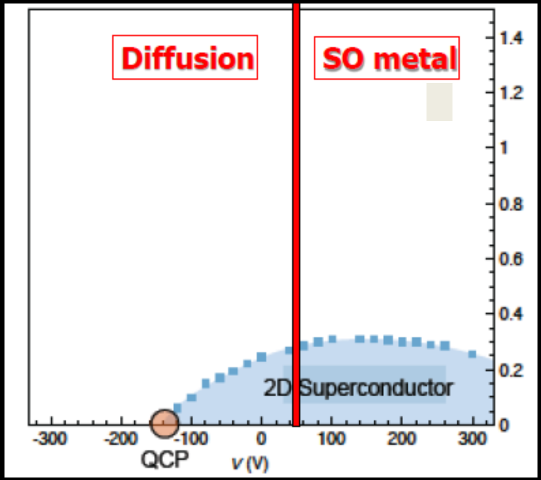
The Band story

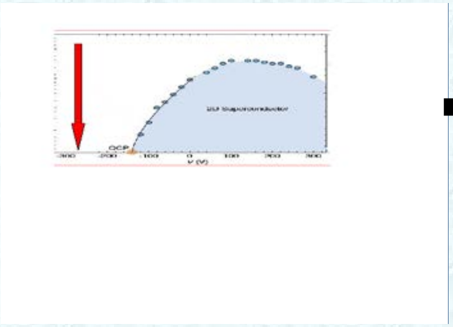
- **Band inversion (t_{2g} orbitals dxy, dxz, dyz)**

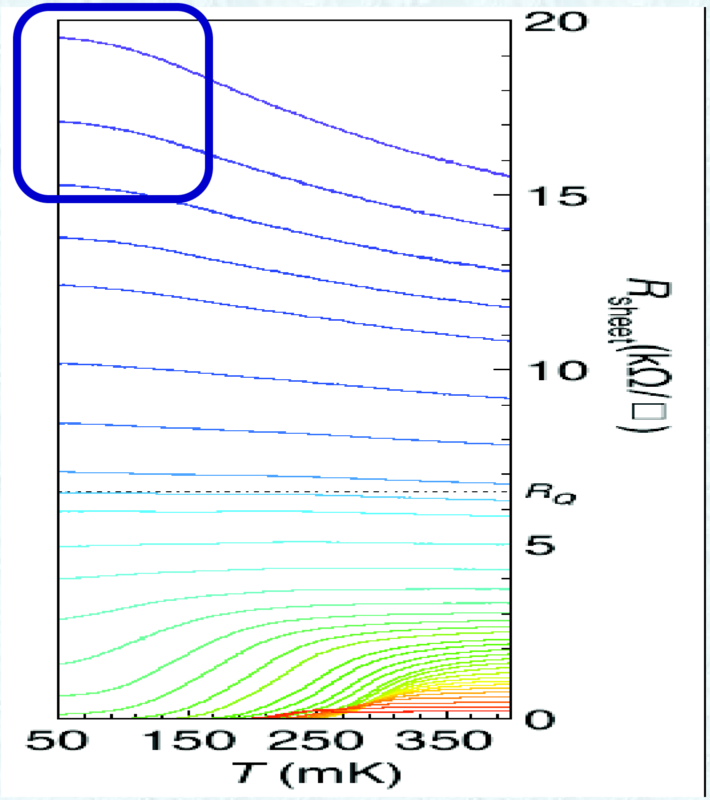
- **(Electric field?) confinement on STO side (mind the dielectric constant)**

- **The carrier concentration puzzle**

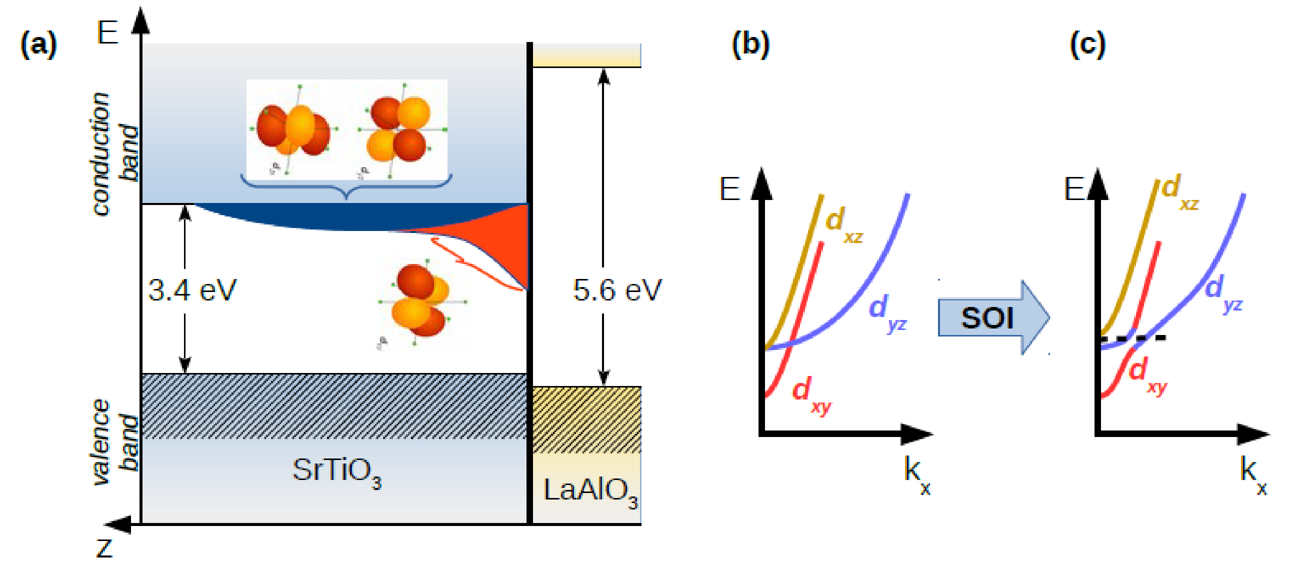
- **It takes two (types of bands) to tango**







In the strongly underdoped regime $k_F l \sim 1$



S. Gariglio et al., Nature Rev. Mat, Jan 2016

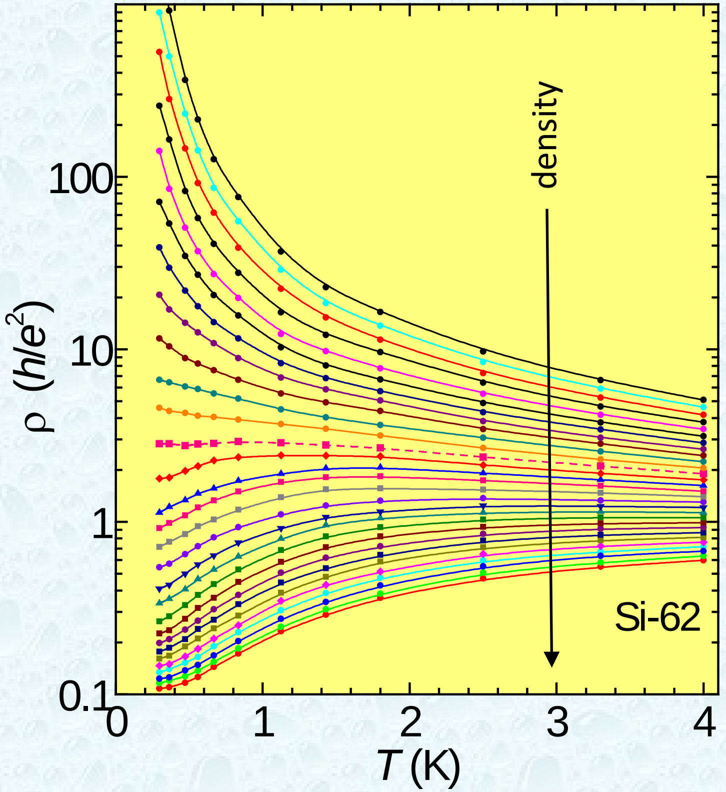
IV. Disorder and interaction effects

2D high mobility sample

S.Kravchenko, VP, et al.,
PRB **50**, 8039 (1994)

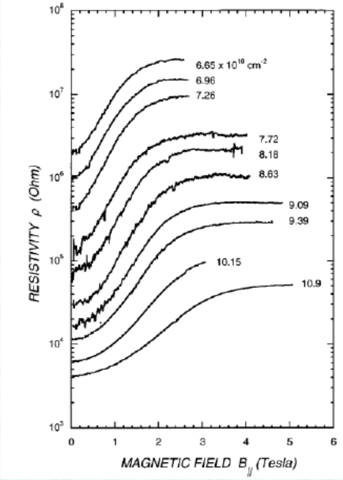
$$E_{ee}/E_F = r_s \sim 10$$

$$E_{\text{e-e}} \sim \frac{e^2}{\epsilon}(\pi n_s)^{1/2}$$



μ=4,5m²/Vs

← N ~10^{11}cm^{-2}



« insulating », poor screening

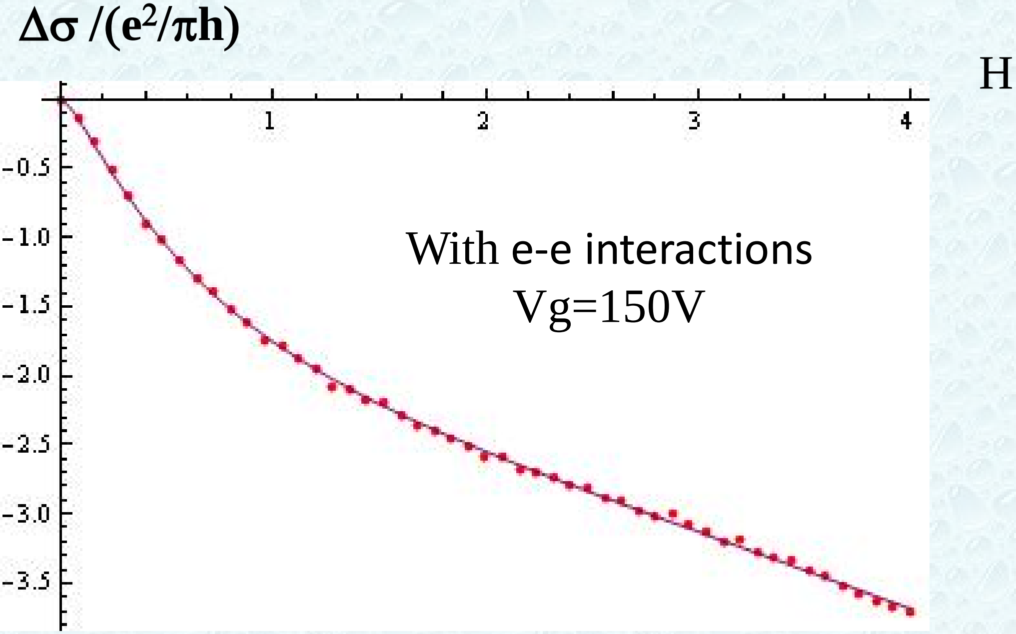
« metallic », good screening

Mott localized

I MIT ! M

Anderson localized

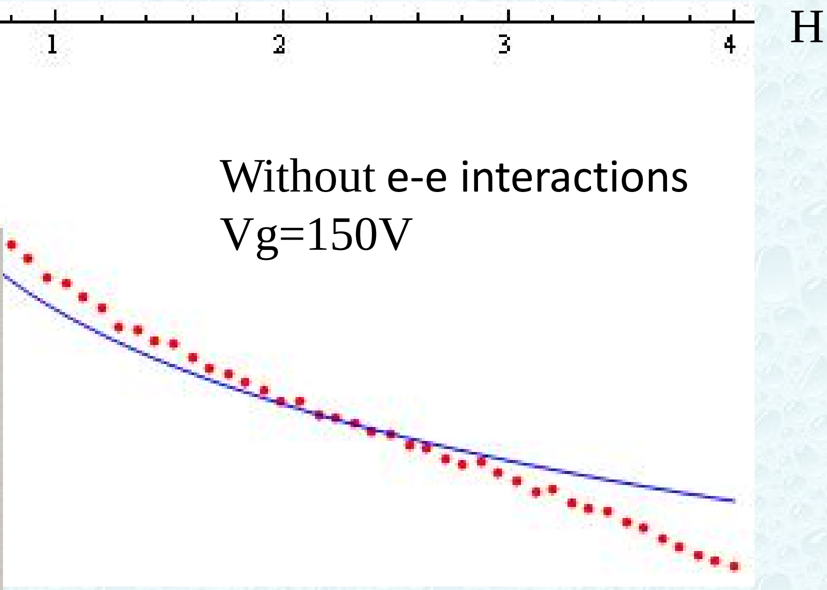
T=1.5K



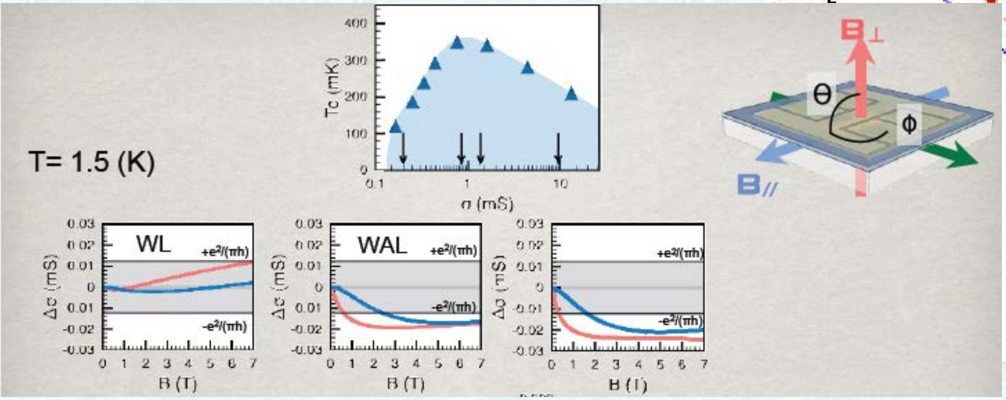
With e-e interactions
Vg=150V

$$\Delta\sigma_{e\text{-}e} \sim -\omega_c/k_F l$$

(Sedrakyan et al
PRL **100, 106806 (2008))**



Without e-e interactions
Vg=150V



Exp. data courtesy A. Caviglia

OR…..

An explanation is proposed of the unusual magnetoresistance, linear in magnetic field and positive, observed recently in nonstoichiometric silver chalcogenides. The idea is based on the assumption that these substances are basically gapless semiconductors with a linear energy spectrum.

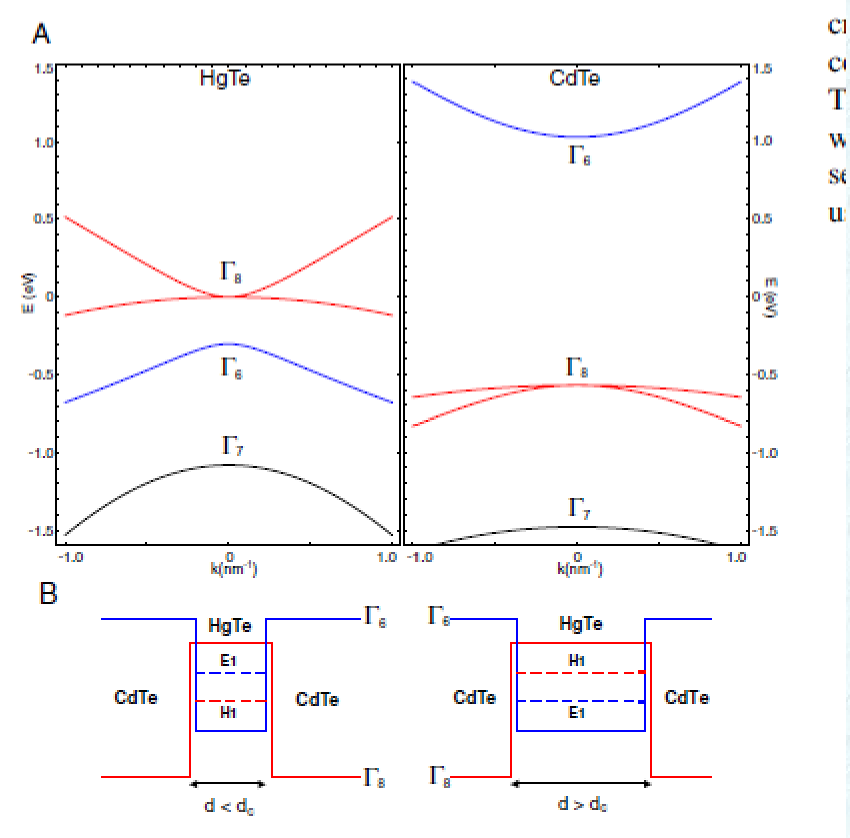
$$\rho_{xx}=\frac{1}{2\pi}\left(\frac{e^2}{\varepsilon_\infty v}\right)^2 \ln \varepsilon_\infty \frac{N_i}{ecn_0^2} H.$$

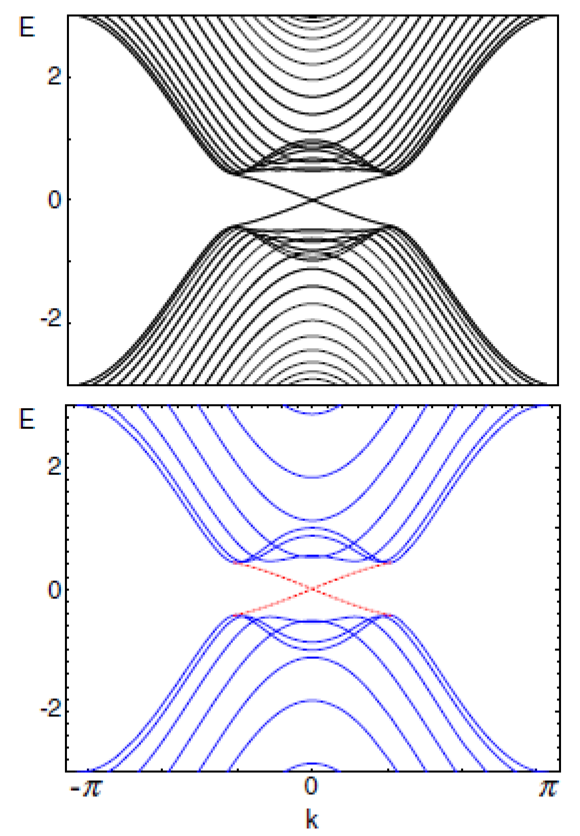
A.A Abrikosov, PRB 58, 2788, 1998

A pinch of topology

Due to large spin-orbit effect

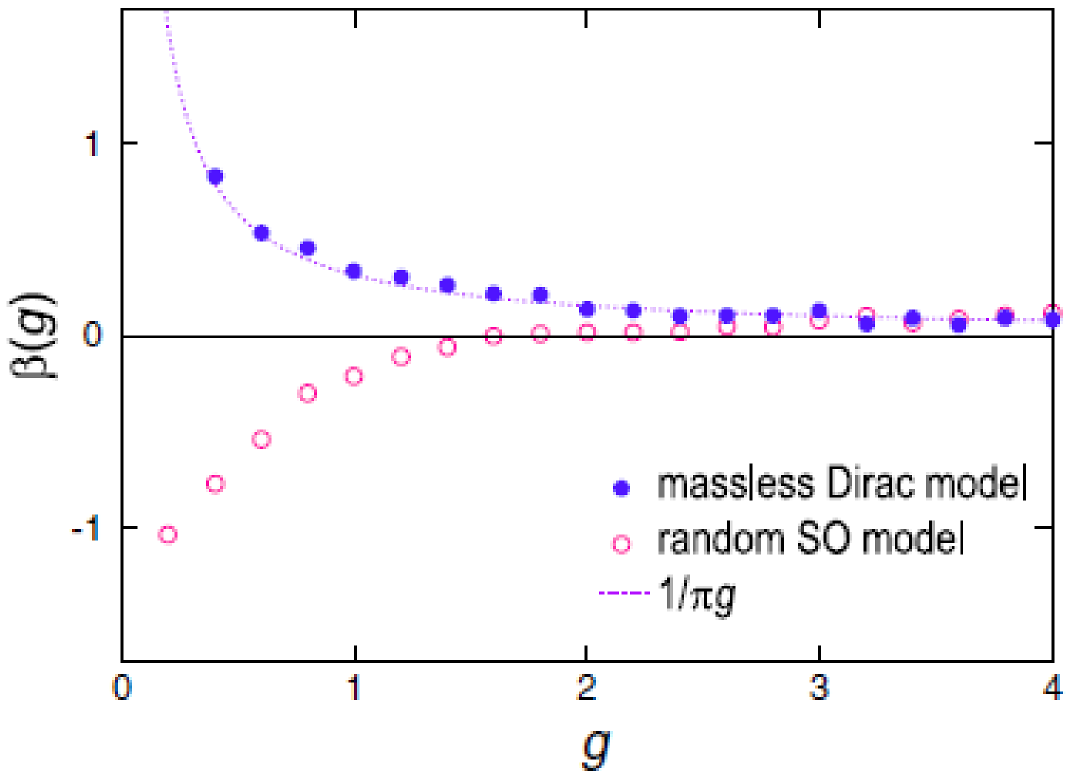
$$|E_1+\rangle, |E_1-\rangle, |H_1+\rangle, |H_1-\rangle$$



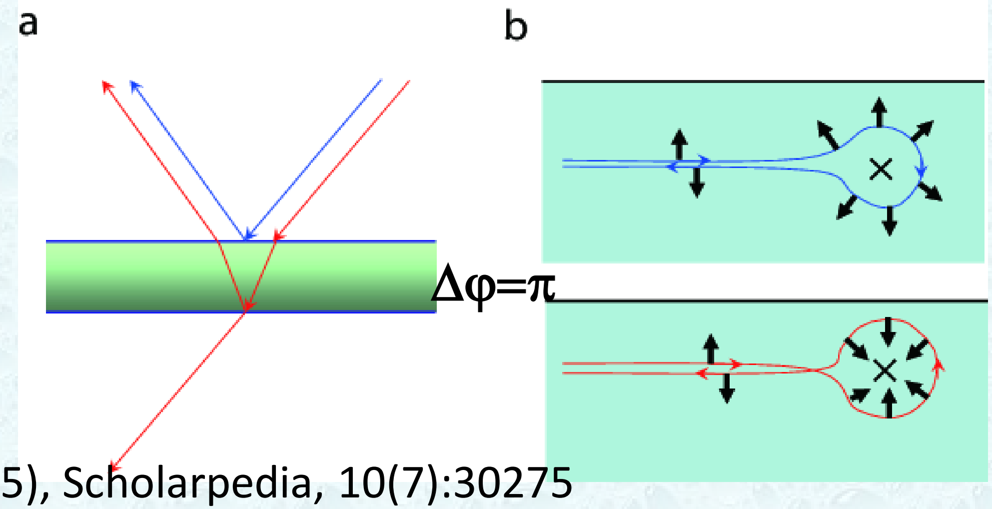


At the boundary between HgTe and CdTe there is a parity inversion ⇒ **edge states**

König, Bühmann, Molenkamp, Zhang et al. J. Phys. Soc. Jpn. 77, 031007 (2008)

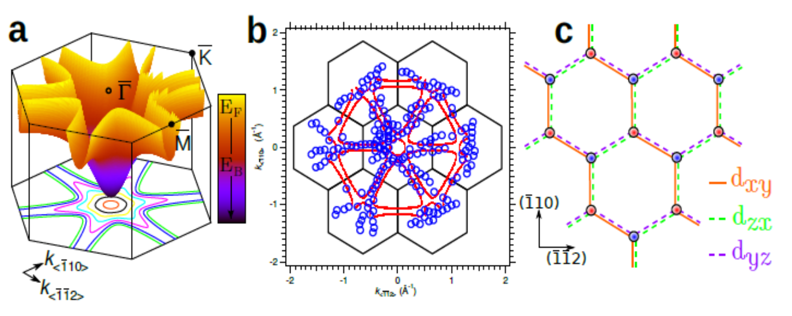


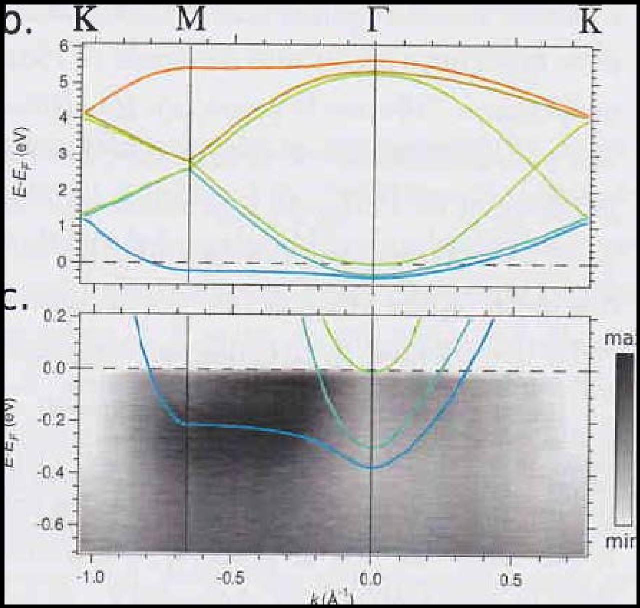
K. Nomura, M. Koshino, S. Ryu, Phys. Rev. Lett 99, 146806 (2007)



Shoucheng Zhang (2015), Scholarpedia, 10(7):30275

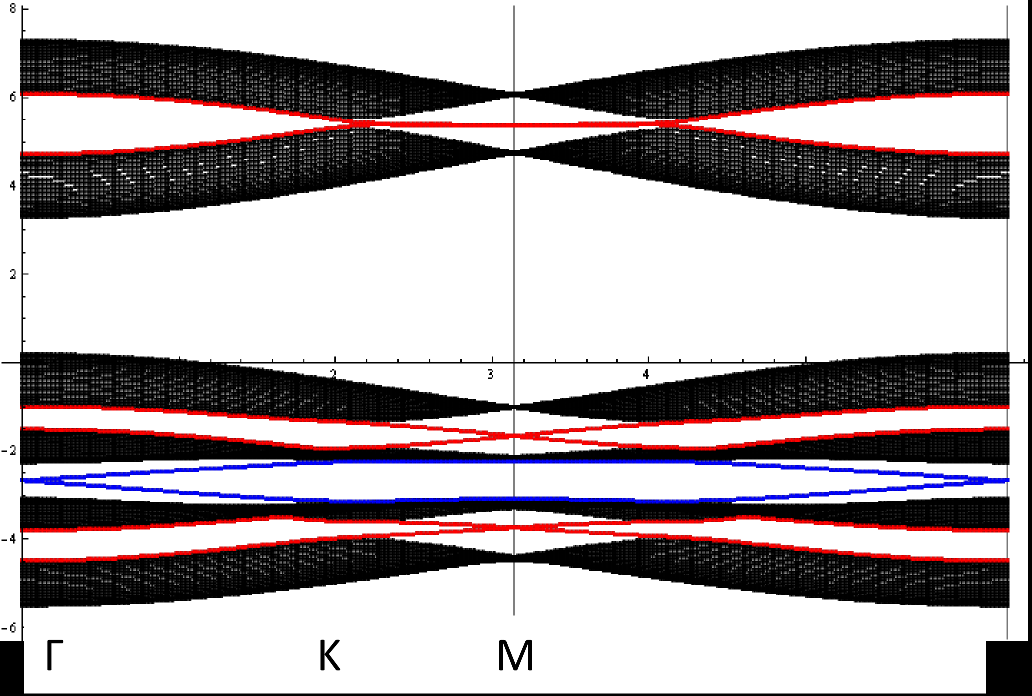
Topological states, really?

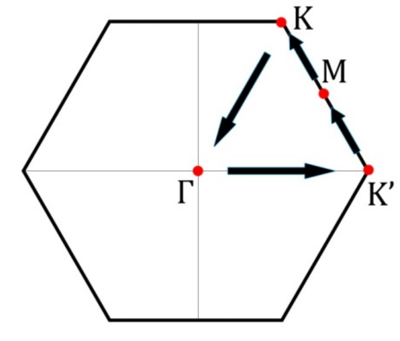




Band-structure vs experiment for (111) surface of KTO

C. Bareille et al,
Scientific Reports 4, 3586 (2014)





edge states

- Edge states are topological