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Magnetic and superconductive **proximity effects** in bilayer and trilayer thin film hybrids of a topological insulator, ferromagnet and cuprate superconductor: A possible new platform for Majorana nano-electronics

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[1] Gad Koren, Phys. Rev. B **97**, 054405 (2018).
[2] Gad Koren, Supercond. Sci. Technol. **31**, 075004 (2018).

Proximity Effects (PE) in thin-film hybrids of:
FM-ferromagnet, TI-topological insulator, SC-superconductor

- Simple hybrids are: bilayers 

 & trilayers 

- We have chosen: The itinerant ferromagnet $SrRuO_3$ as the FM layer, $Bi_{0.5}Sb_{1.5}Te_3$ or Bi_2Se_3 as the TI layer & UD $YB_2Cu_3O_{6+x}$ as the SC layer
- Results found:

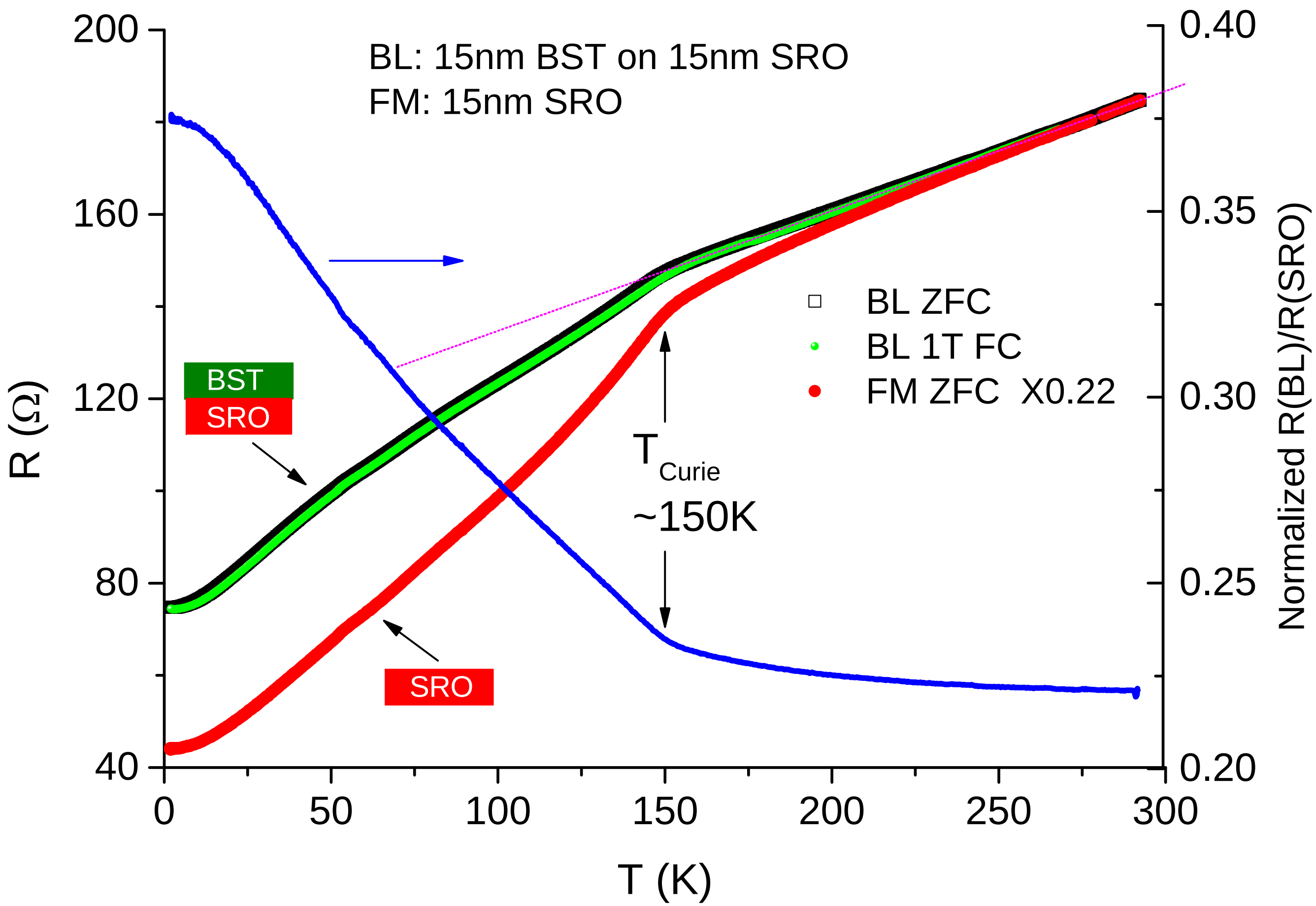
  - A strong proximity-induced ferromagnetism in the TI layer by the "weak" FM layer in the bilayers

  - Strongly suppressed superconductive PE and ferromagnetism in the TI layer of the trilayers
- In a trilayer network of weakly-connected grains under magnetic fields, the existence of Majorana fermions can be realized

  → Possible applications in quantum computing

Transport properties of the bilayers R vs T 

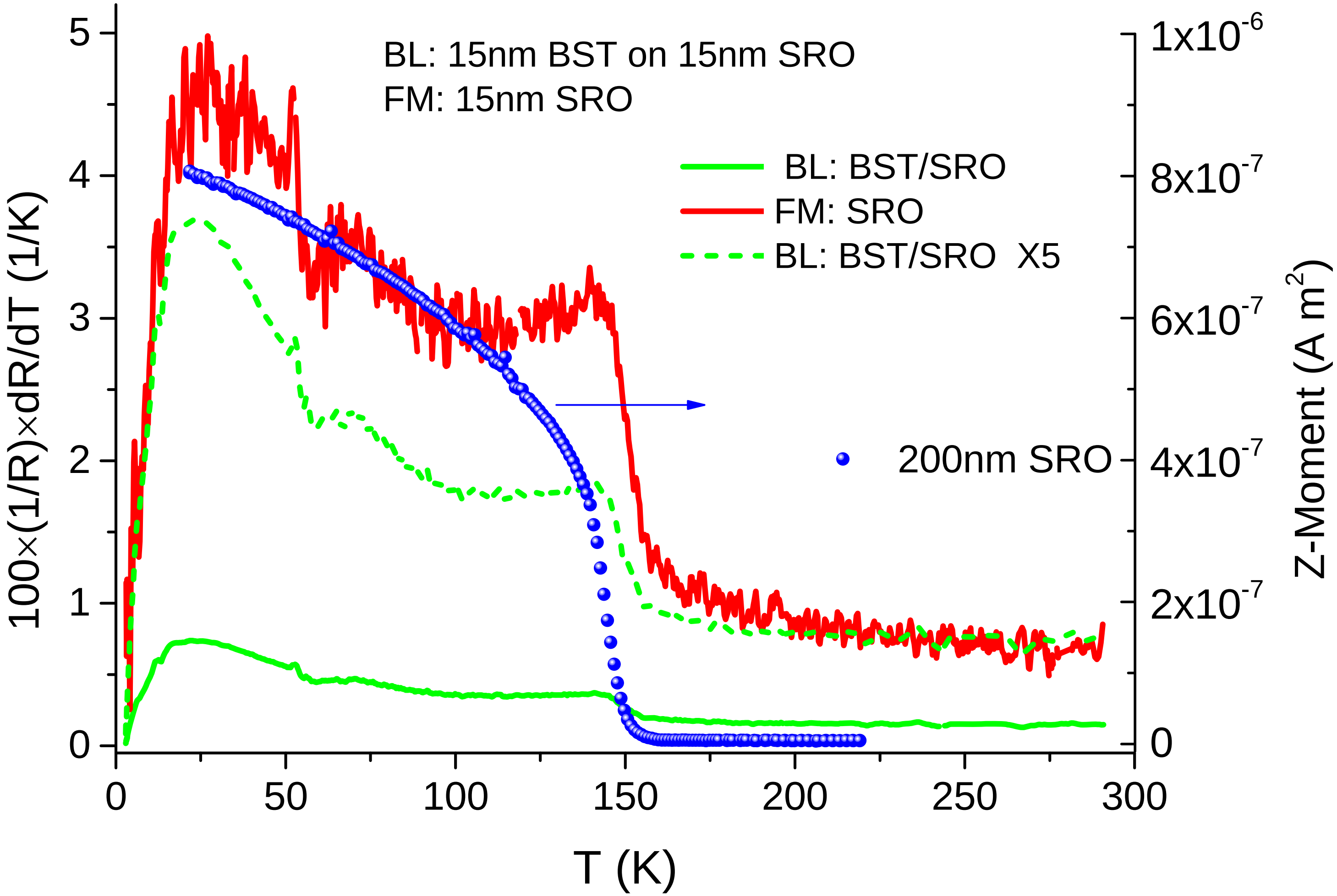
- SRO is the FM reference layer
- FM transition at 150K also in the bilayer
- Increasing ratio of R(BL)/R(FM) below T_{Curie} similar to the magnetization (see next slide)



MPE seen by the Temperature Coefficient of Resistance

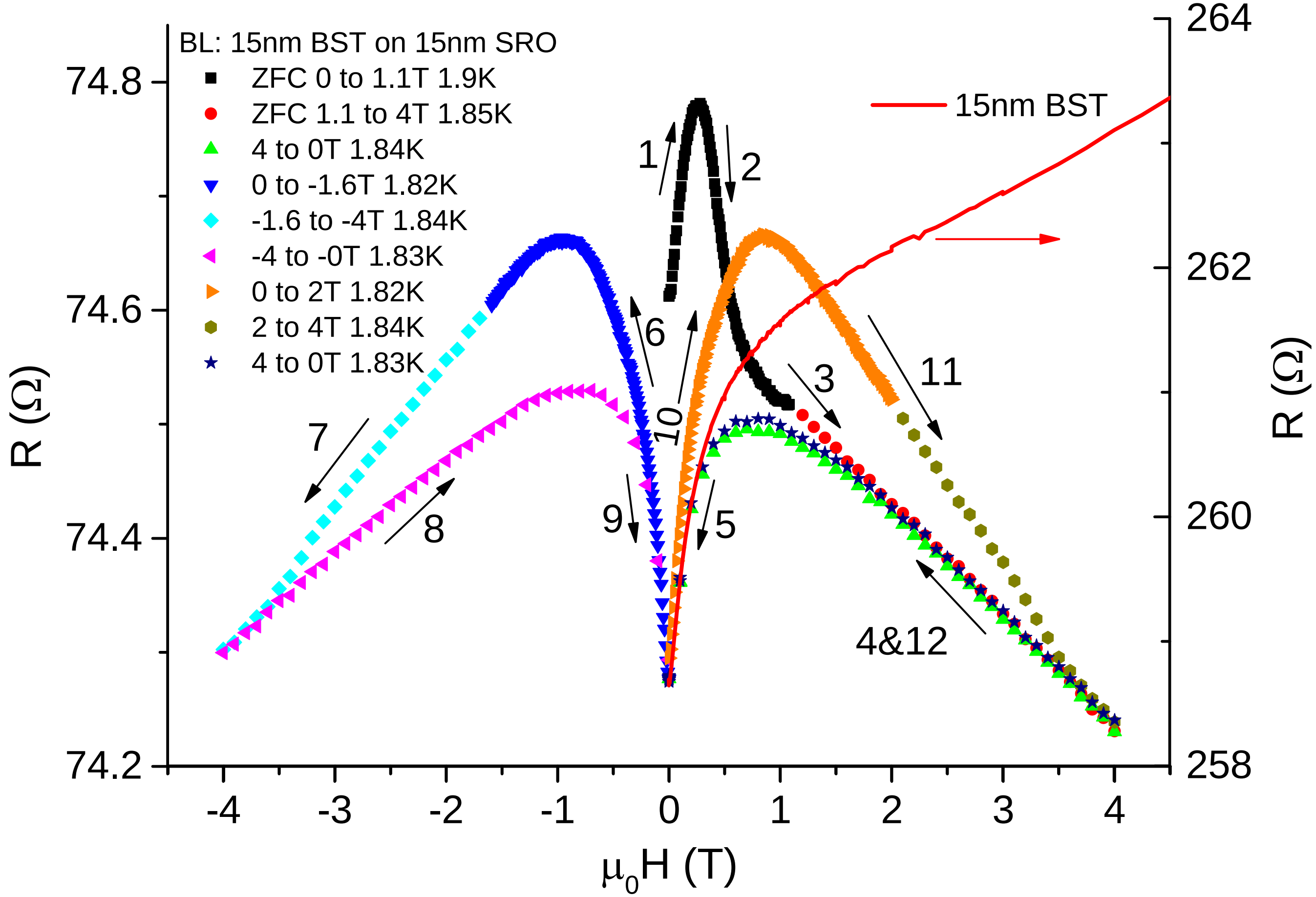
- Similarity of the TCR to magnetization
- TCR in BL, normalized above T_C to that of the reference FM layer, is suppressed

→ Clear signature of a magnetic PE (or MPE)



Magneto-Resistance (MR) loops of the bilayer

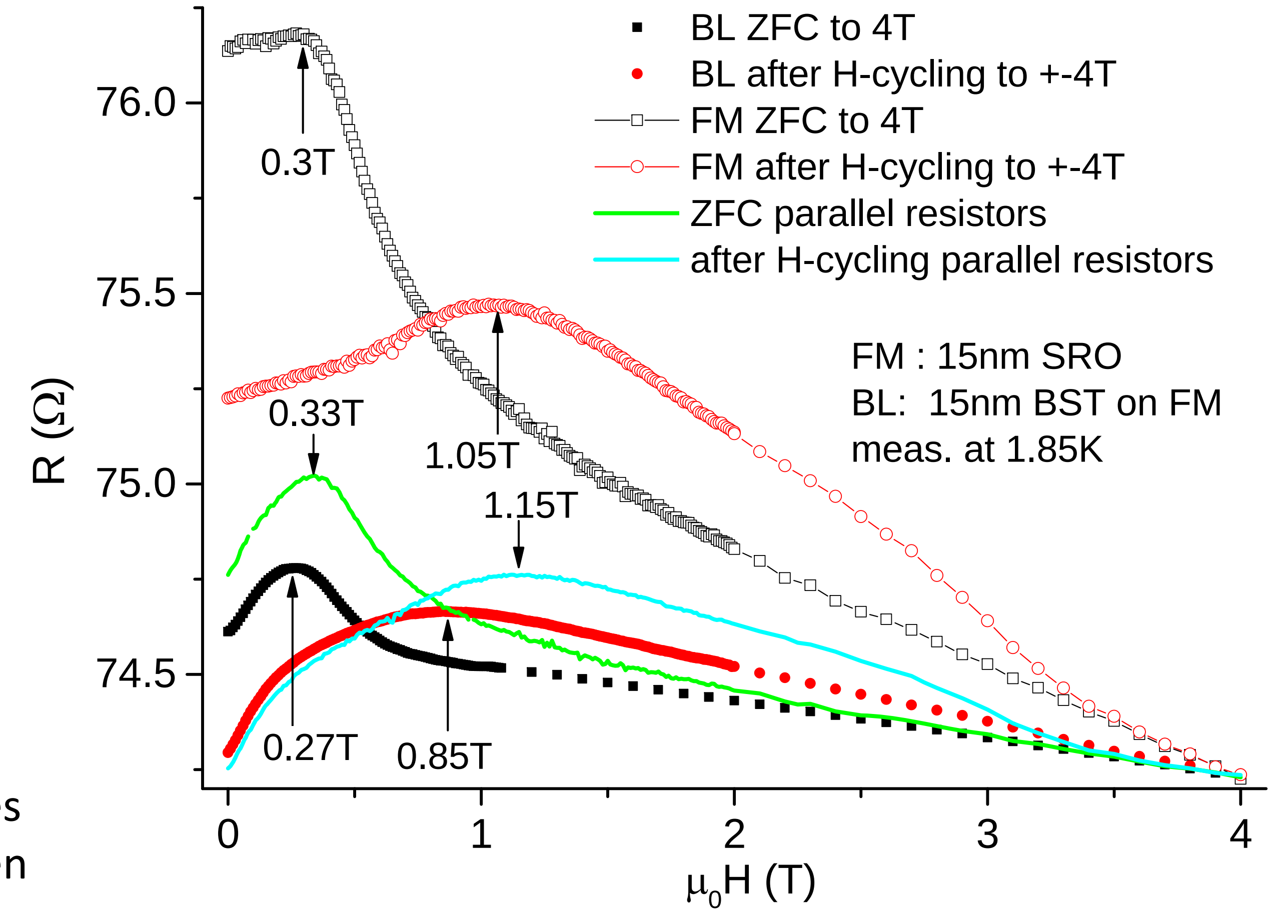
- ZFC starts with many small magnetic domains → higher R(0T)
- Anti-localization in the TI (BST) (#1) See Ref. BST film
- Aligned domains at 4T, reversed only at coercive H of about -1T (#6)
- Then symmetric loops persist (#8-12)



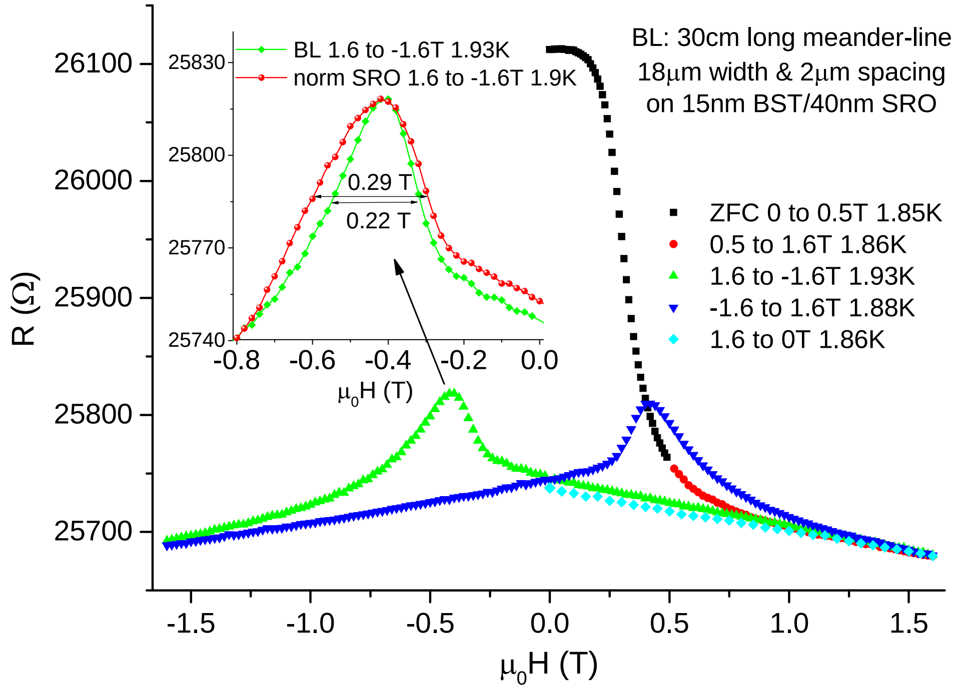
Measured MR vs calculated MR for 2 resistors in parallel

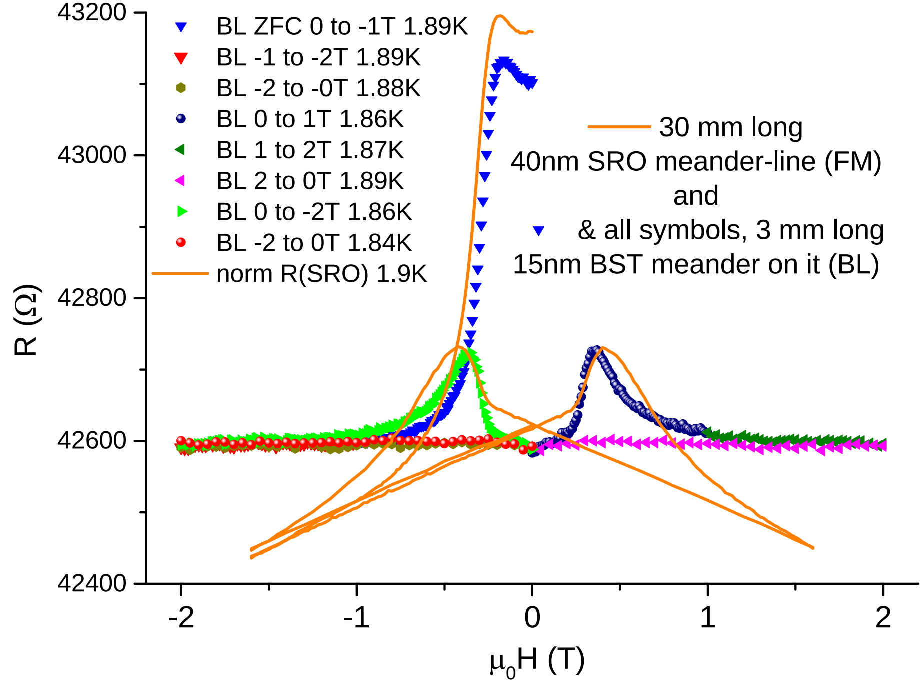
- Measured MR of BL taken from previous slide (#1, 2, 3 & 12)
- Reference MR of stand-alone FM film
- Calculated parallel resistors MR from normalized resistances at 4T

→ Suppressed H_{Coer} for BL vs H_{Coer} of the parallel resistors model, indicates clear interaction between the layers via the MPE



Observed MR loops in meander lines of BL and Ref. FM film with a thicker FM layer

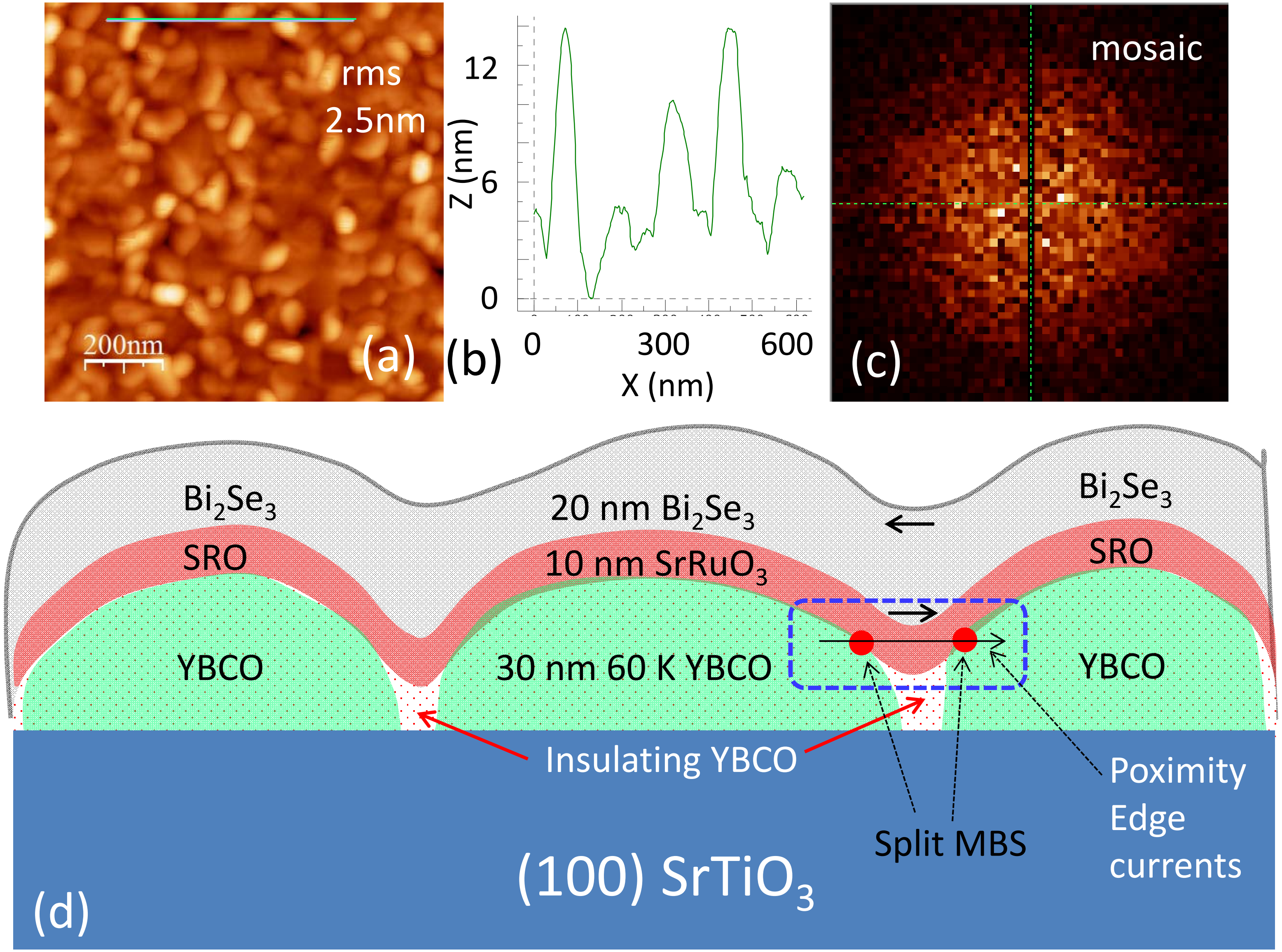




- Meander lines patterning is used in order to increase sensitivity
- Left figure for ***in-situ*** prepared and patterned BL
- Right figure for ***ex-situ*** prepared and patterned Ref. FM film which was measured, Then this was followed by the TI layer deposition and patterning yielding the BL

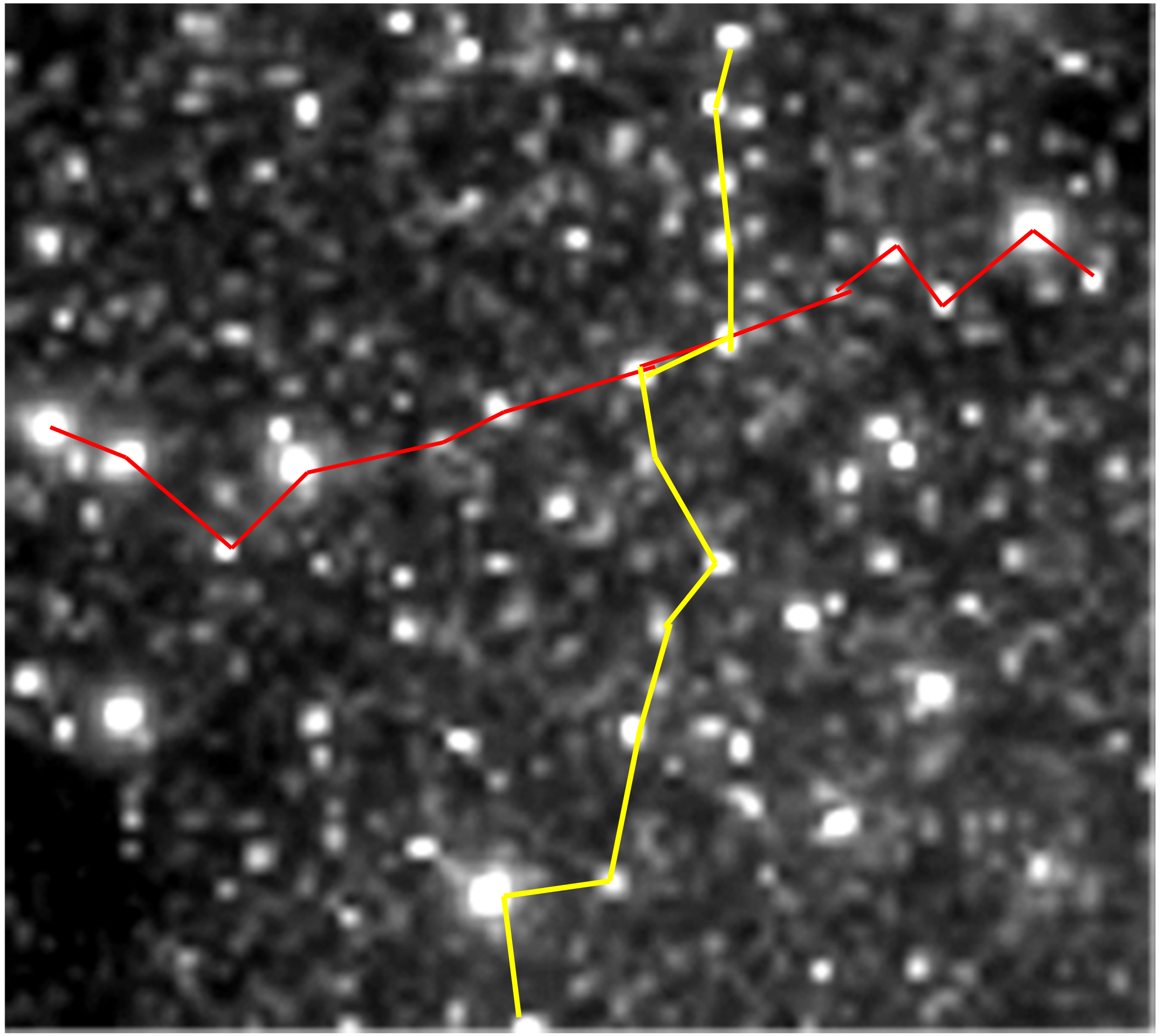
→MPE clearly shifts H_{Coer} to lower values in the BL & narrows the coercive peak as compared to those of the Reference FM film

Next we move to **trilayers** – proposed scenario (**model**)



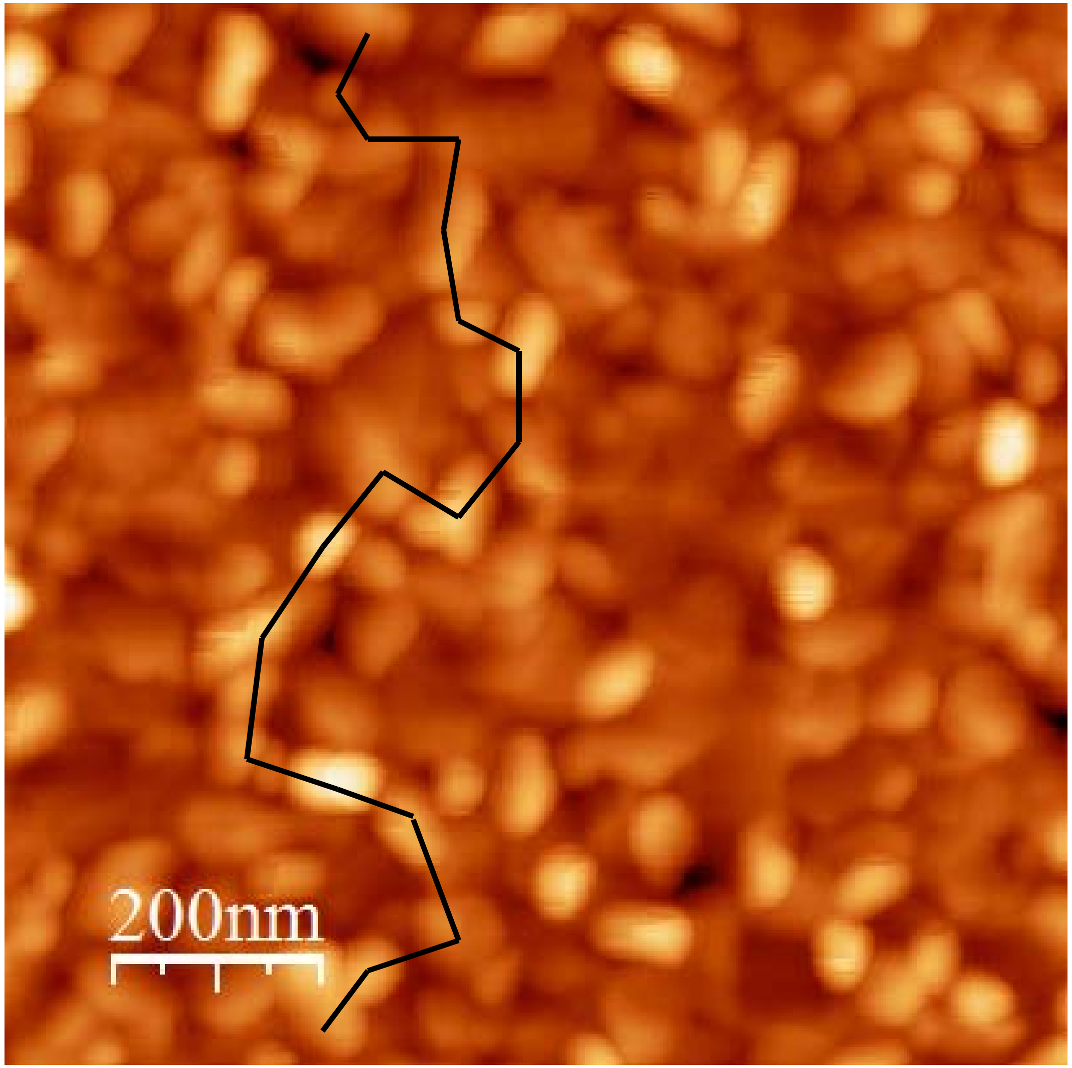
Visualization of **weak-links network** connecting SC grains: The current percolation paths are the **network channels**

- Image of stars in a galaxy (beyond the event horizon of two merging black holes)
- Brighter stars represent stronger SC grains of the T_C~60K phase
- Darker areas in-between represent the weak-links
- Drawn are 2 representative percolation paths or channels between the SC grains forming the network, via which the current flows



And in the actual trilayer: Weak-links network between SC grains

A current percolation path between grains of the trilayer is shown, representing one channel in the network of weak-links



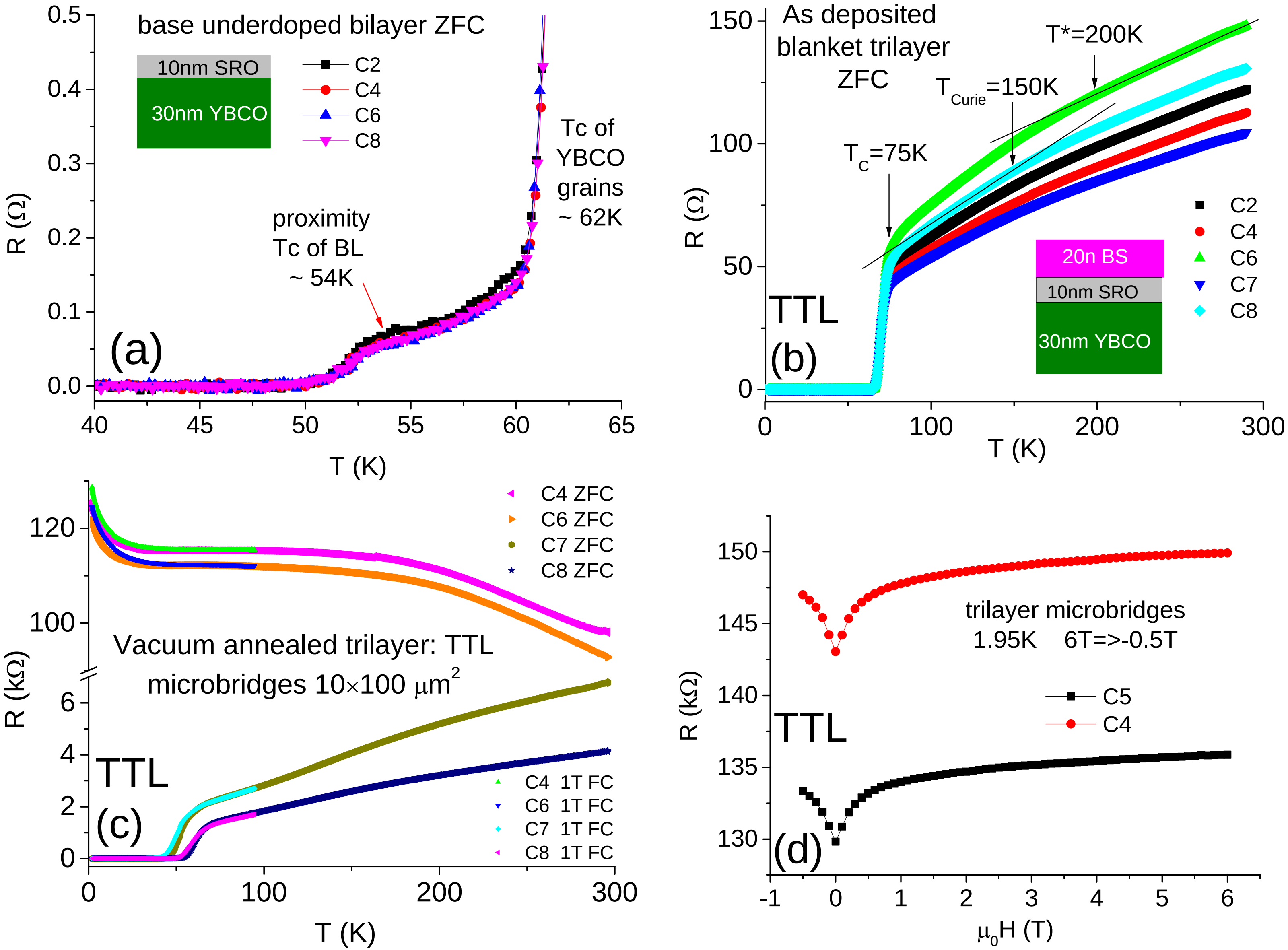
Transport properties: R vs T & R vs H of FM/SC BL & TTL

(a) SC PE in BL

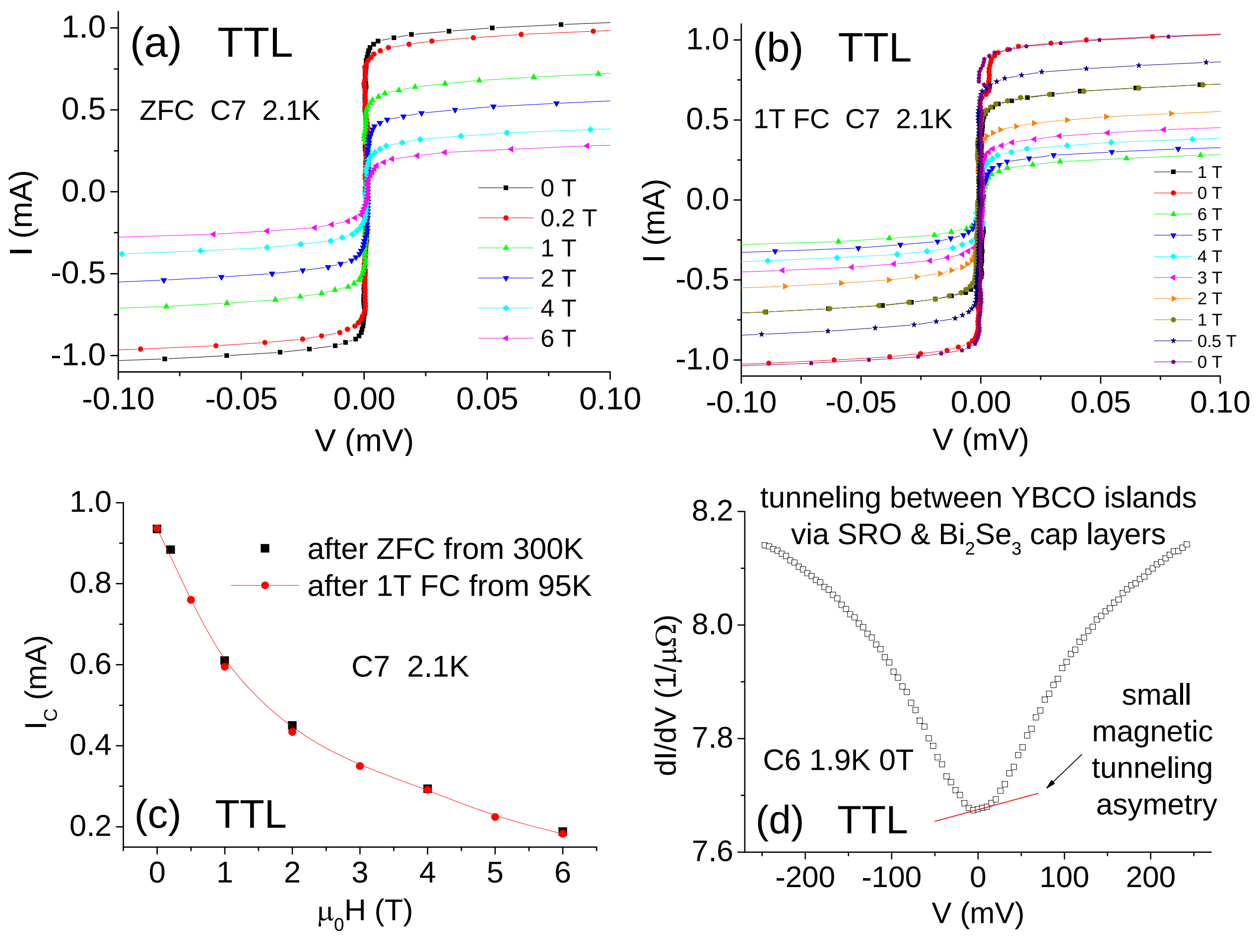
(b) UD & PG T_C < 75K

(c) SC and insulating μ-bridges: percolation

(d) Anti-localization in the TI

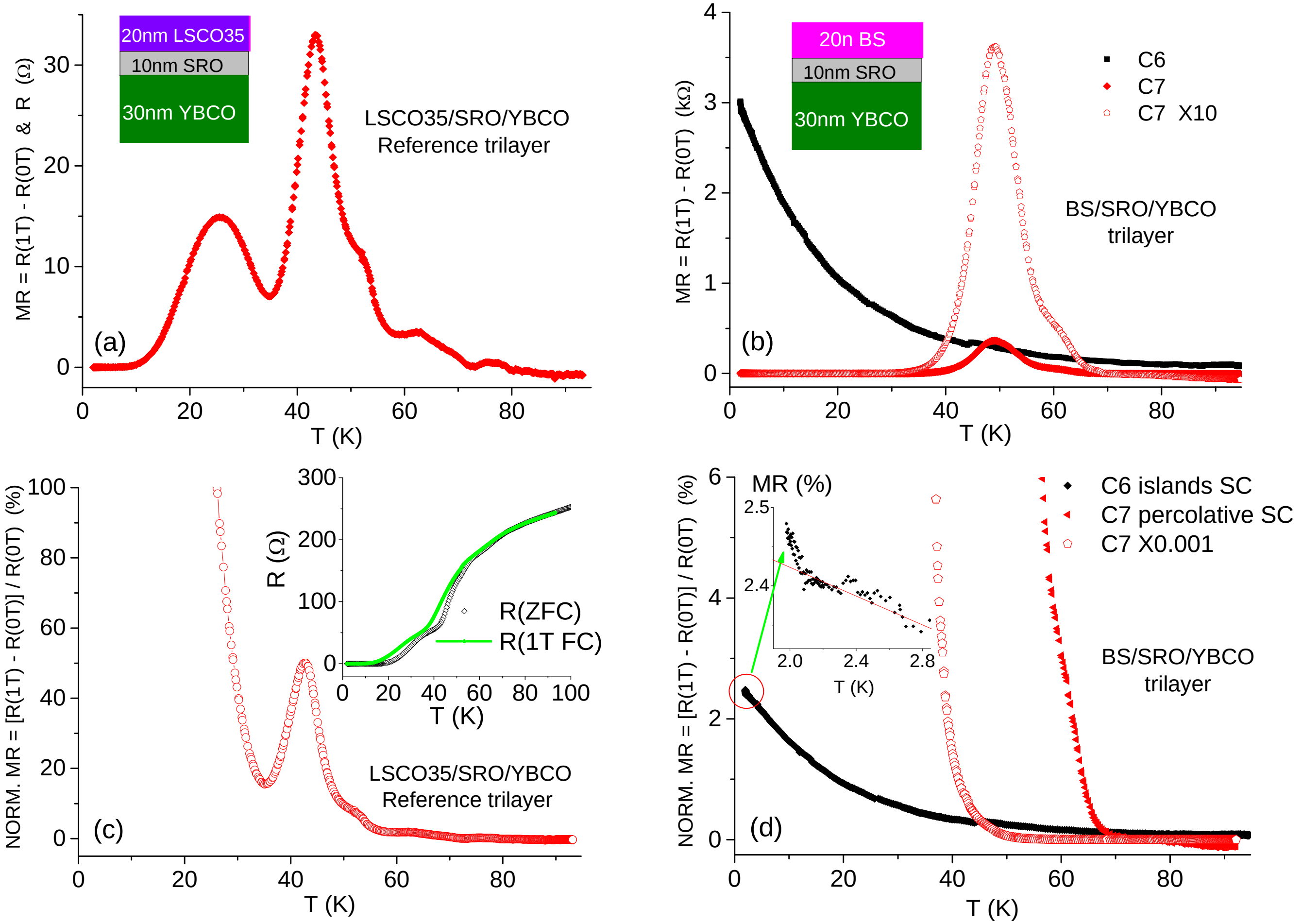


Ic data of an SC bridge under field: same under ZFC and FC & dI/dV of an insulating bridge (d): magnetic asymmetry



Magnetoresistance (MR) vs temperature (T) of a Reference TL (RTL) & a Topological TL (TTL)

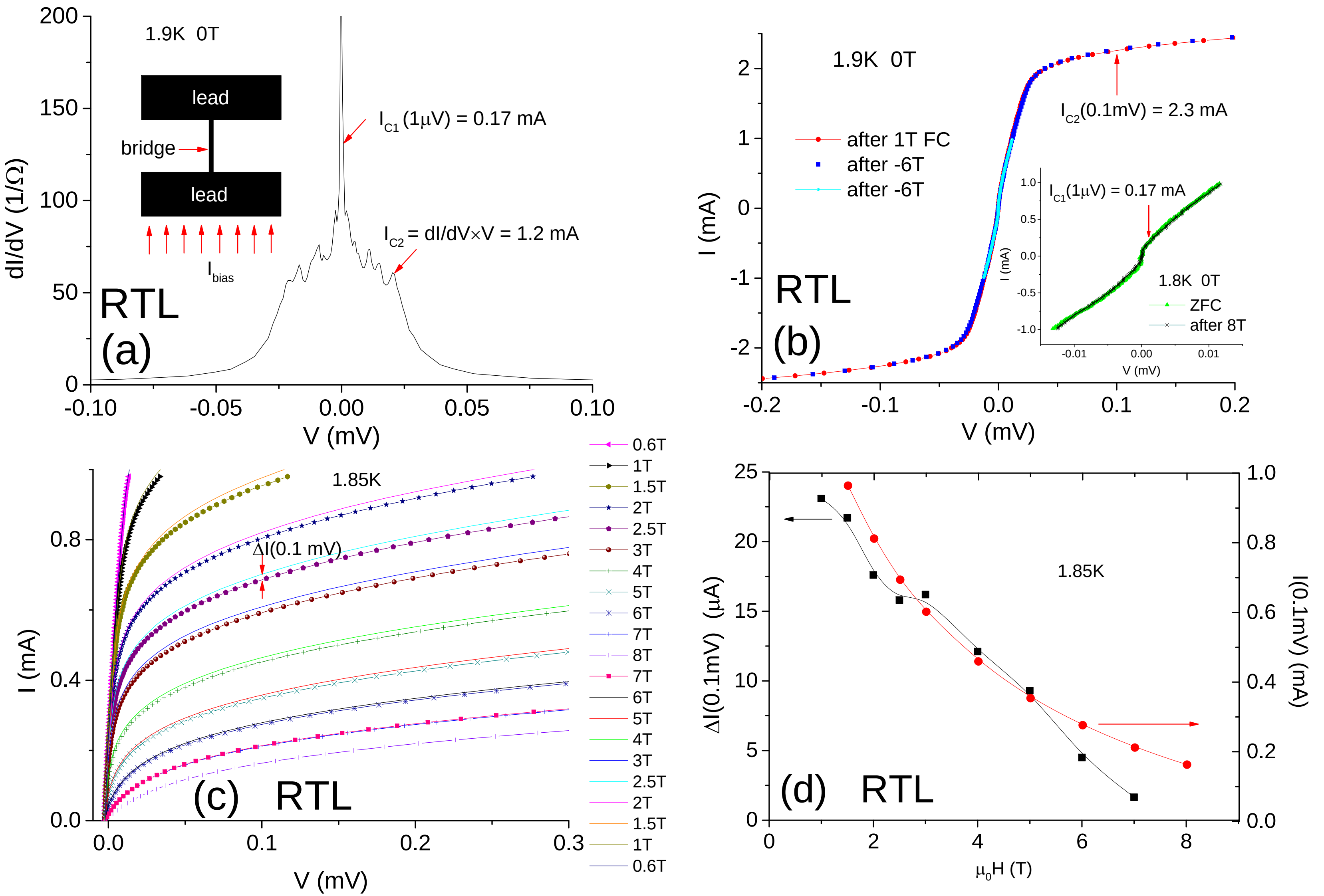
- RTL is needed in order to clarify what is the role of the TI layer
- Peaks in MR show competition between flux flow MR & pinning
- 2 peaks in RTL due to 2 transitions (SC & PE)
- MR in SC TTL (C7 of b) is strongly suppressed and shows no PE peak
- In the insulating bridge (C6 of b), see only MR leading-edge which still indicates SC (of grains)



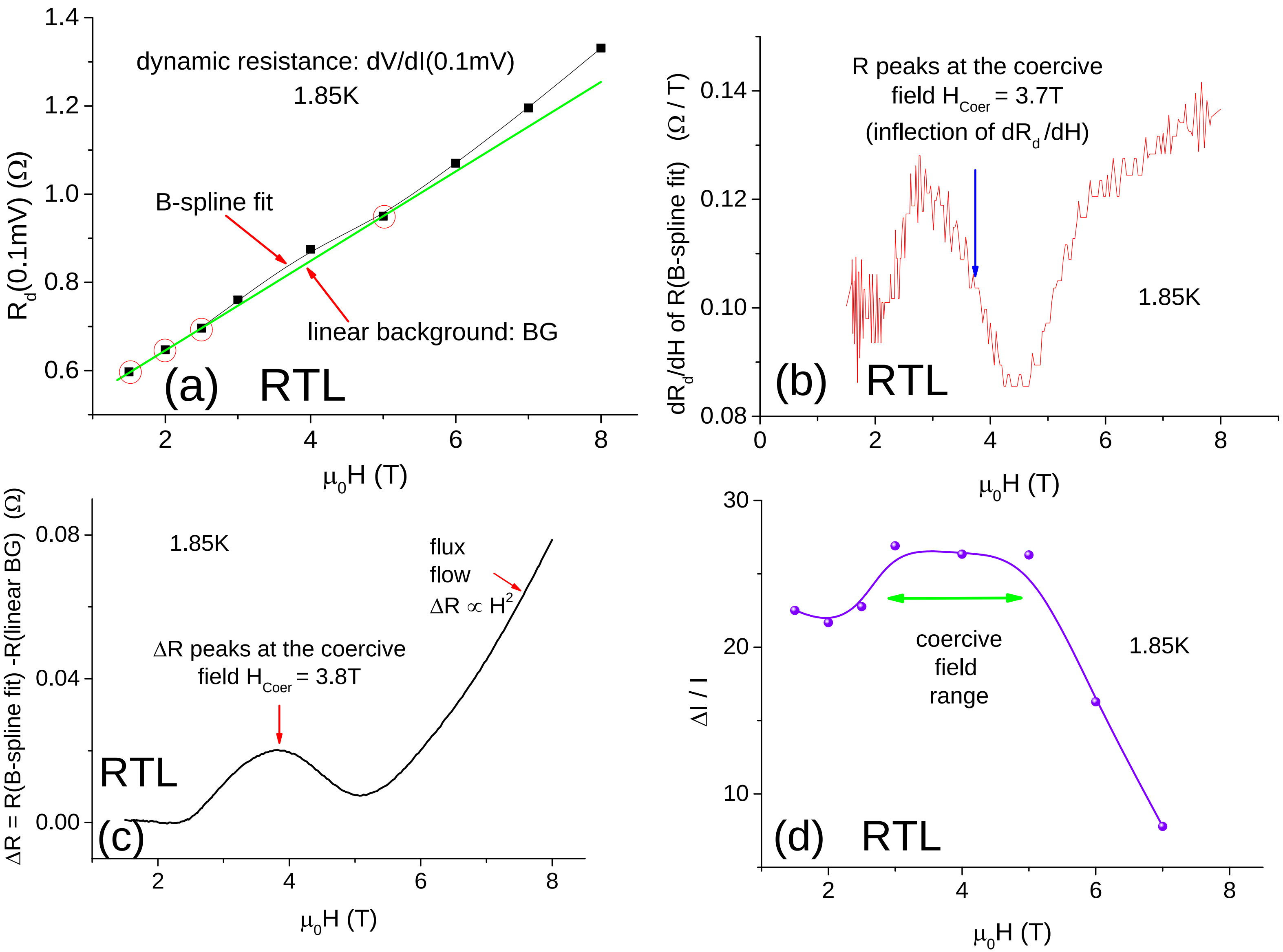
RTL properties

2 Ic of Leads & of bridge

Hysteresis indicates magnetism of FM layer remains



More RTL properties – coercive field at 3.8T



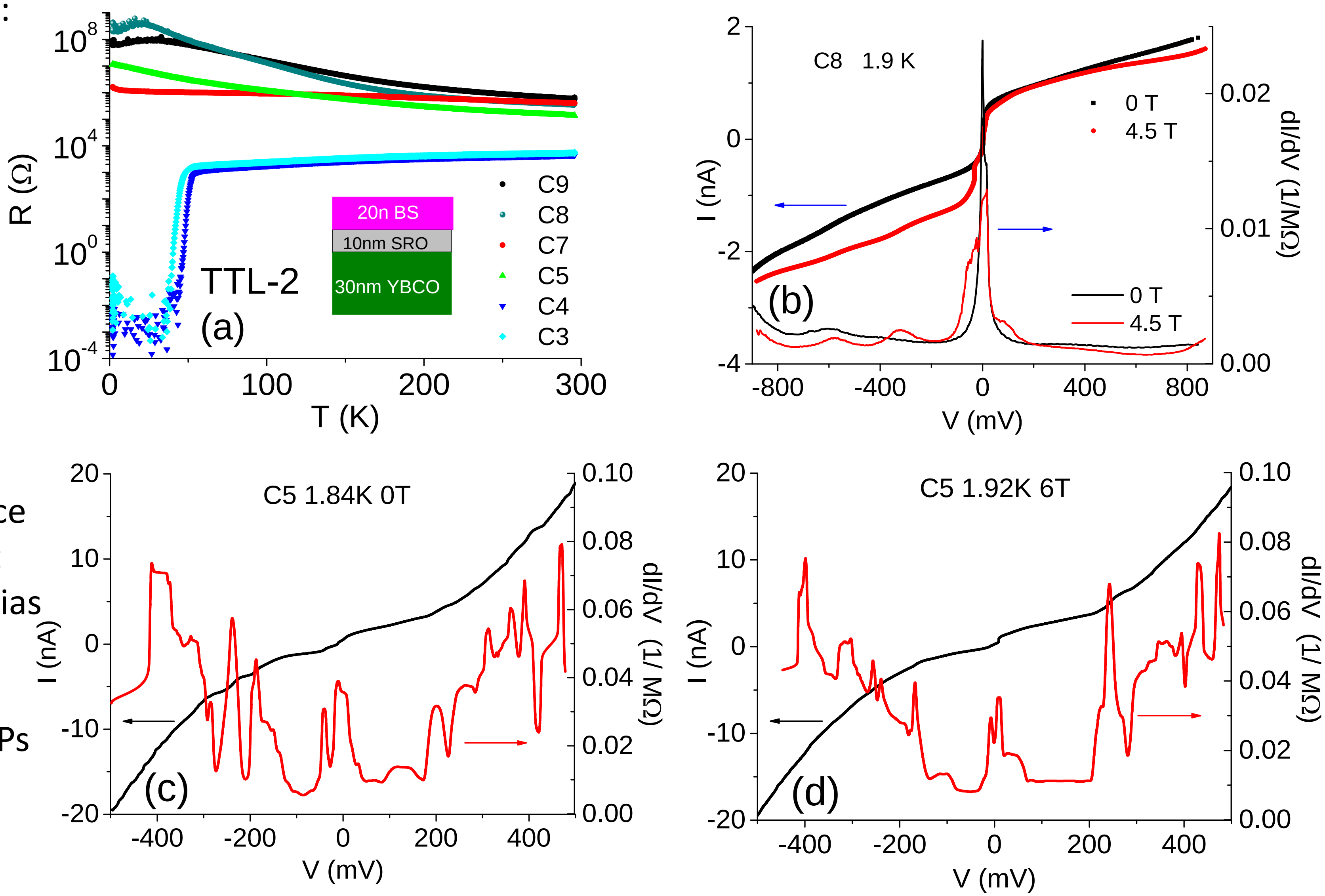
Possible existence of Majorana zero modes in a high resistance bridge

High R (C8):

→less conductive channels in the network

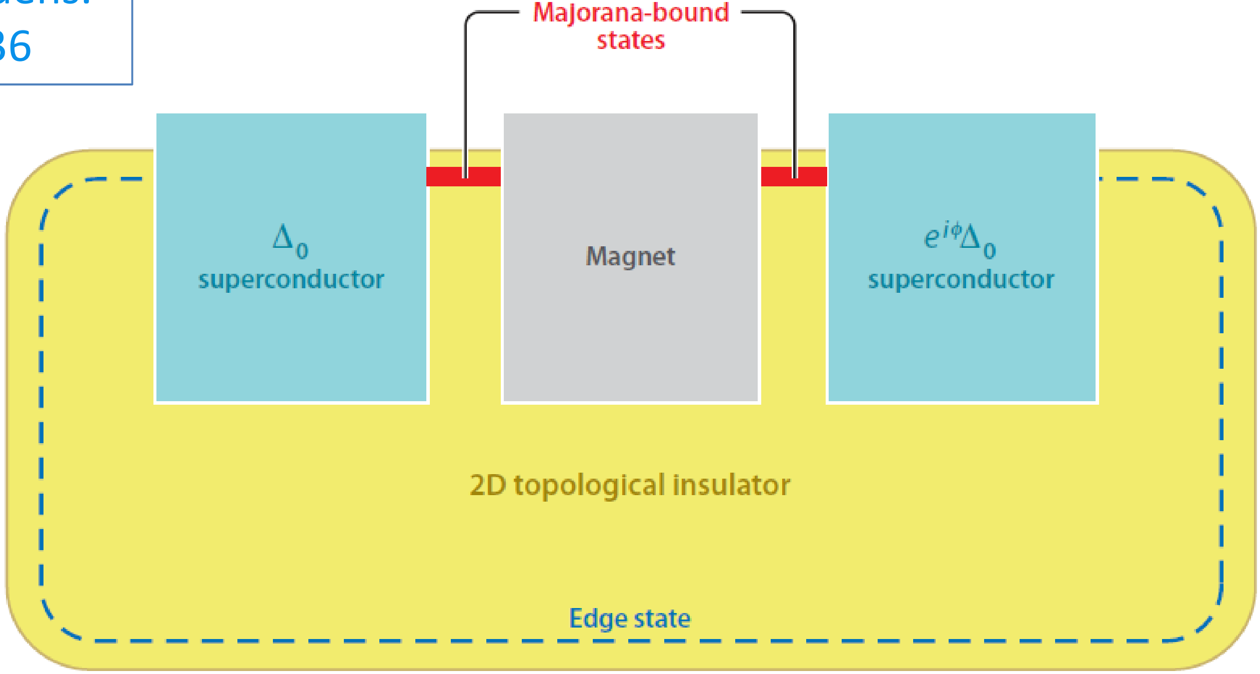
→less conductance Features at Non-zero bias

→enables seeing ZBCPs or MBS



Majorana Bound State (MBS)

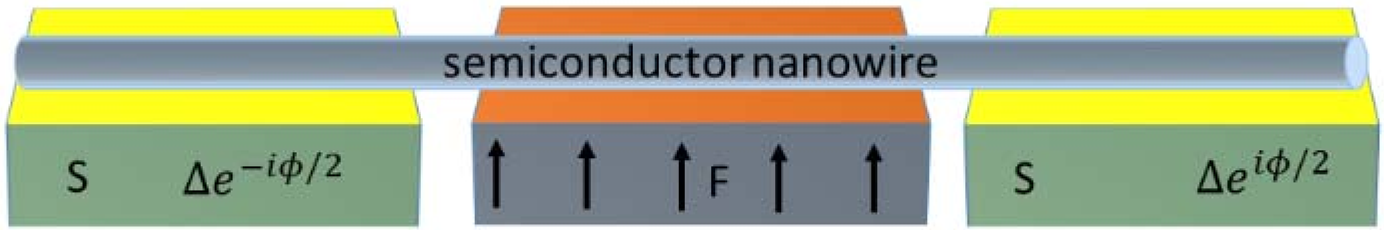
Beenakker, Annu. Rev. Condens. Matter Phys. 2013. 4:113–36



Top view of a 2D topological insulator, contacted at the edge by two superconducting electrodes separated by a magnetic tunnel junction. A pair of Majorana fermions is bound by the superconducting and magnetic gaps.

Alternatively: Lu & Heikkila, arXiv:1905.11135 May 2019

Large Spin-Orbit Coupling in the nanowire, similar to TI



Conclusions

- Magnetic Proximity Effect (MPE) in TI/FM bilayers was demonstrated

- TI/FM/SC trilayers are harder to analyze
- Nevertheless, signatures of the single layers in them were found (Anti-localization of the TI, magnetism of the FM & critical currents in the SC)
- With reduced number of channels in the current network, signature of Majorana fermions (MBS) was found, which could be used in practical applications in future quantum computers