LETTER

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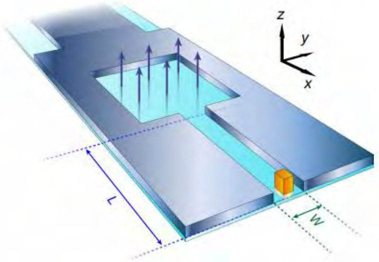
Topological superconductivity in a phase-controlled Josephson junction

Hechen Ren[1,2], Falko Pientka[1,3], Sean Hart[1,4], Andrew T. Pierce[1], Michael Kosowsky[1], Lukas Lunczer[5], Raimund Schlereth[5], Benedikt Scharf[6], Ewelina M. Hankiewicz[6], Laurens W. Molenkamp[5], Bertrand I. Halperin[1] & Amir Yacoby[1]*



Outline

- Motivation
- System + relevant transport quantities
- Theory, Measurements, and Analysis
- Outlook

Motivation

Topological SC could support Majorana states at their boundaries, which would be great to use for qubits some day

Even if the growing collection of signatures of Majoranas is indeed what they are claimed to be, creating a (scalable) system of qubits on 1D systems is extremely challenging

- ➔ intrinsic instabilities in most 1D systems
- ➔ obvious technological obstacles in implementation (even given first point is overcome)

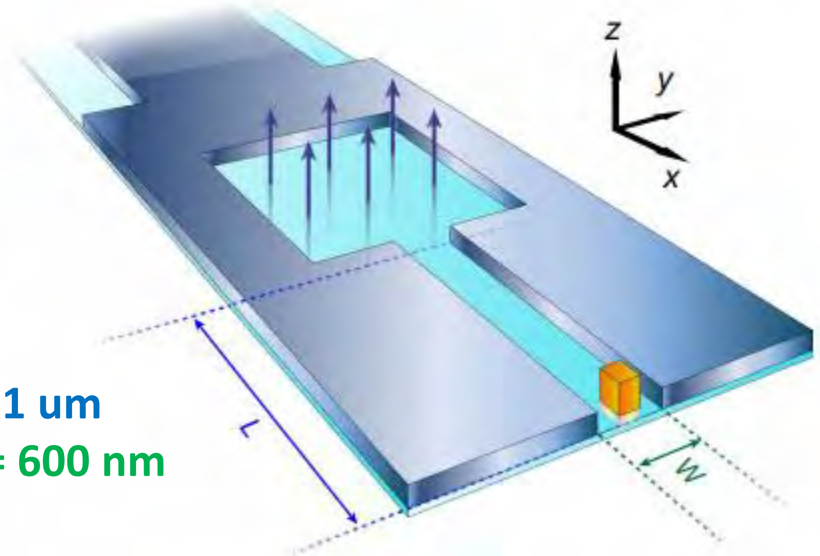
To utilize and understand the full potential of MBS physics, 2D platforms are in demand

- ➔ patterning large-scale networks more* feasible
- ➔ easier* to integrate with other quantum information devices/systems in reproducible/controlled fashion

$* \gtrsim \varepsilon$

Device

- Josephson junction made from HgTe coupled to thin-film aluminum
- Au tunnel probe above edge of the junction to probe the local DOS
- B_z to control phase difference ϕ across junction, B_x to control E_z



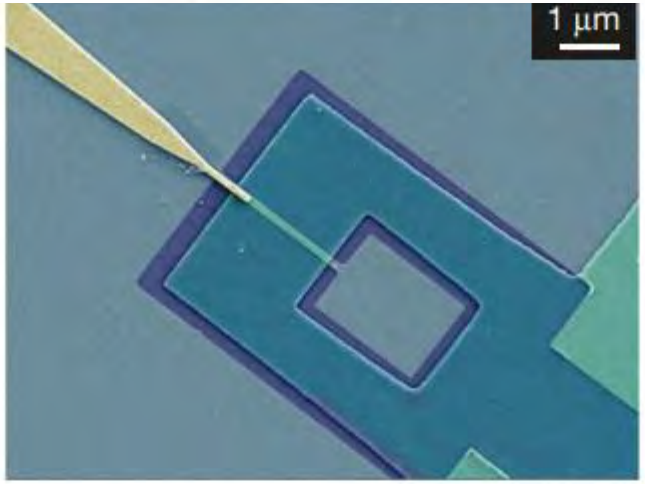
L = 1 um
w = 600 nm

8 nm deep HgTe quantum well

5 nm Ti + 15 nm Al: superconducts up to ~1.8 T (in plane)

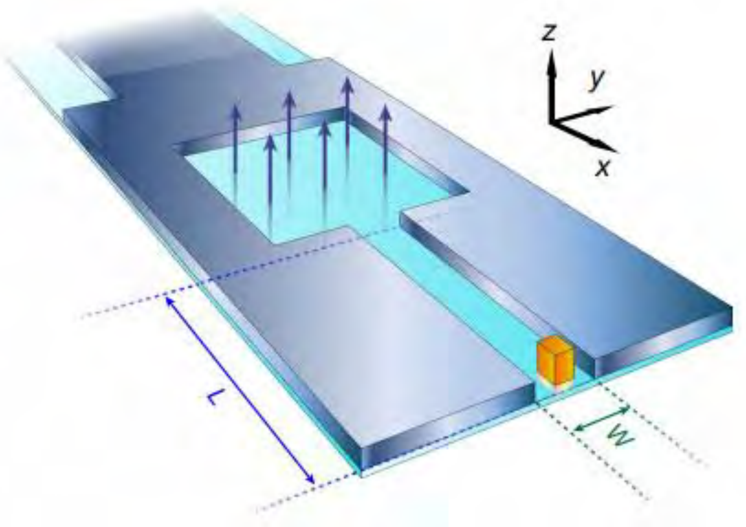
Mobility = 400k cm^2/Vs

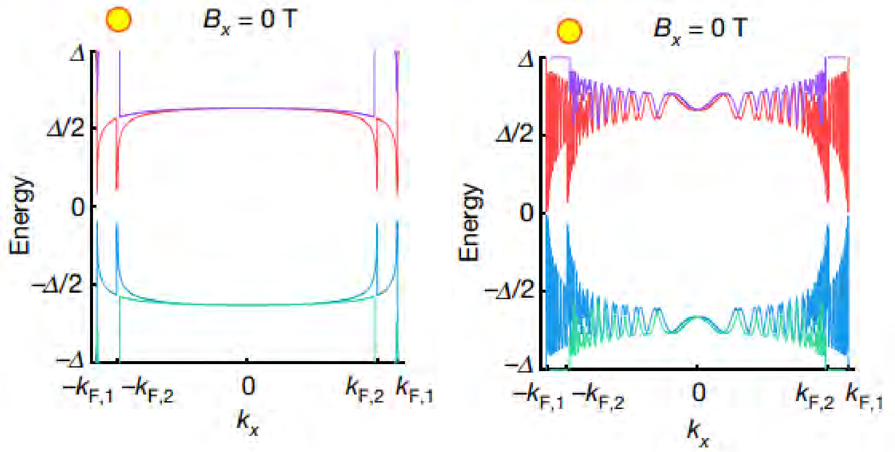
n = 10^11 cm^-2



Theory

- Phase transition between trivial and topological tuned using the phase difference across the junction, ϕ, and the Zeeman energy E_z
- In long, translationally invariant JJ, the supercurrent is carried by bands of ABS in the normal region, formed by successive Andreev reflections at the N-S interfaces
- Energy of each Andreev state a function of ϕ and the phase accumulated by traveling at various angles from the x-direction. This allows for full range of wavevectors k_x, which disperse to form a continuous sub-gap spectrum
- When normal reflection is weak: get mostly flat bands as function of k_x
  Adding in normal reflection widens the bands





Theory

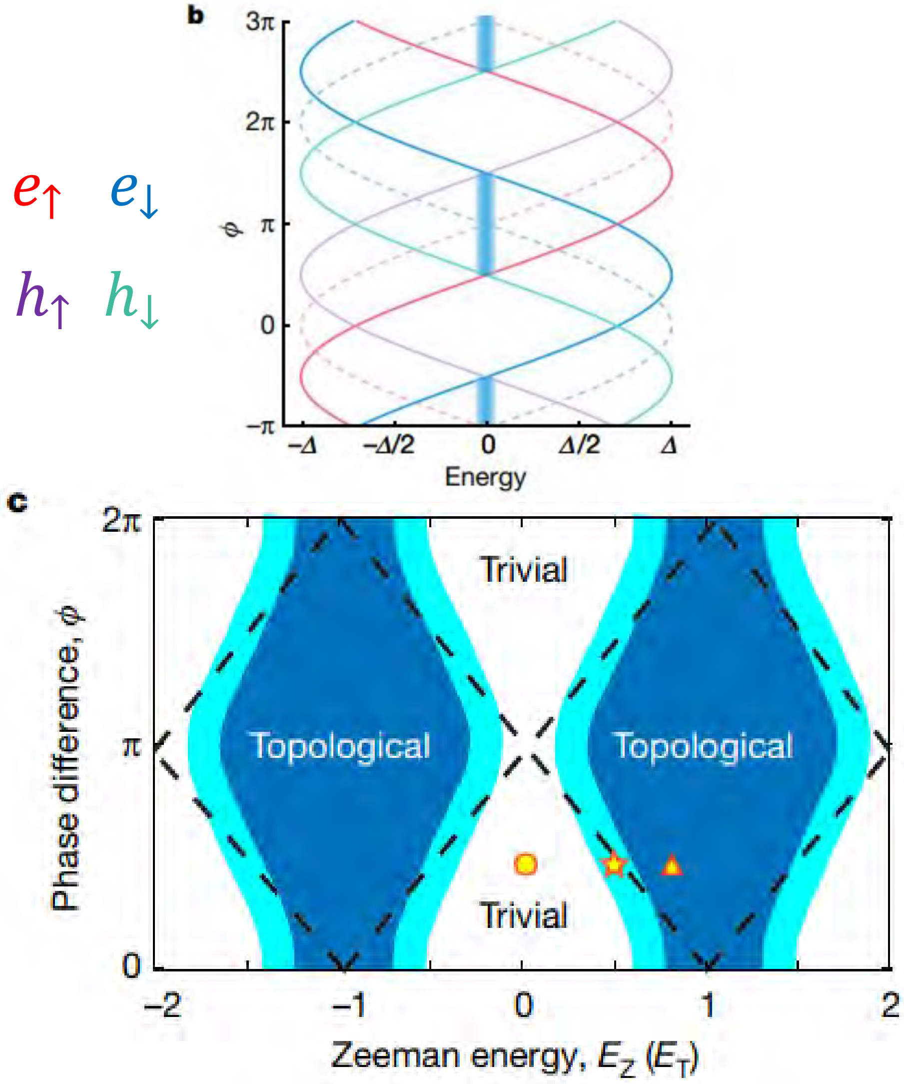
- Topological phase transition occurs (zero energy crossing) at $k_x = 0$
- With $E_z = 0$, Andreev states are 2-fold degenerate and cross at $\phi = \pi$ (in absence of normal reflection)
- Application of B_x separates $k_x = 0$ states by phase difference:

$$\Delta\phi = \frac{2\pi E_Z}{E_T} \qquad E_T = \frac{\pi\hbar v_F}{2W}$$

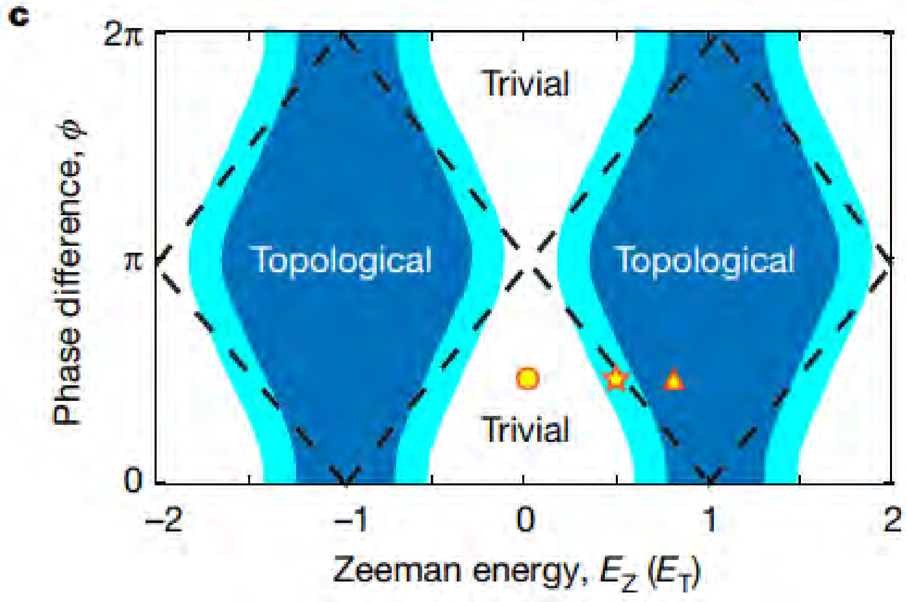
- In range of ϕ values between these crossings the occupancy of fermionic states becomes odd

  ➔System goes into topological superconducting state

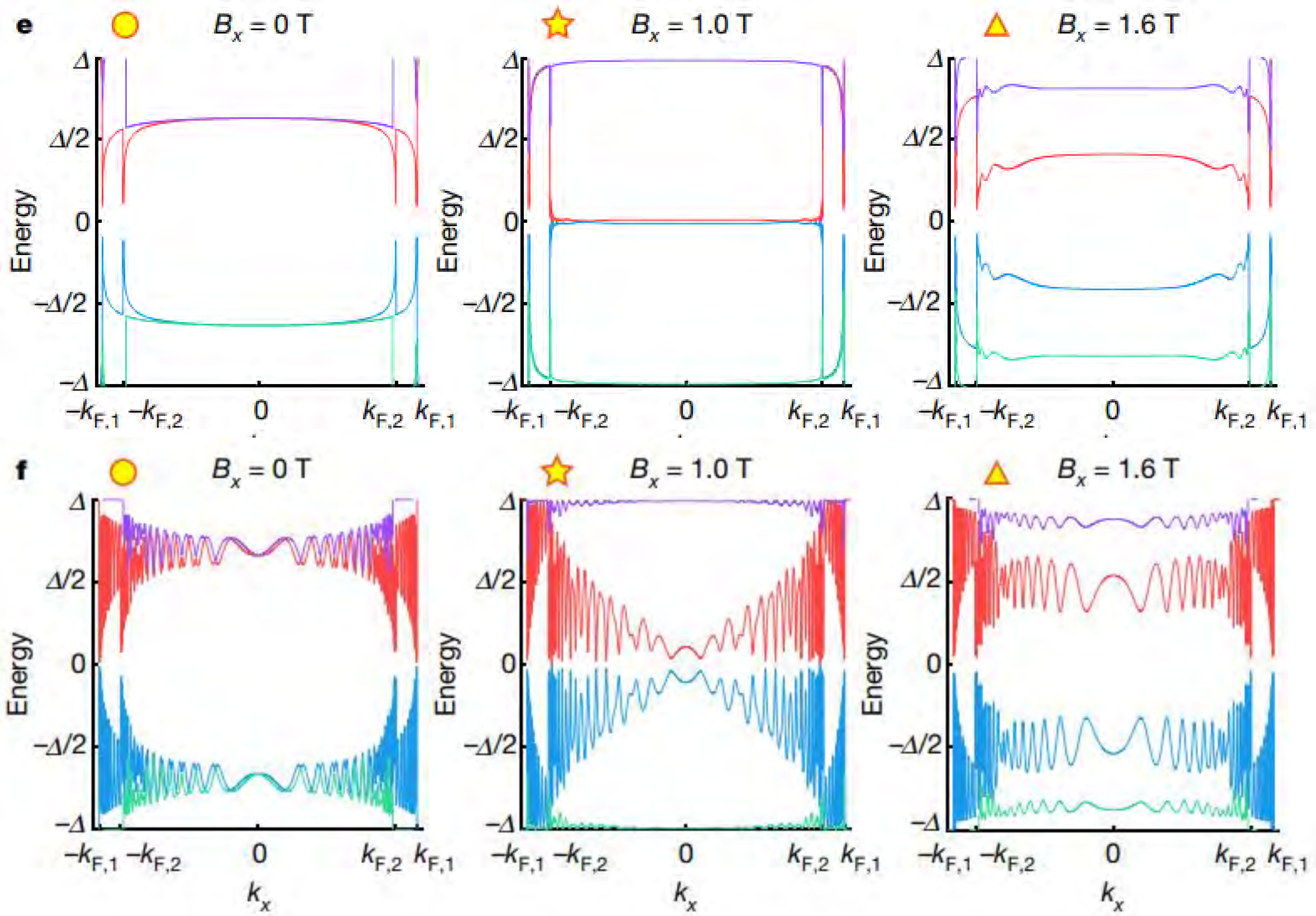
- Can map out the phase boundary in ϕ-E_Z space, yielding topological state in growing range of ϕ as E_Z→E_T
- MBS predicted at end of semi-infinite junctions (1 um is probably not semi infinite)
- Easily can control topological-trivial transition in rapid manner



Trivial-Topological Crossover



Dispersion of Andreev bands:



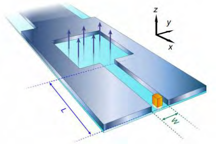
$e_\uparrow$ $e_\downarrow$

$h_\uparrow$ $h_\downarrow$

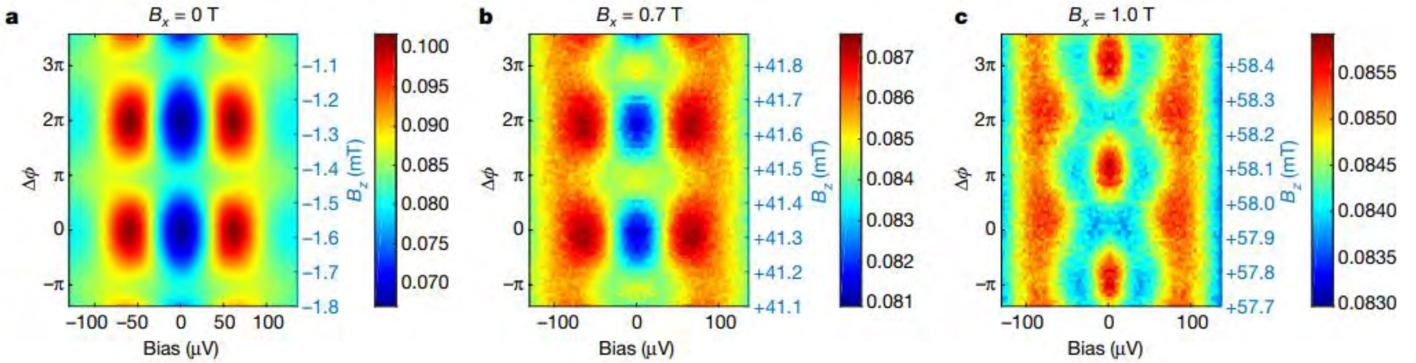
(e) without normal reflection

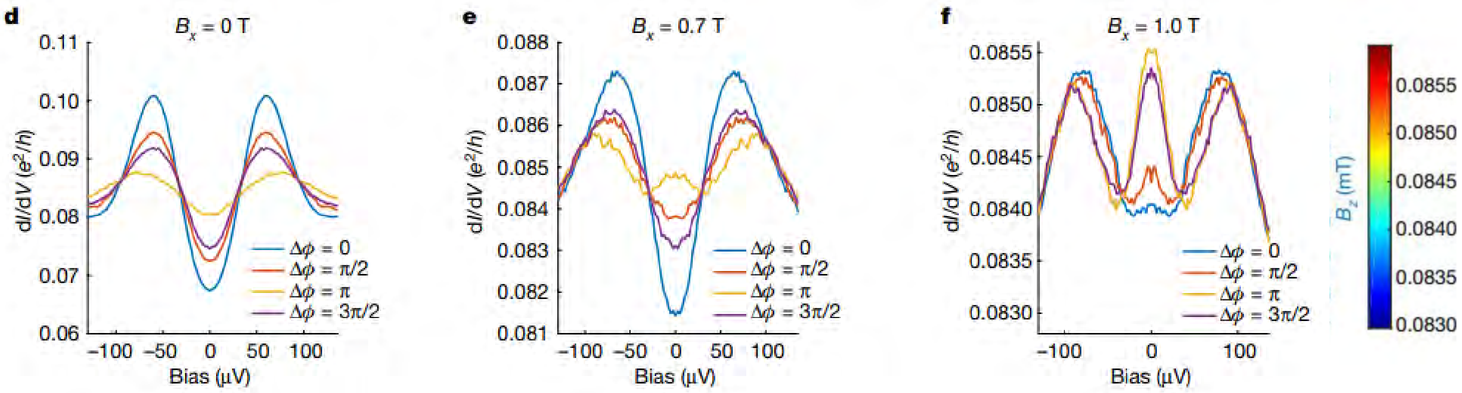
(f) with normal reflection

Measurements

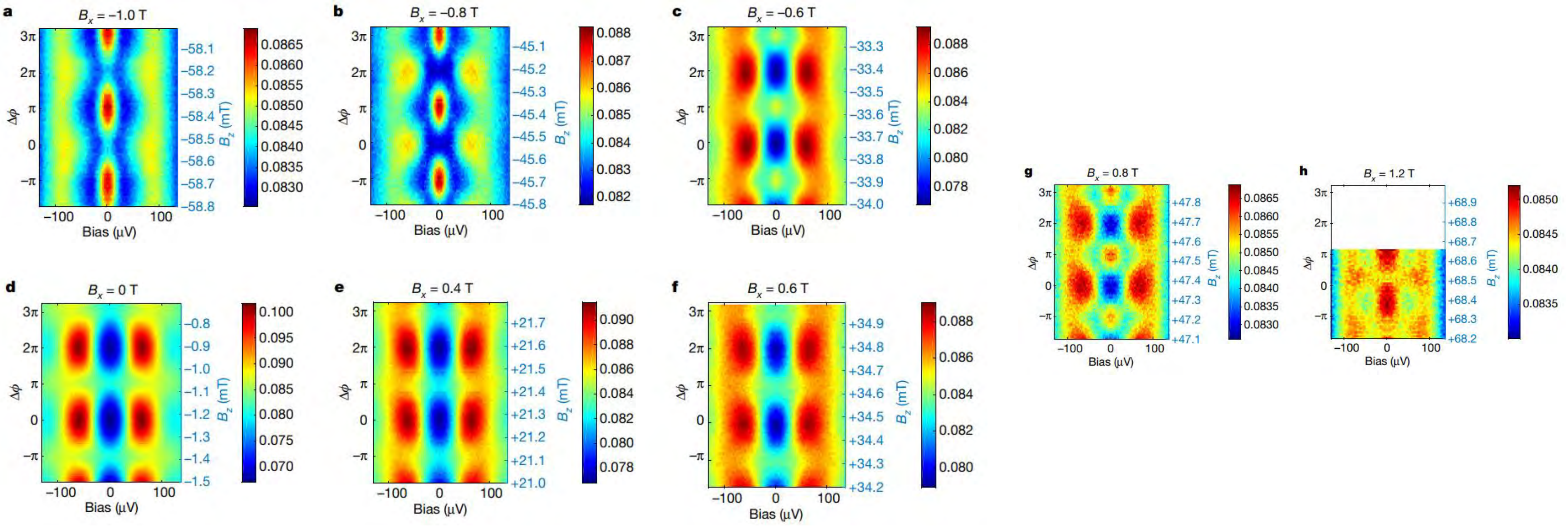


- B_z generates flux which controls $\Delta\phi$
- B_x controls E_z
- Apply AC signal on top of DC voltage to tunnel probe, measure I_{AC} through SC lead to obtain 2-point dI/dV
- At low B_x: tunneling spectra yield minima at 0 bias
  → bulk ABS
- Higher B_x: zero bias peaks over wide range of ϕ, repeating periodically

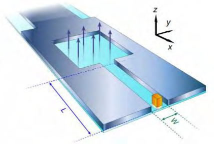




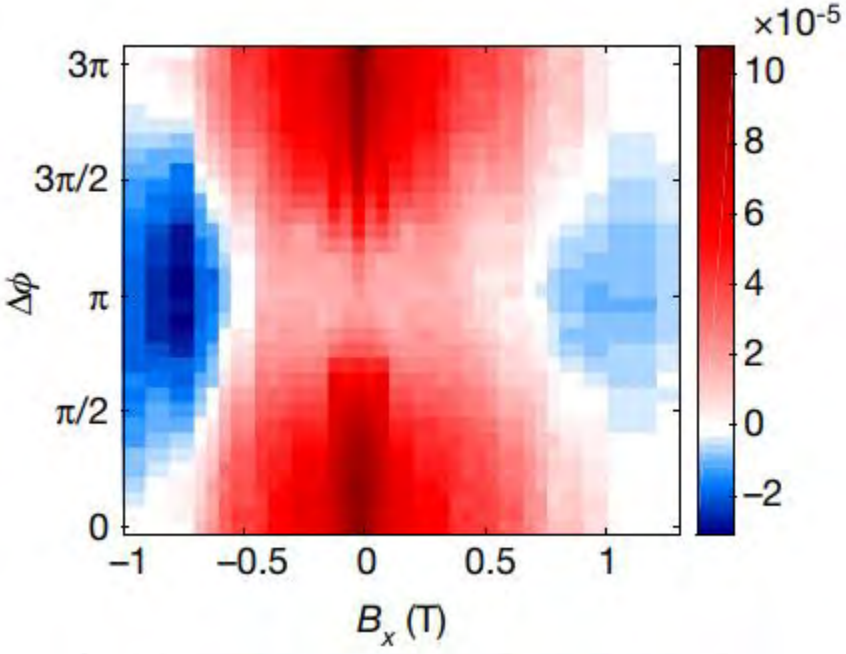
More data

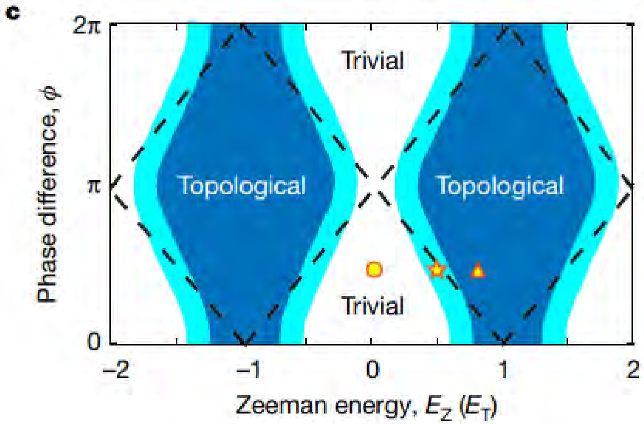

a
B_x = −1.0 T
3π
2π
π
0
−π
Δφ
−100
0
100
Bias (μV)
−58.1
−58.2
−58.3
−58.4
−58.5
−58.6
−58.7
−58.8
B_z (mT)
0.0865
0.0860
0.0855
0.0850
0.0845
0.0840
0.0835
0.0830
b
B_x = −0.8 T
−45.1
−45.2
−45.3
−45.4
−45.5
−45.6
−45.7
−45.8
0.088
0.087
0.086
0.085
0.084
0.083
0.082
c
B_x = −0.6 T
−33.3
−33.4
−33.5
−33.6
−33.7
−33.8
−33.9
−34.0
0.088
0.086
0.084
0.082
0.080
0.078
d
B_x = 0 T
−0.8
−0.9
−1.0
−1.1
−1.2
−1.3
−1.4
−1.5
0.100
0.095
0.090
0.085
0.080
0.075
0.070
e
B_x = 0.4 T
+21.7
+21.6
+21.5
+21.4
+21.3
+21.2
+21.1
+21.0
0.090
0.088
0.086
0.084
0.082
0.080
0.078
f
B_x = 0.6 T
+34.9
+34.8
+34.7
+34.6
+34.5
+34.4
+34.3
+34.2
0.088
0.086
0.084
0.082
0.080
g
B_x = 0.8 T
+47.8
+47.7
+47.6
+47.5
+47.4
+47.3
+47.2
+47.1
0.0865
0.0860
0.0855
0.0850
0.0845
0.0840
0.0835
0.0830
h
B_x = 1.2 T
+68.9
+68.8
+68.7
+68.6
+68.5
+68.4
+68.3
+68.2
0.0850
0.0845
0.0840
0.0835

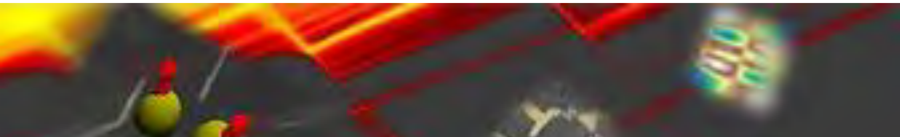
Curvature of ZBP



- Analysis of growing range of phase containing ZBP
  → grows with B_x
- Extract curvature of dI/dV around 0 bias using parabolic fit on raw data
- Done for all values of ϕ and B_x
- Positive curvature → trivial state
- Negative curvature → topological state
- Agrees well with the phase-space model

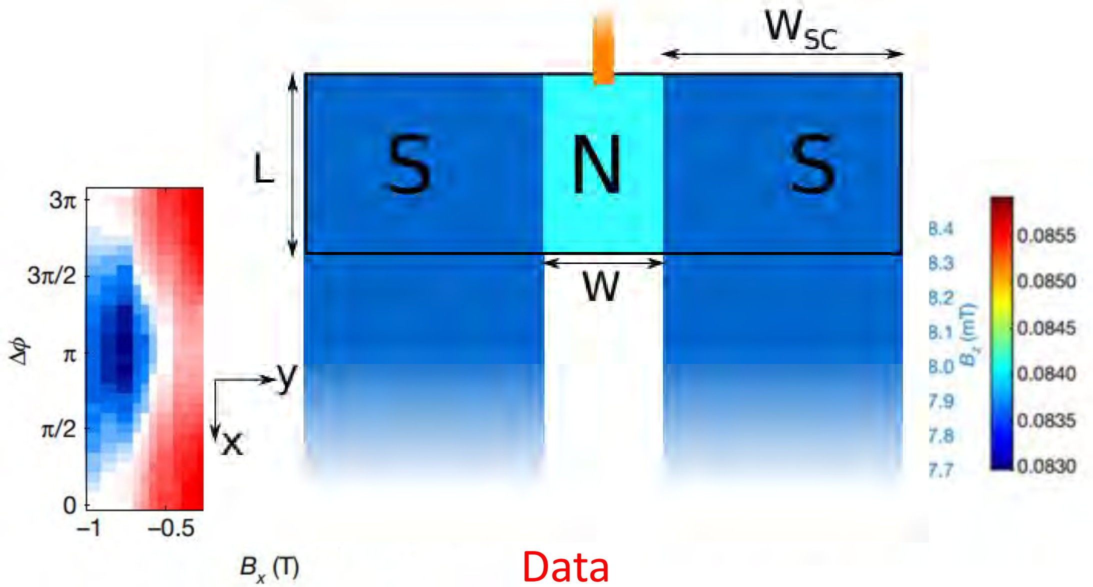




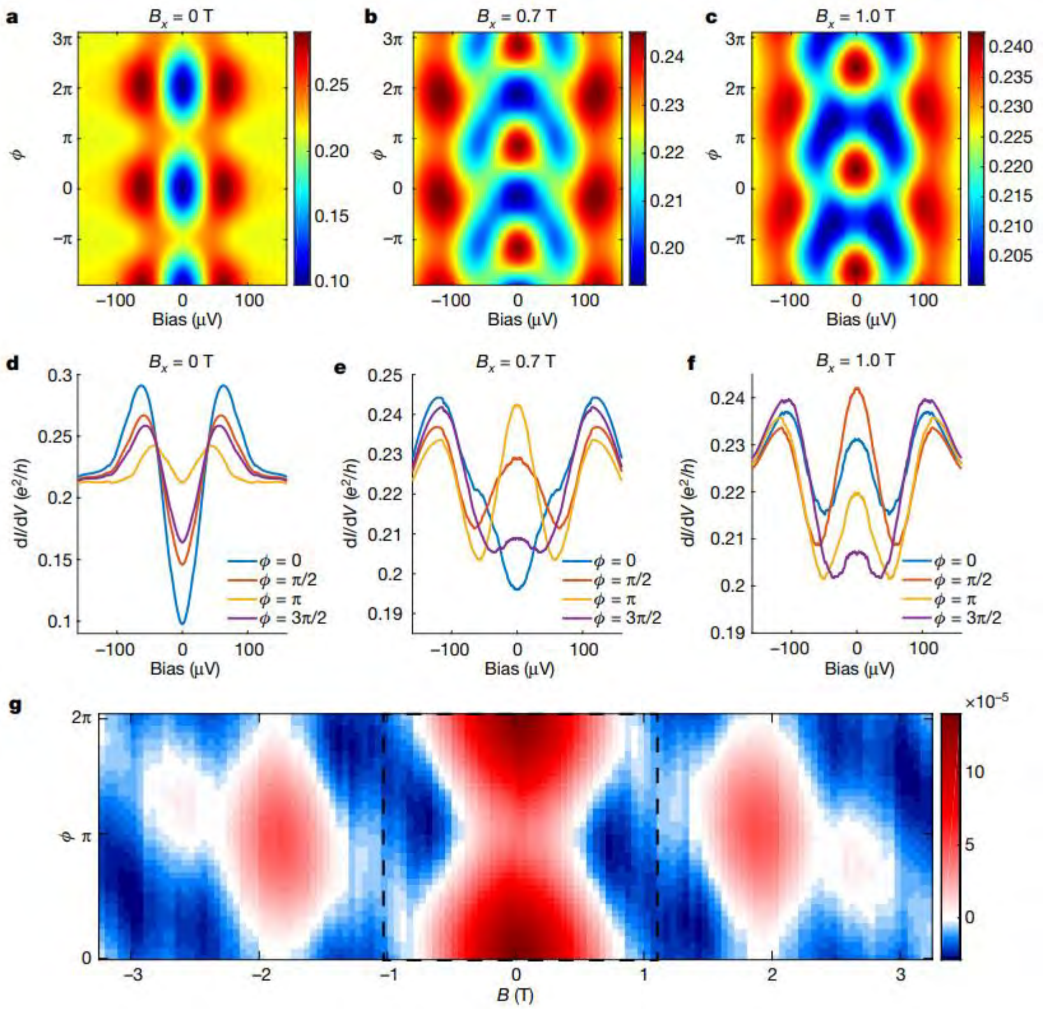


Simulations

- Simulated semiconductor with a tight-binding model with uniform Rashba SOI defined in a rectangular region
- Artificially broadened data to account for experimental resolution
- Reproduces the key features in the experiment



Data

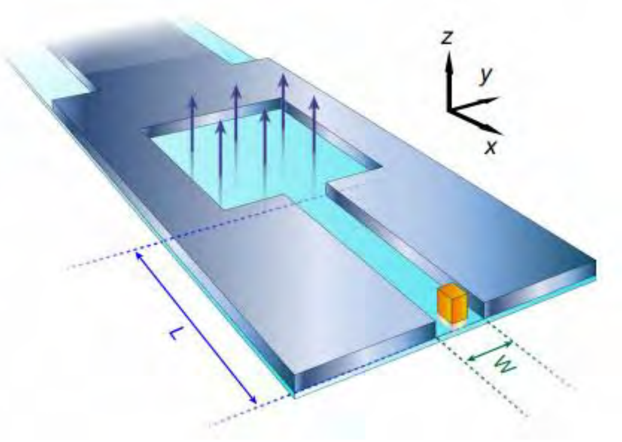


Simulation

Outlook

- In future want to improve interface quality, use narrower and longer junctions to obtain harder SC gap
    - Should enable robust control of topological transition without needing higher B-fields
- Approach doesn’t rely on chemical potential or B-field fine-tuning
- Can be “easily” implemented on other 2D systems
    - Different interplay of phase bias, SOI and Zeeman suggests exciting possibilities for studying topological SC

Thanks for your attention!



LDOS of MBS

Even though the system is in the topological phase, signatures of Majorana states cannot be distinguished from bulk signatures with current dimensions

Estimated (via KWANT) the coherence length of the MBS to be ~45 um