Phase-induced Majorana devices

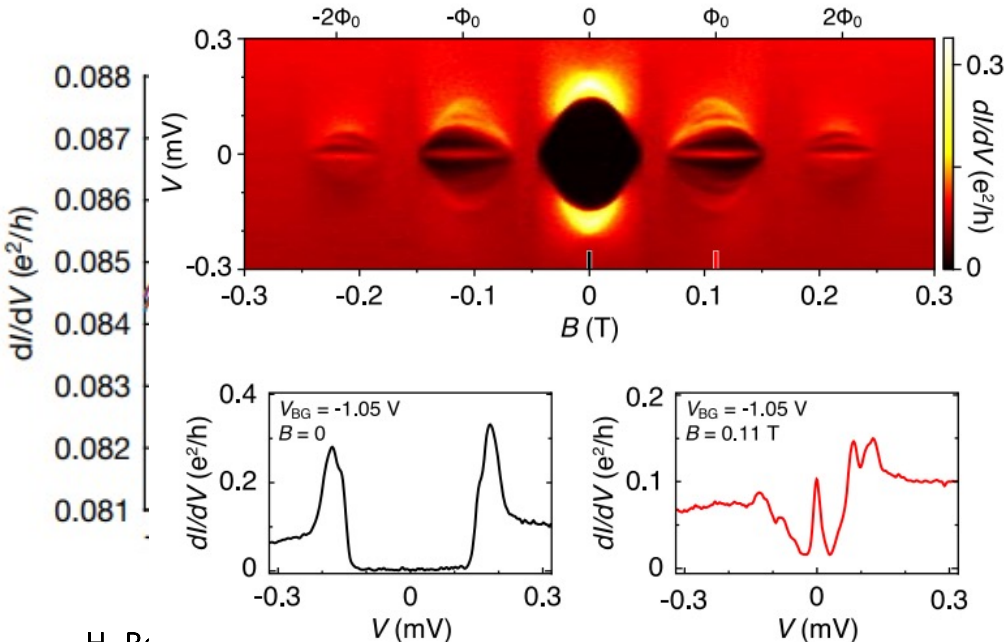
Omri Lesser

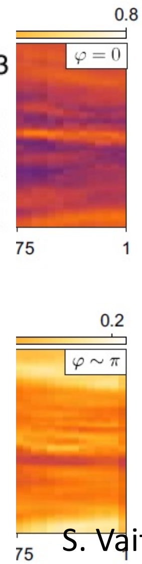
WEIZMANN INSTITUTE OF SCIENCE

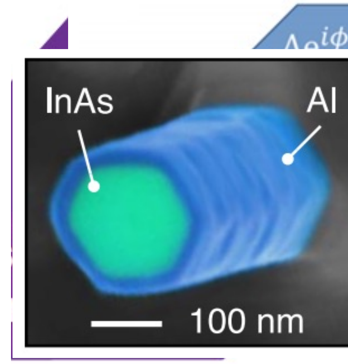
O.L., K. Flensberg, F. von Oppen, Y. Oreg, Phys. Rev. B, 2021

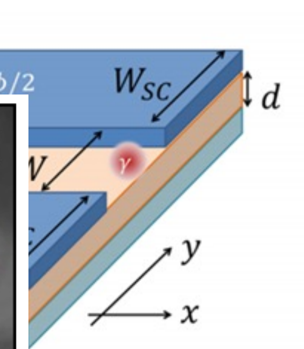
O.L., A. Saydjari, M. Wesson, A. Yacoby, Y. Oreg, arXiv: 2103.05651, 2021

Many existing Majorana platforms require substantial magnetic fields









H. Re...

(Planar Josephson junction)

...ik et al, Science, 2012

S. Vaitiekenas et al, Science, 2020

...nducting nanowire)

(Full-shell nanowire)

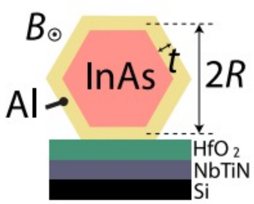
2019

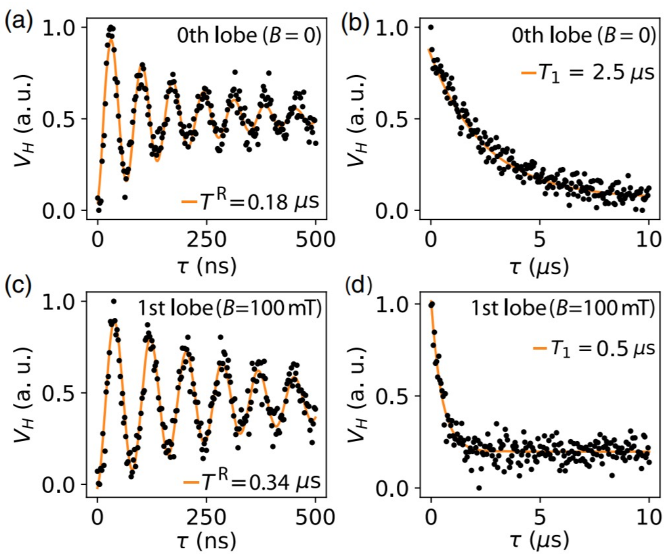
The effects of magnetic fields

PHYSICAL REVIEW LETTERS **125,** 156804 (2020)

Destructive Little-Parks Effect in a Full-Shell Nanowire-Based Transmon

Deividas Sabonis,[1,2,*] Oscar Erlandsson,[1,2,*] Anders Kringhøj,[1,2,*] Bernard van Heck,[3] Thorvald W. Larsen,[1,2] Ivana Petkovic,[1,2] Peter Krogstrup,[1,4] Karl D. Petersson,[1,2] and Charles M. Marcus[1,2]





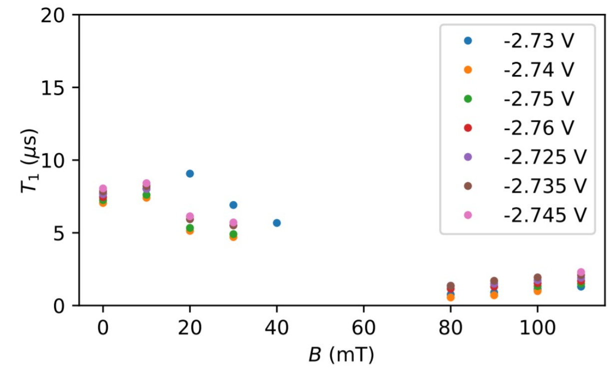
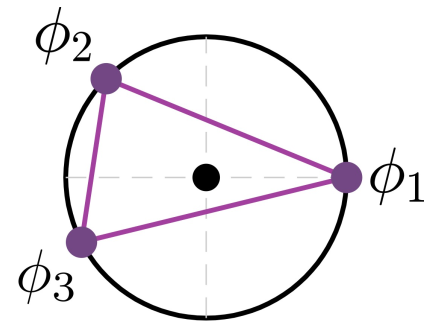


FIG. 1. Qubit lifetime T_1 as a function of the magnetic field at a few different gate V_C voltages. T_1 decreases as the magnetic field is increased, is not measurable in the destructive regime (45 - 75 mT) and eventually recovers in a first lobe, but to values smaller than at zero field.

Replacing a Zeeman or orbital field with SC phase control



- Why is a magnetic field needed?

  To break **time-reversal symmetry**

- Replace with superconducting **phase winding**

  SC phase + Aharonov-Casher phase interference

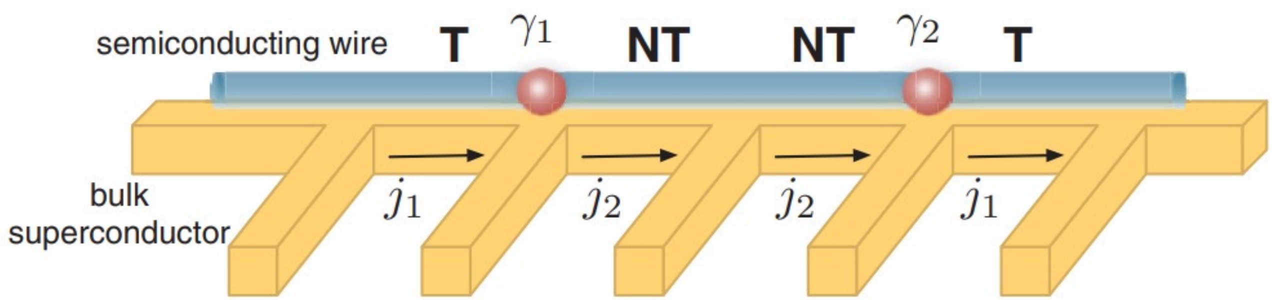
Advantages:

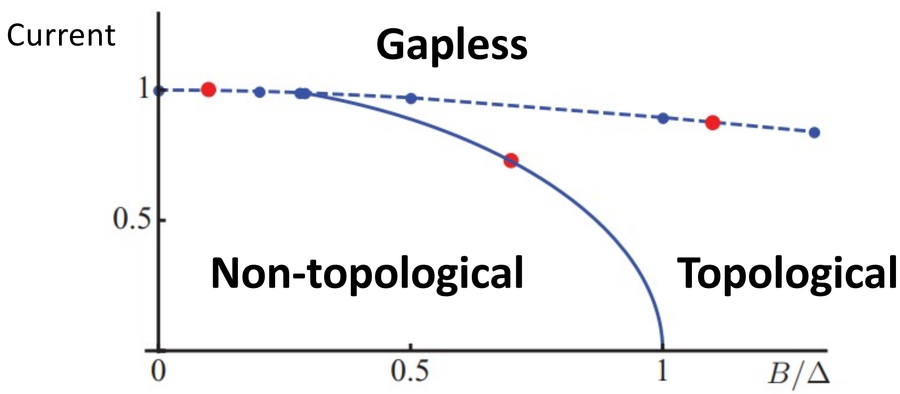
✓ Phases are easy to control with a tiny field or current

✓ No undesired in-gap states, magnetic impurities, etc. that appear also in full-shell wires (Vaitiekenas et al, Science, 2020) and EuS-coated wires (Vaitiekenas et al, Nat. Phys., 2021)

B. van Heck et al, Phys. Rev. B, 2014; A. Melo et al, SciPost Phys., 2019

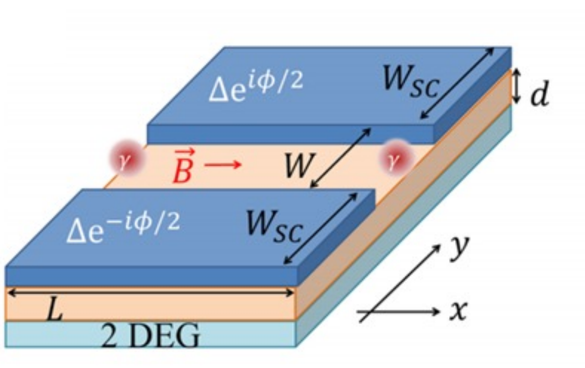
Current-biased nanowires

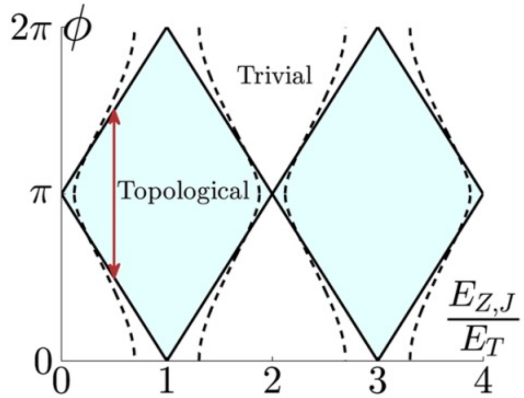


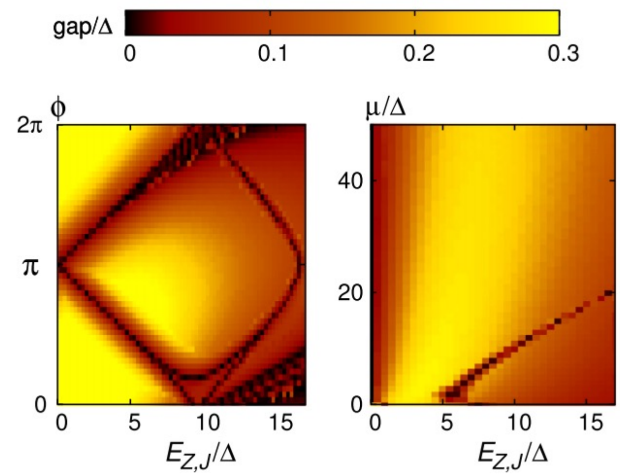


A. Romito et al, Phys. Rev. B, 2012

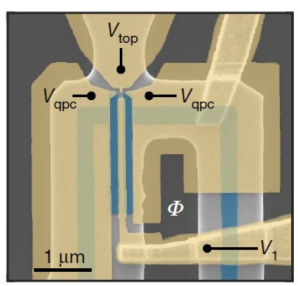
Planar Josephson junctions

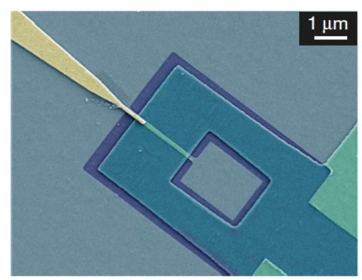






Theory: M. Hell et al, Phys. Rev. Lett., 2017; F. Pientka et al, Phys. Rev. X, 2017

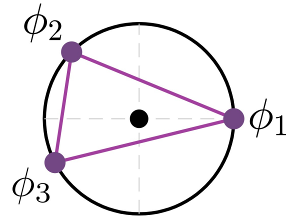




First experiments: A. Fornieri et al, Nature, 2019; H. Ren et al, Nature, 2019

Basic building block

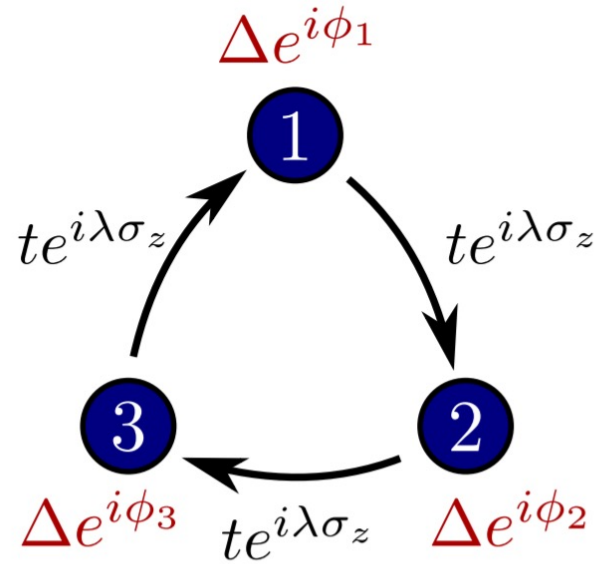
"One's company, two's a crowd, and three's a party" (Andy Warhol)



$$H = \sum_{n=1}^{N} \left(t e^{i\lambda\sigma_z} c_n^\dagger c_{n+1} - \frac{\mu}{2} c_n^\dagger c_n + \mathrm{H.c.} \right) + \sum_{n=1}^{N} \left(\Delta e^{i\phi_n} c_{n,\uparrow}^\dagger c_{n,\downarrow}^\dagger + \mathrm{H.c.} \right)$$

If SC phases form a discrete vortex:

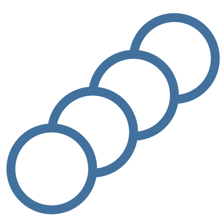
$\Rightarrow$ can tune μ, Δ, λ to get a pair of MZMs, **delocalized** around the ring



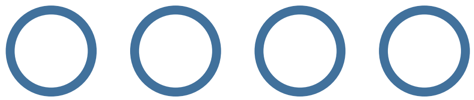
O.L. et al, Phys. Rev. B, 2021; O.L. et al, arXiv: 2103.05651

Two ways to continue

In the "third" dimension
⇓
Cylinder
⇓
Zero-energy states in the ring = phase transition points (at $k = 0$)

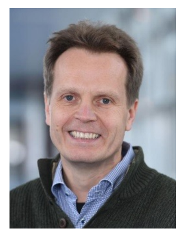


In the plane
⇓
Chain
⇓
Engineer inter-ring coupling to mimic a perfectly localized Kitaev chain



Non-planar models

Three-phase Majorana zero modes at tiny magnetic fields
O.L., K. Flensberg, F. von Oppen, Y. Oreg, Phys. Rev. B, 2021



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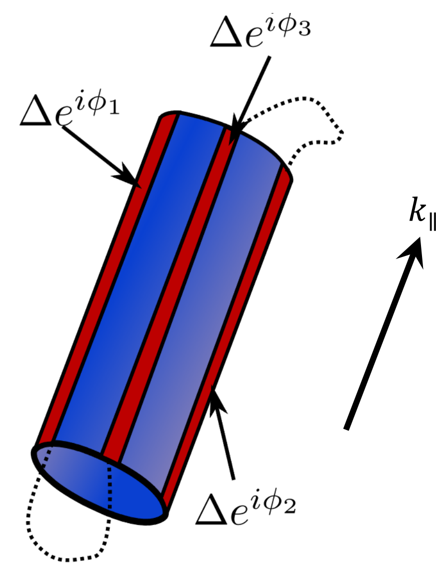
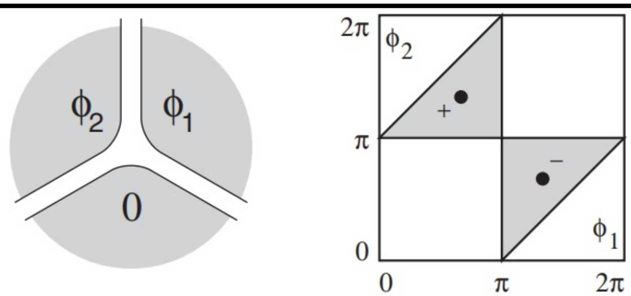
Cylinder model

$$\mathcal{H}(k_{\parallel}=0) = \sum_{n=1}^{N} \sum_{s,s'=\pm} \{-\mu \delta^{ss'} c^{\dagger}_{n,s} c_{n,s'} + [t_{\perp} (e^{i\lambda_n \sigma_z})^{ss'} c^{\dagger}_{n,s} c_{n+1,s'} + \text{H.c.}]\} + \sum_{n=1}^{N} (\Delta e^{i\phi_n} c^{\dagger}_{n,\uparrow} c^{\dagger}_{n,\downarrow} + \text{H.c.})$$



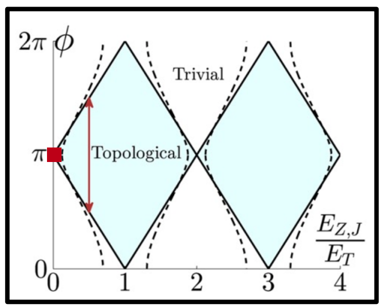
Phase transitions

$$\det \mathcal{H}(k_\parallel = 0)$$
$$= 6\mu^2 t_\perp^2(\Delta^2+\mu^2) - (\Delta^2+\mu^2)^3$$
$$- 3t_\perp^4(\Delta^2+3\mu^2) - 2f\Delta^2 t_\perp^2(\Delta^2+\mu^2+t_\perp^2)$$
$$- 4\mu t_\perp^3 \Lambda(f\Delta^2 - \mu^2 + 3t_\perp^2) - 4t_\perp^6\Lambda^2 = 0$$

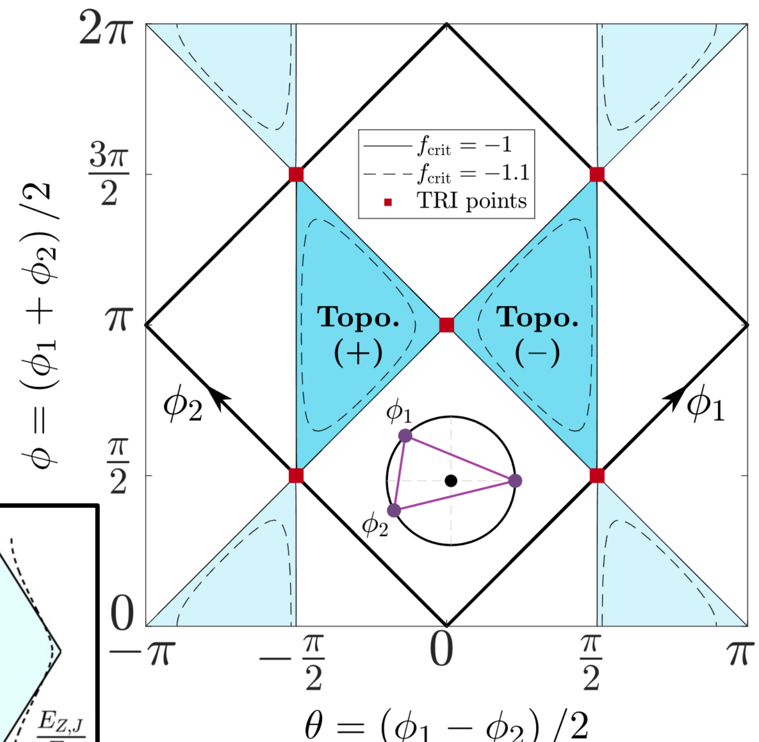


Cf. Fu and Kane, Phys. Rev. Lett., 2008:

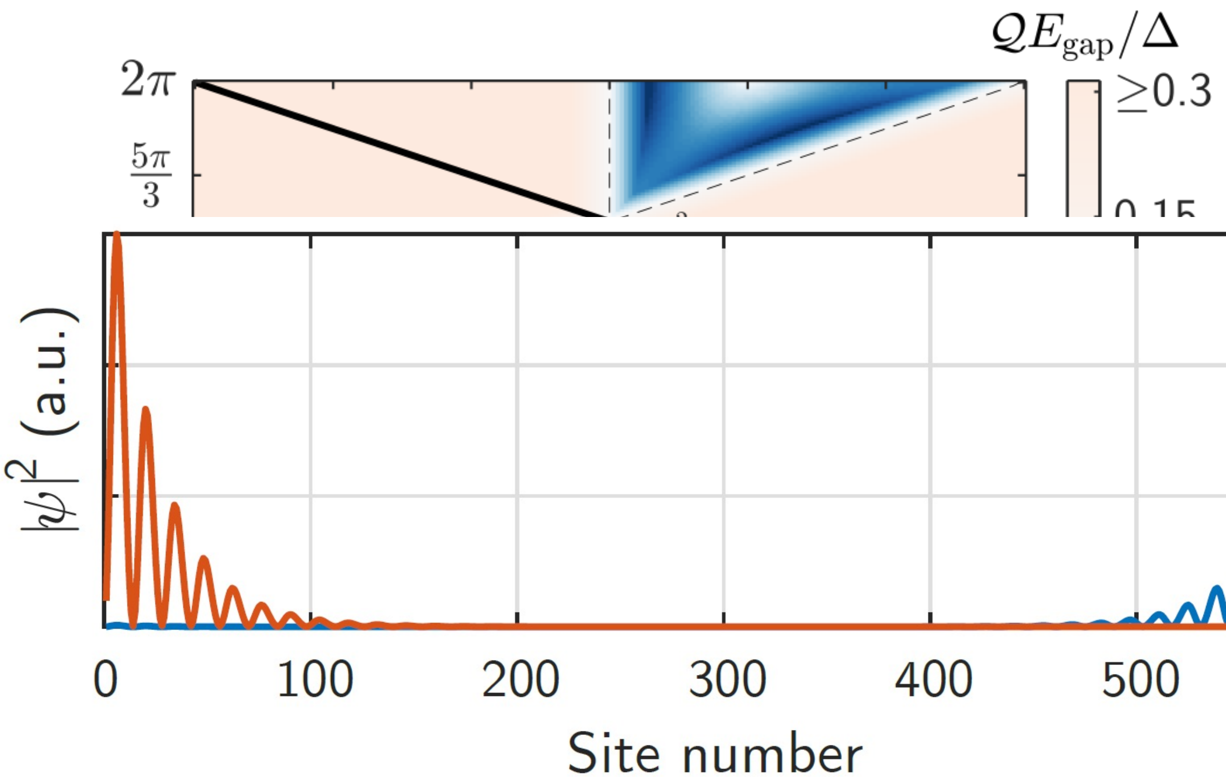
- No topological insulator needed
- Quasi-1D vs 2D



Pientka et al, Phys. Rev. X, 2017



Full phase diagram



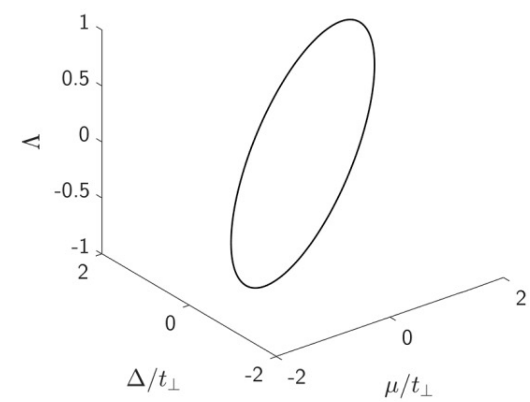
$\mathcal{Q}$ = +1: Trivial

−1: Topological

Optimality condition

- Optimal topological **region** in (θ, ϕ) plane ($f_{\text{crit}} = -1$):

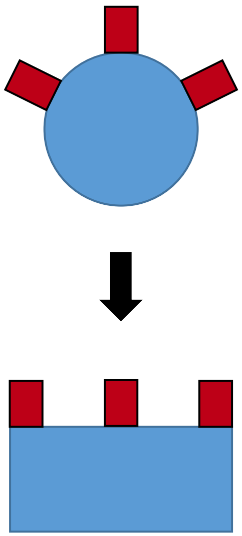
$$\left(\frac{\mu}{t_\perp}, \frac{\Delta}{t_\perp}, \Lambda\right) = \left(\frac{\mu}{t_\perp}, \sqrt{1 - \left(\frac{\mu}{t_\perp}\right)^2}, \frac{\mu}{t_\perp}\right)$$

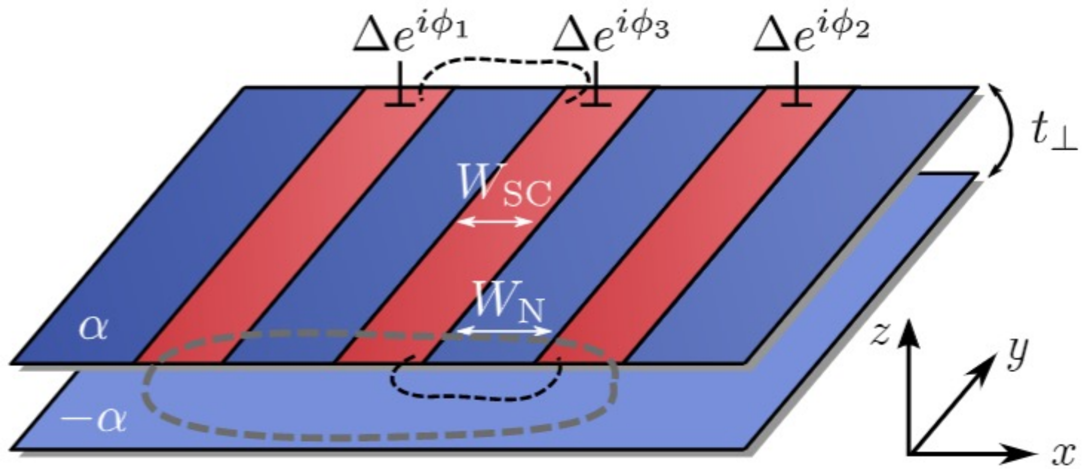


- On this circle, small $\Delta \Rightarrow \mu \approx t_\perp,\ \lambda \approx \Delta / t_\perp$
- In the continuum $E_{\text{SO}} \approx t_\perp \lambda^2$, $L/\ell_{\text{SO}} \approx \lambda$
- Condition for optimality:

$$L\Delta \approx \ell_{\text{SO}} E_{\text{SO}} \approx \alpha$$

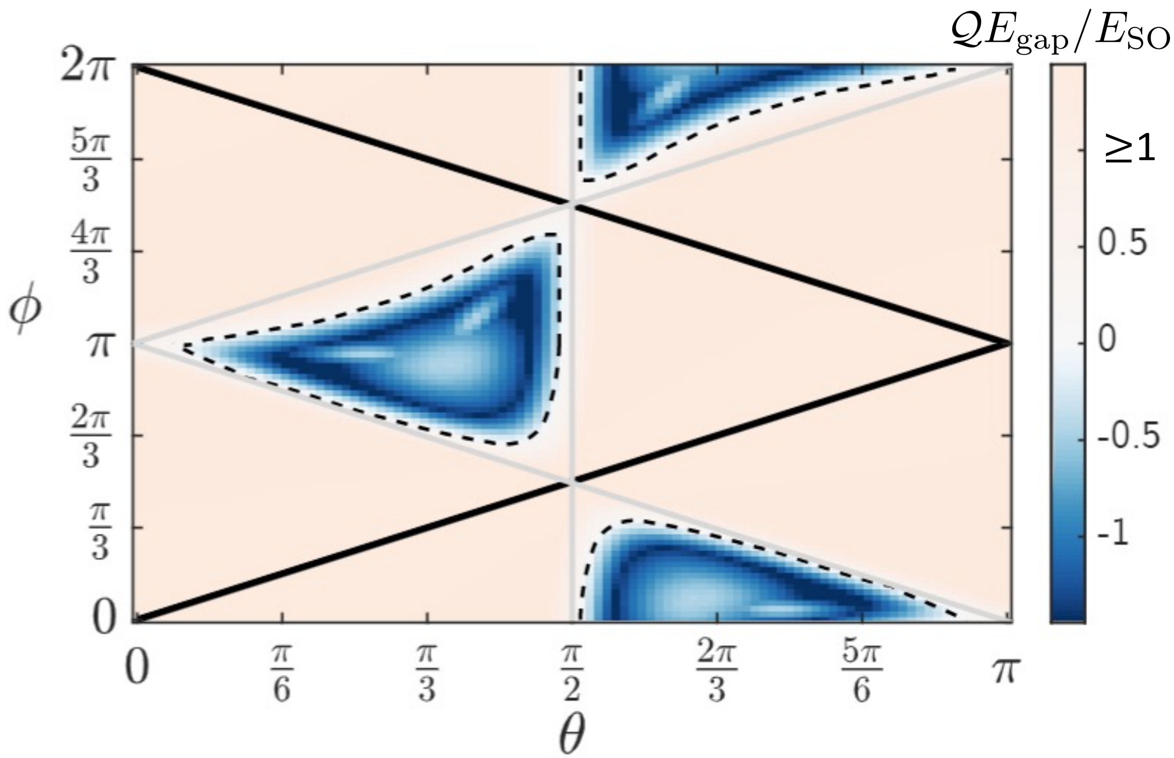
Realistic model: quantum well





$$\mathcal{H} = \left[-\frac{1}{2m^*}(\partial_x^2 + \partial_y^2) - t_\perp \rho_x - \mu\right]\tau_z$$
$$+ i\alpha(\sigma_x \partial_y - \sigma_y \partial_x)\tau_z \rho_z + [\Delta(x)\tau_+ + \Delta^*(x)\tau_-]\rho_\uparrow$$

Realistic model: phase diagram (Al on InAs)

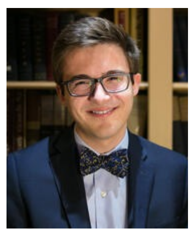


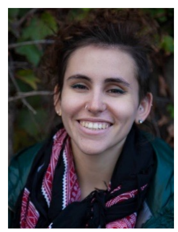
Notice:
$E_{\mathrm{SO}} \approx 40\ \mu\mathrm{eV}$,
$\Delta \approx 1.2\ \mathrm{meV}$
so $E_{\mathrm{SO}} \ll \Delta$

Planar models (single subband)

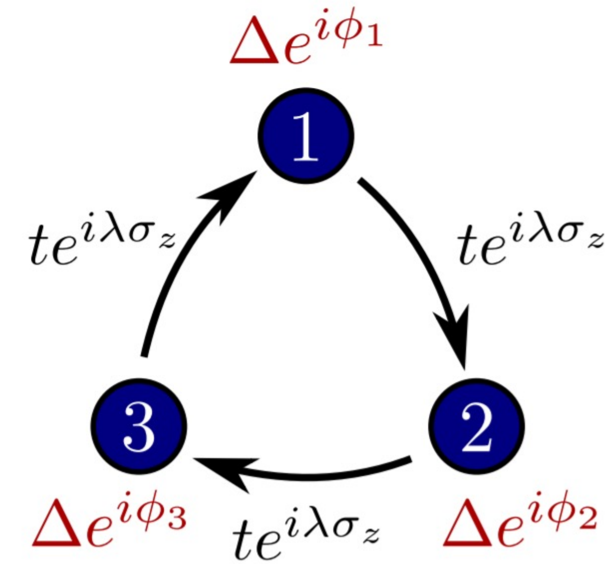
Phase-induced topological superconductivity in a planar heterostructure

O.L., A. Saydjari, M. Wesson, A. Yacoby, Y. Oreg, arXiv: 2103.05651, 2021 (accepted to PNAS)

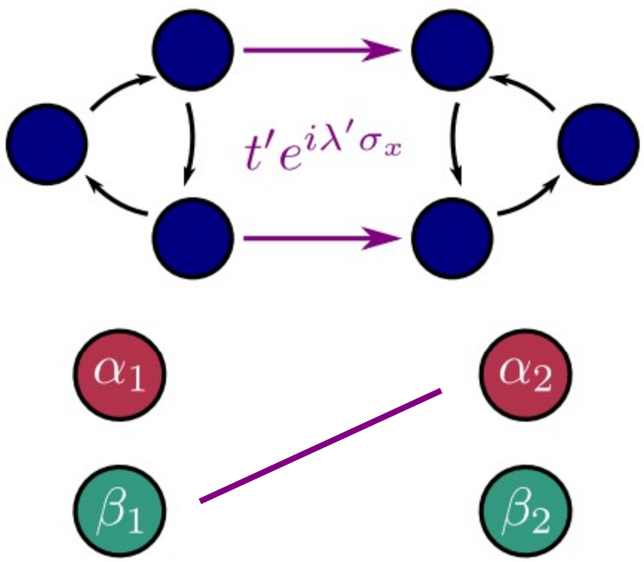


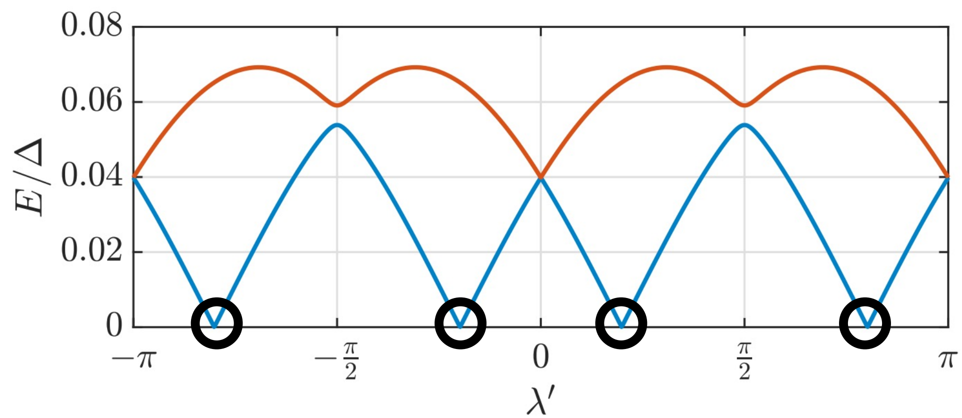


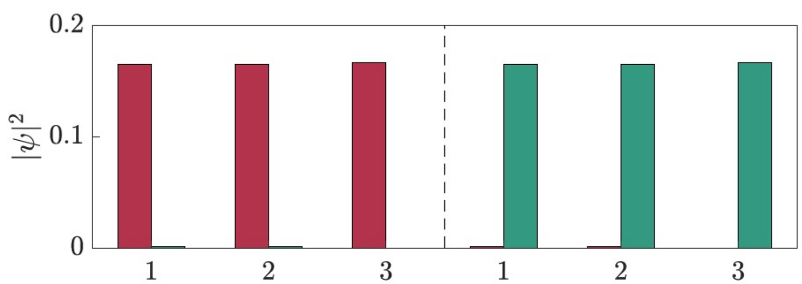
Back to the ring…

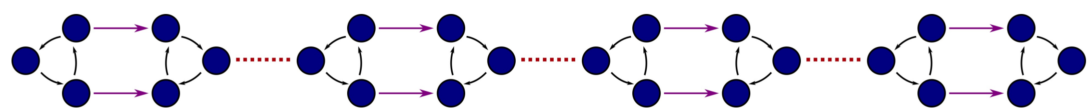


Sweet spot: perfectly localized MZMs

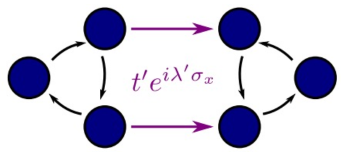


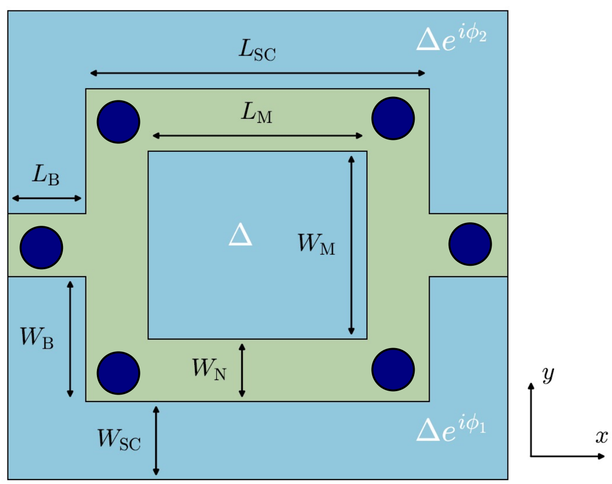


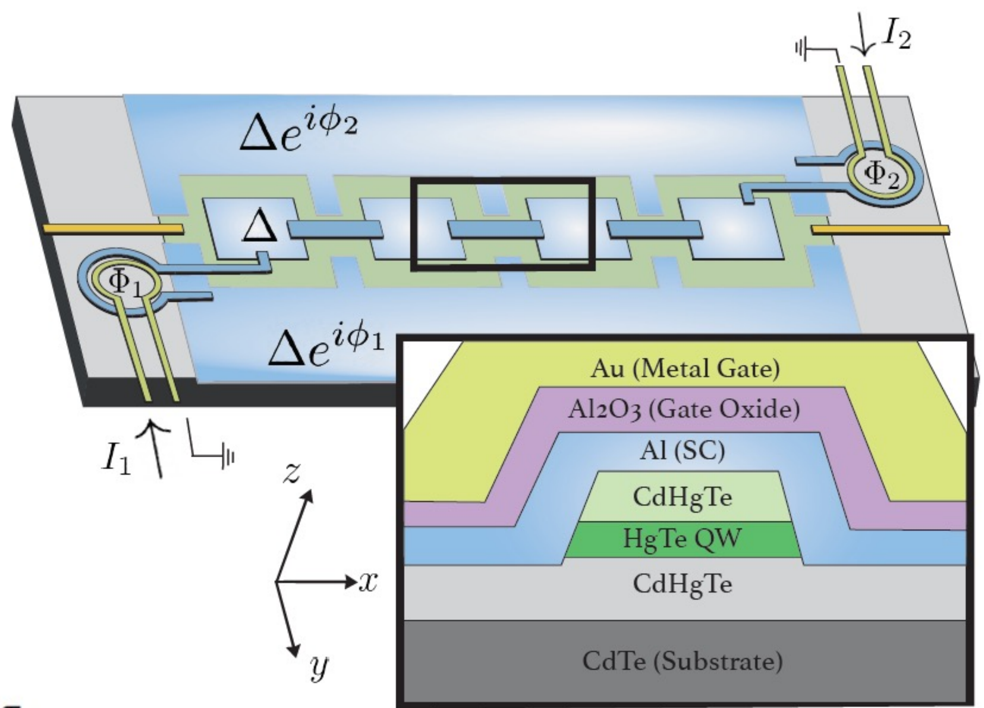




Realistic planar device

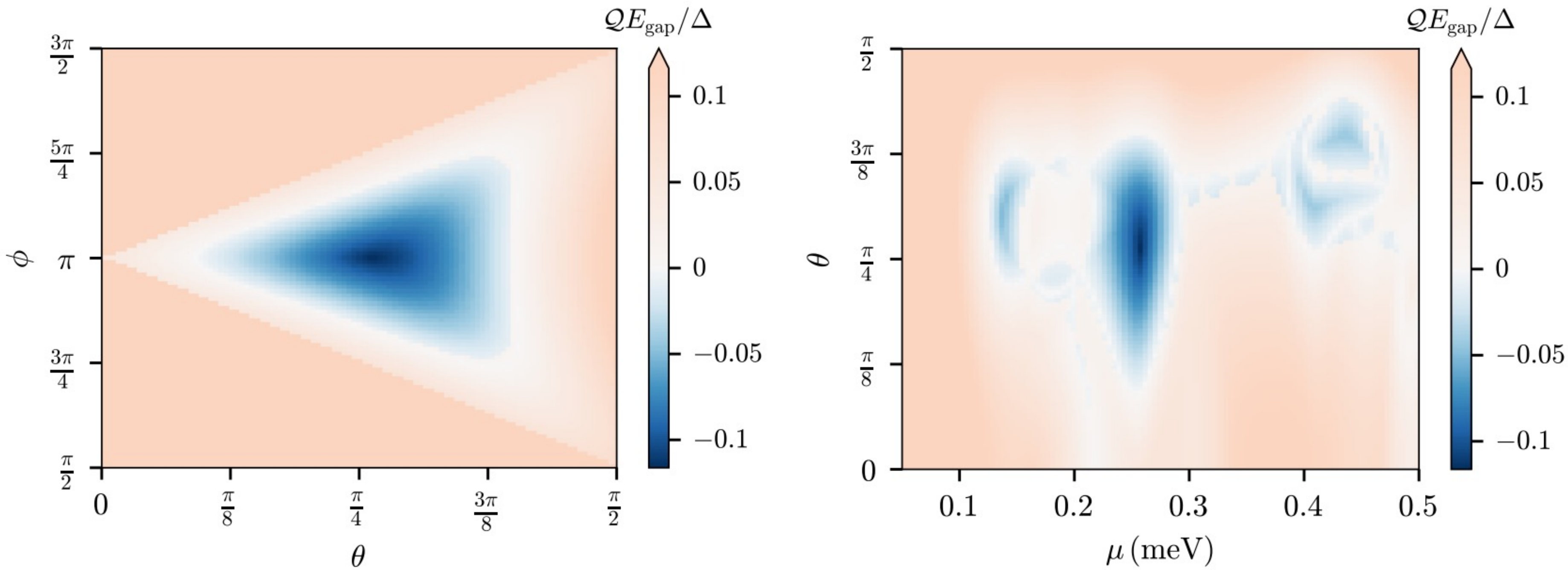






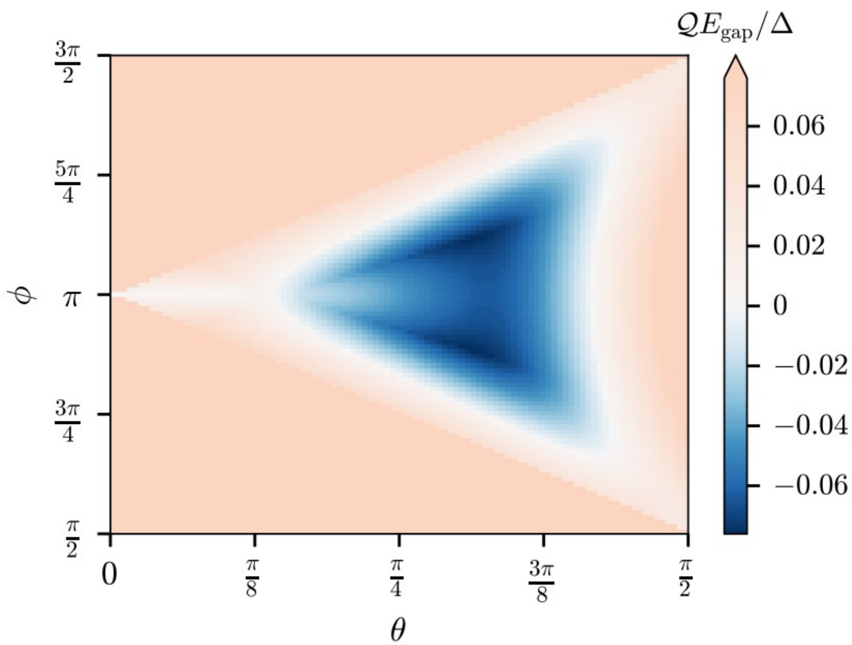
$$H = \left[\frac{\hbar^2}{2m^*}\left(k_x^2 + k_y^2\right) + \hbar\alpha\left(\sigma_y k_x - \sigma_x k_y\right) - \mu\right]\tau_z$$
$$+ \mathrm{Re}\Delta(x,y)\tau_x + \mathrm{Im}\Delta^*(x,y)\tau_y$$

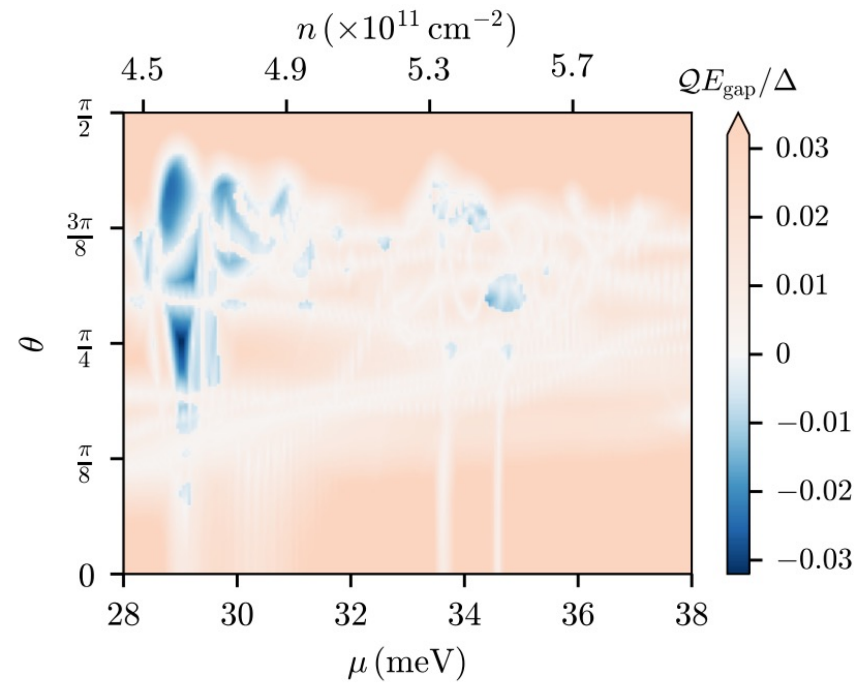
Phase diagrams (Al on HgTe)



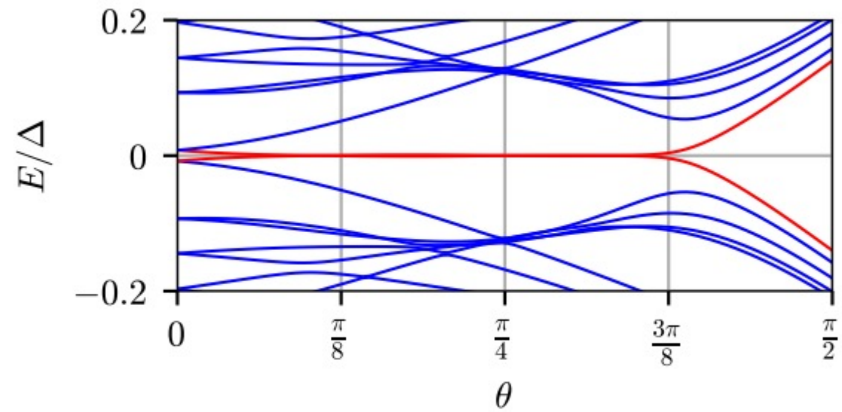
Phase diagrams (Nb on HgTe)

Nb is a large-gap type-II superconductor – it **can** be used in our device

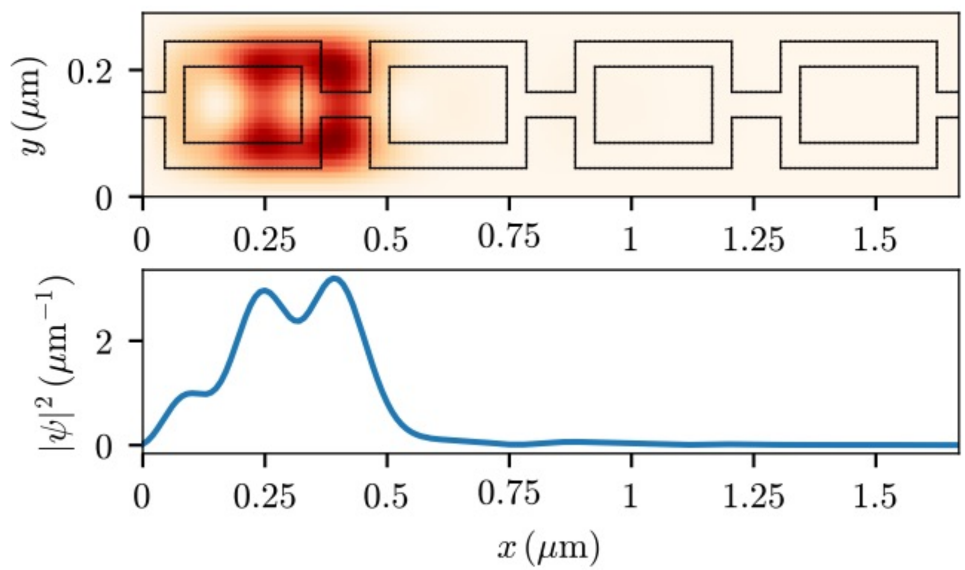




MZM wavefunction



(μ, ϕ are held fixed)



Summary

- Time-reversal symmetry can be broken by SC phase bias
- Required field: < 1μT for micron-size loops
- Geometries: planar or non-planar
- General design principle $\Rightarrow$ many more models

Thank you!

Extra slides

Ring: momentum space analysis

$$H = \sum_{k,\sigma} \left[2t\cos\left(k + \frac{\varphi}{2} + \lambda\sigma\right) - \mu \right] c^\dagger_{k\sigma} c_{k\sigma} + \sum_k \left(\Delta c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} + \text{H.c.} \right)$$

$$H = \frac{1}{2} \sum_k \vec{\Psi}^\dagger_k \mathcal{H}(k) \vec{\Psi}_k,$$

$$\mathcal{H}(k) = \begin{pmatrix} \epsilon_{k\uparrow} & 0 & \Delta & 0 \\ 0 & \epsilon_{k\downarrow} & 0 & \Delta \\ \Delta & 0 & -\epsilon_{-k\downarrow} & 0 \\ 0 & \Delta & 0 & -\epsilon_{-k\uparrow} \end{pmatrix}$$

$$\epsilon_{k\sigma} = -\mu + 2t\cos\left(k + \frac{\varphi}{2} + \lambda\sigma\right)$$

$$\det \mathcal{H}(k) = \left(\Delta^2 + \epsilon_{k\uparrow}\epsilon_{-k\downarrow}\right)\left(\Delta^2 + \epsilon_{k\downarrow}\epsilon_{-k\uparrow}\right) = 0$$

$$-\mu + 2t\cos\left(k + \lambda\sigma + \frac{\varphi}{2}\right) = \Delta$$

$$-\mu + 2t\cos\left(k + \lambda\sigma - \frac{\varphi}{2}\right) = -\Delta$$

$$\mu = 2t\cos\left(\frac{\varphi}{2}\right)\sqrt{1 - \left(\frac{\Delta}{2t\sin\left(\frac{\varphi}{2}\right)}\right)^2}$$