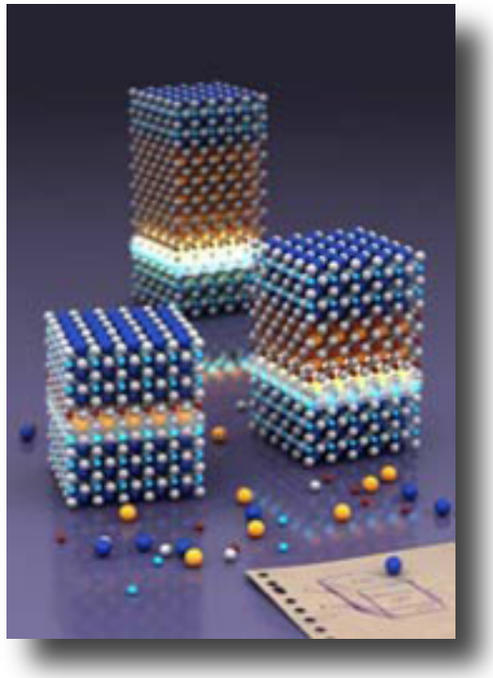
Massachusetts Institute of Technology

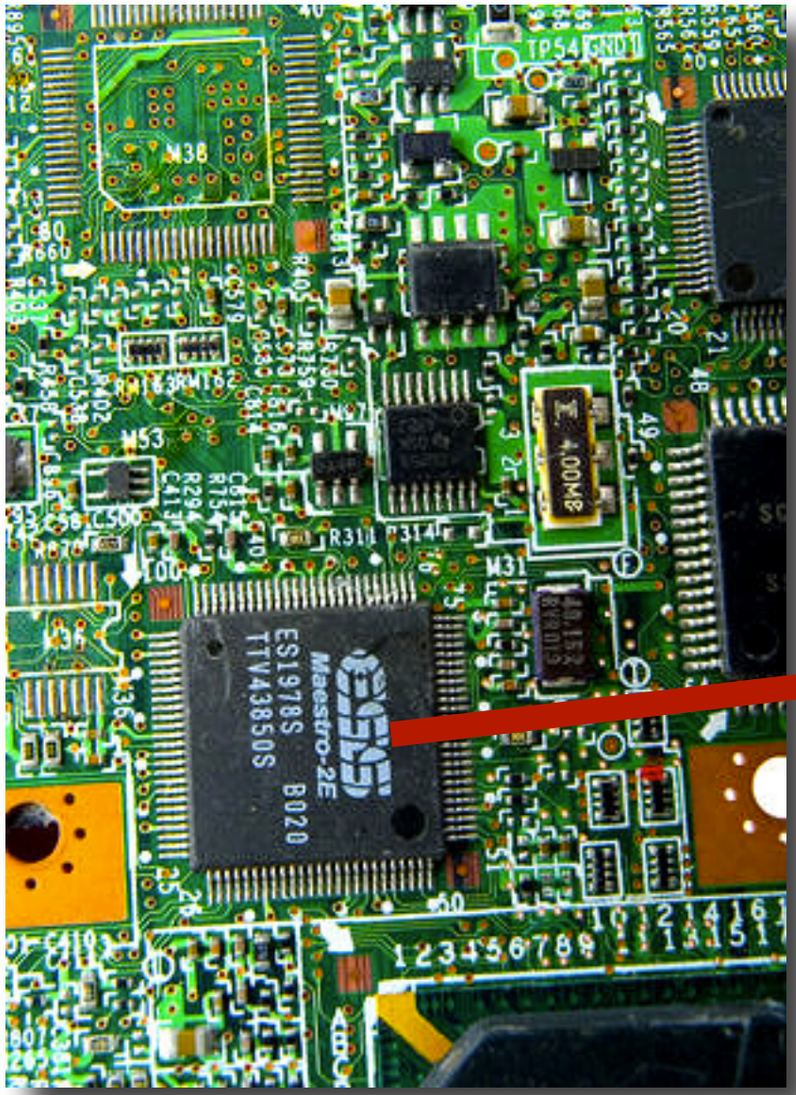


Superconductivity and Ferromagnetism in Oxide Interface Structures: Possibility of Finite Momentum Pairing

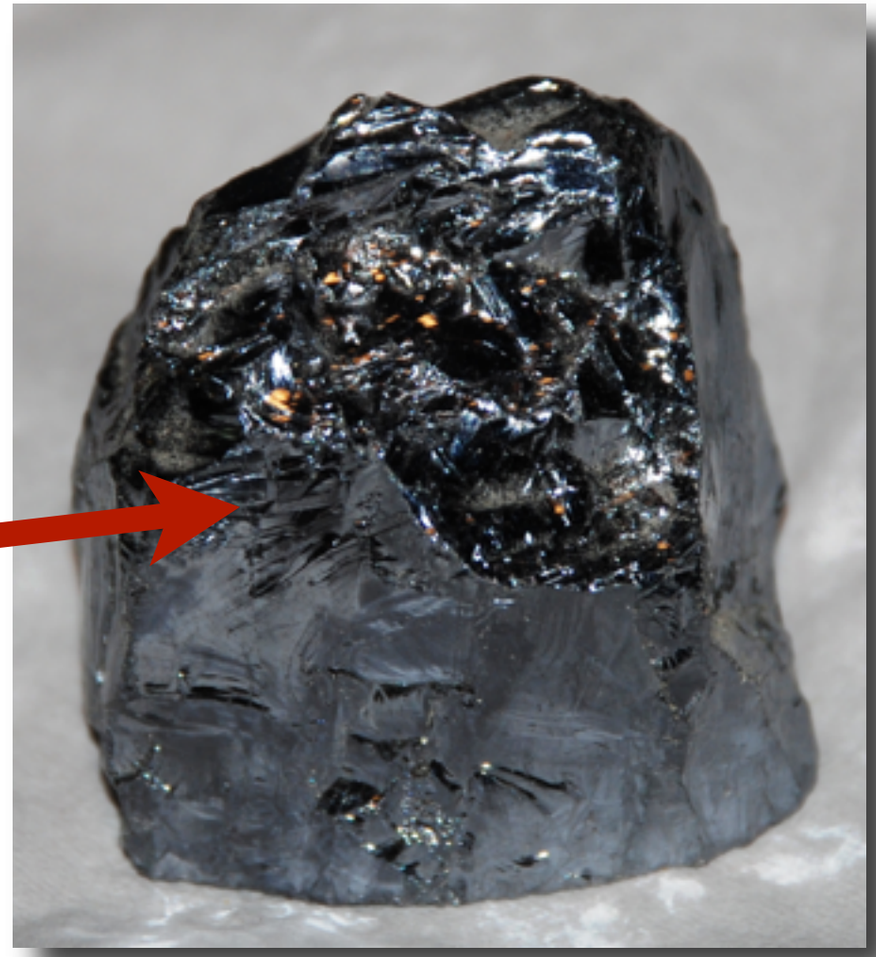
K. Michaeli, A. C. Potter and P. A. Lee

KM, A. C. Potter, P. A. Lee PRL 2012

Semiconductors interfaces

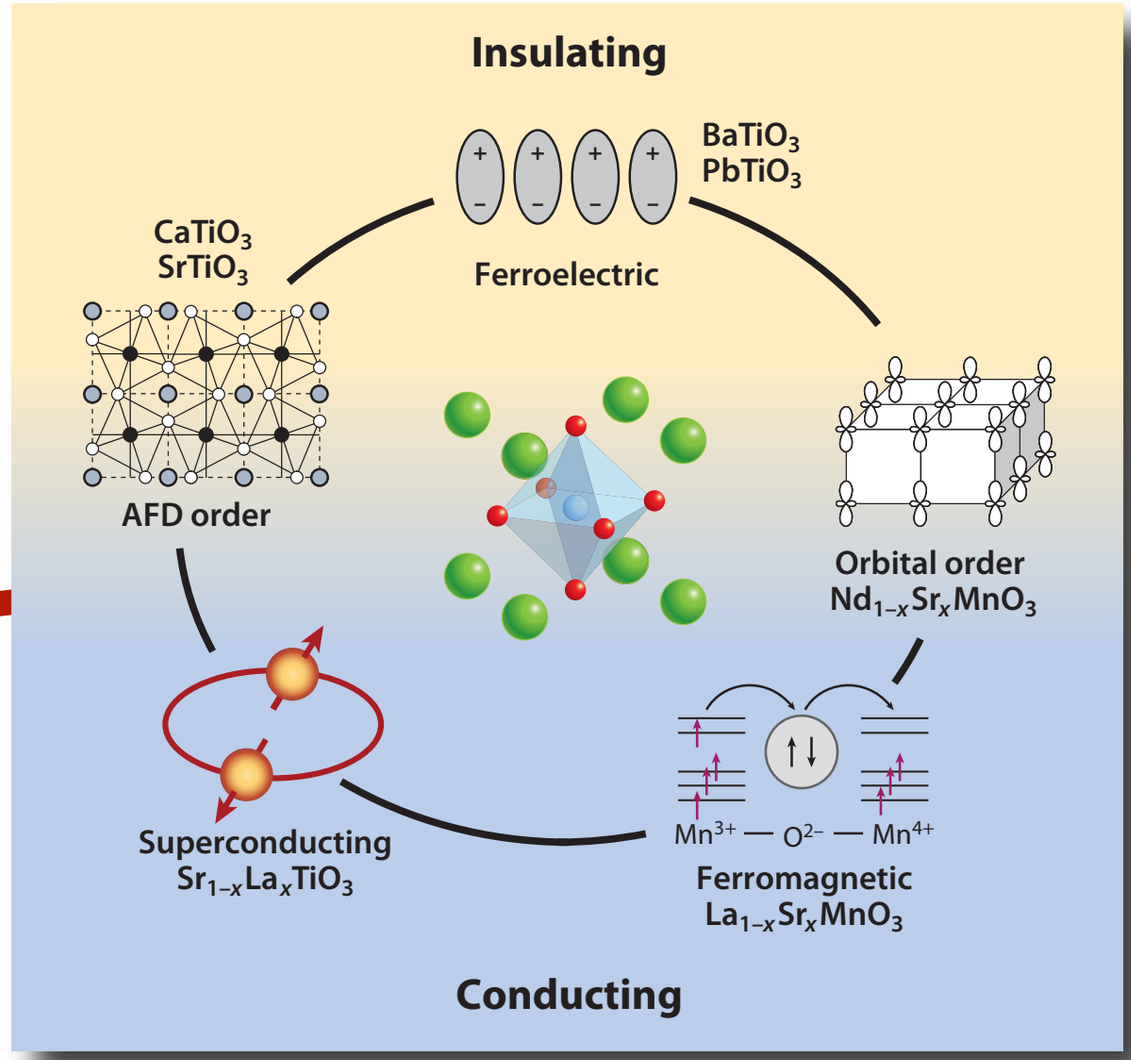


Silicon



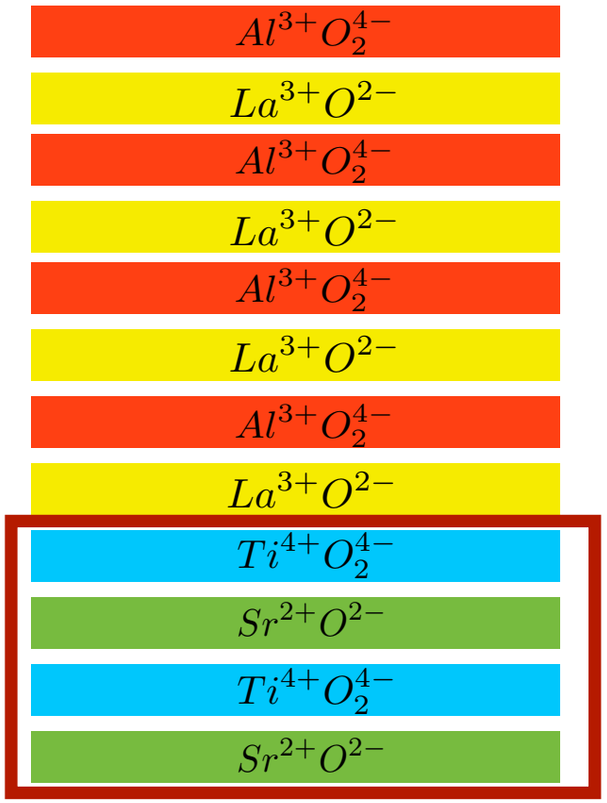
Single particle physics

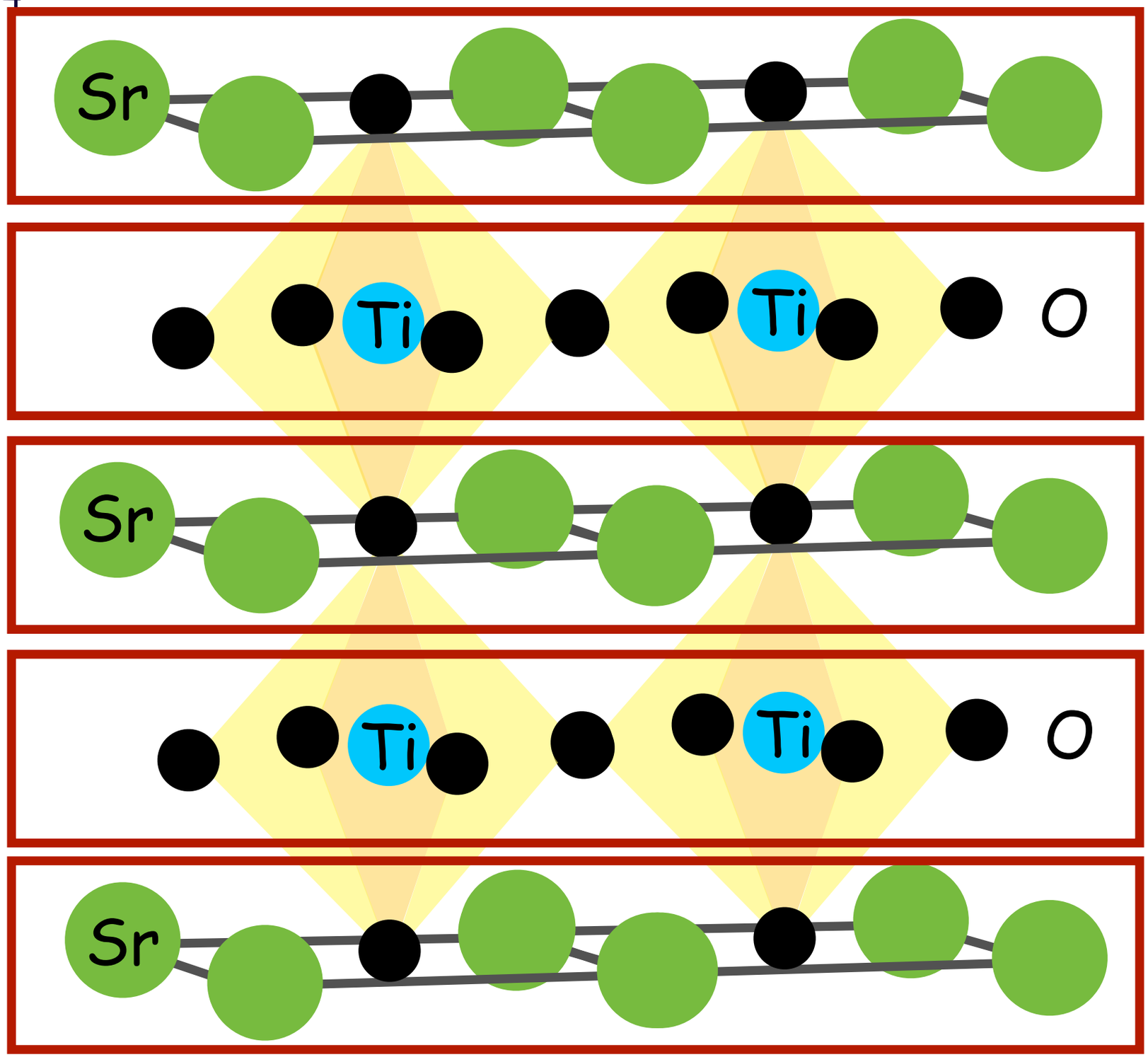
Oxide interfaces-new physics



The oxide interface

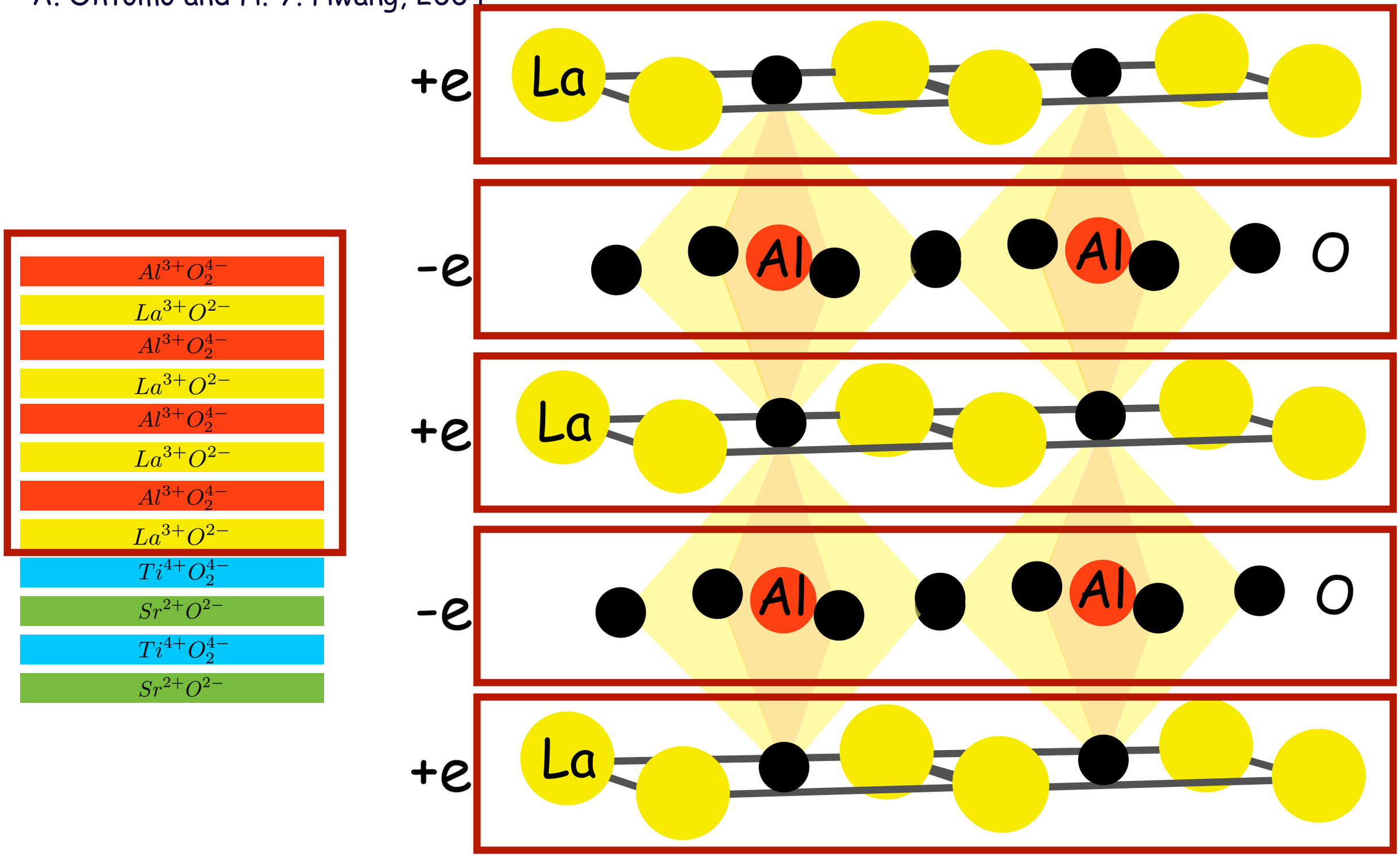
A. Ohtomo and H. Y. Hwang, 2004





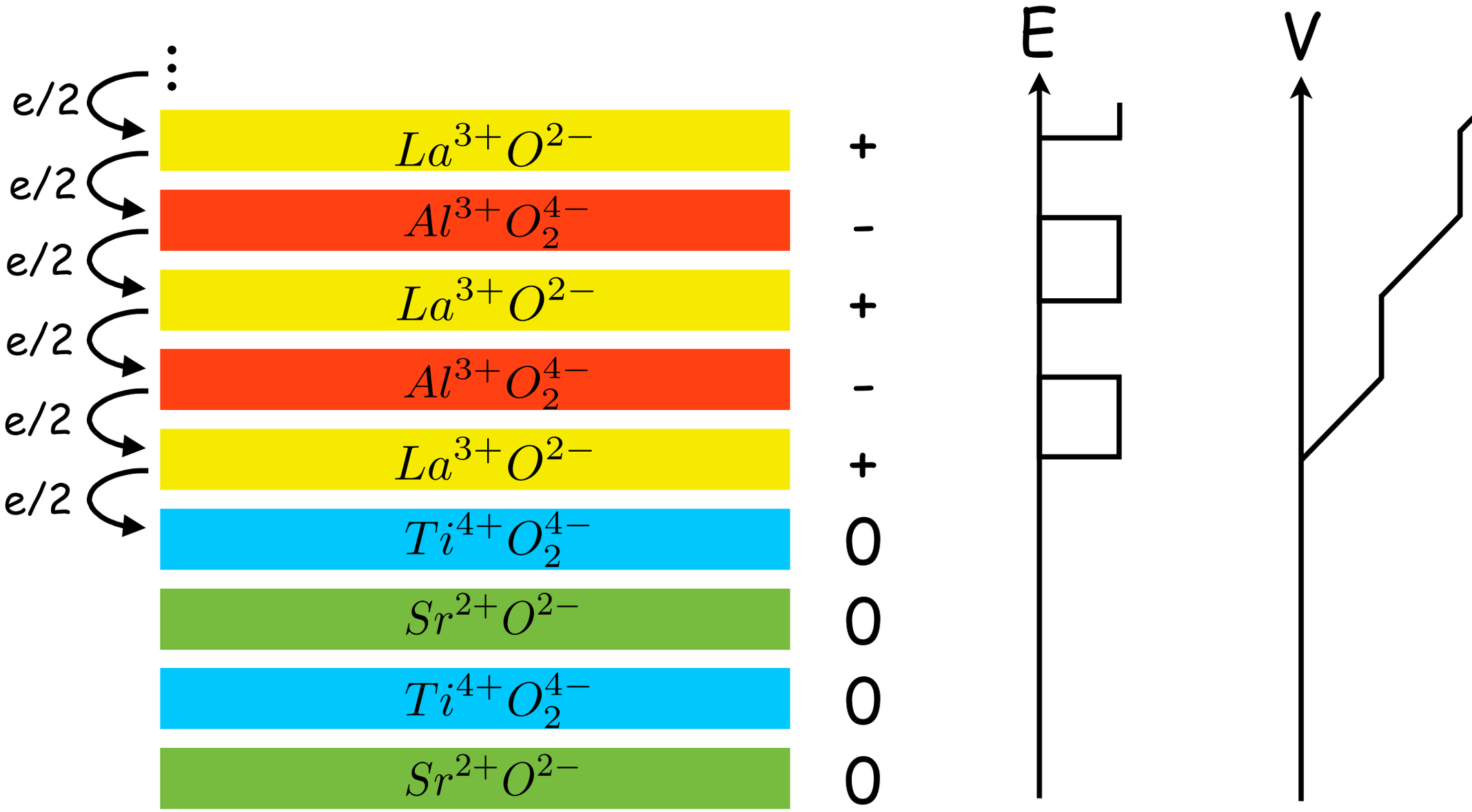
The oxide interface

A. Ohtomo and H. Y. Hwang, 2004



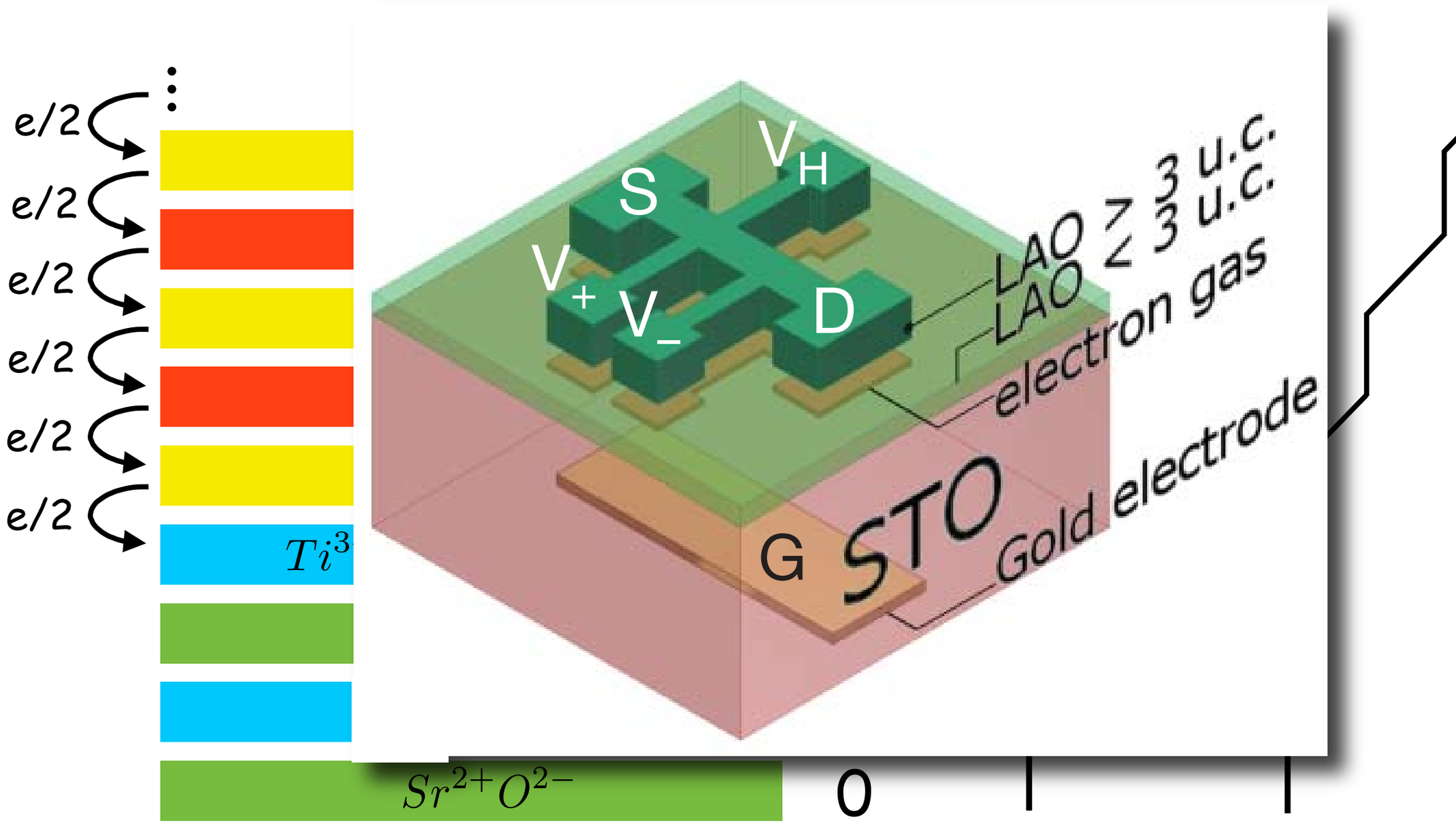
The polar catastrophe

Joining perovskites from two different charge families with atomic abruptness results in a polar discontinuity at the interface

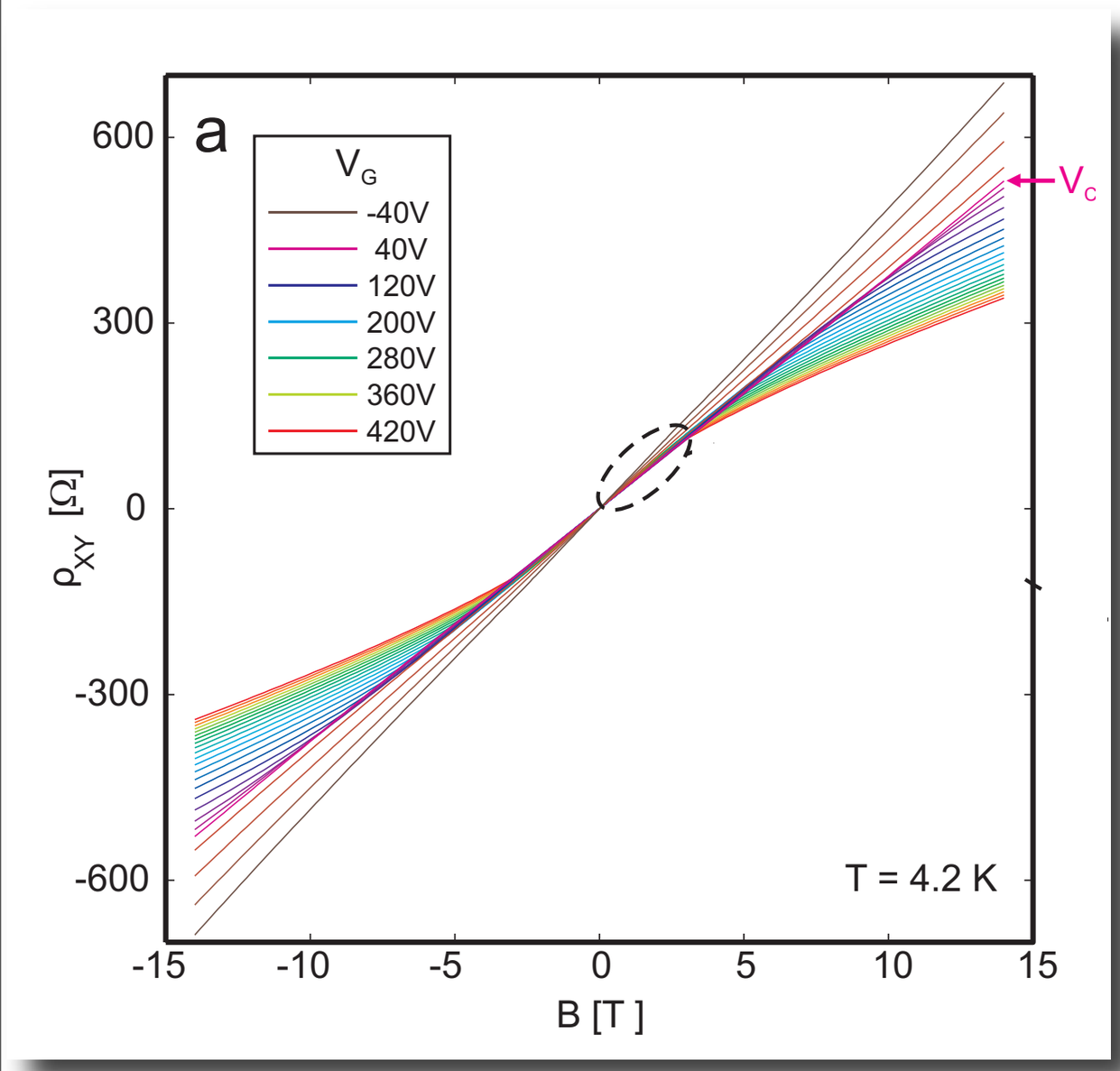


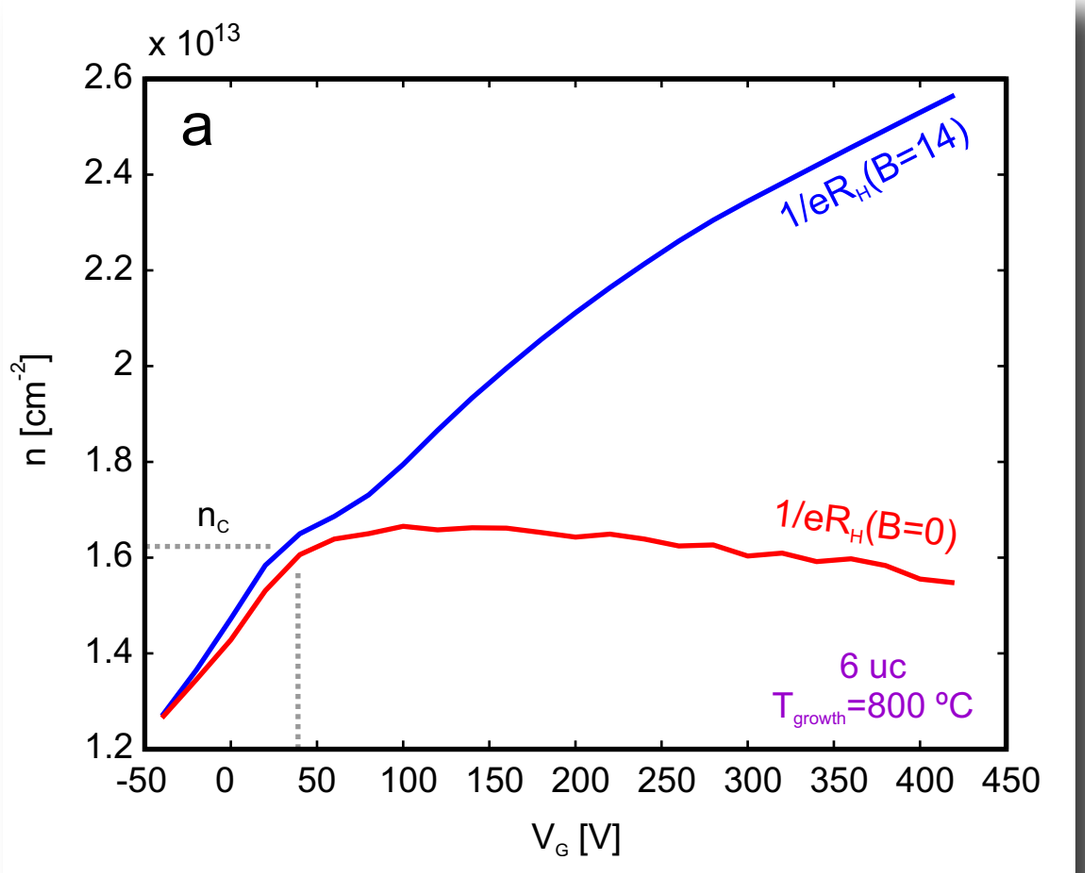
The polar catastrophe

Joining perovskites from two different charge families with atomic abruptness results in a polar discontinuity at the interface



Hall coefficient



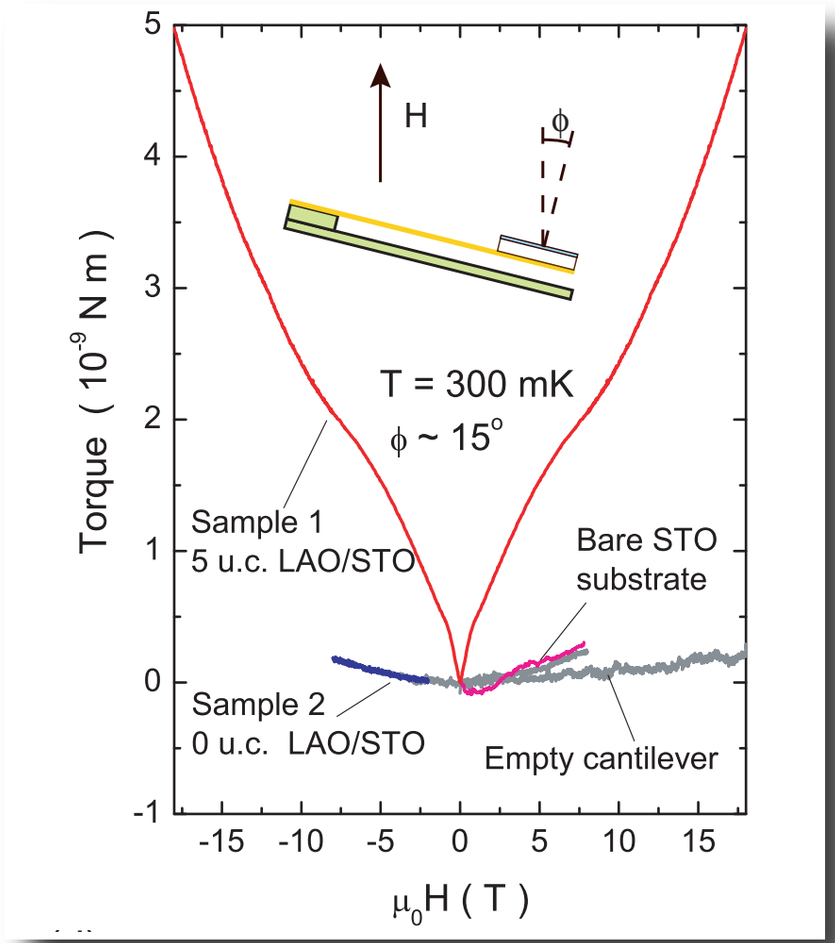


A. Joshua, *et al*, 2011

S. Ilani - next talk

The measured charge carrier density is ~10% of the expected one from the polar catastrophe

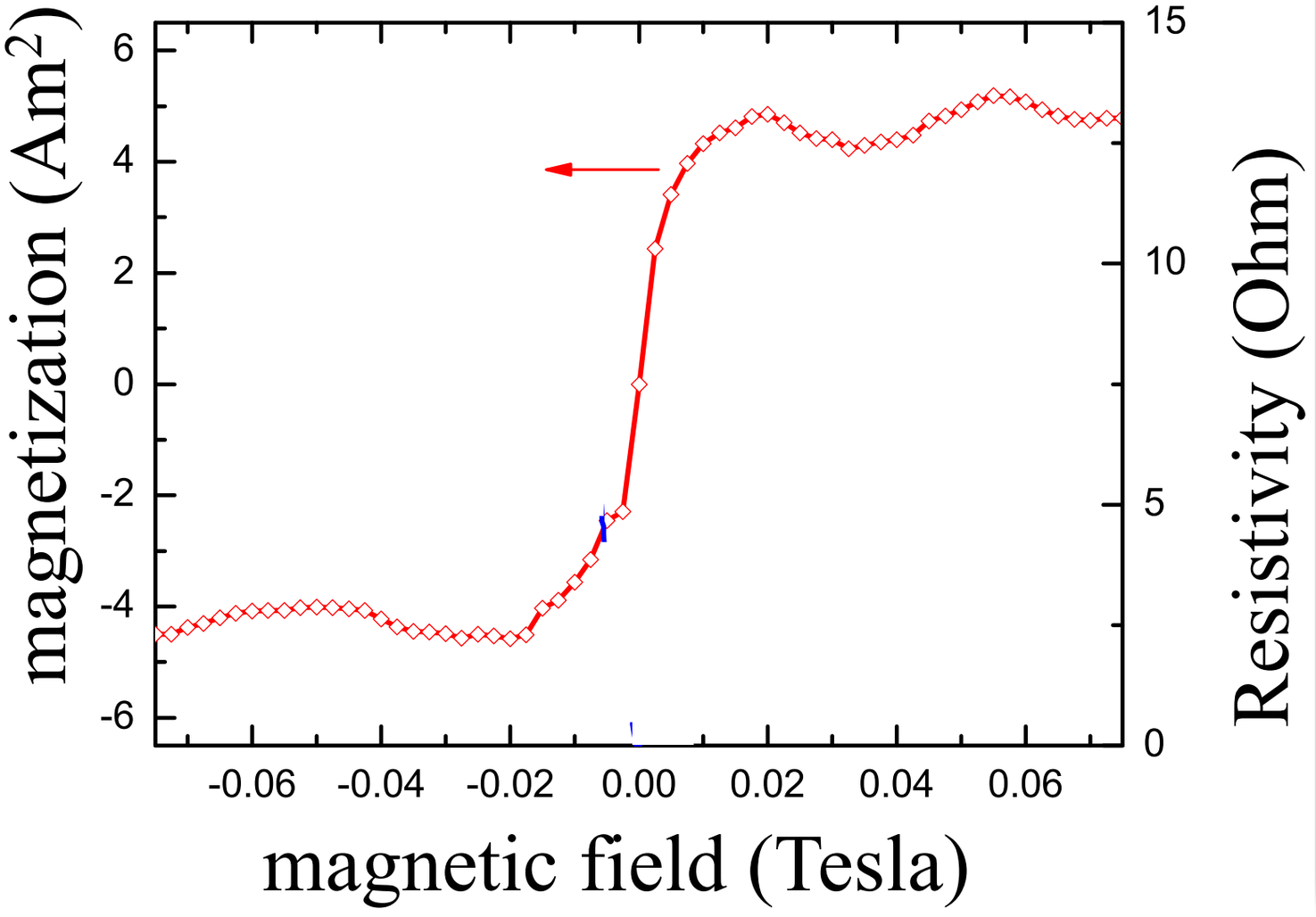
Ferromagnetism



L. Li, *et al*, 2011

$$\tau = \vec{M} \times \vec{H}$$

Ferromagnetism and superconductivity coexist

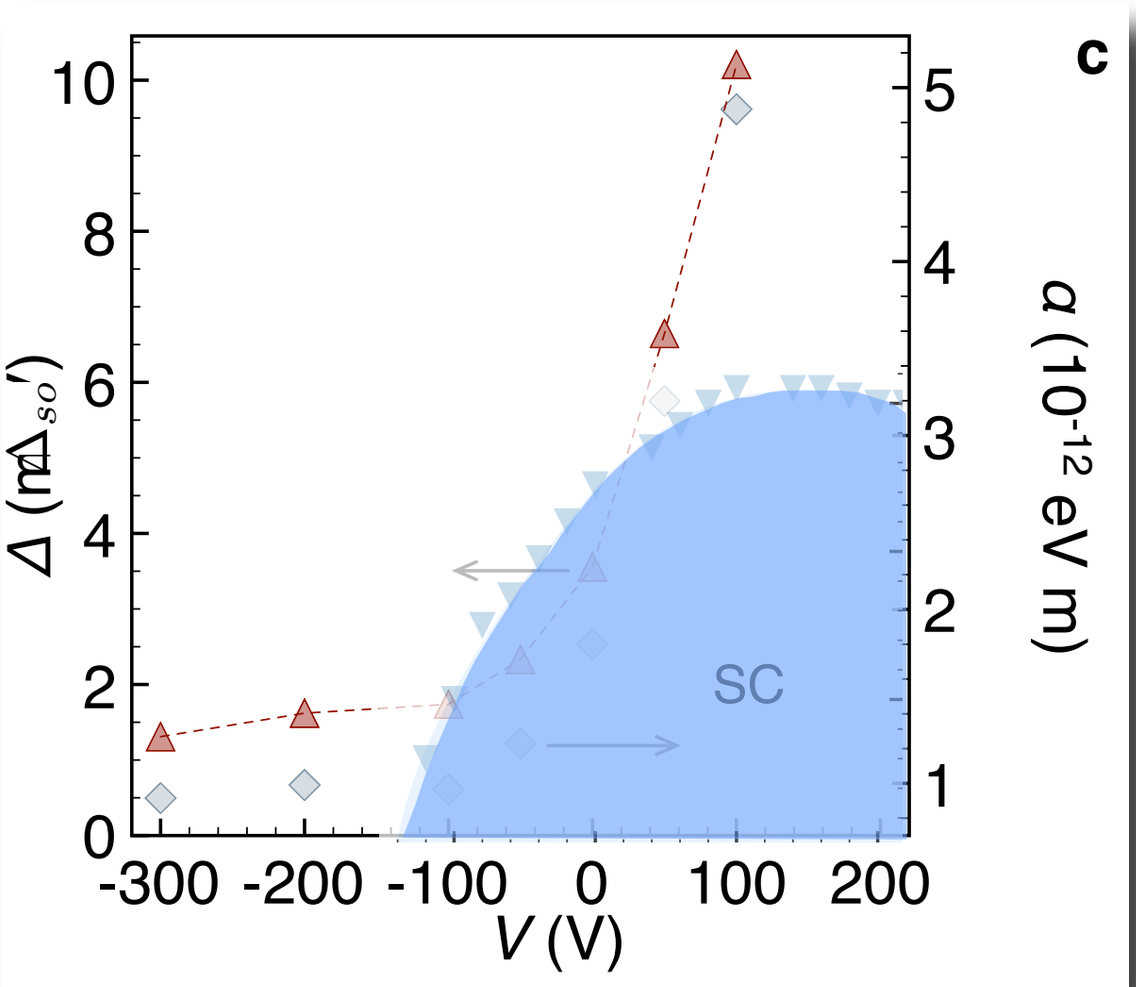


M || interface ~0.3μ_B per unit cell at the interface

The magnetic moment remains the same up to 40K

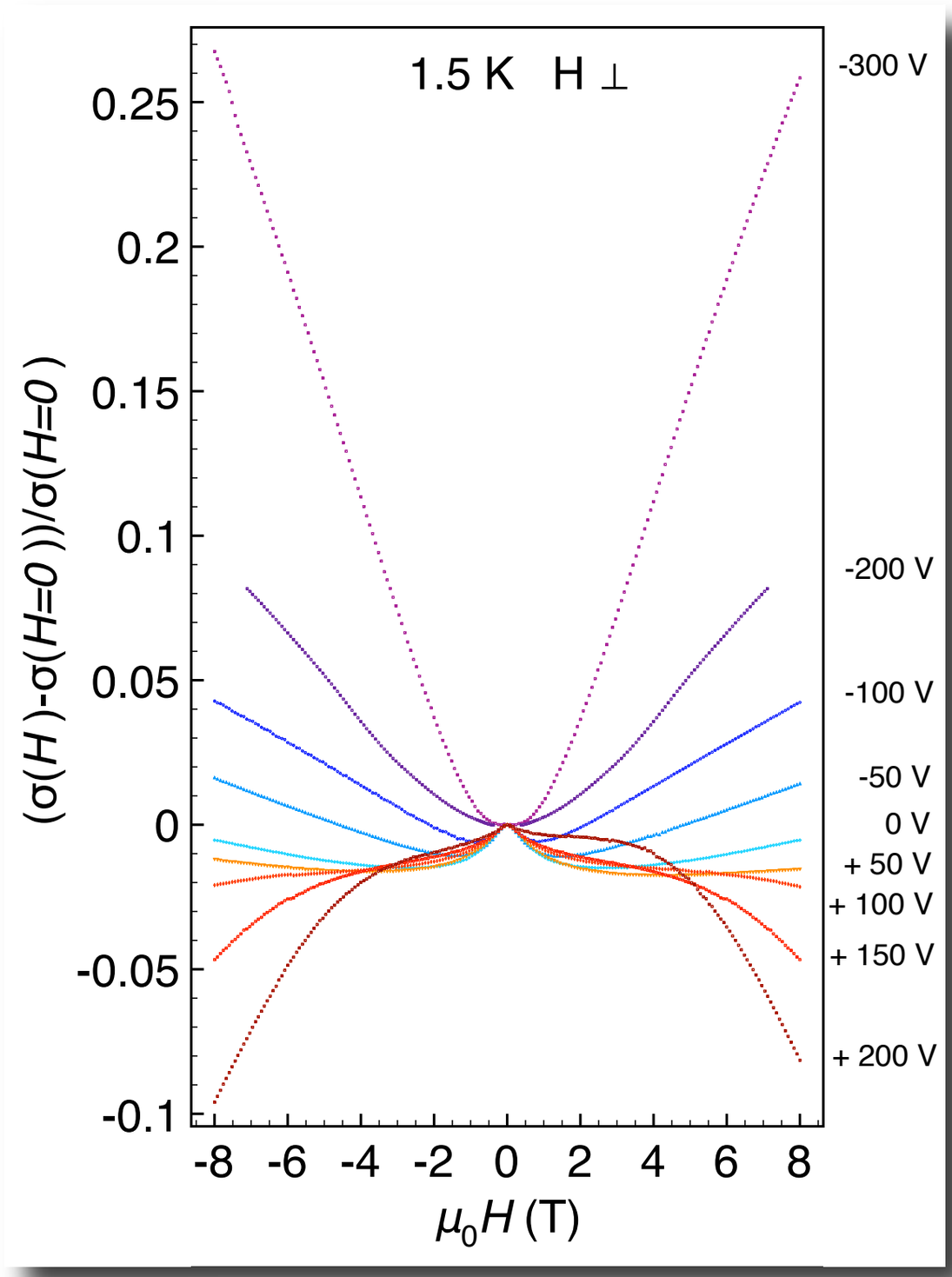
Spin-orbit coupling

Superconductivity is obtained when the spin-orbit coupling starts to grow



A. D. Caviglia, *et al*, 2009

$$\Delta_{so} = \alpha k_F$$



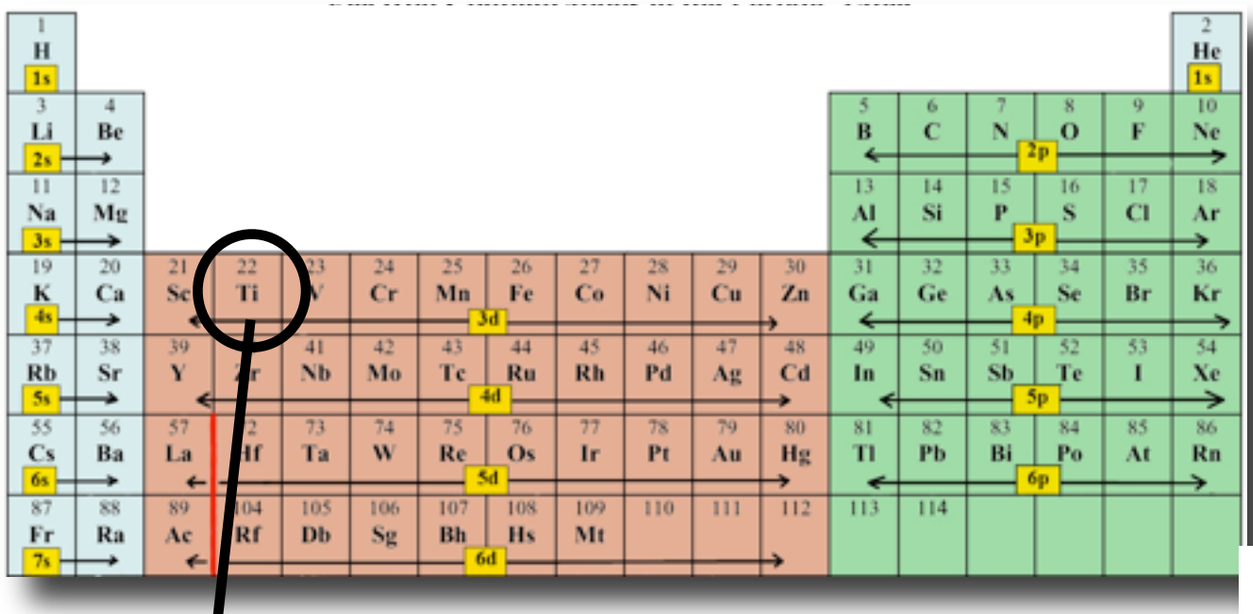
Main experimental results

- Charge carrier density << the polar catastrophe
- Two types of charge carriers
- Ferromagnetism
- Strong spin-orbit coupling
- Coexistence of ferromagnetism and superconductivity

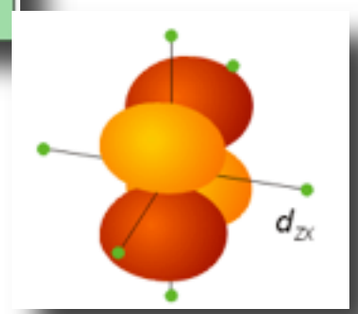
Our Model

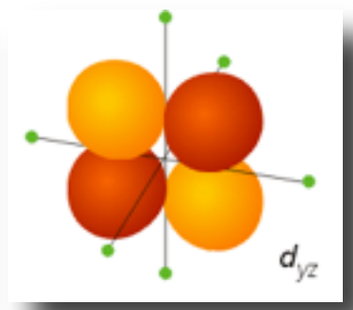
KM, A. C. Potter, P. A. Lee PRL 2012

The polar catastrophe



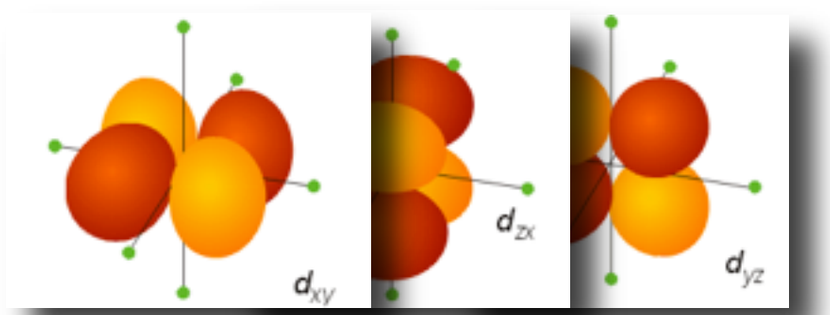
The orbital degeneracy is lifted due to the interface

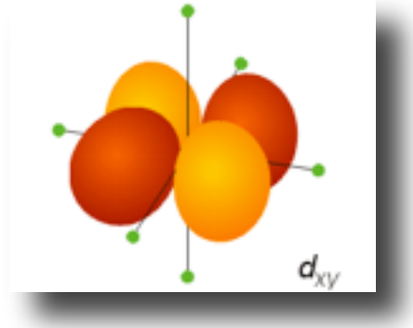


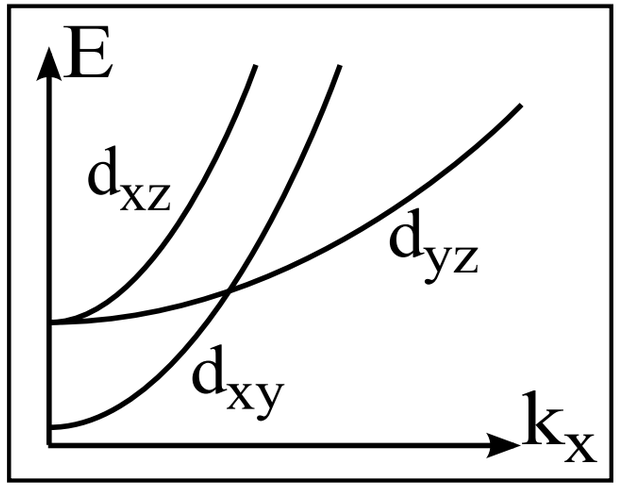


Ti^{3+} has one electron in the 3d orbital

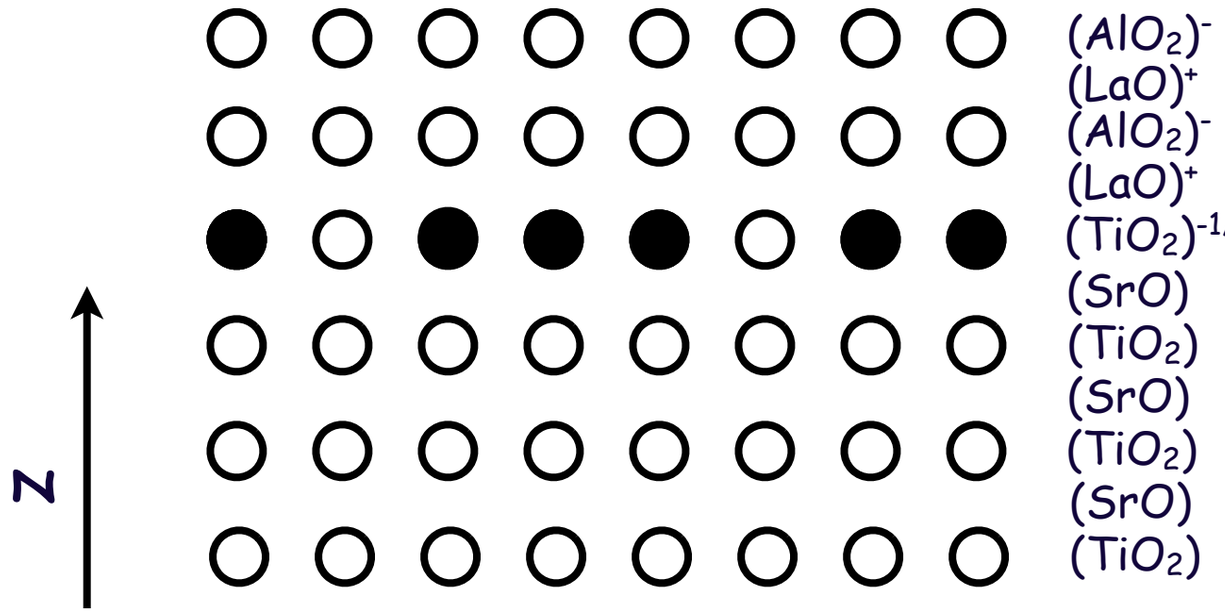
the t_{2g} orbitals

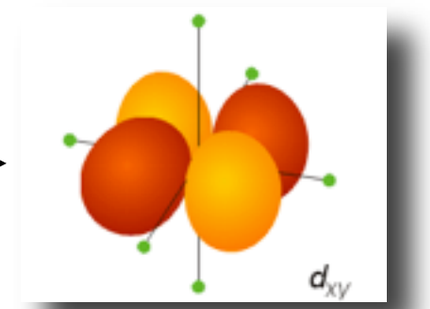






The polar catastrophe



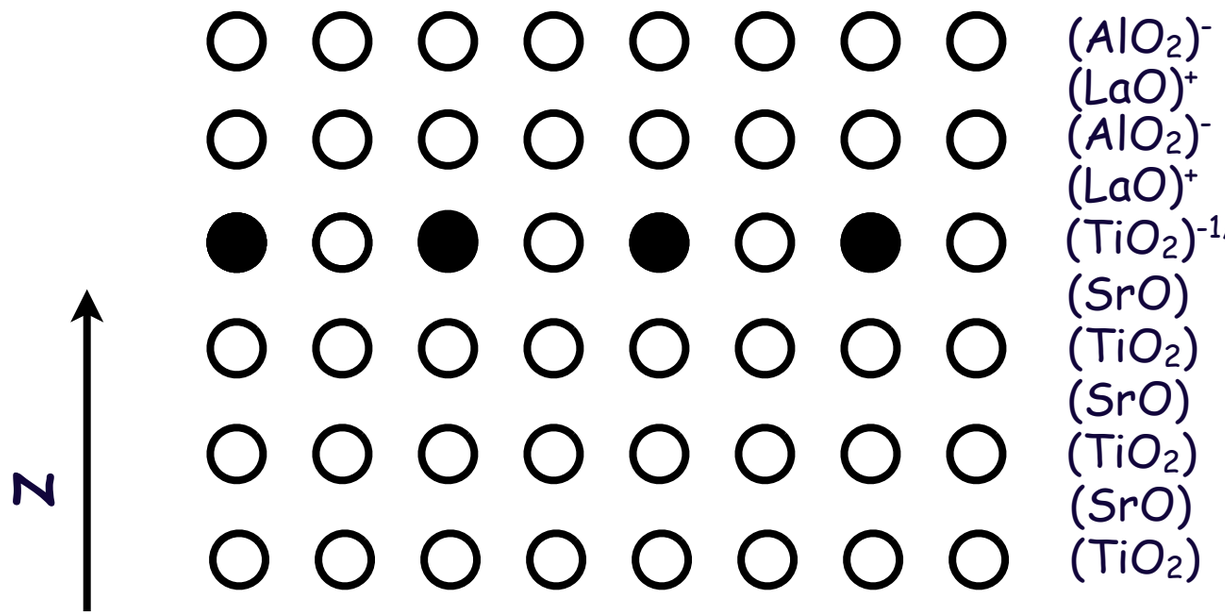


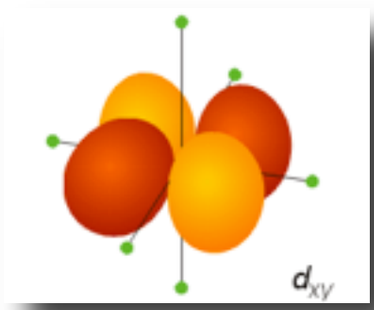
The 1/2e charge per unit cell occupies the d_{xy} orbital at the interface

$$\mathcal{H} = \sum_{<i,j>,\sigma} \left[t_{i,j} c^{\dagger}_{i,\sigma} c_{j,\sigma} + h.c \right] + U \sum_{i} n_{i\uparrow} n_{i\downarrow} + V \sum_{<i,j>,\sigma,\sigma'} n_{i_\sigma} n_{j\sigma'}$$

For t < U,V the electrons in the interface become localized - 1/4 filled Mott insulator

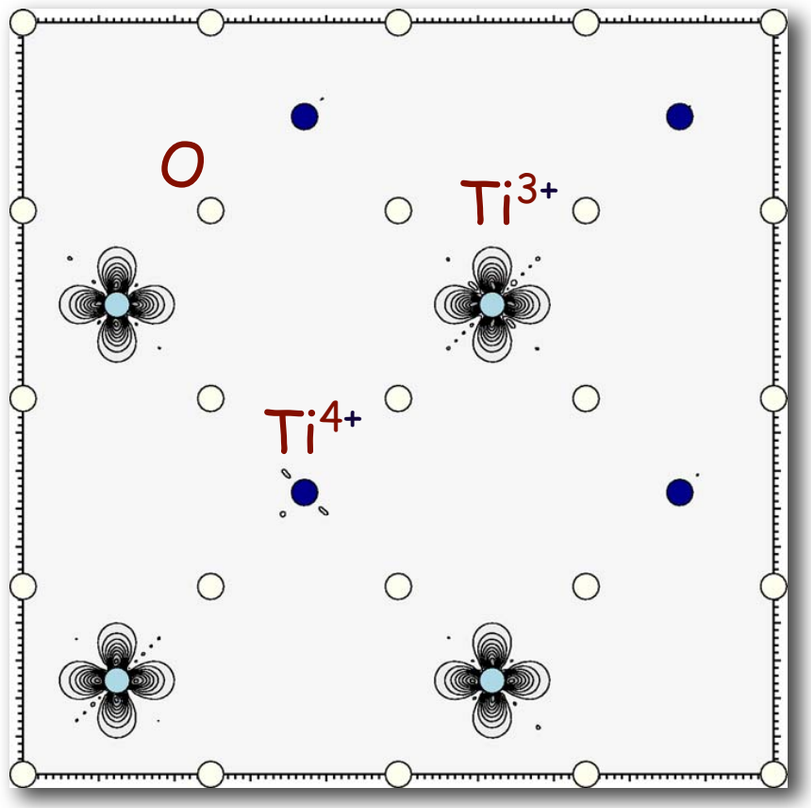
The polar catastrophe



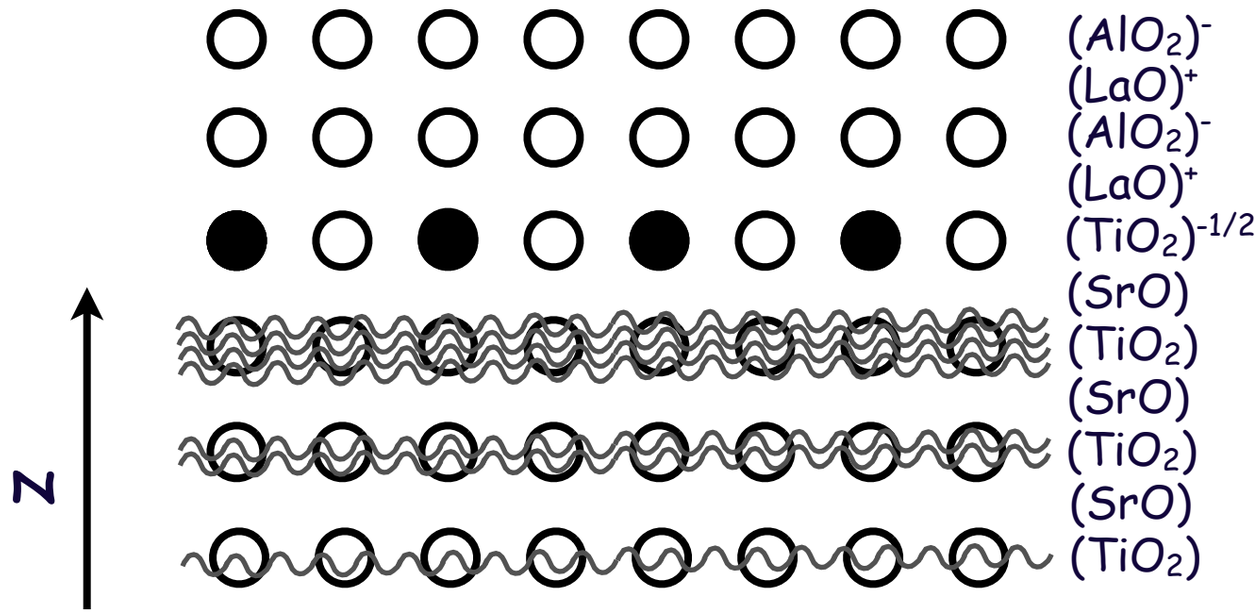


Similar picture has been suggested from LDA+U calculation

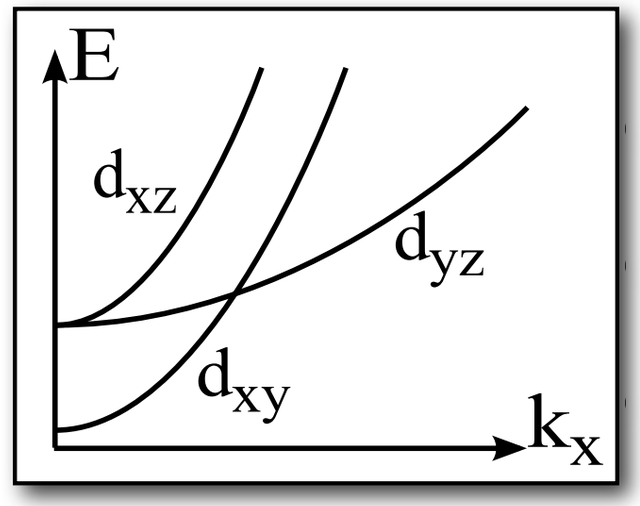
R. Pentcheva and W. E. Pickett, 2006



The charge carriers



Additional charges introduced by impurities and/or gate voltage



The d_{xy} orbital next to the interface

The d_{yz} and d_{xz} orbitals

Main experimental results

- ☑ Charge carrier density << the polar catastrophe
- ☑ Two types of charge carriers
- ☐ Ferromagnetism
- ☐ Strong spin-orbit coupling
- ☐ Coexistence of ferromagnetism and superconductivity

The origin of Ferromagnetism

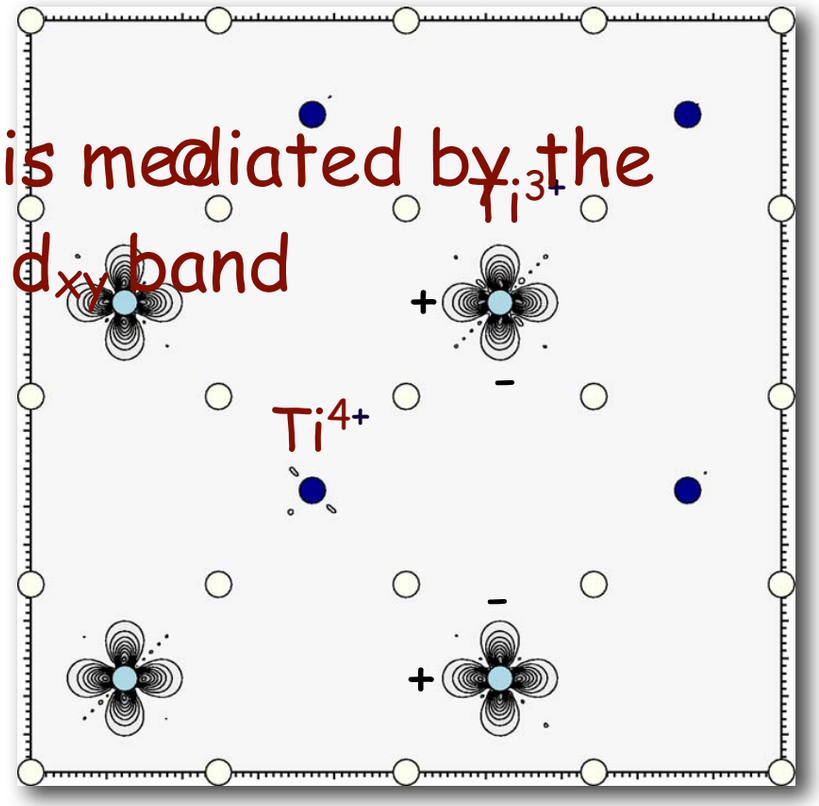
J_{ij}

The exchange interaction of the localized d_{xy} electrons through the oxygens is antiferromagnetic

For J_0=1.3eV → T_F=300K

The ferromagnetic RKKY interaction is mediated by the conduction electrons in the d_{xy} band

In Mn/GaAs J_0~1eV



~1/K_F

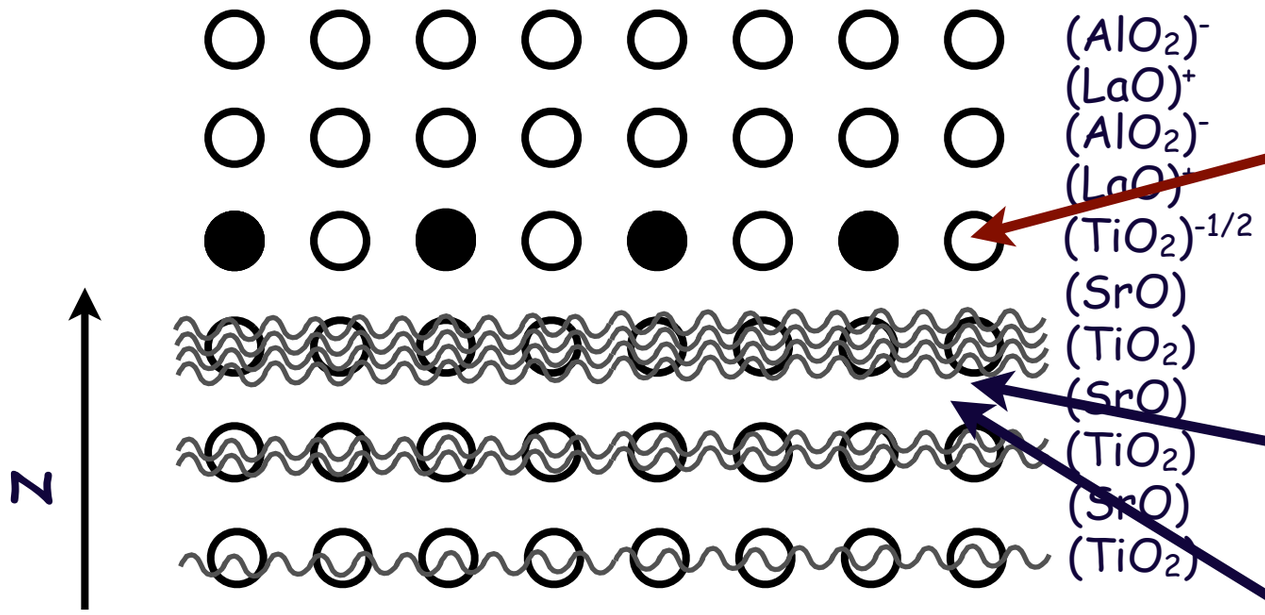
r_{ij}

$(TiO_2)^{+1/2}$

Main experimental results

- ☑ Charge carrier density << the polar catastrophe
- ☑ Two types of charge carriers
- ☑ Ferromagnetism
- ☐ Strong spin-orbit coupling
- ☐ Coexistence of ferromagnetism and superconductivity

Superconductivity

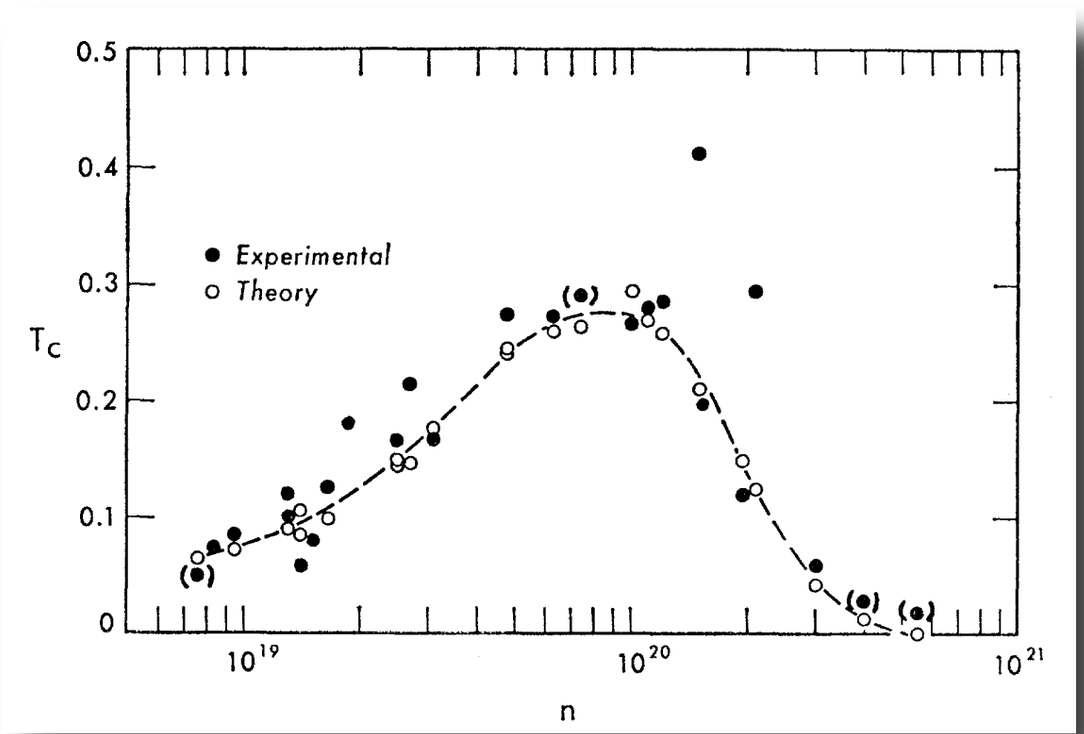


Localized d .d

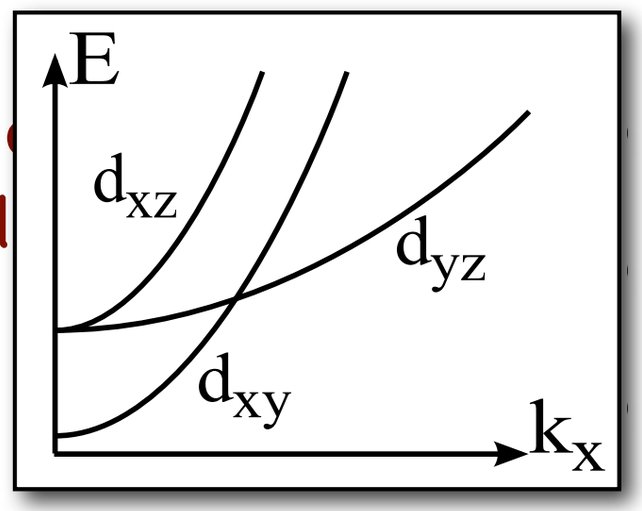
Spin polarized

C ring d_{xy} band

Conducting d_{yz} + d_{xz} bands



Phonon-m
supercond



C. S. Koonce, *et al*, 1967

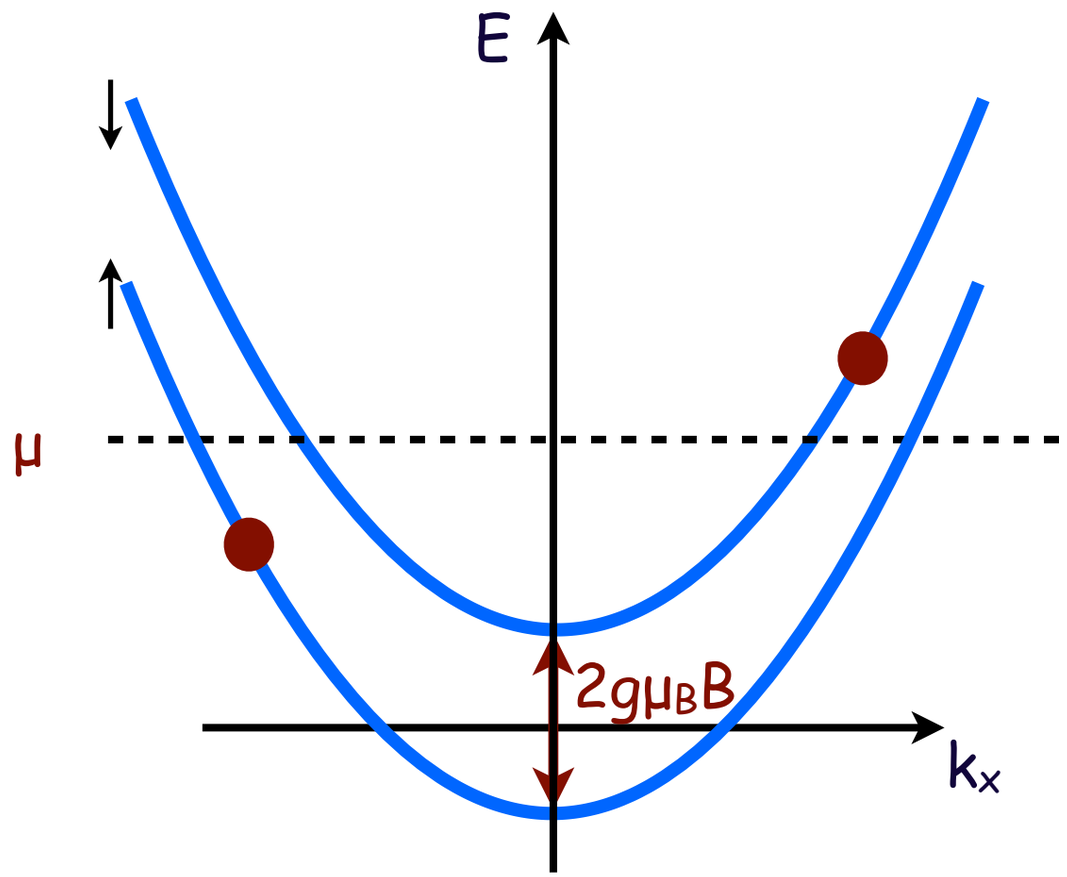
Coexistence of SC and FM

Superconductivity in the presence of a Zeeman field

Paring $|k,\uparrow\rangle$ and $|-k,\downarrow\rangle$ – the

Zeeman field acts as pair-breaking mechanism

$$g\mu_B B_c = \frac{\Delta_0}{\sqrt{2}}$$



The FFLO state

Paring $|k+q/2,\uparrow\rangle$ and $|-k+q/2,\downarrow\rangle$ -

the Zeeman field is no longer pair-breaking

$$\Delta(\vec{r}) = \Delta e^{i\vec{q}\cdot\vec{r}}$$

The FFLO state

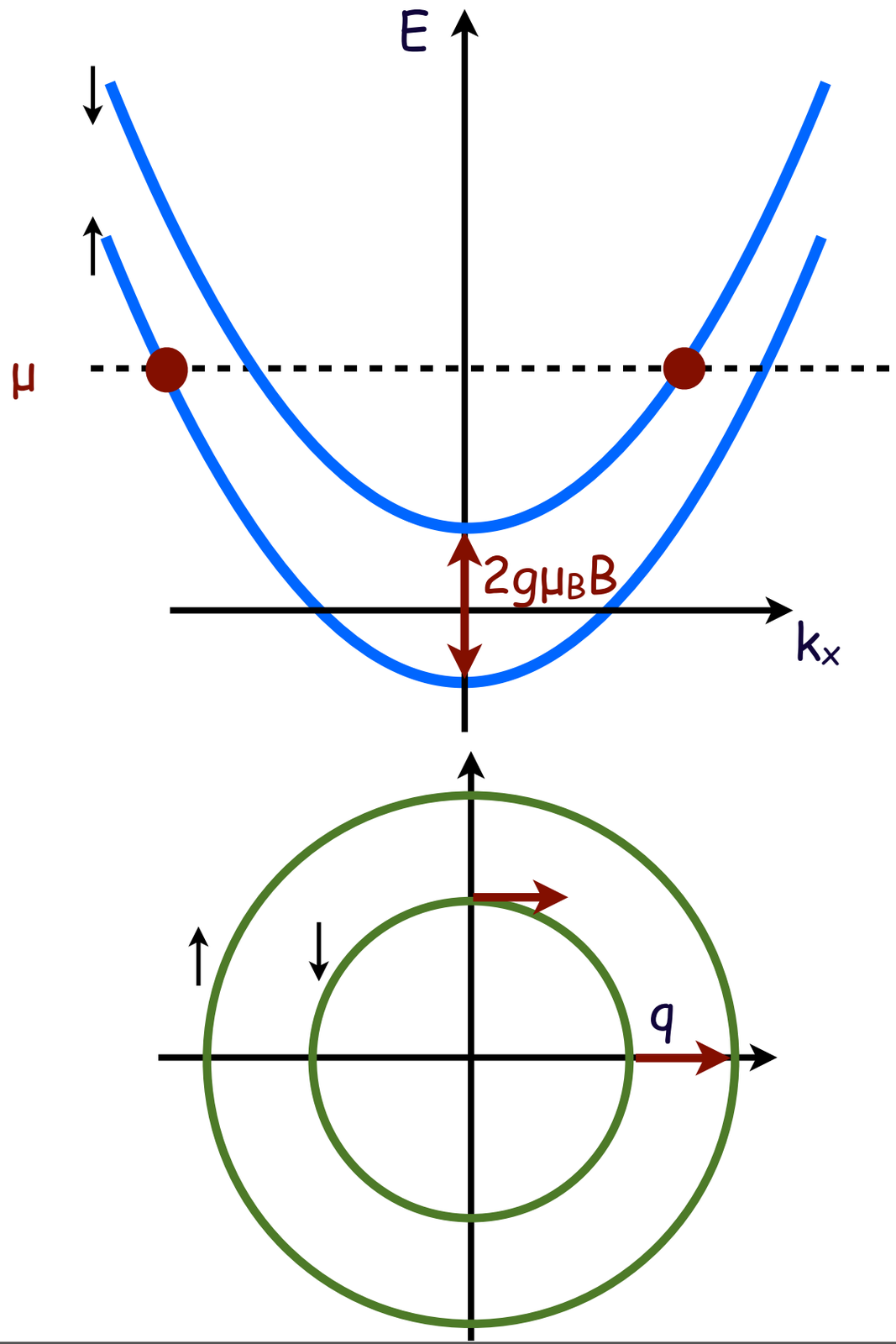
P. Fulde and R. A. Ferrell, 1964

A. I. Larkin and Yu. N. Ovchinnikov, 1964

$$g\mu_B B_c^{FFLO} = 0.754\Delta_0$$

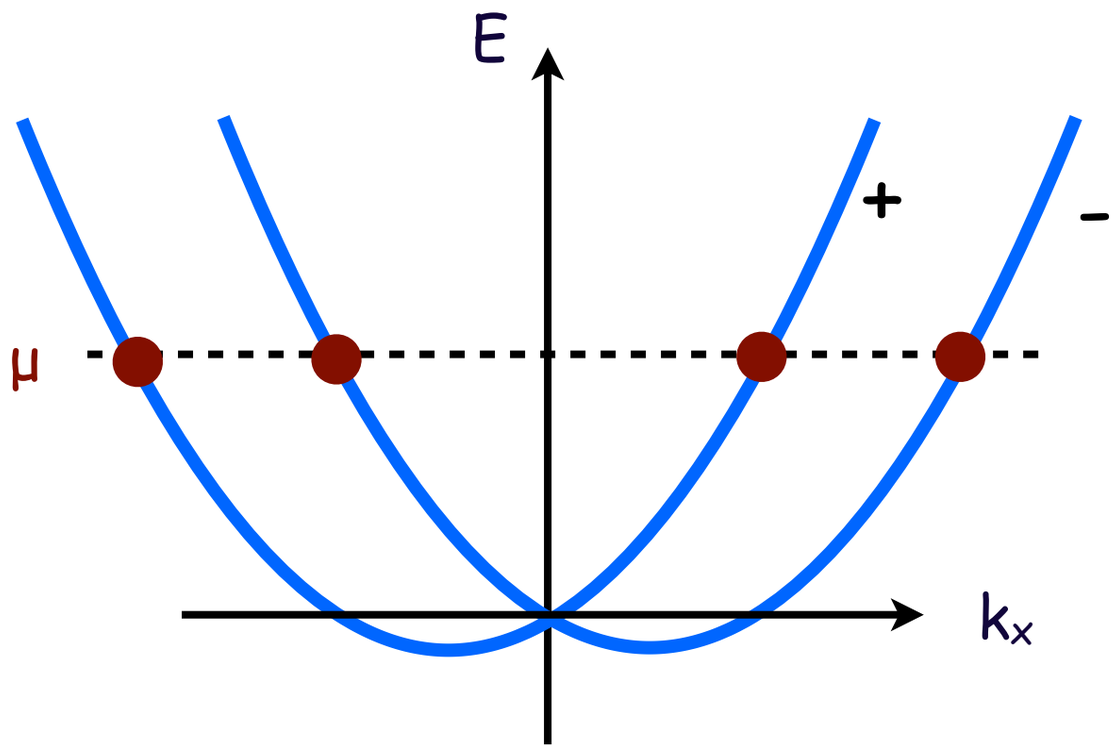
$$g\mu_B B_c^{q=0} = 0.71\Delta_0$$

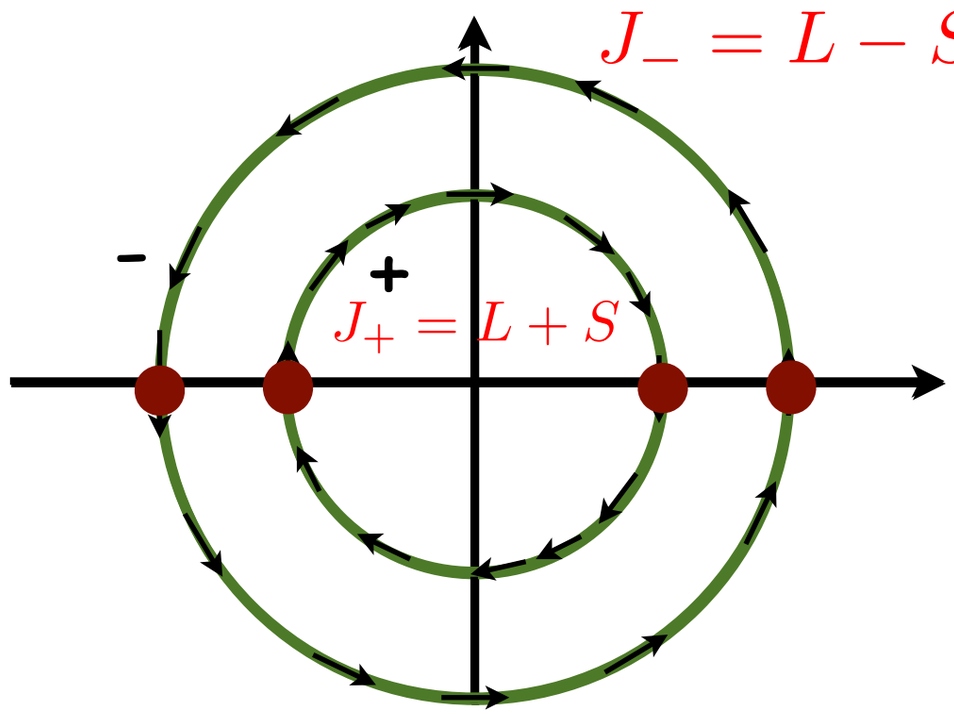
Disorder kills quickly the FFLO state ($1/\tau > \Delta_0$)



Superconductivity and spin-orbit coupling

$\mathcal{H}_{so} = \alpha \hat{z} \cdot (\vec{k} \times \vec{\sigma})$ The two Rashba bands: $\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha |\vec{k}|$





The eigenstates do not have a well defined spin and orbital angular momentum, rather they are described by the total angular momentum.

Superconducting pairing between the time reversal pairs
$|k,+\rangle$, $|-k,+\rangle$ and $|k,-\rangle$, $|-k,-\rangle$

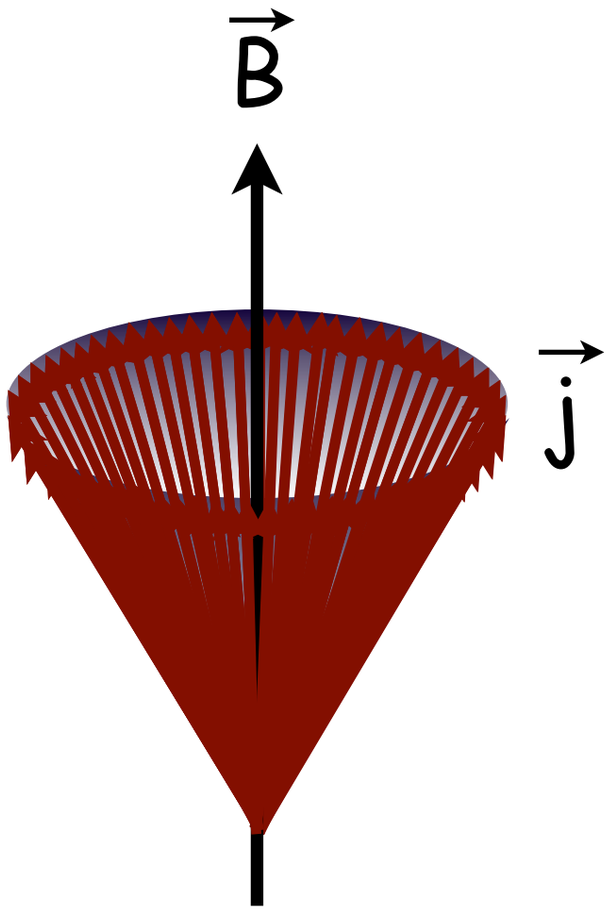
The FFLO state and spin-orbit coupling

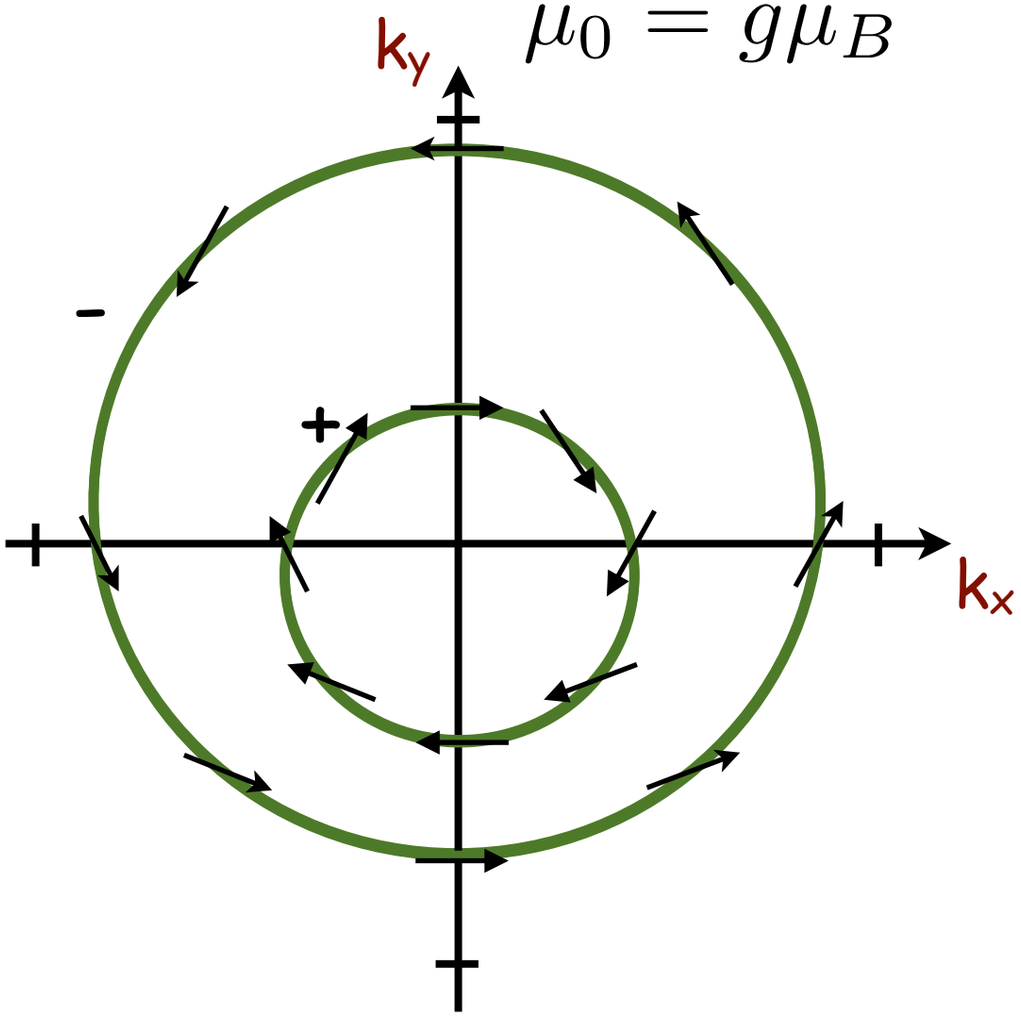
The two Rashba bands in the presence of a Zeeman field: $\vec{B} = B\hat{x}$

$$\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha\sqrt{k_x^2 + (k_y + \mu_0 B/\alpha)^2}$$

$\mu_0 = g\mu_B$

j is no longer a good quantum number.



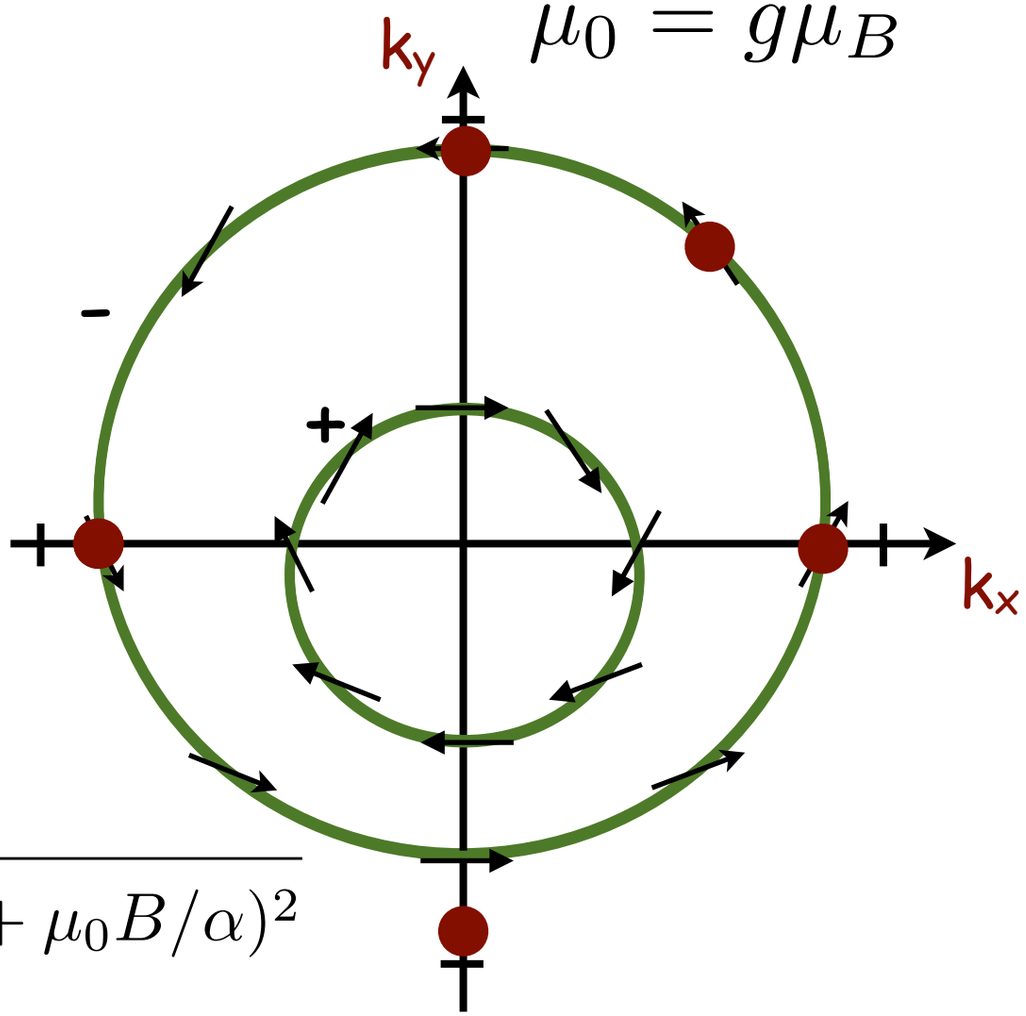


The FFLO state and spin-orbit coupling

The two Rashba bands in the presence of a Zeeman field: $\vec{B} = B\hat{x}$

$$\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha\sqrt{k_x^2 + (k_y + \mu_0 B/\alpha)^2}$$

$\mu_0 = g\mu_B$



j is no longer a good quantum number.

Creating pairs with finite momentum $\vec{q} \perp \vec{B}$:

$$\varepsilon_{k+q/2}^{\pm} = \frac{k_x^2}{2m} + \frac{(k_y + q/2)^2}{2m} \pm \alpha\sqrt{k_x^2 + (k_y + q/2 + \mu_0 B/\alpha)^2}$$

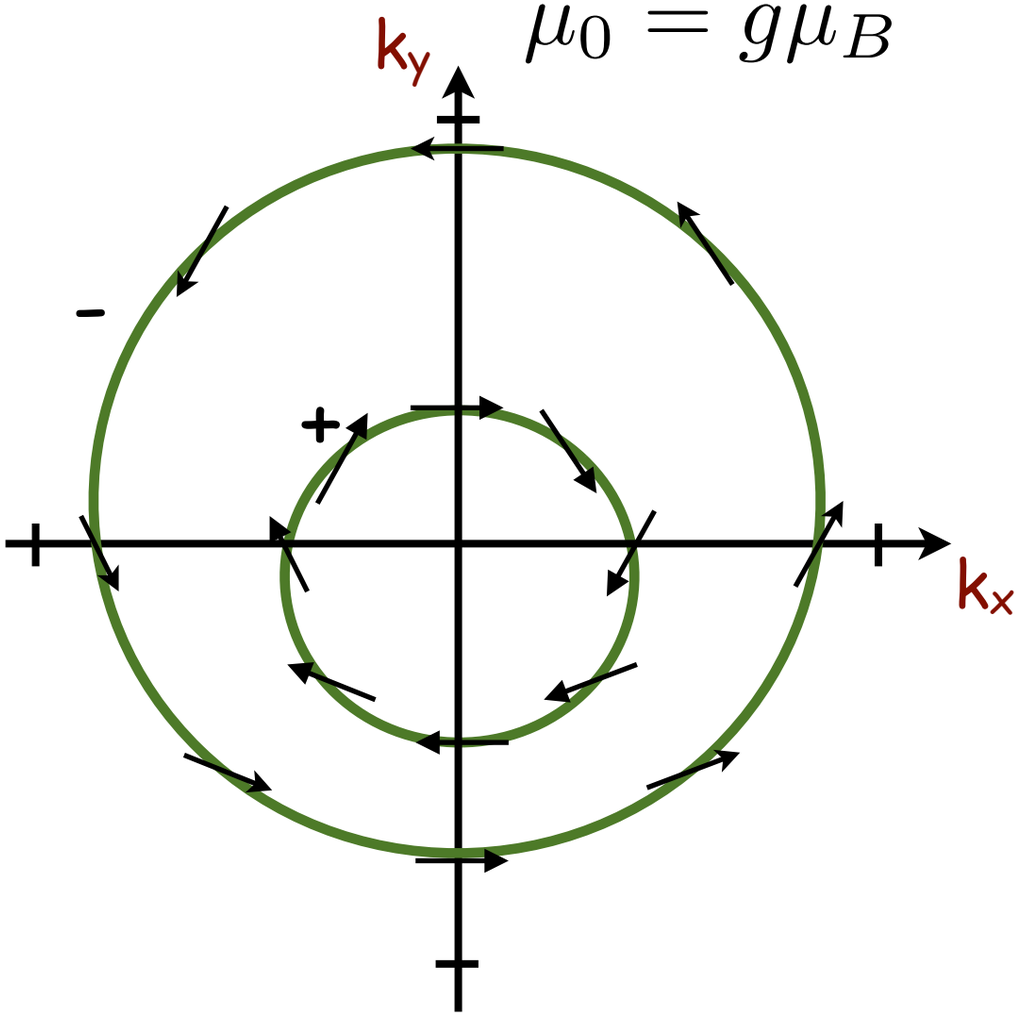
$$\varepsilon_{-k+q/2}^{\pm} = \frac{k_x^2}{2m} + \frac{(k_y - q/2)^2}{2m} \pm \alpha\sqrt{k_x^2 + (k_y - q/2 - \mu_0 B/\alpha)^2}$$

The FFLO state and spin-orbit coupling

The two Rashba bands in the presence of a Zeeman field: $\vec{B} = B\hat{x}$

$$\varepsilon_k^{\pm} = \frac{k^2}{2m} \pm \alpha\sqrt{k_x^2 + (k_y + \mu_0 B/\alpha)^2}$$

$\mu_0 = g\mu_B$



j is no longer a good quantum number.

Creating pairs with finite momentum $\vec{q} \perp \vec{B}$:

$$\varepsilon^{\pm}_{k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| + \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

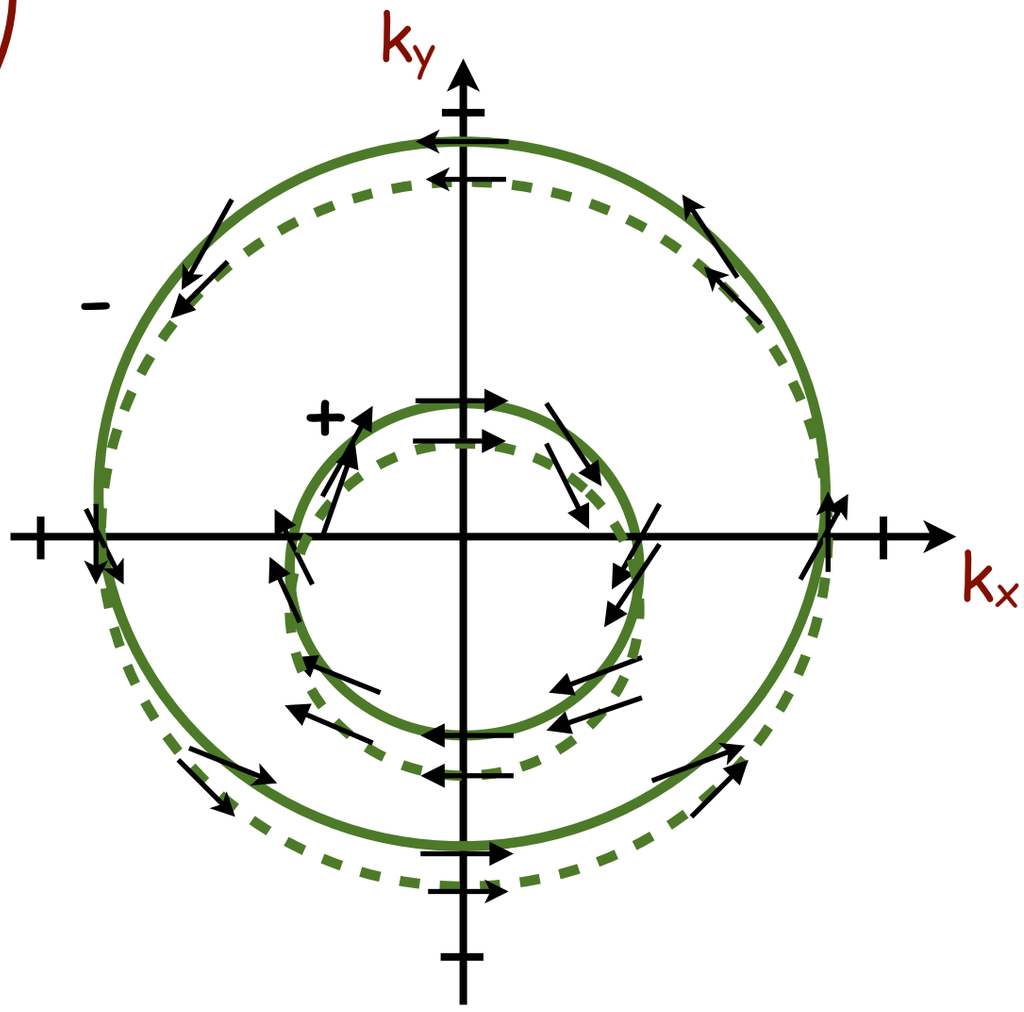
$$\varepsilon^{\pm}_{-k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| - \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

The FFLO state and spin-orbit coupling

$$\varepsilon^{\pm}_{k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| + \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

$$\varepsilon^{\pm}_{-k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| - \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

$$q = \frac{2\mu_0 B}{v_F}$$

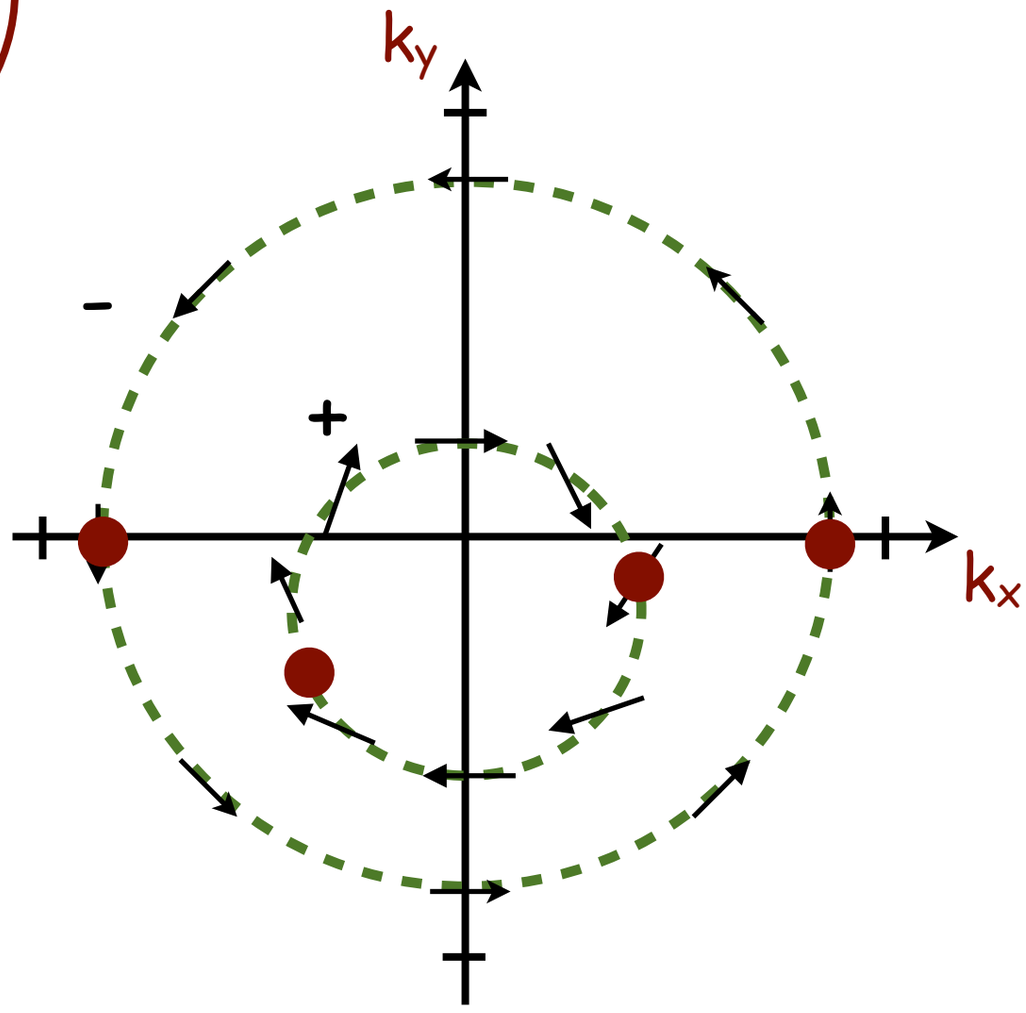


The FFLO state and spin-orbit coupling

$$\varepsilon^{\pm}_{k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| + \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

$$\varepsilon^{\pm}_{-k+q/2} \approx \frac{k^2}{2m} \pm \alpha|\vec{k}| - \frac{1}{2}\left(V_F q \pm 2\mu_0 B\right)\sin\theta$$

$$q = \frac{2\mu_0 B}{v_F}$$



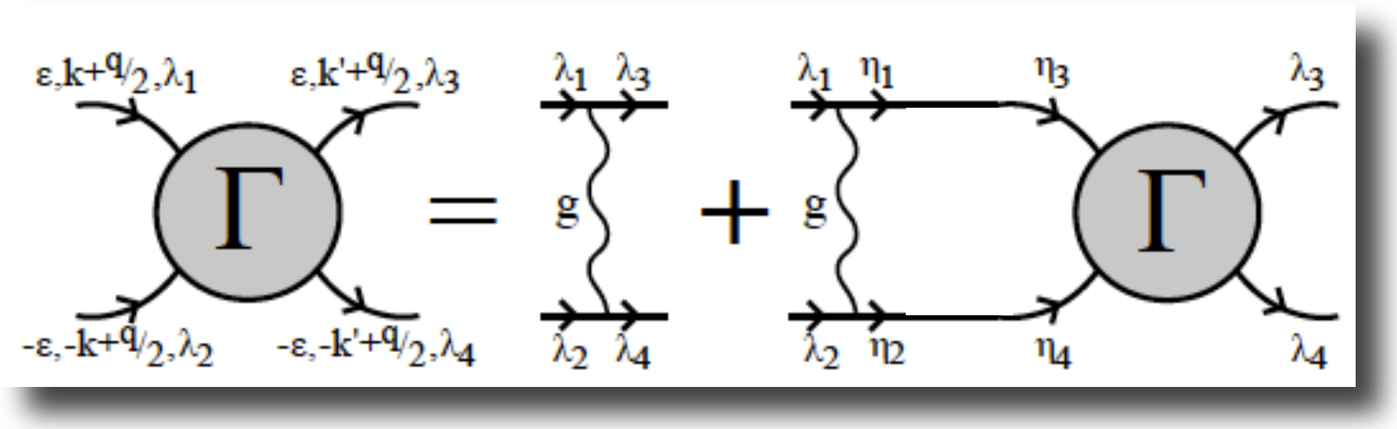
Pairs of electrons in the - band are not affected by the magnetic field

Pairs of electrons in the + band feel the decoherence effect of the magnetic field

The critical field is mainly determined by the + band

The FFLO state and spin-orbit coupling

The critical field is found by solving the vertex equation for the attractive interaction:

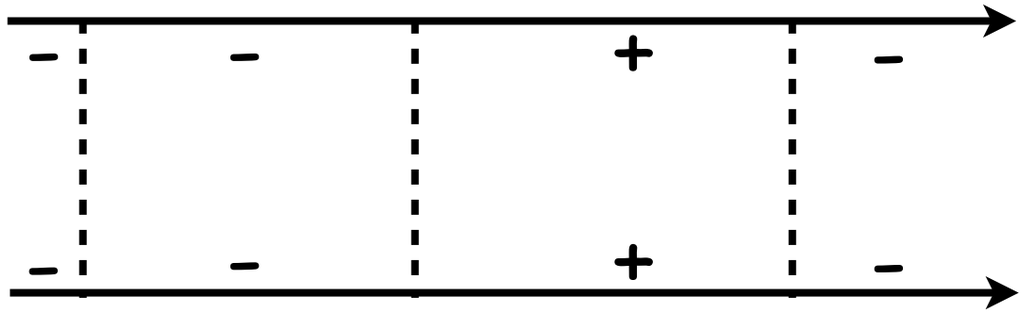


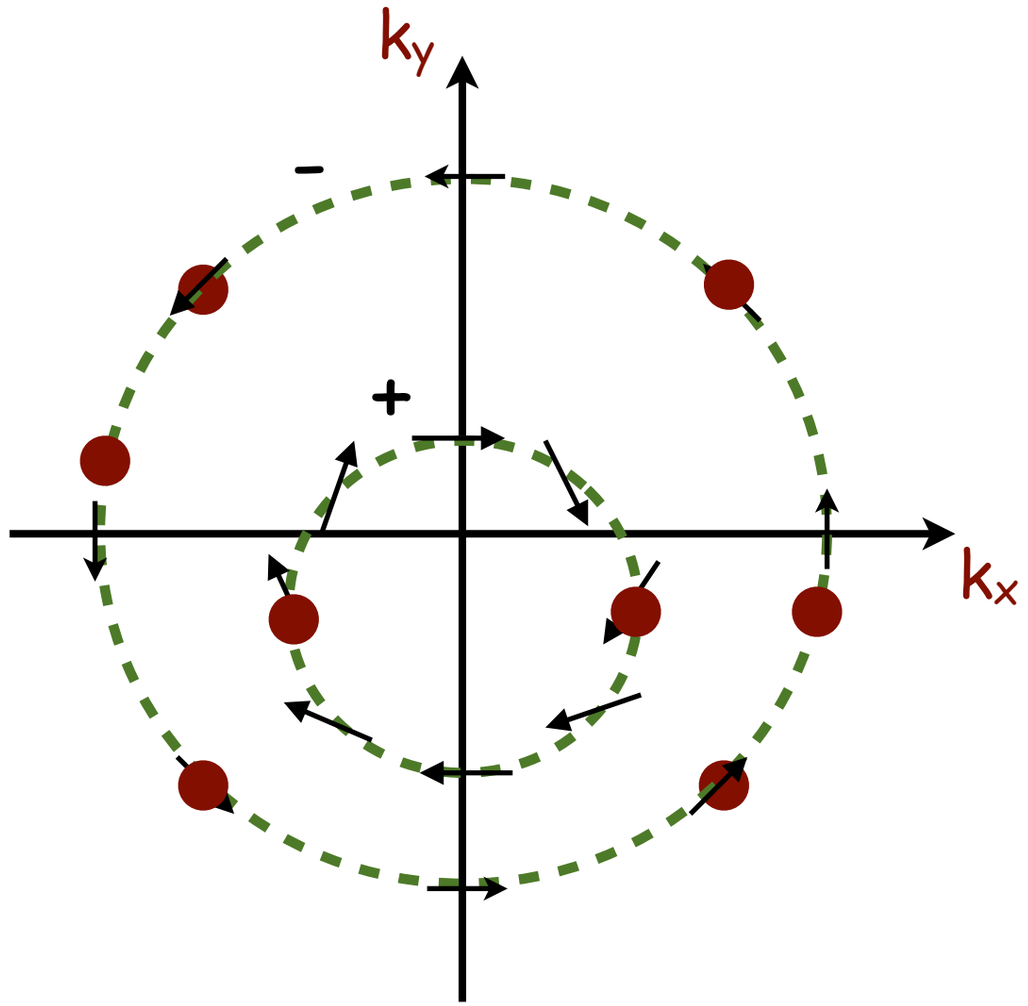
and obtaining the magnetic field in which the interaction diverges

$$\mu_0 B_c \sim \Delta_0 \left(\frac{\Delta_{so}}{\Delta_0} \right)^x \qquad 1/2 < x < 2/3$$

V. Barzykin and L.P. Gorkov, 2002

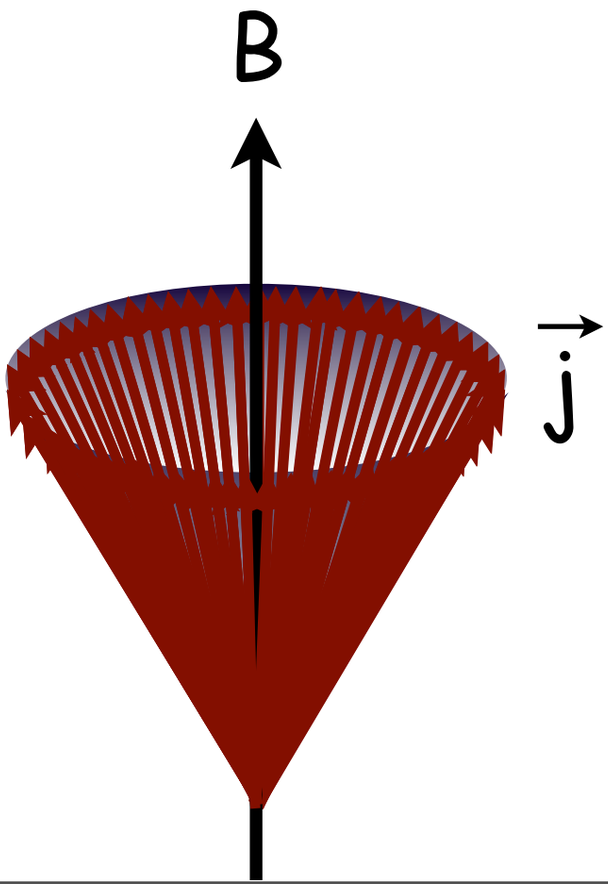
Low impurity concentration $1/\tau < \Delta_0$



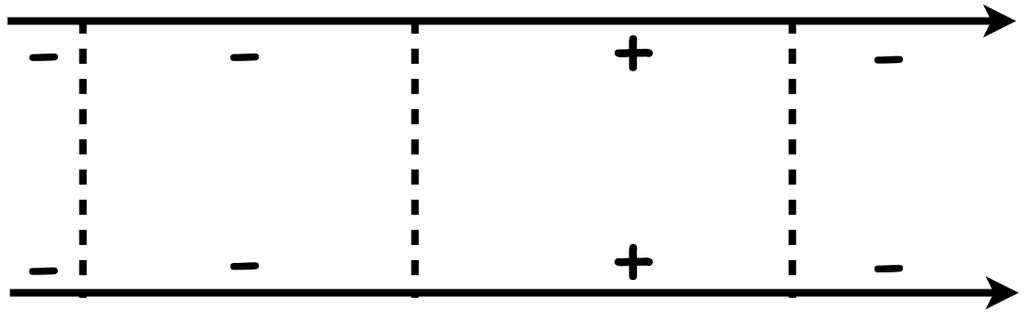


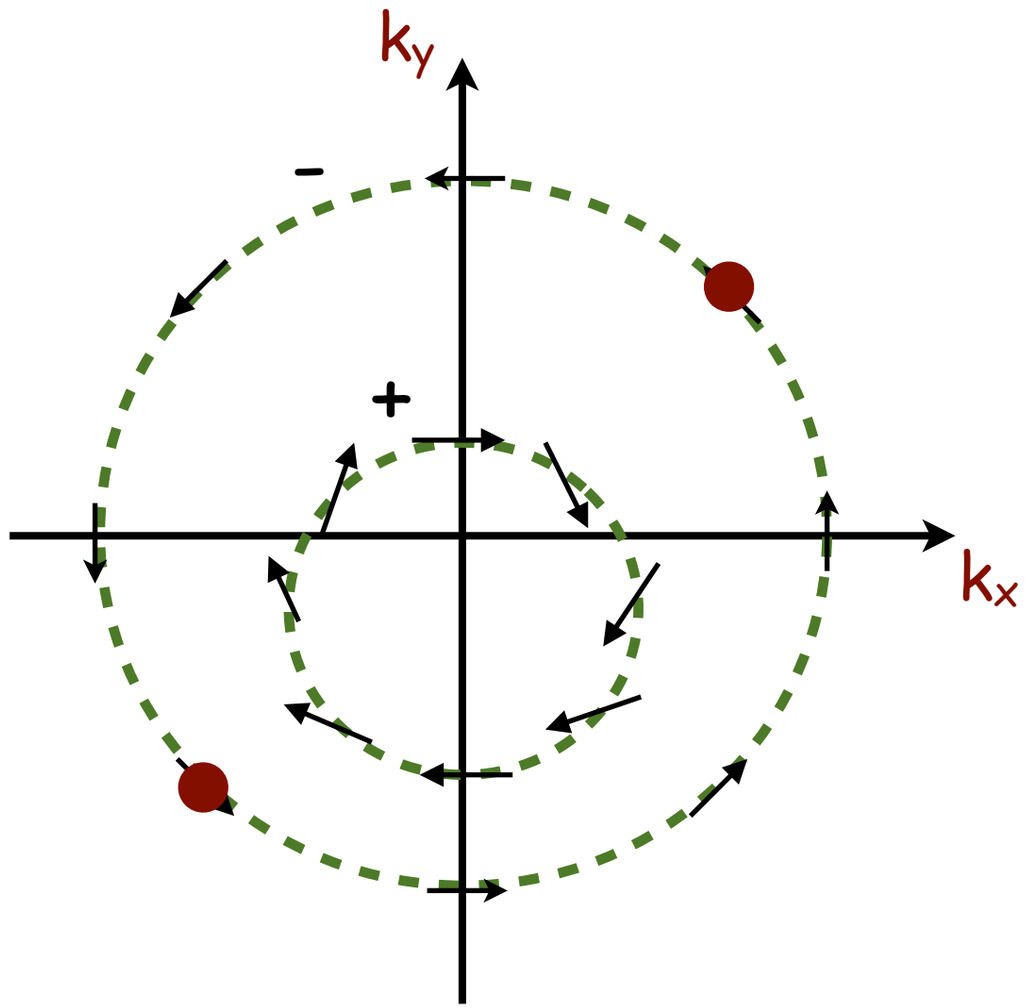
Scattering of a pair to the - band does not affect the pairing

$$1/\tau < \Delta_0 < \mu_0 B$$



Low impurity concentration $1/\tau < \Delta_0$





Scattering of a pair to the - band does not affect the pairing

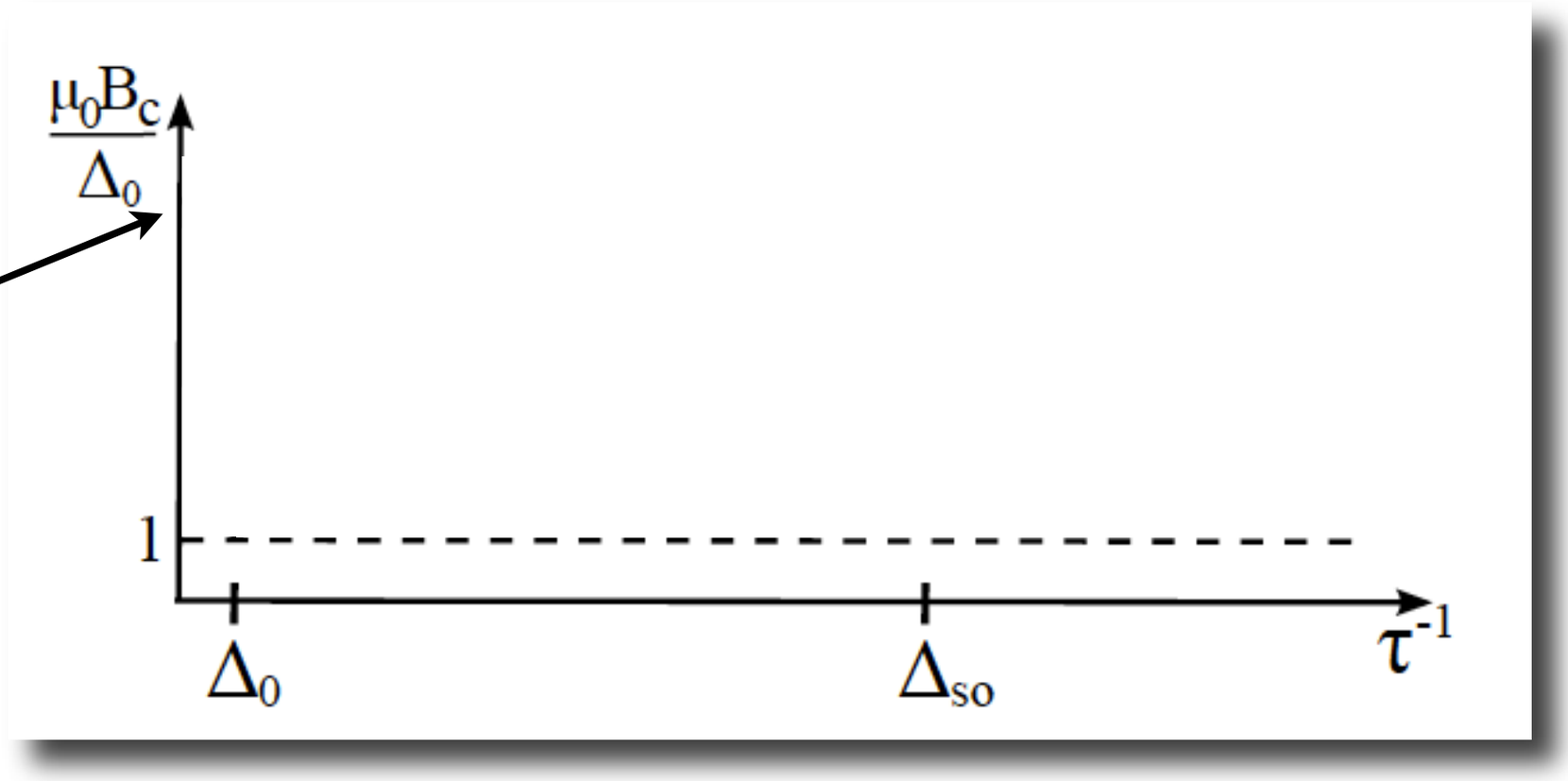
Scattering of a pair to the + band leads to their decoherence

All pairs feel the pair-breaking effect of the Zeeman field

$$\mu_0 B_c \sim \Delta_0 \left(\Delta_0 \tau\right)^y$$

$$y > 1$$

Low impurity concentration $1/\tau < \Delta_0$

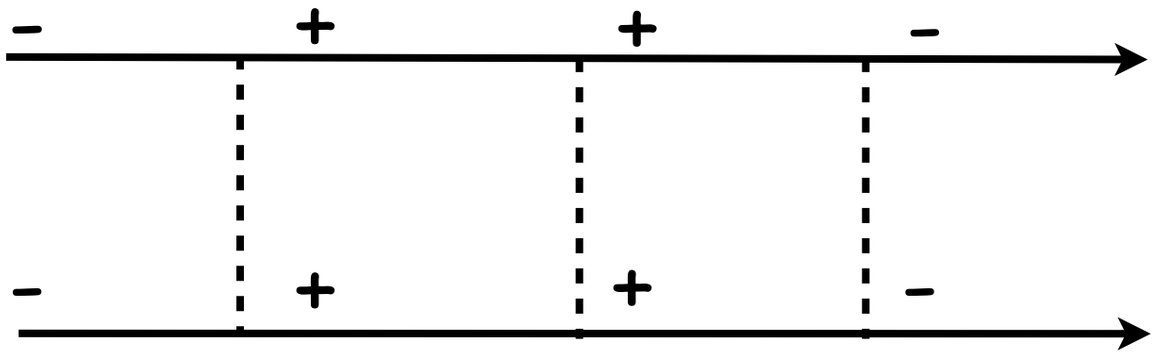


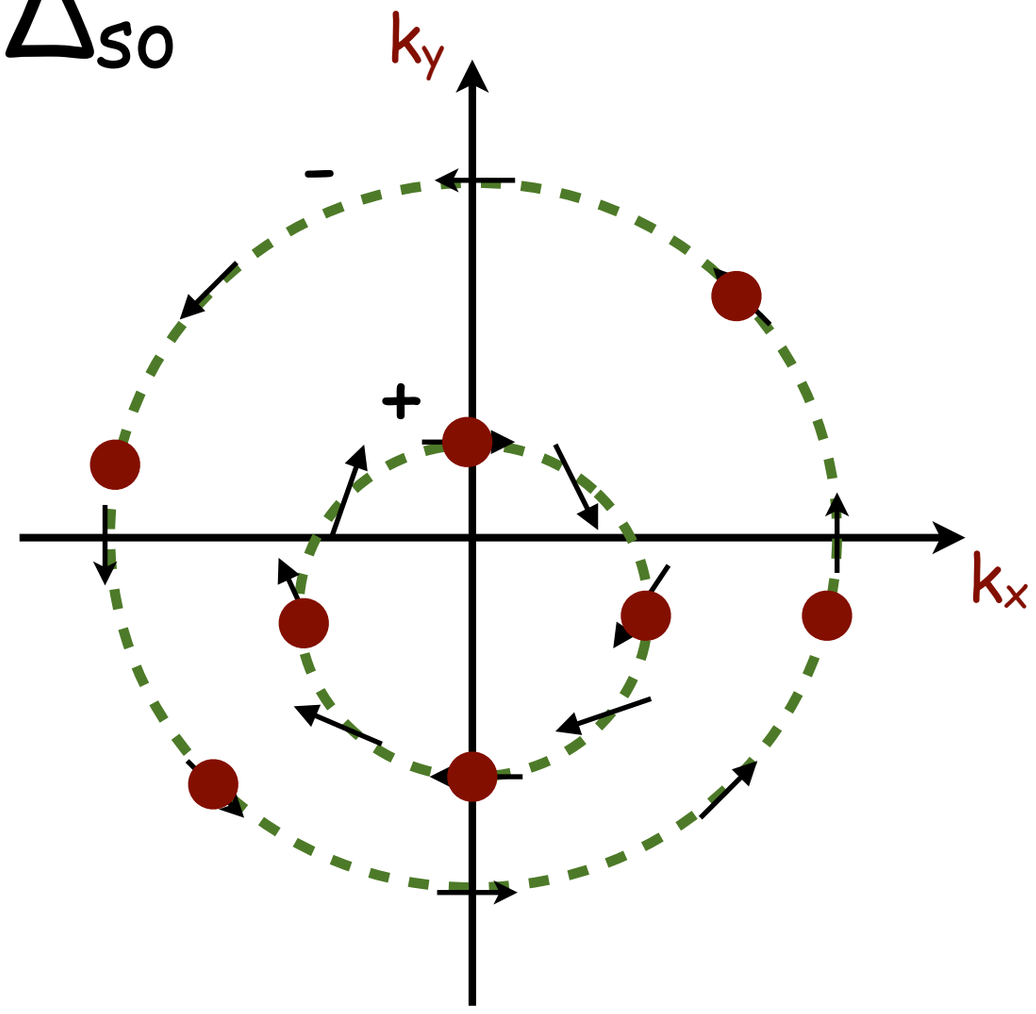
$$\mu_0 B_c \sim \Delta_0 \left(\Delta_0 \tau\right)^y$$

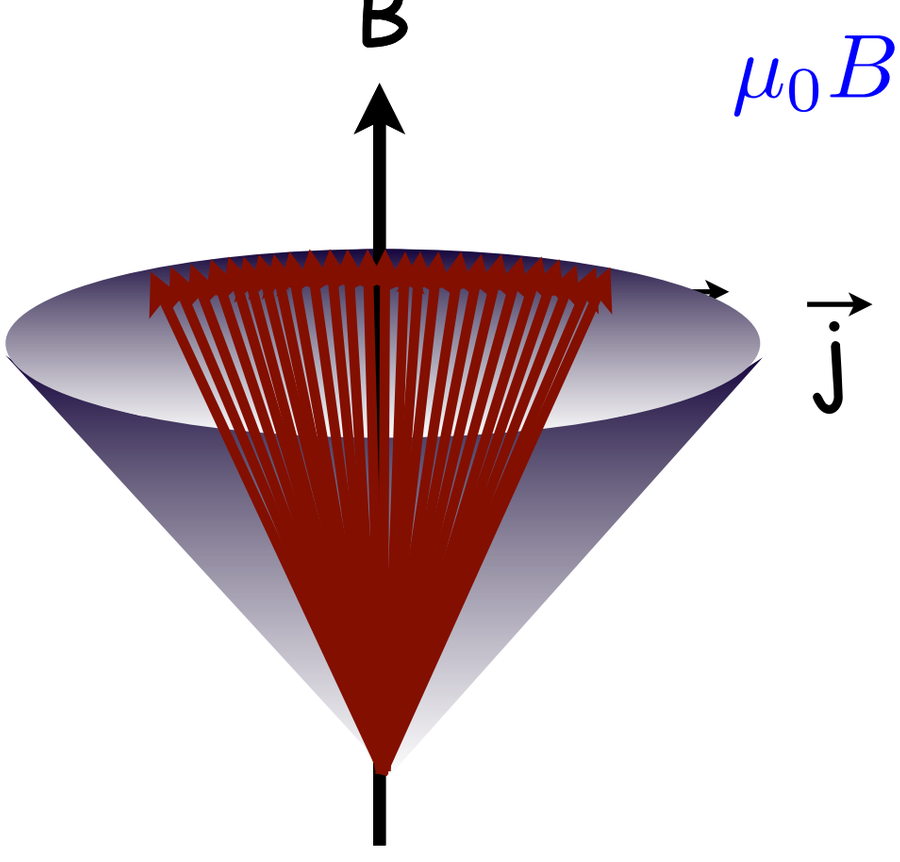
$$y > 1$$

Intermediate impurities concentration

$$\Delta_0 < 1/\tau < \Delta_{so}$$







$$\mu_0 B < 1/\tau$$

The total angular momentum of a pair in the - band does not complete a single precession before it is scattered by the impurities.

Intermediate impurity concentration

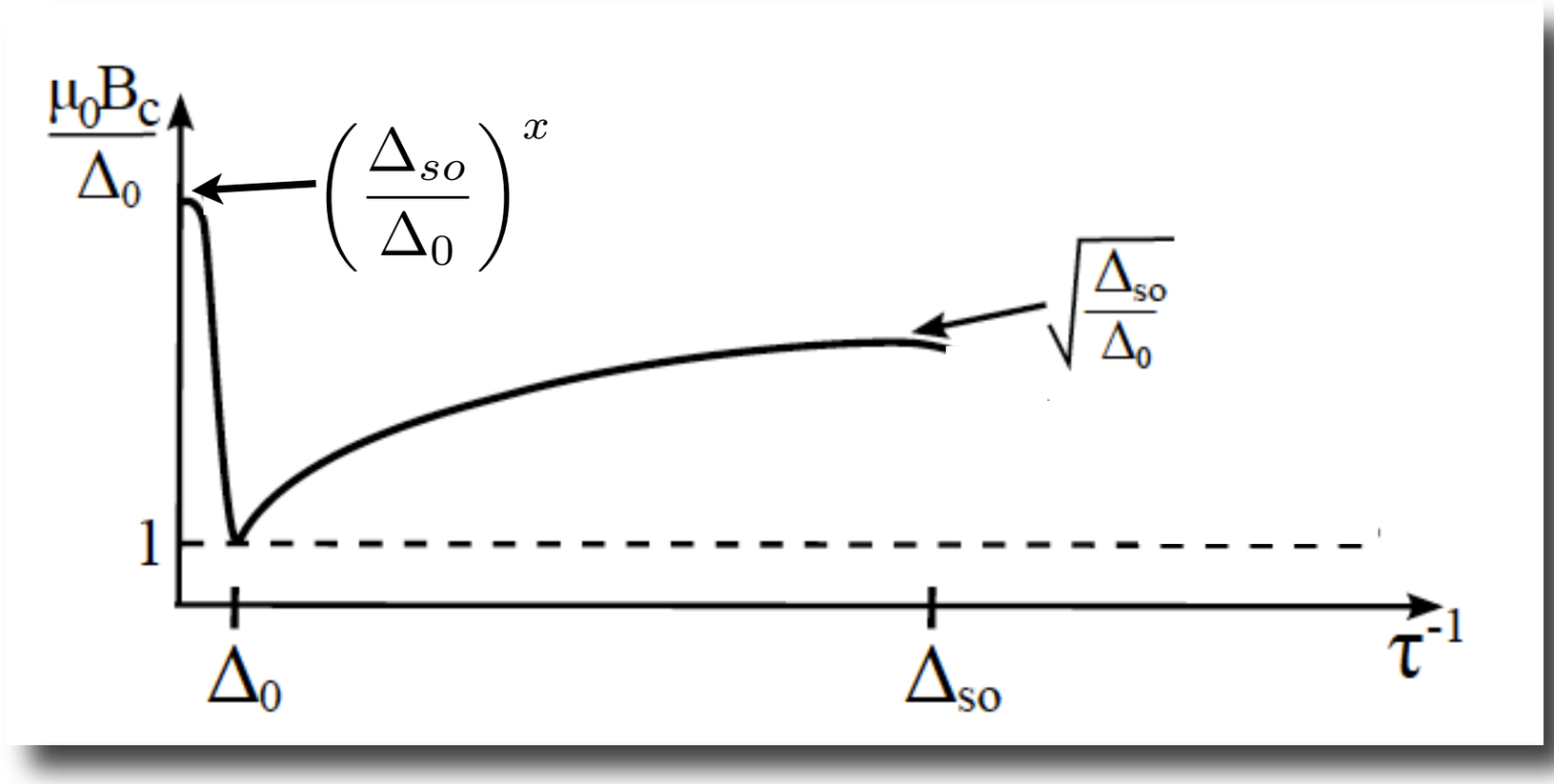
$$\Delta_0 < 1/\tau < \Delta_{so}$$

The precession becomes diffusive and the effective field seen by the electrons is $(\mu_0 B)^2 \tau \ll \mu_0 B$

The scattering by impurities helps to reduce the effect of the magnetic field

$$\mu_0 B_c \sim \frac{\Delta_0}{\sqrt{\Delta_0 \tau}}$$

$$1/\tau \to \Delta_{so} \longrightarrow \Delta_0 \sqrt{\frac{\Delta_{so}}{\Delta_0}}$$



Similar result obtained by O. Dimitrova and M.V. Feigel'man, 2007

High impurity concentration $\Delta_{so}<1/\tau$

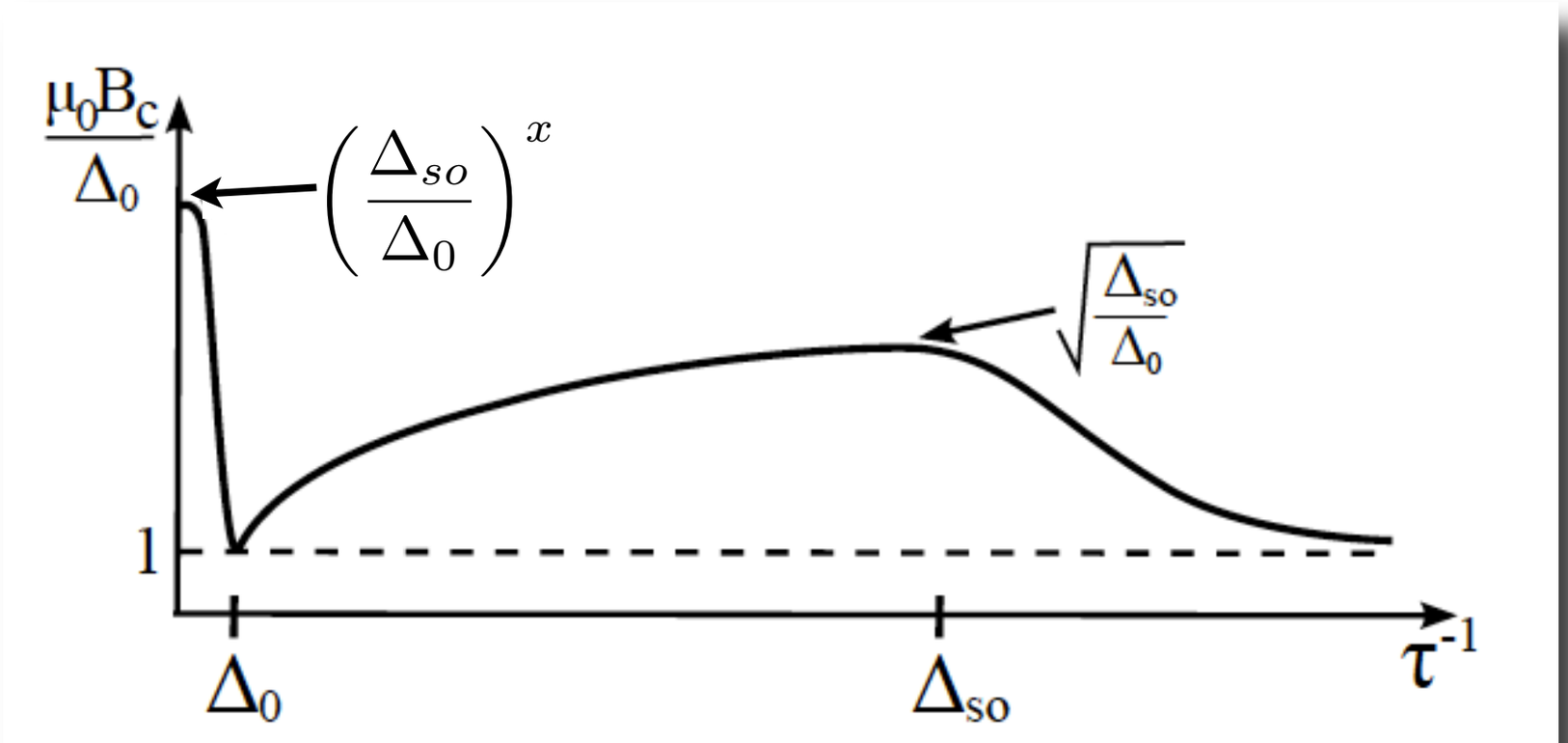
Due to the D'yakonov-Perel mechanism
the spin decouples form the momentum

The Zeeman field has the same effect as
in a system without spin-orbit coupling

The FFLO state dies with
increasing disorder

$$\mu_0 B_c \sim \frac{\Delta_0}{\sqrt{\Delta_0 \tau_s}}$$

$$\tau_s = \Delta_{so}^2 \tau \ll \tau^{-1}$$



Main experimental results

- ☑ Charge carrier density << the polar catastrophe
- ☑ Two types of charge carriers
- ☑ Ferromagnetism
- ☑ Strong spin-orbit coupling
- ☑ Coexistence of ferromagnetism and superconductivity