Exponential suppression of the topological gap in self-consistent intrinsic Majorana nanowires

Francisco Lobo
Elsa Prada
Pablo San-Jose

Introduction

What are Majoranas?

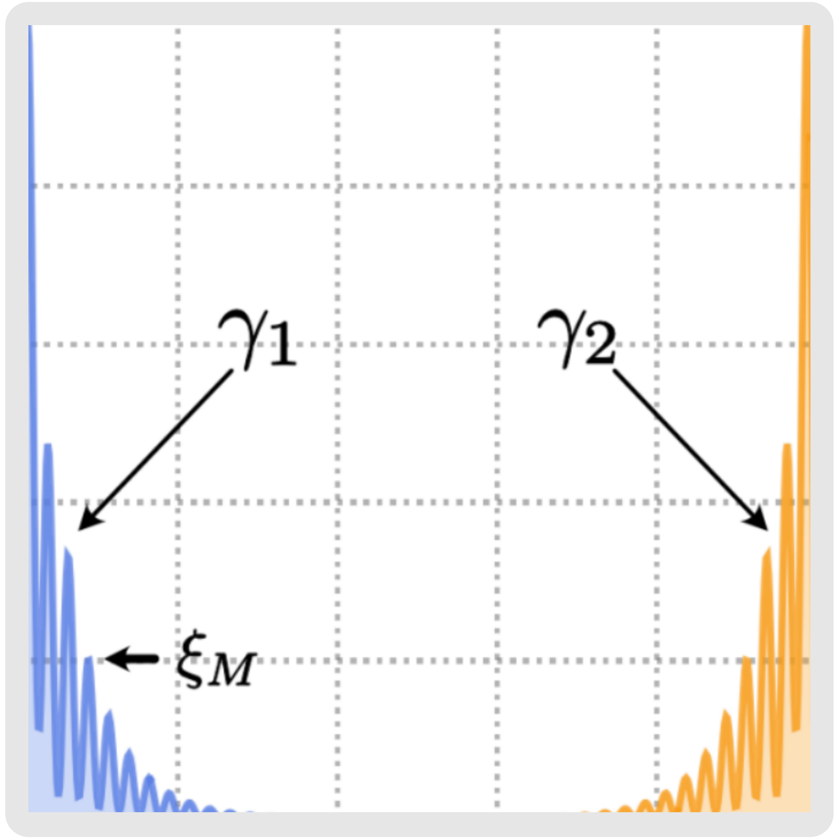
- topologically protected states
- spatially bound, zero-charge, zero-spin, zero-energy fractionalized quasiparticles
- non-Abelian anyon statistics

What are they usefull for?

Fault-tolerant qubits

Possible platforms?

Hybrid nanowires



DOI:10.1038/s42254-020-0228-y

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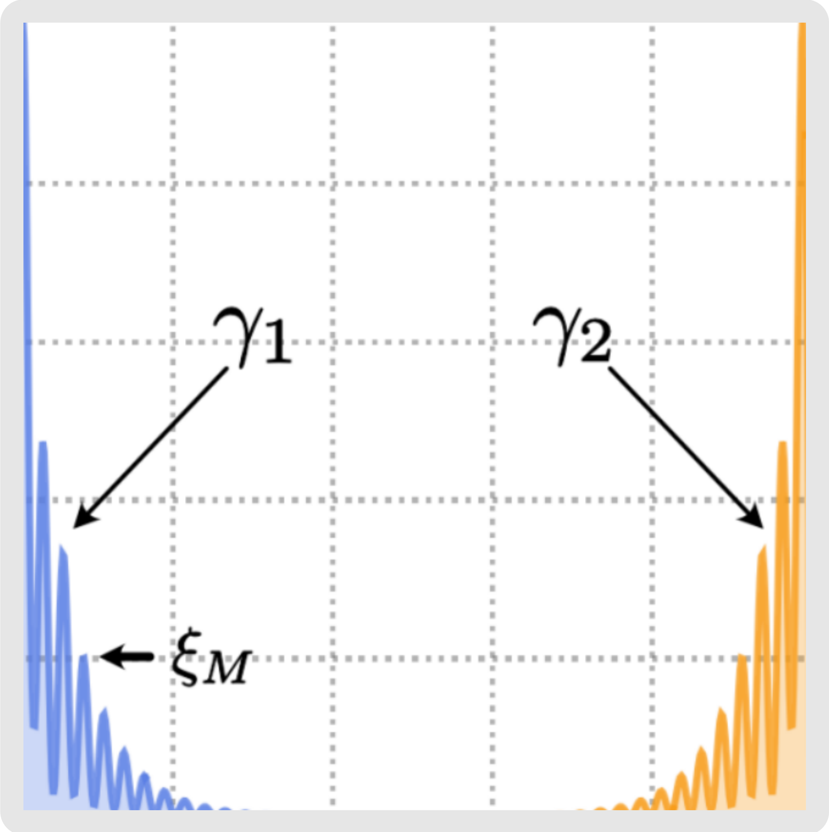

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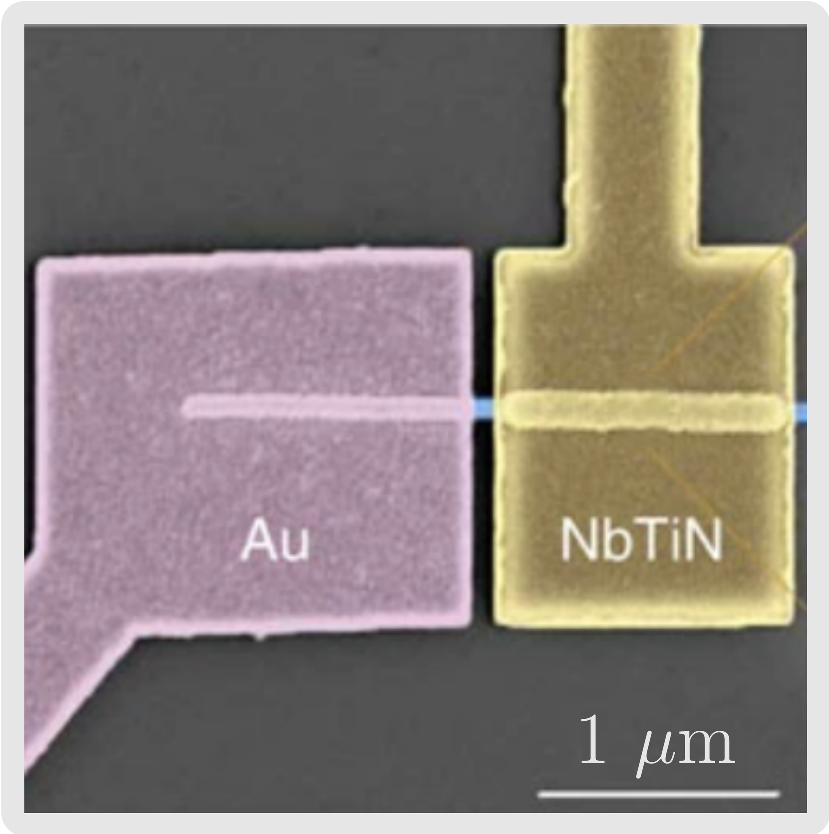
Motivation

Why aren't they more prevalent in quantum computation then?

Unambiguous signature of Majoranas in hybrid systems due to:

- smooth confinement
- trivial state pinning
- metalization
- disorder



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Possible solution?

Topological intrinsic superconductivity

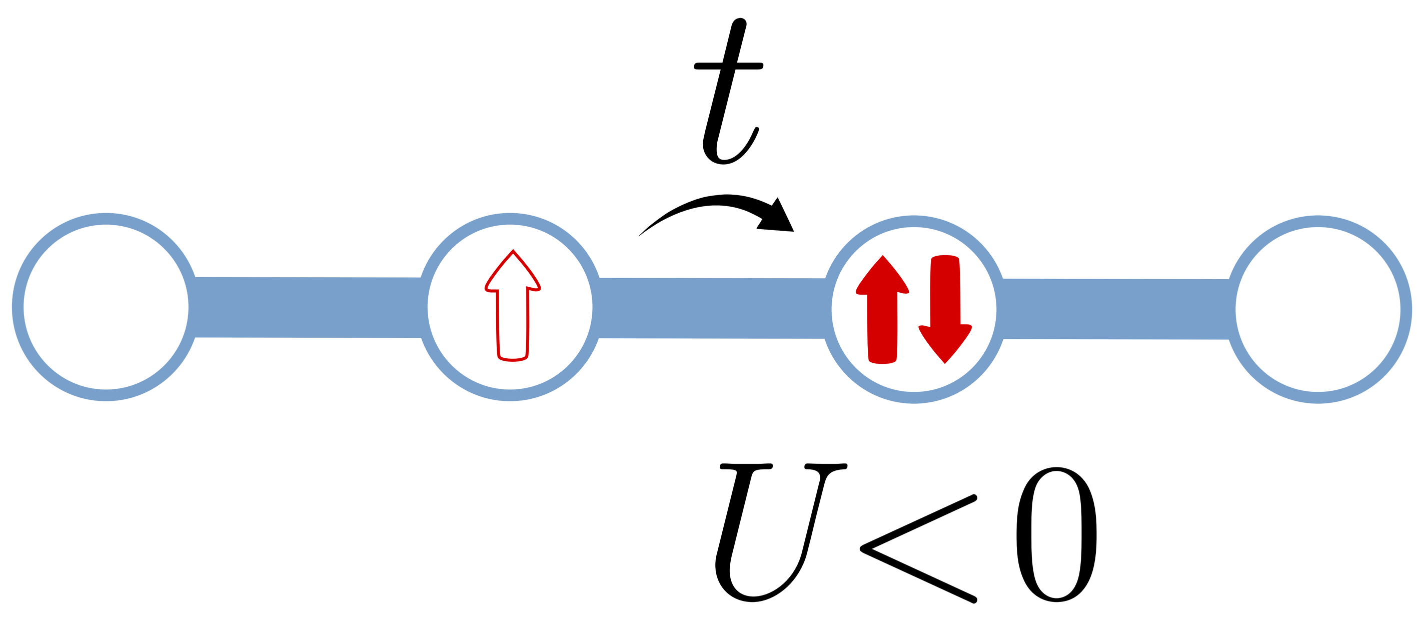
Self-consistent superconductivity

Hubbard model

$$H^{\mathrm{Hub}} = H_0 + H_U$$

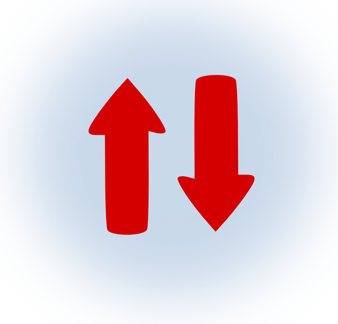
Hopping

On-site attraction



BCS mean-field theory

$$\Sigma_{\mathrm{BCS}} = \sum_i \underbrace{U \left\langle c_{i\uparrow} c_{i\downarrow} \right\rangle} c^\dagger_{i\downarrow} c^\dagger_{i\uparrow} + \mathrm{h.c.}$$



Cooper pair

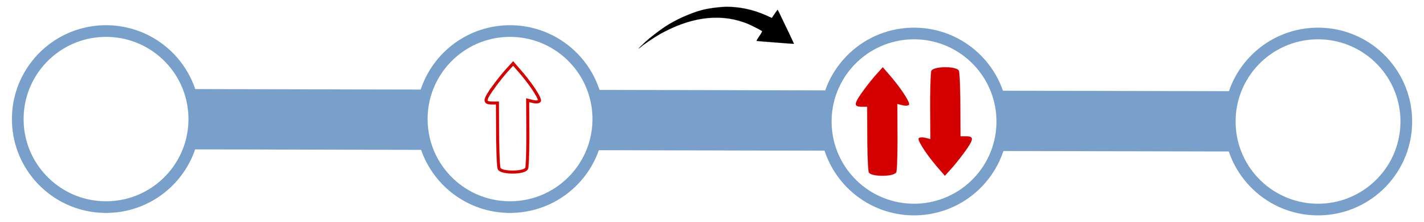
anomalous order parameter
superconducting pairing Δ^{ii}

Self-consistent superconductivity

Hubbard model

$$H^{\text{Hub}} = H_0 + H_U$$

t



$U<0$

Hopping

On-site attraction

BCS mean-field theory

$$\Sigma_{\text{BCS}} = \sum_i \underbrace{U \left\langle c_{i\uparrow} c_{i\downarrow} \right\rangle}\, c^\dagger_{i\downarrow} c^\dagger_{i\uparrow} + \text{h.c.}$$

Cooper pair

anomalous order parameter
superconducting pairing Δ^{ii}

Hartree-Fock-Bogoliobouv mean-field theory

Nambu doubling → $\check{c}^\dagger_i = \begin{pmatrix} c^\dagger_{i\uparrow} & c^\dagger_{i\downarrow} & c_{i\uparrow} & c_{i\downarrow} \end{pmatrix}$

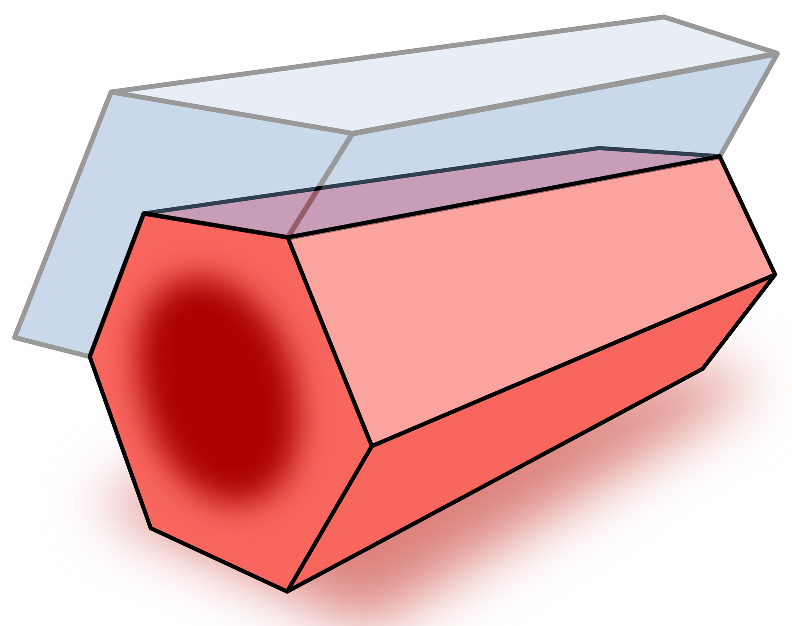
$\rho^{ii}_{e\sigma,e\sigma'} = \langle c^\dagger_{i\sigma'} c_{i\sigma} \rangle$ and $\rho^{ii}_{h\sigma,e\sigma'} = \langle c_{i\sigma'} c_{i\sigma} \rangle$

$$\Sigma_{\text{HFB}} = \frac{1}{2} \sum_{i\sigma\sigma'} (c^\dagger_{i\sigma}, c_{i\sigma}) \check{\Sigma}^{ii}_{\sigma\sigma'} \begin{pmatrix} c_{i\sigma'} \\ c^\dagger_{i\sigma'} \end{pmatrix}$$

$$\check{\Sigma}^{ij} = U\delta_{ij} \left(\frac{1}{2} \text{Tr}(\tau_z \tilde{\rho}^{ii}) \tau_z - \tau_z \tilde{\rho}^{ii} \tau_z \right)$$

Nambu symmetrized rDM

Oreg-Lutchyn majorana nanowire

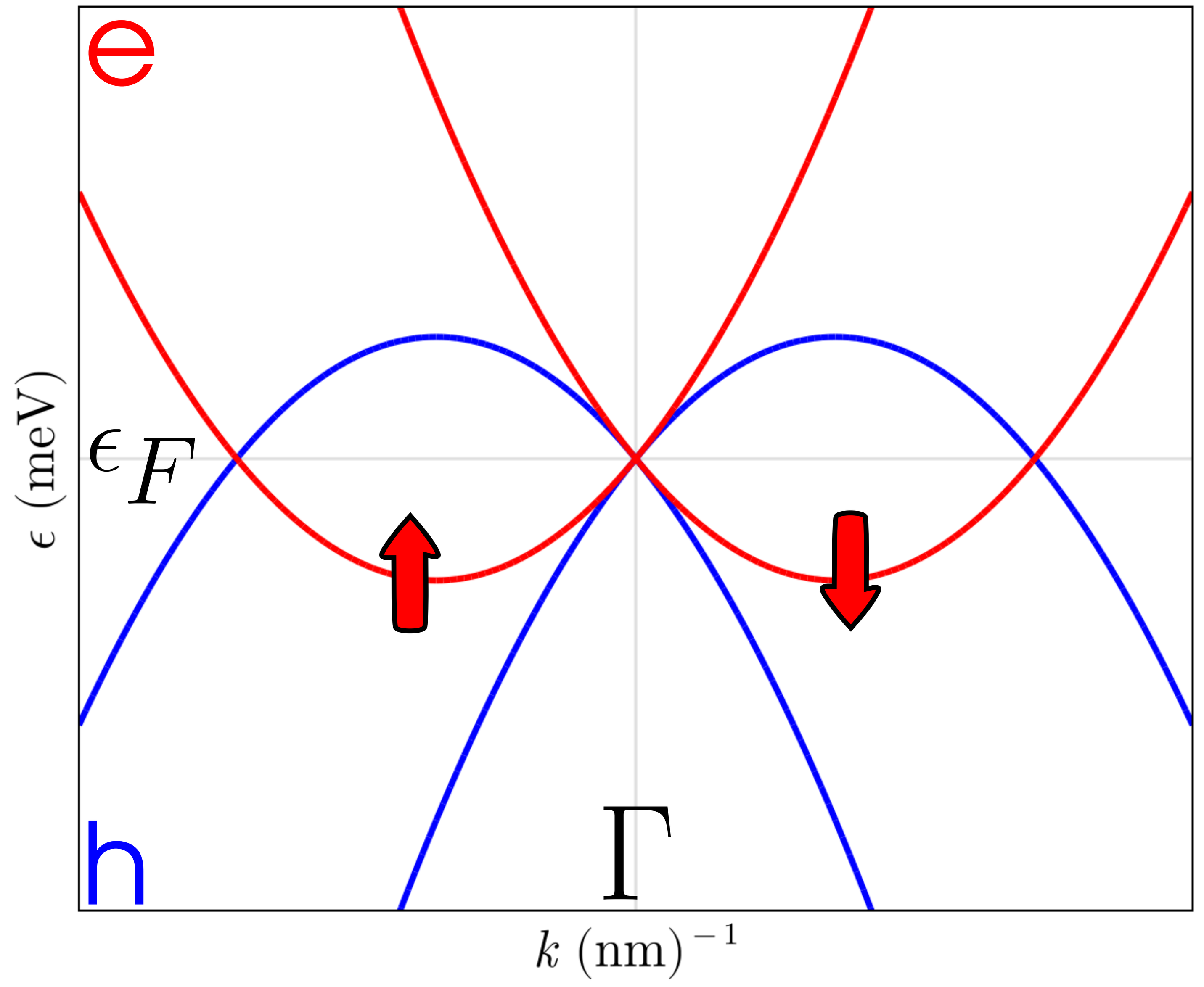


super
(integrated out)
semi
fixed $\Delta^{ii} \neq 0$

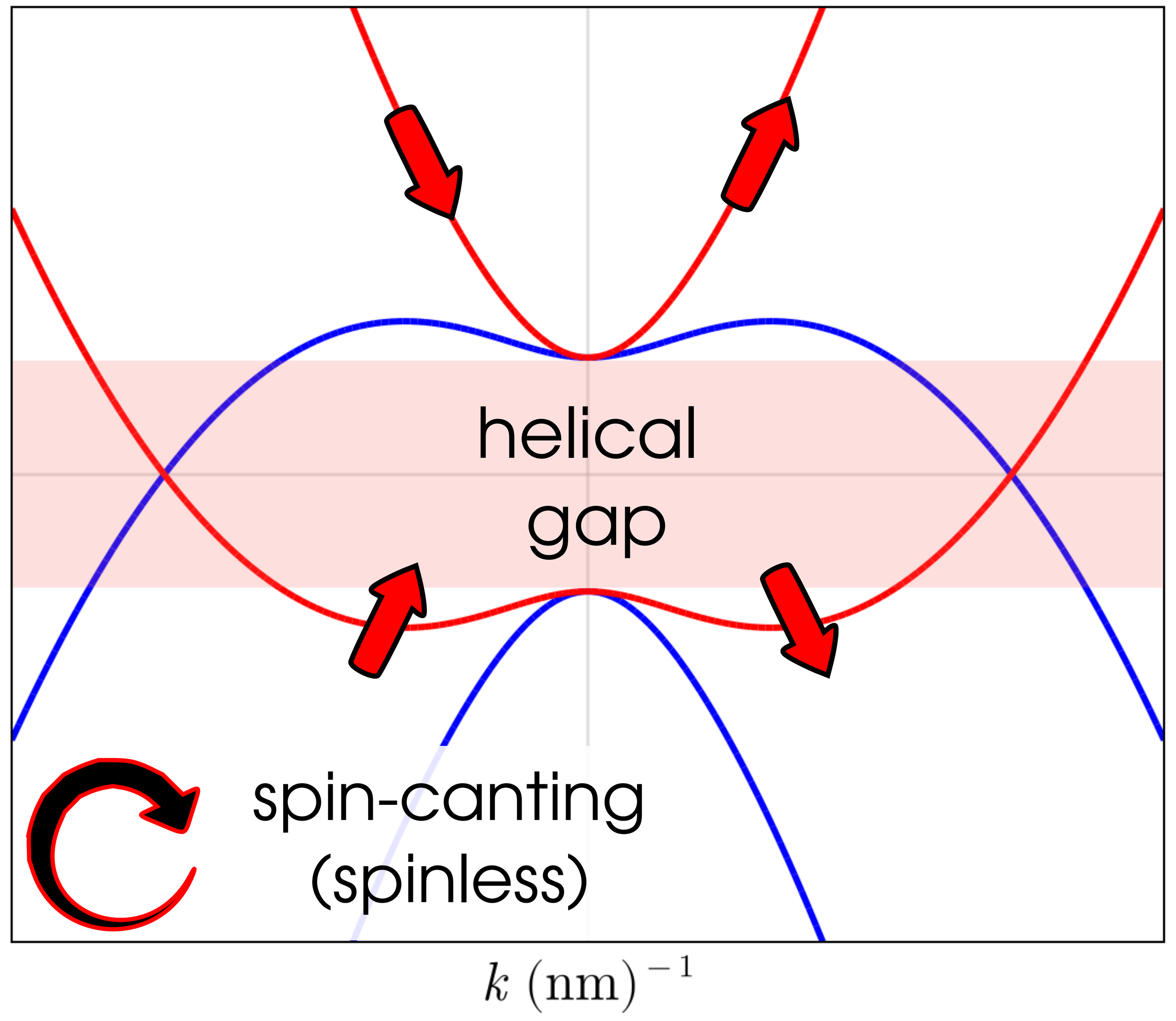
Kinectics Rashba Zeeman Pairing

$$H^{\mathrm{OL}} = H_0 + H_{\mathrm{SOC}} + H_{\mathrm{Z}} + H_{\Delta^{ii}}$$

SOC

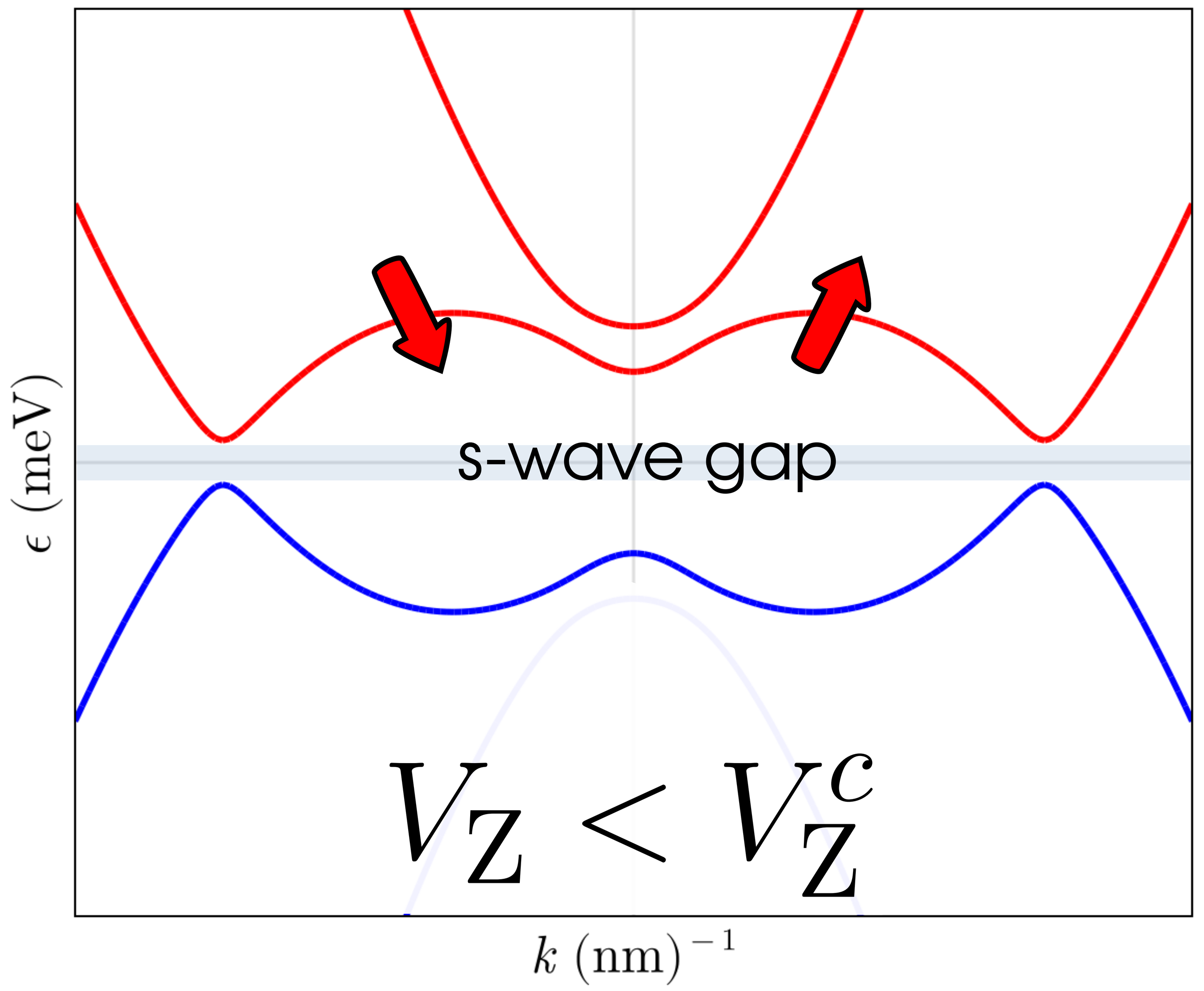


SOC + Zeeman

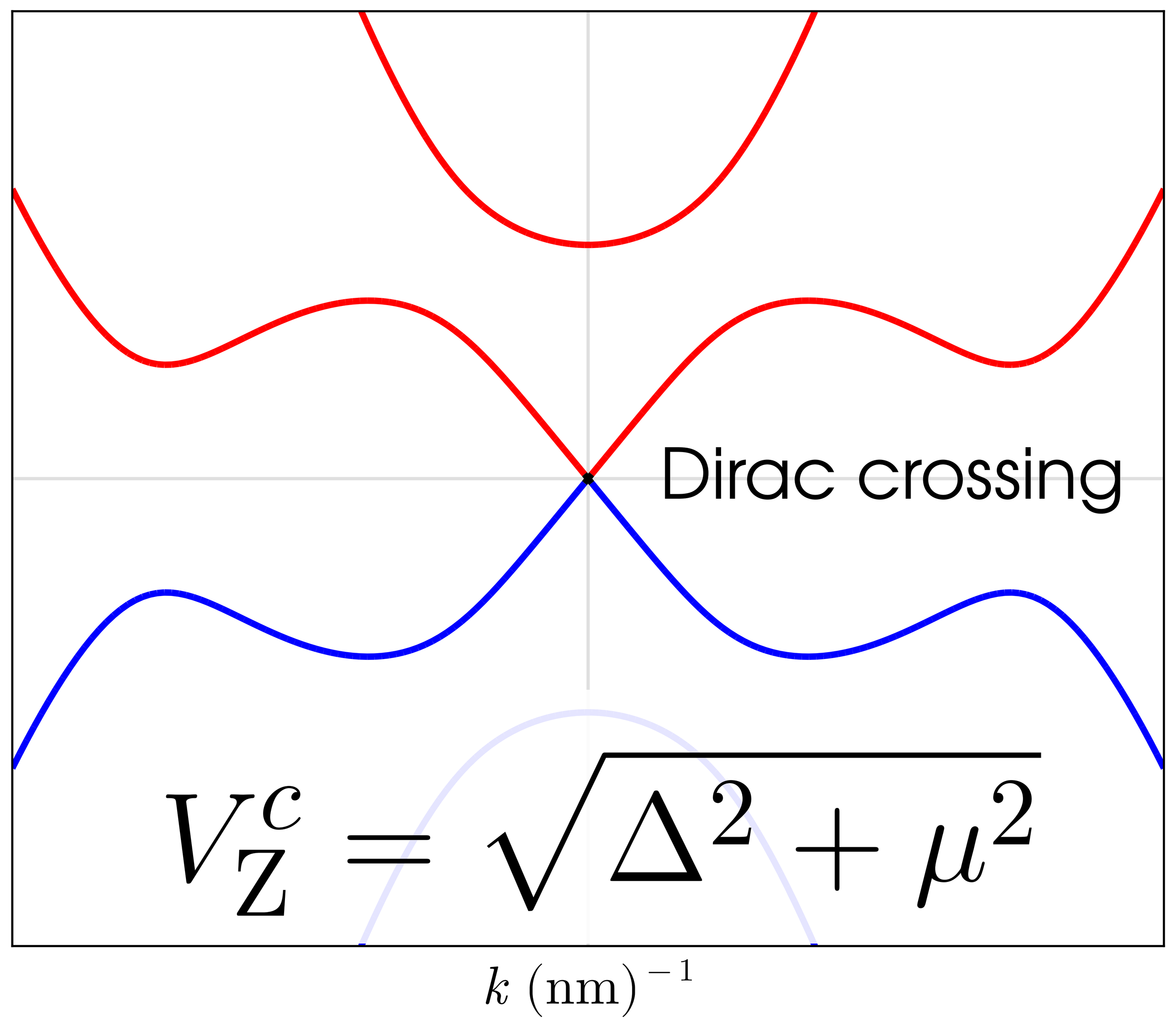


Oreg-Lutchyn

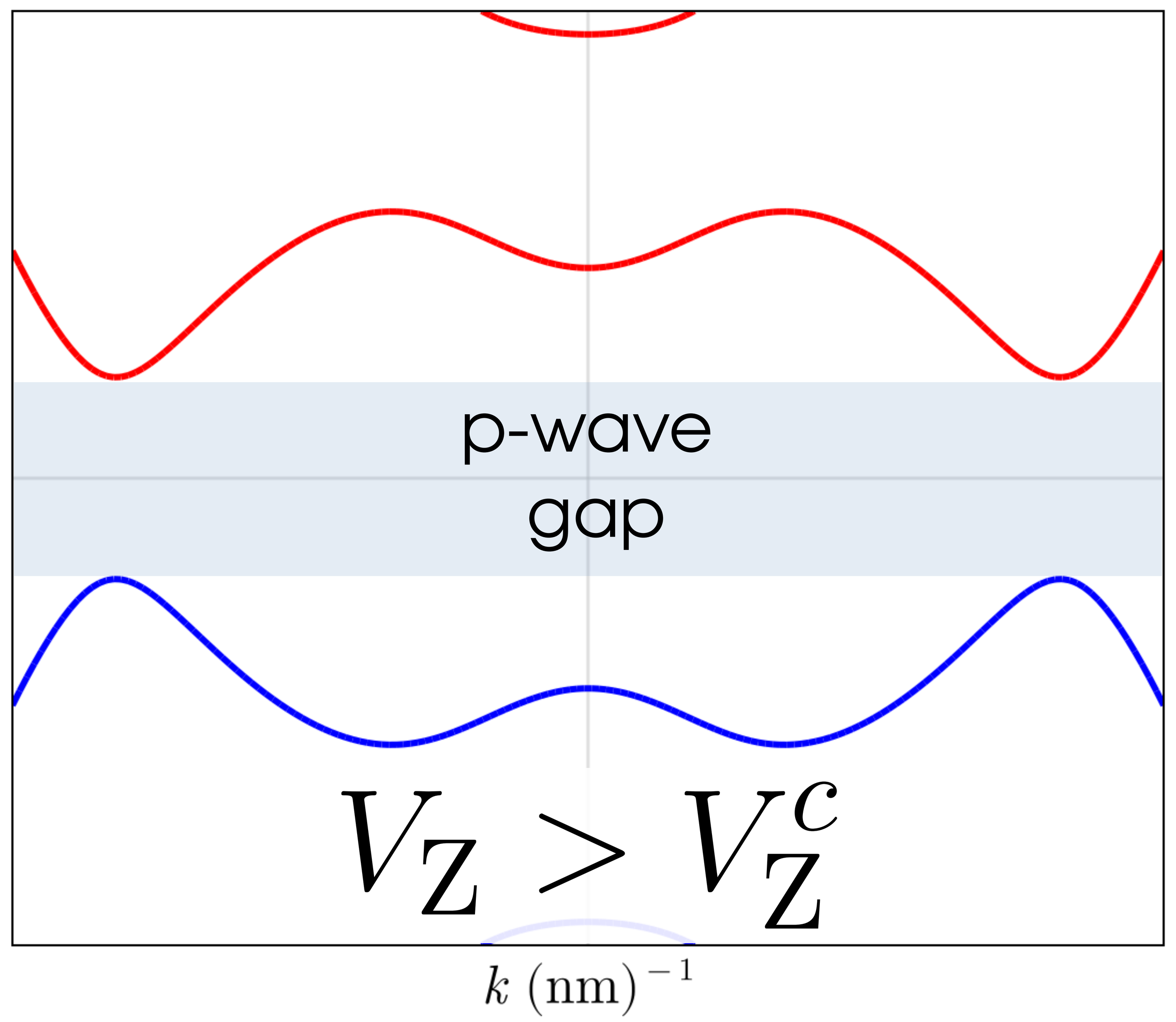
Trivial



Critical

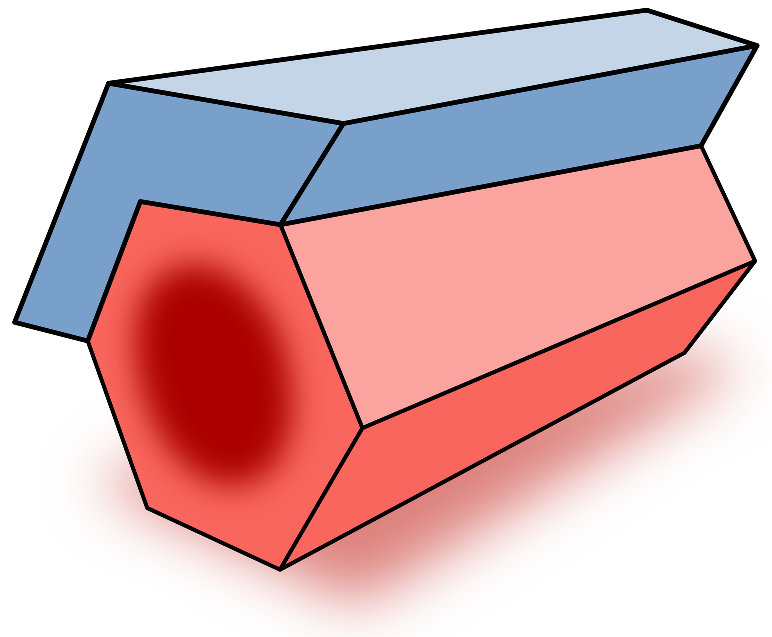


Topological

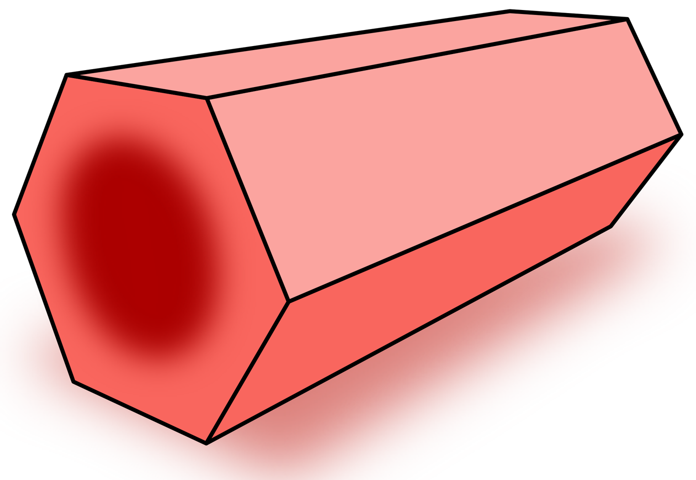


Self-consistent majorana nanowires

hybrid v.s intrinsic



super
$(U = 0)$
semi
$(U < 0)$



semi
$(U < 0)$

$$H^{\mathrm{hyb}} = H_0^{\mathrm{SM}} + H_{\mathrm{Z}}^{\mathrm{SM}} + H_{\mathrm{SOC}}^{\mathrm{SM}} + H_0^{\mathrm{SC}} + H_{\mathrm{Z}}^{\mathrm{SC}} + \Sigma_{\mathrm{HFB}}^{\mathrm{SC}} + H^{\text{SC-SM}}$$

$$H^{\mathrm{int}} = H_0 + H_{\mathrm{SOC}} + H_{\mathrm{Z}} + \Sigma_{\mathrm{HFB}}$$

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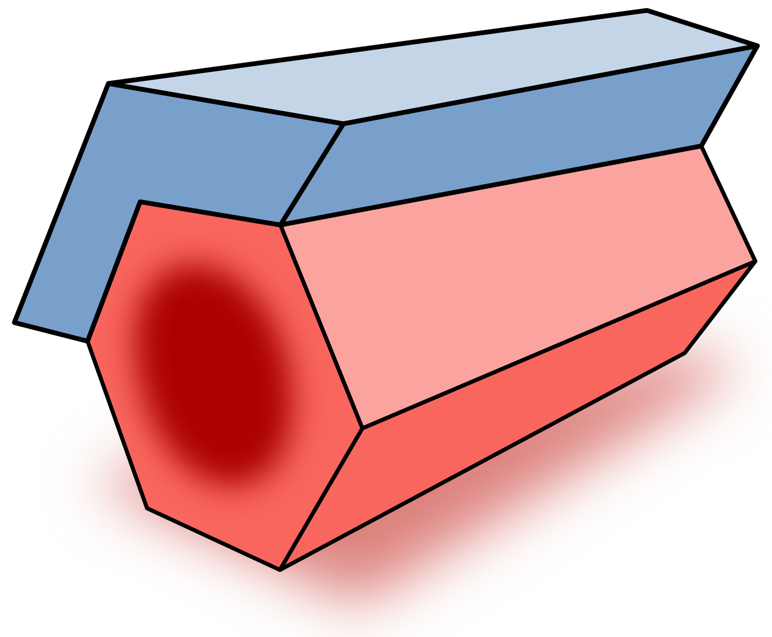

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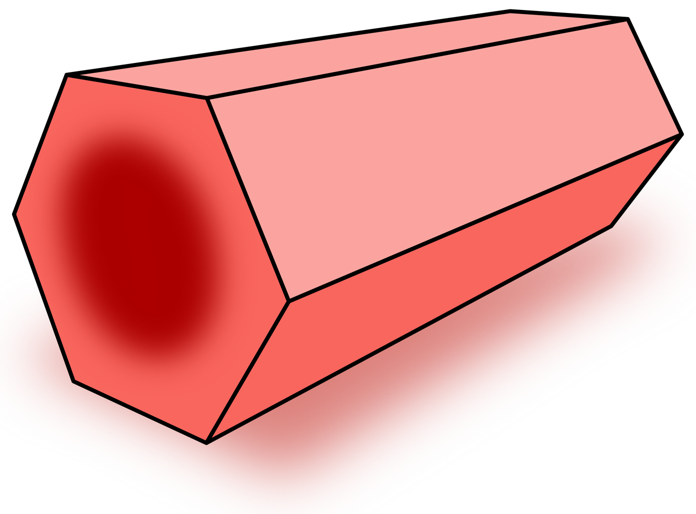

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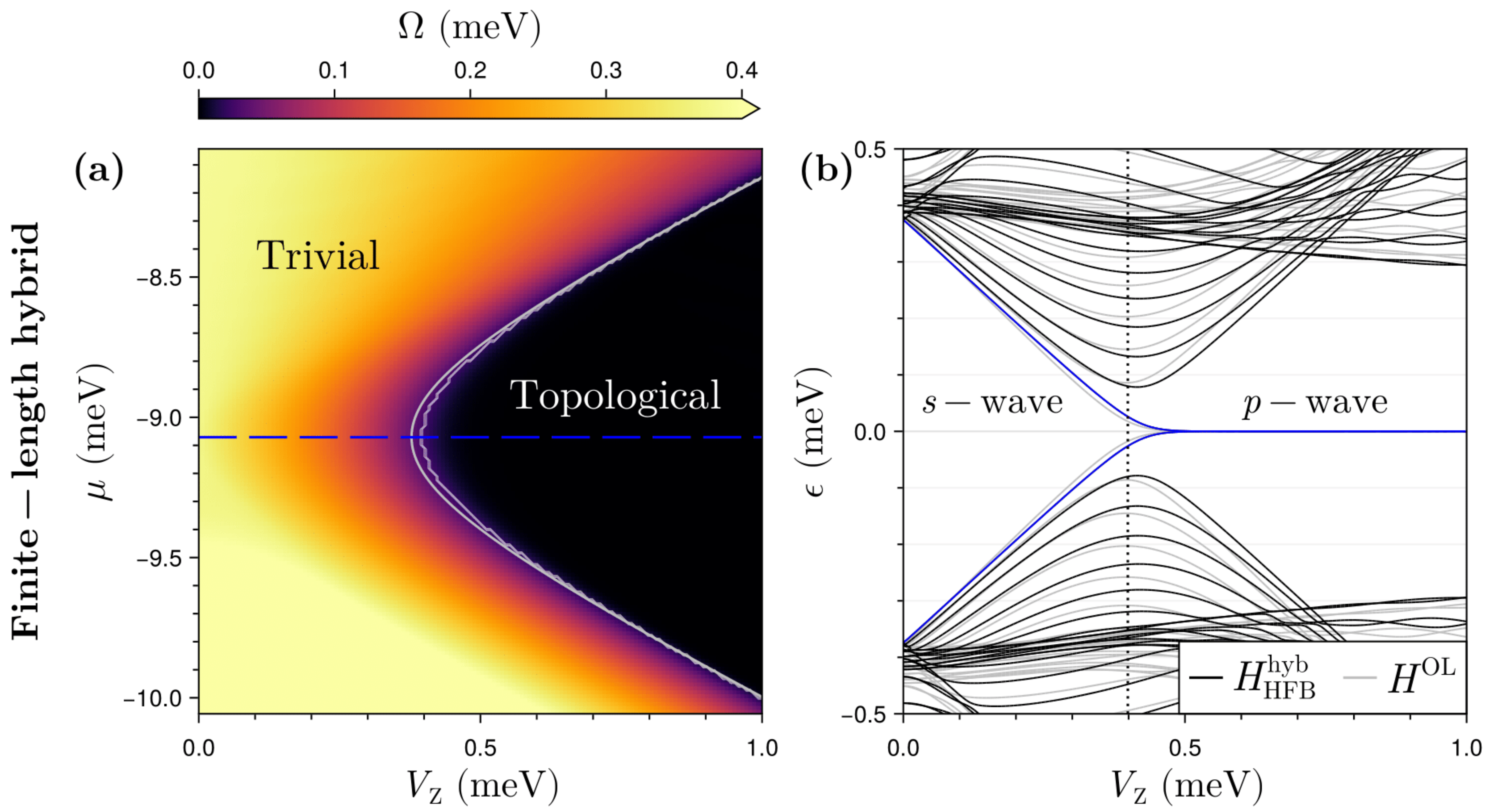
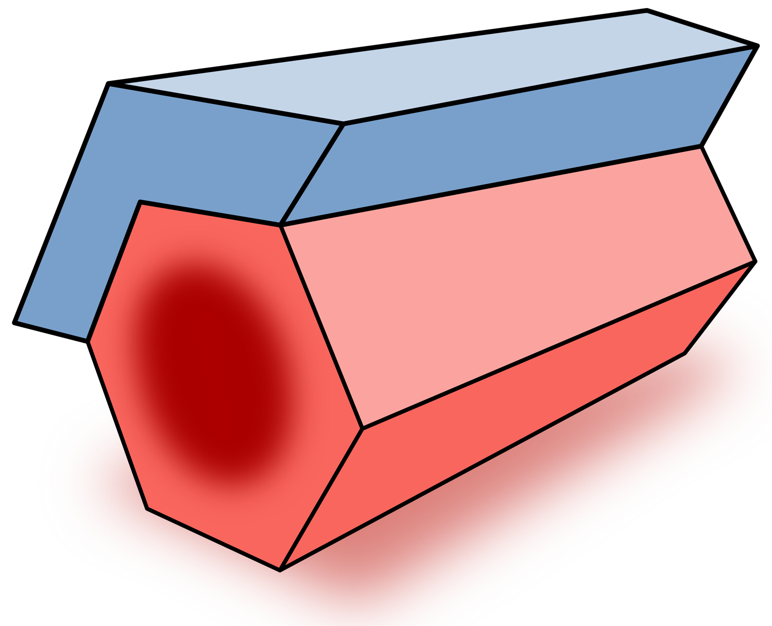
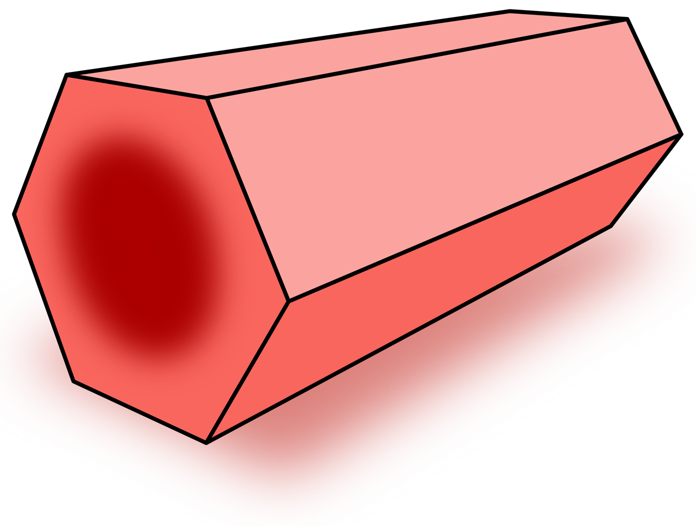


Self-consistent majorana nanowires

hybrid v.s intrinsic





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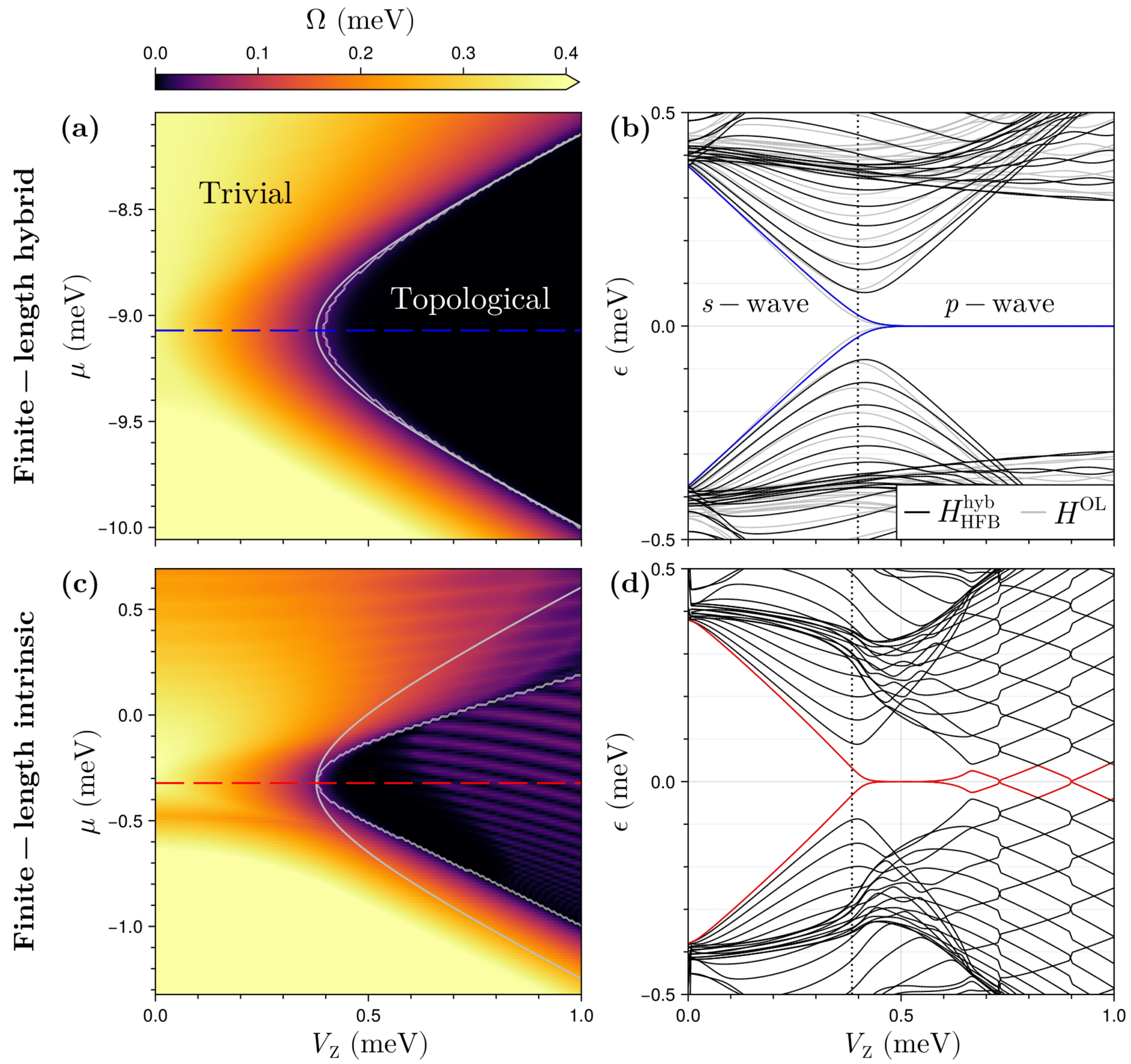
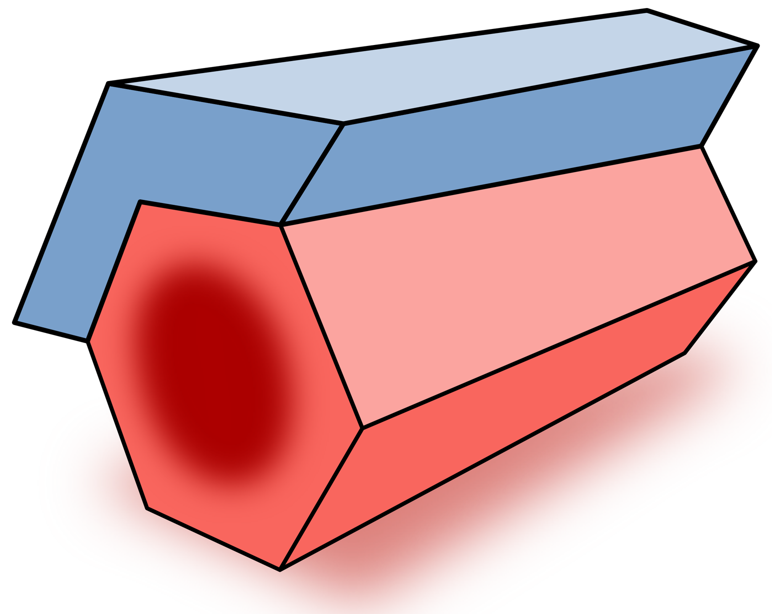


Self-consistent majorana nanowires

hybrid v.s intrinsic



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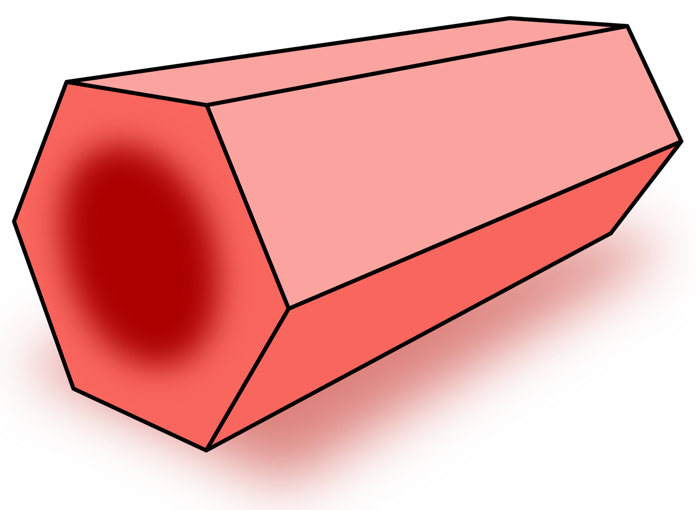

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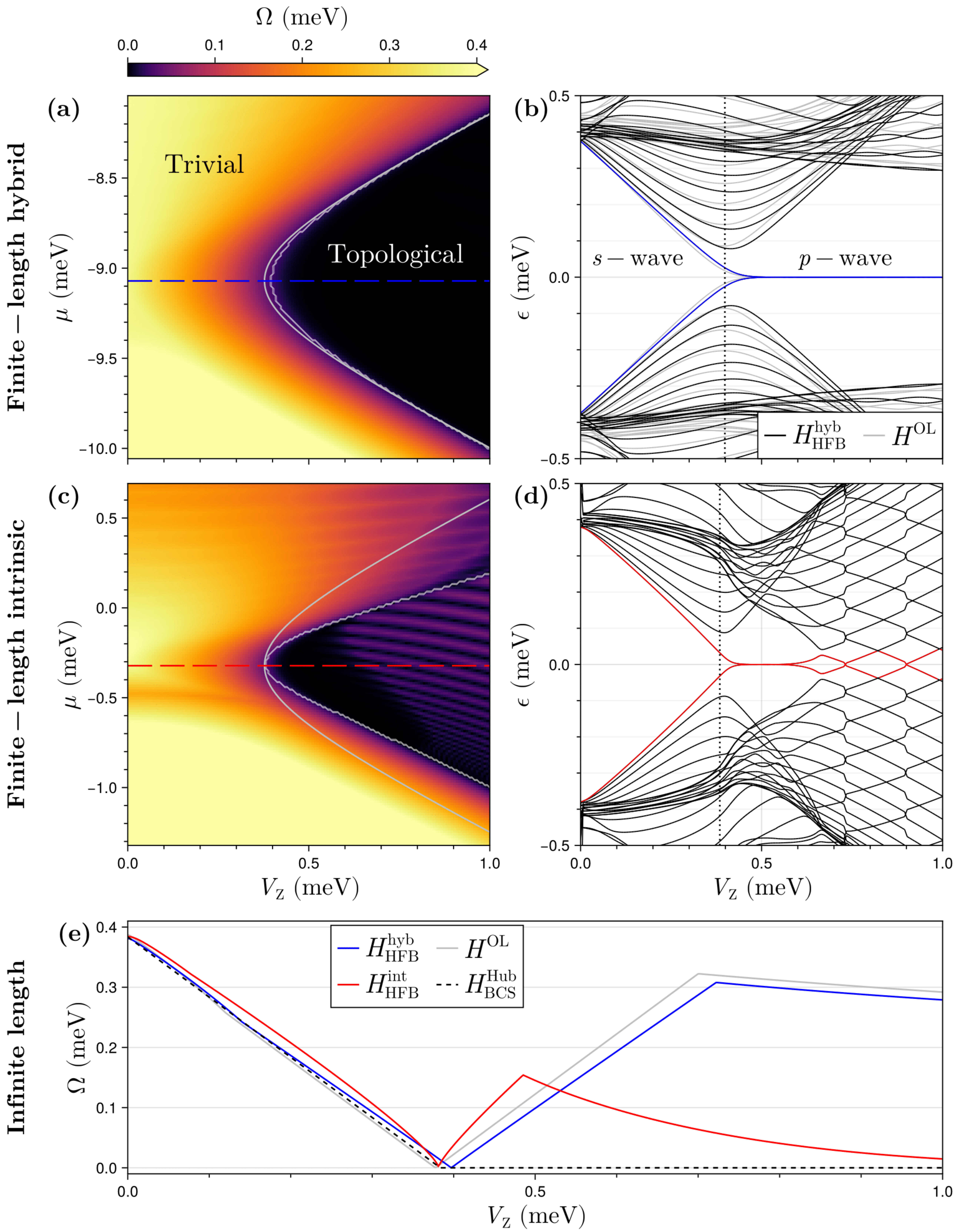
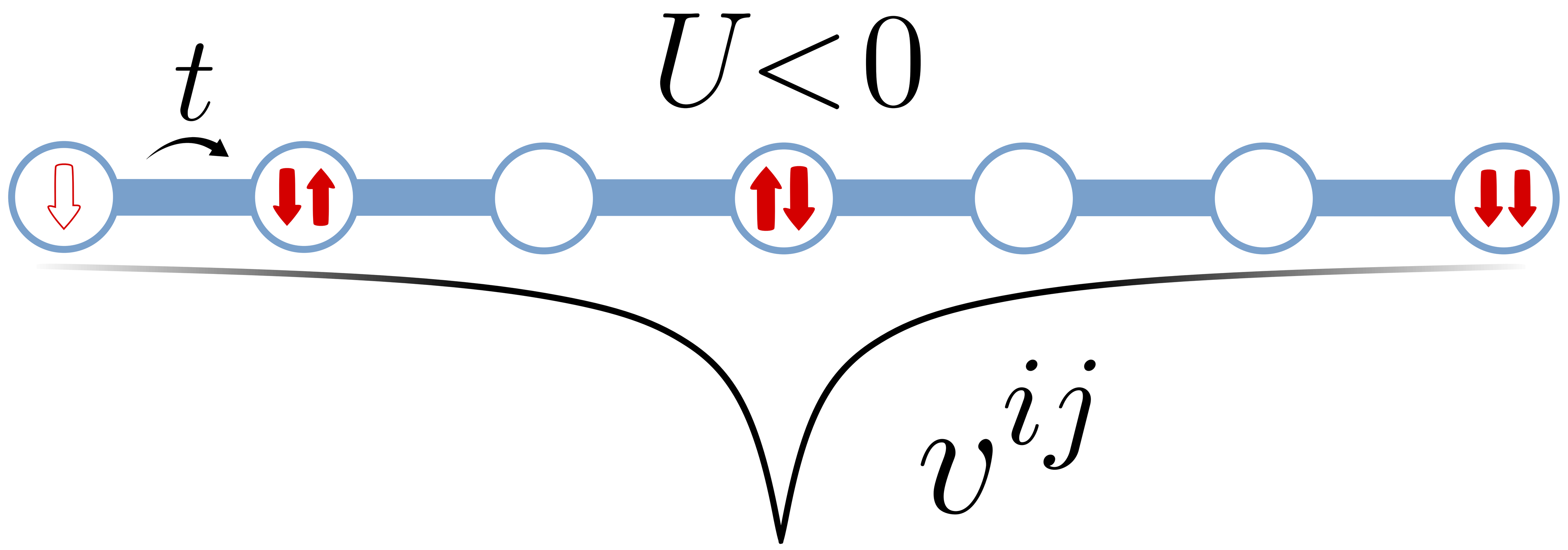


Intrinsic model w/ finite range interactions

$$H_U \longrightarrow H_{\text{int}} \text{ for } i \neq j$$

with a screened Coulomb interaction of screening length λ

(imposed onsite Hubbard still)



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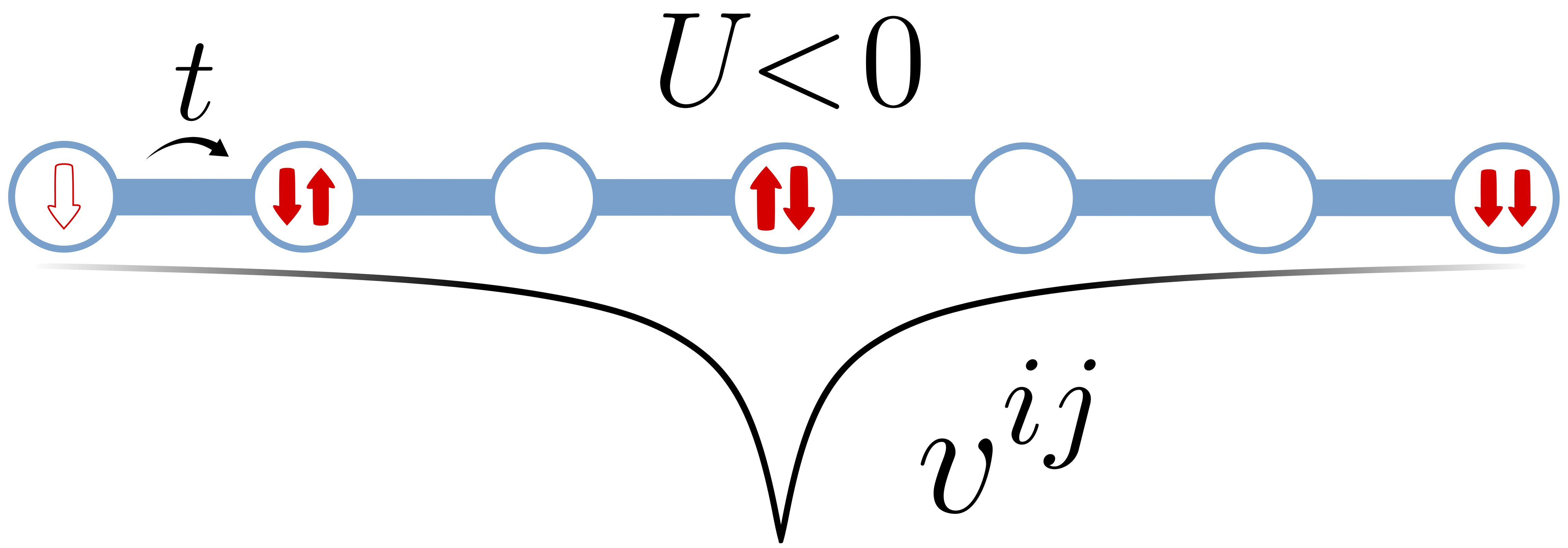
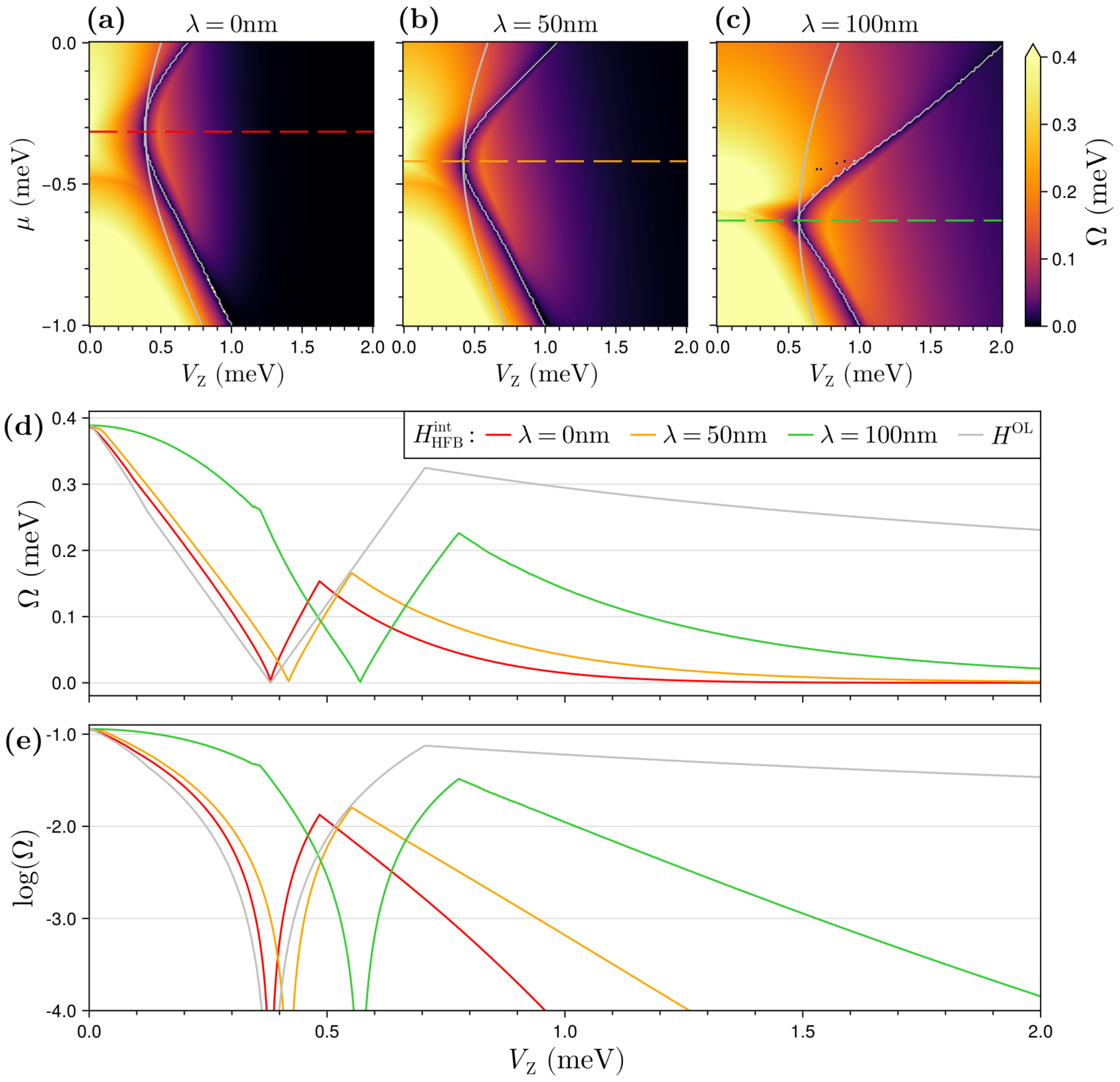


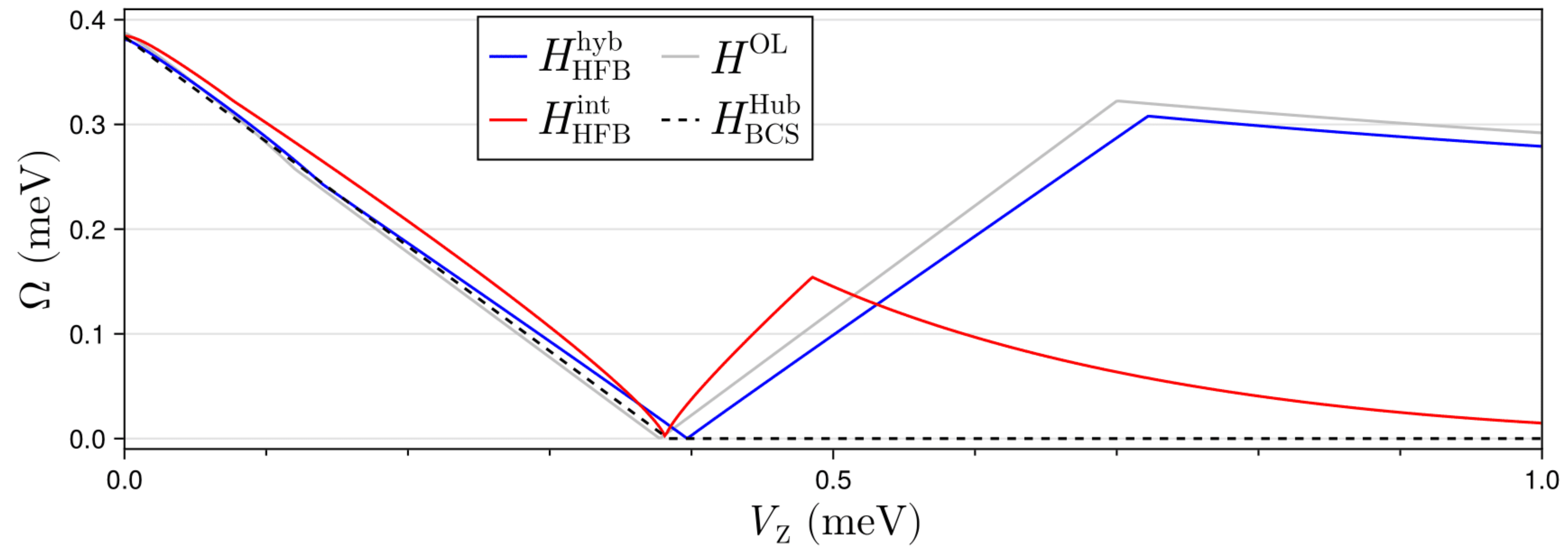


Conclusions

So, is topological intrinsic superconductivity promising for 1D Majorana nanowires?

Not really. It appears to be a problematic approach:

- exponential decay of the minigap
  - spinlessness versus superconductivity
  - weak spin canting of spinless carriers *



But the developed self-consistent superconductivity methodology can prove to be fructiferous for other systems

* does not affect Majoranas obtained by the time-reversal symmetric Fu-Kane approach. DOI: 10.1103/PhysRevLett.100.096407

Thank you for listening!
Any questions?

arXiv:2412.15174