Superconductivity in 2DEG at $LaAlO_3/SrTiO_3$ interface

P. Wójcik[1], M. Zegrodnik[2] , and M.P. Nowak[2]

[1]*Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Krakow, Poland*

[2]*Academic Centre for Materials and Nanotechnology, AGH University of Science and Technology, Krakow, Poland*

Outline:

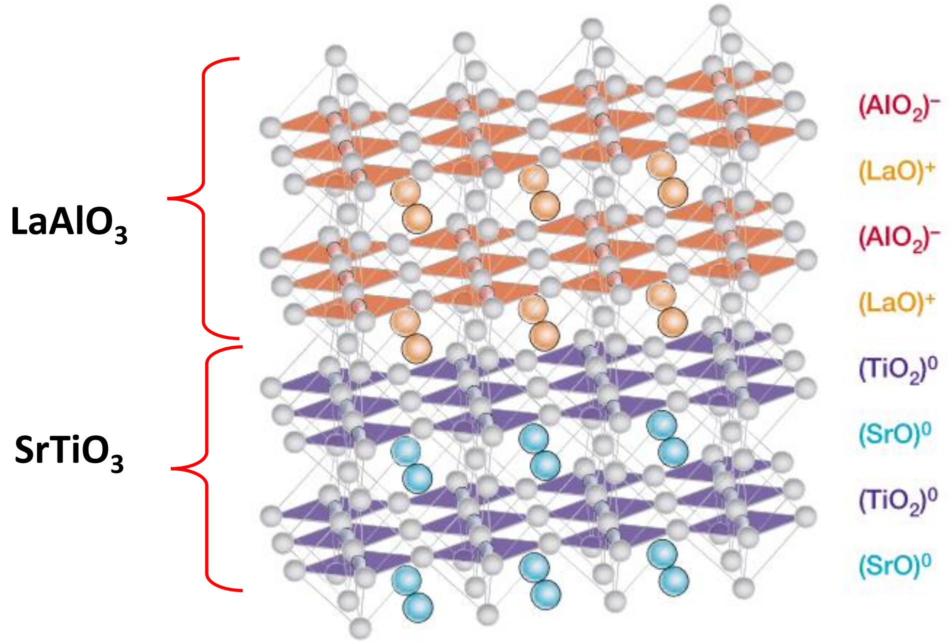
I. Motivation - 2DEG at theLaAlO_3/$SrTiO_3$ interface

II. Model of the paired phase at the LaAlO_3/$SrTiO_3$ interface

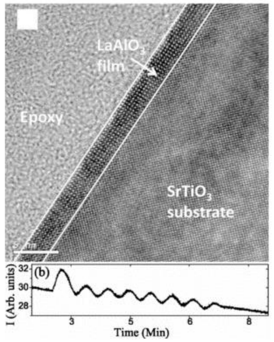
III. Results:
   i. Carrier density dependence of the critical temperature
   ii. Effect of electron-electron repulsion
   iii. Position of the Lifshitz transition with respect to the T_c maxima.
   iv. LAO/STO in (110) direction

IV. Conclusions

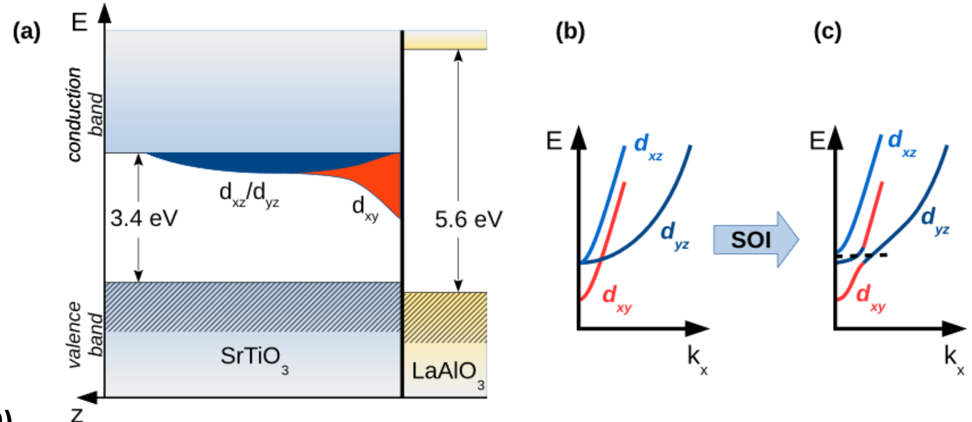
2DEG at the LAO/STO interface



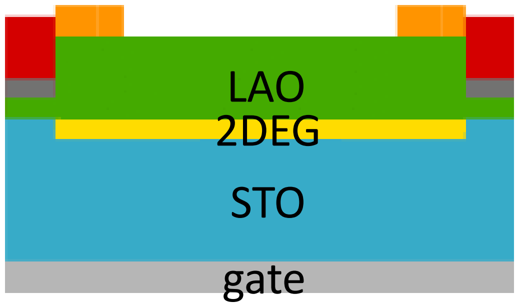
A. Ohtomo, H. Y. Hwang, Science 427, 423 (2007)



Phys. Rev. B 80, 140403(R) (2009)



S. Gariglio et al., APL Materials 4, 060701 (2016)



P. Maier et al., Appl. Phys. Lett. 110 903506 (2017)

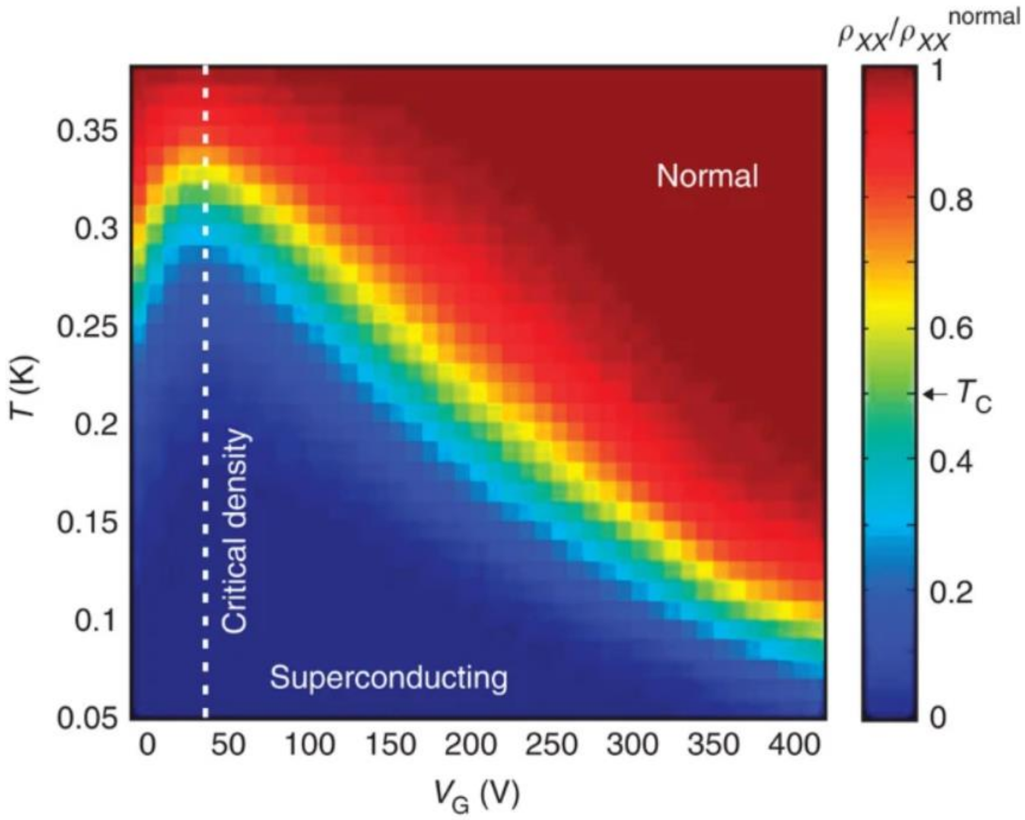
Properties:

a) Two dimensional electron gas
b) Spin-orbit interaction
c) Ferroelectricity
d) Magnetism
e) **Superconductivity (low electron density !)**
f) Superconductivity + magnetism

We can control all of them by gate voltage !!!

Superconductivity at the LAO/STO interface

Characteristic dome of the critical temperature



A. Joshua et al., Nat. Commun 3, 1129 (2012)

Possible explanations:

1. **Electronic correlations** –
   E. Maniv et al., Nat. Commun 6, 8239 (2015)
2. **Non trivial link between spin-orbit interaction and superconductivity.**
   P. K. Rout et al., Phys. Rev. Lett. 119, 237002 (2017)
3. **Strong pair breaking effect in dirty limit**
   T. V. Trevisan et al., Phys. Rev. Lett. 121, 127002 (2018)

Scenario 1: Electronic correlations.

ARTICLE

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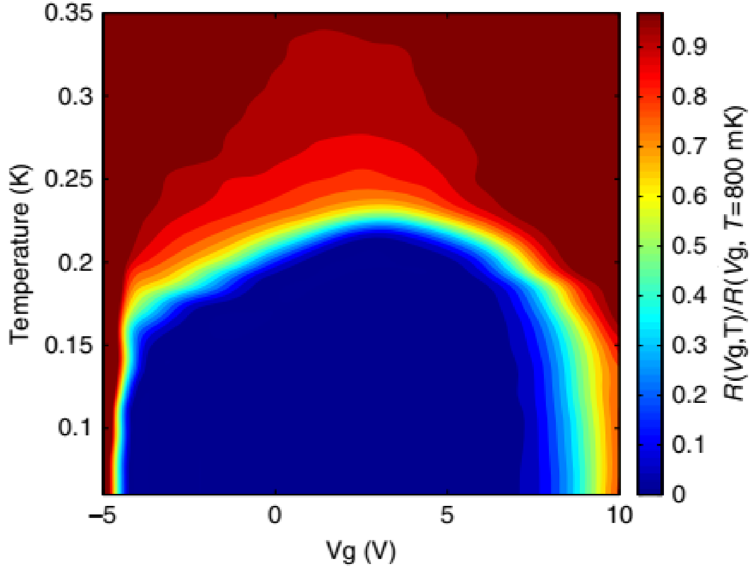
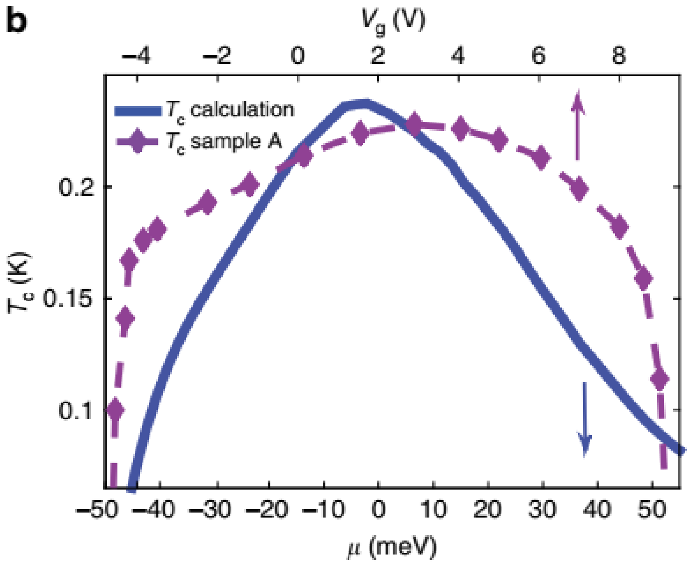
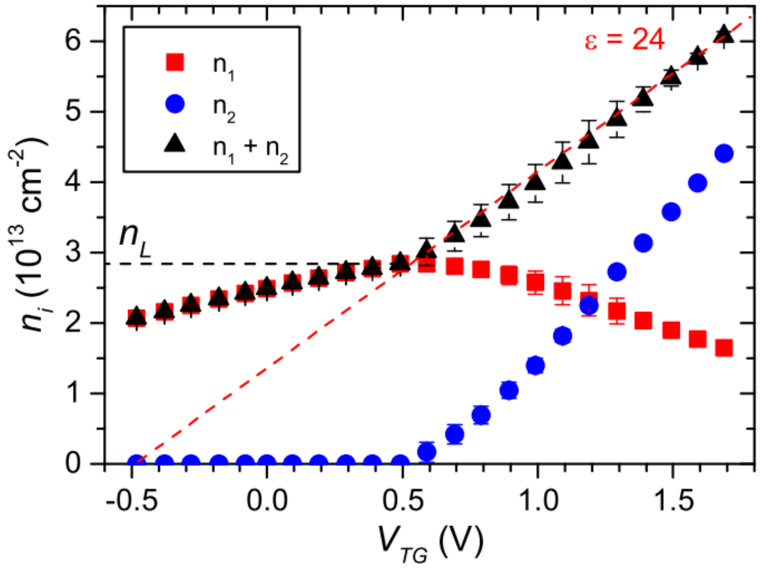
OPEN

Strong correlations elucidate the electronic structure and phase diagram of $LaAlO_3/SrTiO_3$ interface

E. Maniv[1], M. Ben Shalom[1], A. Ron[1], M. Mograbi[1], A. Palevski[1], M. Goldstein[1] & Y. Dagan[1]







PRL, 118, 106401 (2017)

Scenario 2: Non trivial link between spin-orbit interaction and superconductivity.

PRL **119**, 237002 (2017) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2017

Link between the Superconducting Dome and Spin-Orbit Interaction in the (111) $LaAlO_3/SrTiO_3$ Interface

P. K. Rout, E. Maniv, and Y. Dagan*

Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel Aviv 69978, Israel

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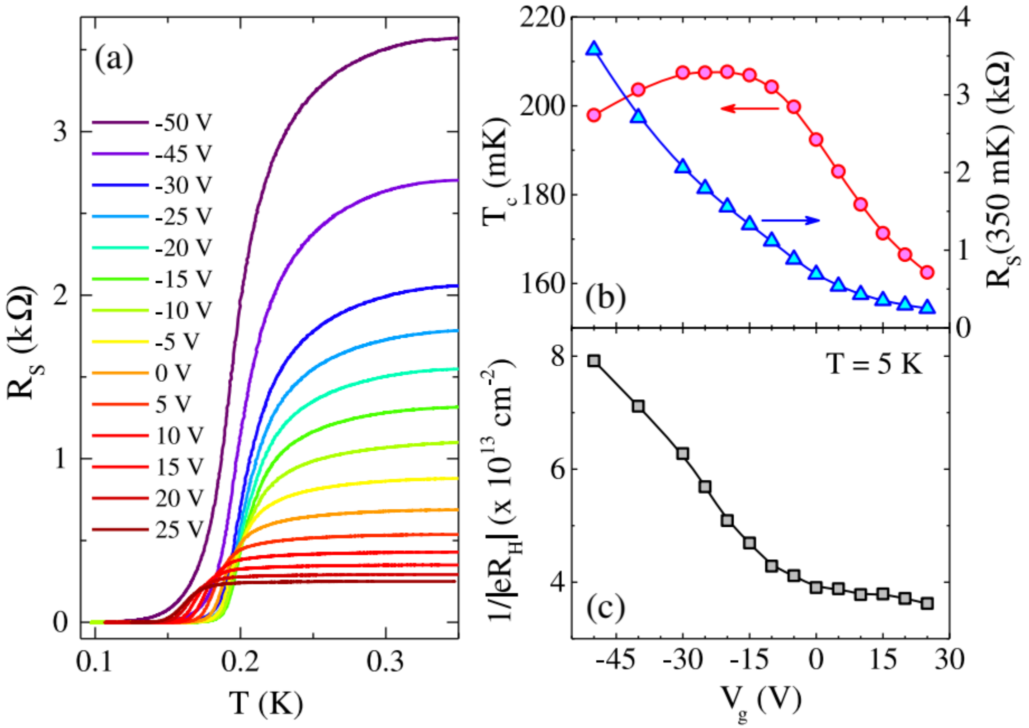
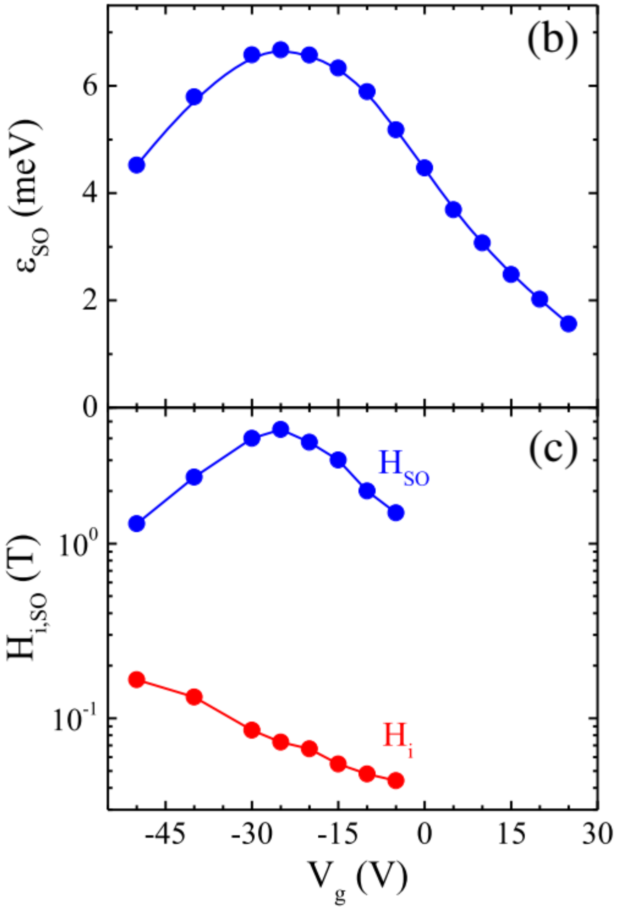




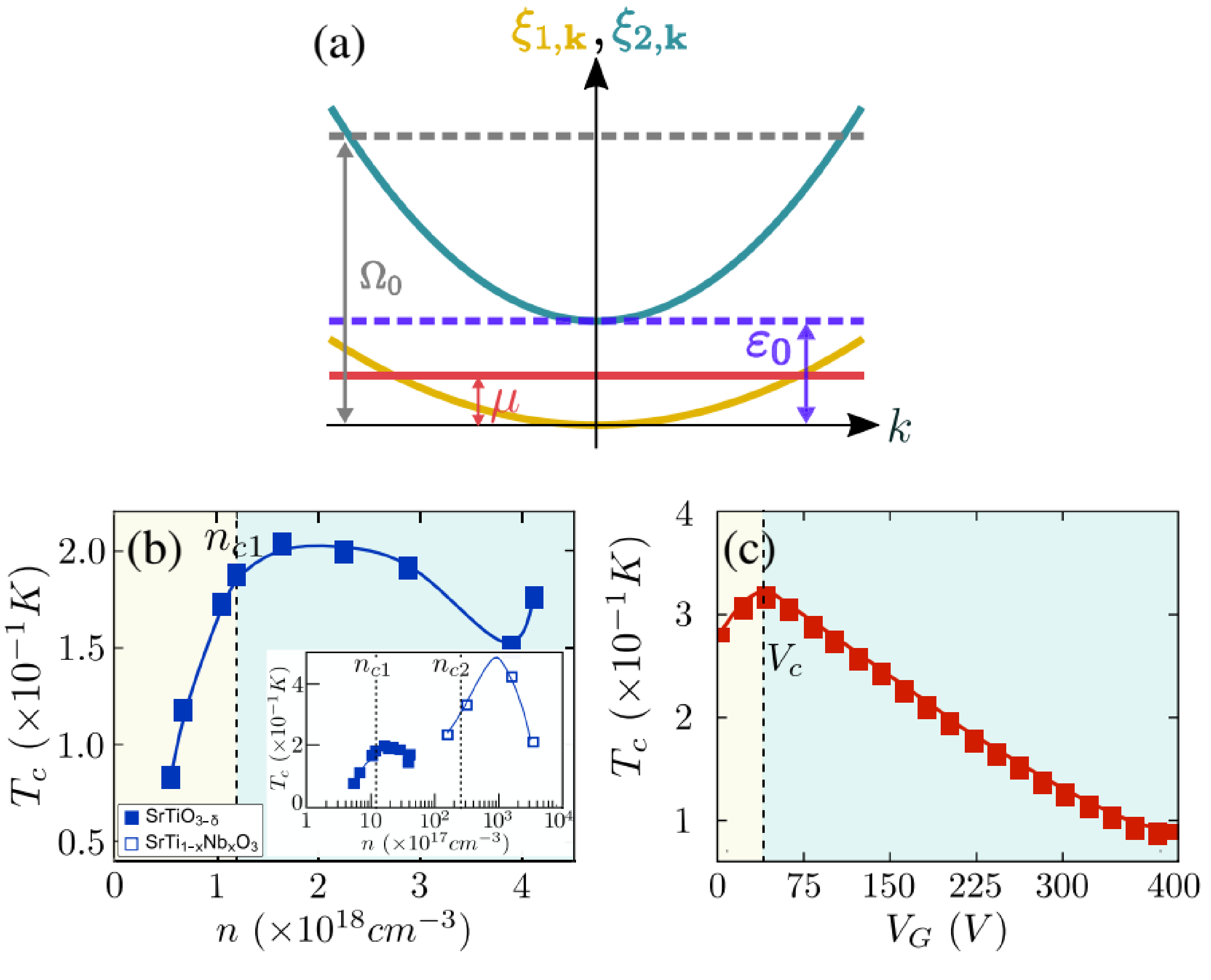
Scenario 3: Strong pair breaking effect in dirty limit.

PHYSICAL REVIEW LETTERS **121,** 127002 (2018)

Unconventional Multiband Superconductivity in Bulk $SrTiO_3$ and $LaAlO_3/SrTiO_3$ Interfaces

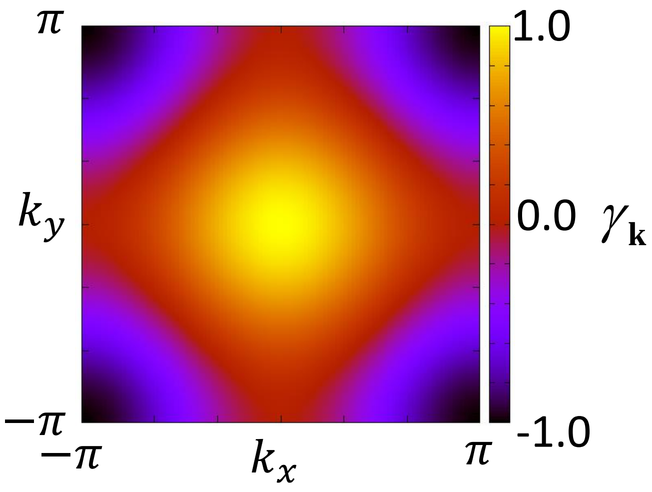
Thaís V. Trevisan,[1,2] Michael Schütt,[1] and Rafael M. Fernandes[1]
[1]*School of Physics and Astronomy, University of Minnesota, Minneapolis 55455, USA*
[2]*Instituto de Física Gleb Wataghin, Unicamp, Rua Sérgio Buarque de Holanda, 777, CEP 13083-859 Campinas, SP, Brazil*

- Repulsive interband interaction
- Two band model
- Maxima of Tc exactly in Lifshitz transition

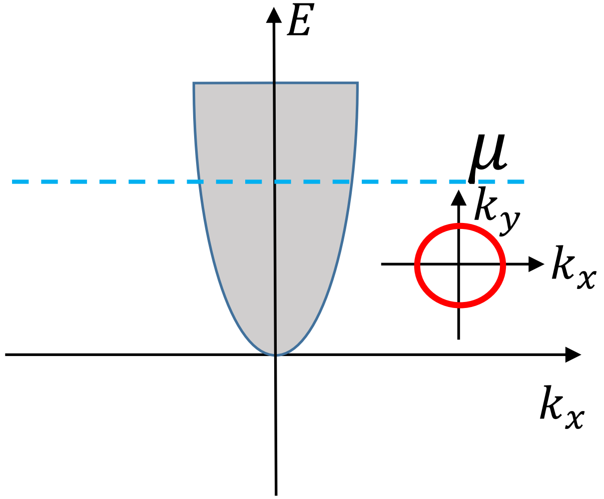


Can the Tc dome be induced by the symmetry of the gap.

Gap symmetry

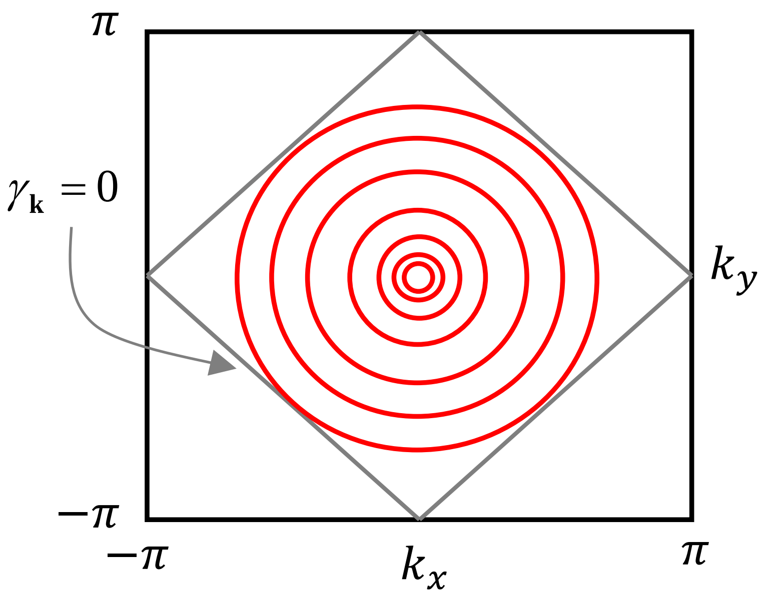


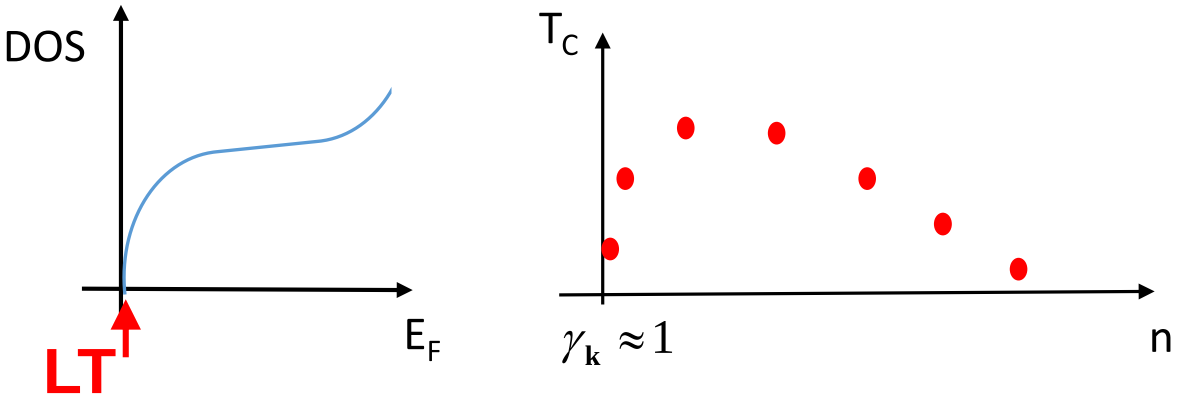
Fermi surface



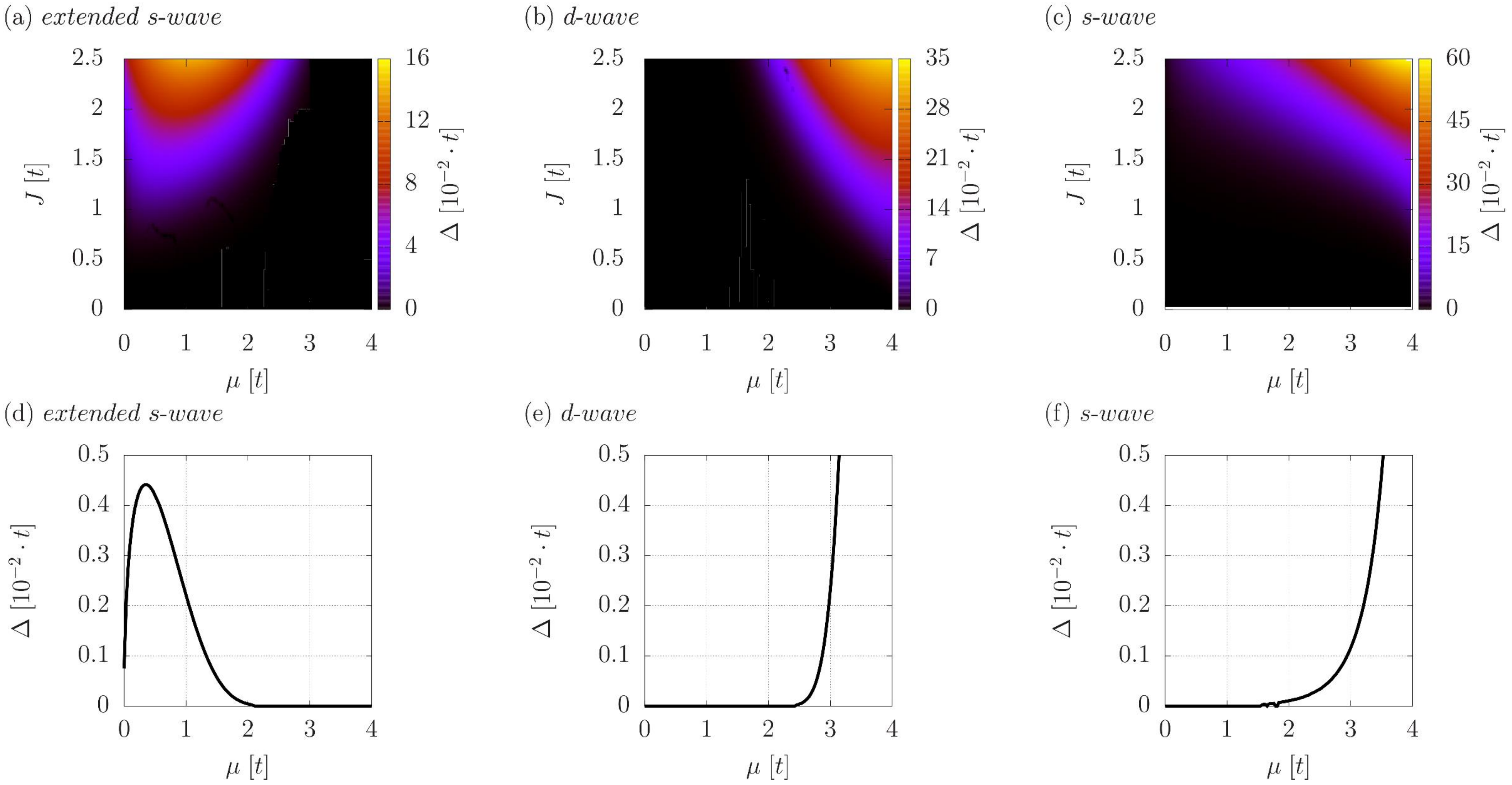
Extended s-wave symmetry

$$\boxed{\Delta(\mathbf{k}) = 4\Delta\gamma_{\mathbf{k}} \quad \text{with} \quad \gamma_{\mathbf{k}} = (\cos k_x + \cos k_y)/2}$$





Can the T_c dome be induced by the symmetry of the gap.



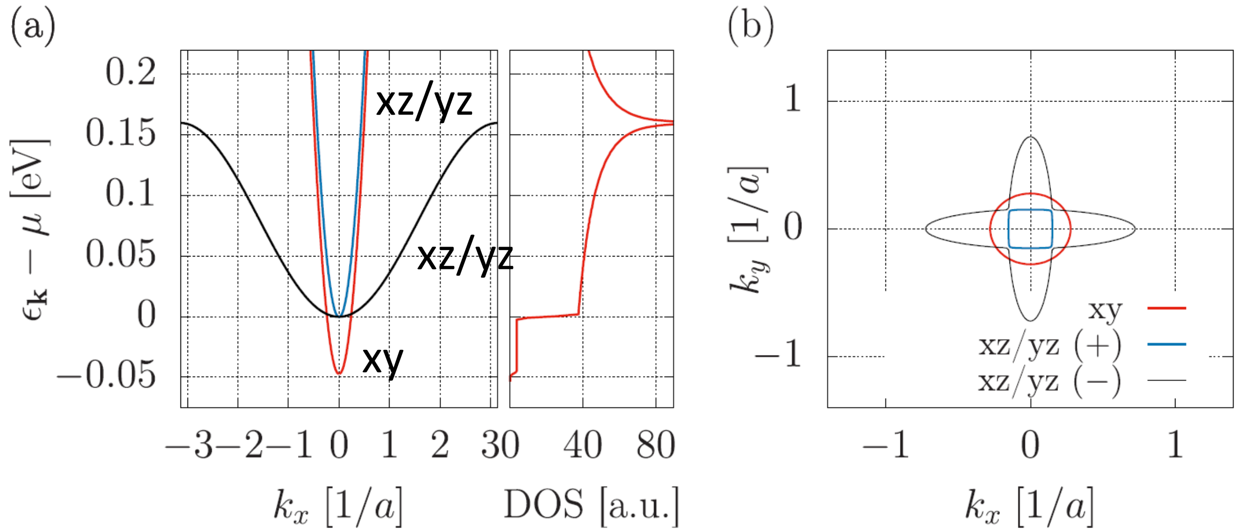
Theoretical model

Hamiltonian

$$\widehat{H} = \widehat{H}_{TBA} + \widehat{H}_U + \widehat{H}_{SC}$$

$$\hat{H}_{\mathrm{TBA}} = \sum_{\mathbf{k}ll'\sigma\sigma'} \hat{c}^{\dagger}_{\mathbf{k},l,\sigma} (\hat{H}_0 + \cancel{\hat{H}_{\mathrm{SO}}} + \cancel{\hat{H}_{\mathrm{RSO}}}) \hat{c}_{\mathbf{k},l',\sigma'}$$

$$\widehat{H}_0 = \begin{pmatrix} \epsilon_{\boldsymbol{k}}^{xy} & 0 & 0 \\ 0 & \epsilon_{\boldsymbol{k}}^{xz} & \epsilon_{h\boldsymbol{k}} \\ 0 & \epsilon_{h\boldsymbol{k}} & \epsilon_{\boldsymbol{k}}^{yz} \end{pmatrix}$$



$$\epsilon_{\mathbf{k}}^{xy} = 4t_l - \Delta_E - 2t_l \cos k_x - 2t_l \cos k_y,$$

$$\epsilon_{\mathbf{k}}^{xz} = 2t_l + 2t_h - 2t_l \cos k_x - 2t_h \cos k_y,$$

$$\epsilon_{\mathbf{k}}^{yz} = 2t_l + 2t_h - 2t_h \cos k_x - 2t_l \cos k_y,$$

$$\epsilon_{h\mathbf{k}} = 2t_d \sin k_x \sin k_y$$

Theoretical model

Hamiltonian

$$\hat{H} = \hat{H}_{TBA} + \hat{H}_U + \hat{H}_{SC}$$

$$\hat{H}_{\mathrm{TBA}} = \sum_{\mathbf{k}ll'\sigma\sigma'} \hat{c}^{\dagger}_{\mathbf{k},l,\sigma} (\hat{H}_0 + \cancel{\hat{H}_{\mathrm{SO}}} + \cancel{\hat{H}_{\mathrm{RSO}}}) \hat{c}_{\mathbf{k},l',\sigma'}$$

$$\hat{H}_0 = \begin{pmatrix} \epsilon^{xy}_{\boldsymbol{k}} & 0 & 0 \\ 0 & \epsilon^{xz}_{\boldsymbol{k}} & \epsilon_{h\boldsymbol{k}} \\ 0 & \epsilon_{h\boldsymbol{k}} & \epsilon^{yz}_{\boldsymbol{k}} \end{pmatrix}$$

Coulomb repulsion

$$\hat{H}_U = U \sum_{il} \hat{n}_{il\uparrow} \hat{n}_{il\downarrow} + V \sum_{ill'} \hat{n}_{il}\, \hat{n}_{\boldsymbol{il'}}$$

$$U = V = 2\ \mathrm{eV}$$

Theoretical model

Hamiltonian

$$\hat{H} = \hat{H}_{TBA} + \hat{H}_U + \hat{H}_{SC}$$

$$\hat{H}_{\mathrm{TBA}} = \sum_{\mathbf{k}ll'\sigma\sigma'} \hat{c}^{\dagger}_{\mathbf{k},l,\sigma}\left(\hat{H}_0 + \cancel{\hat{H}_{\mathrm{SO}}} + \cancel{\hat{H}_{\mathrm{RSO}}}\right)\hat{c}_{\mathbf{k},l',\sigma'}$$

$$\hat{H}_0 = \begin{pmatrix} \xi^{xy}_{\mathbf{k}} & 0 & 0 \\ 0 & \xi^{xz}_{\mathbf{k}} & \epsilon_{h\mathbf{k}} \\ 0 & \epsilon_{h\mathbf{k}} & \xi^{yz}_{\mathbf{k}} \end{pmatrix} \otimes \hat{\sigma}_0$$

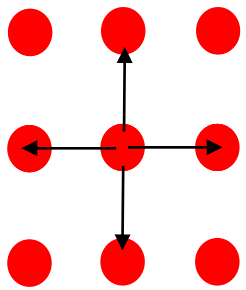
Coulomb repulsion

$$\hat{H}_U = U\sum_{il}\hat{n}_{il\uparrow}\hat{n}_{il\downarrow} + V\sum_{ill'}\hat{n}_{il}\,\hat{n}_{il'}$$

$$U = V = 2\ \mathrm{eV}$$

Superconducting pairing

$$\hat{H}_{SC} = -J\sum_{ijl}\underbrace{\hat{c}^{\dagger}_{il\uparrow}\hat{c}^{\dagger}_{jl\downarrow}\hat{c}_{il\downarrow}\hat{c}_{jl\uparrow}}_{\text{pairing}} - J'\sum_{ijl}\underbrace{\hat{c}^{\dagger}_{il\uparrow}\hat{c}^{\dagger}_{jl\downarrow}\hat{c}_{il'\downarrow}\hat{c}_{jl'\uparrow}}_{\text{pair-hopping}}$$



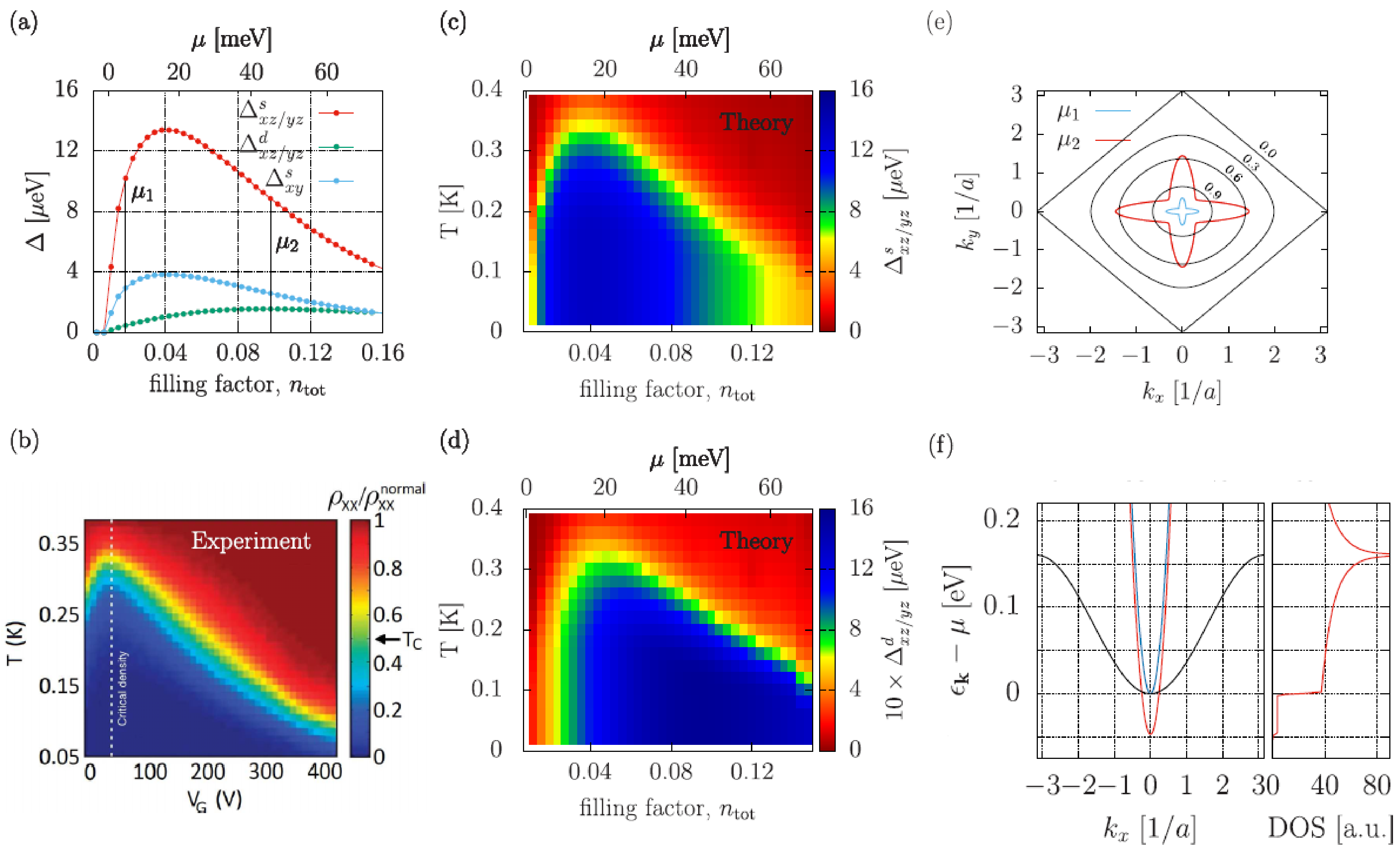
$$\boxed{\begin{aligned} \Delta^{xy}_{\mathbf{k}} &= 4\Delta^{s}_{xy}\gamma^{s}_{\mathbf{k}} \\ \Delta^{xz/yz}_{\mathbf{k}} &= 4\Delta^{s}_{xz/yz}\gamma^{s}_{\mathbf{k}} \pm 4\Delta^{d}_{xz/yz}\alpha_{\mathbf{k}}\gamma^{d}_{\mathbf{k}} \end{aligned}}$$

$$\gamma^{s}_{\mathbf{k}} = (\cos k_x + \cos k_y)/2$$

$$\gamma^{d}_{\mathbf{k}} = (\cos k_x - \cos k_y)/2$$

$$\alpha_{\mathbf{k}} = \frac{\epsilon^{xz}_{\mathbf{k}} - \epsilon^{yz}_{\mathbf{k}}}{\sqrt{\left(\epsilon^{xz}_{\mathbf{k}} - \epsilon^{yz}_{\mathbf{k}}\right)^2 + 4\epsilon^2_{h\mathbf{k}}}}$$

Results – dome of the critical temperature



A. Joshua et al., Nat. Commun 3, 1129 (2012)

MZ, P. Wójcik, Phys. Rev. B 102, 085420 (2020)

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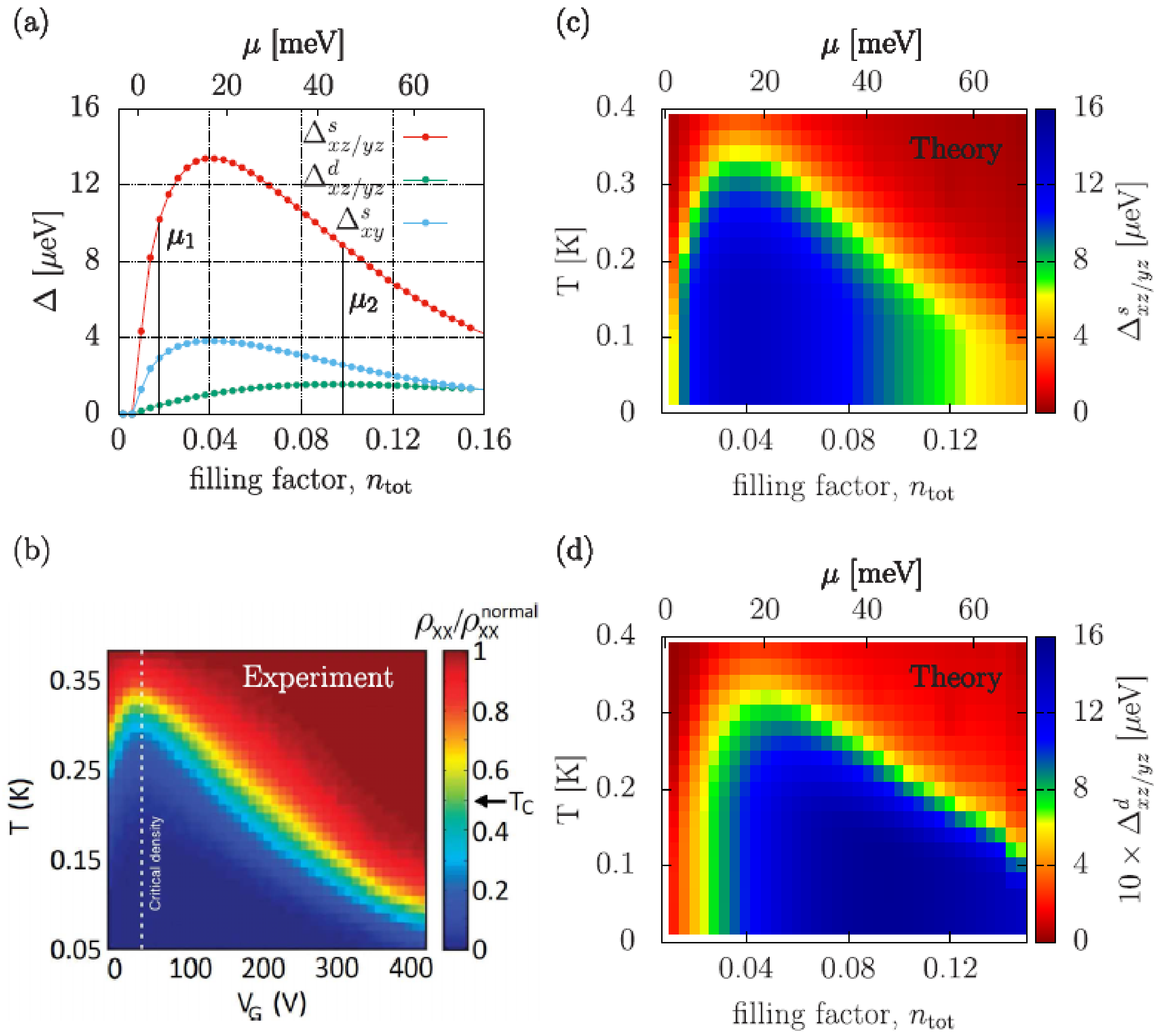
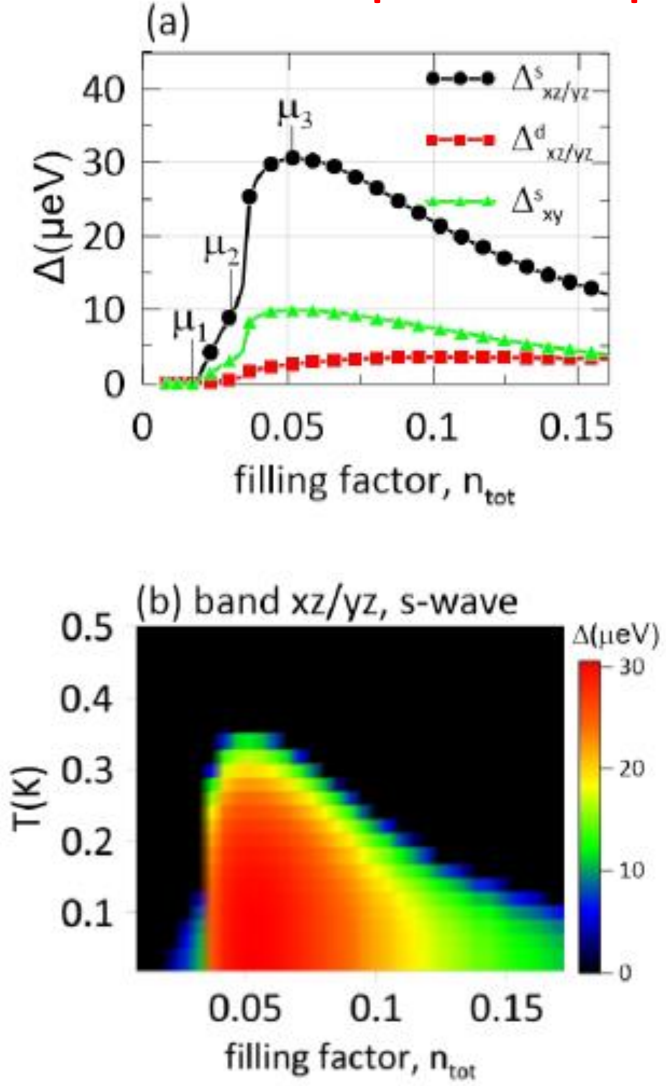


Spin-orbit coupling !!!



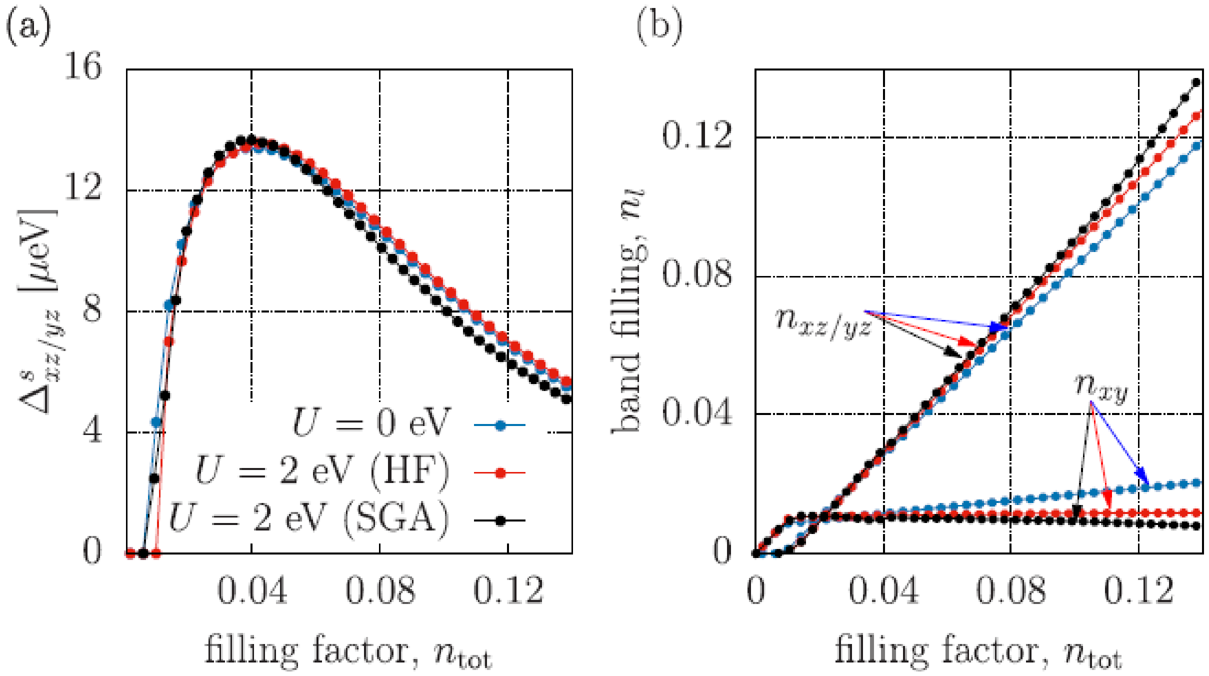
A. Joshua et al., Nat. Commun 3, 1129 (2012)

MZ, P. Wójcik, Phys. Rev. B 102, 085420 (2020)

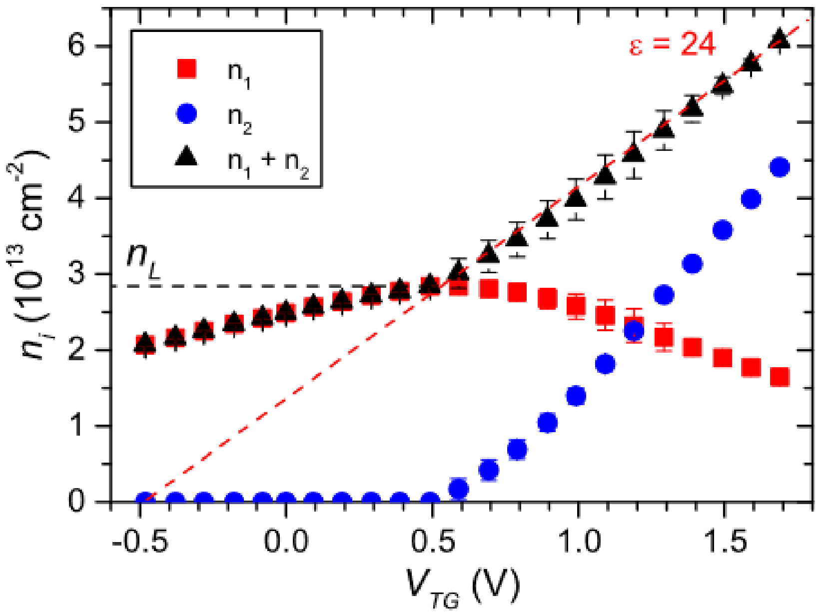
Results – dome of the critical temperature

Coulomb repulsion

$$\hat{H}_{HF} = \ldots + \sum_{\mathbf{k}} \left[\left(\varepsilon_{\mathbf{k}xy} + V n_{xz} + V n_{yz} \right) \hat{n}_{\mathbf{k}xy} \right] + \ldots$$



MZ, P. Wójcik, Phys. Rev. B 102, 085420 (2020)



A. E. M. Smink et al., Phys. Rev. Lett. 118, 106401 (2017)

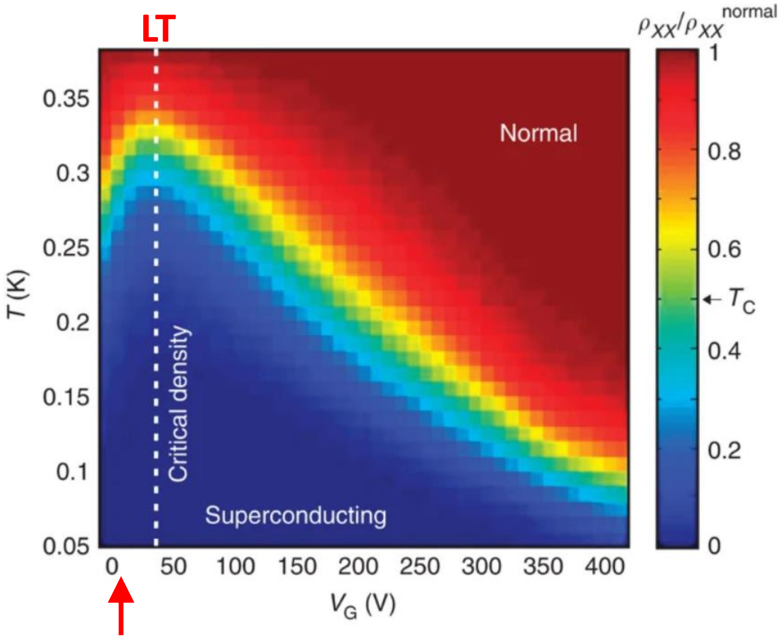
For (001) direction electronic correlations do not play an important role !

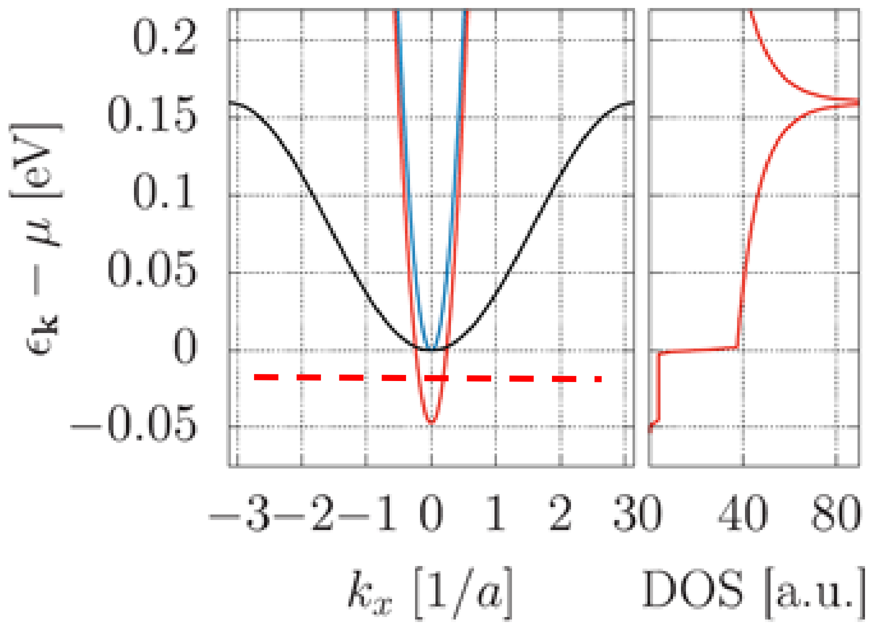
Results – localization of LT versus maximal Tc

Strong pair breaking effect in dirty limit -

T. V. Trevisan et al., Phys. Rev. Lett. 121, 127002 (2018)

A. Joshua et al., Nat. Commun 3, 1129 (2012)





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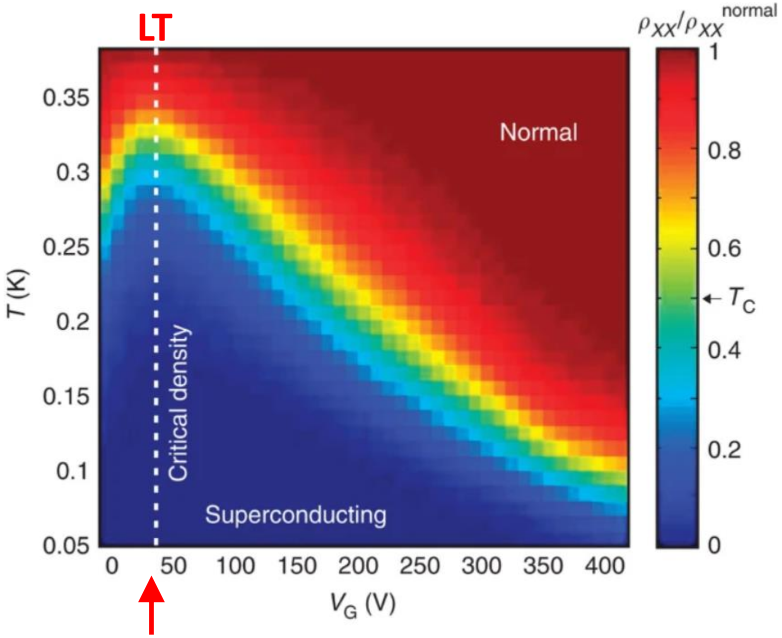
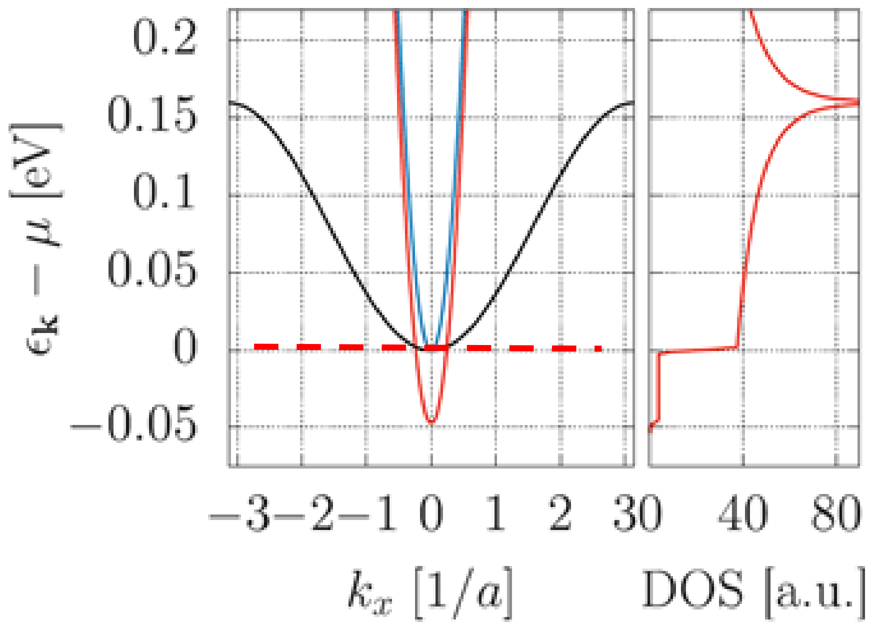
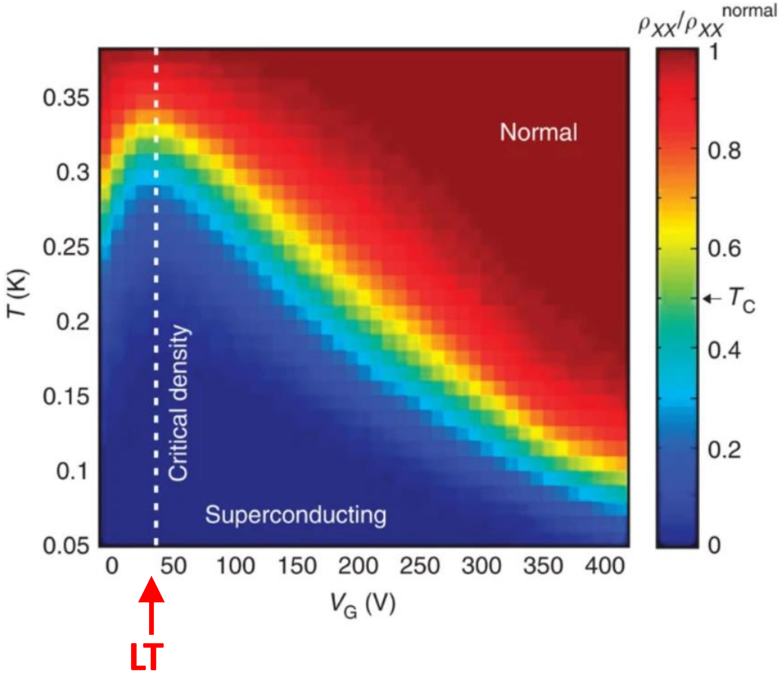


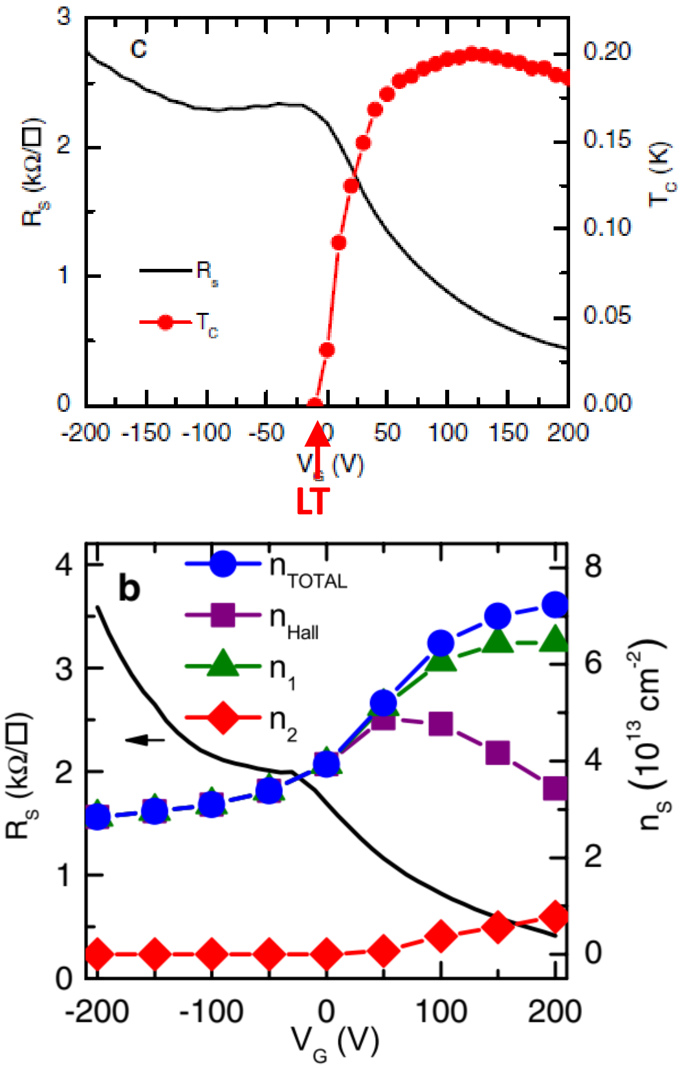


Results – localization of LT versus maximal Tc

J. Biscars et al., Phys. Rev. Lett. 108, 247004 (2012)

A. Joshua et al., Nat. Commun 3, 1129 (2012)





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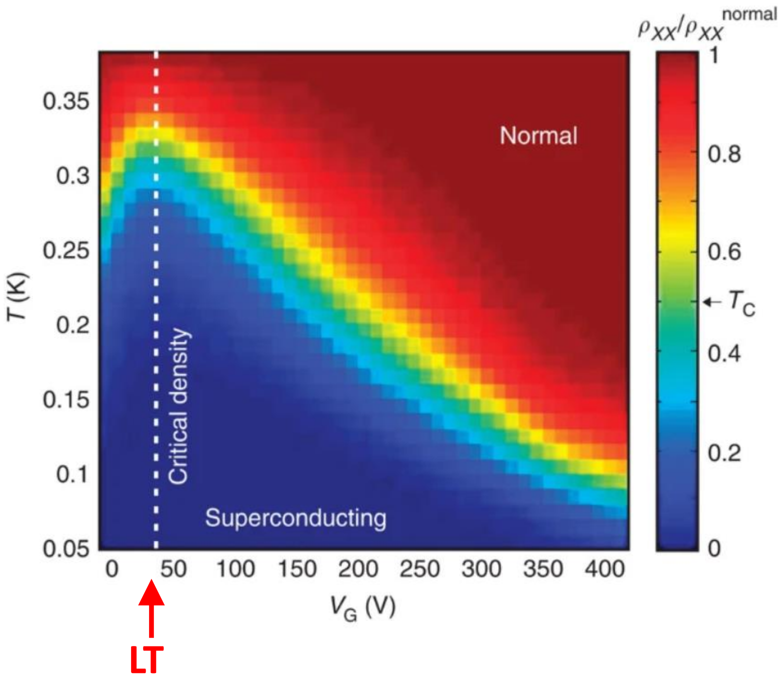
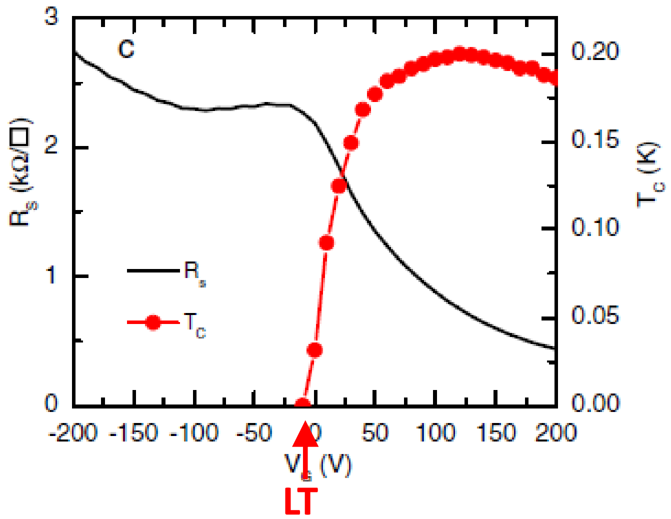
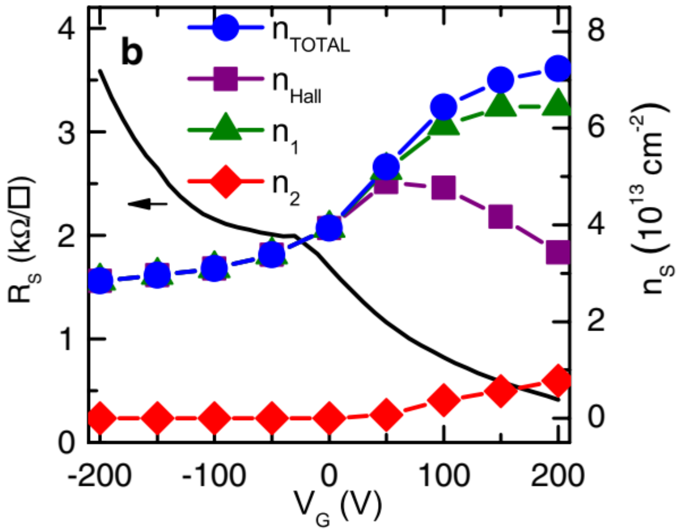
A. Joshua et al., Nat. Commun 3, 1129 (2012)

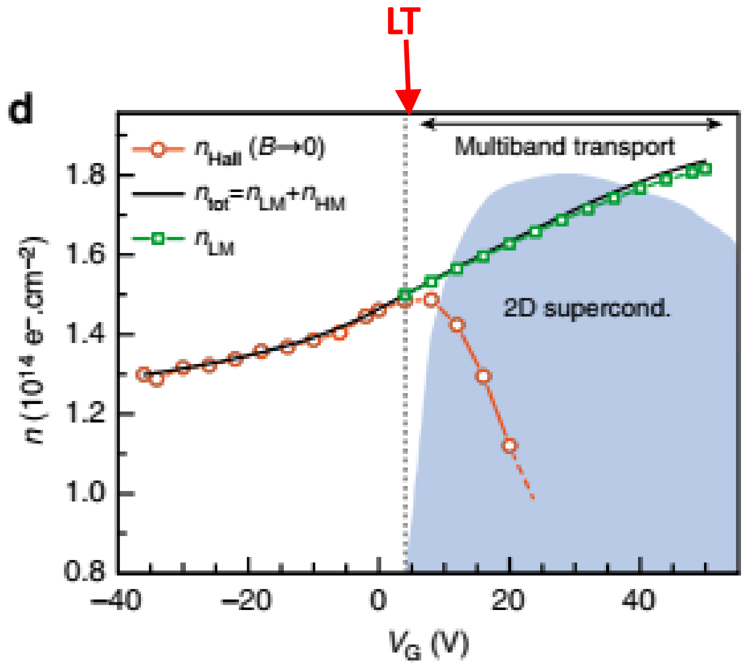


J. Biscars et al., Phys. Rev. Lett. 108, 247004 (2012)





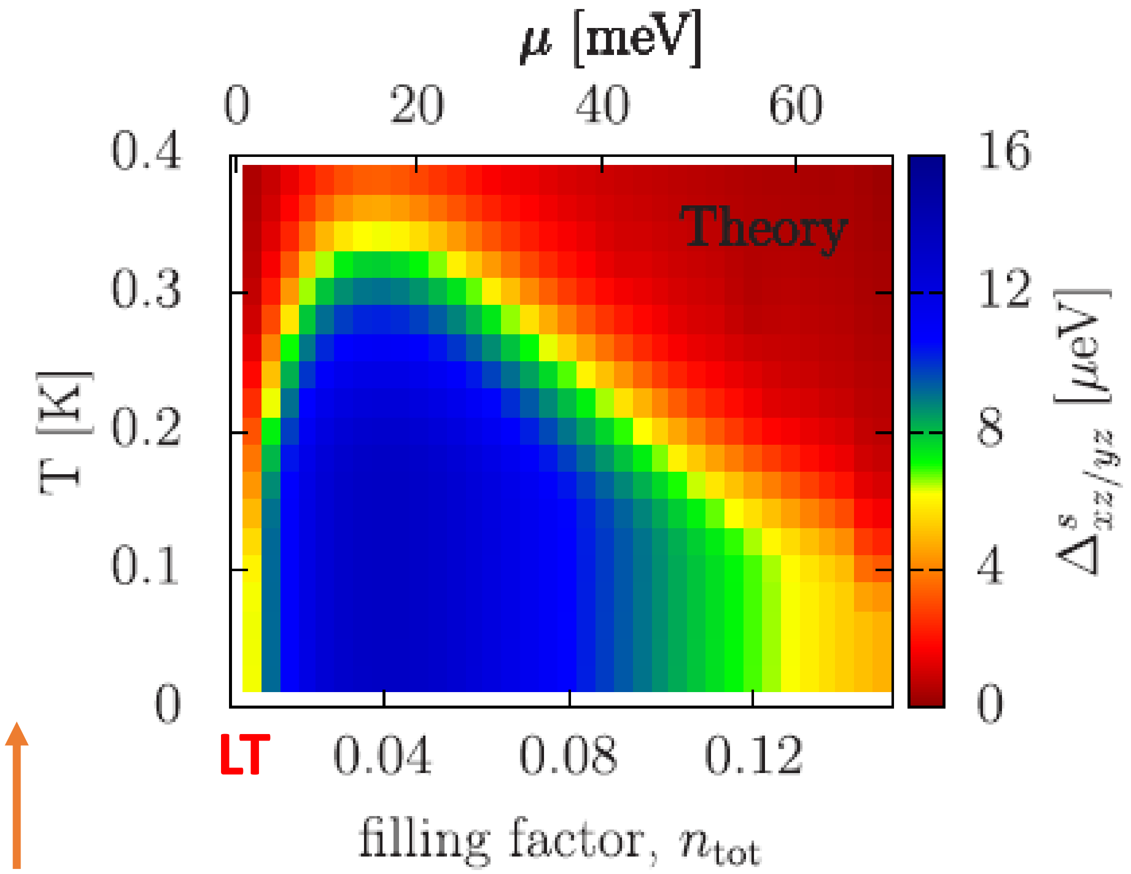
„This suggests that the emergence of the superconducting phase is mainly related to the filling of dxz/dyz bands, whose high density of states is favorable to superconductivity.„

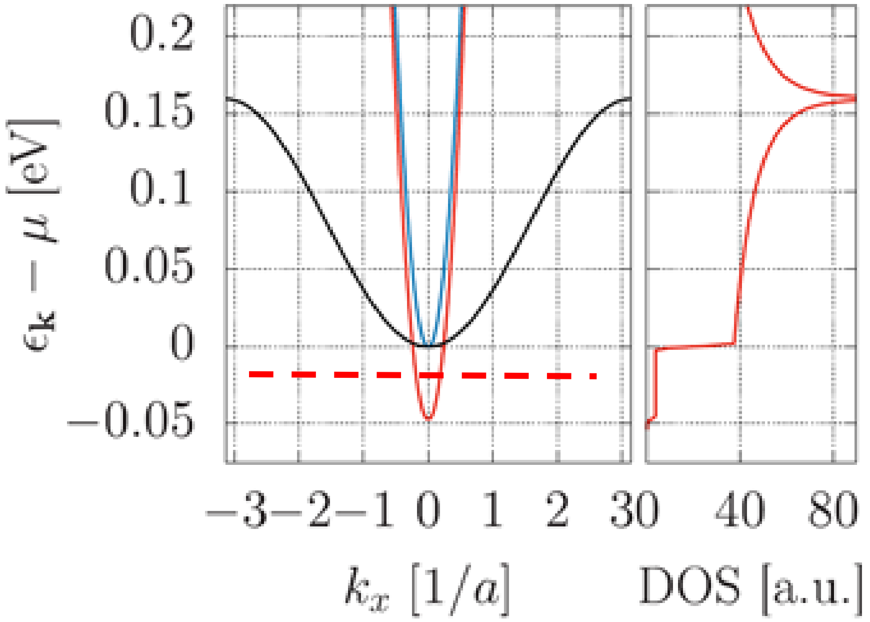


G. Singh et al., Nat Comm. 9, 407 (2018)

Results – localization of LT versus maximal Tc

Model based on the extended s-wave symmetry of the gap.





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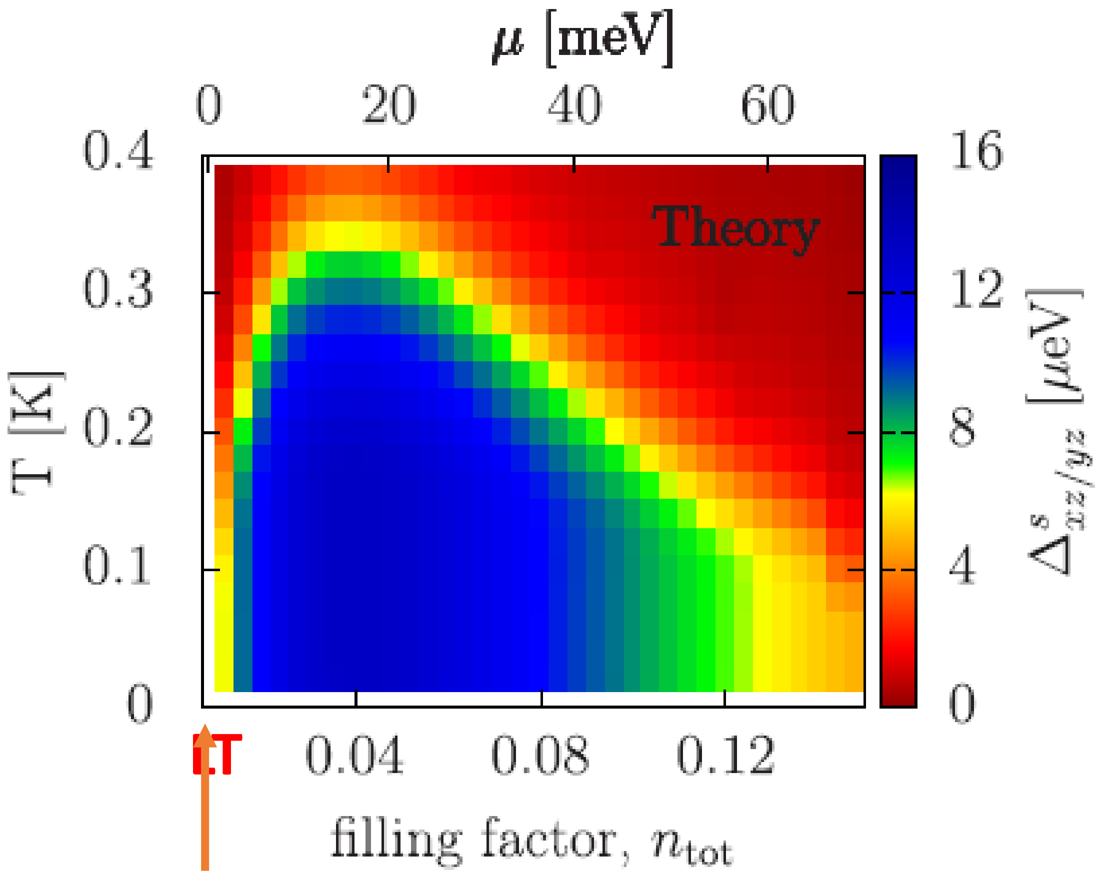

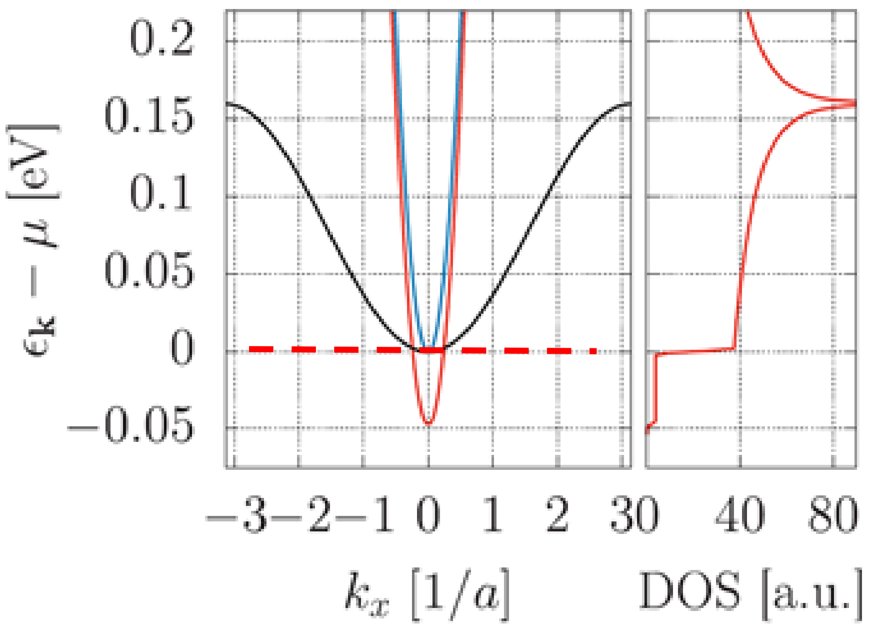

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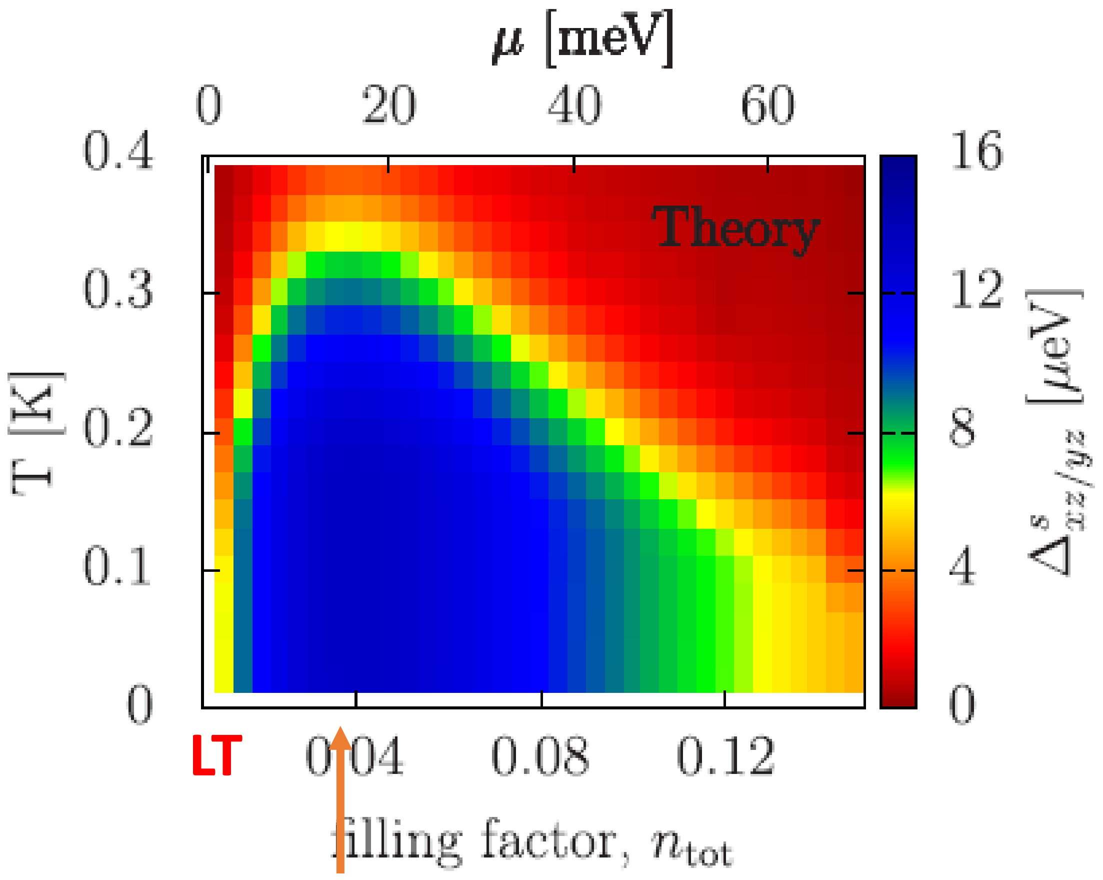
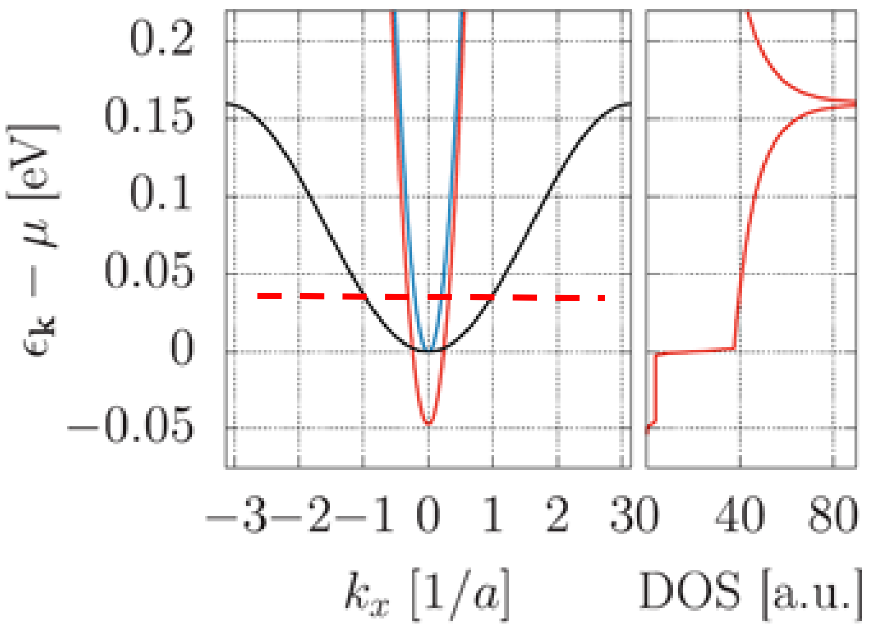


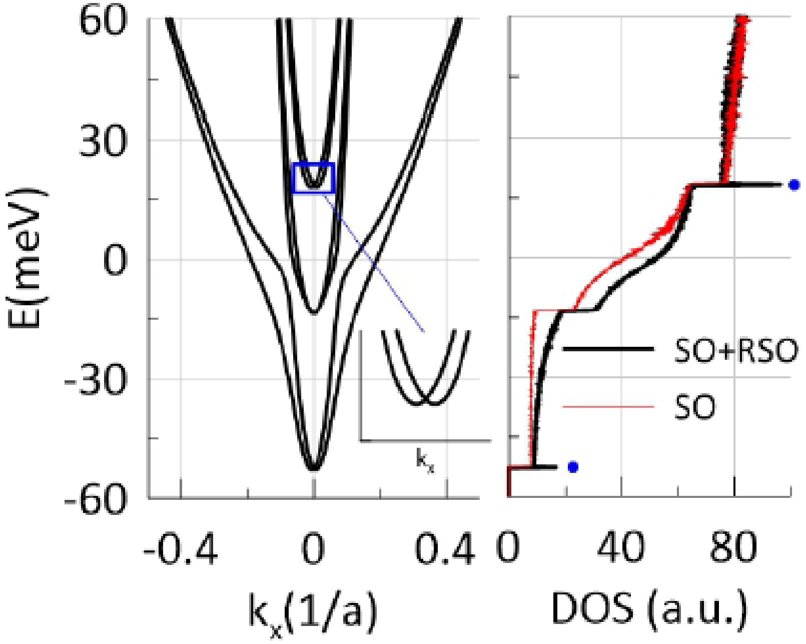


Effect of the spin-orbit interaction

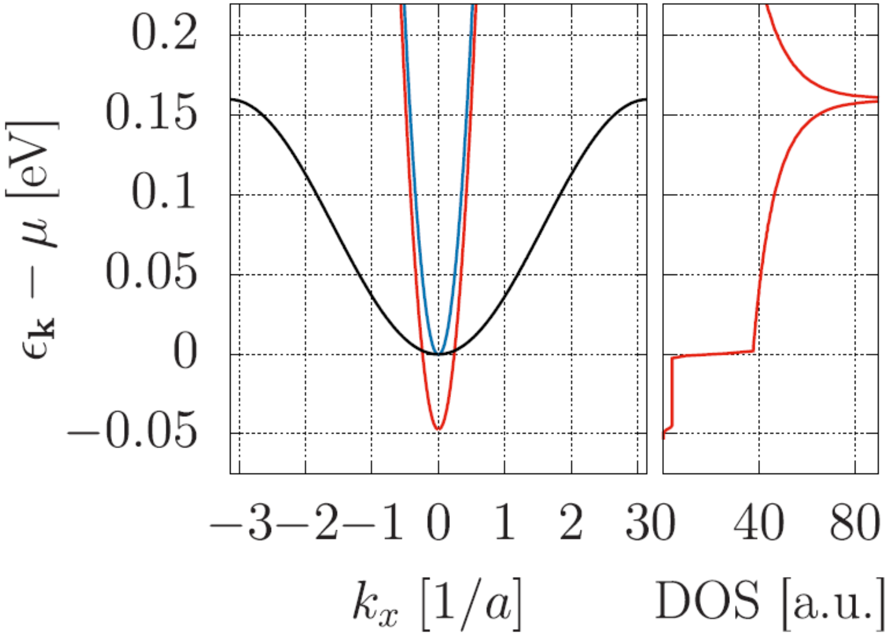
$$\hat{H}_{\mathrm{TBA}} = \sum_{\mathbf{k}ll'\sigma\sigma'} \hat{c}^{\dagger}_{\mathbf{k},l,\sigma} \left(\hat{H}_0 + \cancel{\hat{H}_{\mathrm{SO}}} + \cancel{\hat{H}_{\mathrm{RSO}}}\right)\hat{c}_{\mathbf{k},l',\sigma'}$$

$$\hat{H}_{RSO} = \Delta_{RSO} \begin{pmatrix} 0 & i\sin k_y & i\sin k_x \\ -i\sin k_y & 0 & 0 \\ -i\sin k_x & 0 & 0 \end{pmatrix} \otimes \hat{\sigma}_0 \qquad \hat{H}_{SO} = \frac{\Delta_{SO}}{3} \begin{pmatrix} 0 & i\hat{\sigma}_x & -i\hat{\sigma}_y \\ -i\hat{\sigma}_x & 0 & i\hat{\sigma}_z \\ i\hat{\sigma}_y & -i\hat{\sigma}_z & 0 \end{pmatrix}$$

with SOC

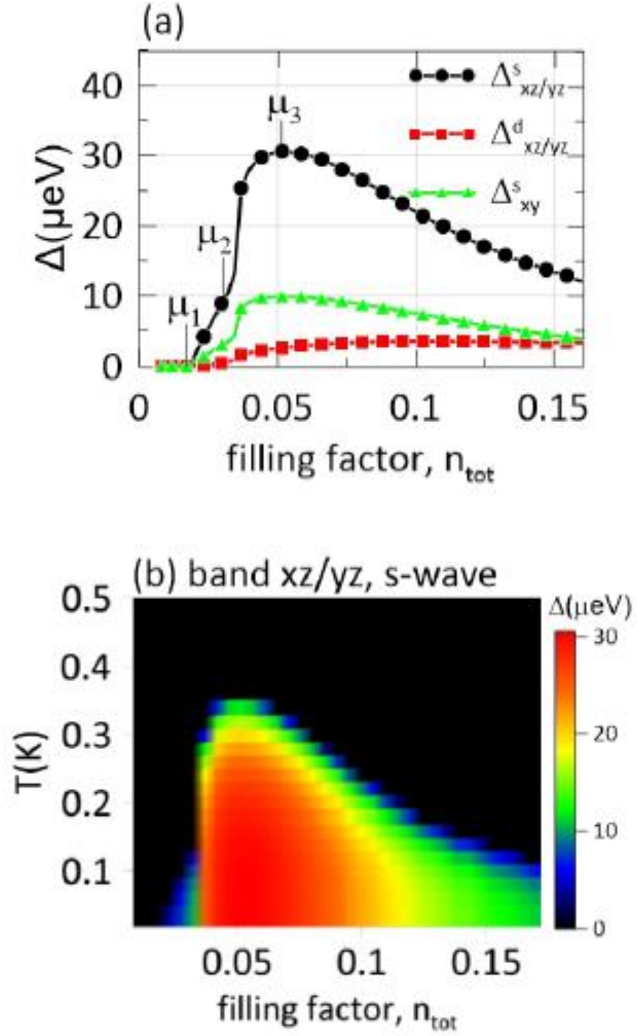


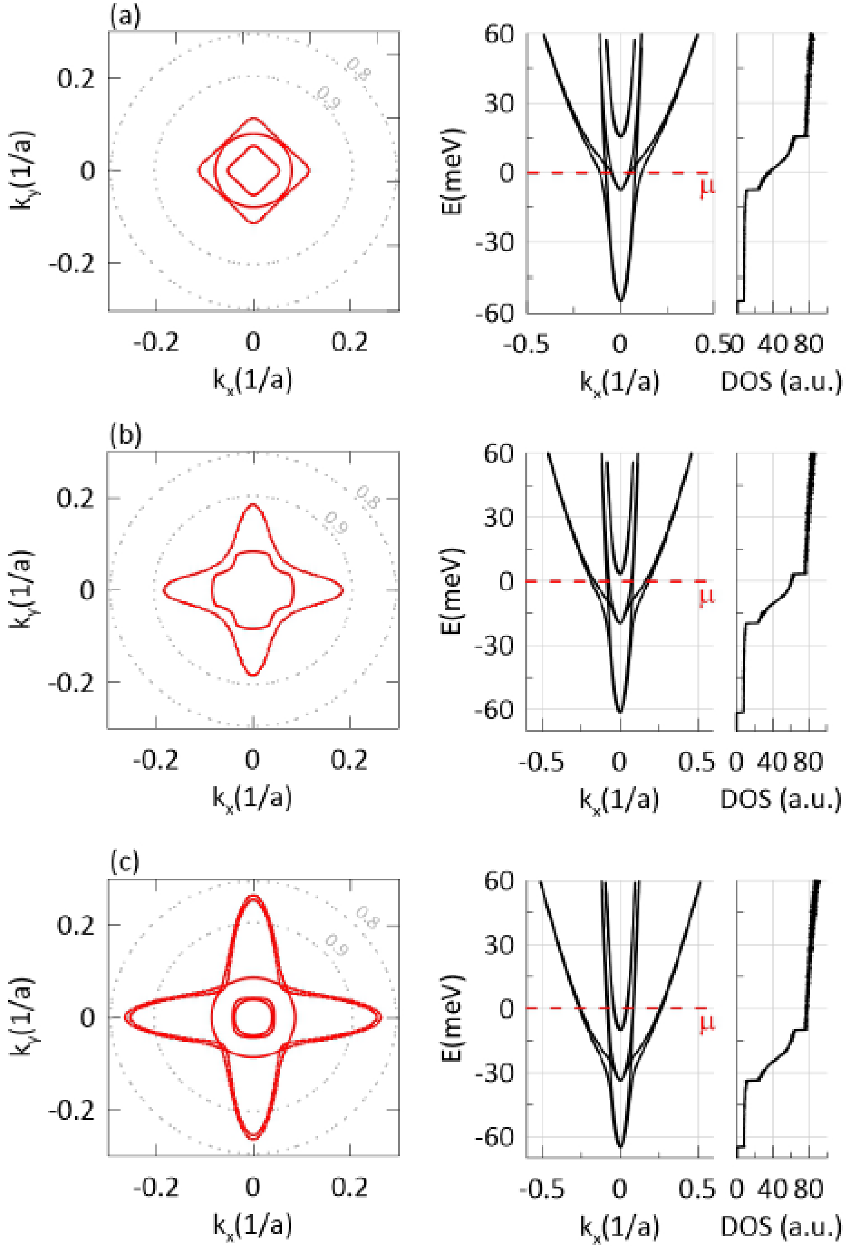
without SOC



Effect of the spin-orbit interaction

$\Delta_{RSO} = \Delta_{SO}$=30 meV



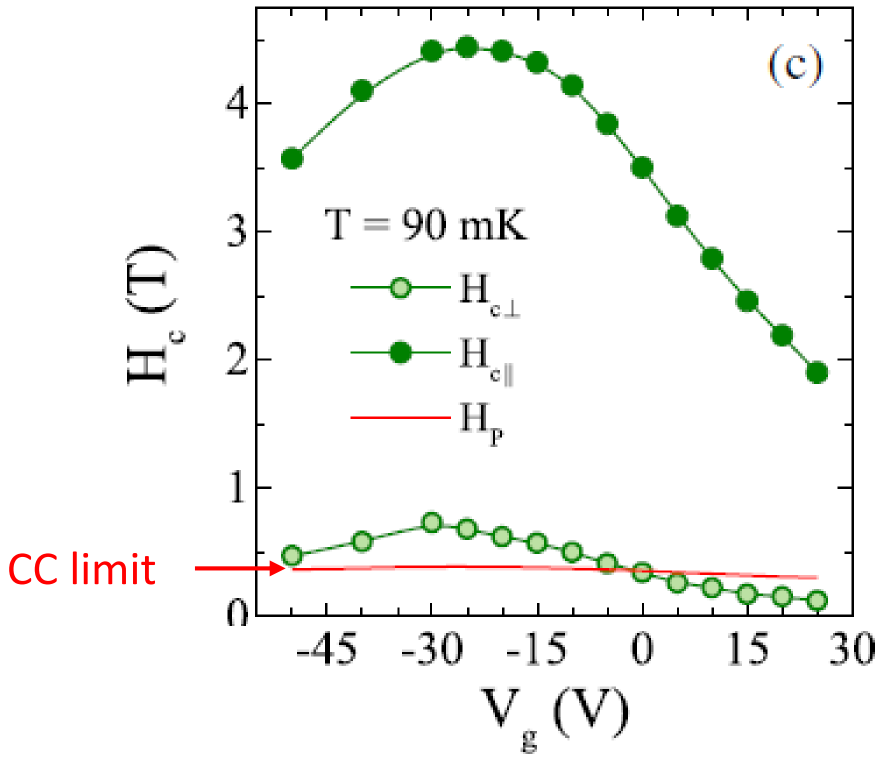


P. Wójcik, MZ, MPN Phys. Rev. B 104, 174501 (2021)

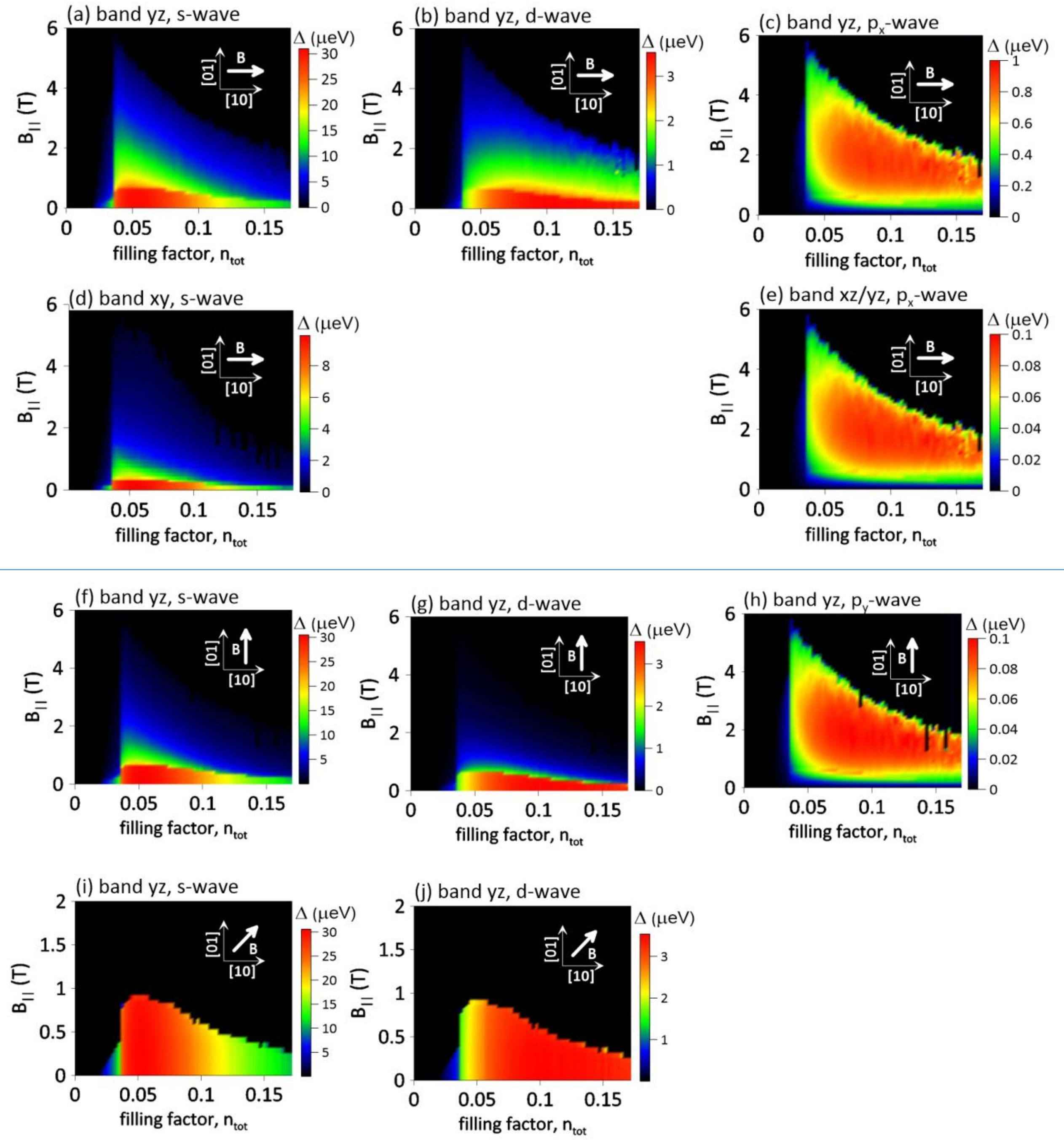
Critical magnetic field

Critical magnetic field beyond CC limit !!!

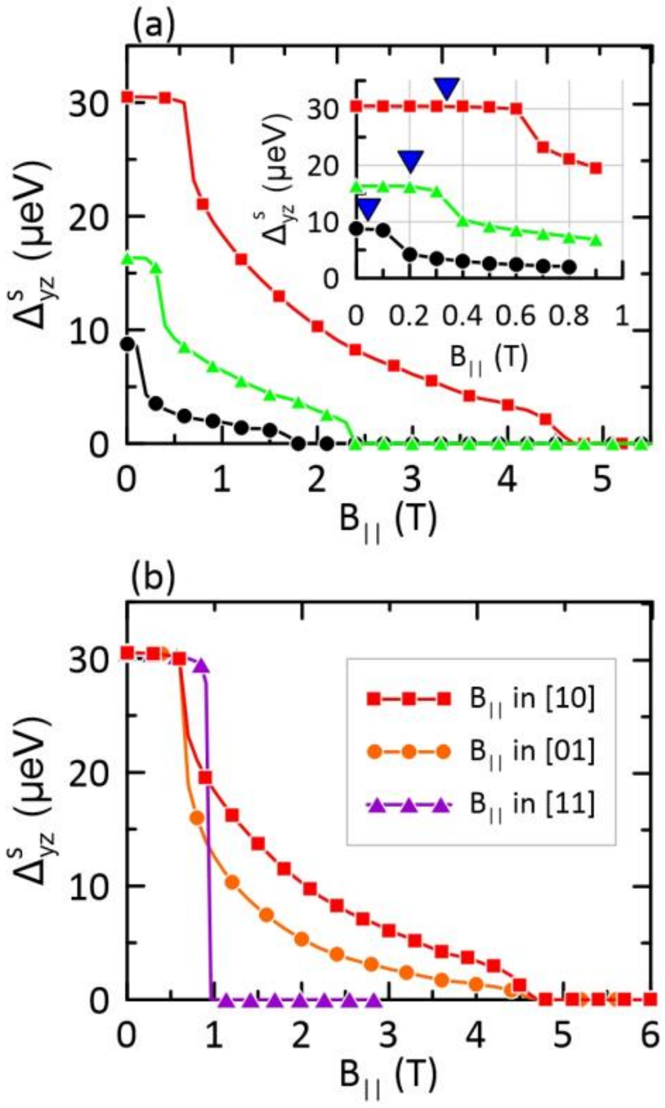
$$B_{c||} = \frac{\Delta}{\sqrt{2} g \mu_B}$$

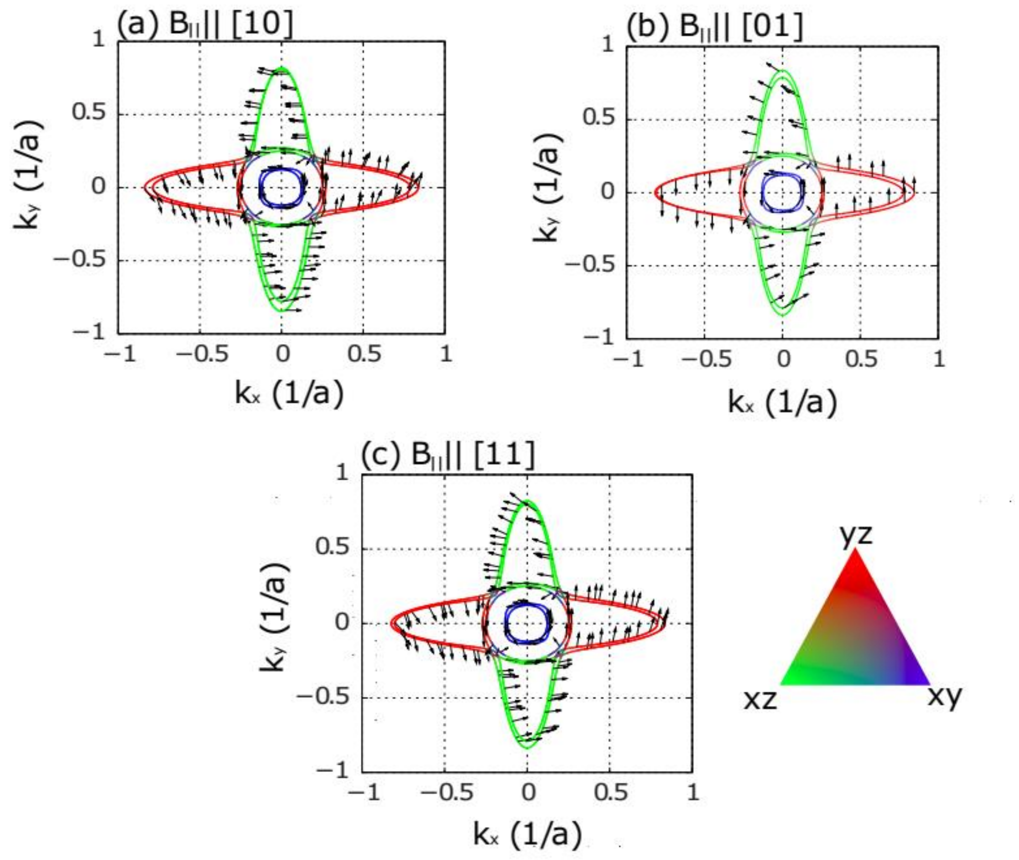


P. K. Rout et al., Phys. Rev. Lett. 119, 237002 (2017)



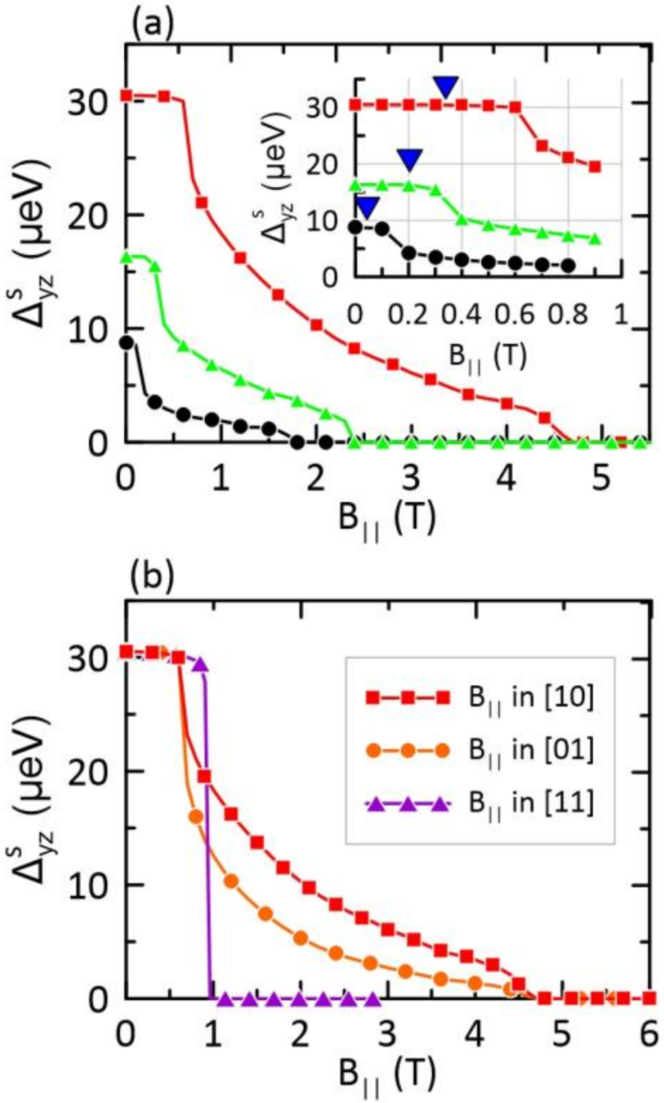
Critical magnetic field

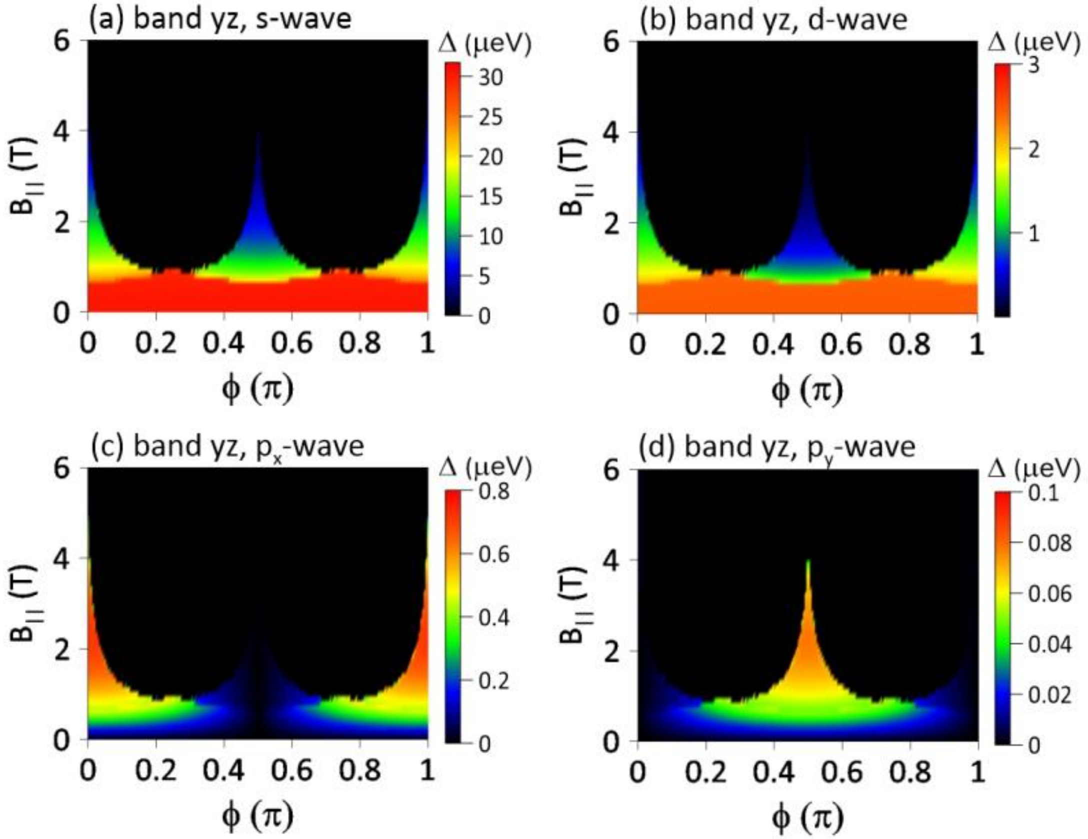




Long superconducting tail in the presence of spin-orbit interaction.

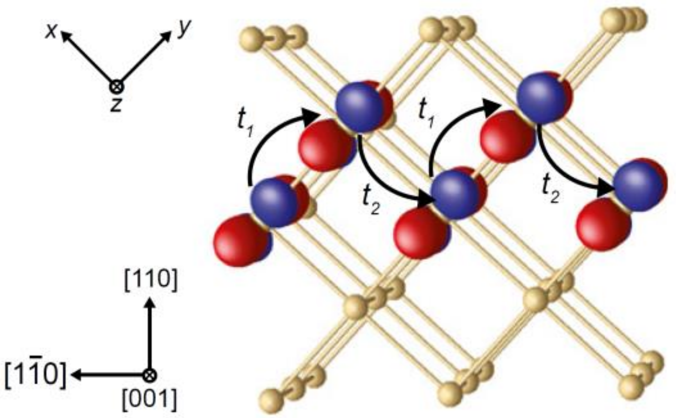
Critical magnetic field



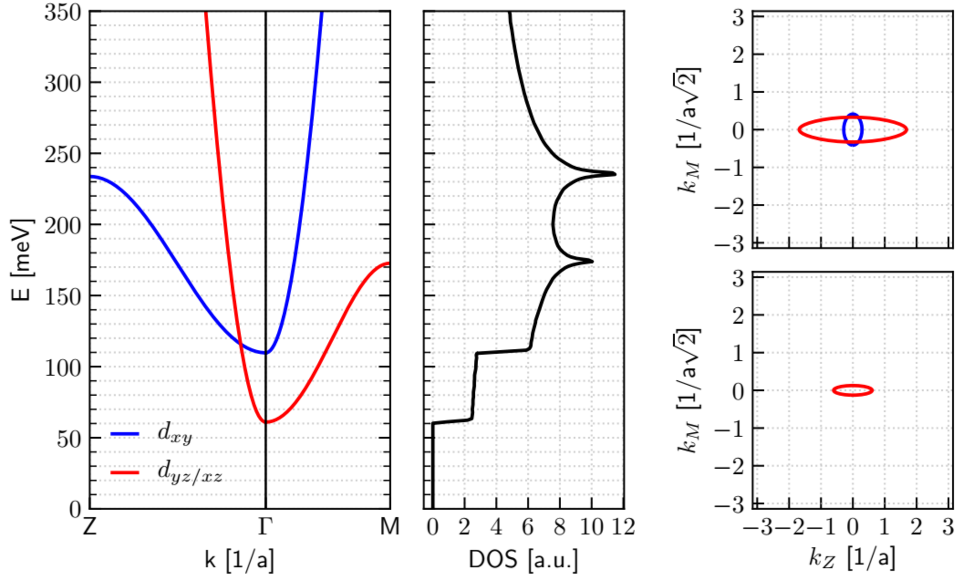


- Critical magnetic field higly beyond CC limit
- Strong anisotropy of critical field

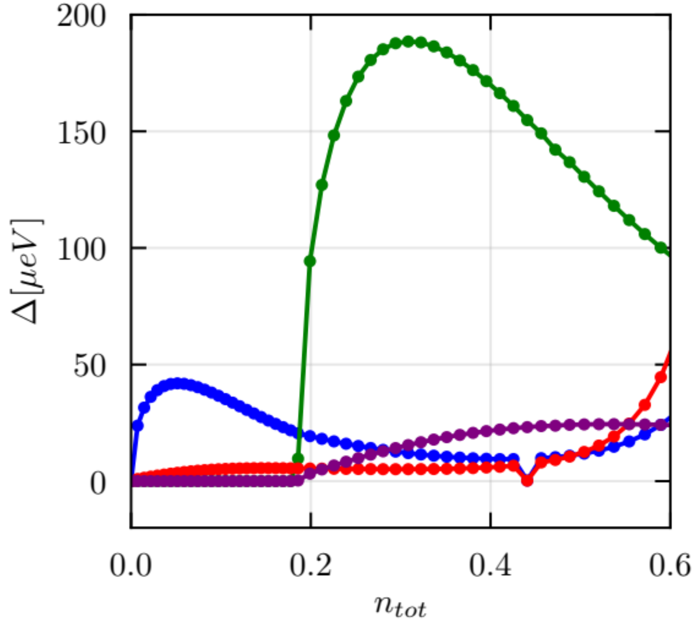
LAO/STO in (110) direction



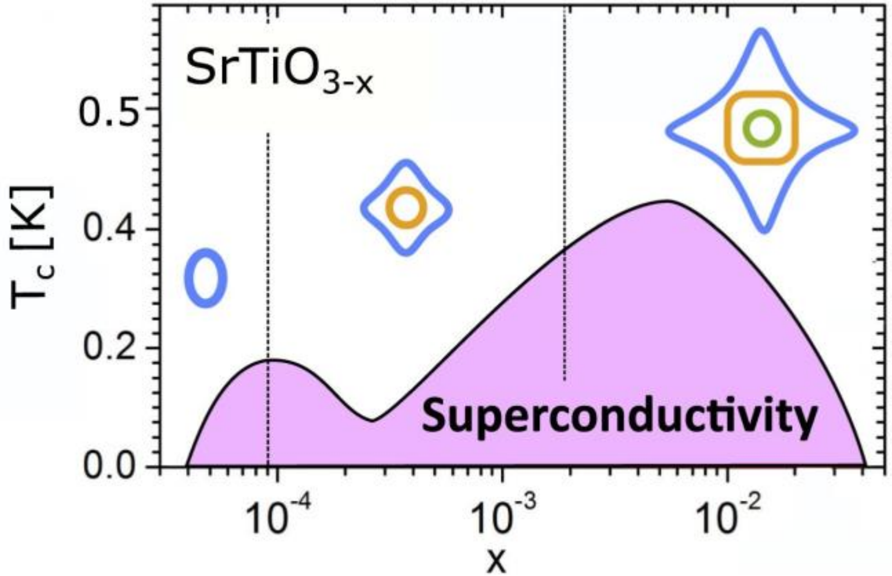
Electronic structure



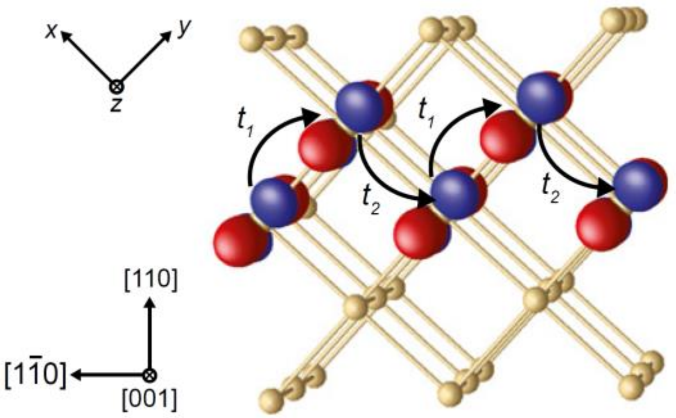
Superconducting gap for low pairing strength



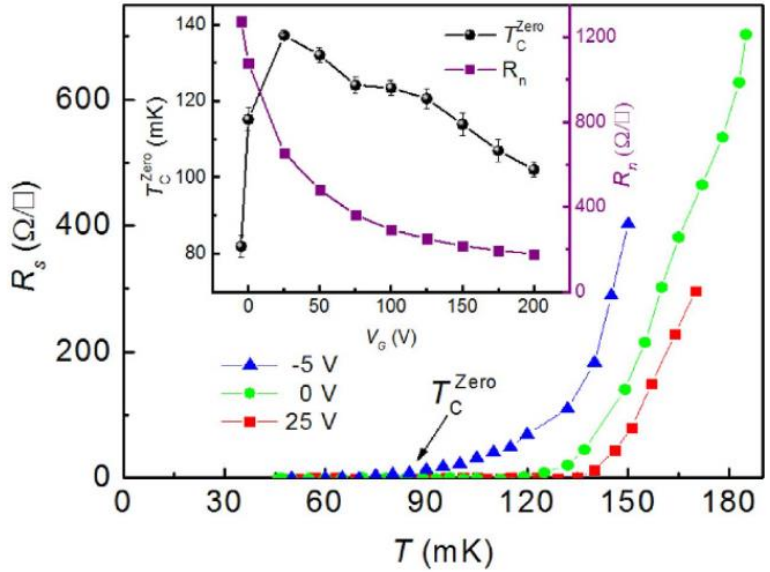
Phase diagram for bulk STO



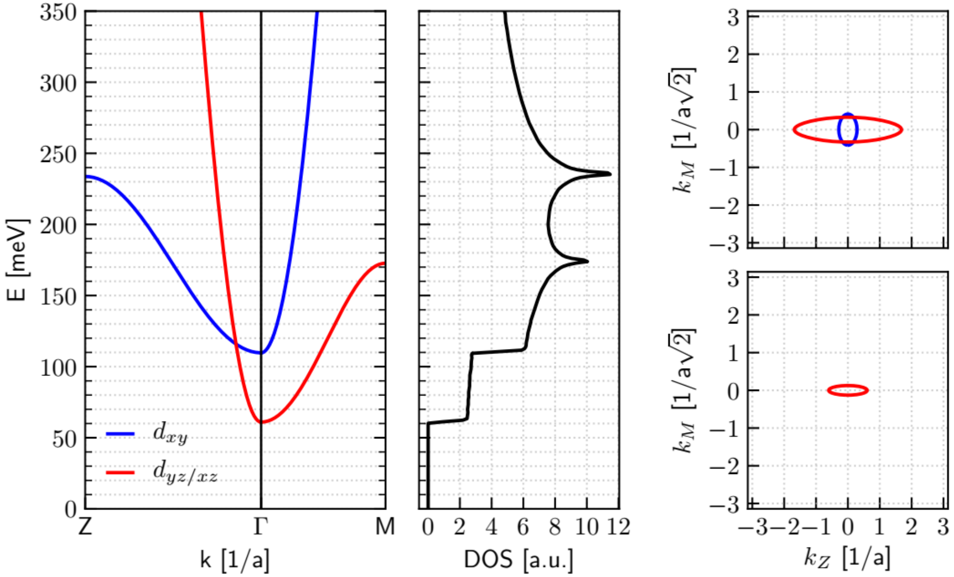
LAO/STO in (110) direction



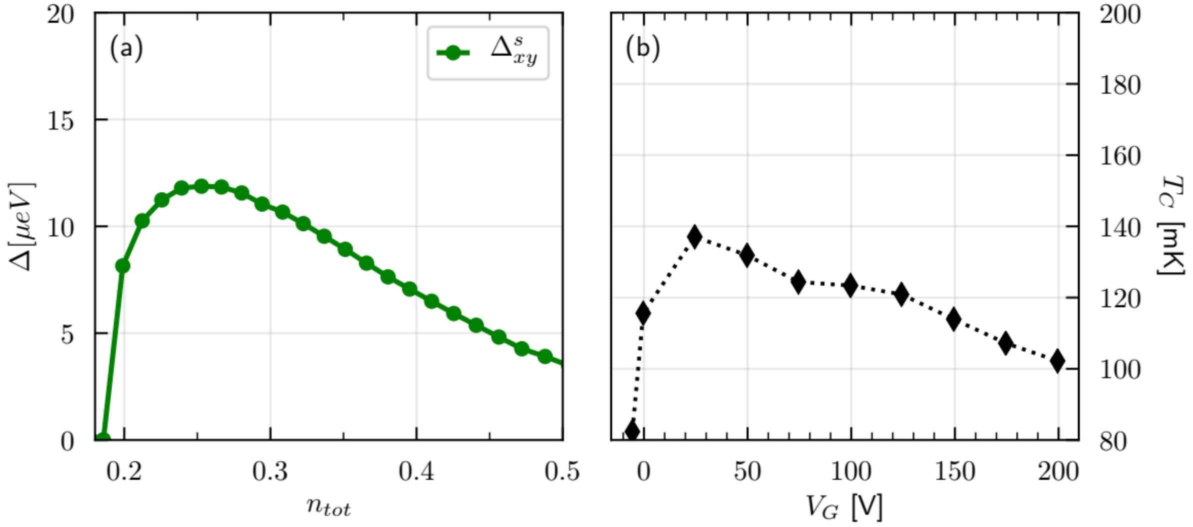
Experiment



Electronic structure



Theory vs. experiment



LAO/STO in (110) direction

ARTICLES
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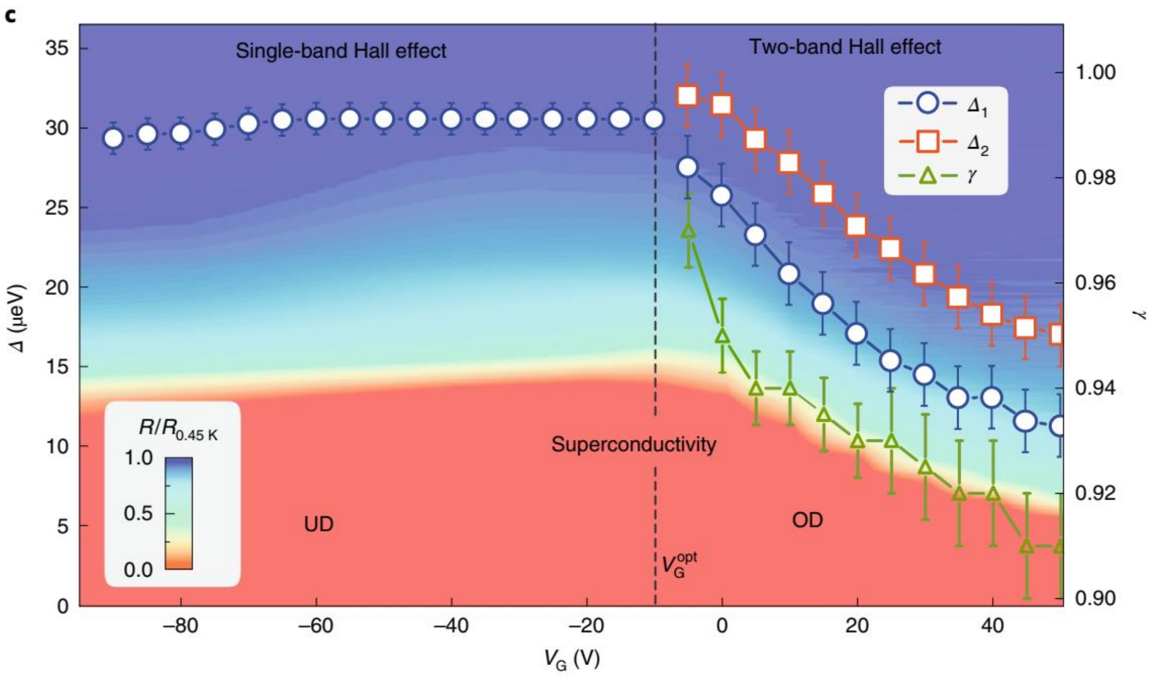
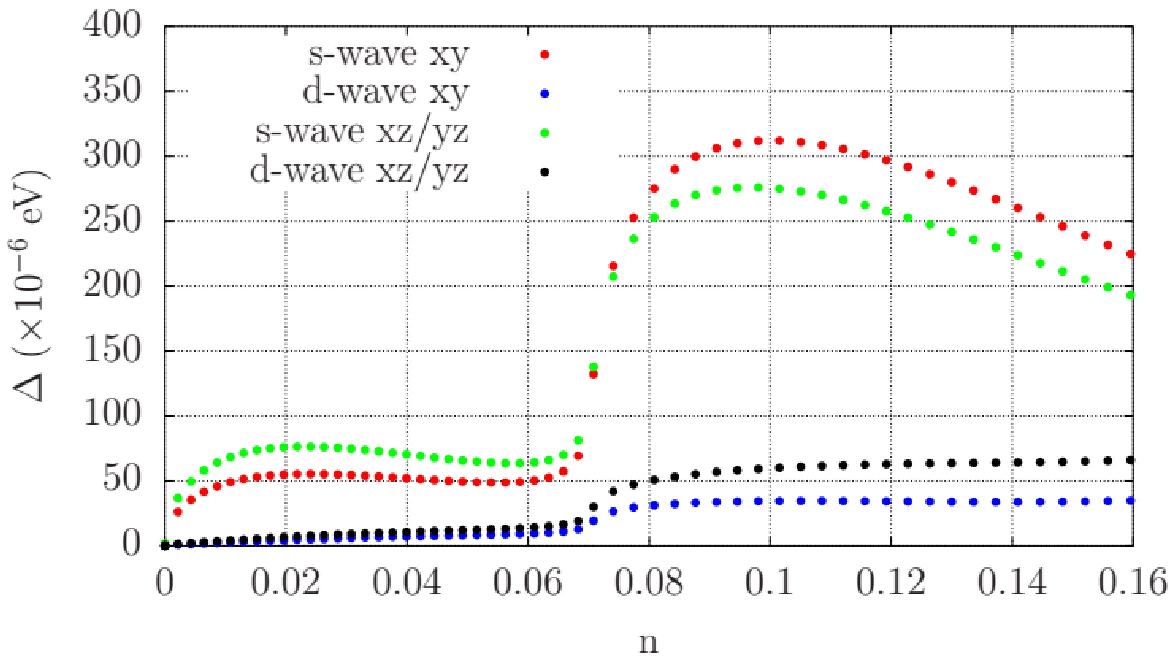
Gap suppression at a Lifshitz transition in a multi-condensate superconductor

G. Singh[1,2], A. Jouan[1,2], G. Herranz[3], M. Scigaj[3], F. Sánchez[3], L. Benfatto[4,5], S. Caprara[4,5], M. Grilli[4,5], G. Saiz[1,2], F. Couëdo[1,2], C. Feuillet-Palma[1,2], J. Lesueur[1,2] and N. Bergeal[1,2*]





Hypothesis: In this experiement the authors see both domes overlapped due to the intersubband Cooper pairs hopping.

Conclusions

1. We have obtained a dome-like behaviour of T_C which is also observed in the experiments. In our approach this effect is due to the *extended s-wave* symmetry of the gap realized within a real-space pairing scenario

2. According to our analysis the lower critical concentration for the apearance of the superconducting phase corresponds to the Lifshitz Transition after which the upper *xz* and *yz* bands start to be populated.

3. According to our analysis the non-monotonic behaviour of the number of electrons occupying the lower band is due to the inter-orbital Coulomb interaction.

4. Neither the electron-electron interaction, nor the spin-orbit coupling modify significantly the shape of the T_C as a function of doping in our model. The SC dome still appears after the inclusion of both factors.

5. **The symmetry of the gap and the pairing mechanism is still open question which need further experimental studies.**