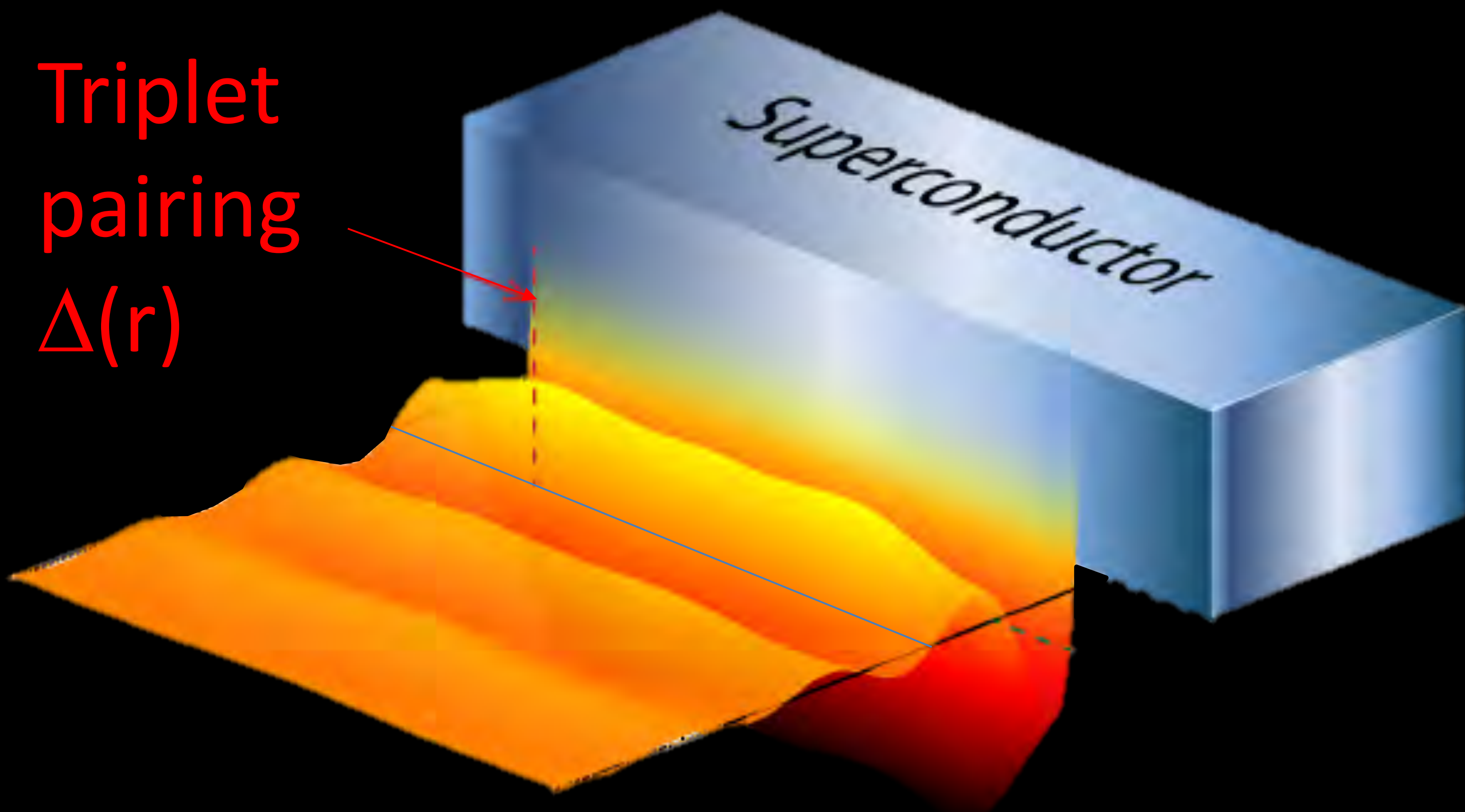
A New Spin on Superconductivity

Amir Yacoby, Harvard University



Unconventional Superconductivity: Finite momentum pairing -Triplet pairing

Breaking of an additional symmetry: translational symmetry; spin symmetry…

1964 – Fulde-Ferrell; Larkin-Ovchinnikov

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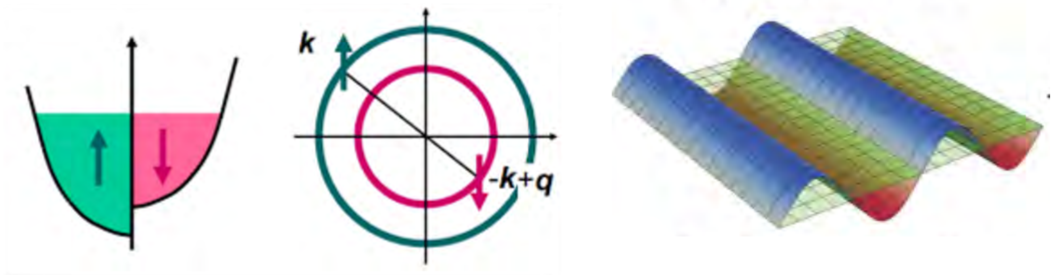
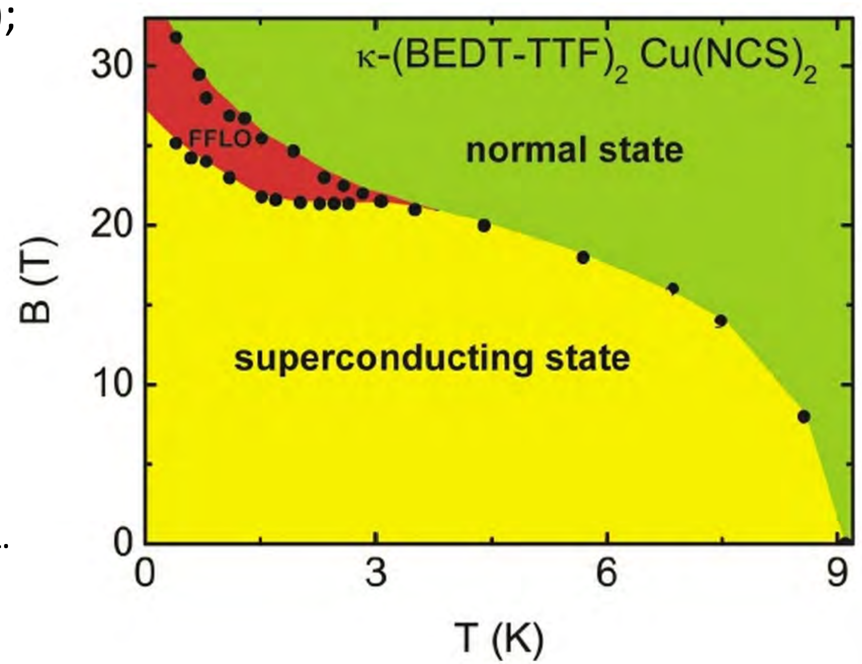


Spatially varying order parameter

P. Fulde, R. A. Ferrell, Phys. Rev. 135, A550 (1964); A. I. Larkin, Y. N. Ovchinnikov, Sov. Phys. JETP 20, 762 (1965).

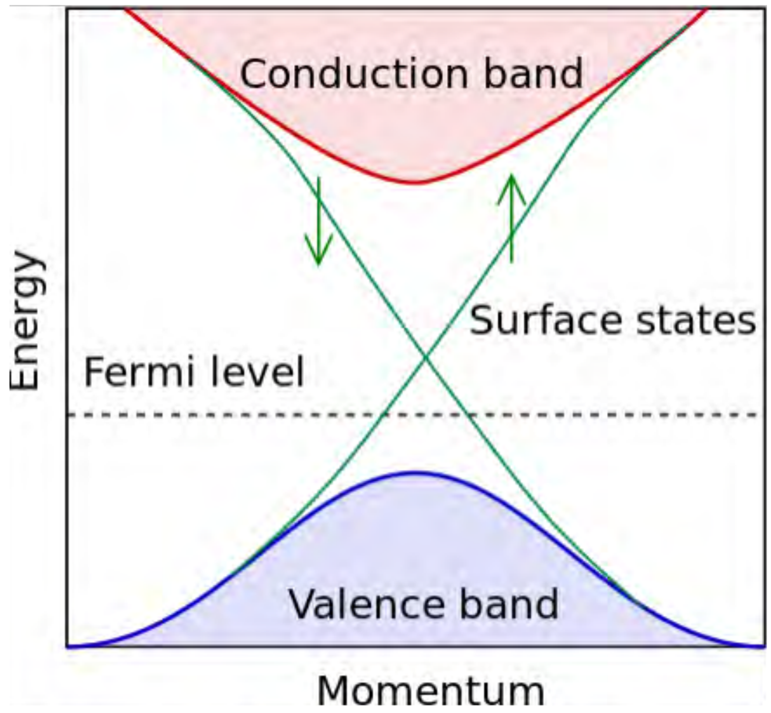


Organic SC:
H. Shimahara, in A.G. Lebed (ed.): The Physics of Organic Superconductors and Conductors, Springer, Berlin (2008)

heavy-fermion material $CeCoIn_5$
Bianchi, A.; Movshovich, R.; Capan, C.; Pagliuso, P.G.; Sarrao, J.L. Phys. Rev. Lett 91, 03’.

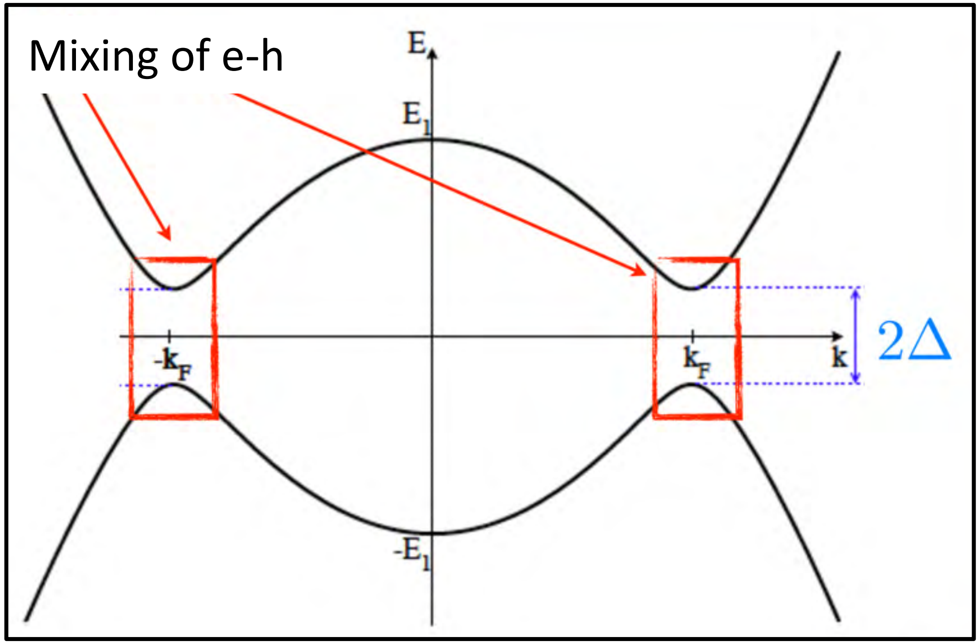
Topological Insulators and Topological Superconductors

Insulators



Topological insulators have electronic surface states

Superconductors



Topological superconductors have Majorana surface states

Bulk Topological Superconductivity

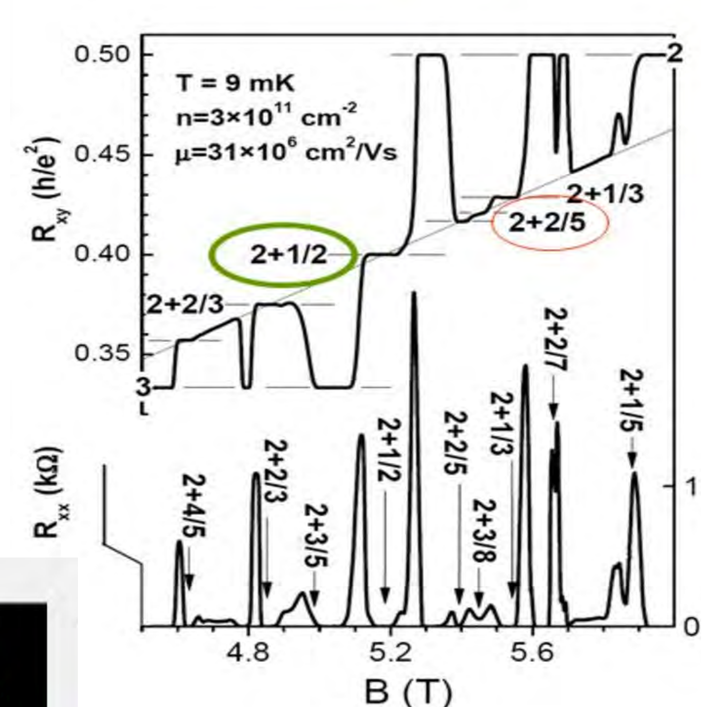
V=5/2 FQHE – Read and Green

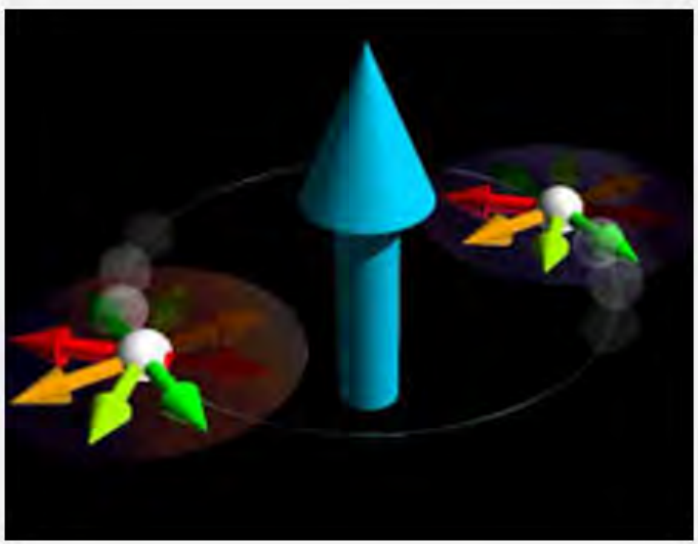
Non Abelian particles – when exchanged wave function changes completely

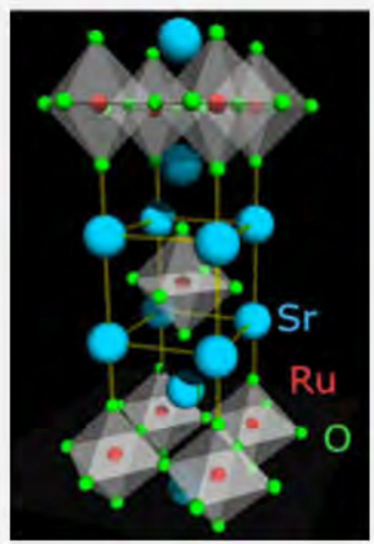
$e^*=e/4$.

M. Heiblum et al, 2010
V. Venkatachalam, AY, Nature 2010

J.S. Xia et al., PRL (2004).





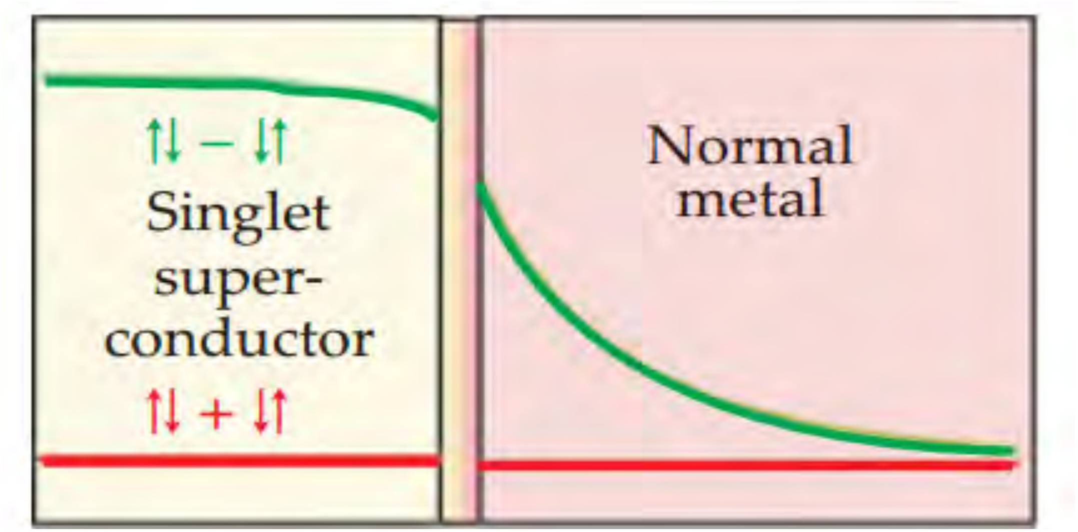


SrRu4O2
Y. Maeno

Unconventional Superconductivity: Finite momentum pairing -Triplet pairing

- Superconductor – Ferromagnetic junctions

See review: Matthias Eschrig, Phys. Today 64(1), 43 (2011)



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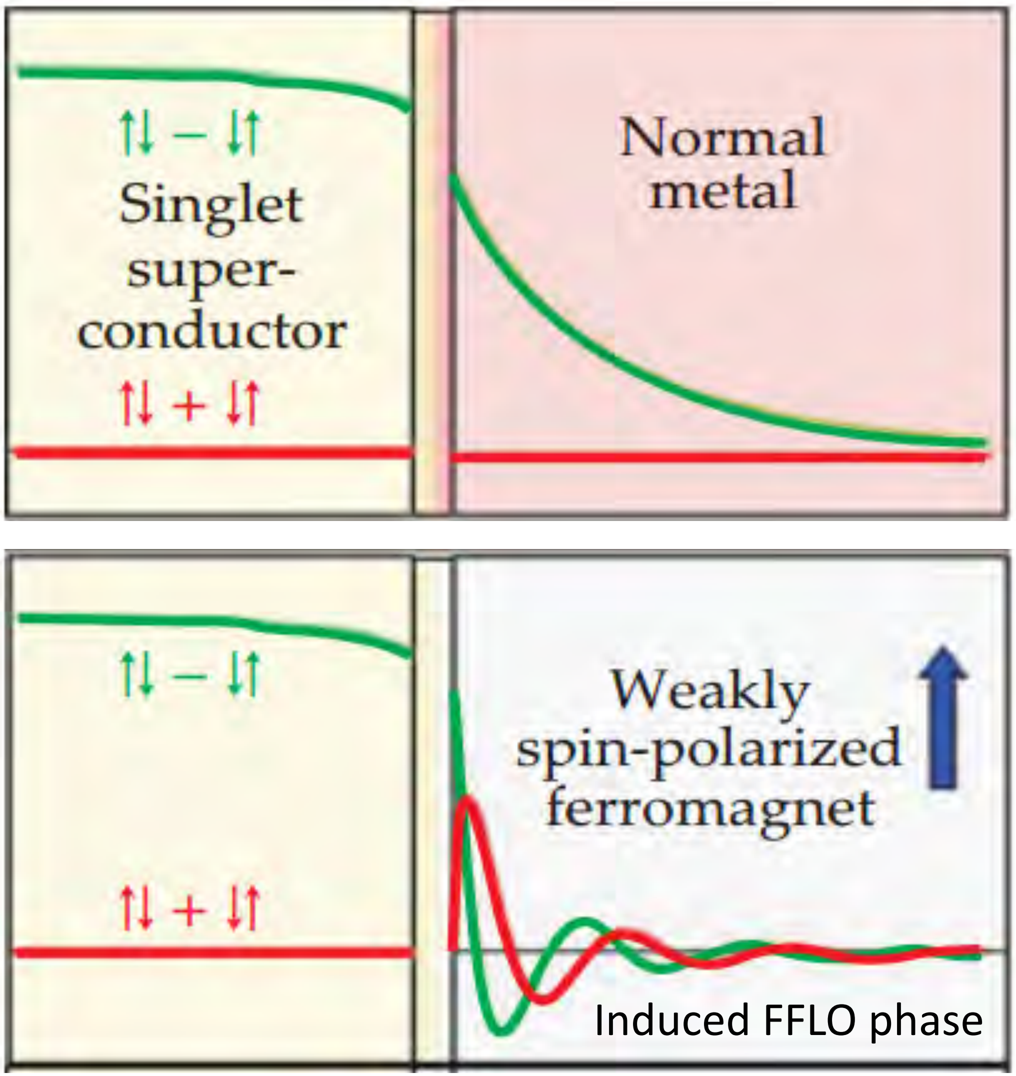


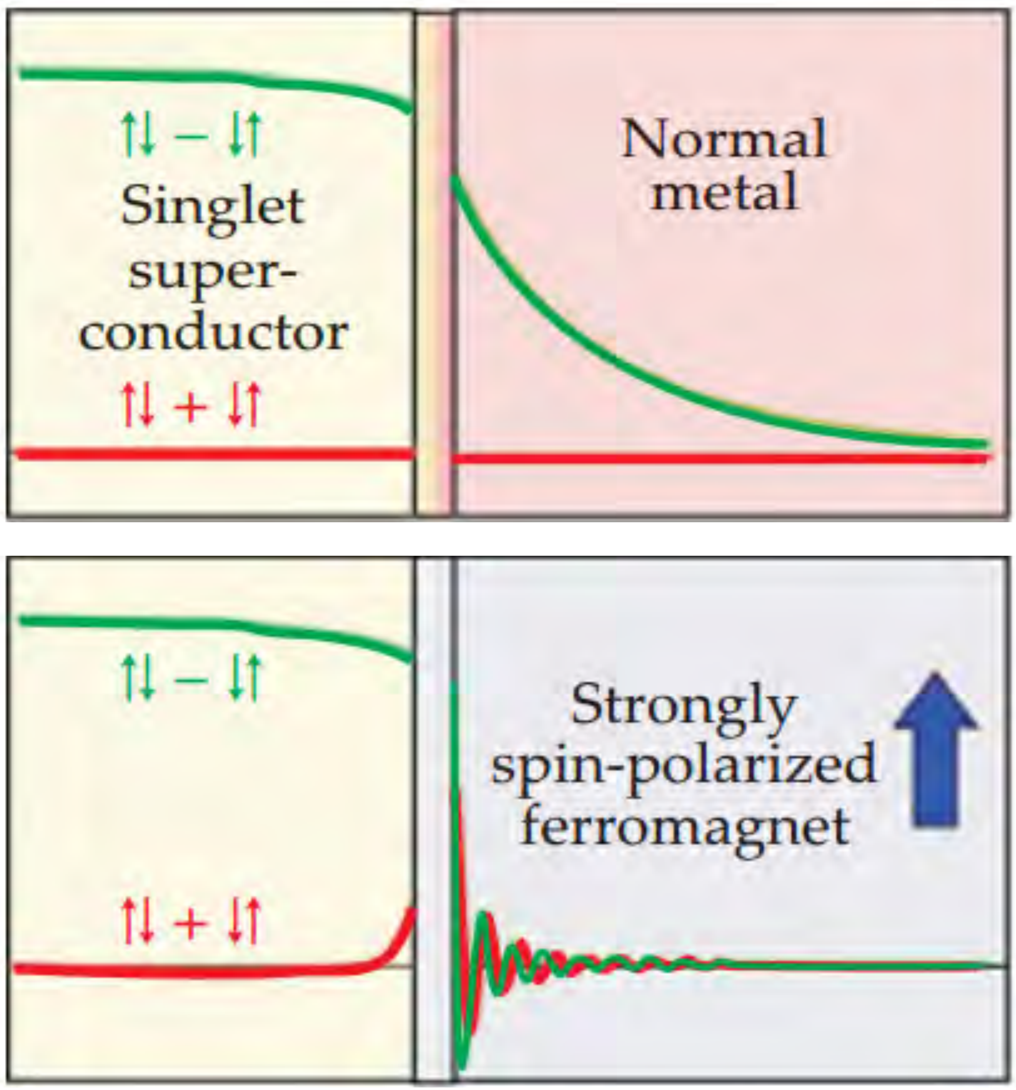
Theory:
Buzdin 1982

Experiments:2001-2
Ryazanov et al;
Golubov et al; Kontos et al and Palevski

Unconventional Superconductivity:
Finite momentum pairing -Triplet pairing

- Superconductor – Ferromagnetic junctions

See review: Matthias Eschrig, Phys. Today 64(1), 43 (2011)



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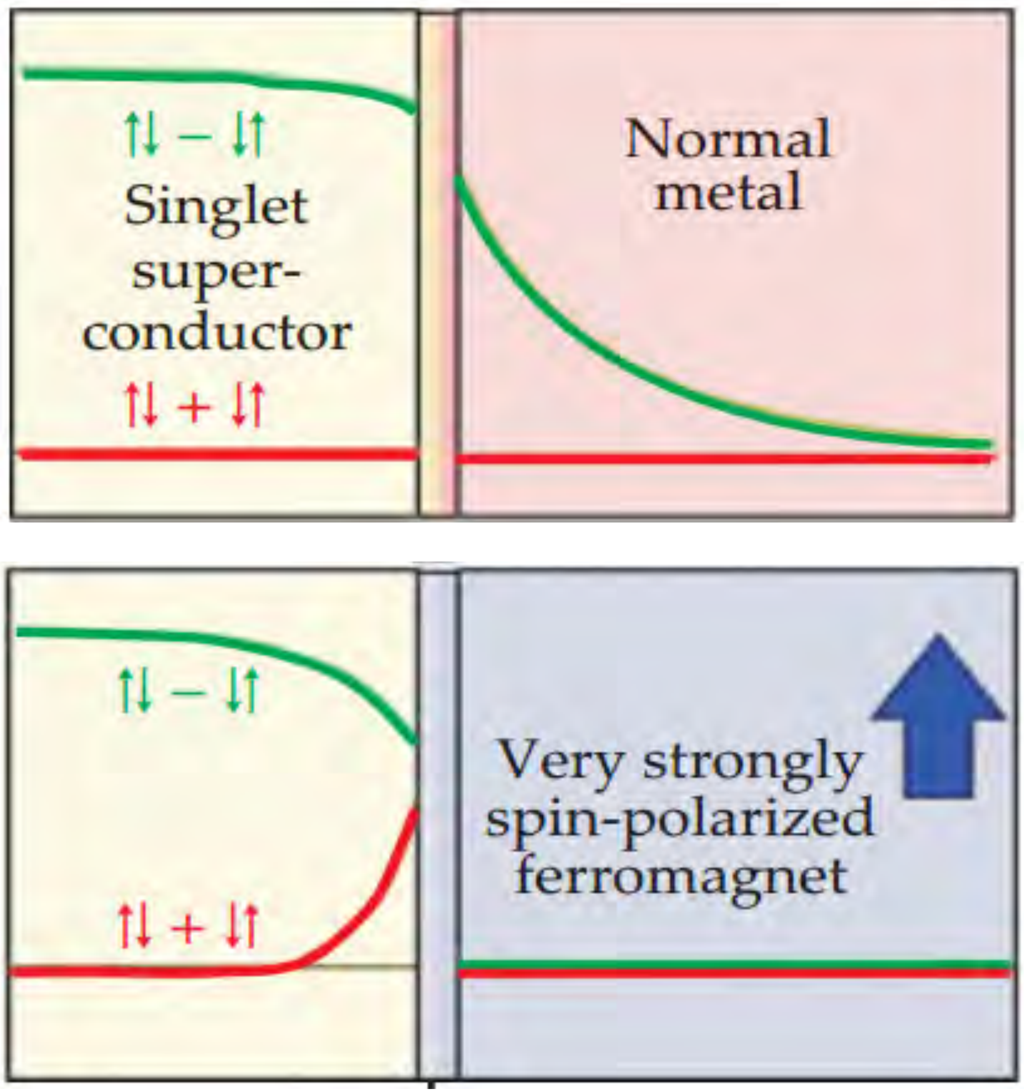
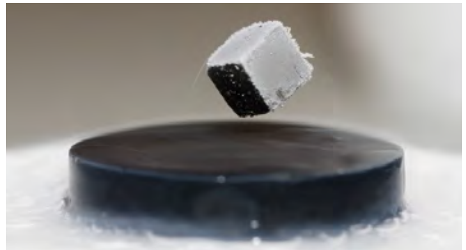
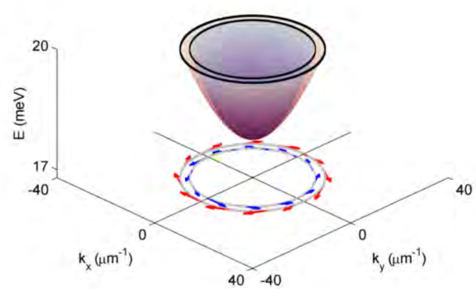


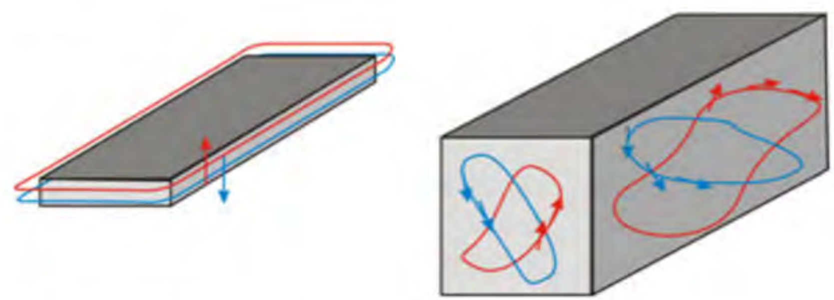
Unconventional Superconductivity from Hybrid Devices

'Conventional Phases'



Materials with strong spin momentum locking

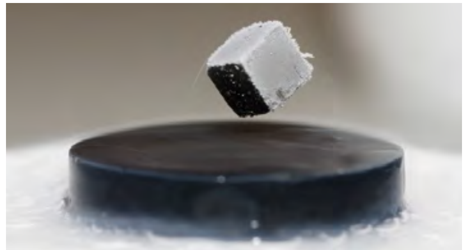




Topological Insulators

Unconventional Superconductivity from Hybrid Devices

'Conventional Phases'



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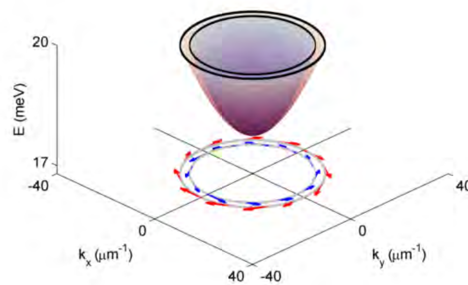
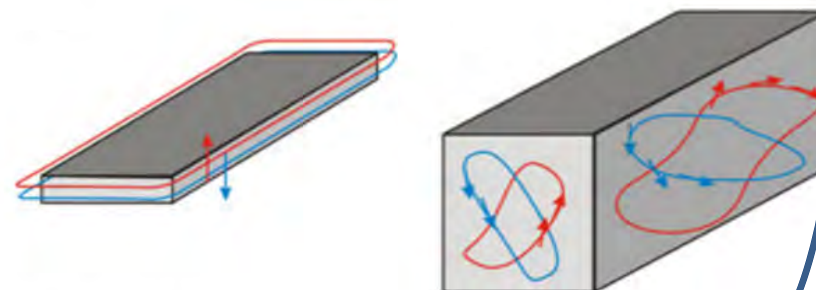
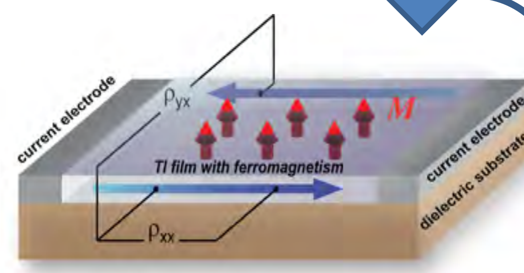




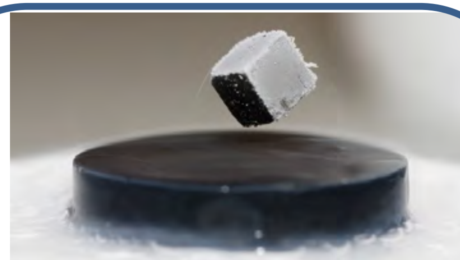
Topological Insulators



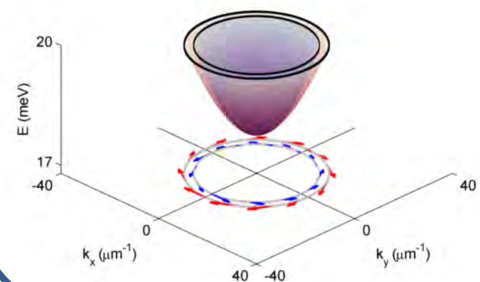
Quantum Anomalous Hall Effects: Dissipationless transport and chiral Majorana modes

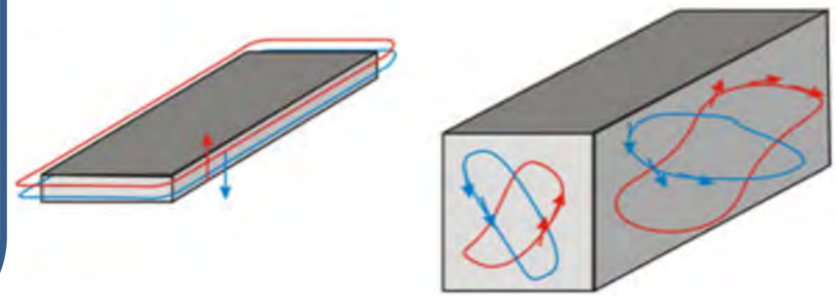
Unconventional Superconductivity from Hybrid Devices

‘Conventional Phases’

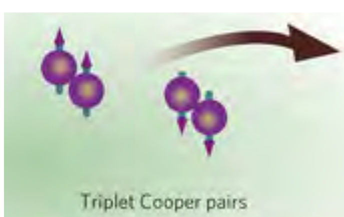


Materials with strong spin momentum locking



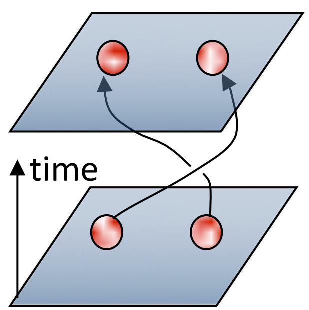


Topological Insulators

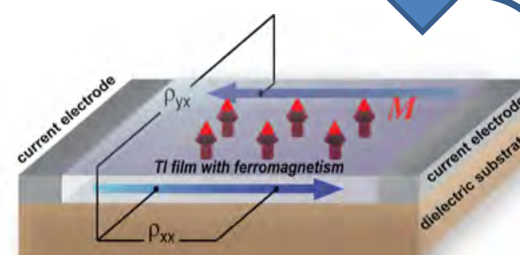


Triplet superconductivity:
Unconventional superconductivity

$$\psi(r_1, r_2) \neq e^{i\varphi}\psi(r_2, r_1)$$

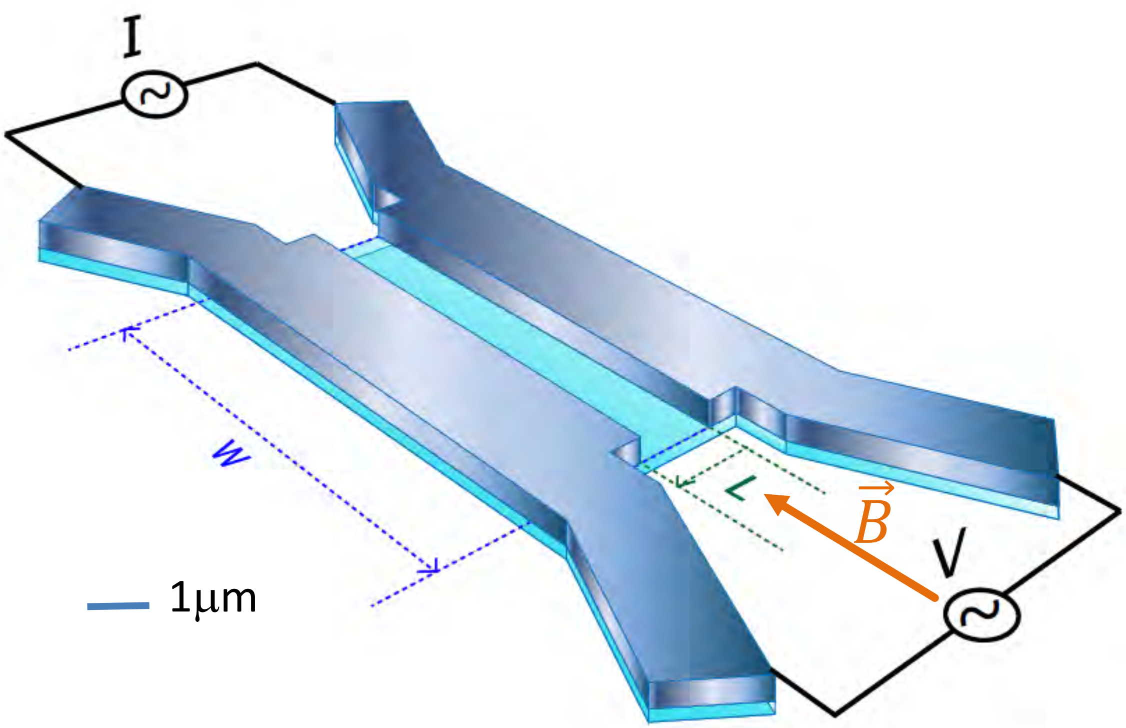


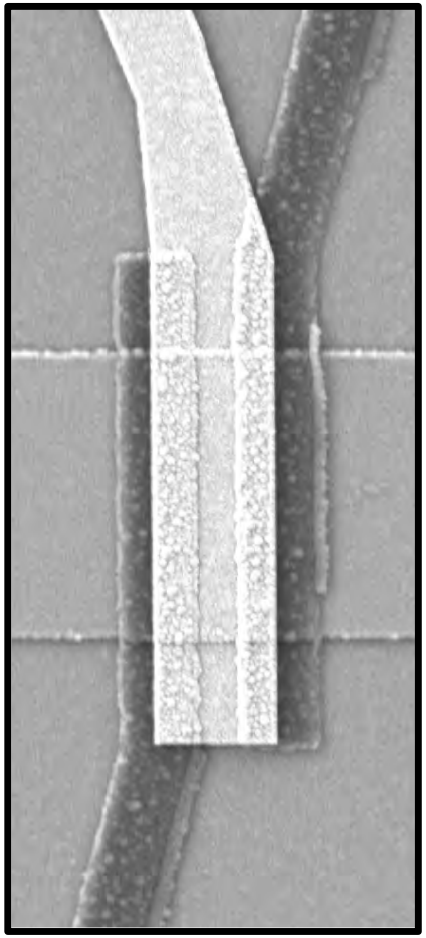
Topological Superconductivity:
Non Abelian Statistics -
Topological quantum computing



Quantum Anomalous Hall Effects:
Dissipationless transport and chiral Majorana modes

Experimental Geometry





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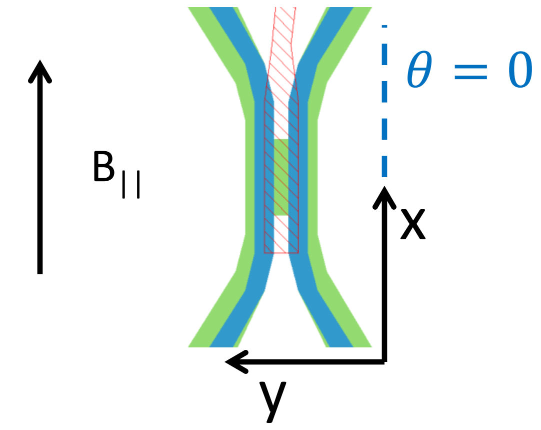
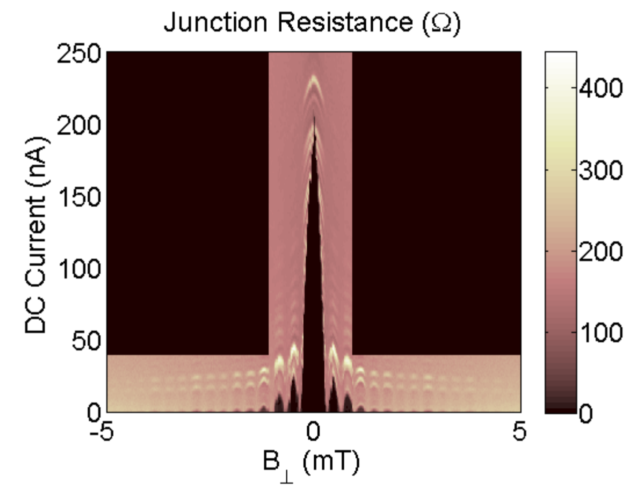
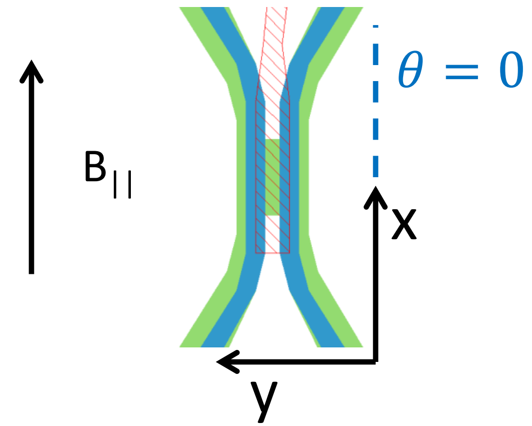
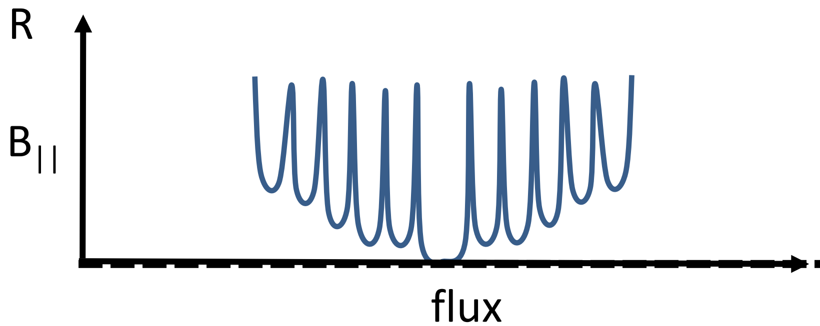
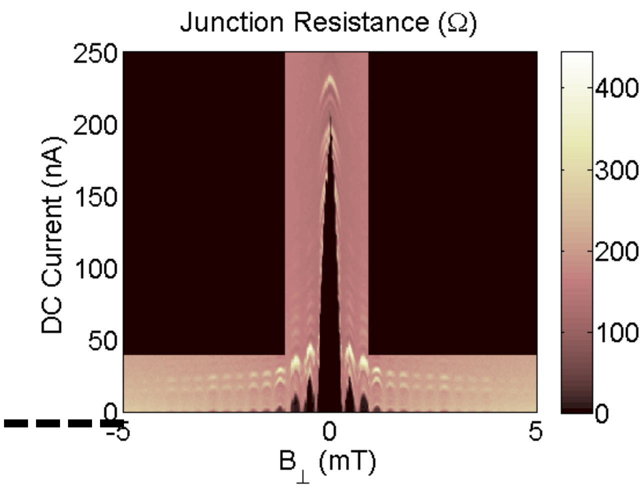




Experimental Geometry – In Plane Magnetic Field







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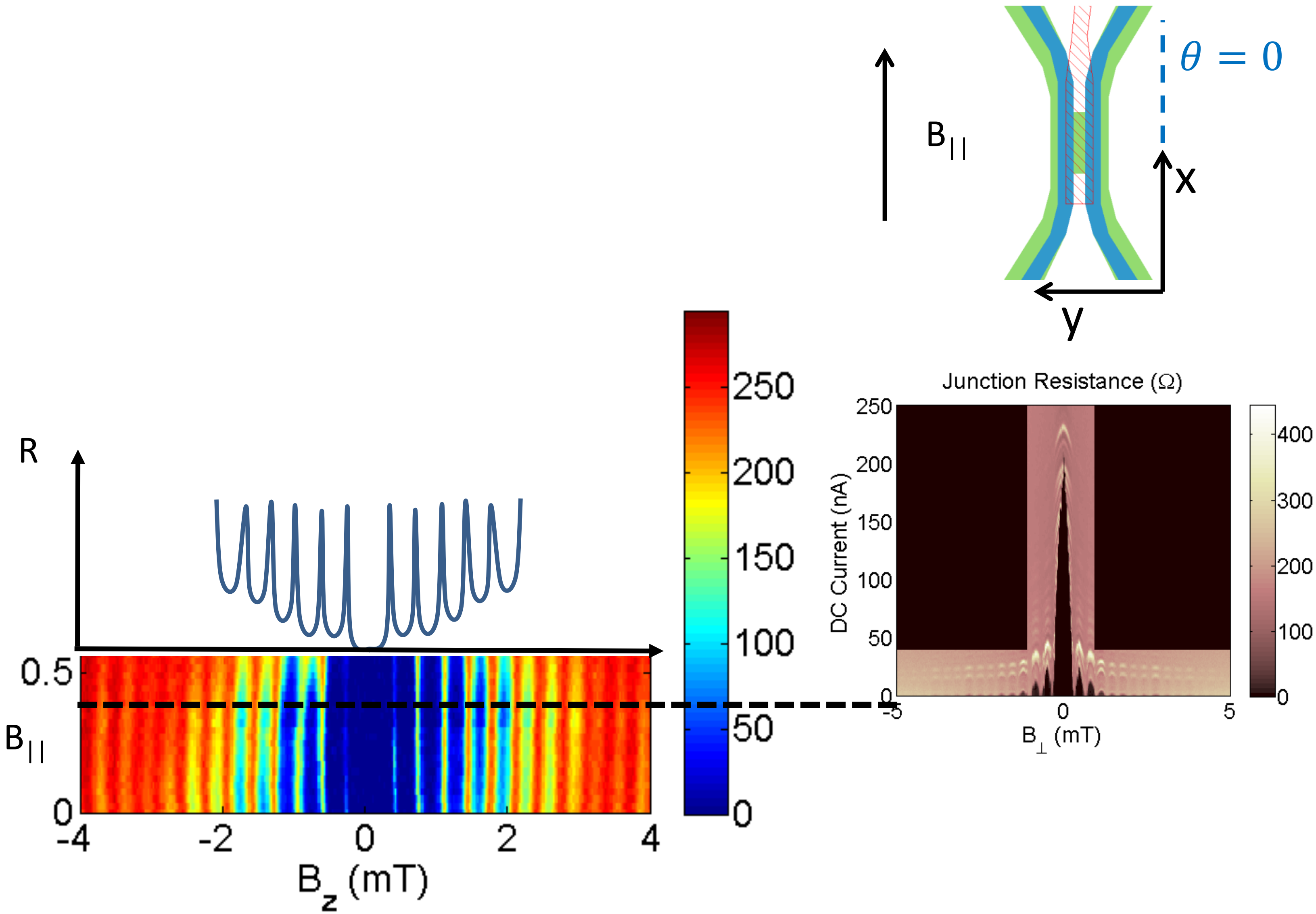

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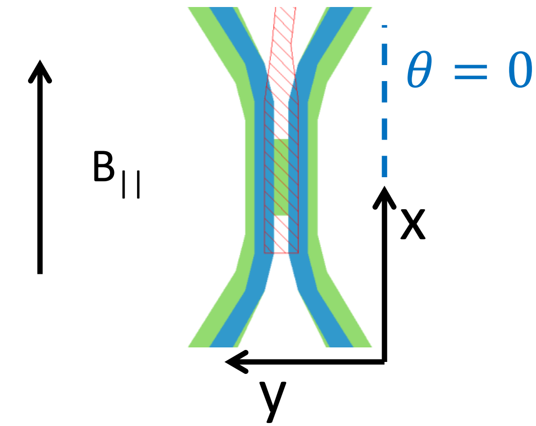

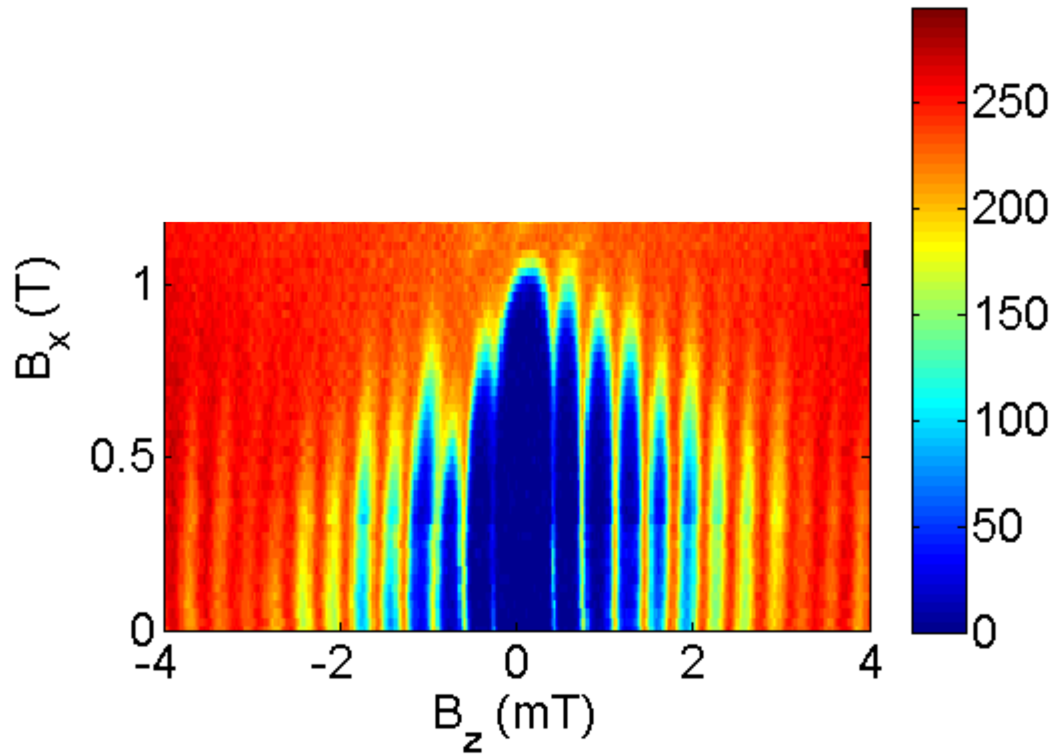

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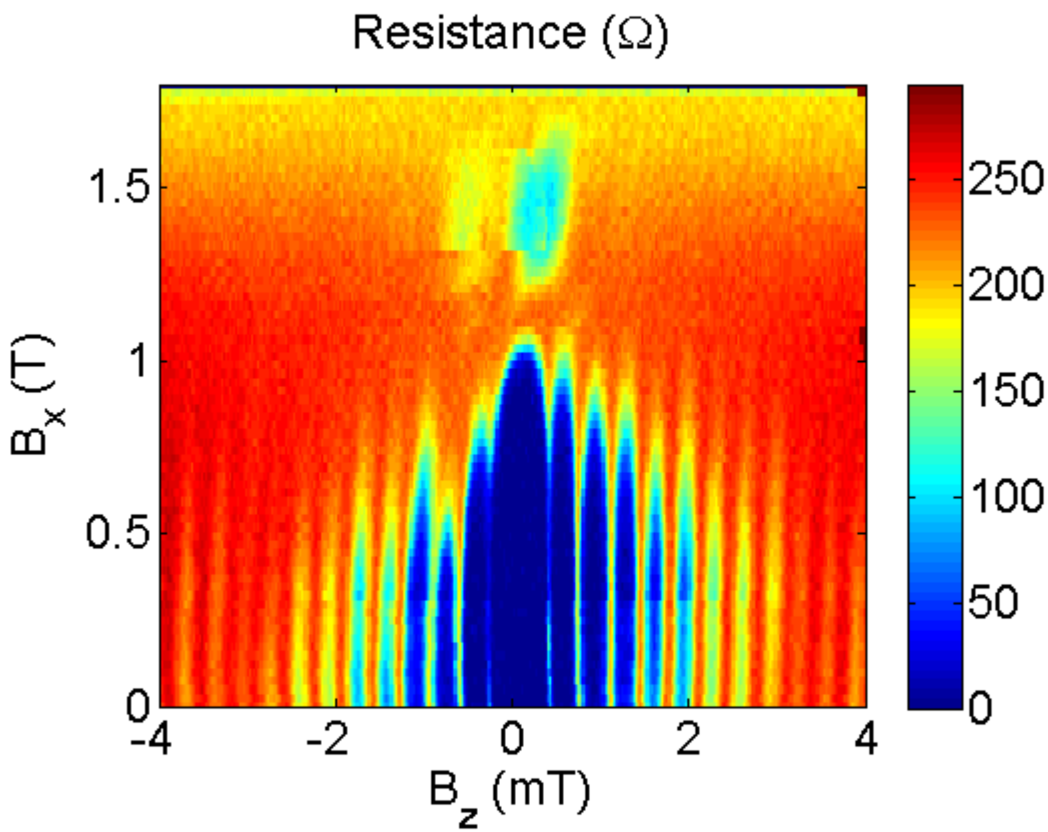
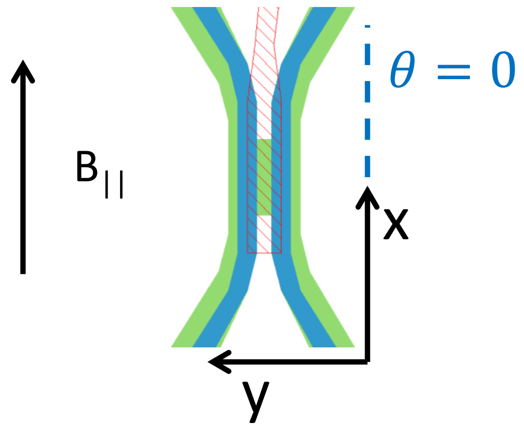
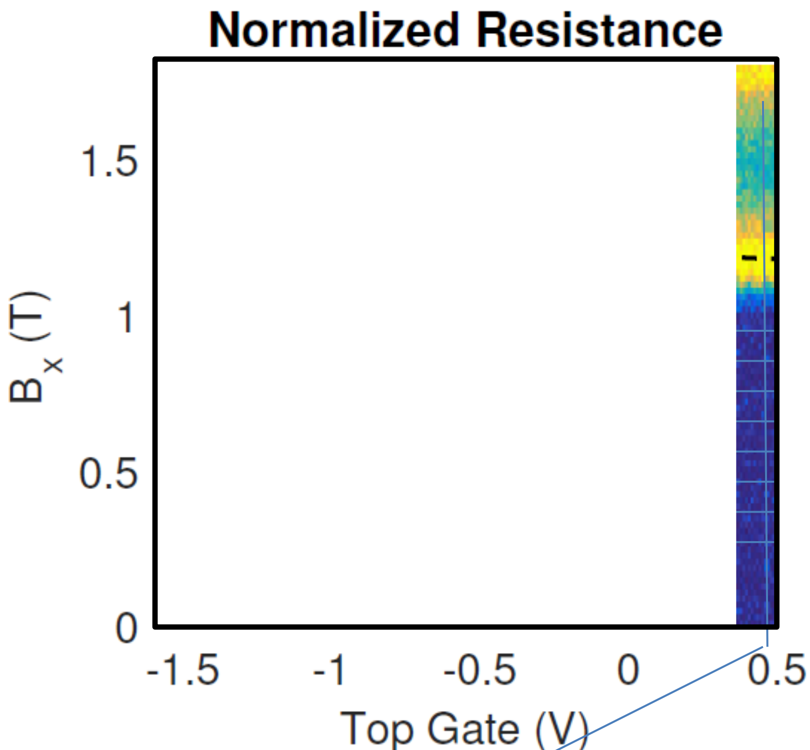
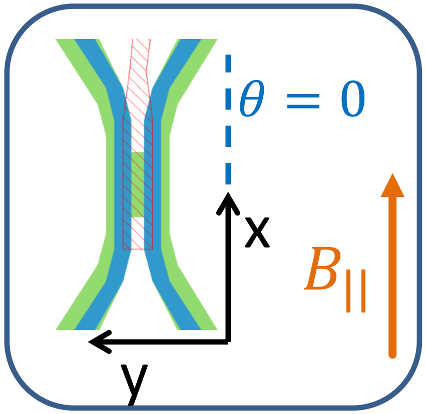


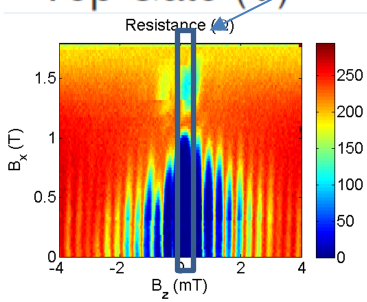


Phase Diagram of $B_{||}$ perpendicular to current flow

Aluminum







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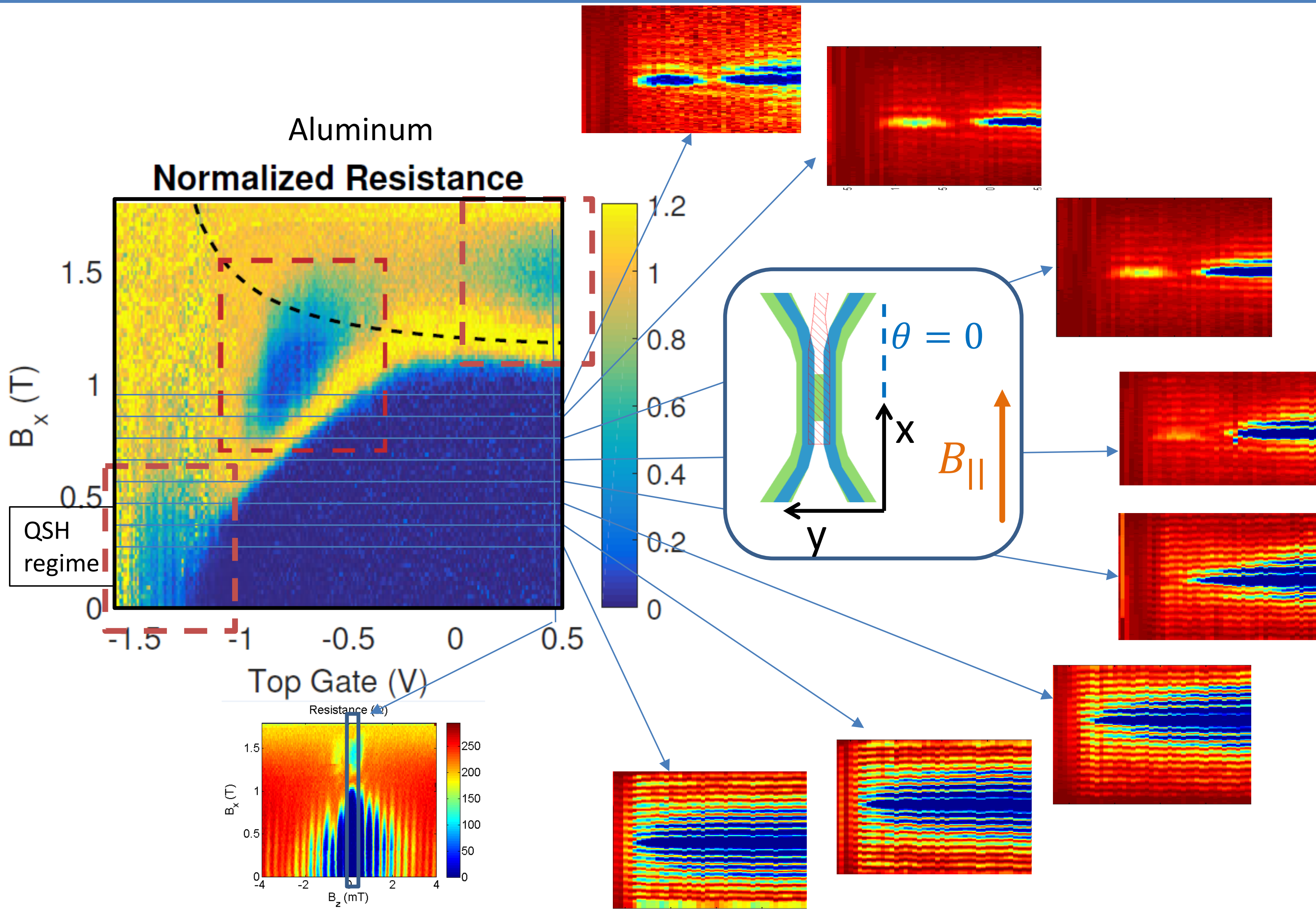
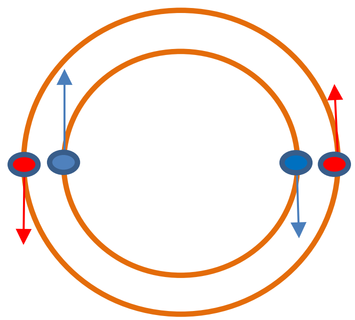


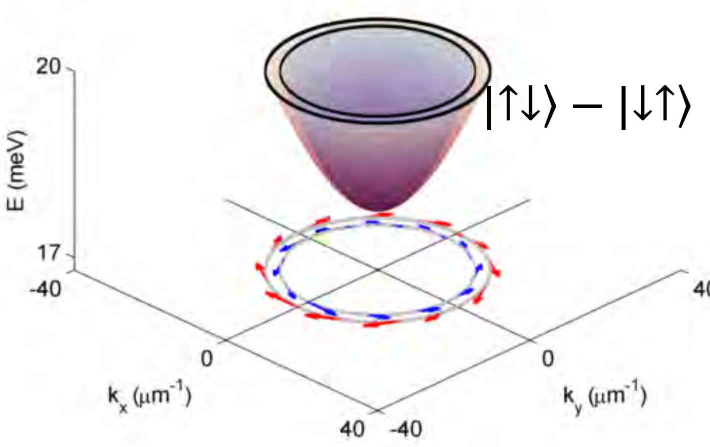
Expectations with Rashba Spin-Orbit Interaction

B=0

Pairing with each Fermi surface



$\vec{B} = (0\text{ T}, 0\text{ T}, 0\text{ T})$



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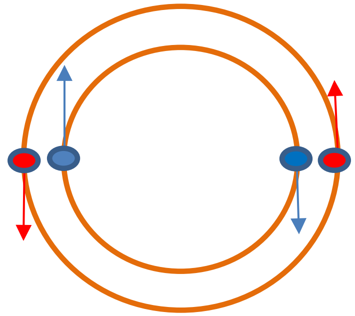
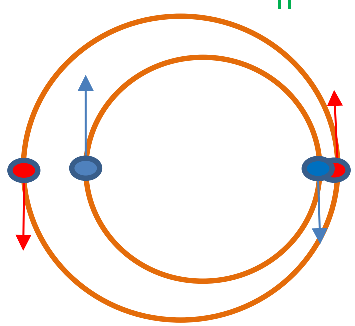


B>0

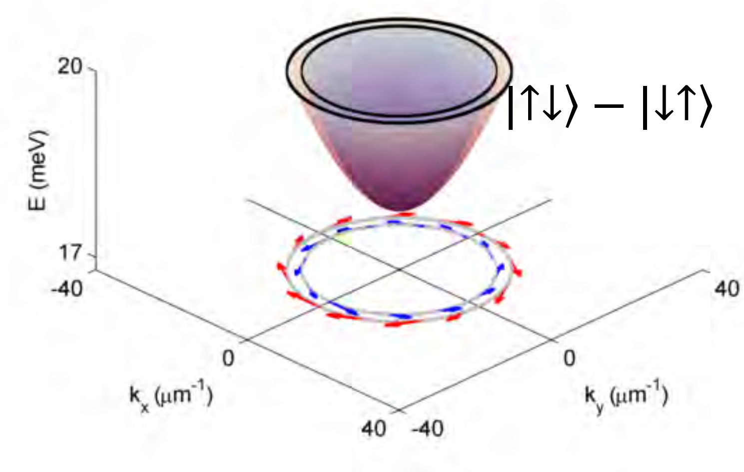
Some pairs acquire momentum $\Delta K \perp B_{||}$



$$\Delta K = \frac{E_Z}{\hbar V_F}$$

$$e^{i\overrightarrow{\Delta K}\cdot\vec{r}}\left|\uparrow\downarrow\right\rangle - e^{-i\overrightarrow{\Delta K}\cdot\vec{r}}\left|\downarrow\uparrow\right\rangle$$

$\vec{B} = (0\ \mathrm{T}, 0\ \mathrm{T}, 0\ \mathrm{T})$



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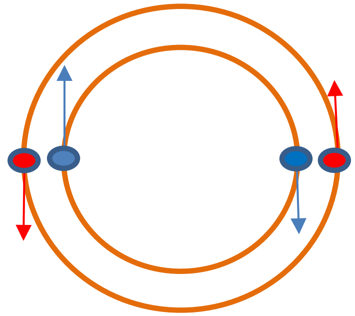
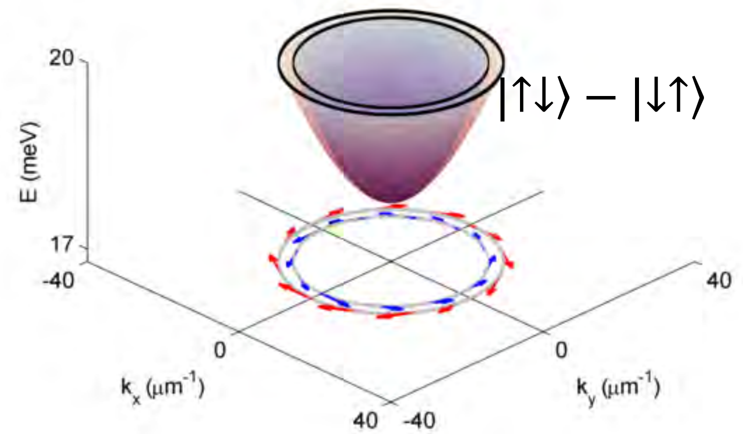


$\vec{B} = (0\text{ T}, 0\text{ T}, 0\text{ T})$



B>0

$$\Delta K = \frac{E_Z}{\hbar V_F}$$

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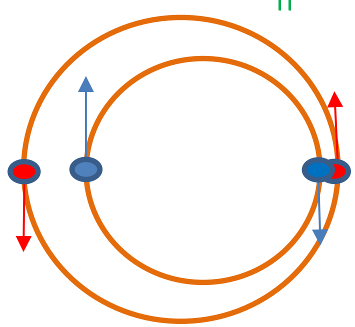
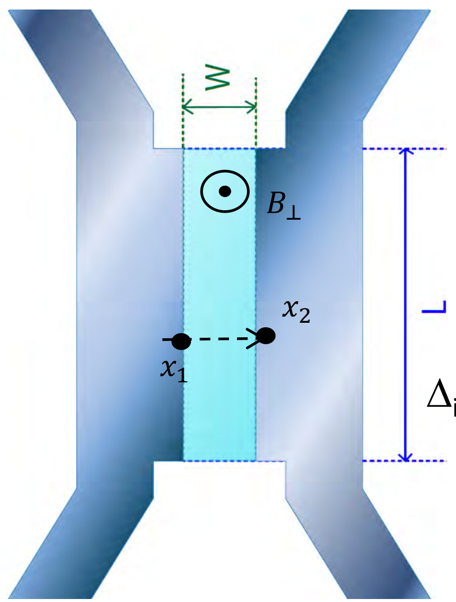


$$e^{i\overrightarrow{\Delta K}\cdot\vec{r}}\,|\uparrow\downarrow\rangle - e^{-i\overrightarrow{\Delta K}\cdot\vec{r}}\,|\downarrow\uparrow\rangle$$

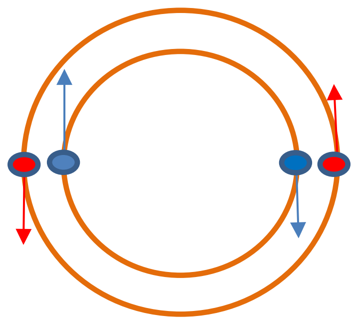


Δ_{ind}=Cos$(\overrightarrow{\Delta K}\cdot W)|S\rangle$+iSin$(\overrightarrow{\Delta K}\cdot W)|T0\rangle$

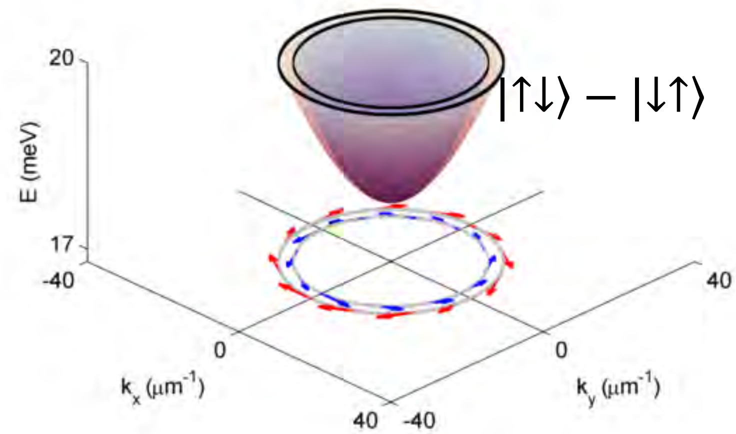
Expectations with Rashba Spin-Orbit Interaction

B=0

Pairing with each Fermi surface



$\vec{B} = (0\ \mathrm{T}, 0\ \mathrm{T}, 0\ \mathrm{T})$



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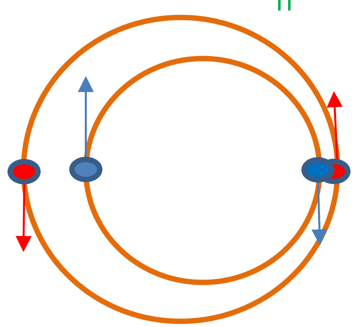
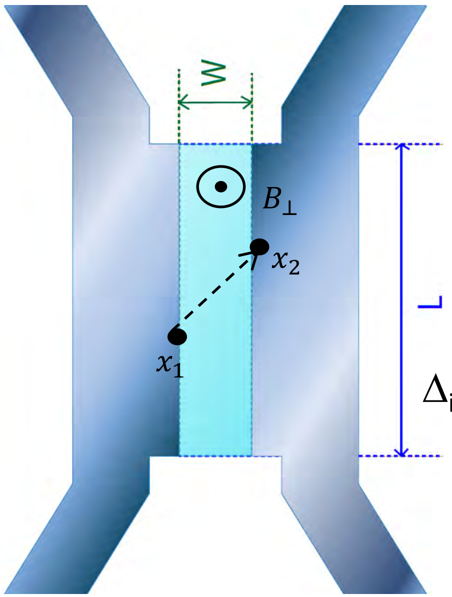


$$\Delta K = \frac{E_Z}{\hbar V_F}$$

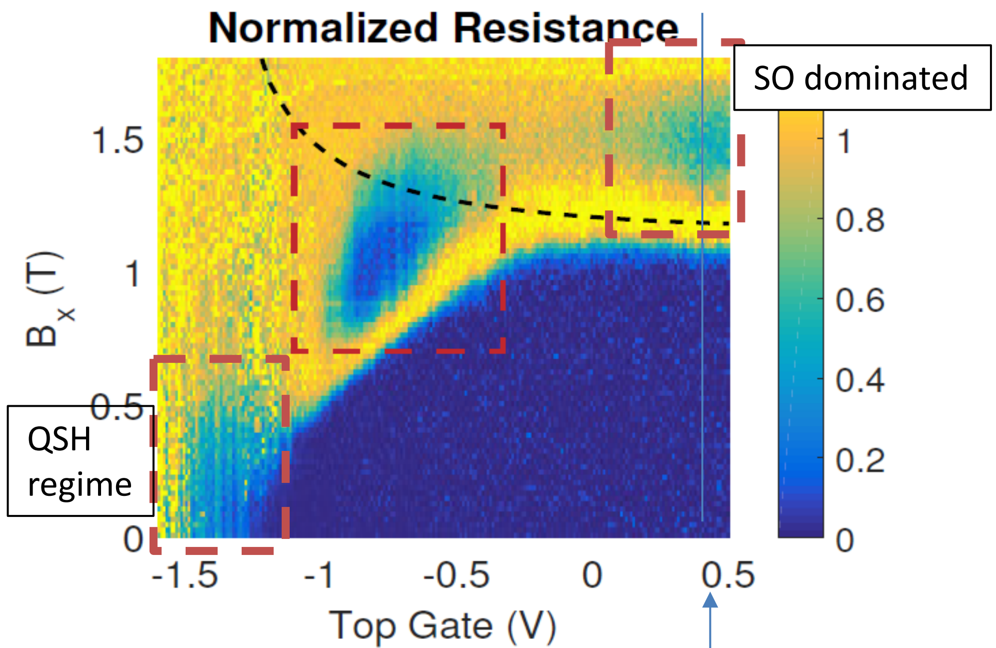
$$e^{i\overrightarrow{\Delta K}\cdot\vec{r}}\,|\uparrow\downarrow\rangle - e^{-i\overrightarrow{\Delta K}\cdot\vec{r}}\,|\downarrow\uparrow\rangle$$

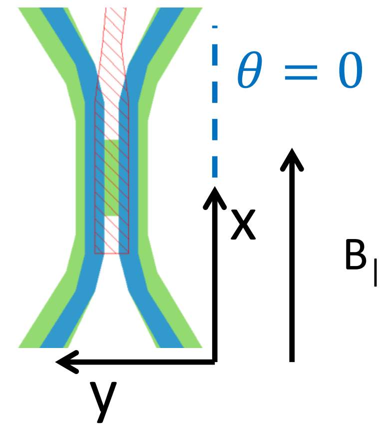


Summing over all trajectories

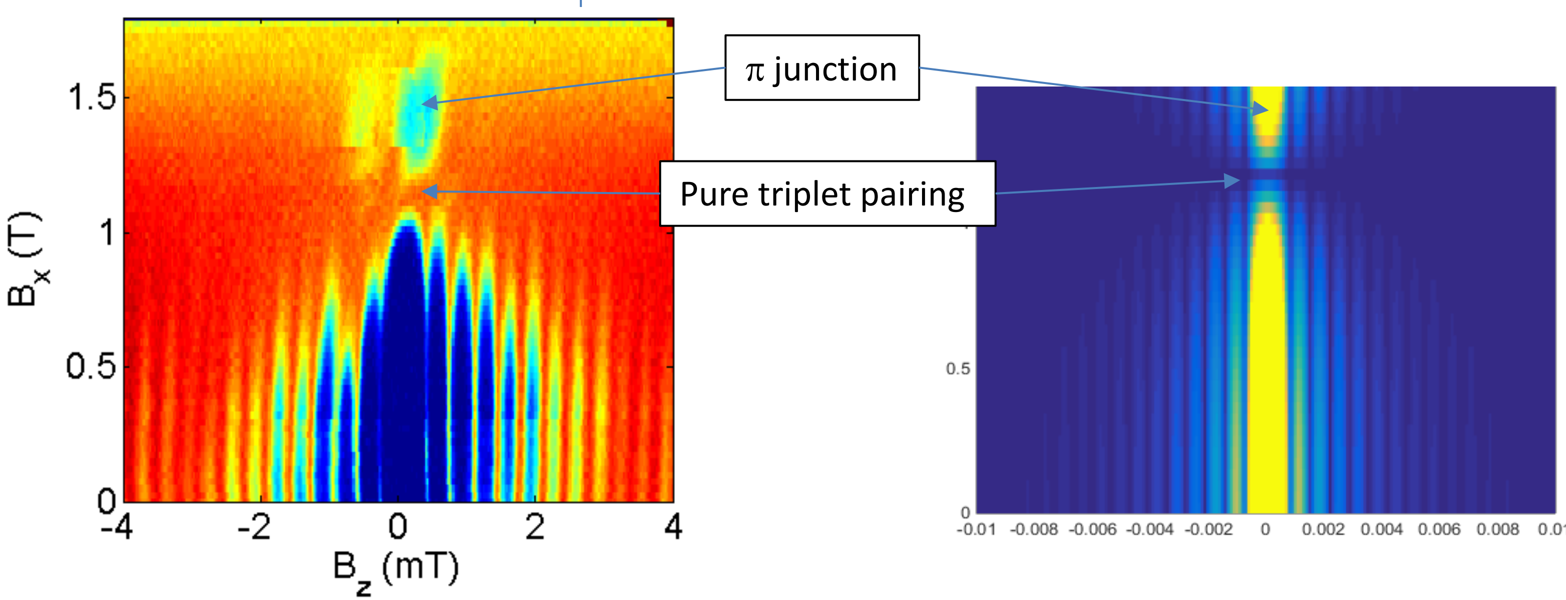
$$\Delta_{ind} = \mathrm{Cos}(\overrightarrow{\Delta K}\cdot W)|S\rangle + i\mathrm{Sin}(\overrightarrow{\Delta K}\cdot W)|T0\rangle$$

Spin-Orbit Dominated Regime

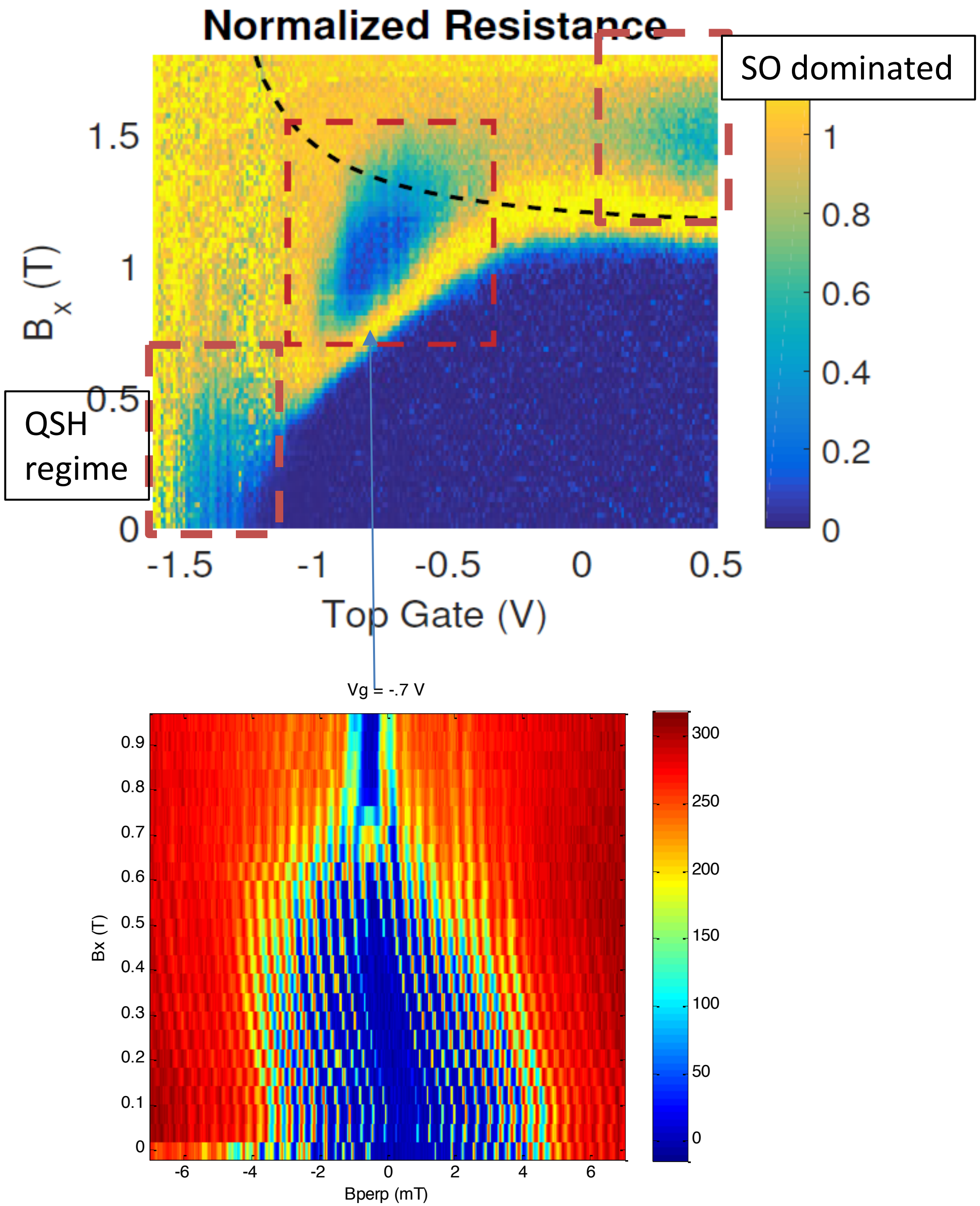


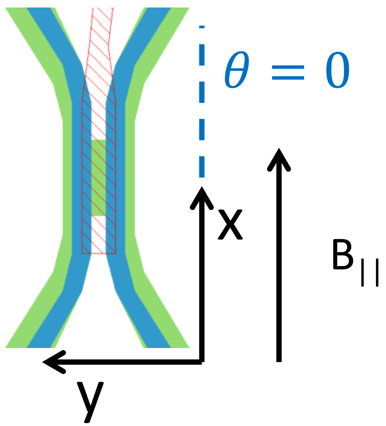


$$\Delta_{ind}\text{=Cos}(\overrightarrow{\Delta K}\cdot W)|S\rangle\text{+iSin}(\overrightarrow{\Delta K}\cdot W)|T0\rangle$$



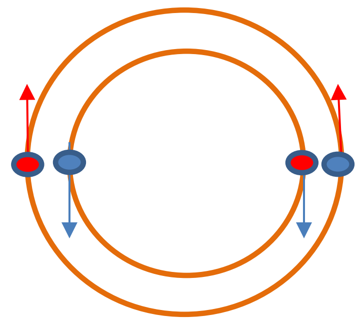
Lower Density Regime





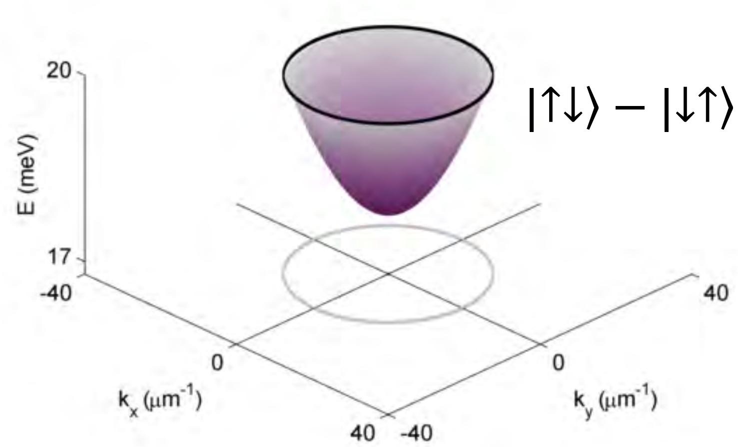
Zeeman Only

All pairs acquire momentum



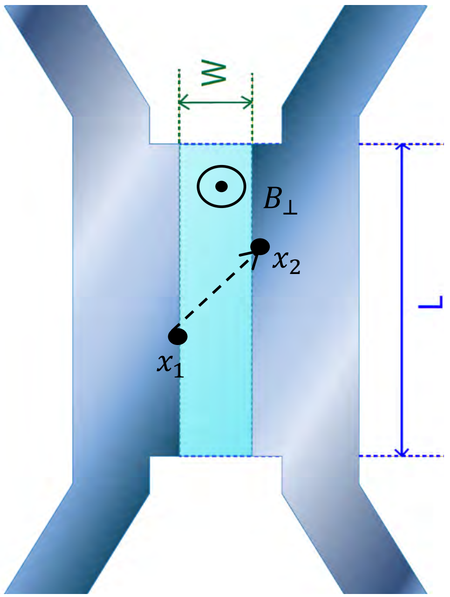
$e^{-i\overrightarrow{\Delta K}\cdot\vec{r}}|\uparrow\downarrow\rangle - e^{i\overrightarrow{\Delta K}\cdot\vec{r}}|\downarrow\uparrow\rangle$

$\vec{B} = (0\text{ T}, 0\text{ T}, 0\text{ T})$



Resembles S-F-S Junctions – tunable

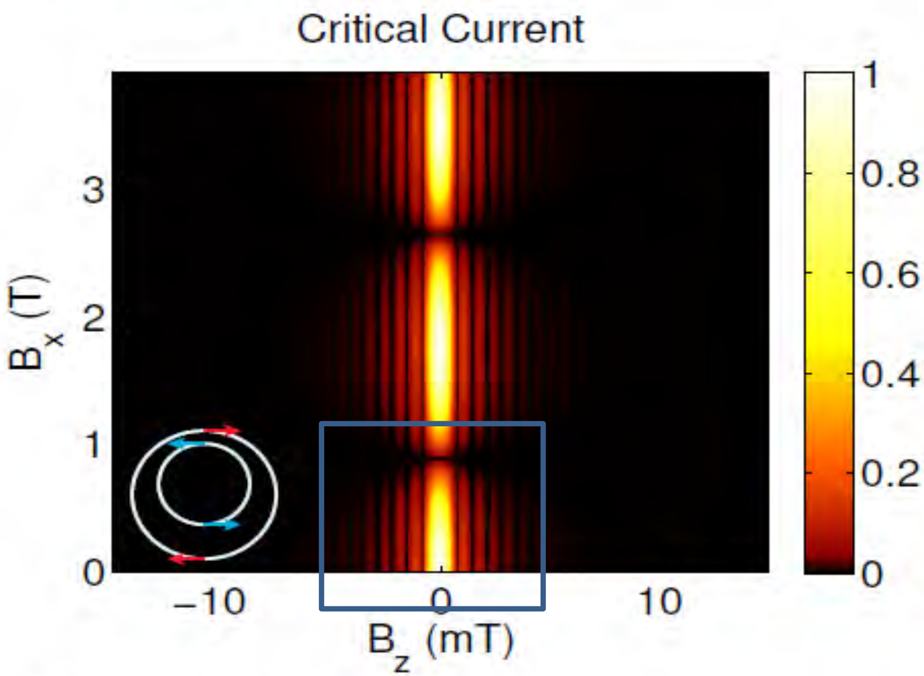
'Induced' - FFLO



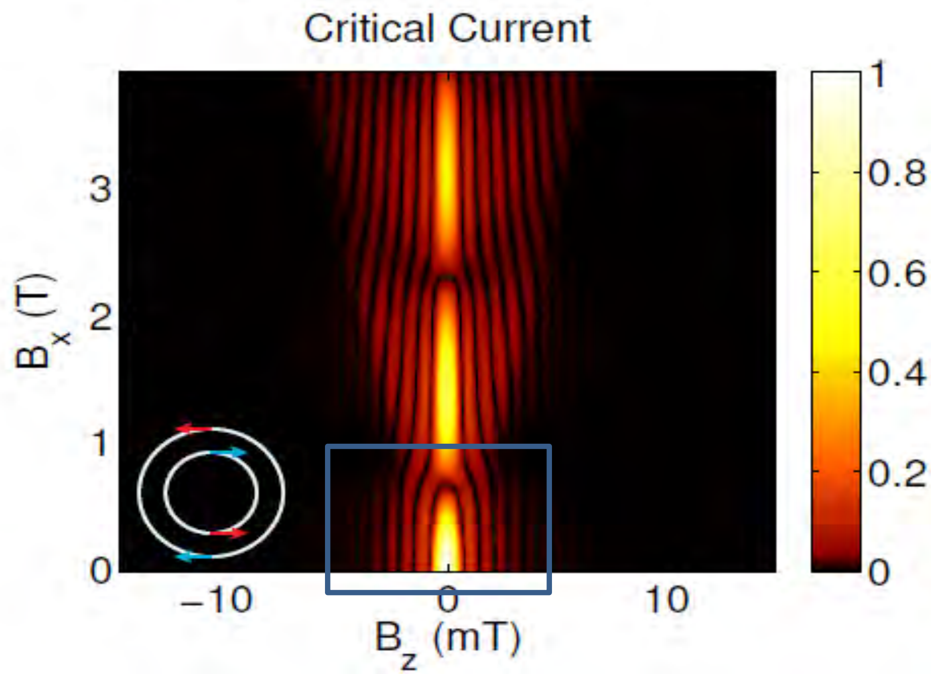
Δ_{ind}=Cos$(\overrightarrow{\Delta K}\cdot(\overrightarrow{X_2}-\overrightarrow{X_1}))|S\rangle$+iSin$(\overrightarrow{\Delta K}\cdot(\overrightarrow{X_2}-\overrightarrow{X_1}))|T0\rangle$

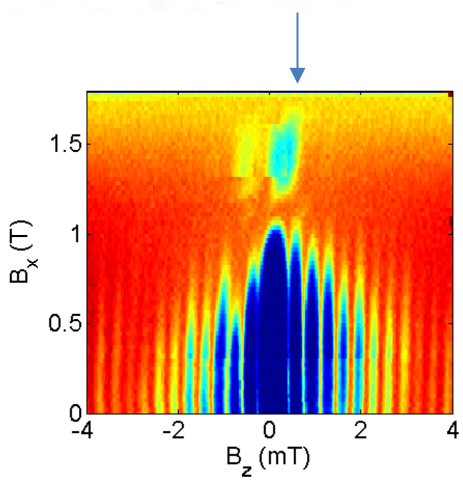
Rashba vs Zeeman

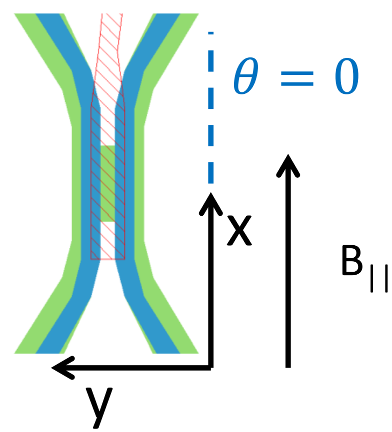
Rashba dominated

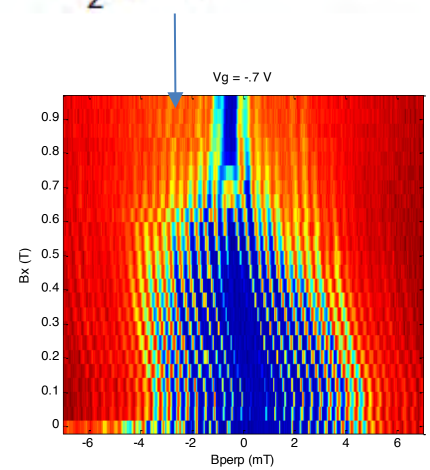


Zeeman only

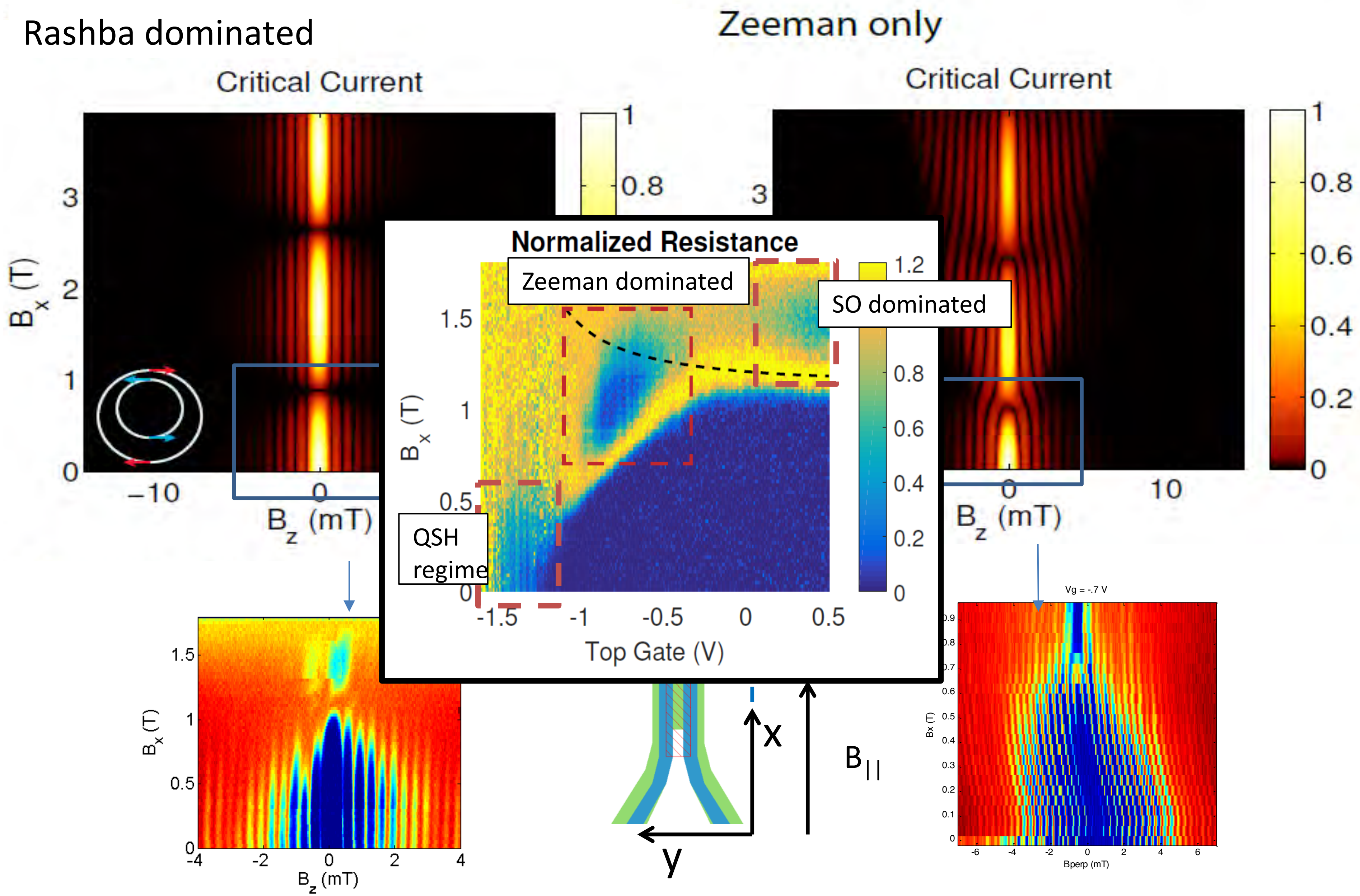




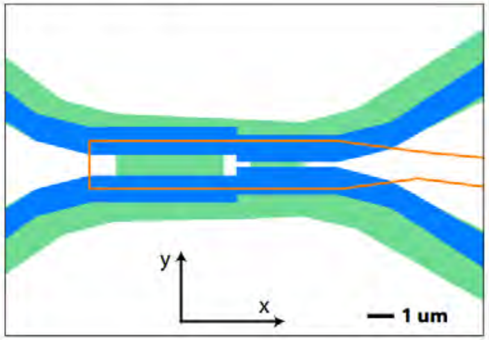




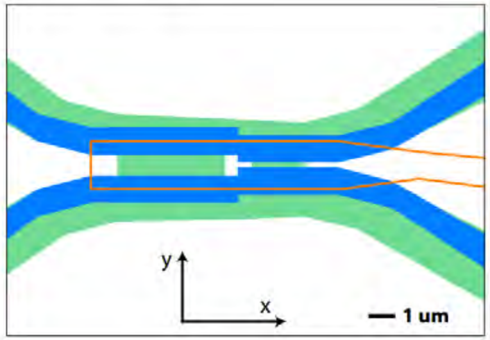
Rashba vs Zeeman

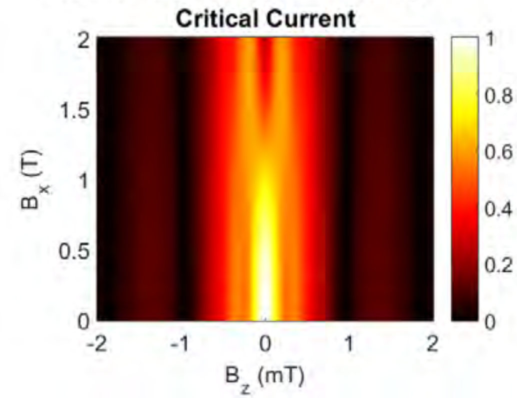


π phase shift and π junction

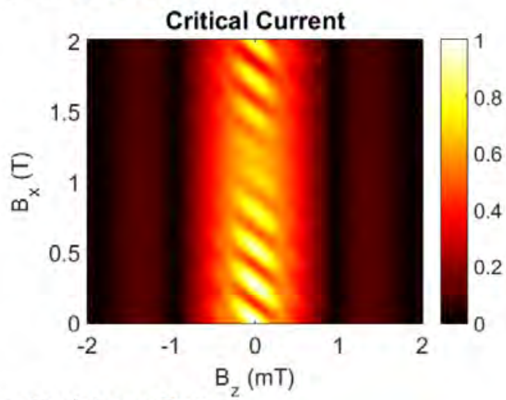


π phase shift and π junction

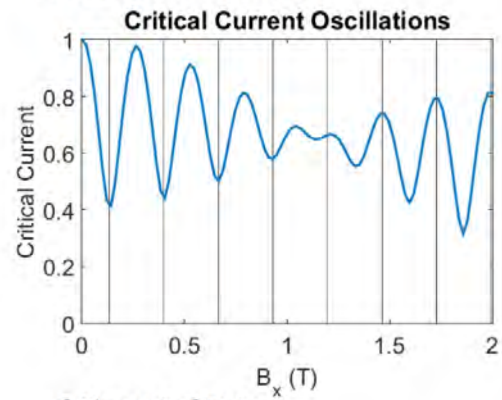




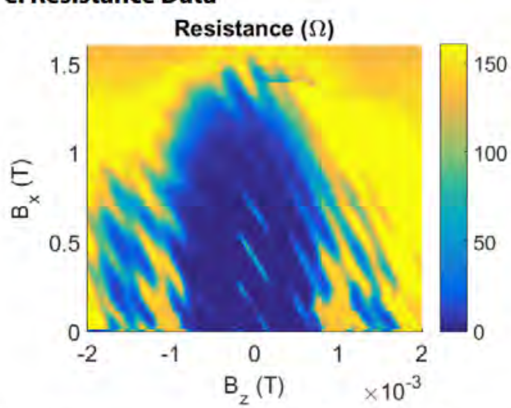
c. Simulation with Screening



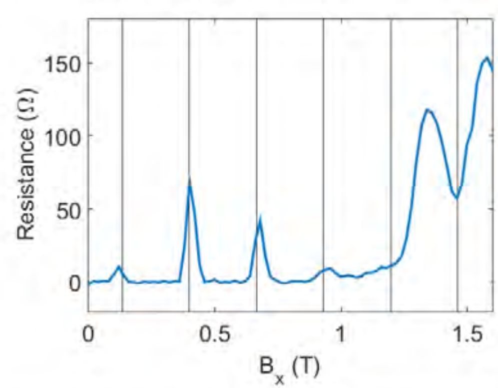
d. Simulation of Linecut



e. Resistance Data

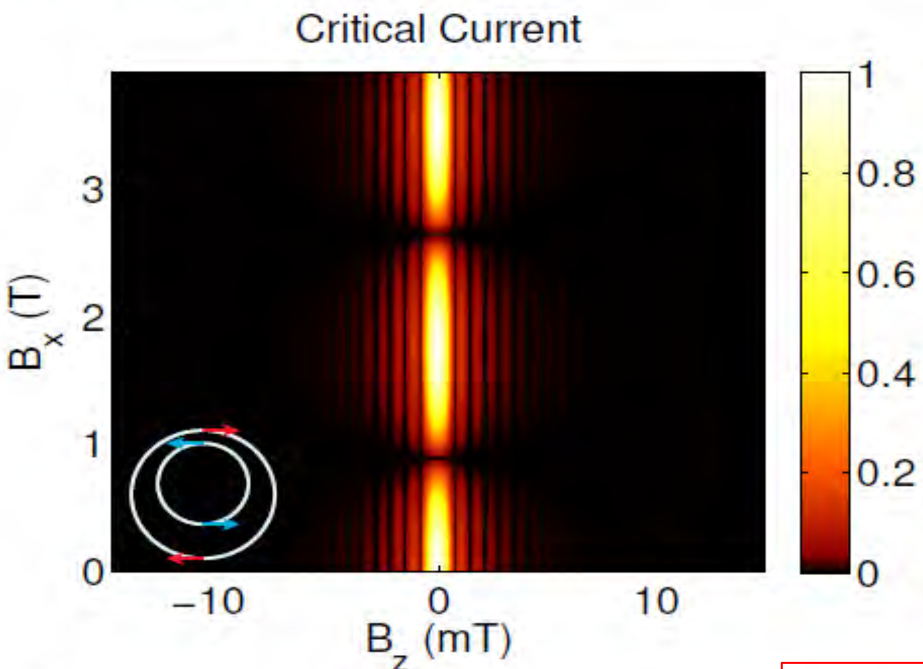


f. Linecut of Data

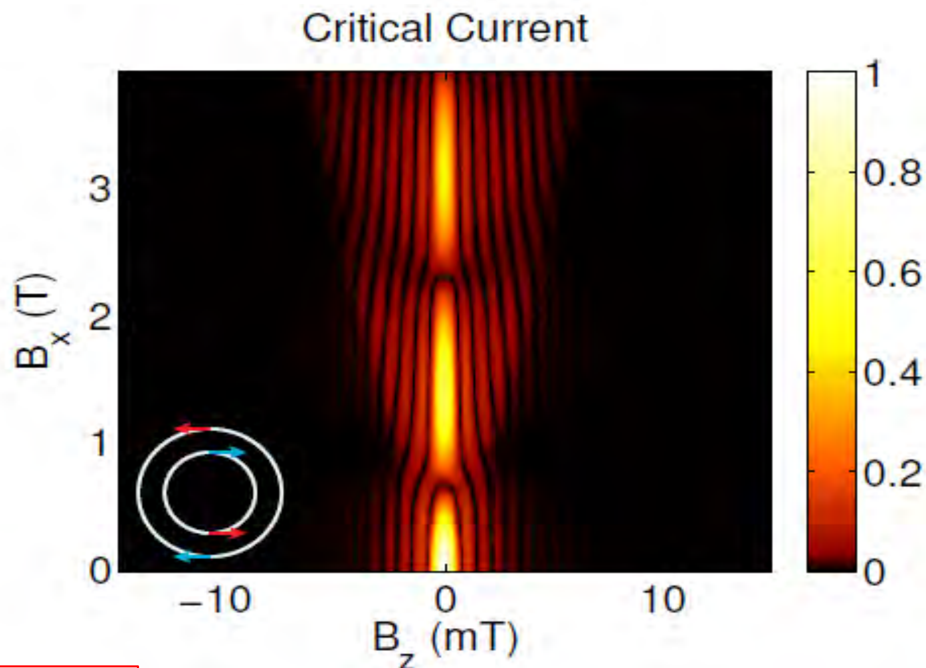


Rashba vs Zeeman

Rashba dominated

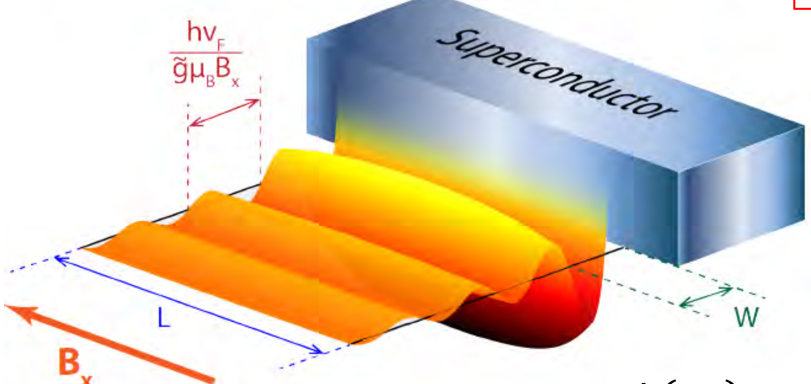


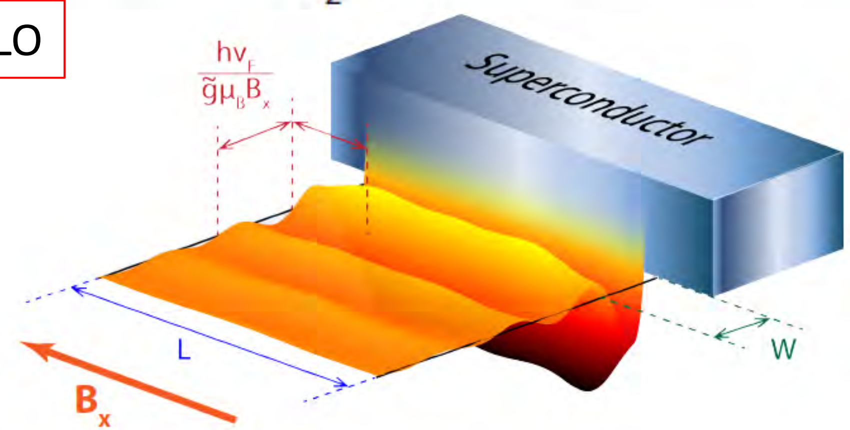
Zeeman Dominated



Induced FFLO

Δ_{ind}=Cos($\Delta\acute{K}\cdot W$)$|S\rangle$+iSin($\Delta\acute{K}\cdot W$)$|T0\rangle$



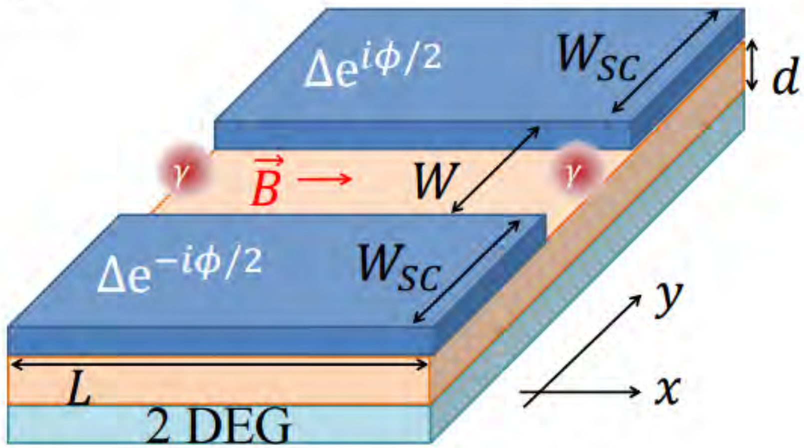


Decay independent of B

$$\Delta(x_2)_{ind} = \left|\int_{-L/2}^{L/2} dx_1 \, [\lambda_1(x_1) F_0(x_1, x_2)]\right|$$

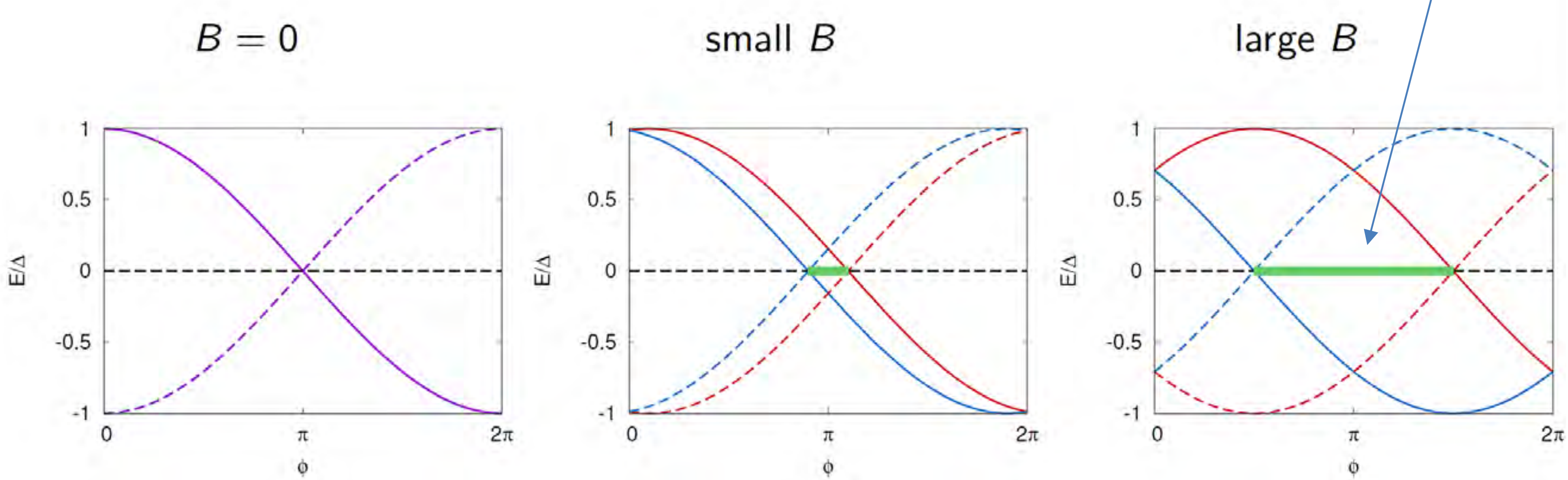
New Theoretical Insight

Topological transition only governed by Kx=0



- Narrow junction
- Neglect normal reflections

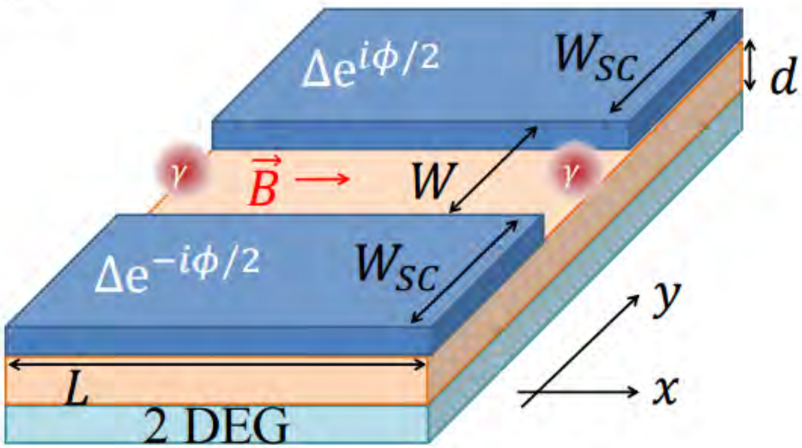
- Topological superconductor

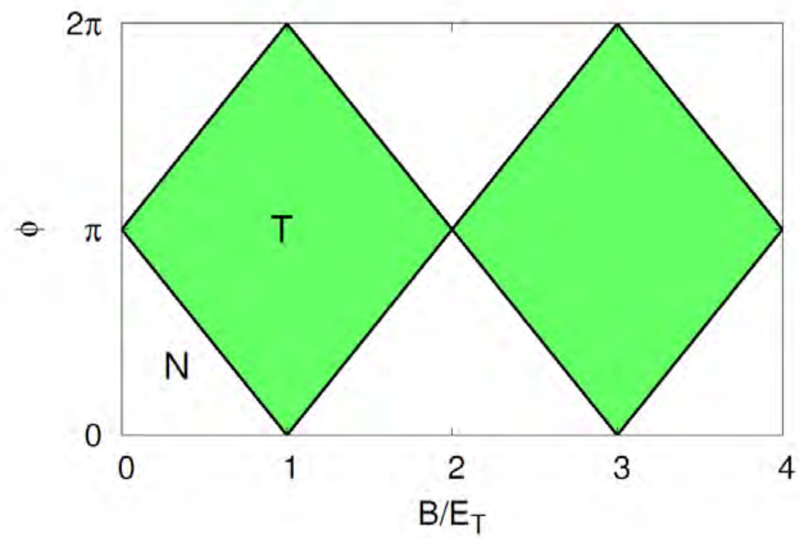


F. Pientka, AY, et al arXiv 2016

Topological Switch

Topological transition only governed by Kx=0





- $\phi = 0$ system *always* trivial
- $\phi = \pi$ system *always* topological

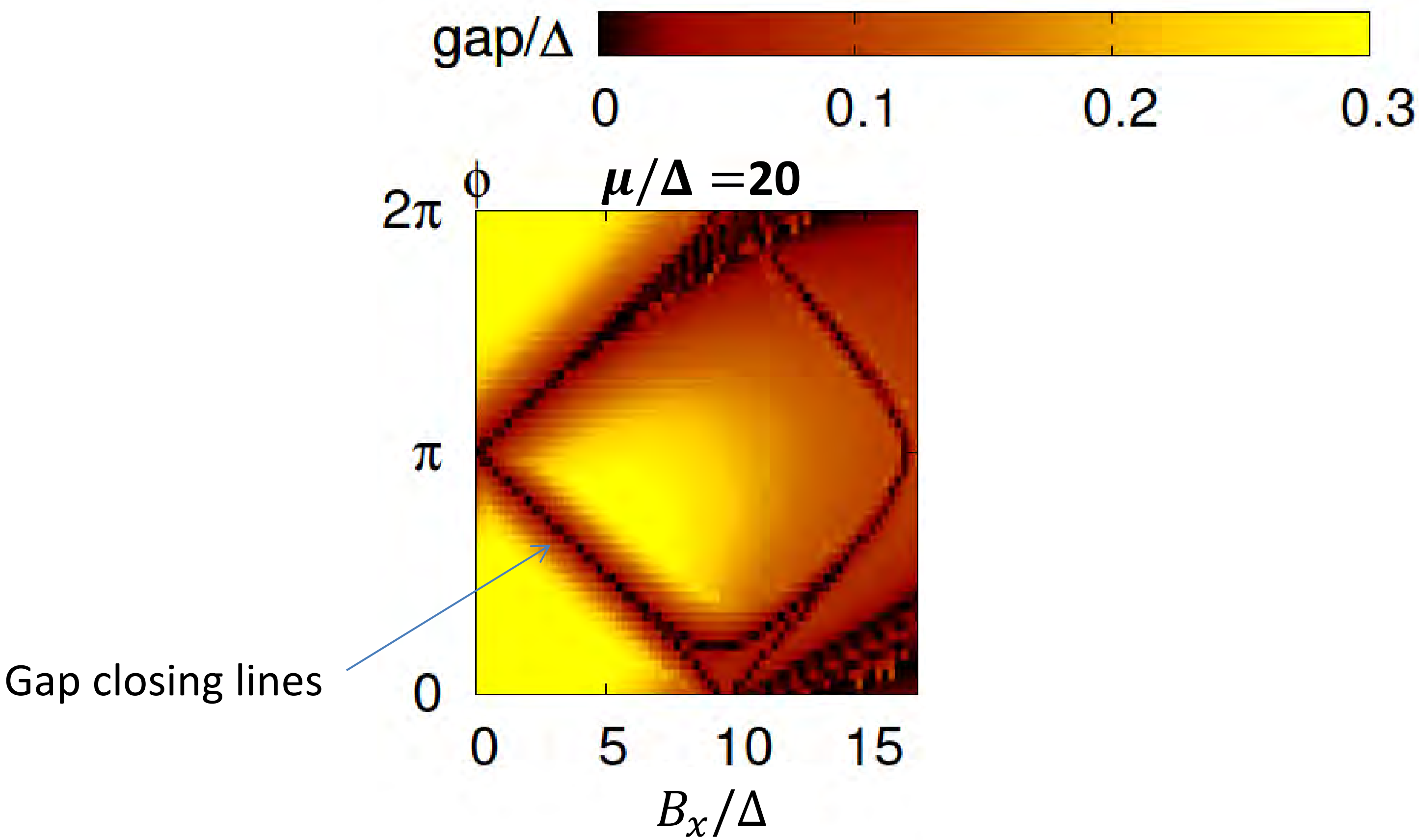
topology at $\phi = 0, \pi$
independent of μ, B, Δ and W

topology switch

F. Pientka, AY, et al arXiv 2016

Magnitude of the Gap

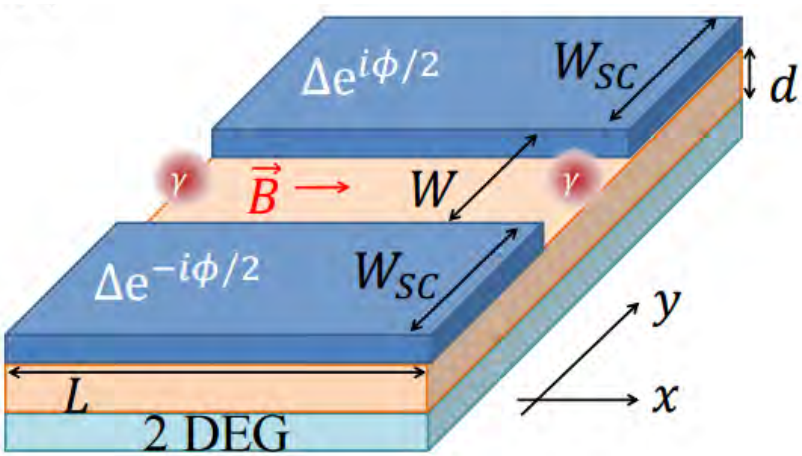
Gap obtained numerically using scattering matrix approach, $\Delta = {}^{1}/_{mW^2}$

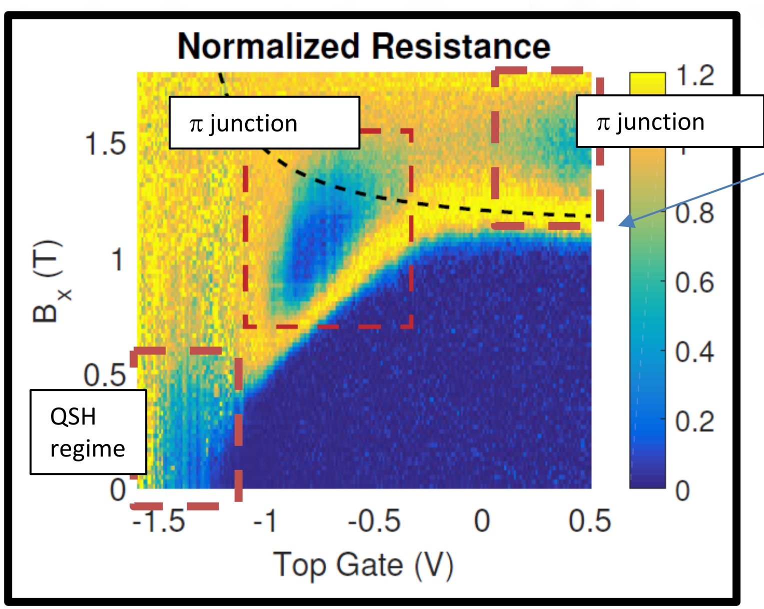


Gap of order Δ in the topological region!

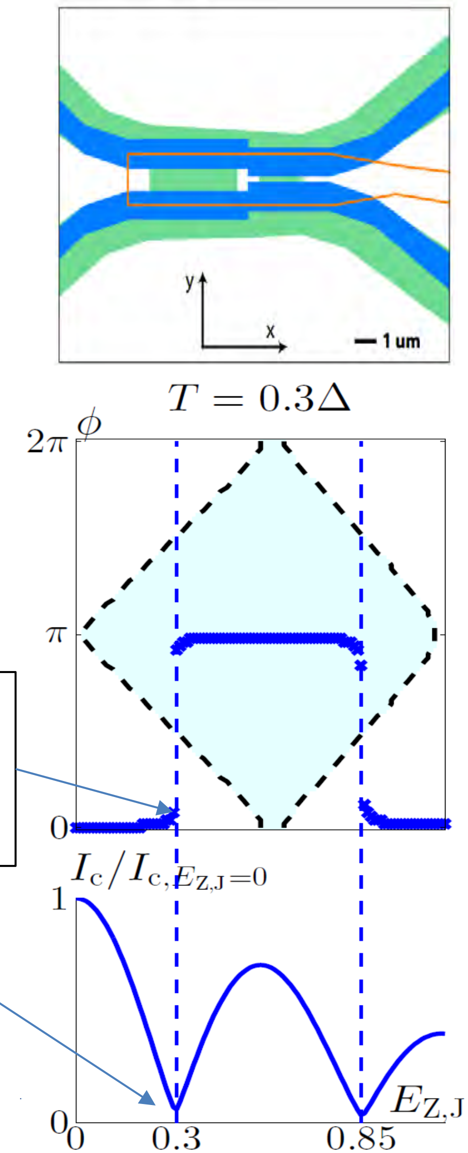
Size of the gap is insensitive to μ!

Self Tuning into Topological Phase



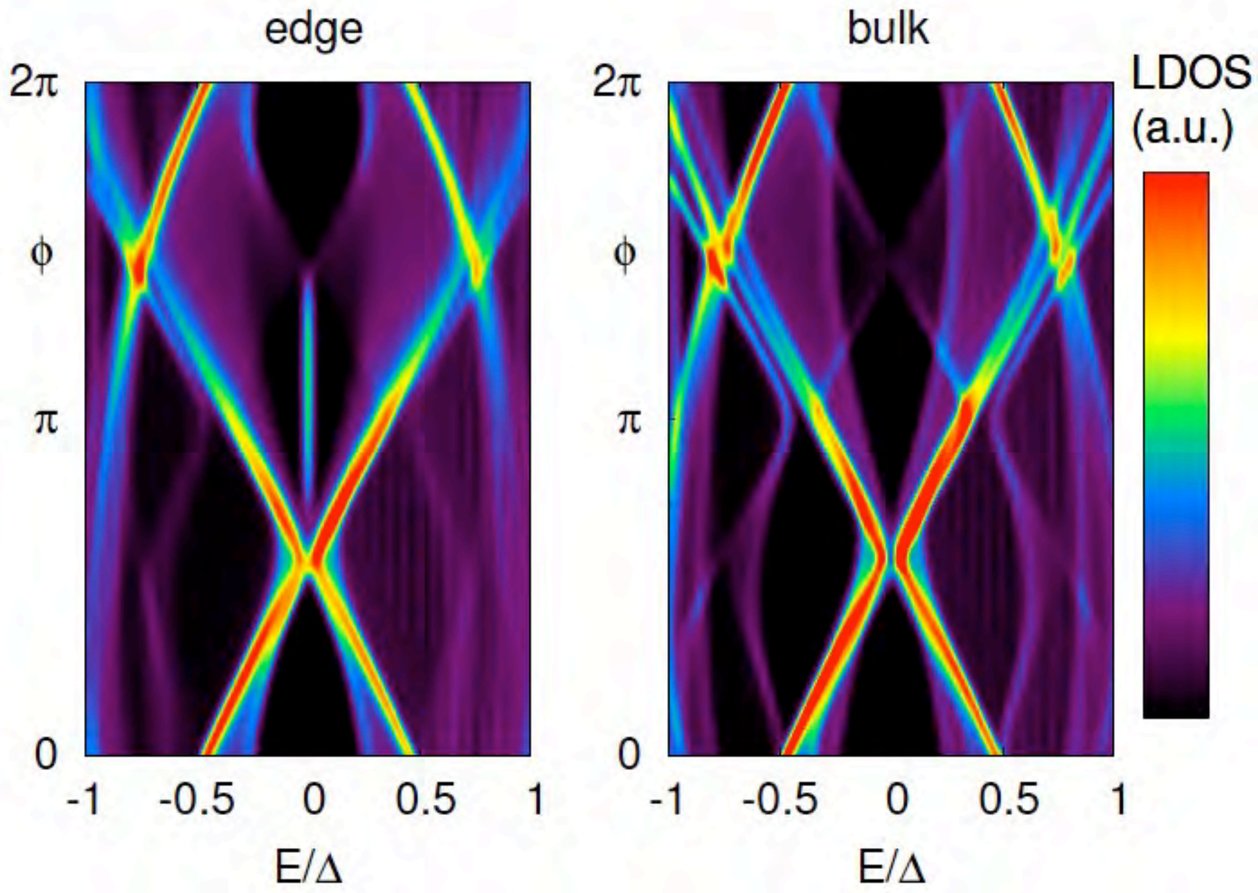


First order topological phase transition

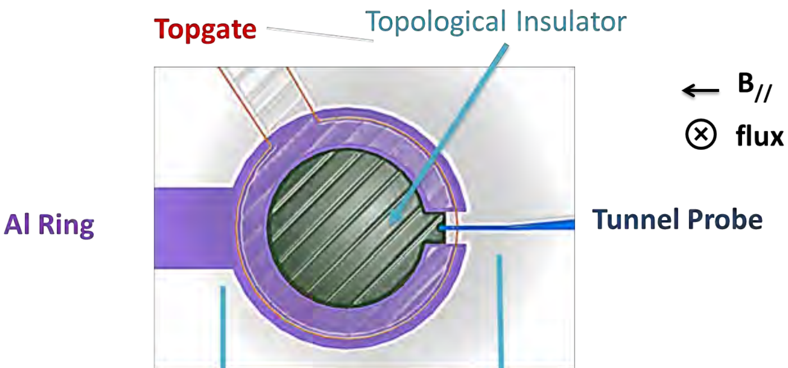


F. Pientka, AY, et al arXiv 2016

Search for Majorana End States

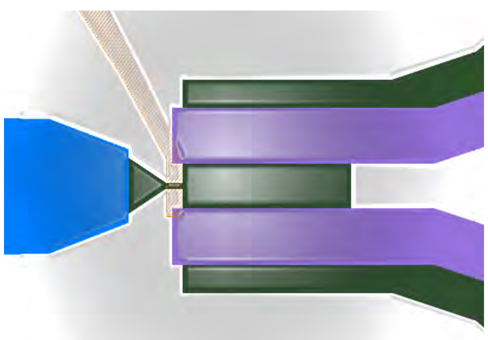


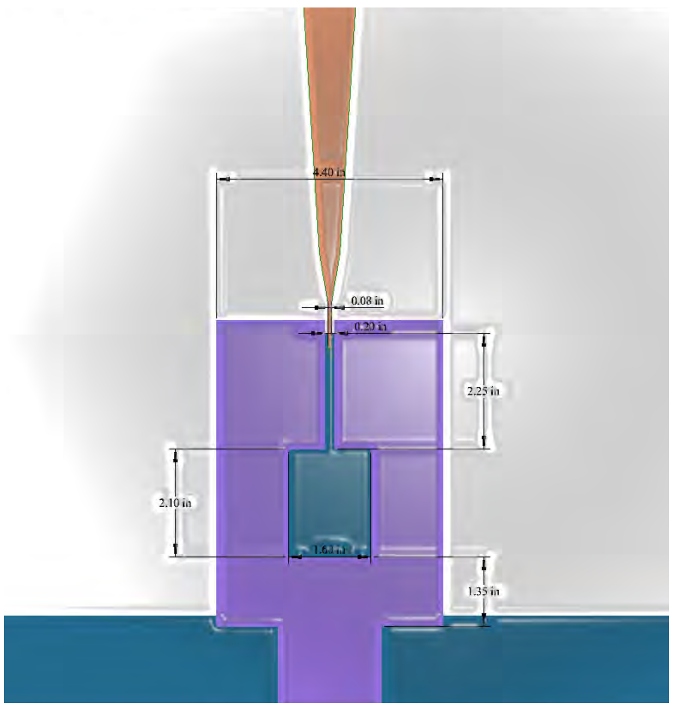
Tunneling Spectroscopy



Measure differential conductance between tunnel probe and superconductor

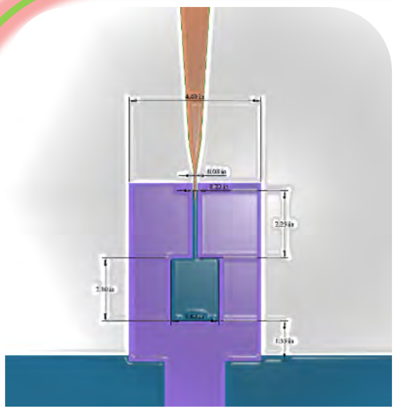
Flux control – 'a Topology Switch'

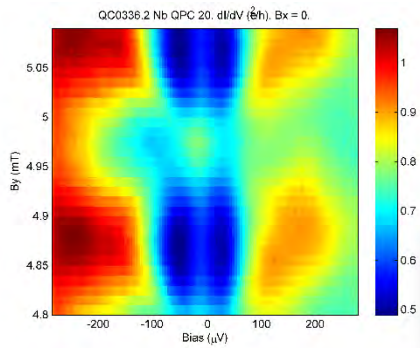
- 

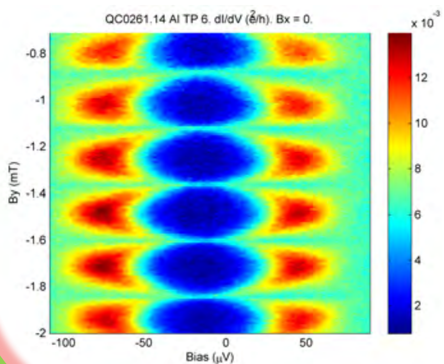


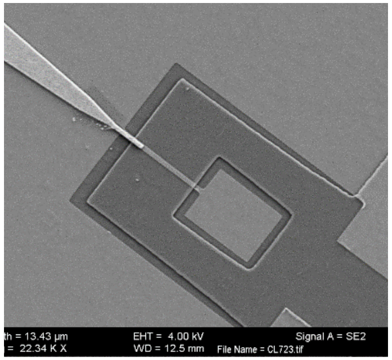
Planar Josephson junction devices with tunnel probes

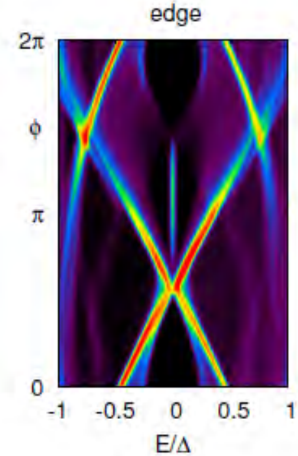
Local Density of States Measurement and Calculation

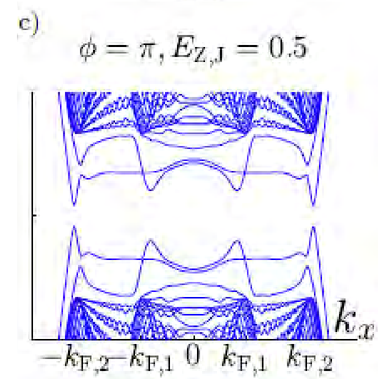








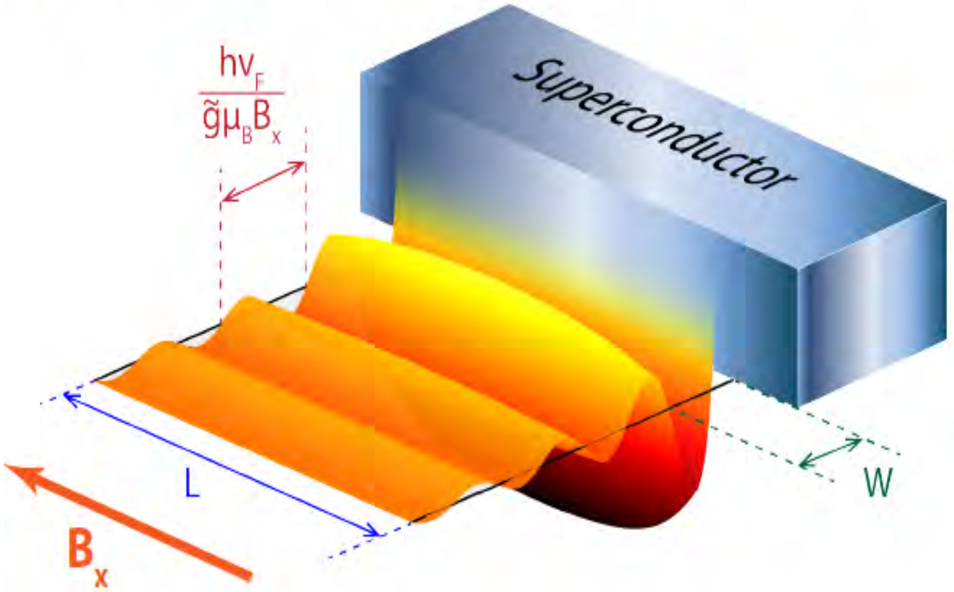




Pientka, et. al. Arxiv:1609.09482.

Outlook:

- Can we use this measurement approach to determine the presence of p-type order?
- Can we determine what is the underlying p-type order (T+, T-, To)?



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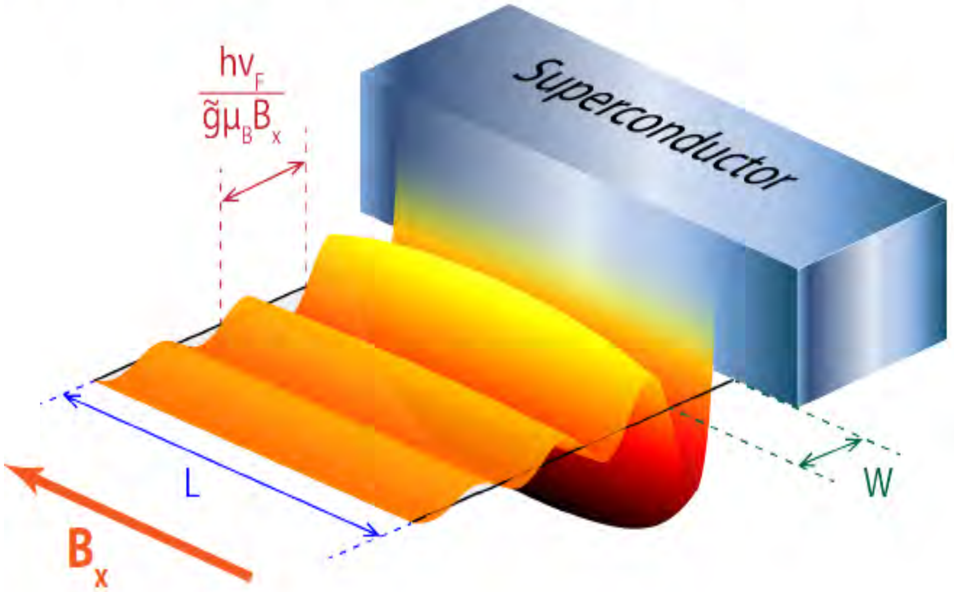
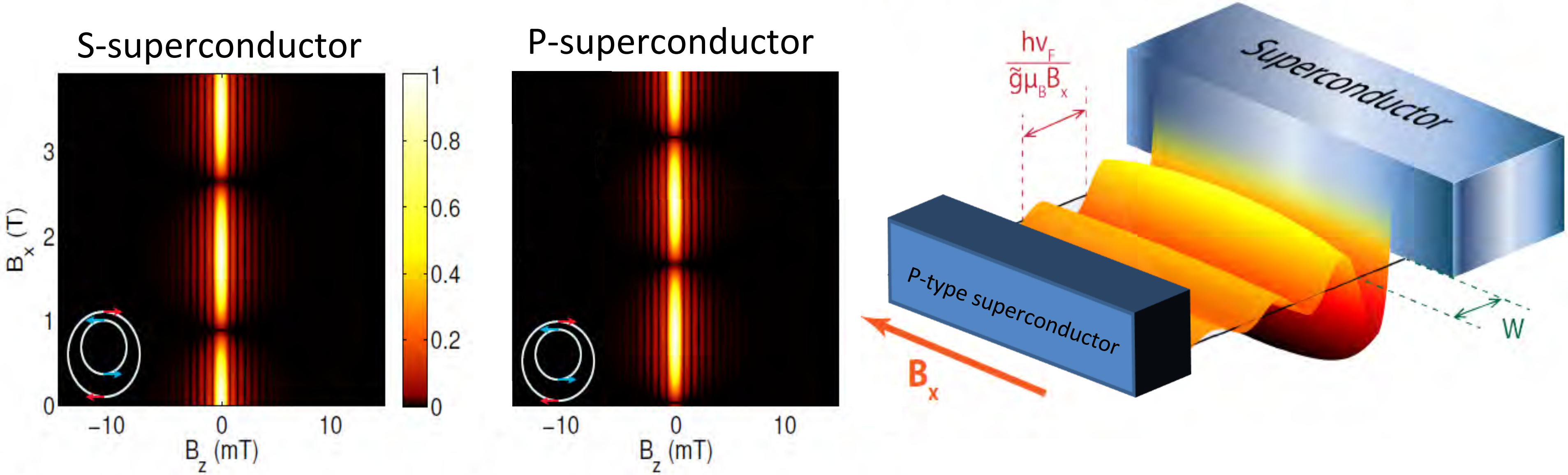




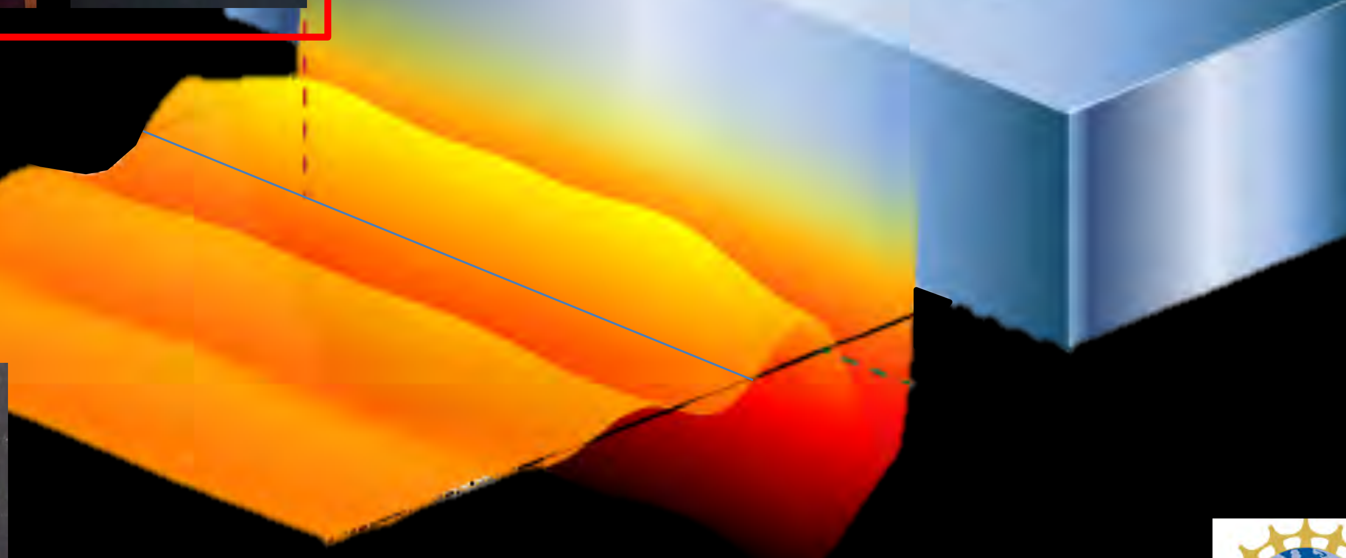
A New Spin on Superconductivity

Sean Hart, Hechen Ren, Michael Kosowsky, Bert Halperin, Harvard University
L. Molenkamp's group, University of Wurzburg

Triplet pairing



In collaboration with:
F. Pientka, A. Keselman, A. Stern, E. Berg

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