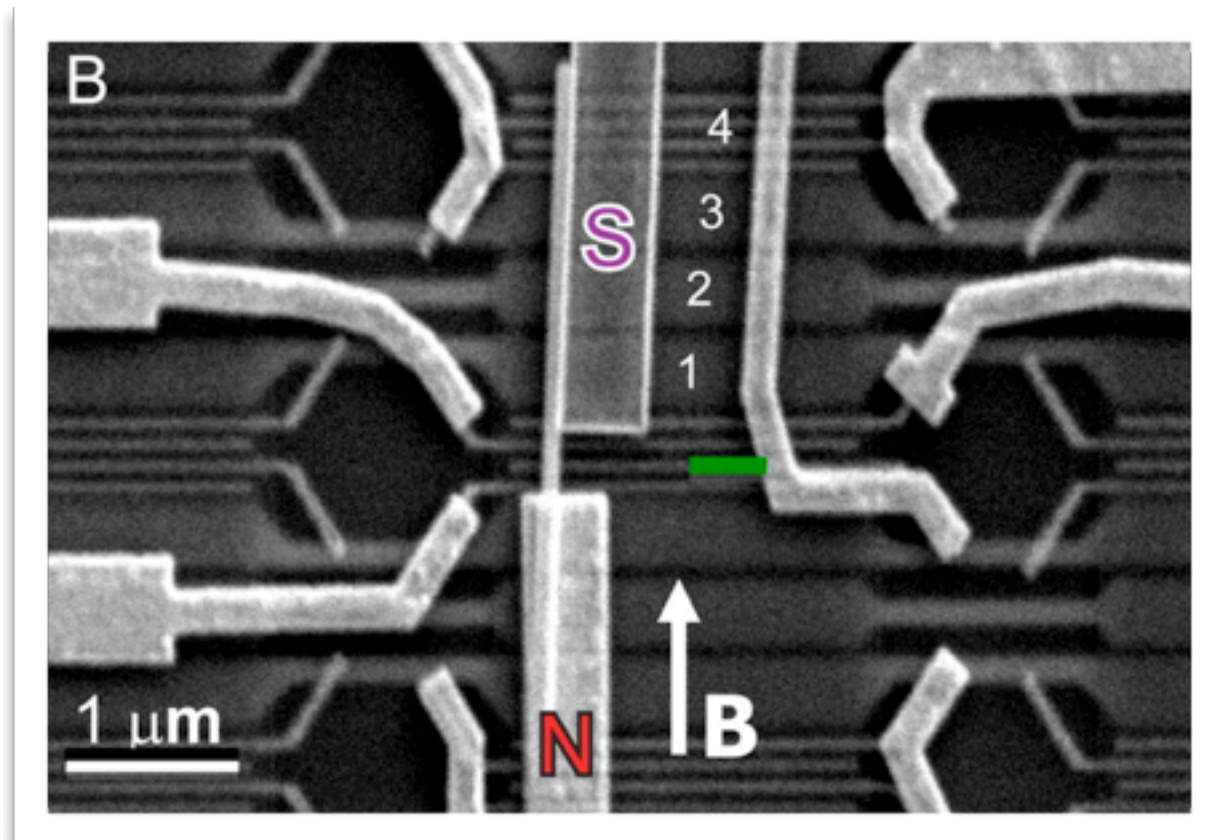
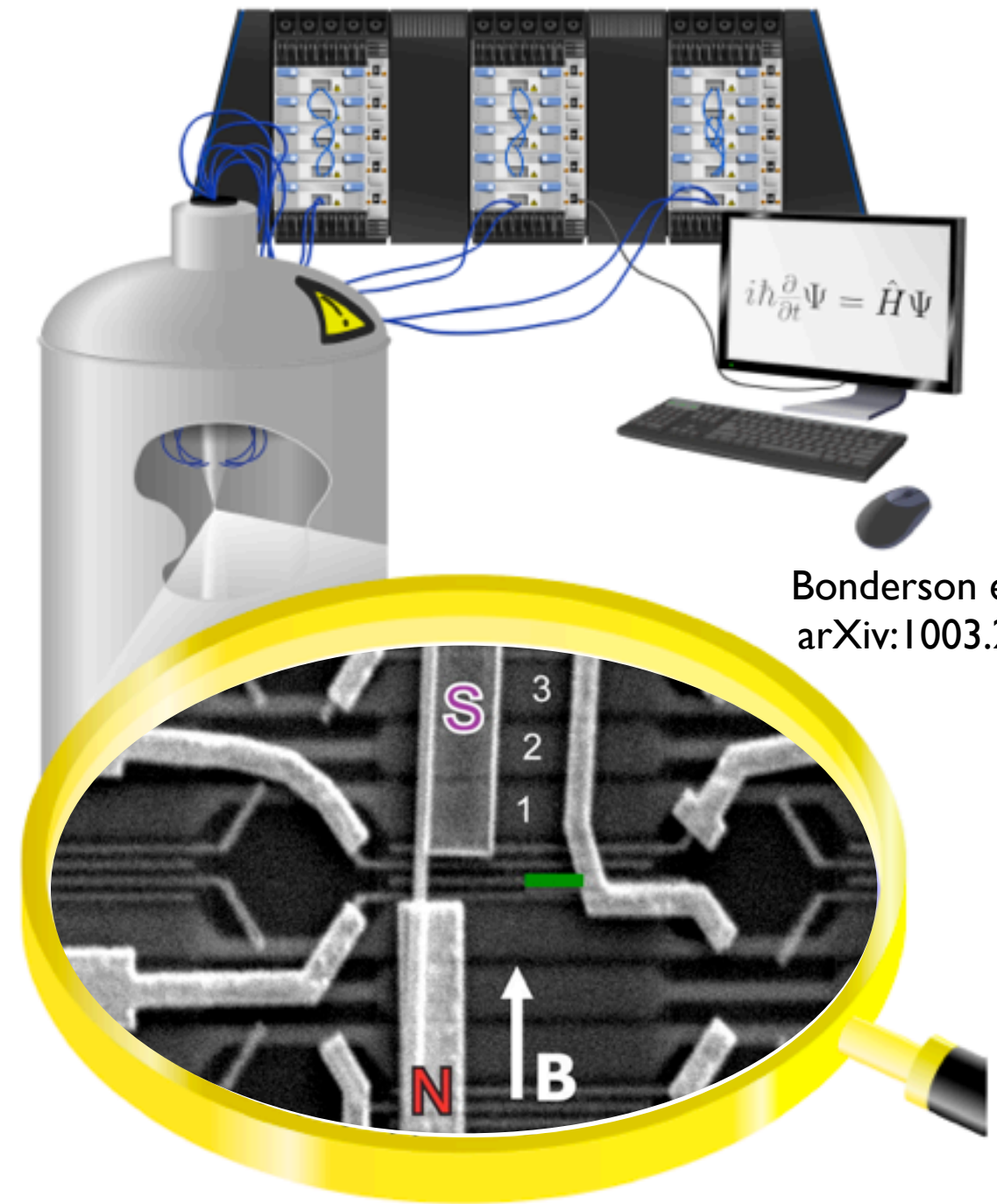


Majorana materializes



Mourik et al., Science 2012



Bonderson et al.,
arXiv:1003.2856

Jason Alicea (Caltech)

Acknowledgments

Anton Akhmerov (Harvard)
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Liang Jiang (Caltech)
Takuya Kitagawa (Harvard)
Shu-Ping Lee (Caltech)
Netanel Lindner (Caltech)
Roman Lutchyn (Station Q)
Roger Mong (Caltech)

Chetan Nayak (Station Q)
Yuval Oreg (Weizmann)
David Pekker (Caltech)
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Alessandro Romito (Berlin)
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Oleg Starykh (Utah)
Ady Stern (Weizmann)
Miles Stoudenmire (UCI)
Felix von Oppen (Berlin)
Conan Weeks (UBC)
Ruqian Wu (UCI)
Amir Yacoby (Harvard)



Outline

- Majorana fermions: what they are & why they're interesting
- The quest for Majorana in the solid state
- Getting the most out of Majorana fermions
- Experimental status & closing remarks

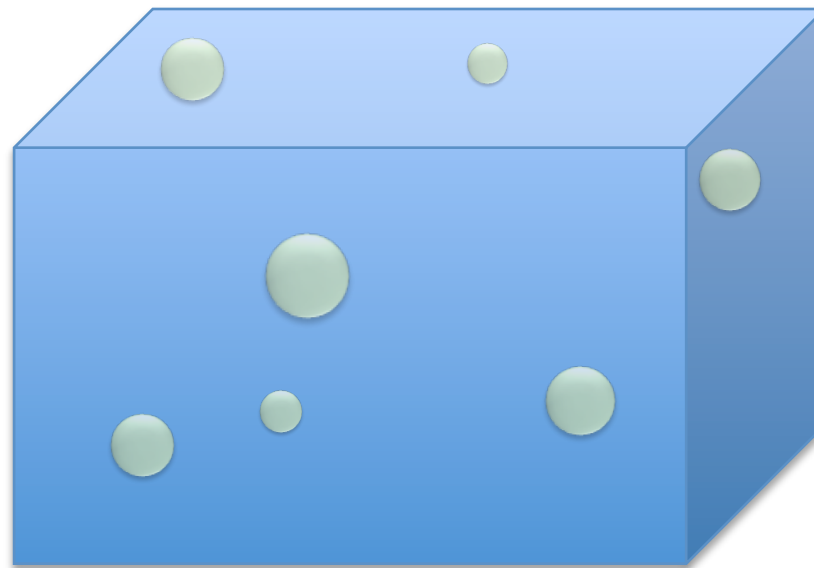
Outline

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Exchange statistics

Describes how wavefunctions transform when indistinguishable particles exchange positions

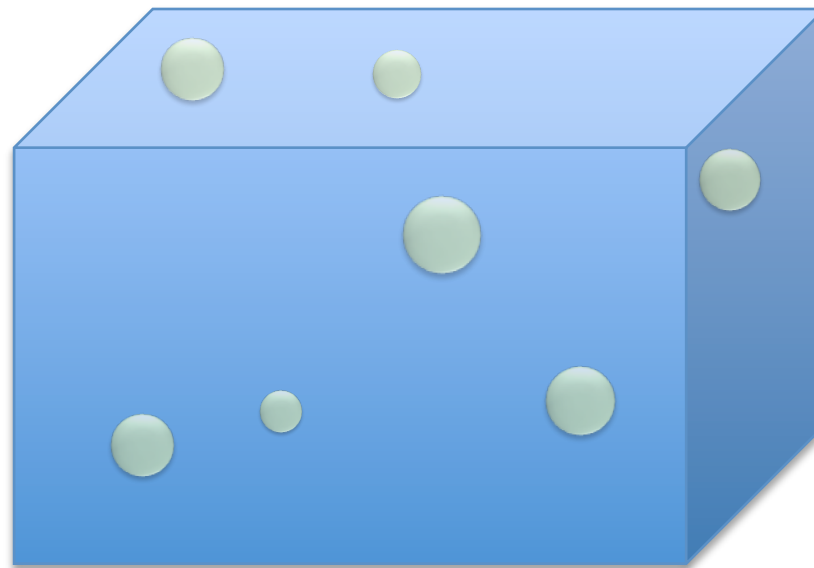
$$\psi(\mathbf{r}_1, \dots, \mathbf{r}_N)$$



Exchange statistics

Describes how wavefunctions transform when indistinguishable particles exchange positions

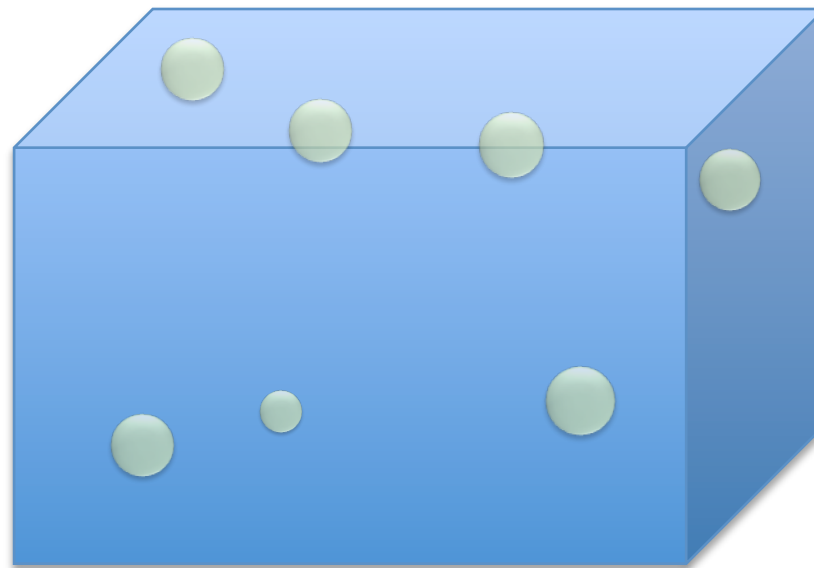
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Exchange statistics

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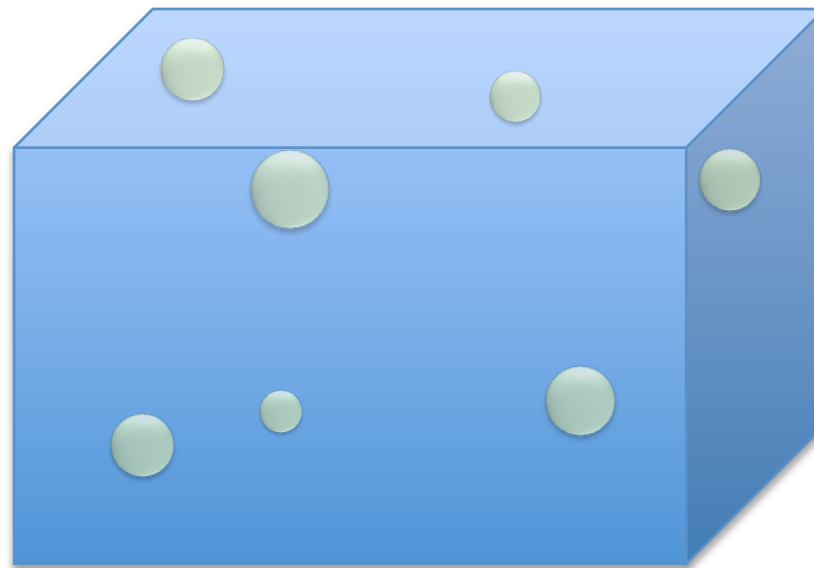
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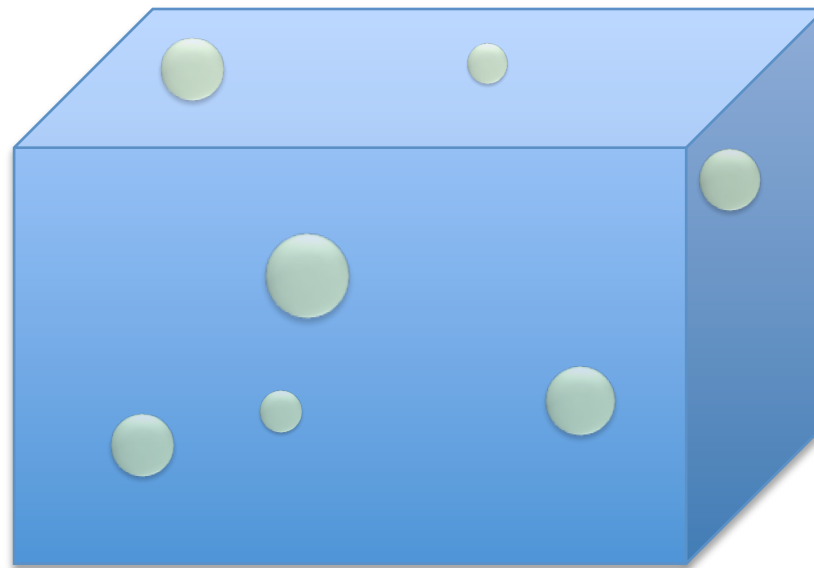
$$\psi(\mathbf{r}_1, \dots, \mathbf{r}_N)$$



Exchange statistics

Describes how wavefunctions transform when indistinguishable particles exchange positions

$$\psi(\mathbf{r}_1, \dots, \mathbf{r}_N) \longrightarrow \psi'(\mathbf{r}_1, \dots, \mathbf{r}_N)$$



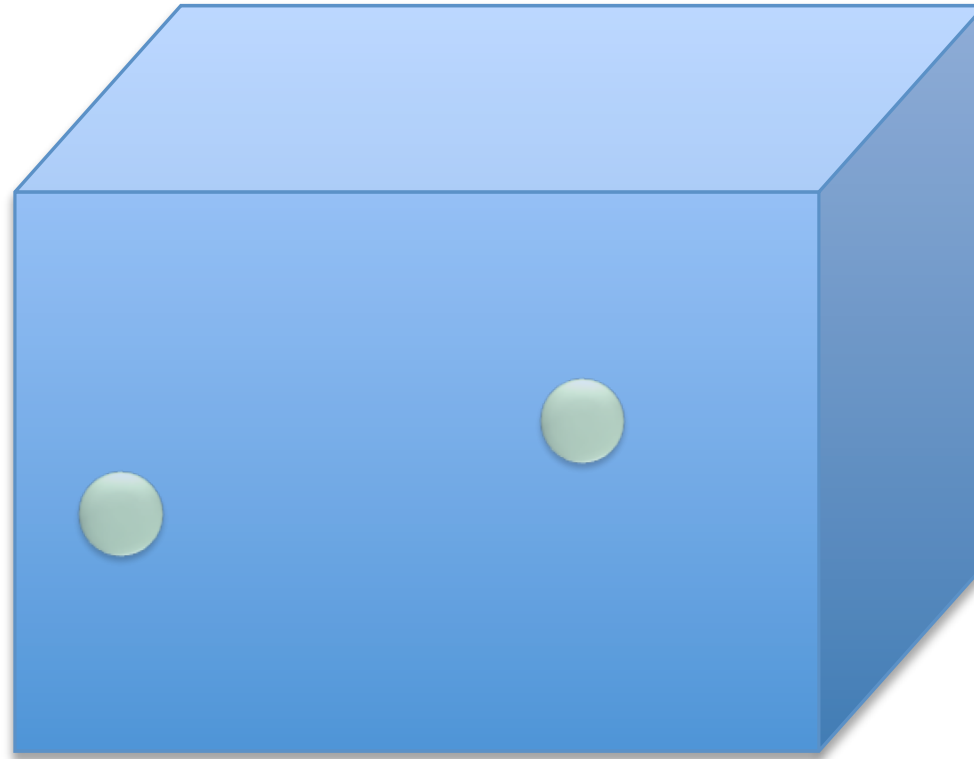
Extraordinarily fundamental!

Underlies most condensed matter phenomena.

Role of dimensionality

d = 3

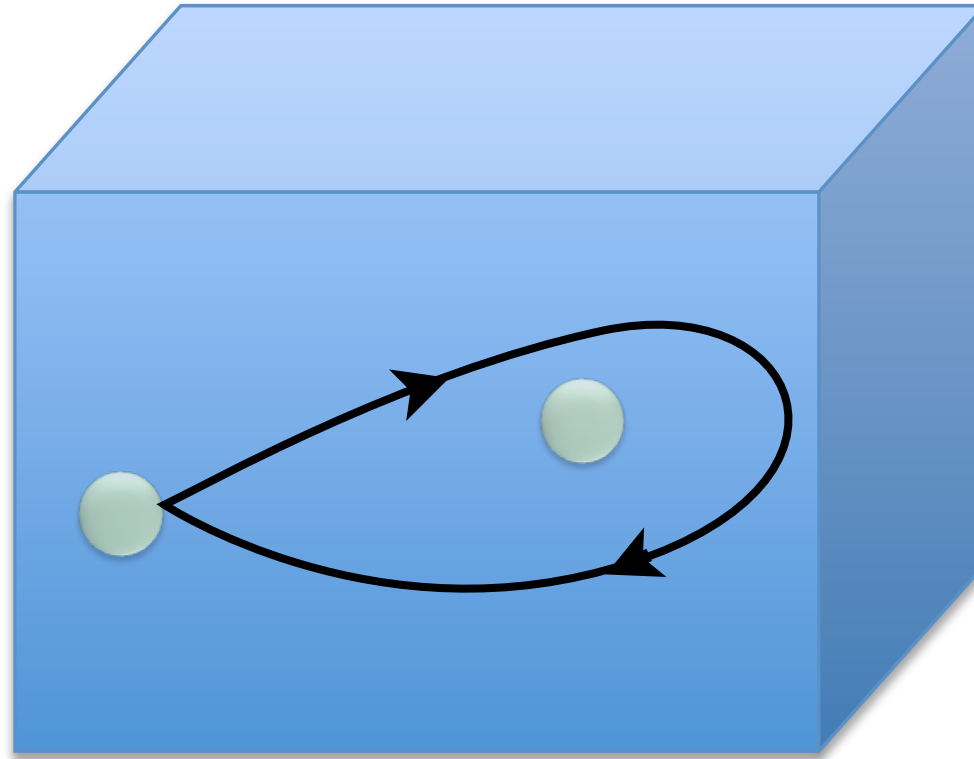
Only bosons &
fermions



Role of dimensionality

$d = 3$

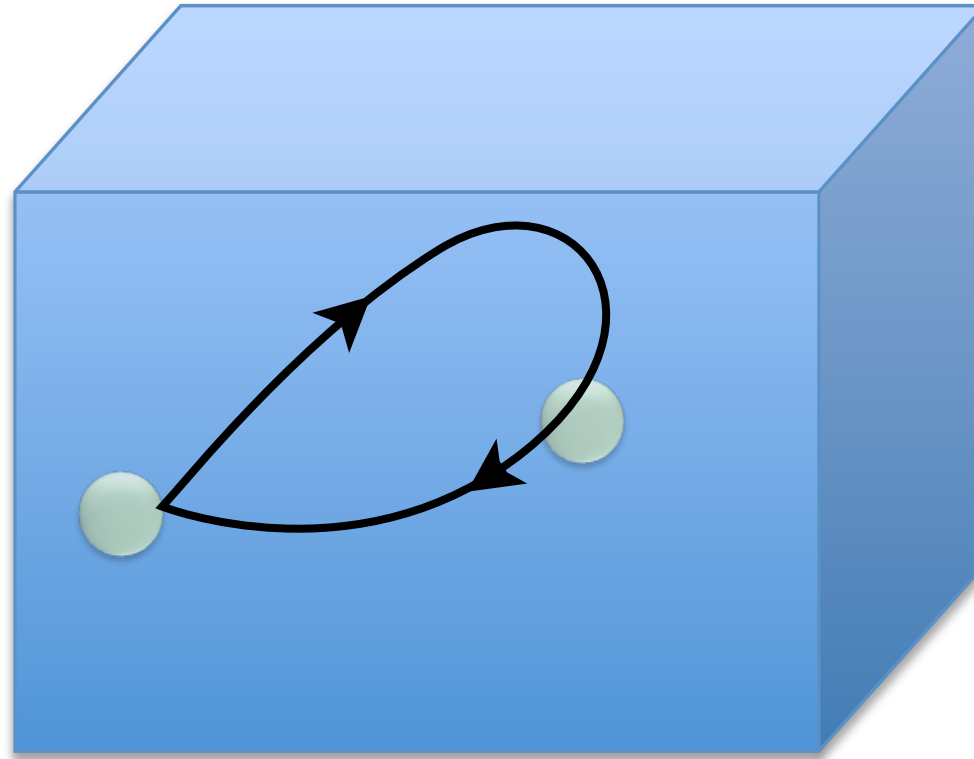
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Role of dimensionality

d = 3

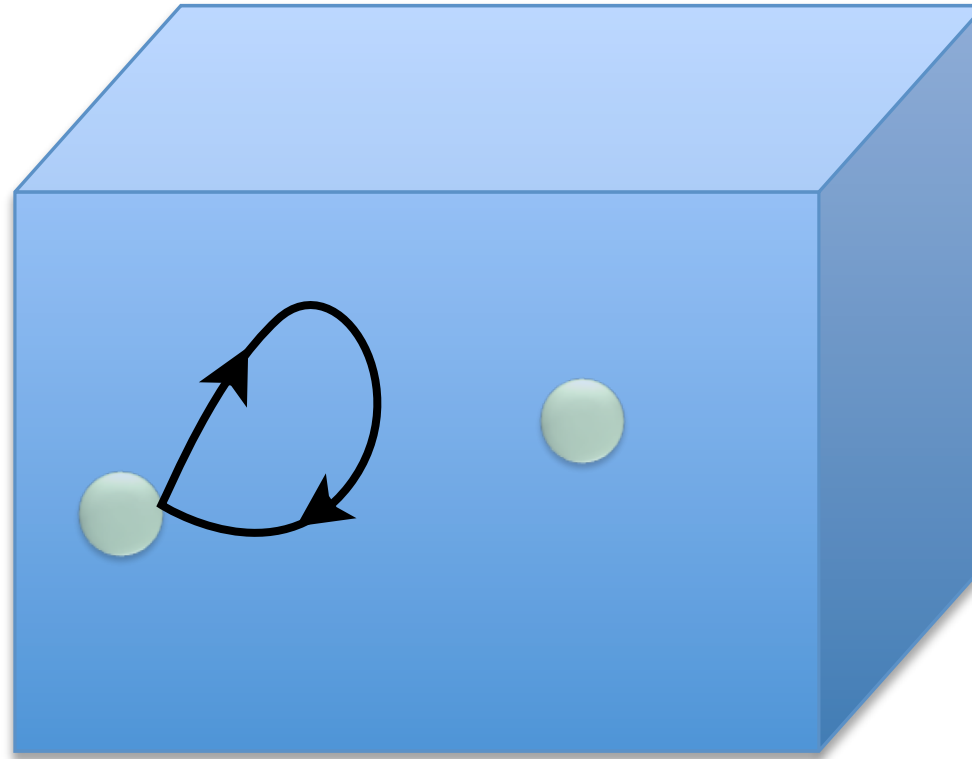
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Role of dimensionality

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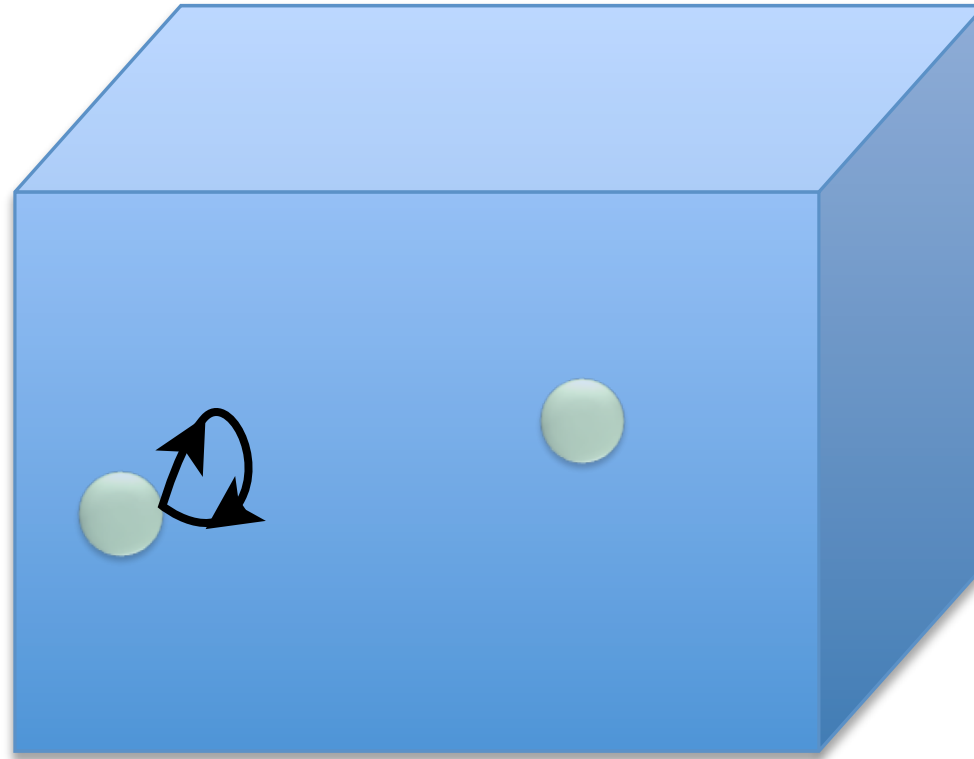
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Role of dimensionality

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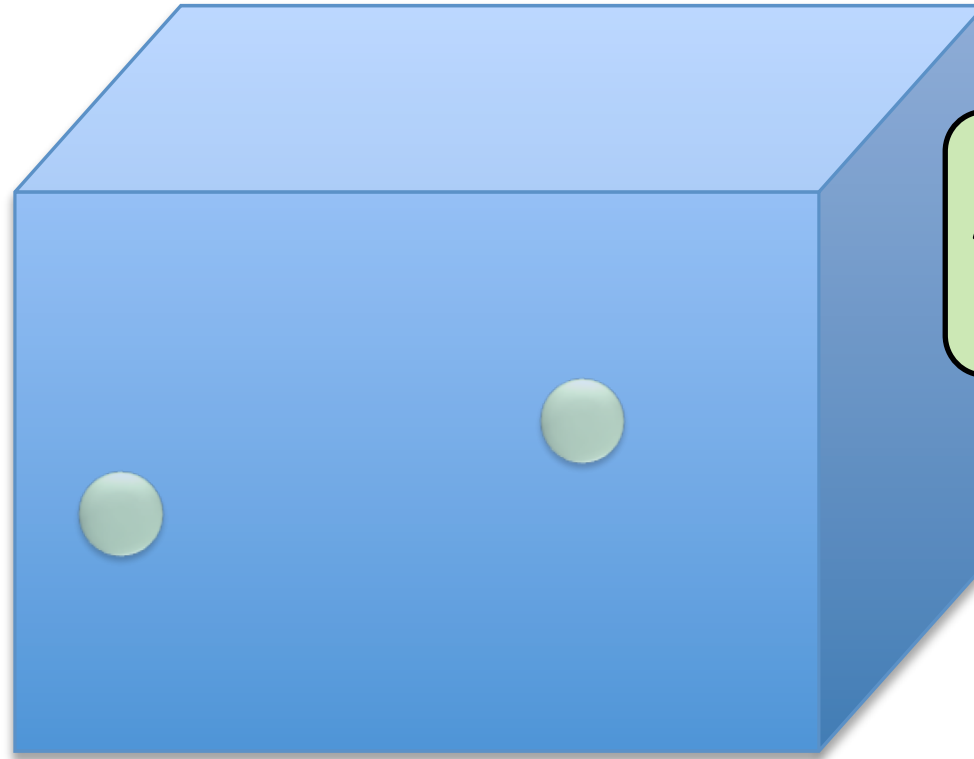
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Role of dimensionality

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Only bosons &
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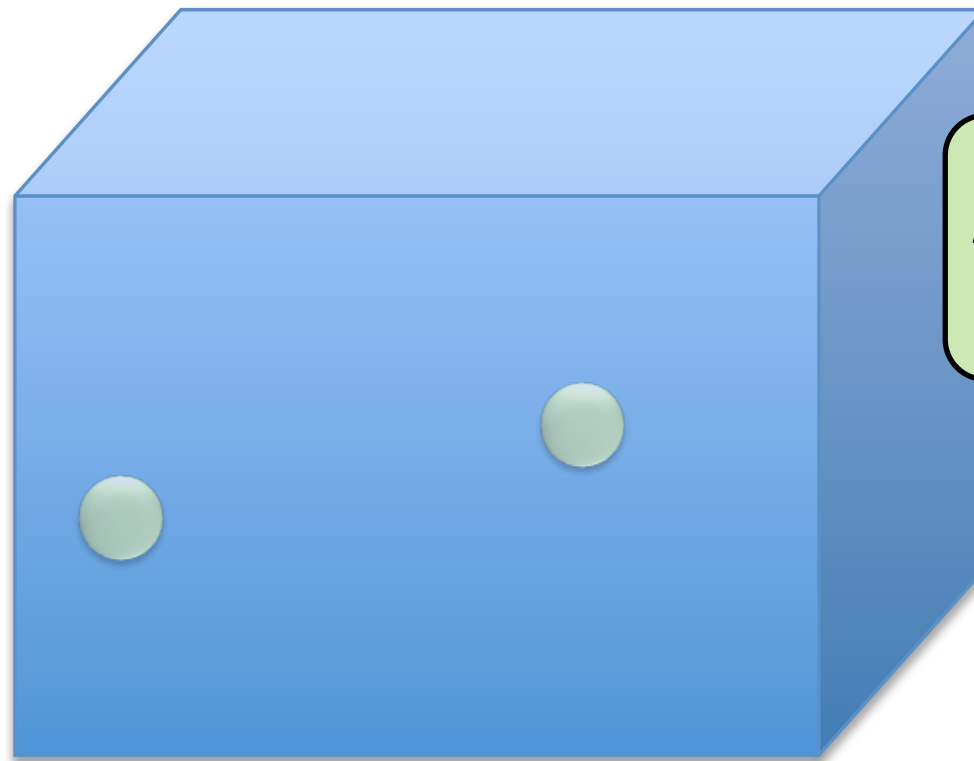


$$\psi \rightarrow \pm \psi$$

Role of dimensionality

d = 3

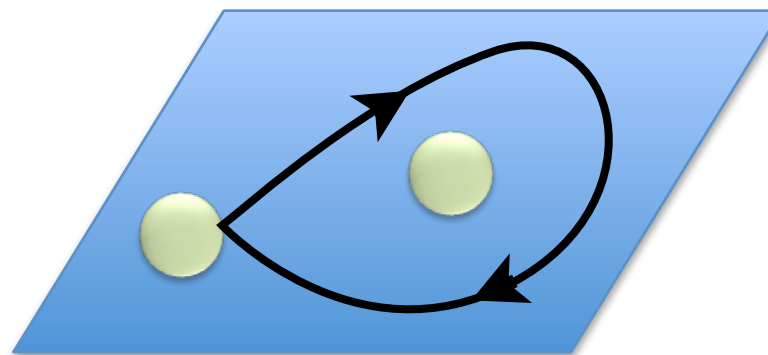
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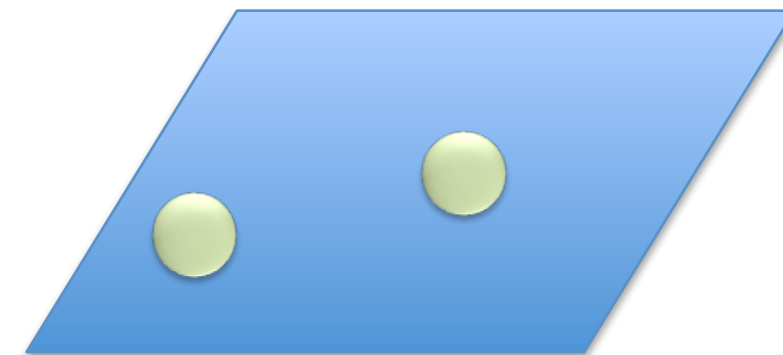
$$\psi \rightarrow \pm \psi$$

d = 2

Anyons are now possible!



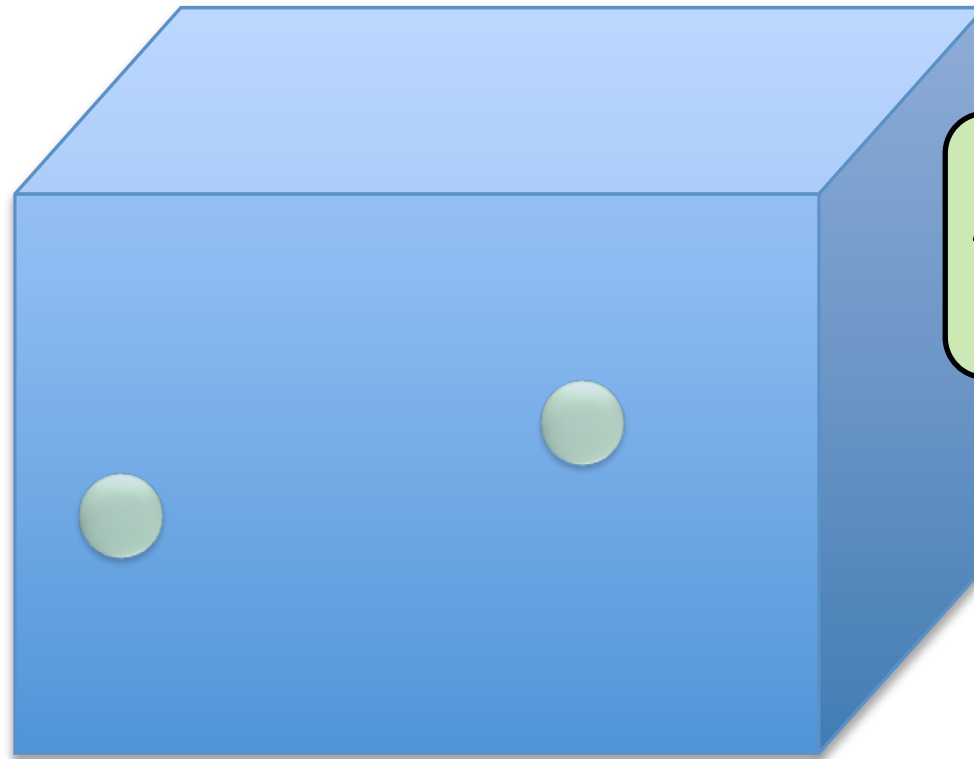
\neq



Role of dimensionality

d = 3

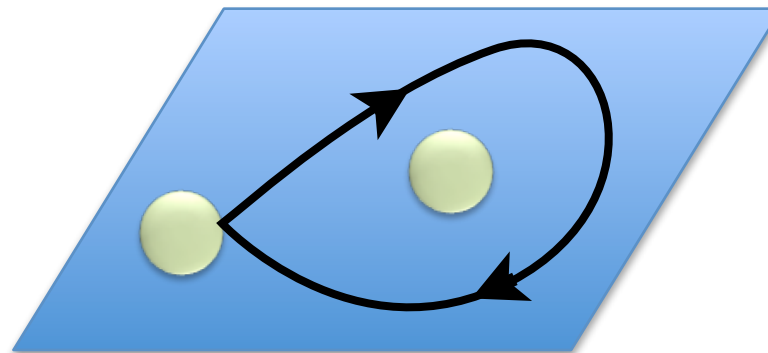
Only bosons & fermions



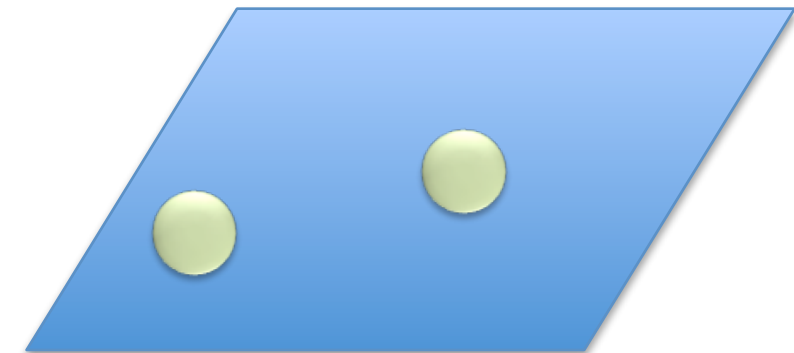
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d = 2

Anyons are now possible!



\neq



d = 1

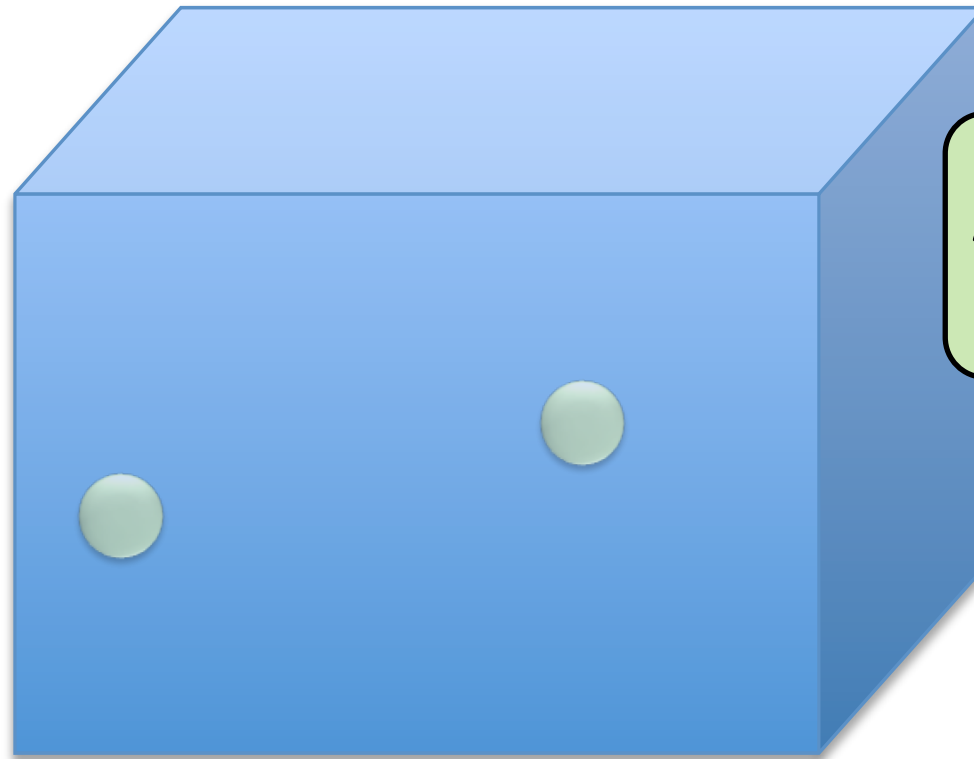
Exchange not well defined...



Role of dimensionality

d = 3

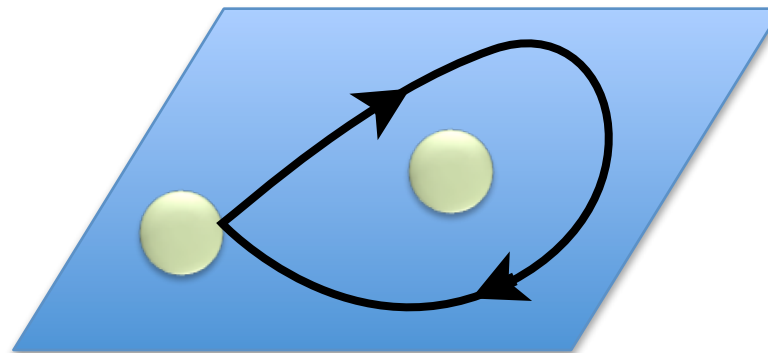
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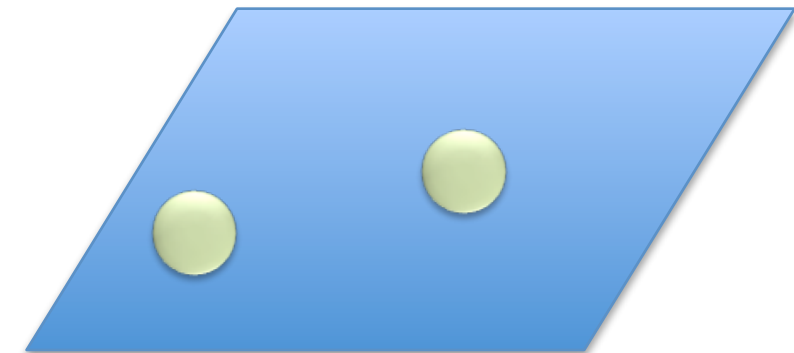
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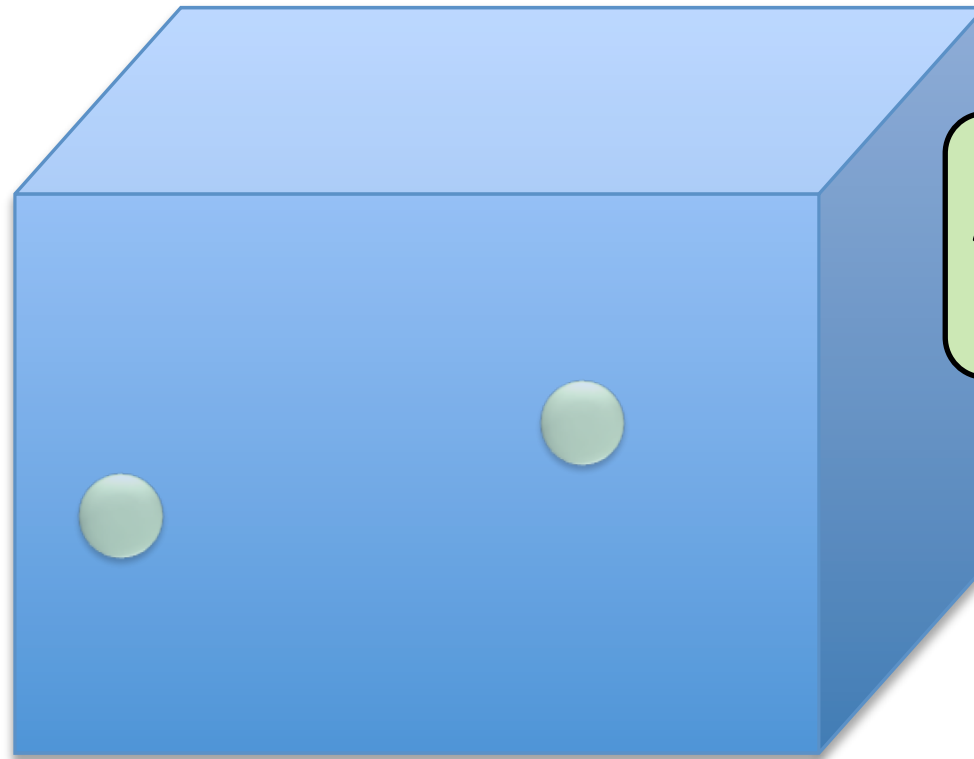
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Role of dimensionality

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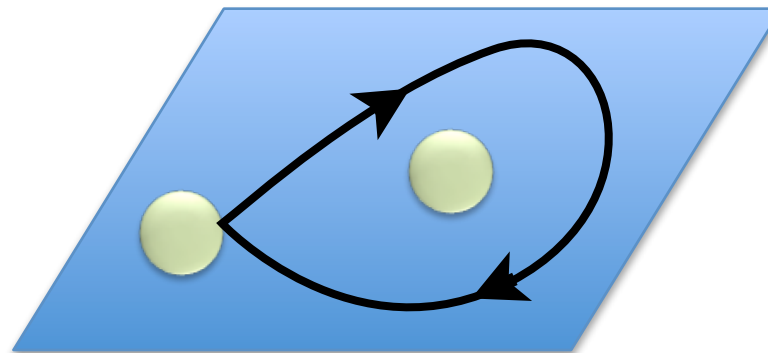
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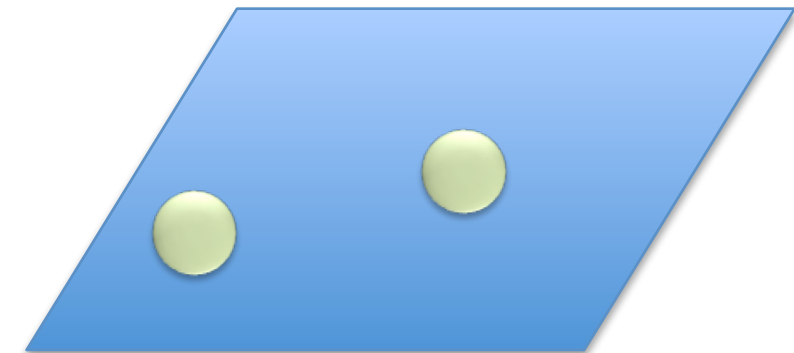
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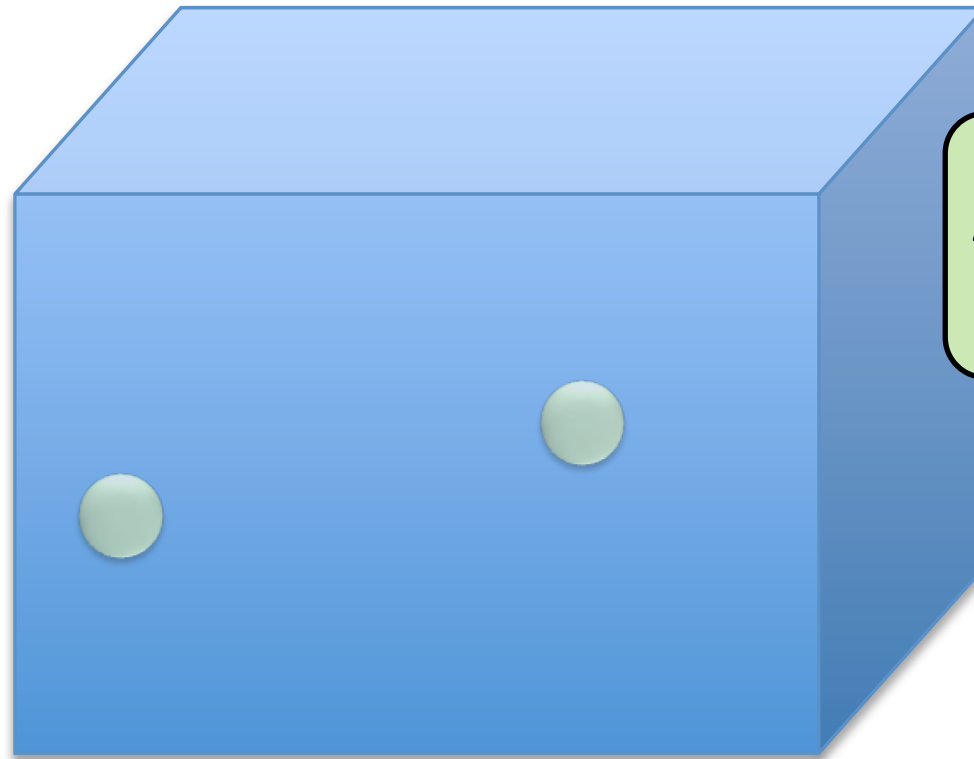
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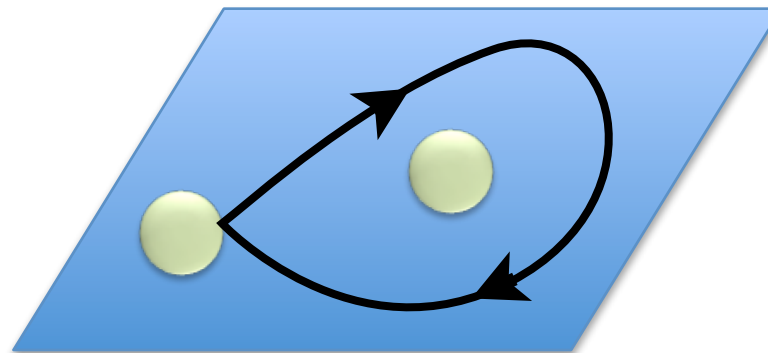
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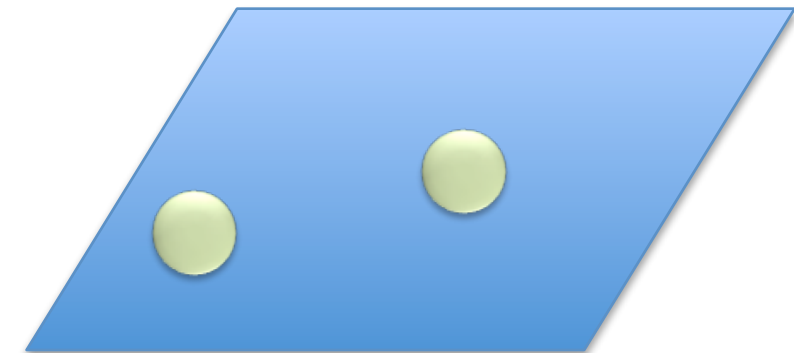
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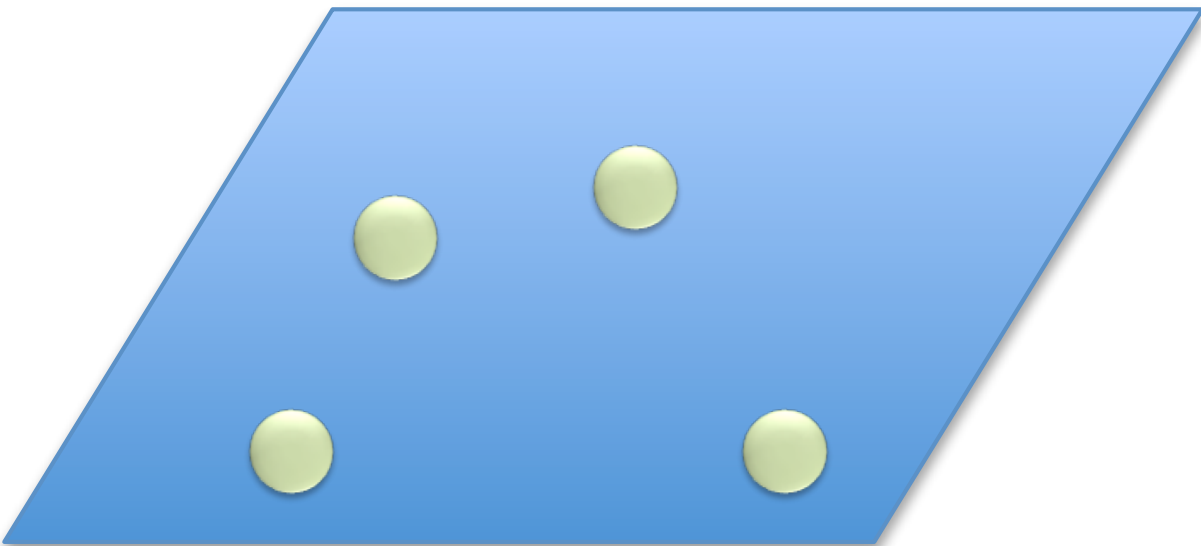
d = 1

Exchange not well defined...



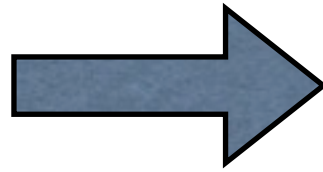
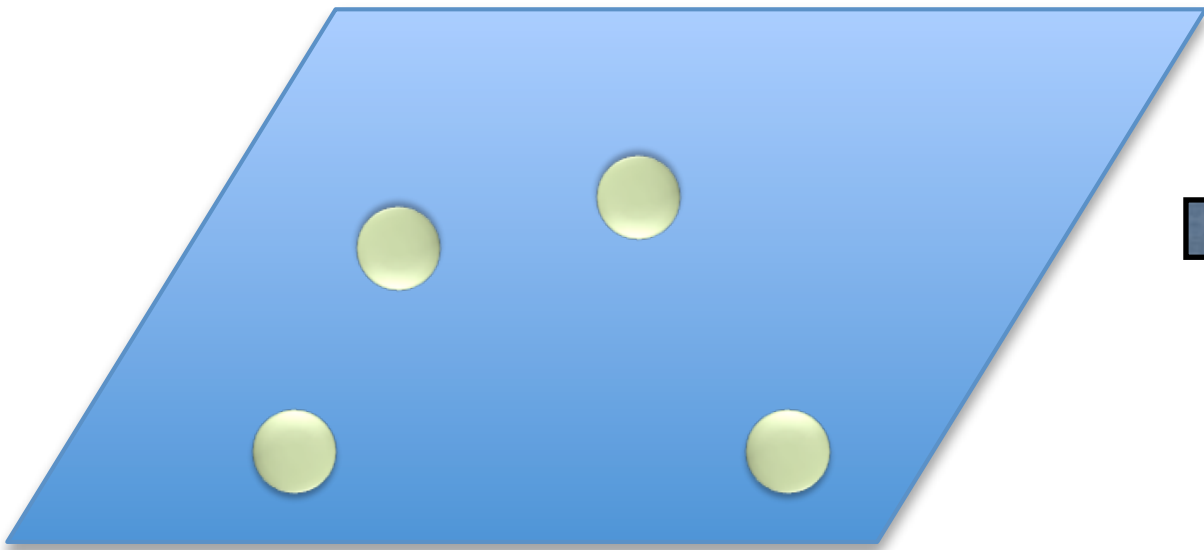
...because particles inevitably “collide”

Non-Abelian anyons



ψ_a

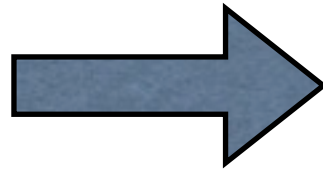
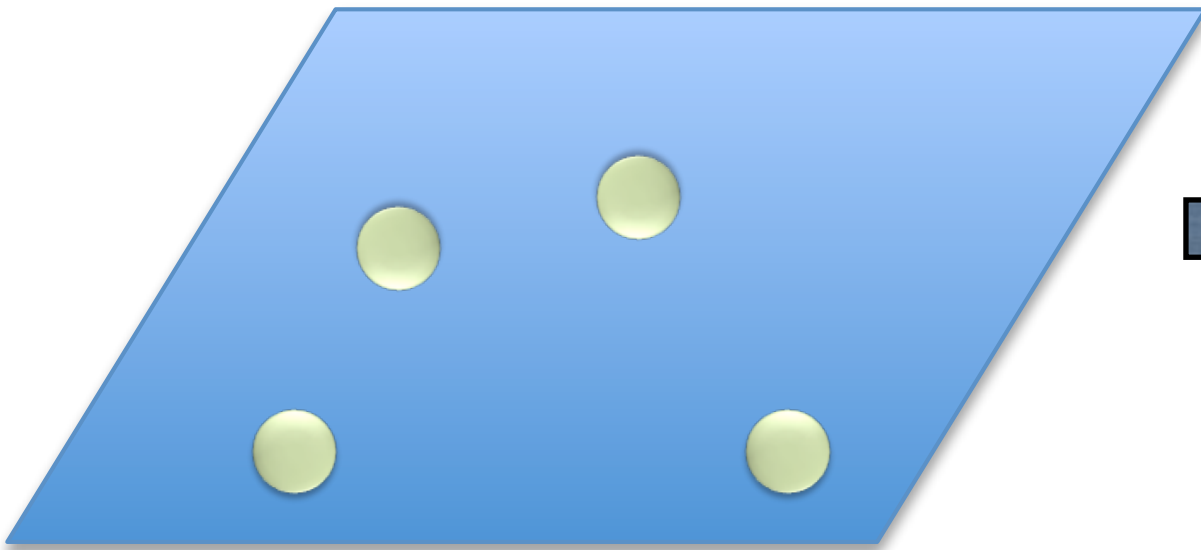
Non-Abelian anyons



“Rotates” wavefunction to
a different quantum state!

$$\psi_a \longrightarrow U_{ab} \psi_b$$

Non-Abelian anyons



“Rotates” wavefunction to a different quantum state!

$$\psi_a \rightarrow U_{ab} \psi_b$$

**Urgently wanted for
topological quantum
computation**

Kitaev; Freedman; Preskill; Frohlich, etc.
Nayak, Simon, Stern, Freedman, & Das
Sarma, RMP 80, 1083 (2008)

Simplest source of non-Abelian statistics: **Majorana fermions**

The “inventor” of Majorana fermions



Ettore Majorana (1906-1938?)

"There are many categories of scientists: people of second and third rank, who do their best, but do not go very far; there are also people of first-class rank, who make great discoveries, fundamental to the development of science. **But then there are the geniuses, like Galileo and Newton. Well Ettore Majorana was one of them.**" -Enrico Fermi

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"Majorana had greater gifts than anyone else in the world. **Unfortunately he lacked one quality which other men generally have: plain common sense.**" -Enrico Fermi

The Search for Majorana fermions

Majorana fermions

are their own antiparticle

$$\gamma = \gamma^\dagger$$



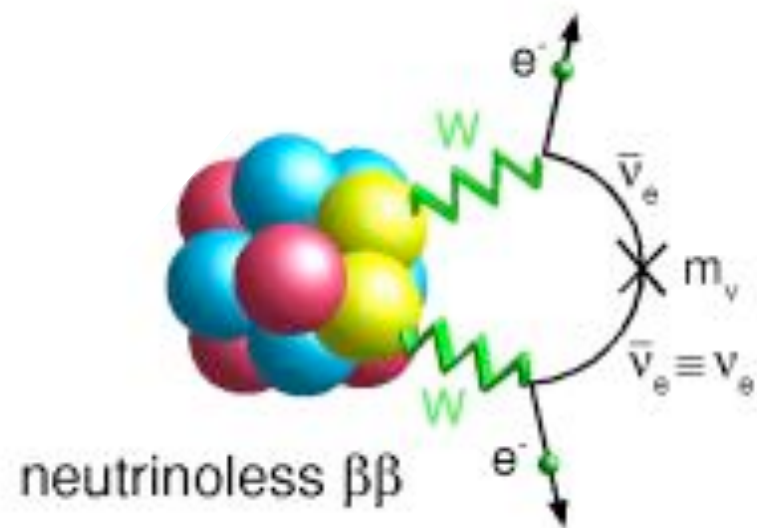
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Majorana fermions
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Neutrinos?



The Search for Majorana fermions

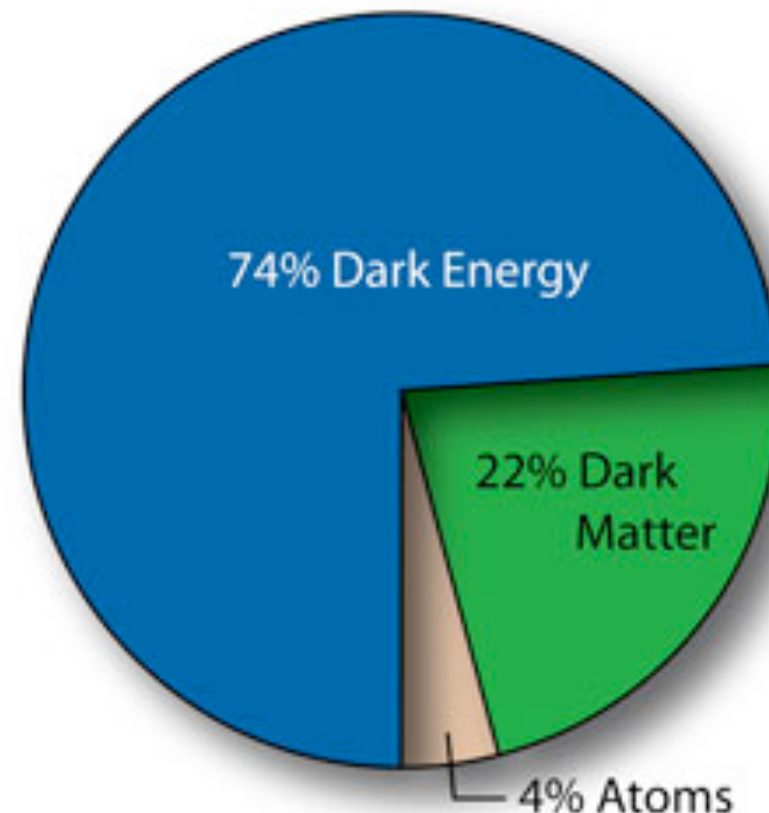
Majorana fermions
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Neutrinos?

Supersymmetry?

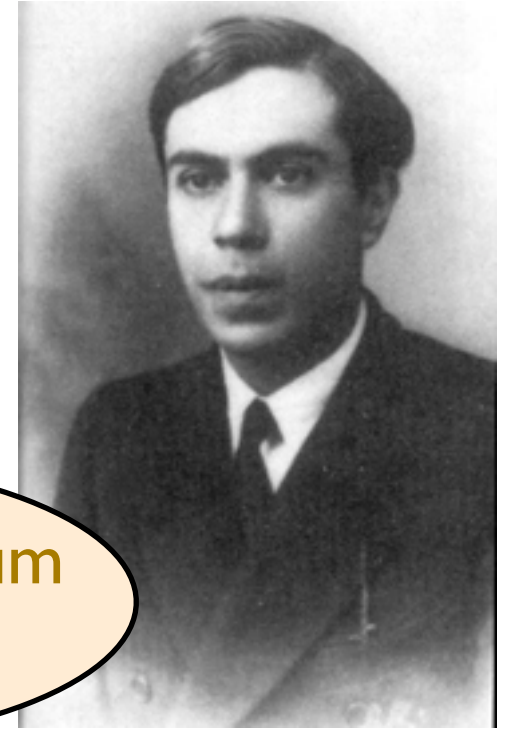


The Search for Majorana fermions

Majorana fermions

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Neutrinos?

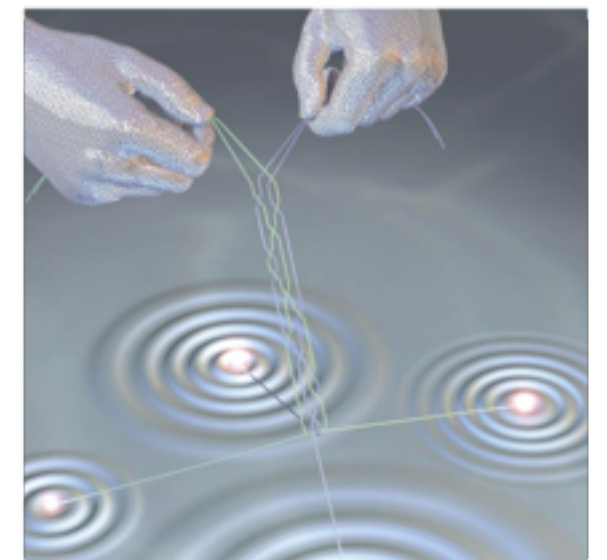
Supersymmetry?

Cold atoms?

Fractional quantum
Hall effect?

Superconductors?

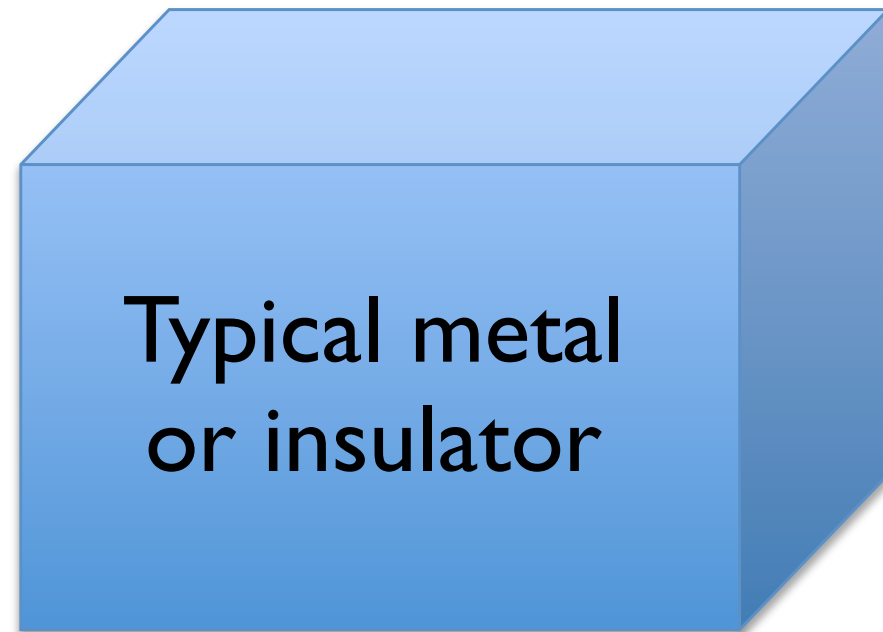
Observation would reveal something quite profound about nature.



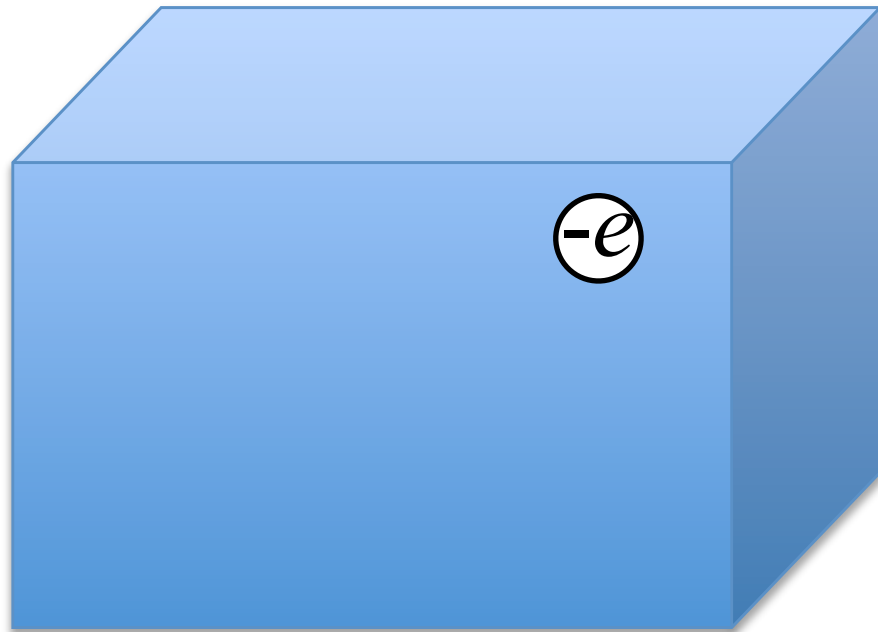
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- **The quest for Majorana in the solid state**
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Majorana fermions in ***condensed matter***?

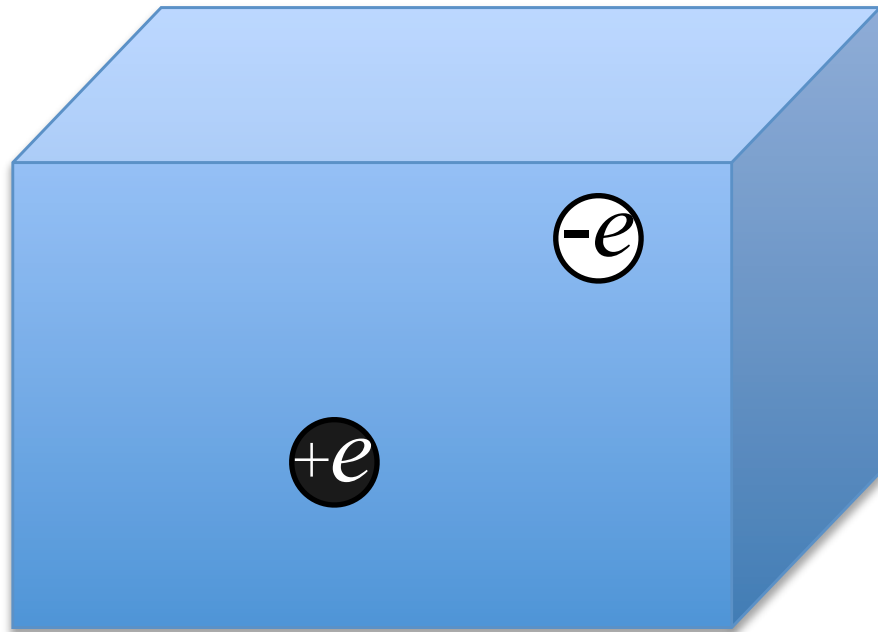


Majorana fermions in ***condensed matter***?



$c^\dagger |\psi\rangle$ (Adds an electron)

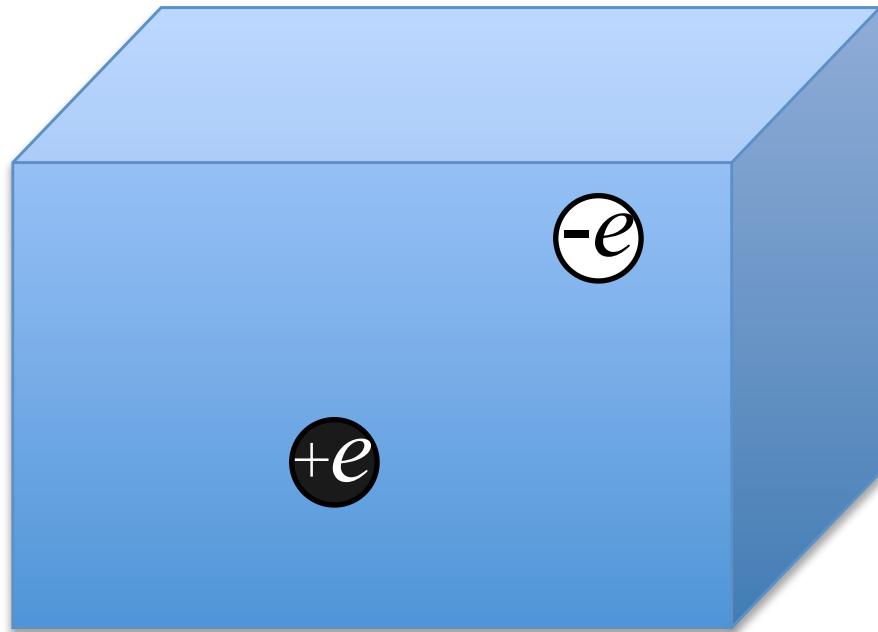
Majorana fermions in ***condensed matter***?



$c^\dagger |\psi\rangle$ (Adds an electron)

$c |\psi\rangle$ (Adds a hole)

Majorana fermions in **condensed matter**?



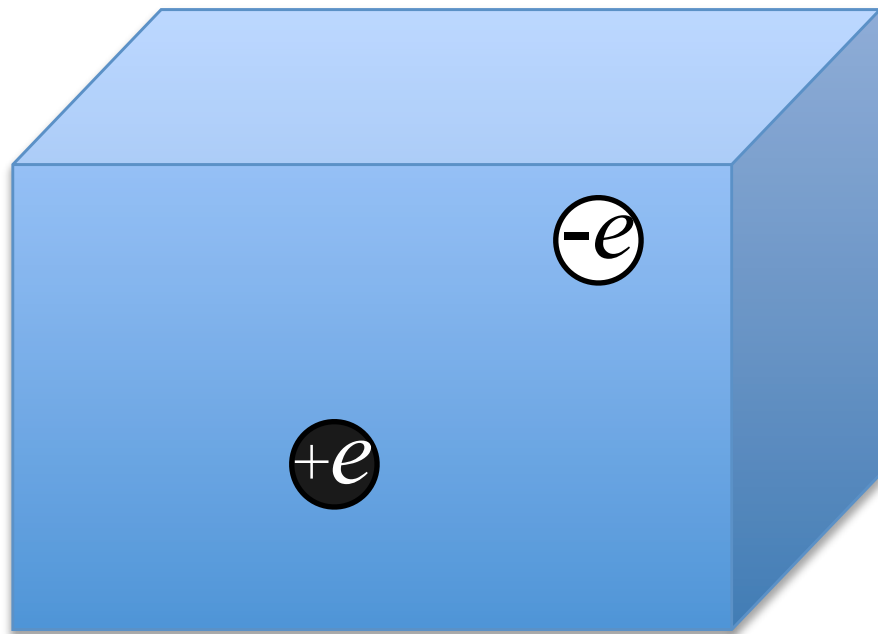
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$$c^\dagger \neq c$$

Majorana appears only through **emergent** excitations

Majorana fermions in **condensed matter**?

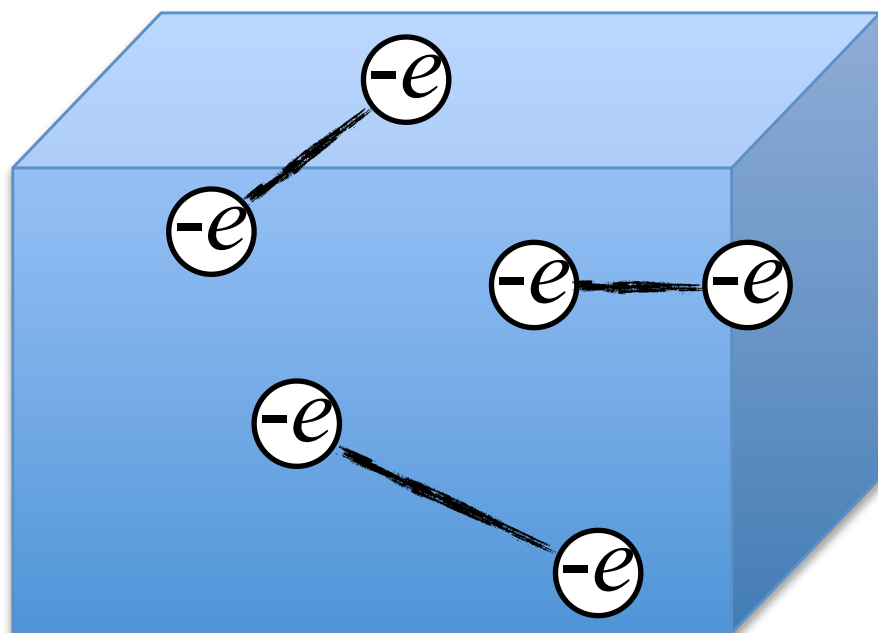


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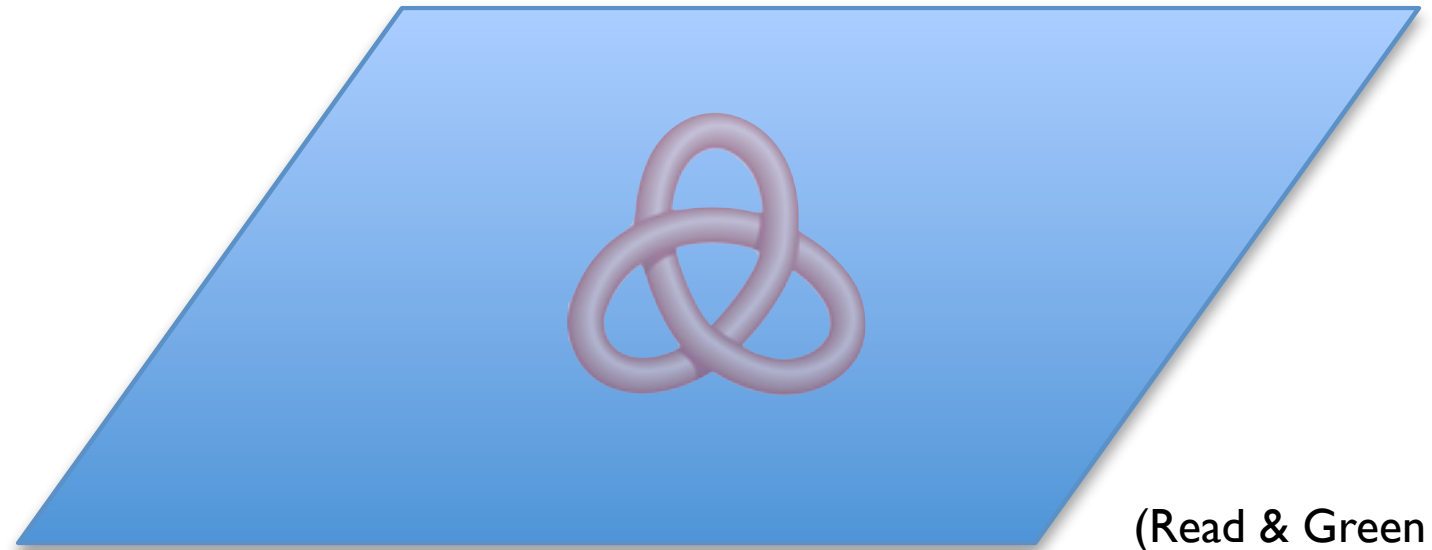
Superconductors
are natural platforms

$$f^\dagger \sim uc^\dagger + vc$$

Majorana via **topological** superconductivity



**“Spinless” 2D
superconductor**

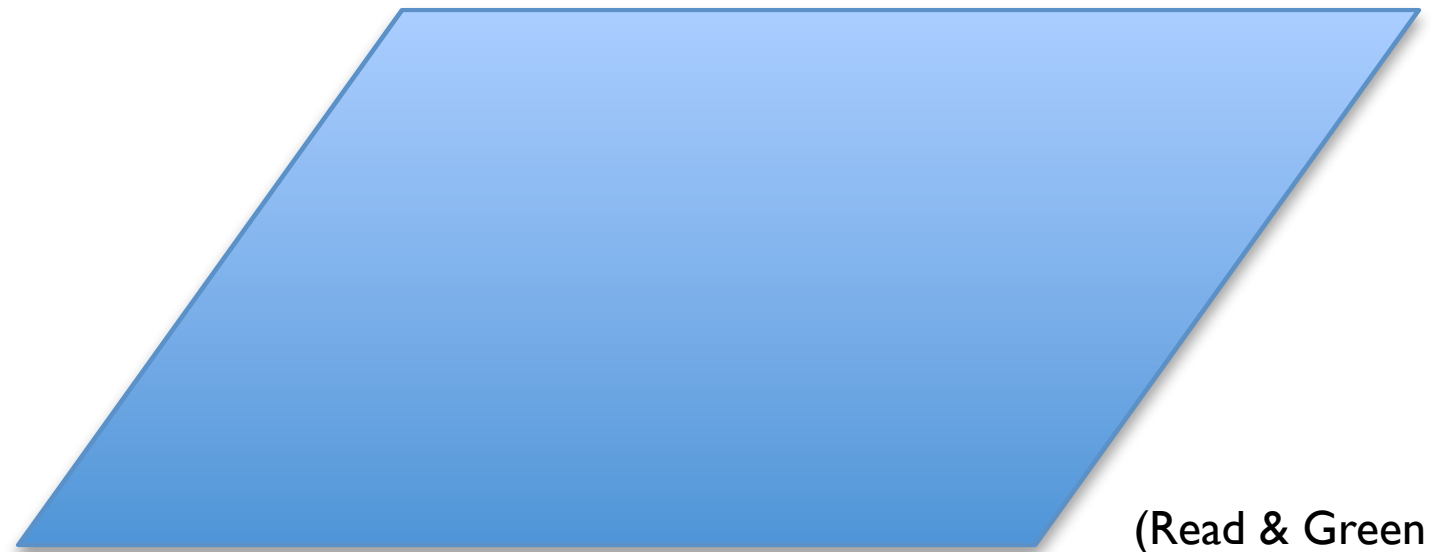


(Read & Green 2000;
Ivanov 2001)

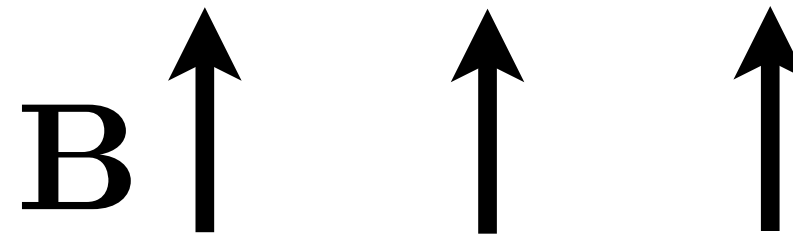
Majorana via **topological** superconductivity



**“Spinless” 2D
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(Read & Green 2000;
Ivanov 2001)

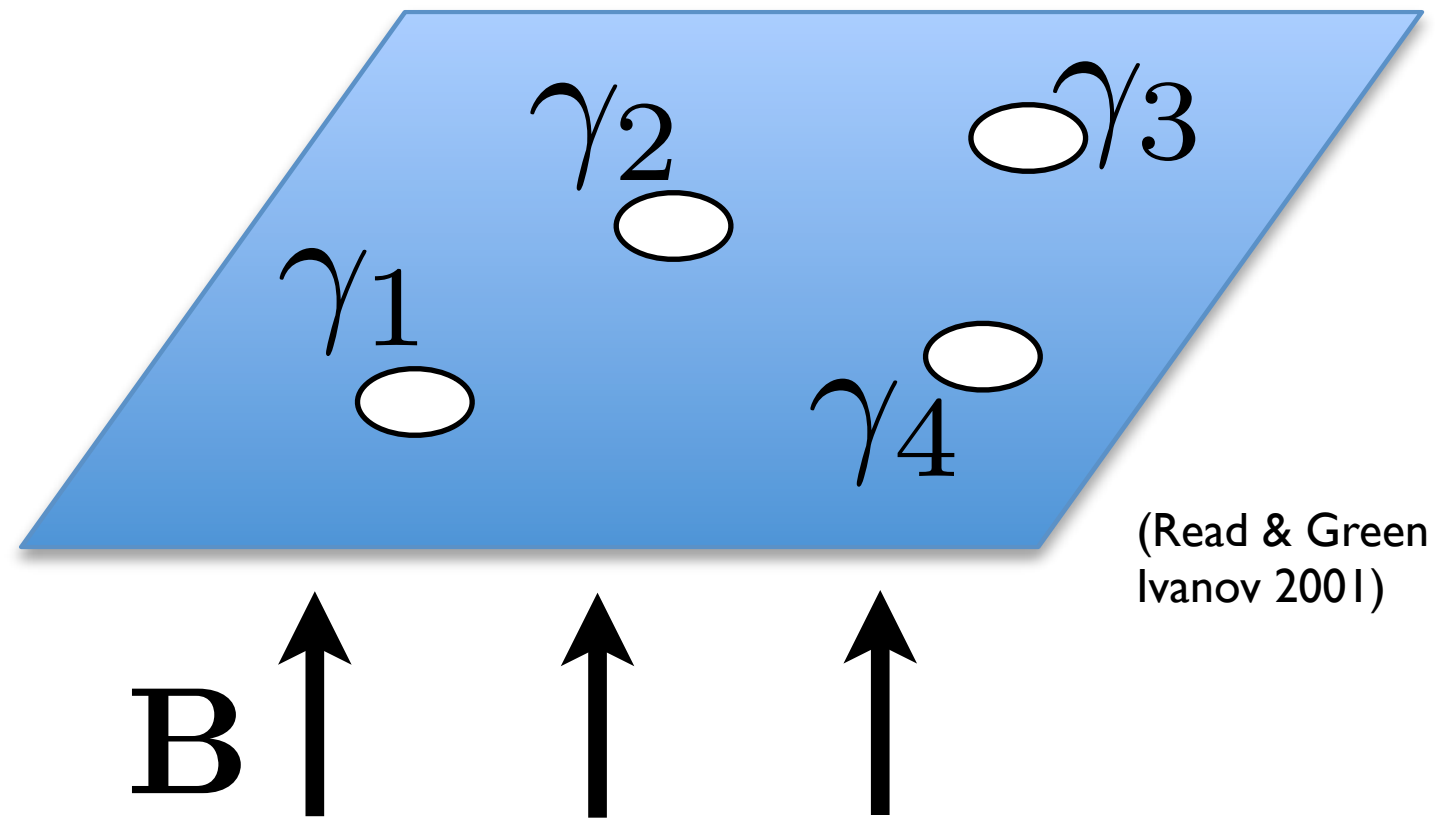


Majorana via **topological** superconductivity



“Spinless” 2D superconductor

Vortices bind
Majorana zero-modes



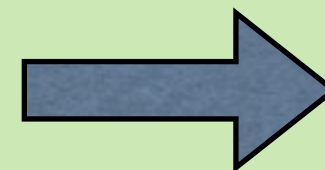
(Read & Green 2000;
Ivanov 2001)

One Majorana = “half” a usual fermion

$$f_A = \gamma_1 + i\gamma_2$$

$$f_B = \gamma_3 + i\gamma_4$$

Ground-state degeneracy
+ non-locality



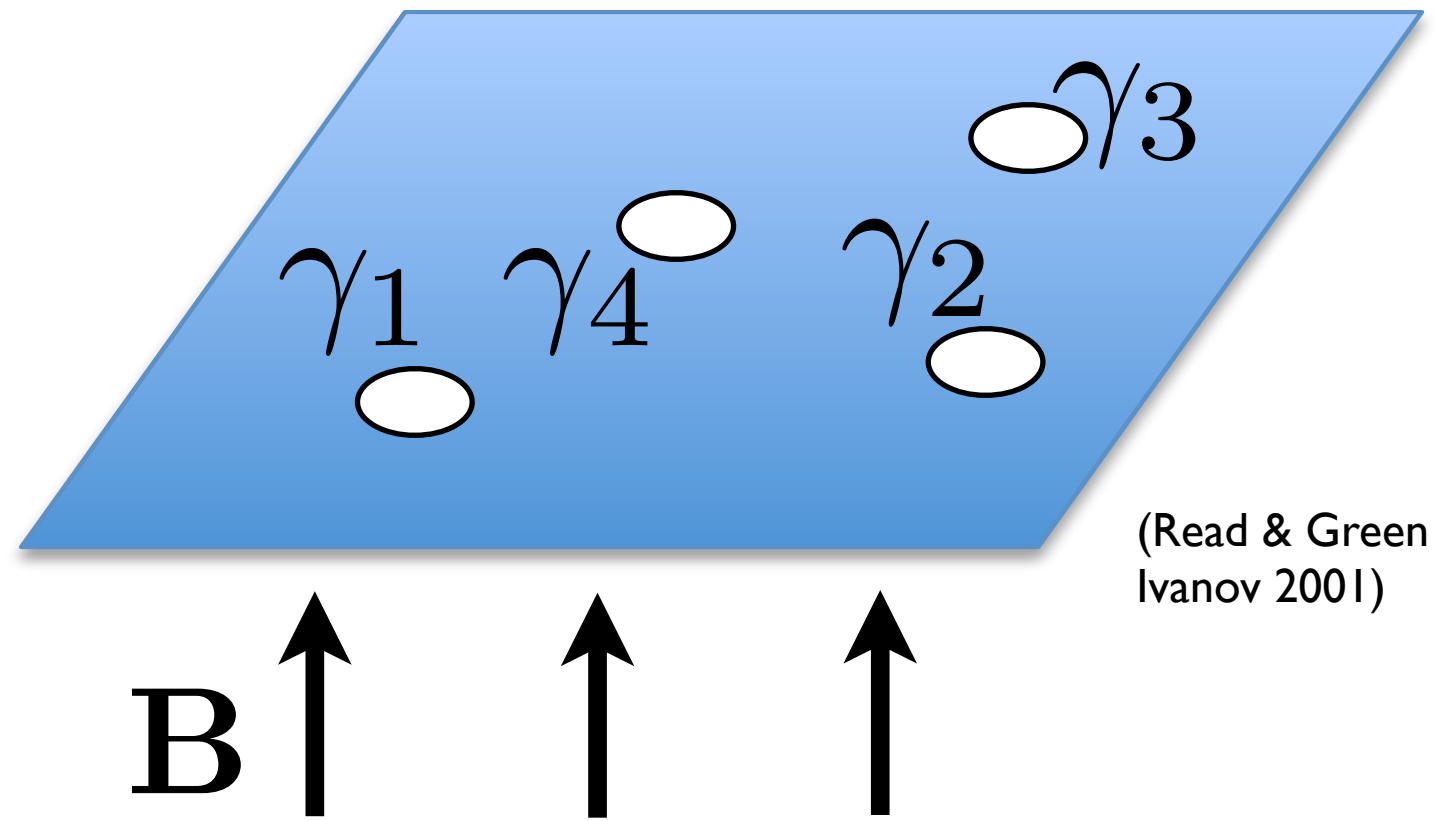
Vortices exhibit
non-Abelian
statistics

Majorana via **topological** superconductivity



“Spinless” 2D superconductor

Vortices bind
Majorana zero-modes



(Read & Green 2000;
Ivanov 2001)



“Spinless” 1D superconductor



(Kitaev 2001)

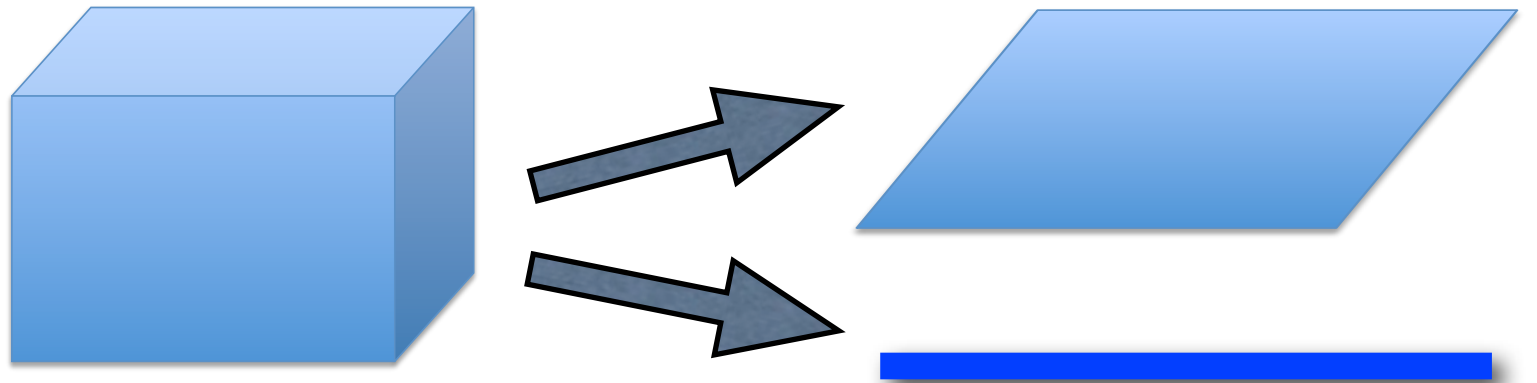
Majorana zero-modes
localize at the ends of the
system...

...but are they interesting &
useful? **YES!**

The basic challenge

“Spinless” 1D, 2D superconductivity is hard to find

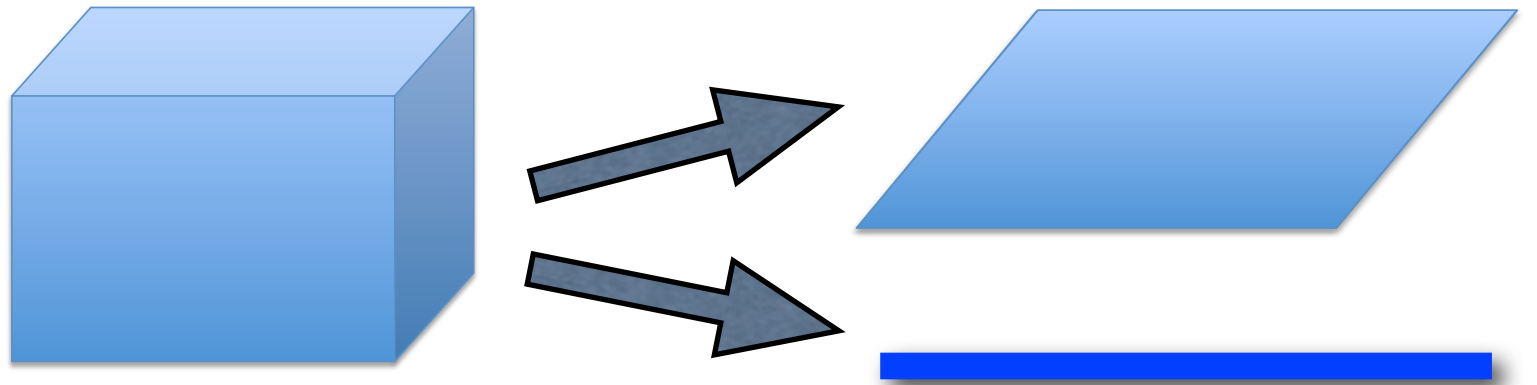
I. We live in 3D



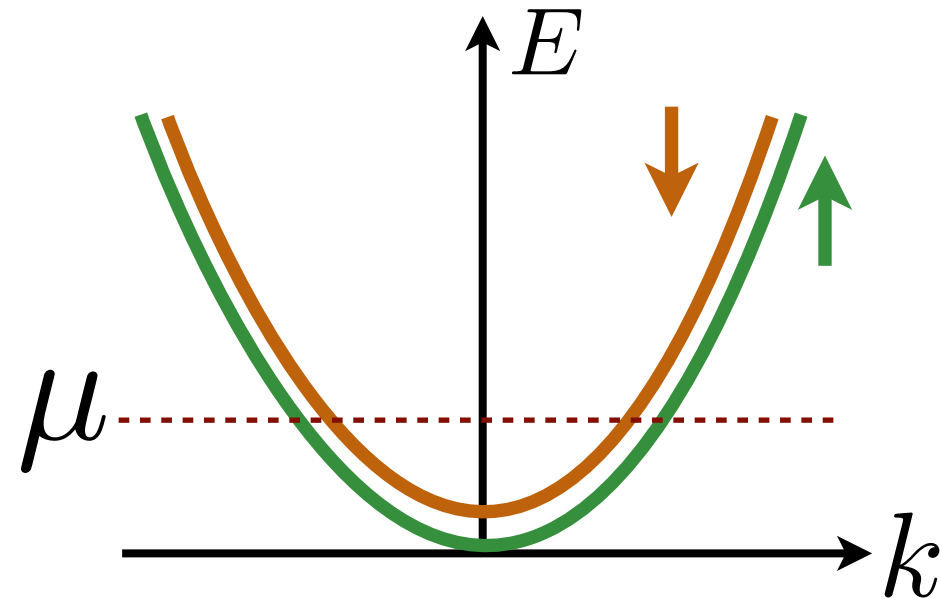
The basic challenge

“Spinless” 1D, 2D superconductivity is hard to find

1. We live in 3D



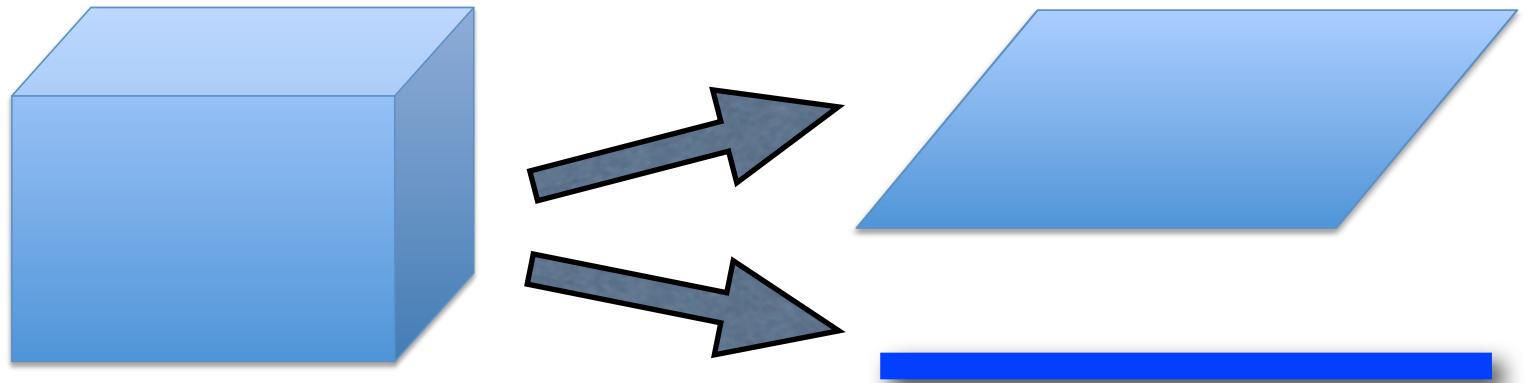
2. Electrons carry spin



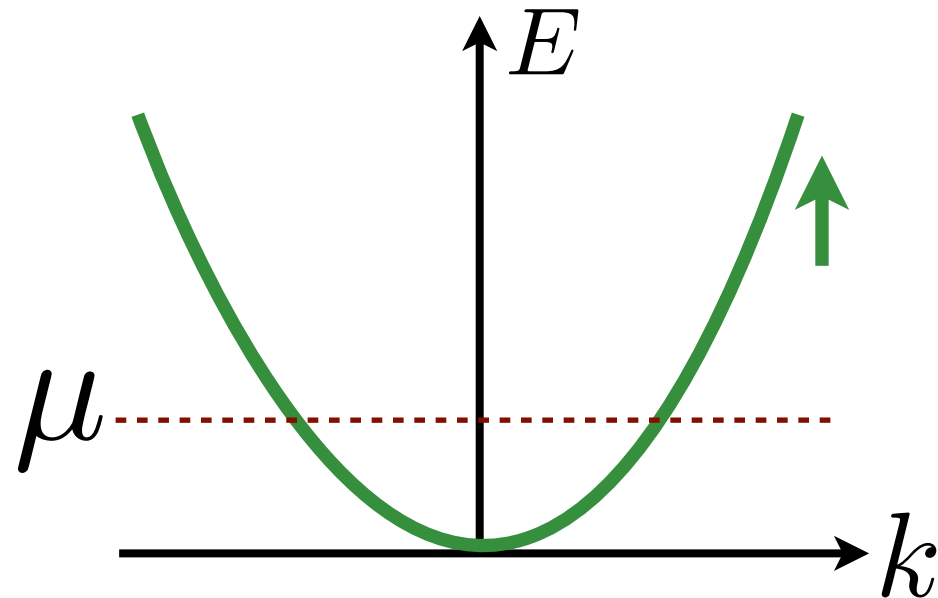
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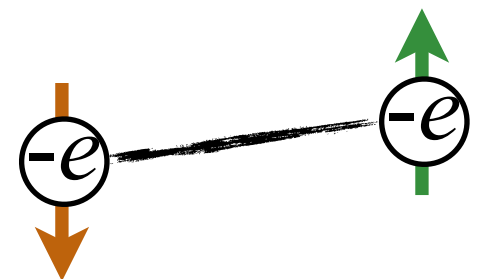
1. We live in 3D



2. Electrons carry spin



3. Vast majority of superconductors form **spin-singlet** Cooper pairs



Two ways forward

I. Search for new compounds w/exotic superconductivity

Two ways forward

I. Search for new compounds w/exotic superconductivity

Matthias's 6th rule: Stay away from theorists!

Two ways forward

1. Search for new compounds w/exotic superconductivity

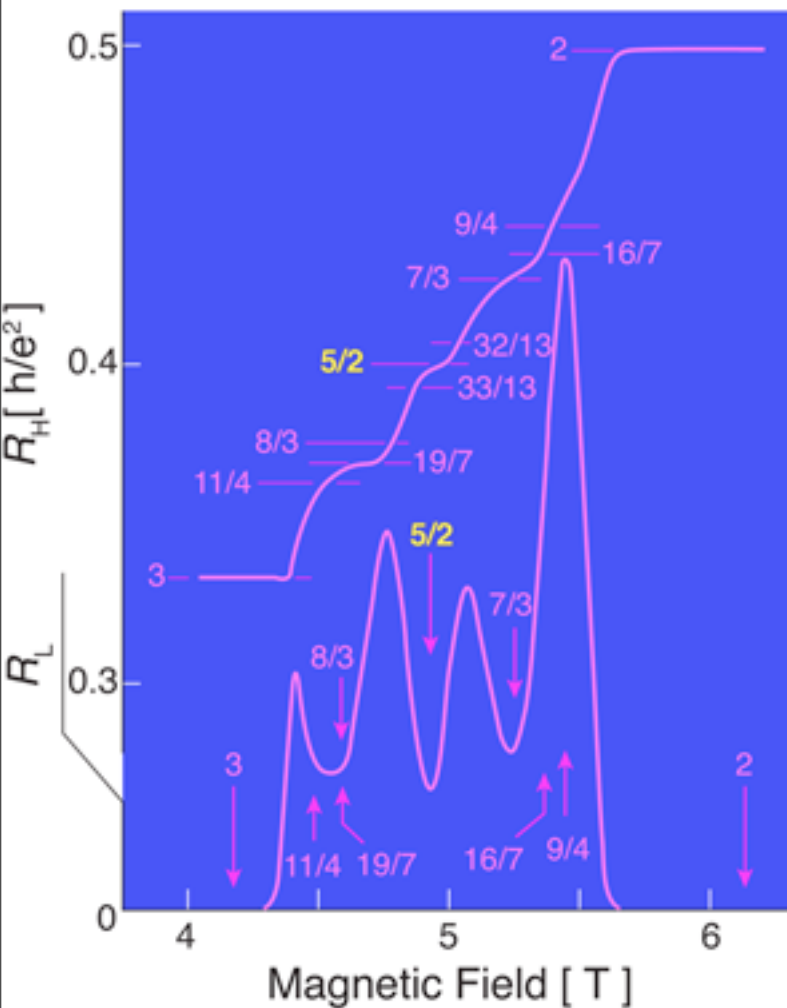
Matthias's 6th rule: Stay away from theorists!

2. “Engineer” topological superconductivity from available materials

Theorists **can** be useful, particularly if methods involve **weakly interacting electrons**

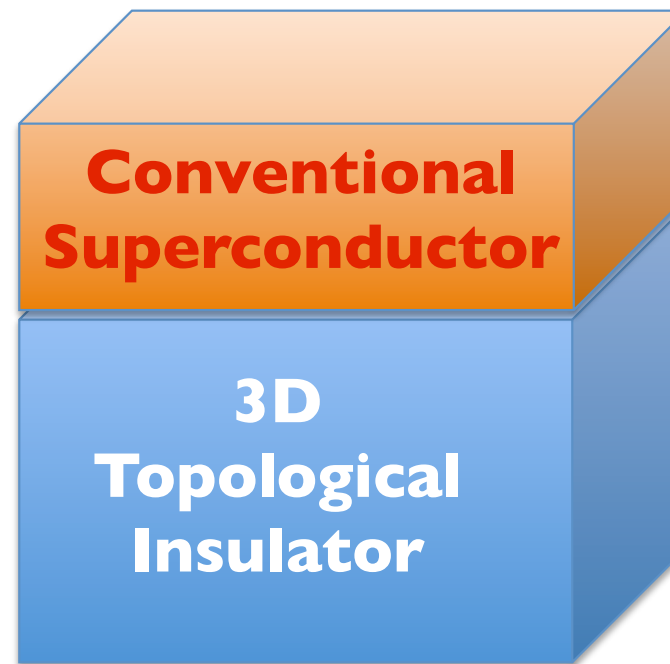
Many roads to Majorana fermions in 2D

“Intrinsic”

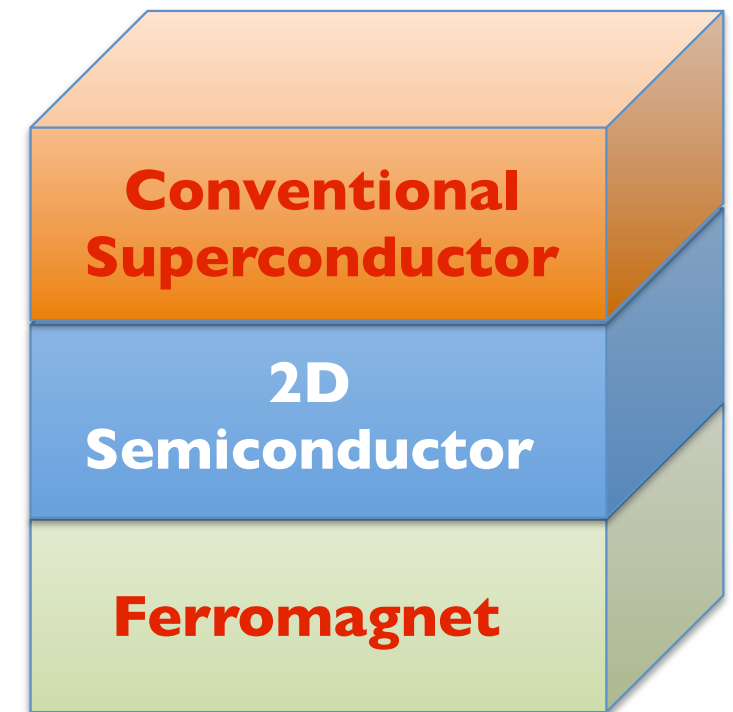


Willet, Eisenstein, et al. (1987)
Moore & Read (1991)
Bonderson, Kitaev, Shtengel (2006)
Stern & Haperin (2006)

“Engineered”

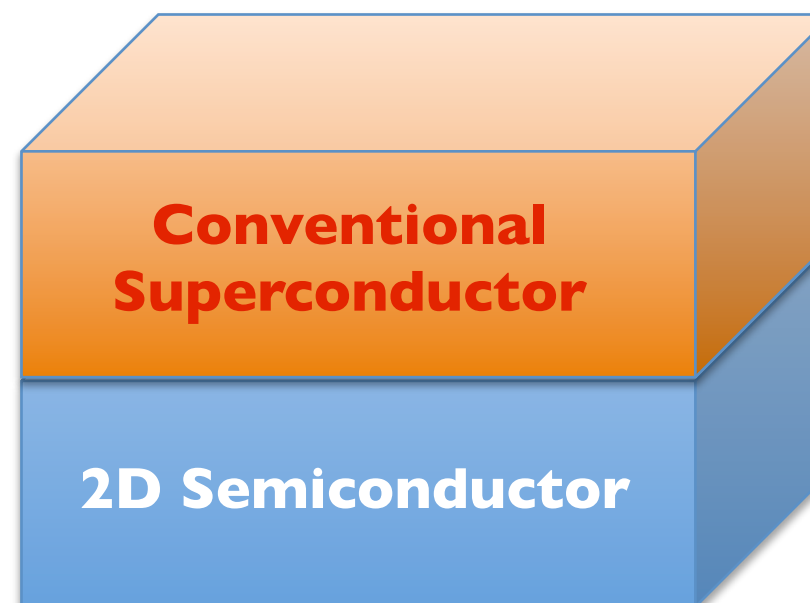


Fu & Kane (2008)



Sau, Tewari, Lutchyn, Das Sarma (2010)

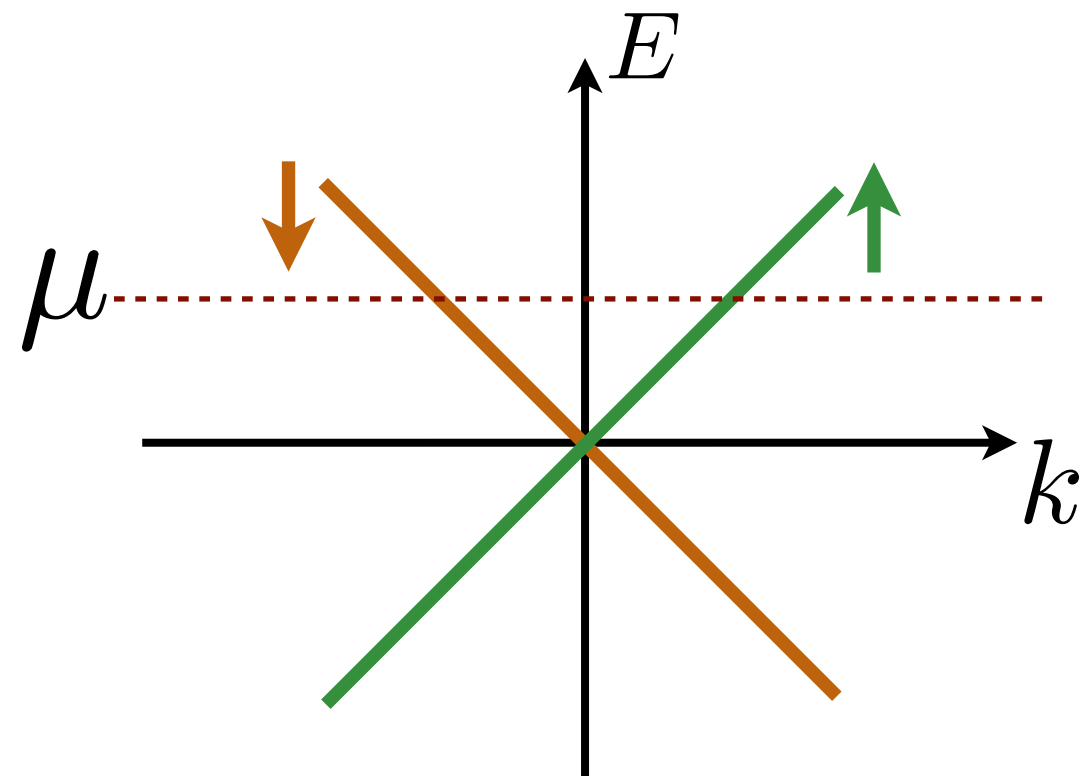
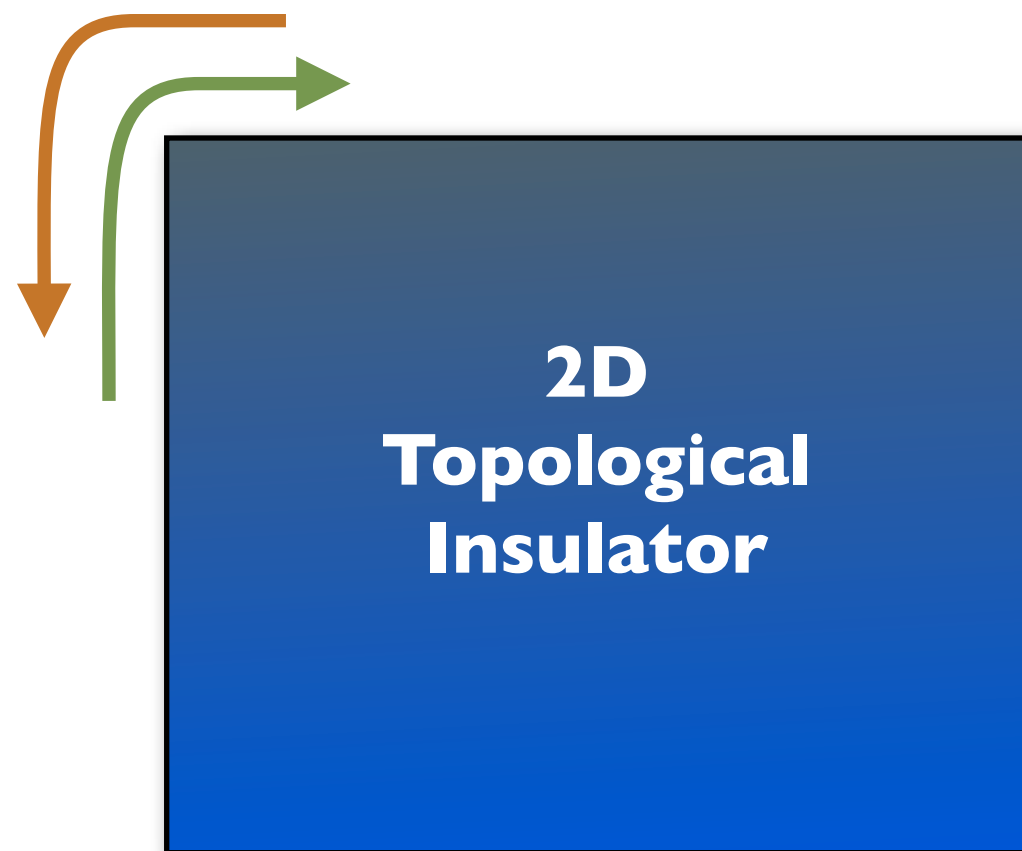
B
→



Alicea (2010)

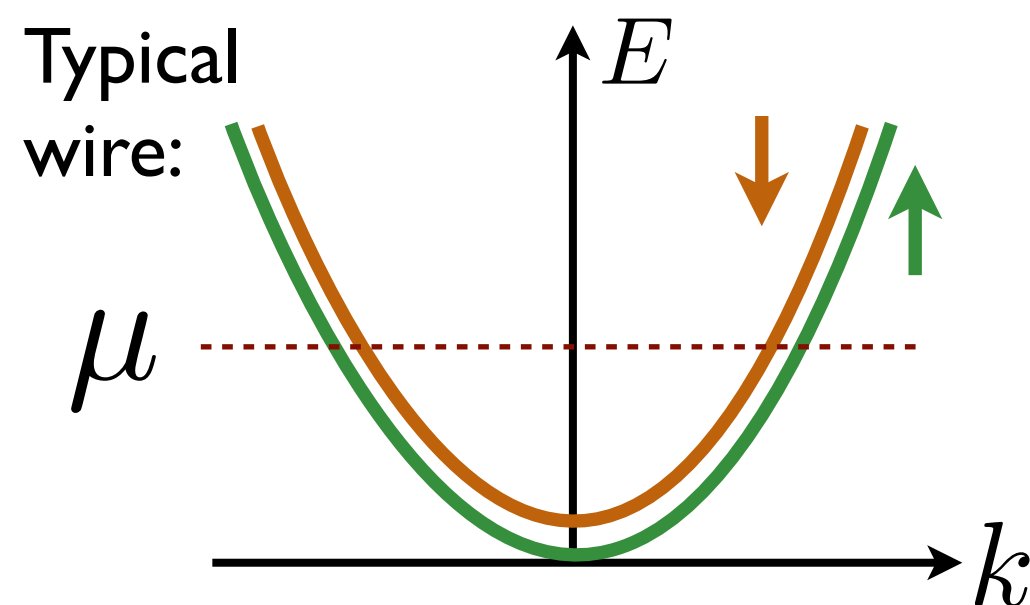
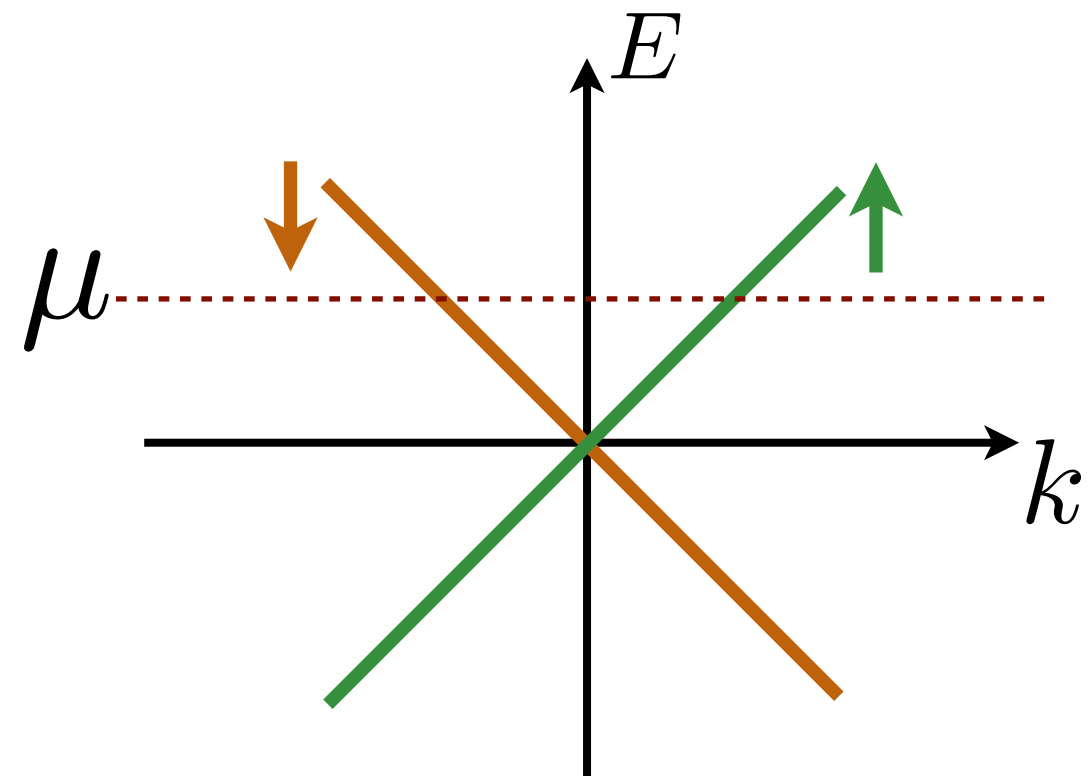
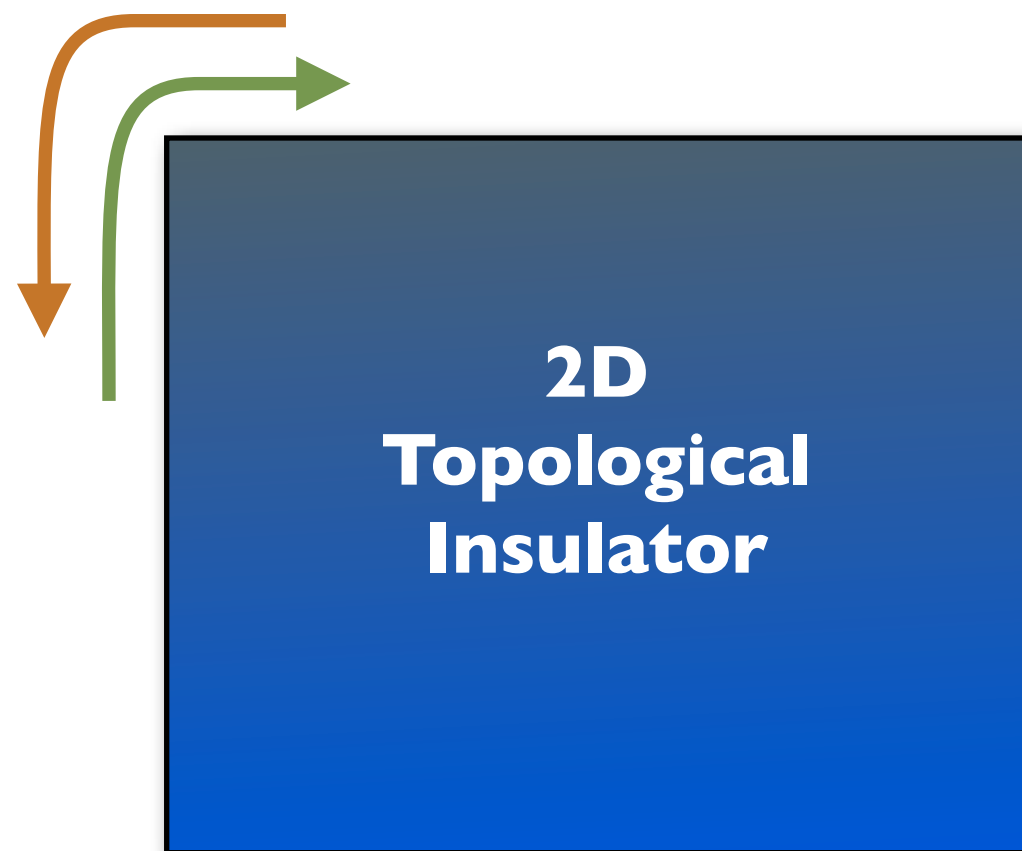
...lots of others

1D “spinless” superconductivity via edge states



- I. By construction 1D & “spinless”
- II. Easy to make superconducting

1D “spinless” superconductivity via edge states



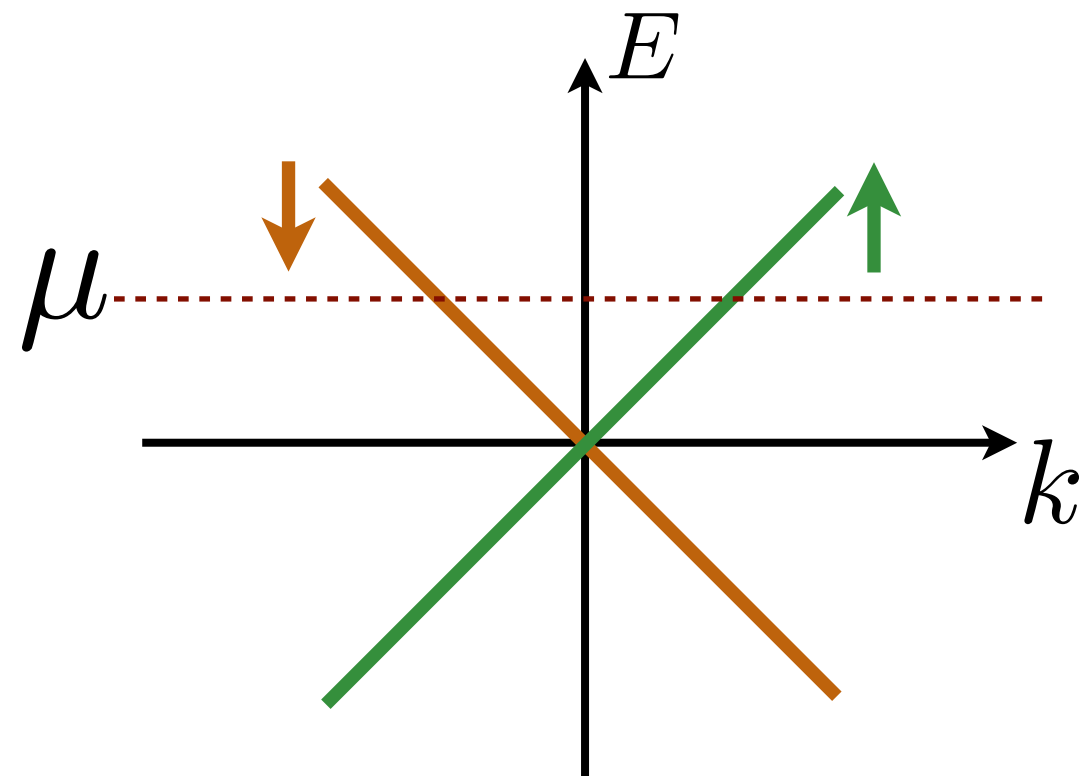
- I. By construction 1D & “spinless”
- II. Easy to make superconducting

1D “spinless” superconductivity via edge states

Ordinary Superconductor

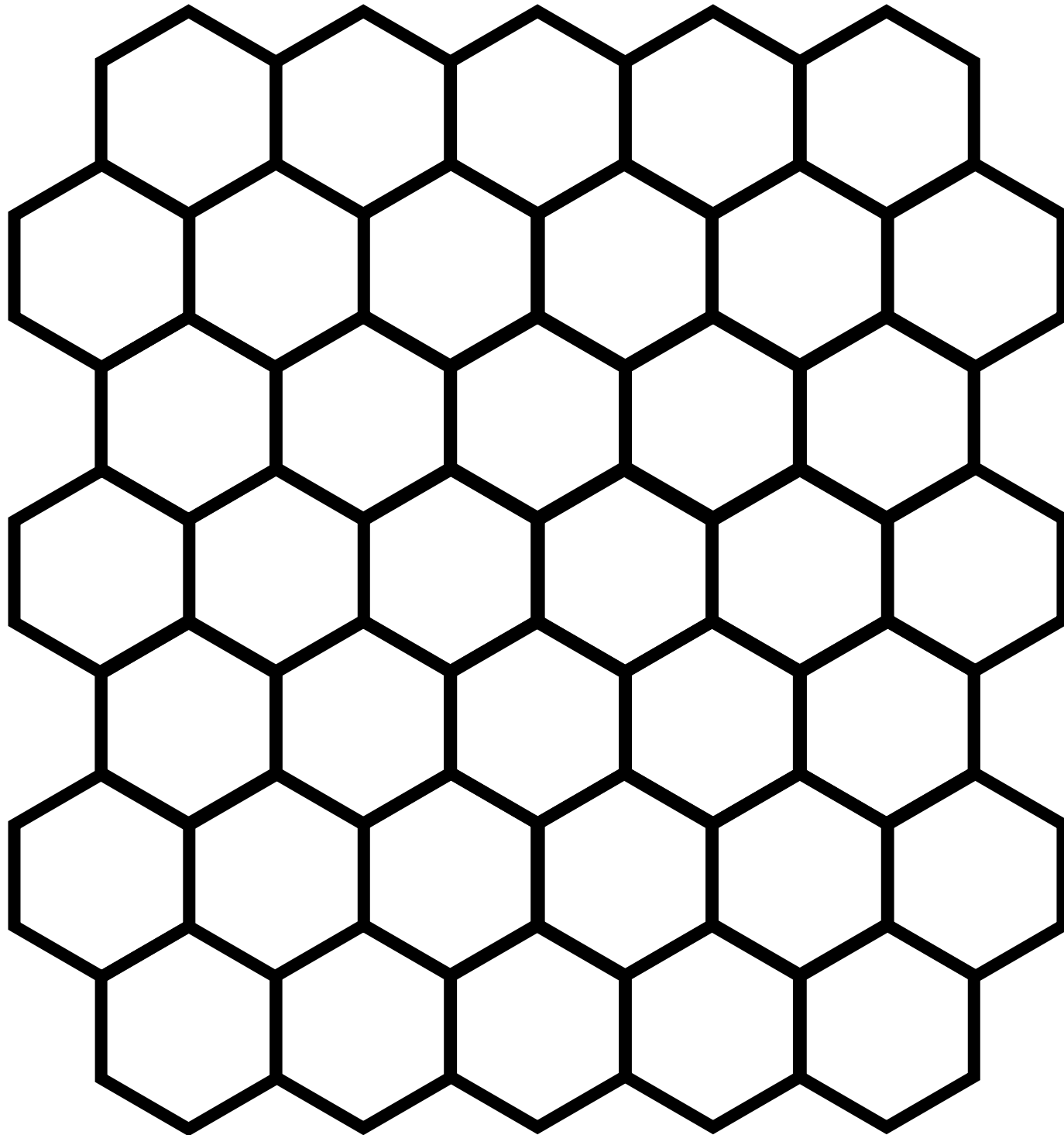
2D
Topological
Insulator

Small number of 2D
topological insulators



- I. By construction 1D & “spinless”
- II. Easy to make superconducting

Aside: Topological insulator in **graphene**?

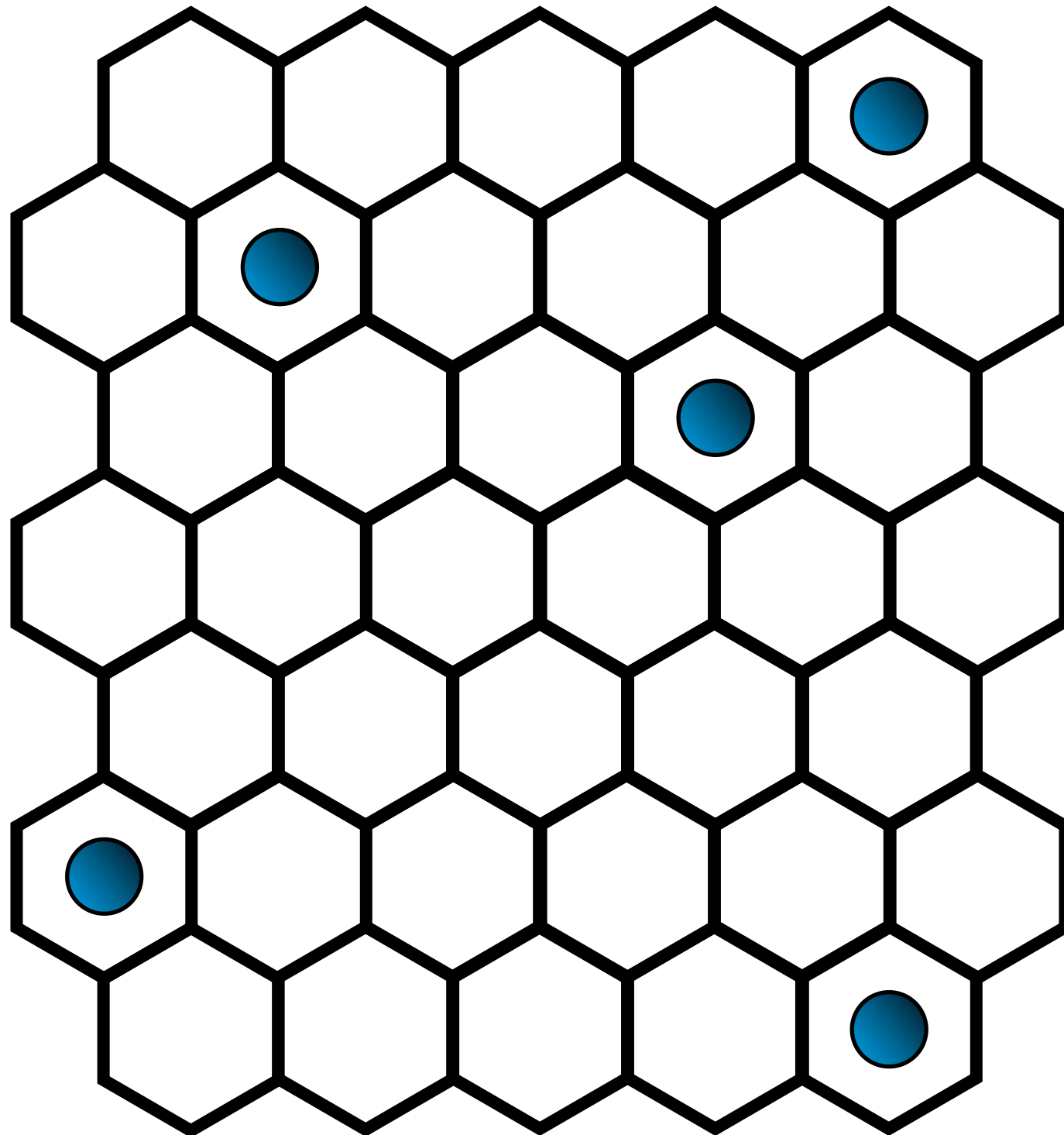


1st proposed topological insulator, but gap is tiny:
 $< 0.01 \text{ meV}$

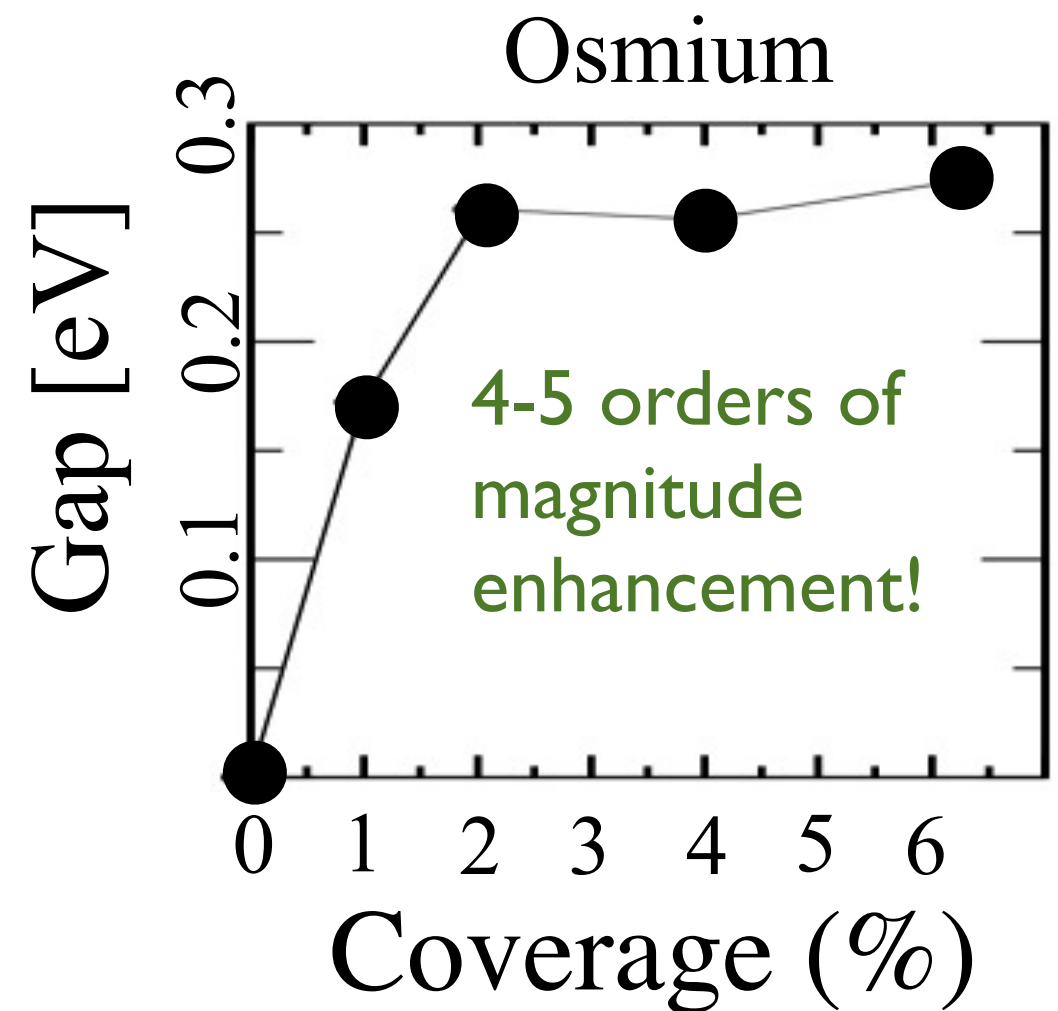
Kane & Mele, PRL (2005)

Weeks, Hu, Alicea, Franz, Wu, PRX (2011); Hu et al., arXiv:1206.4320

Aside: Topological insulator in **graphene**?

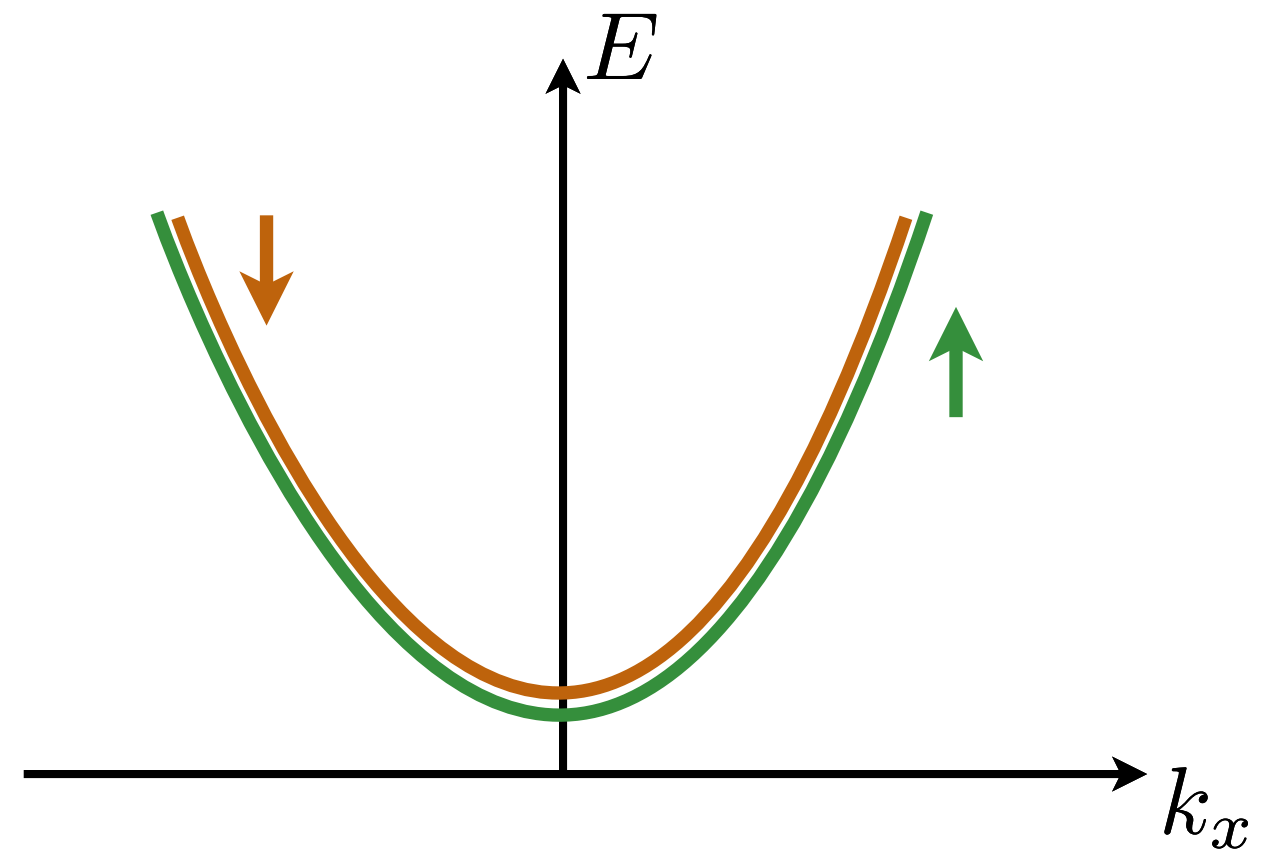
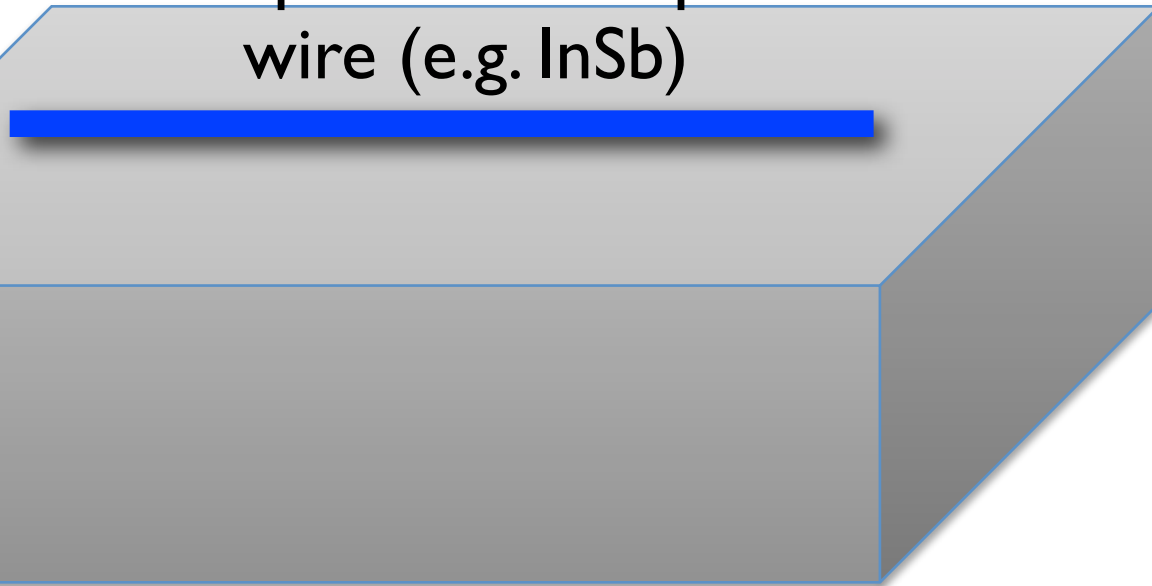


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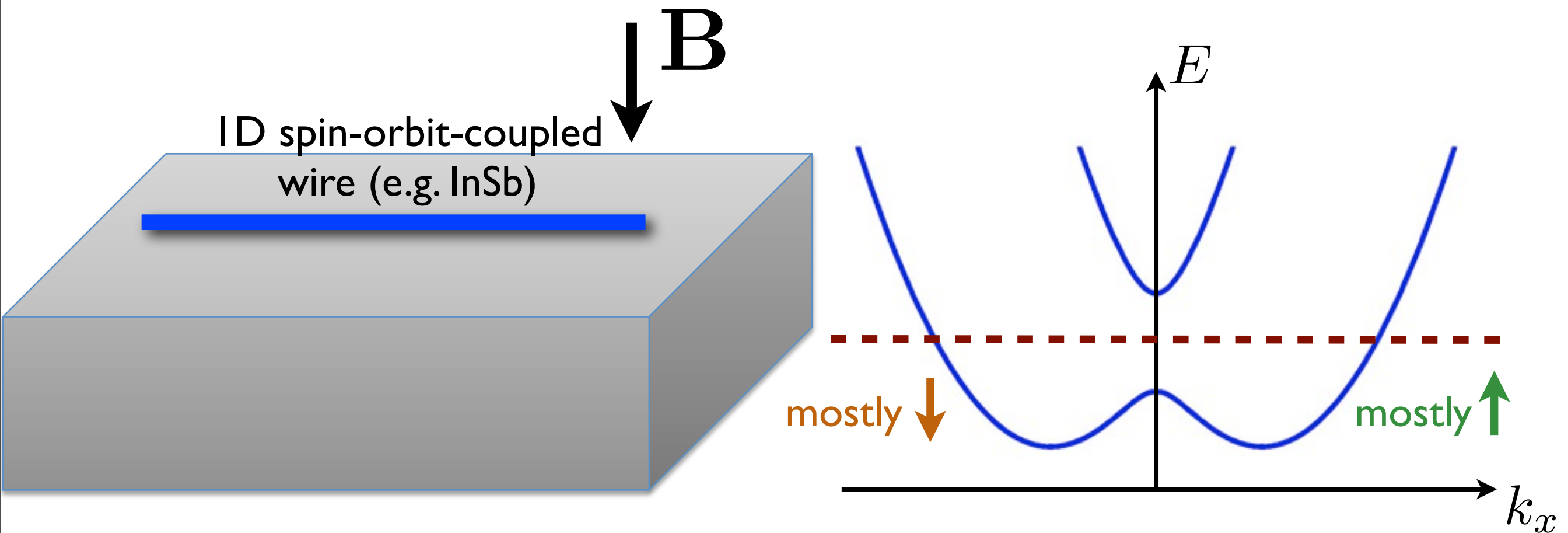


Majorana fermions in 1D wires

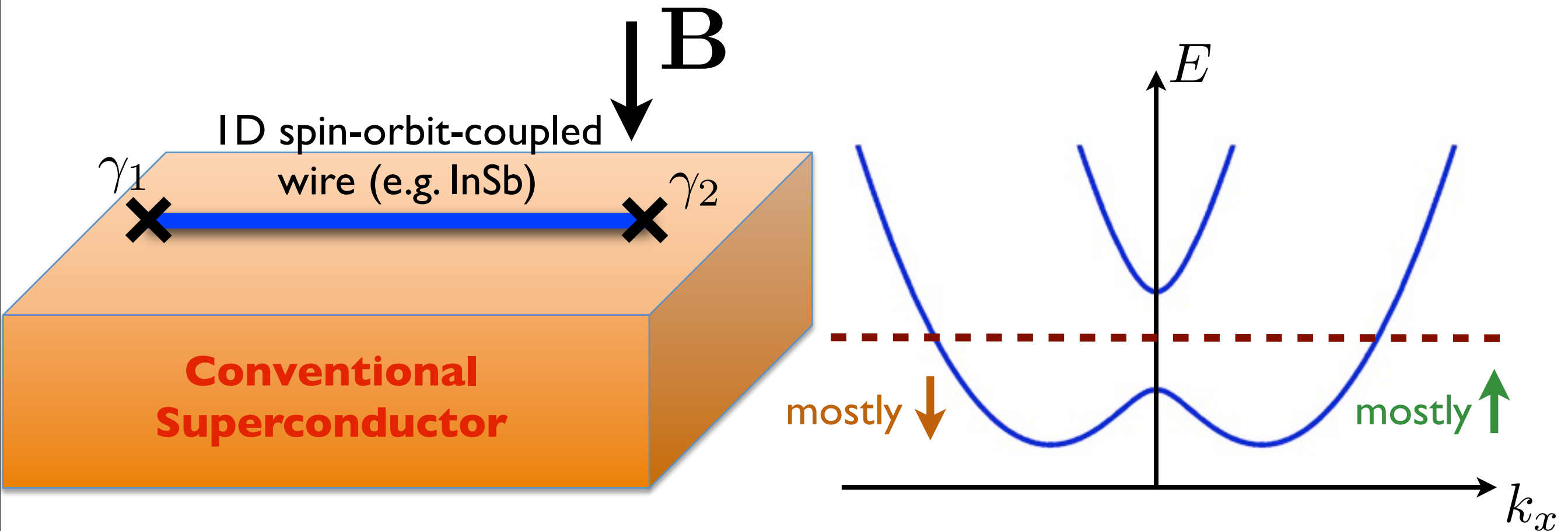
1D spin-orbit-coupled
wire (e.g. InSb)



Majorana fermions in 1D wires



Majorana fermions in 1D wires

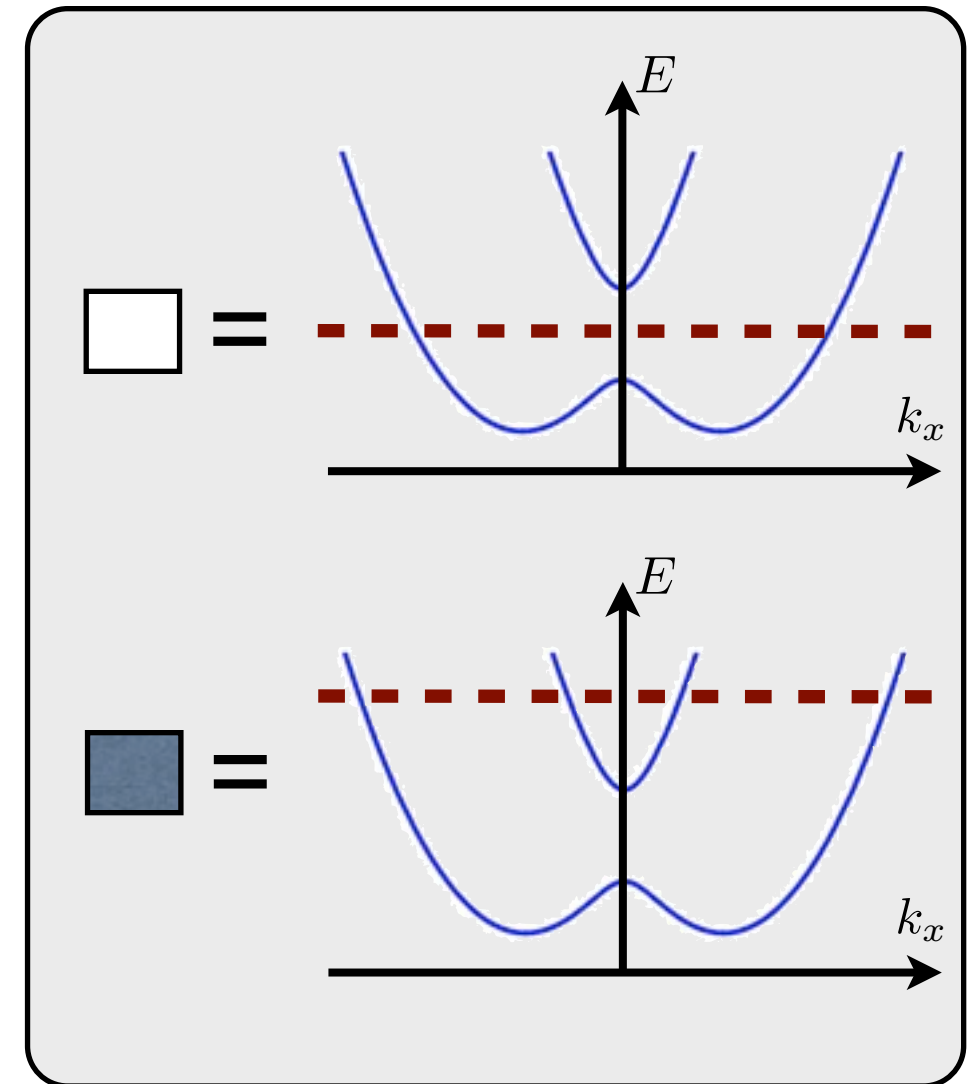
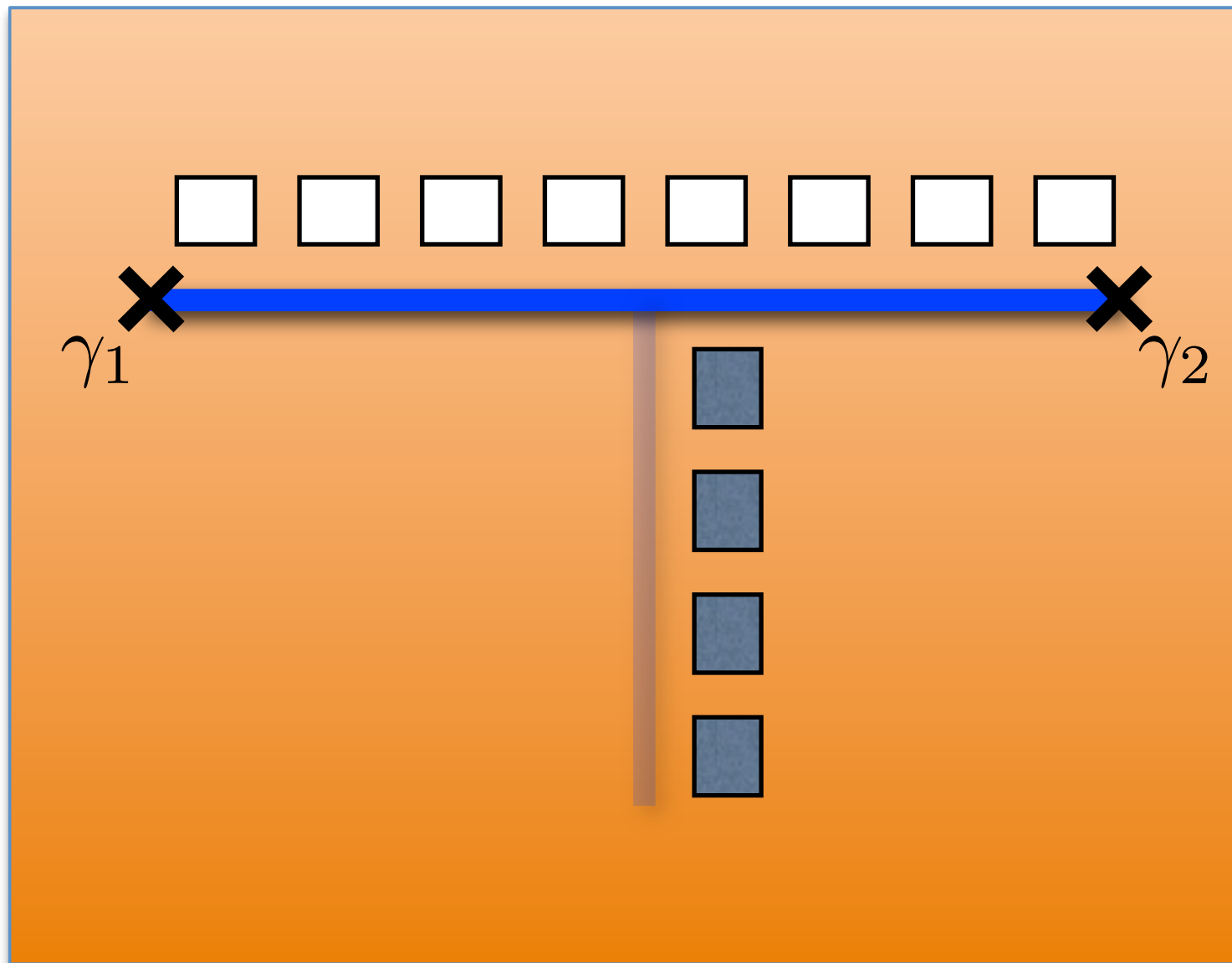


**Generates a 1D ‘spinless’ superconductor
with Majorana fermions!**

Outline

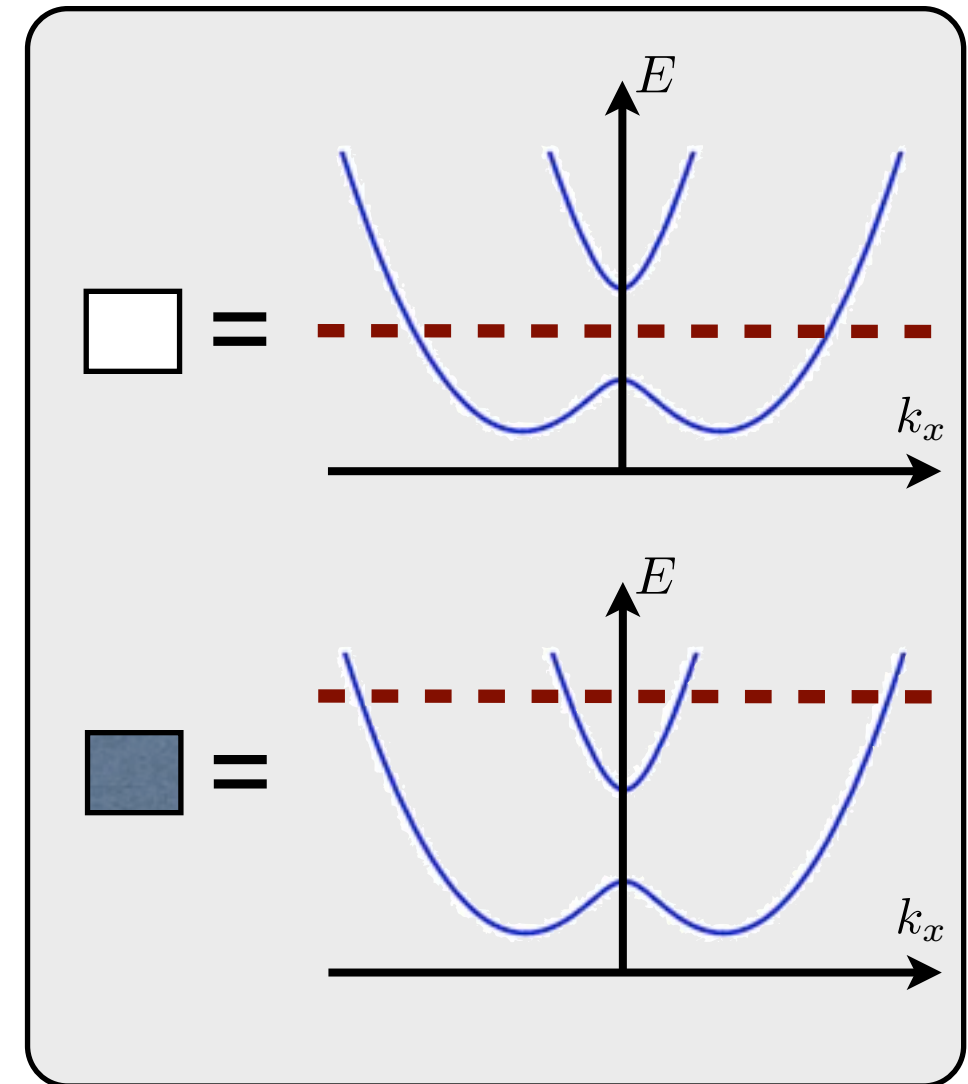
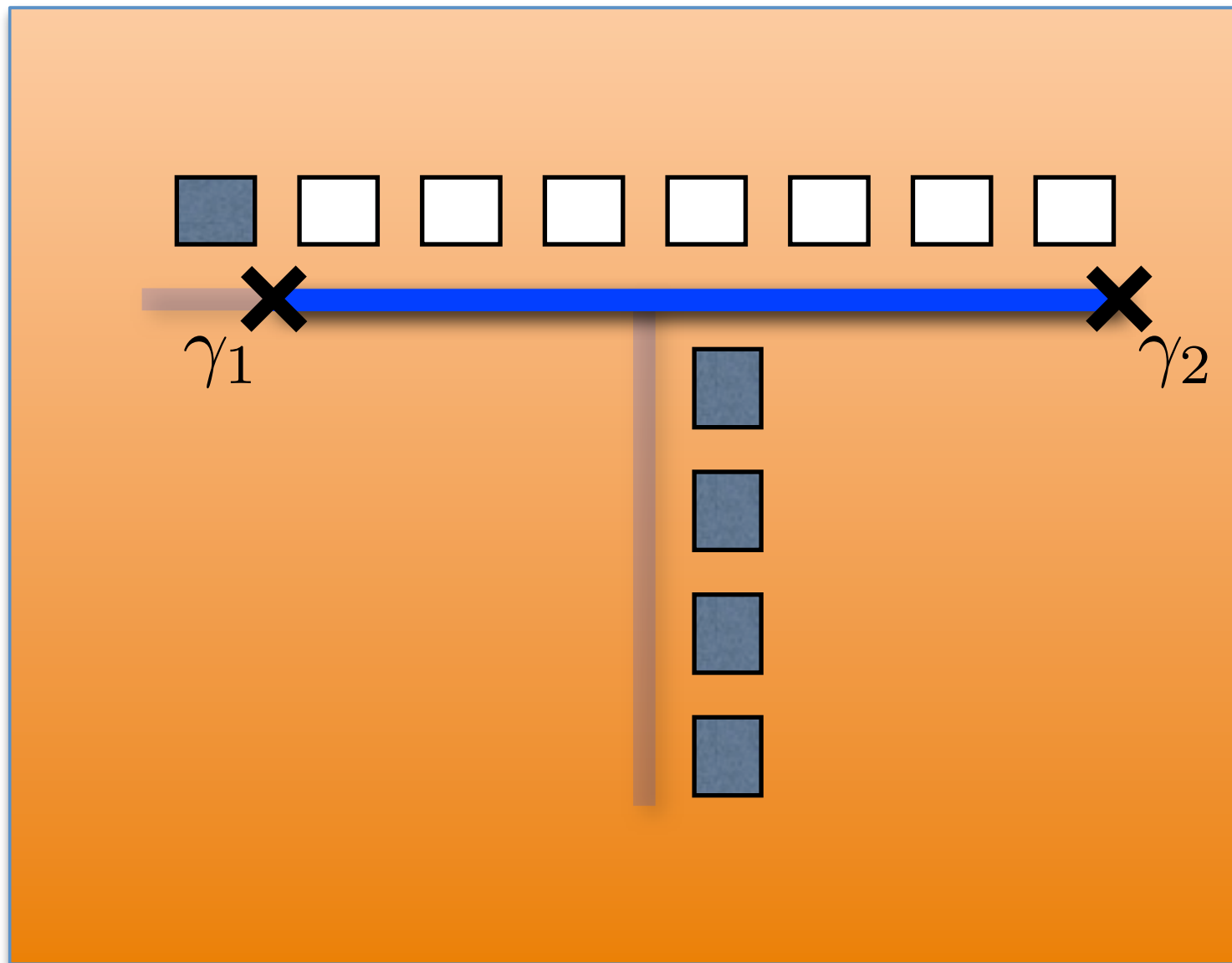
- Majorana fermions: what they are & why they're interesting
- The quest for Majorana in the solid state
- **Getting the most out of Majorana fermions**
- Experimental status & closing remarks

Harnessing non-Abelian statistics



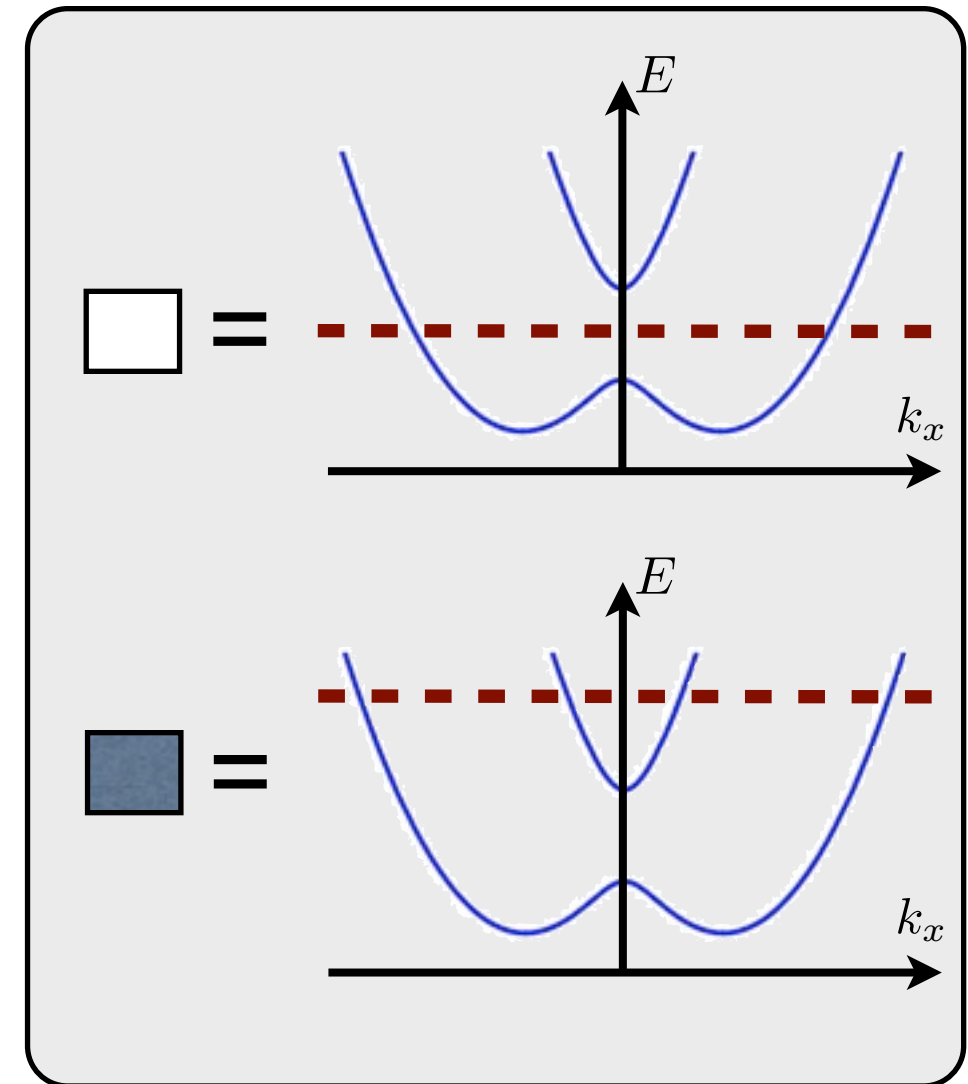
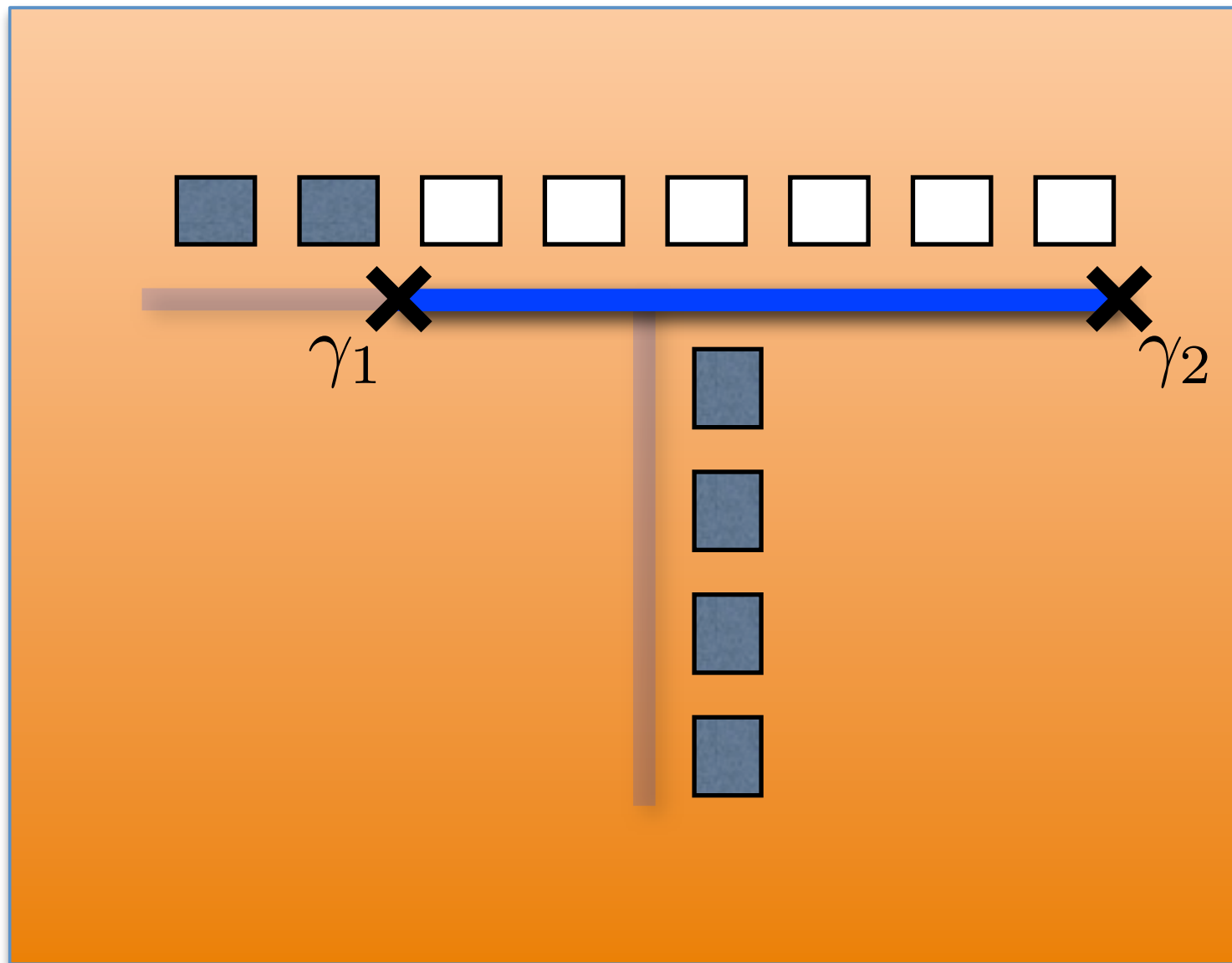
Alicea, Oreg, Refael, von Oppen, Fisher, Nature Phys. 2010
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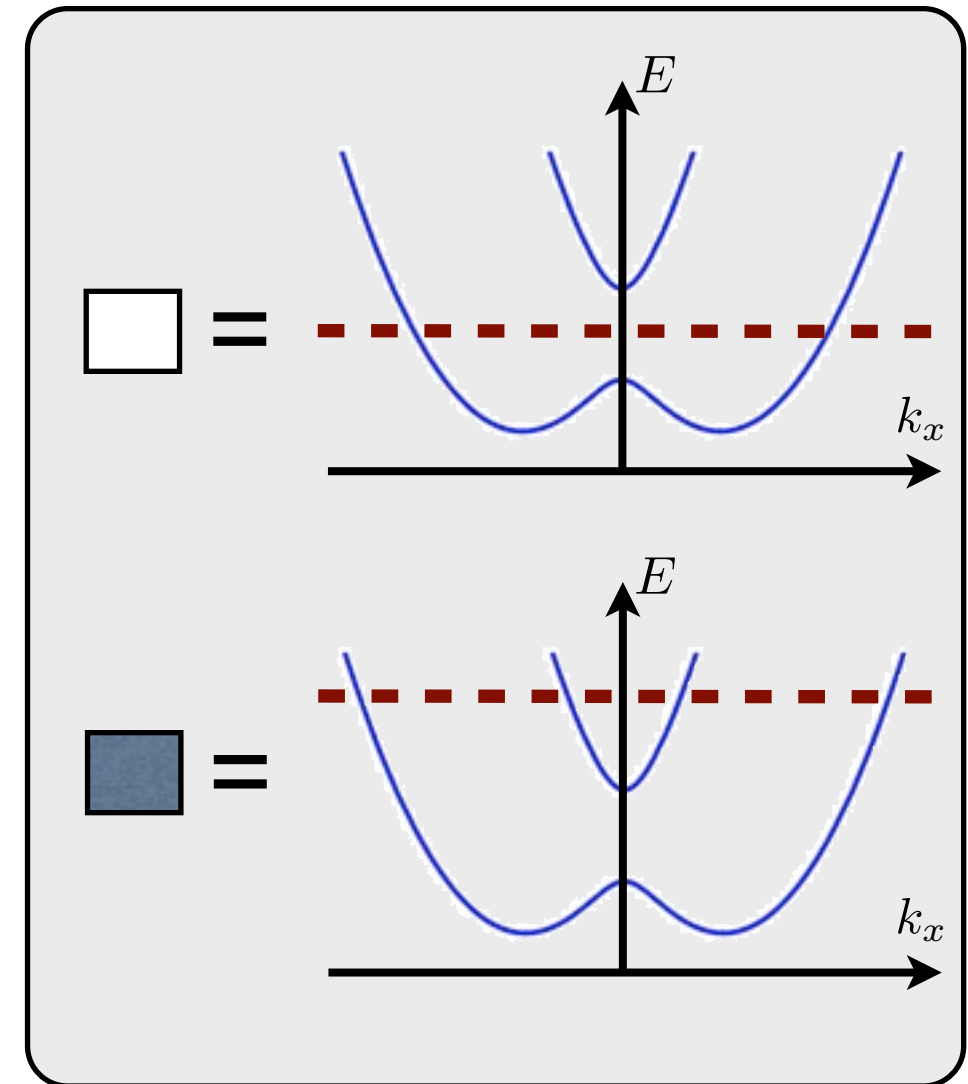
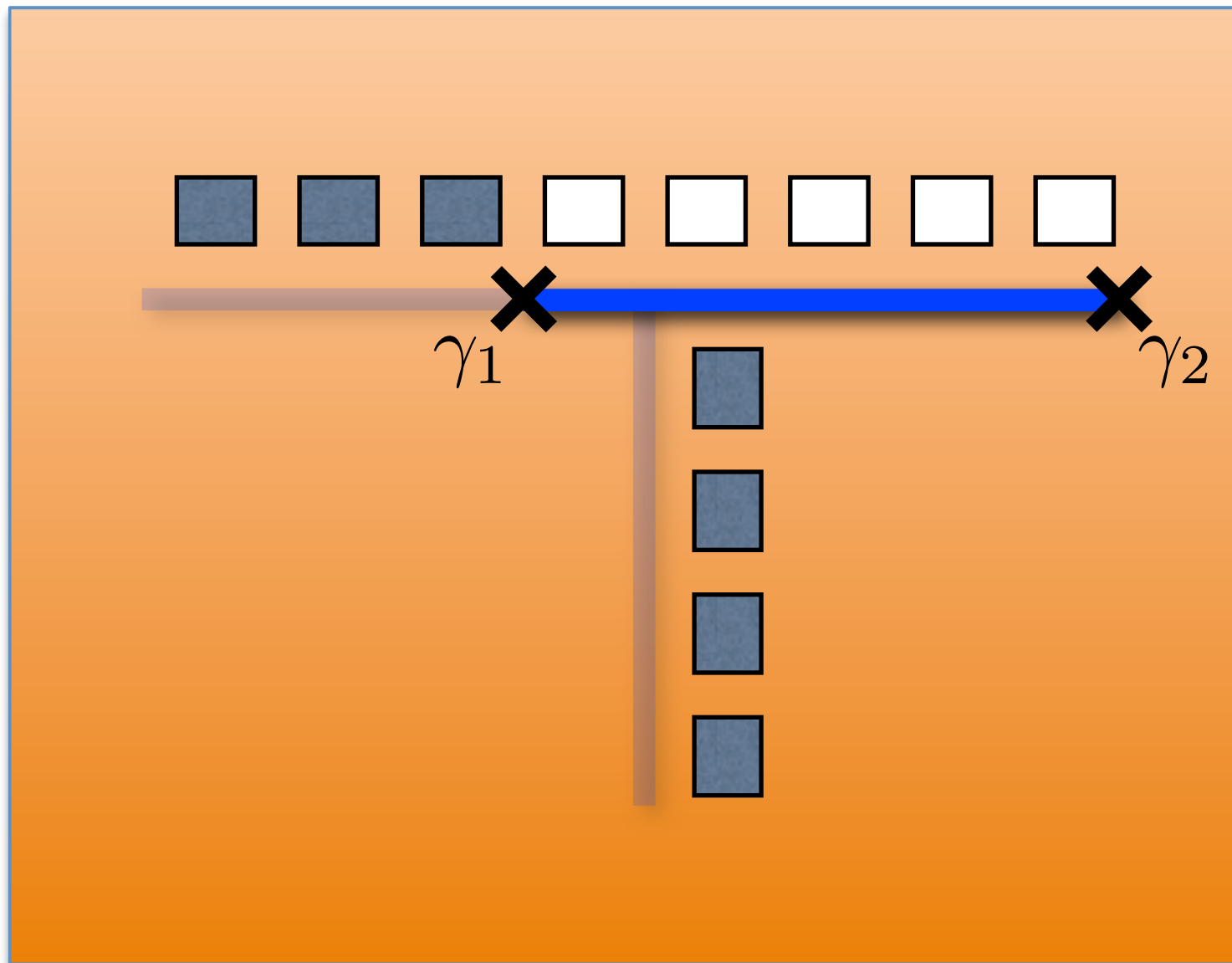
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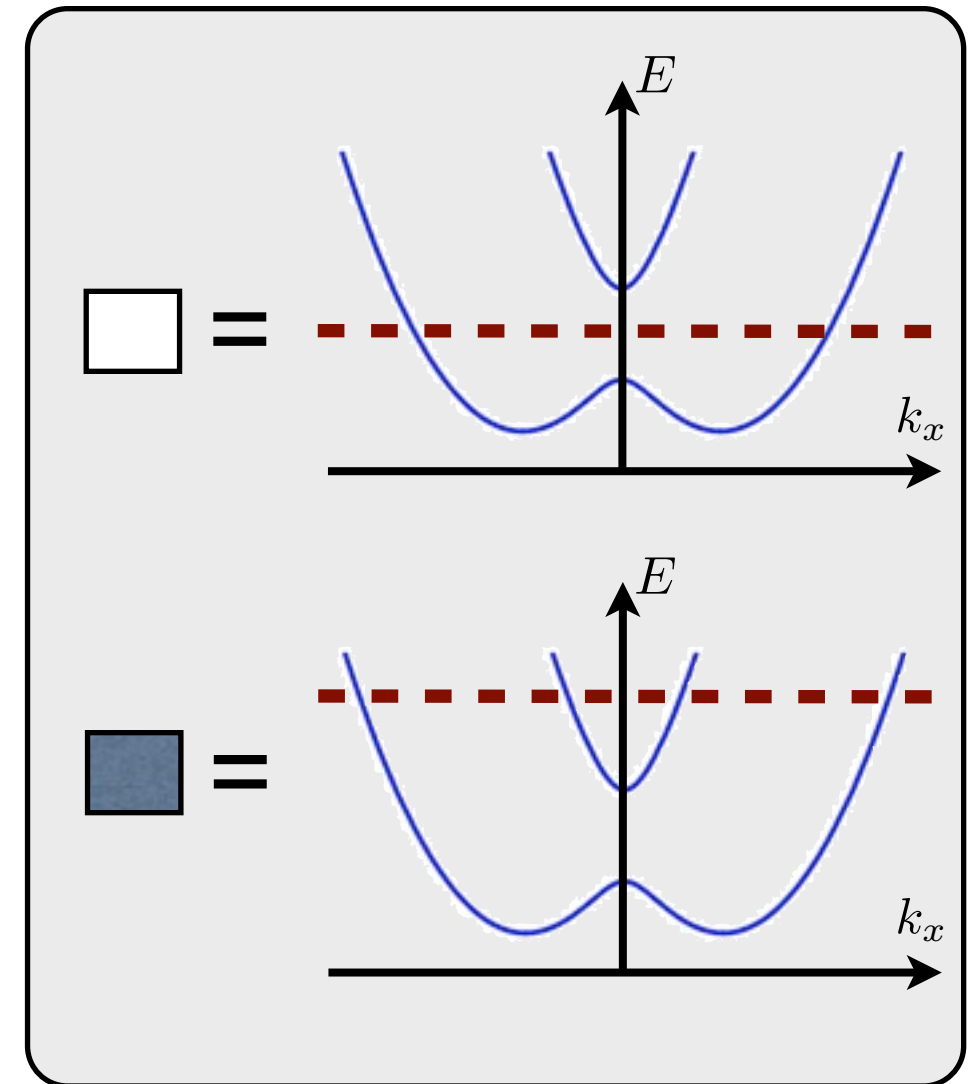
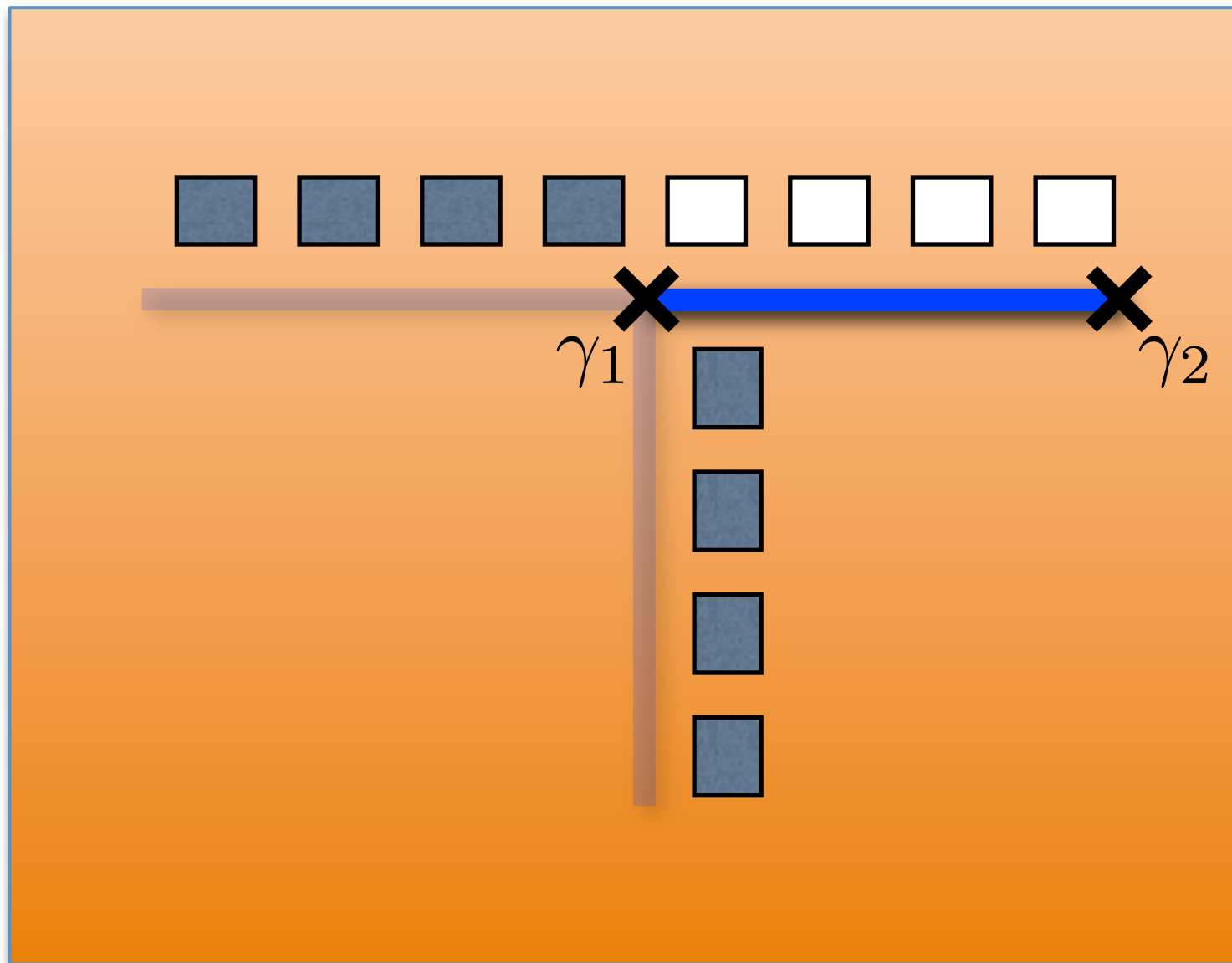
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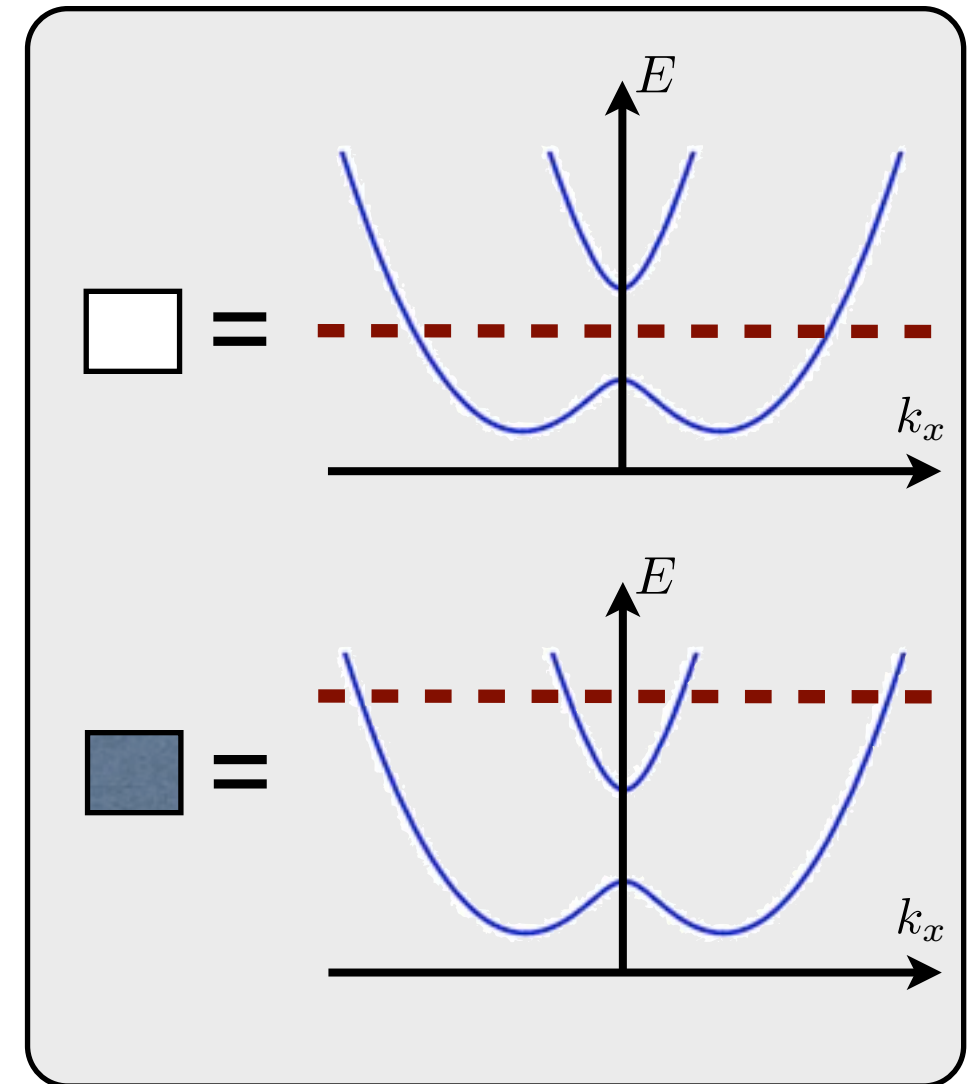
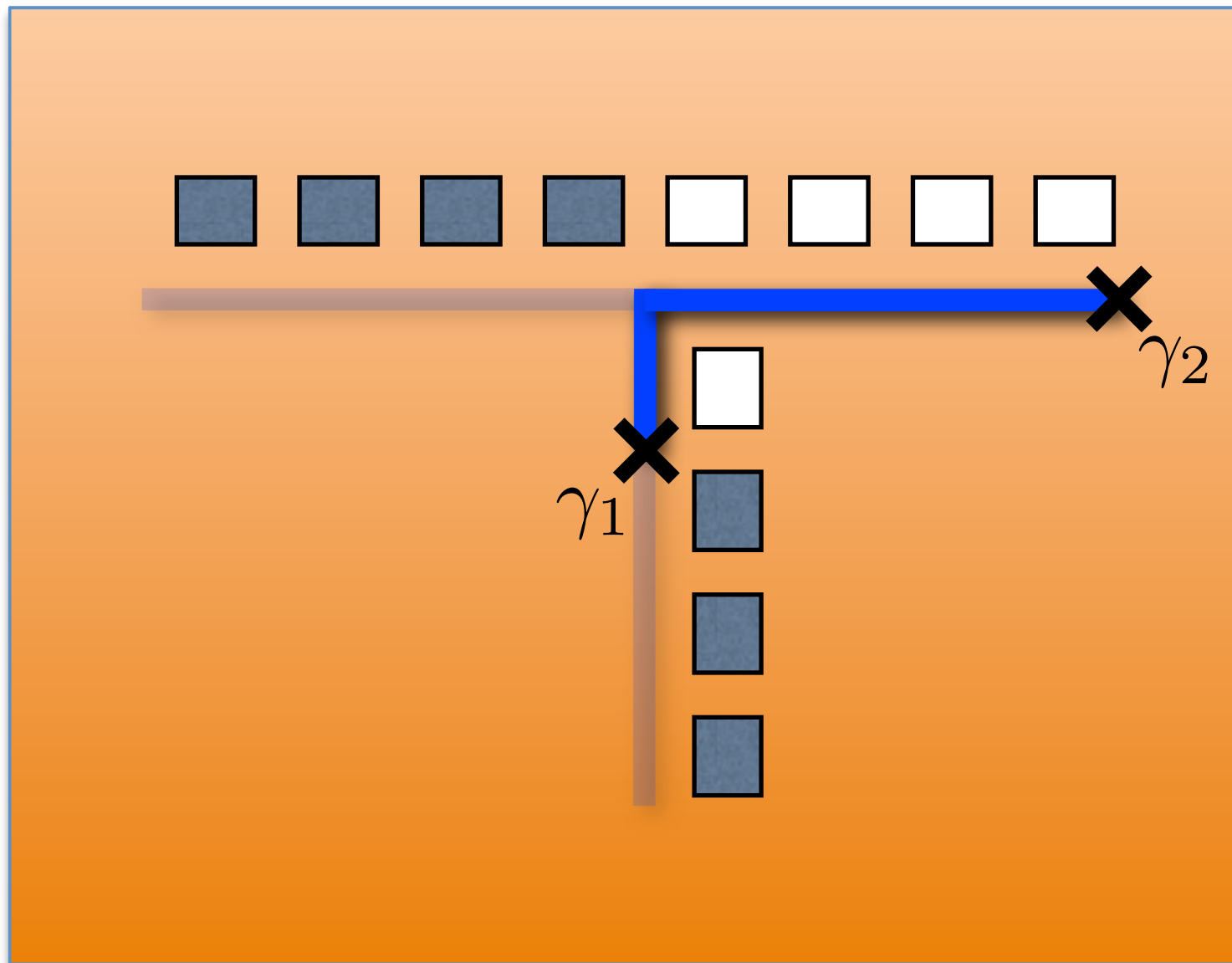
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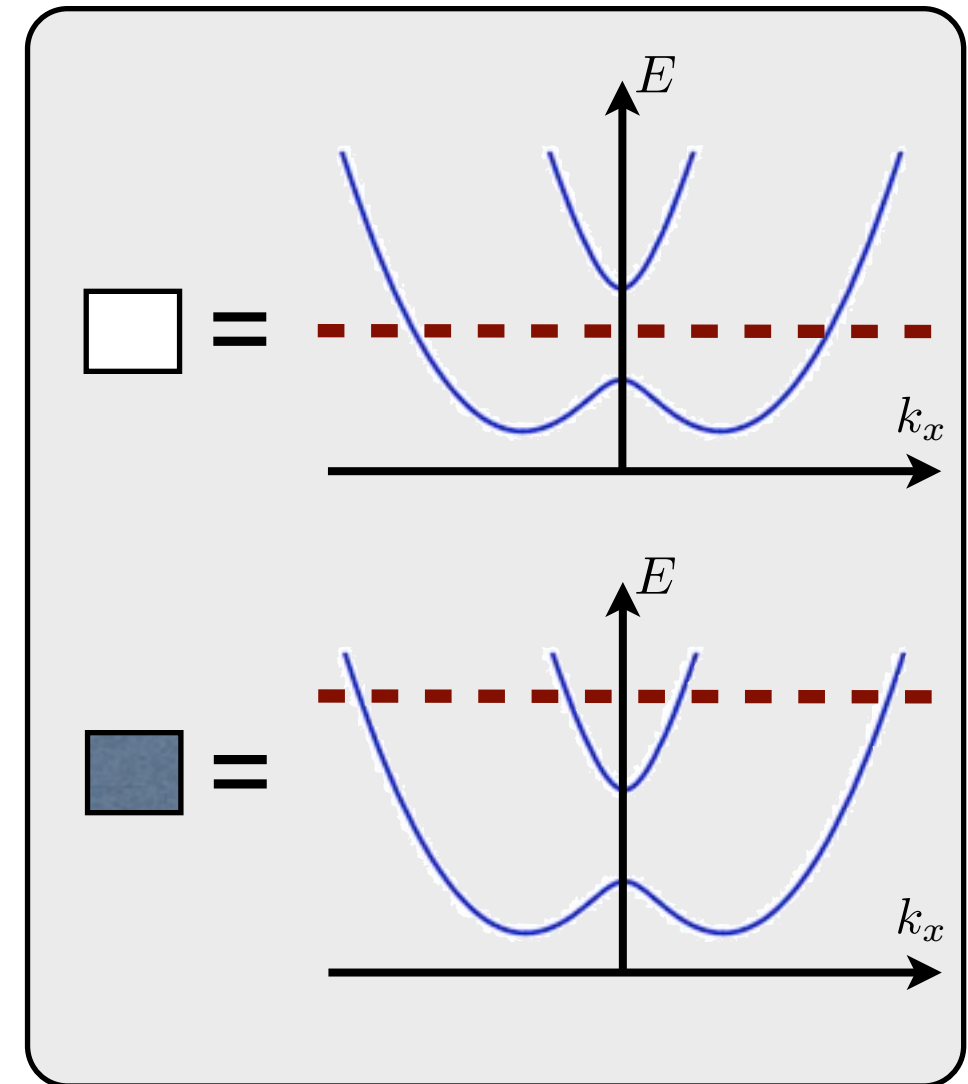
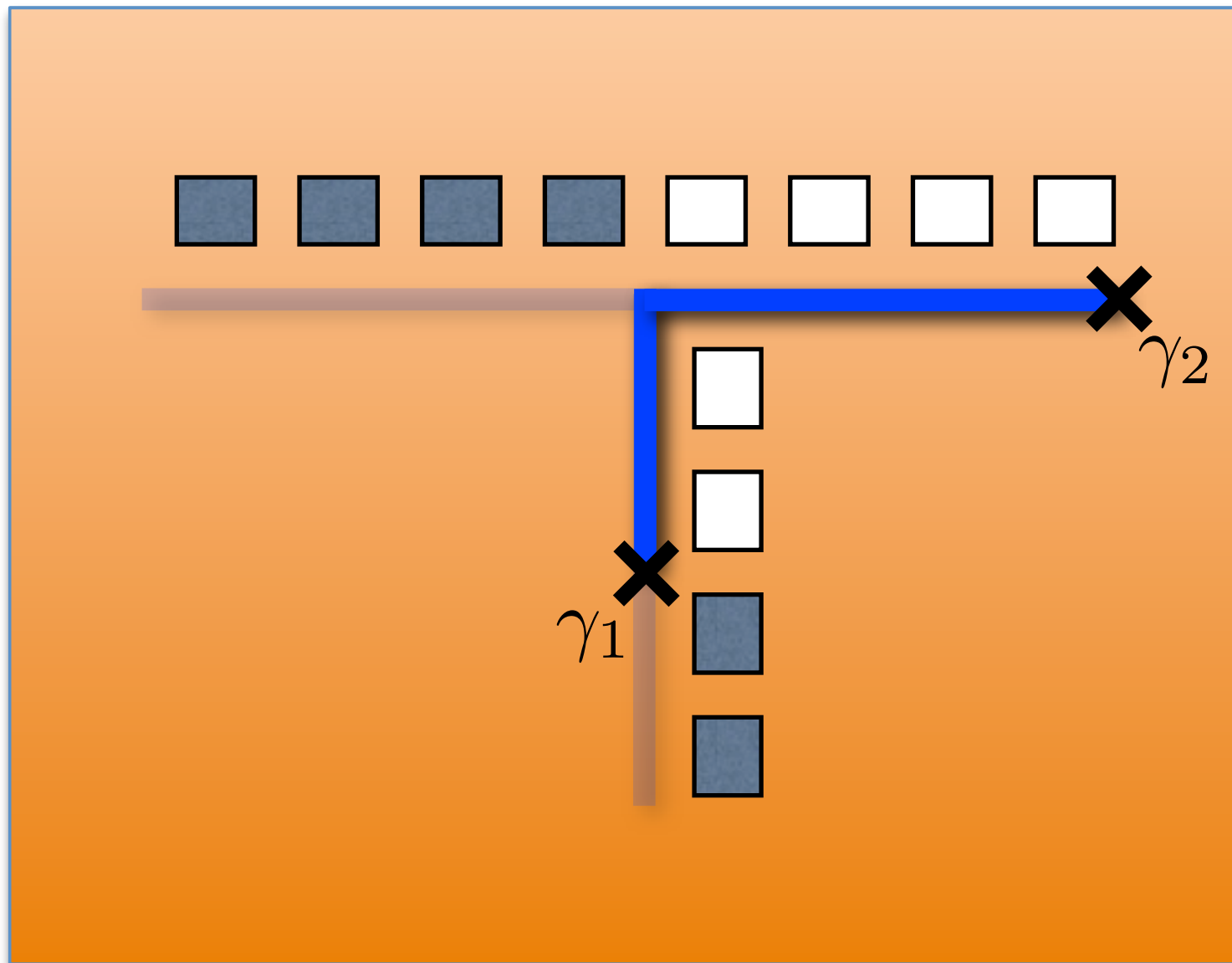
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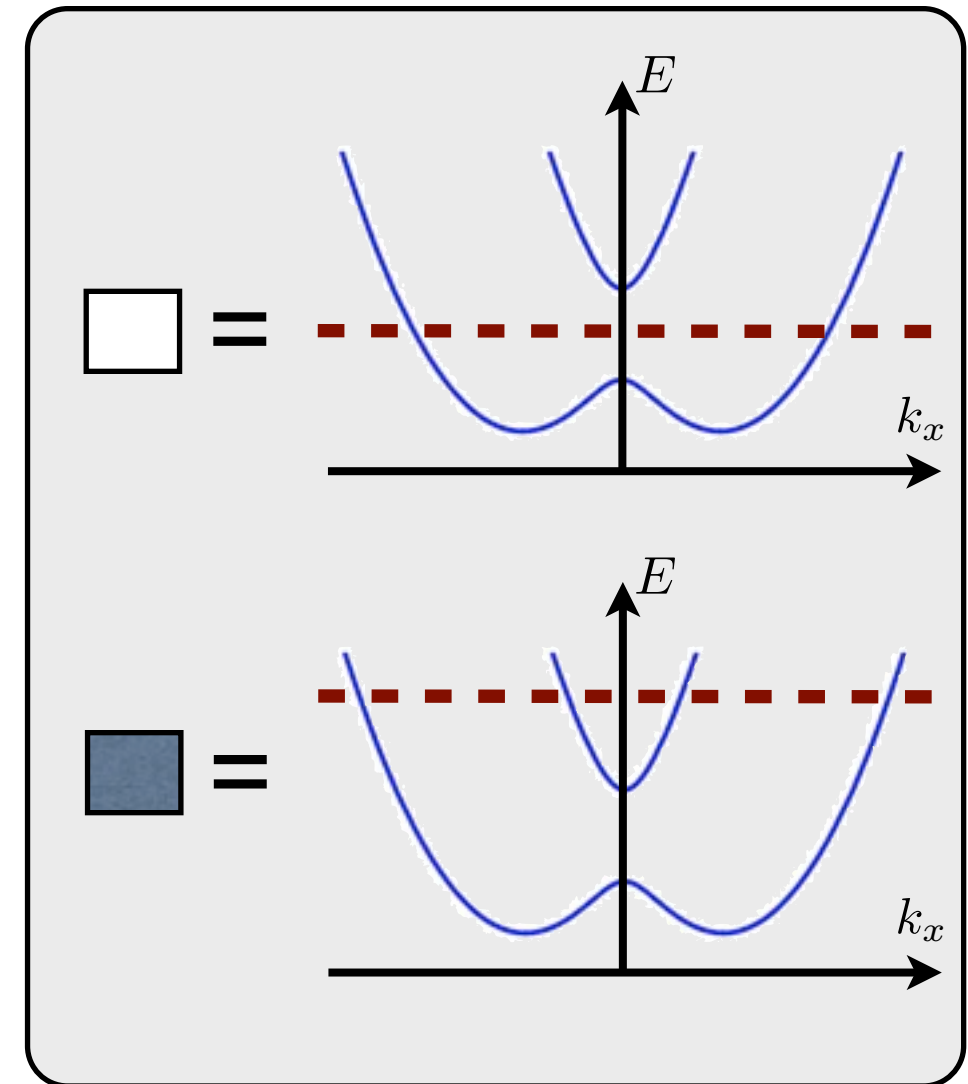
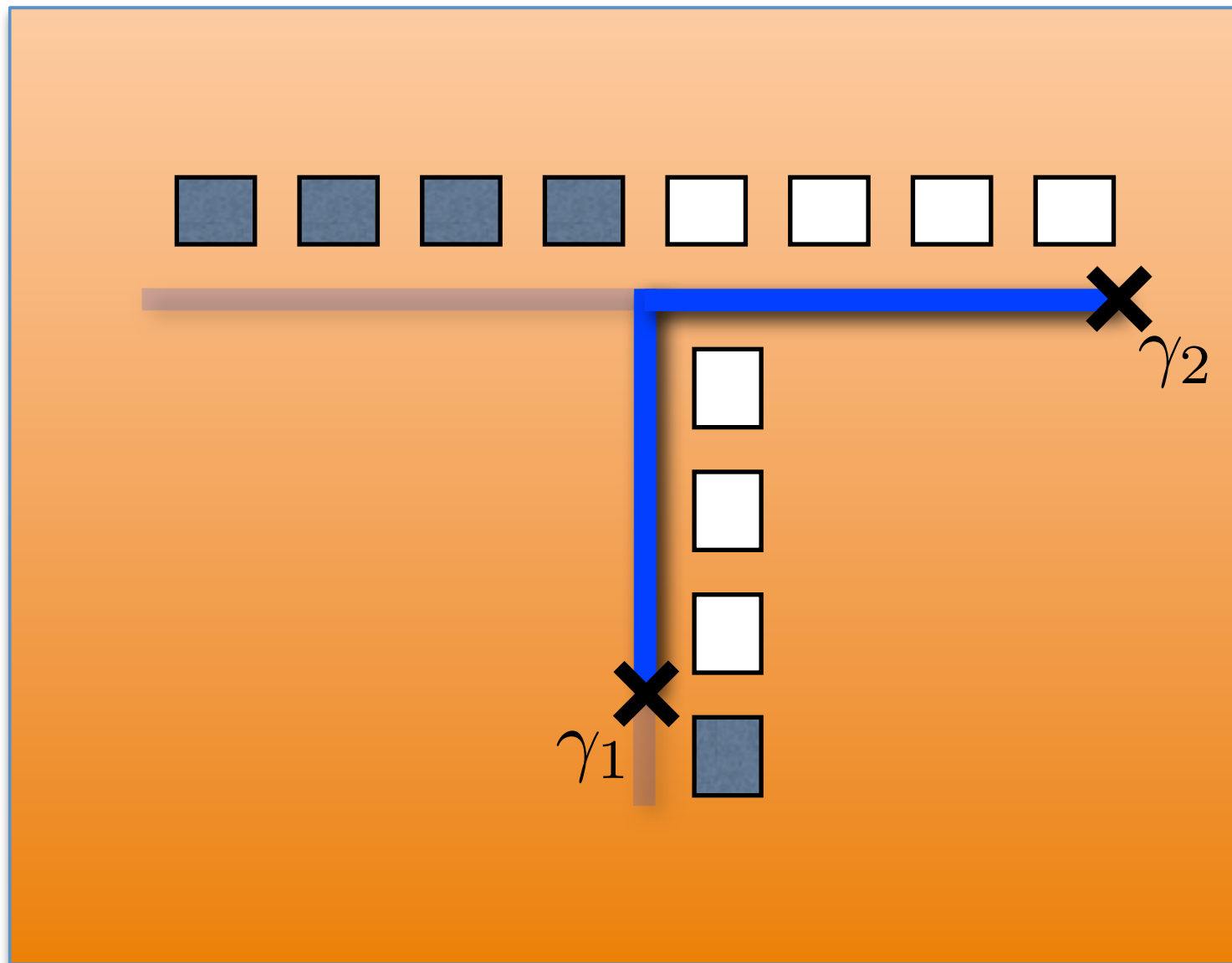
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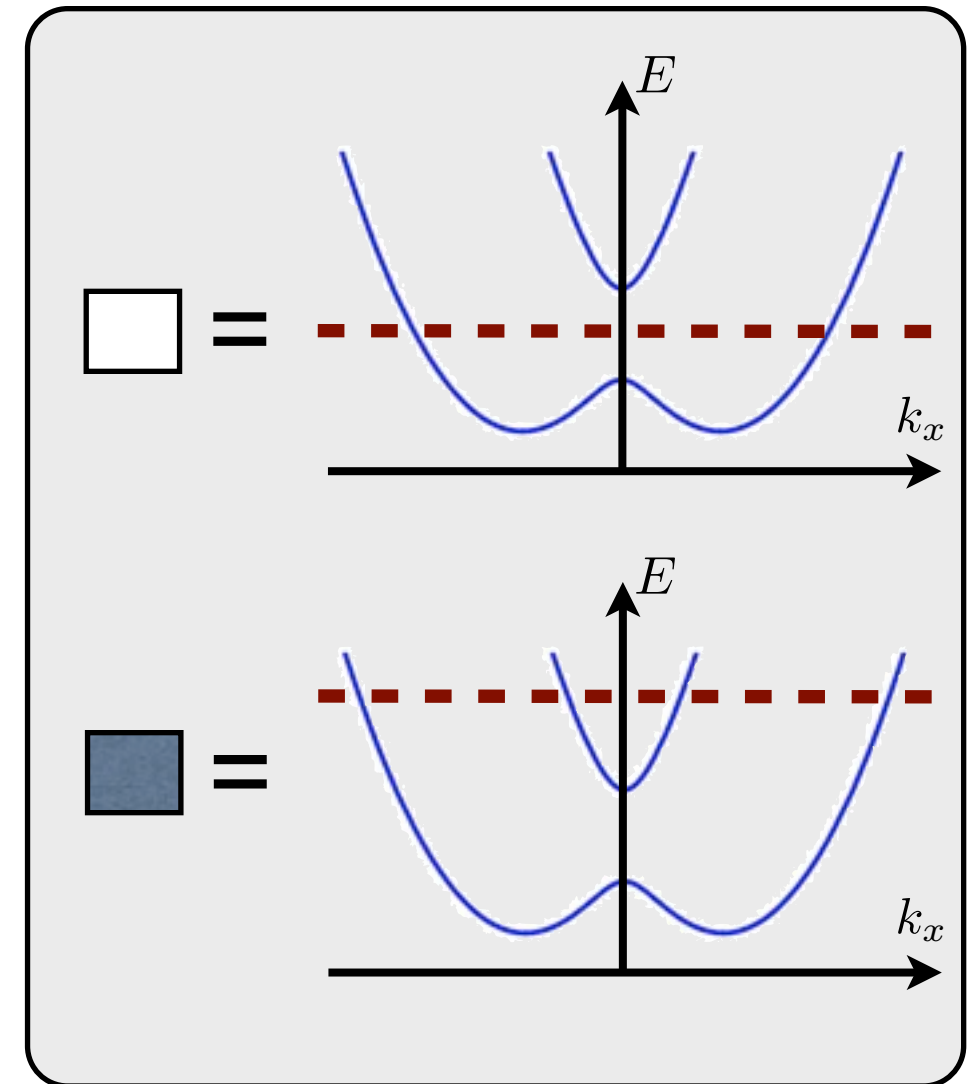
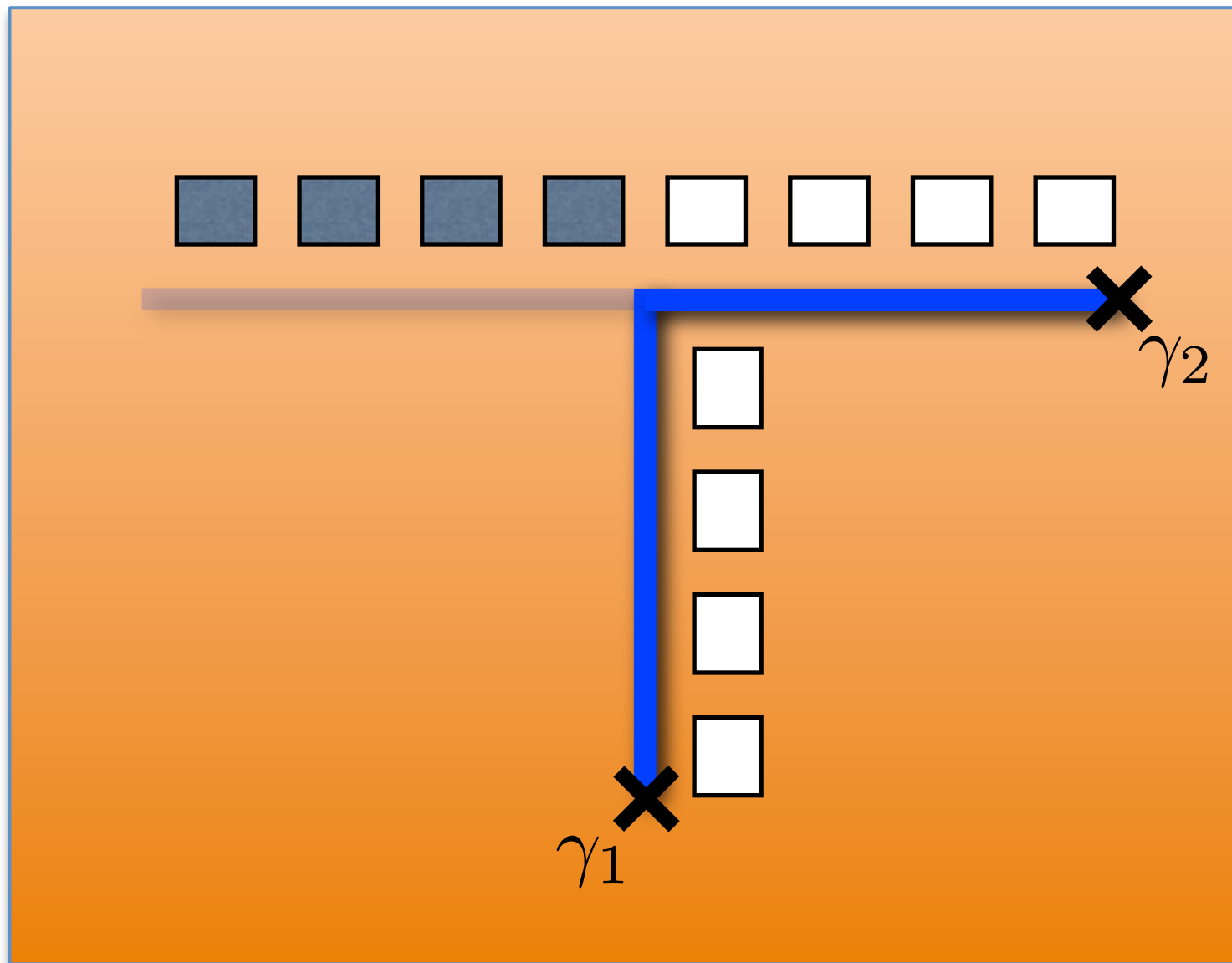
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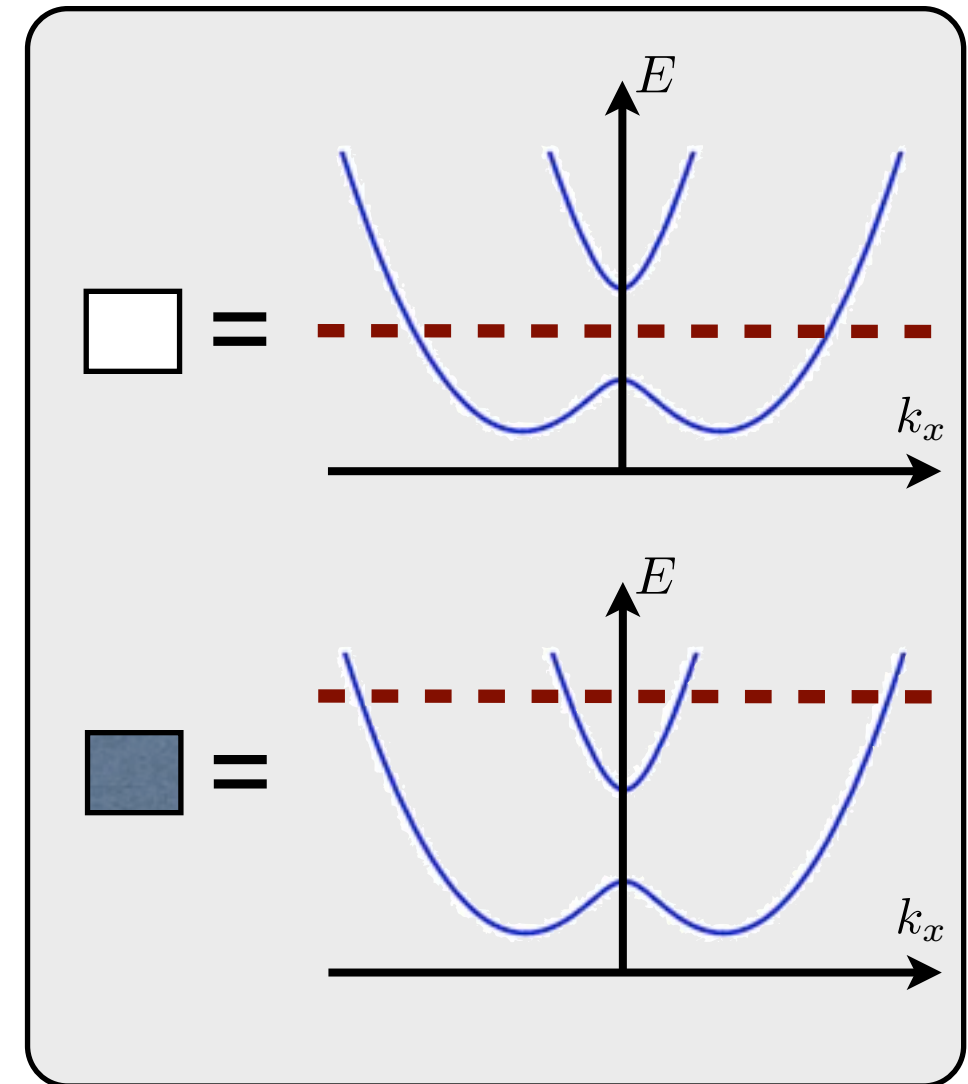
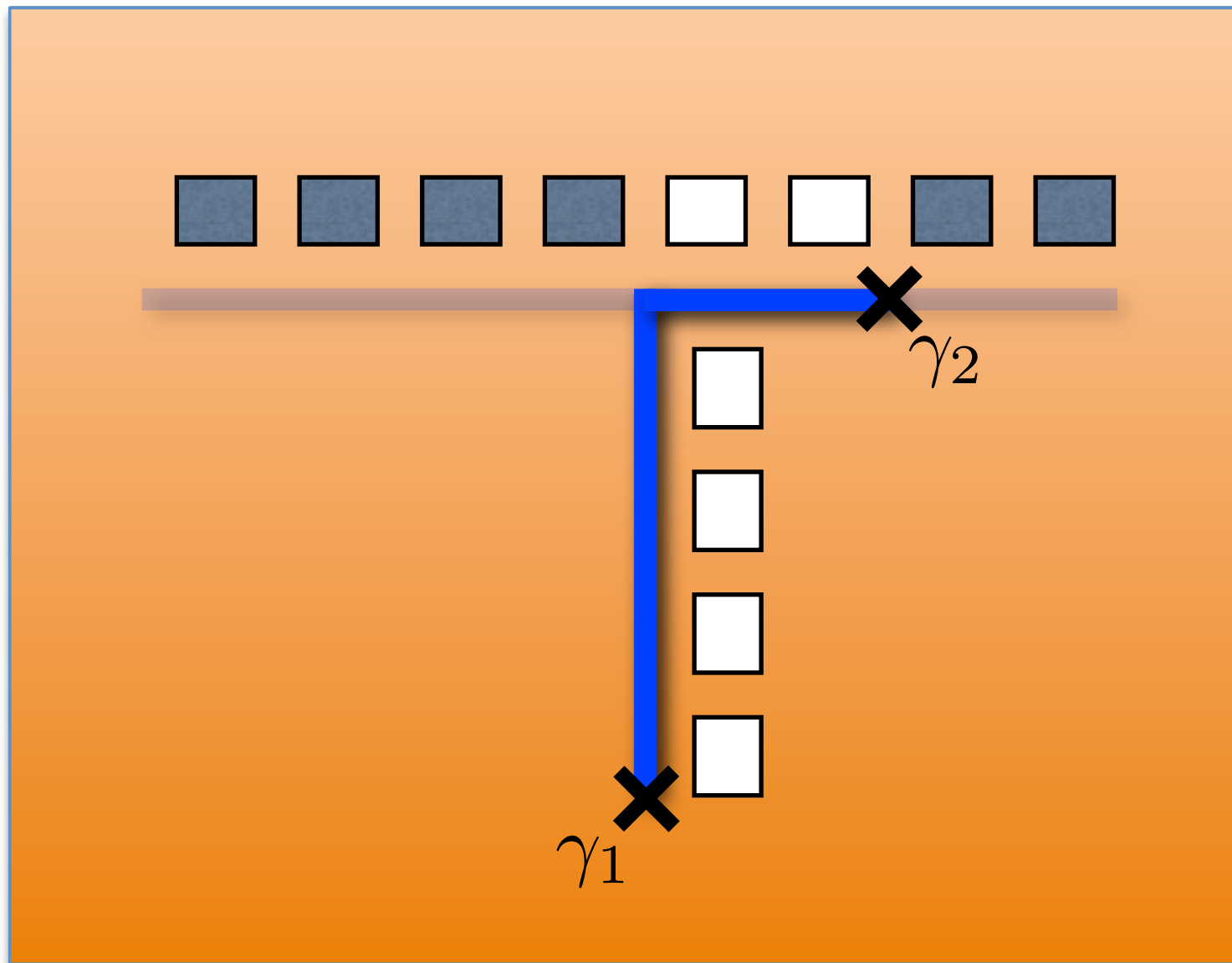
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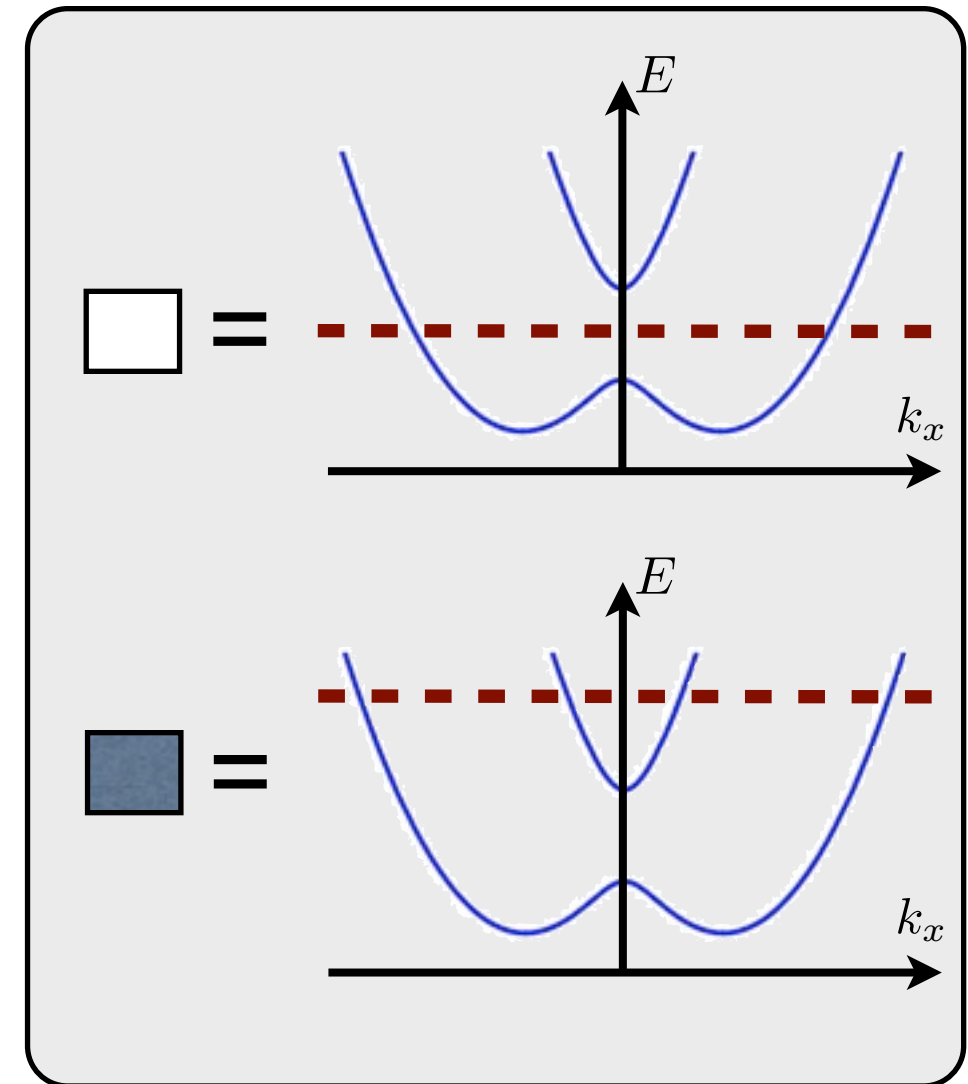
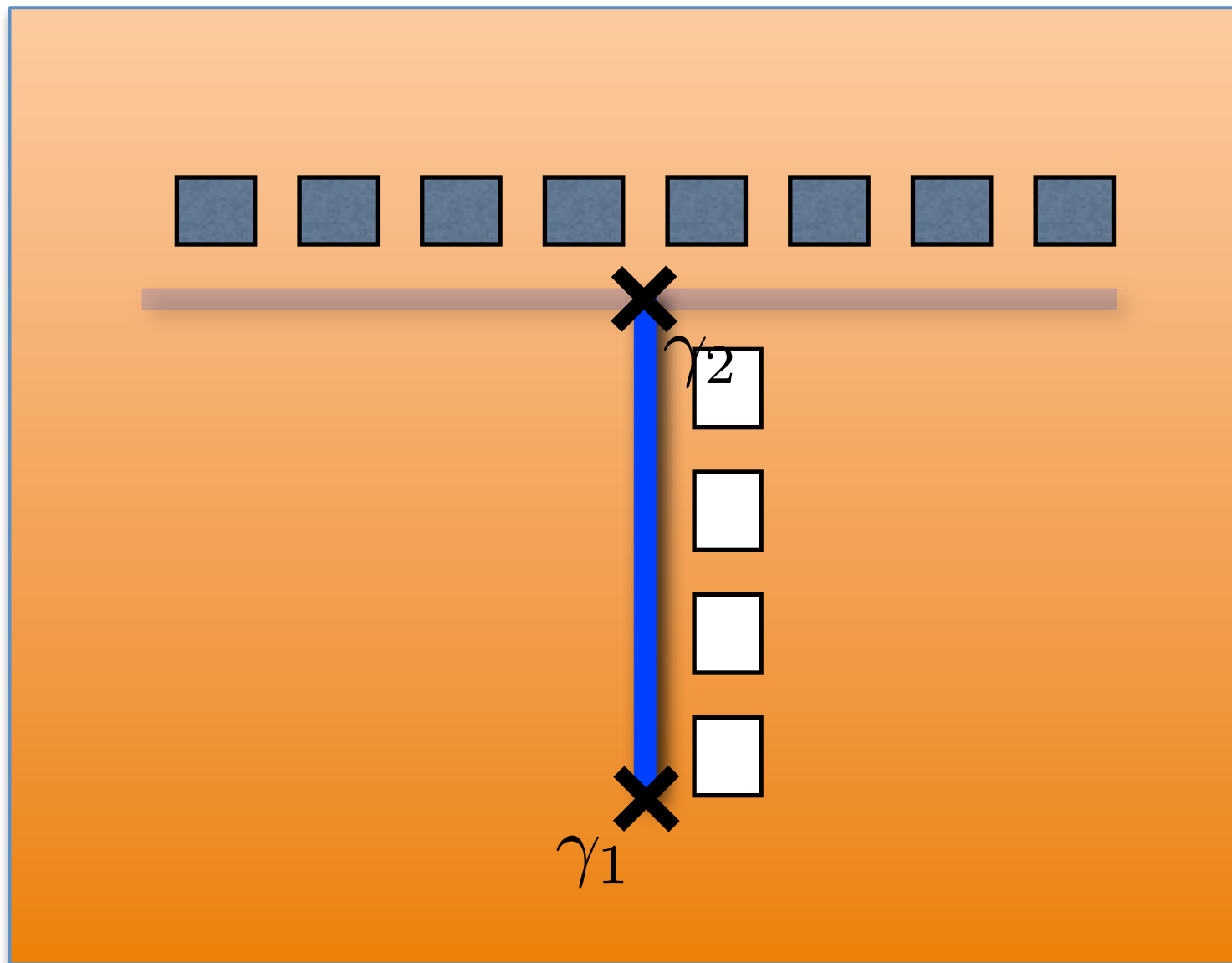
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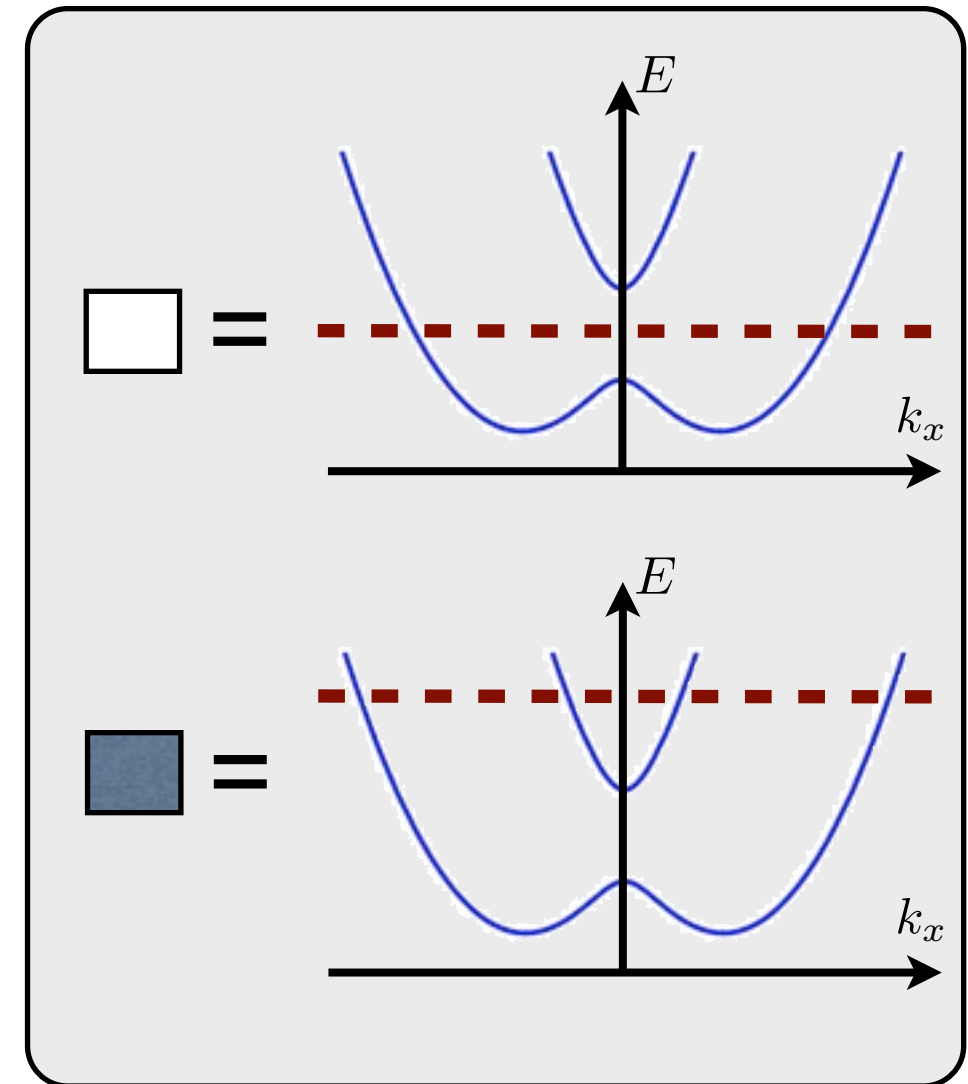
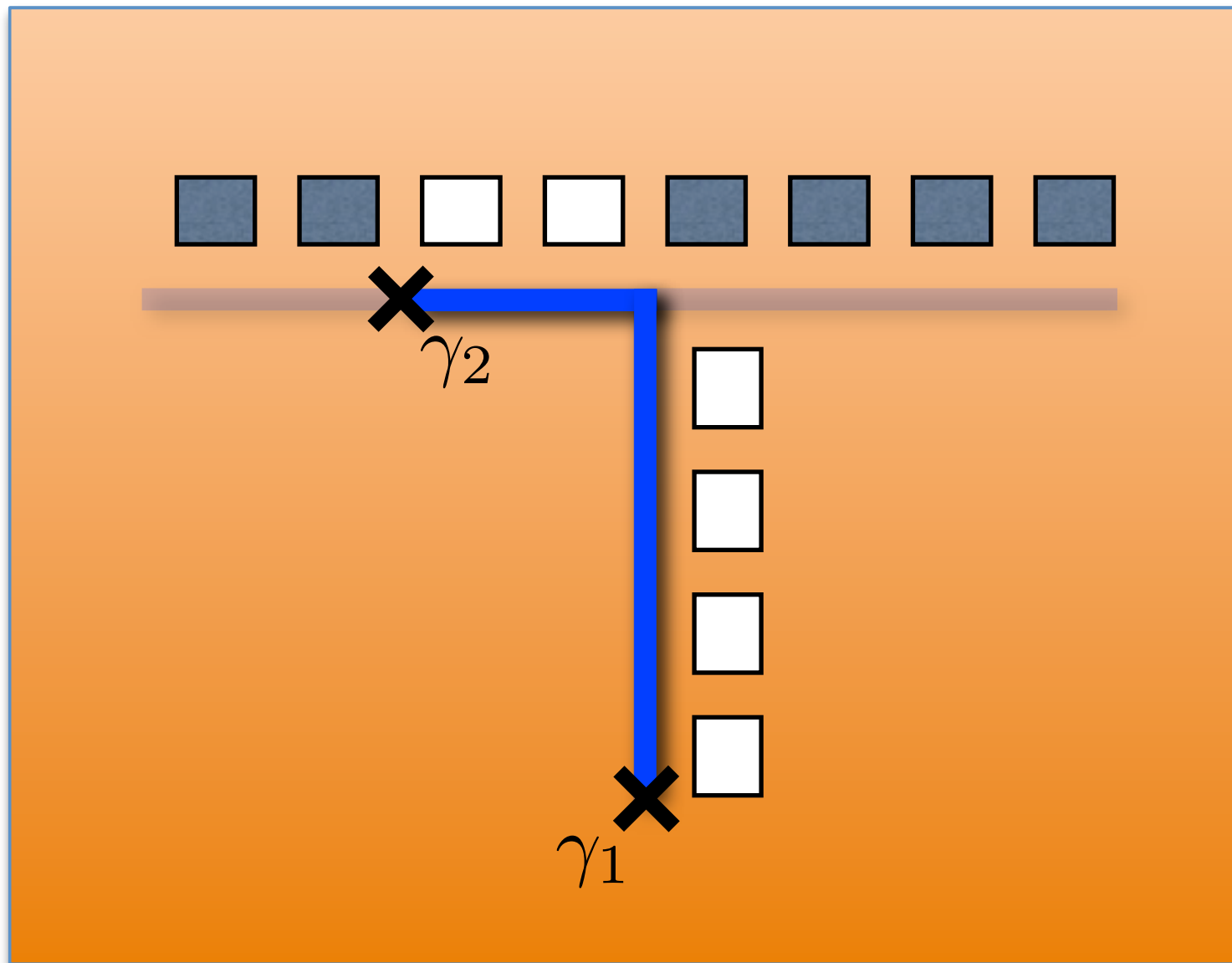
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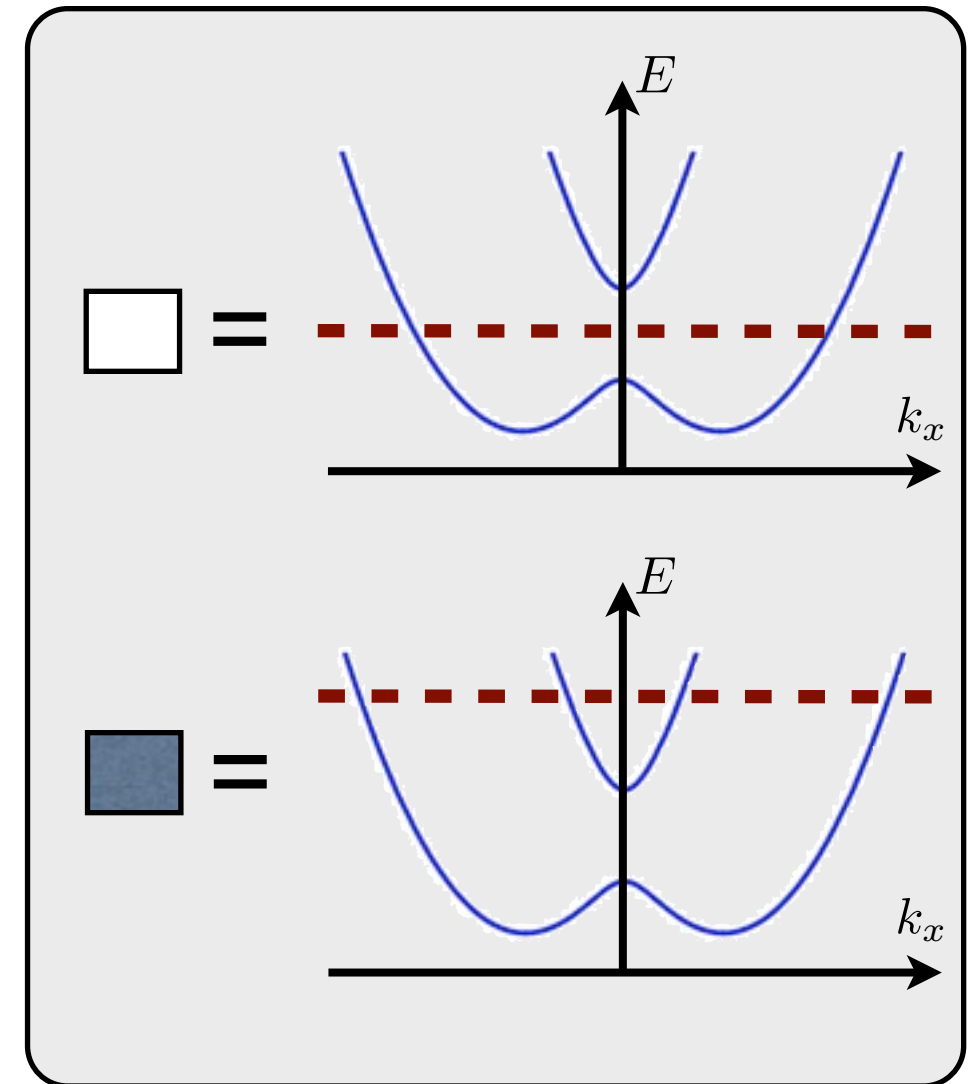
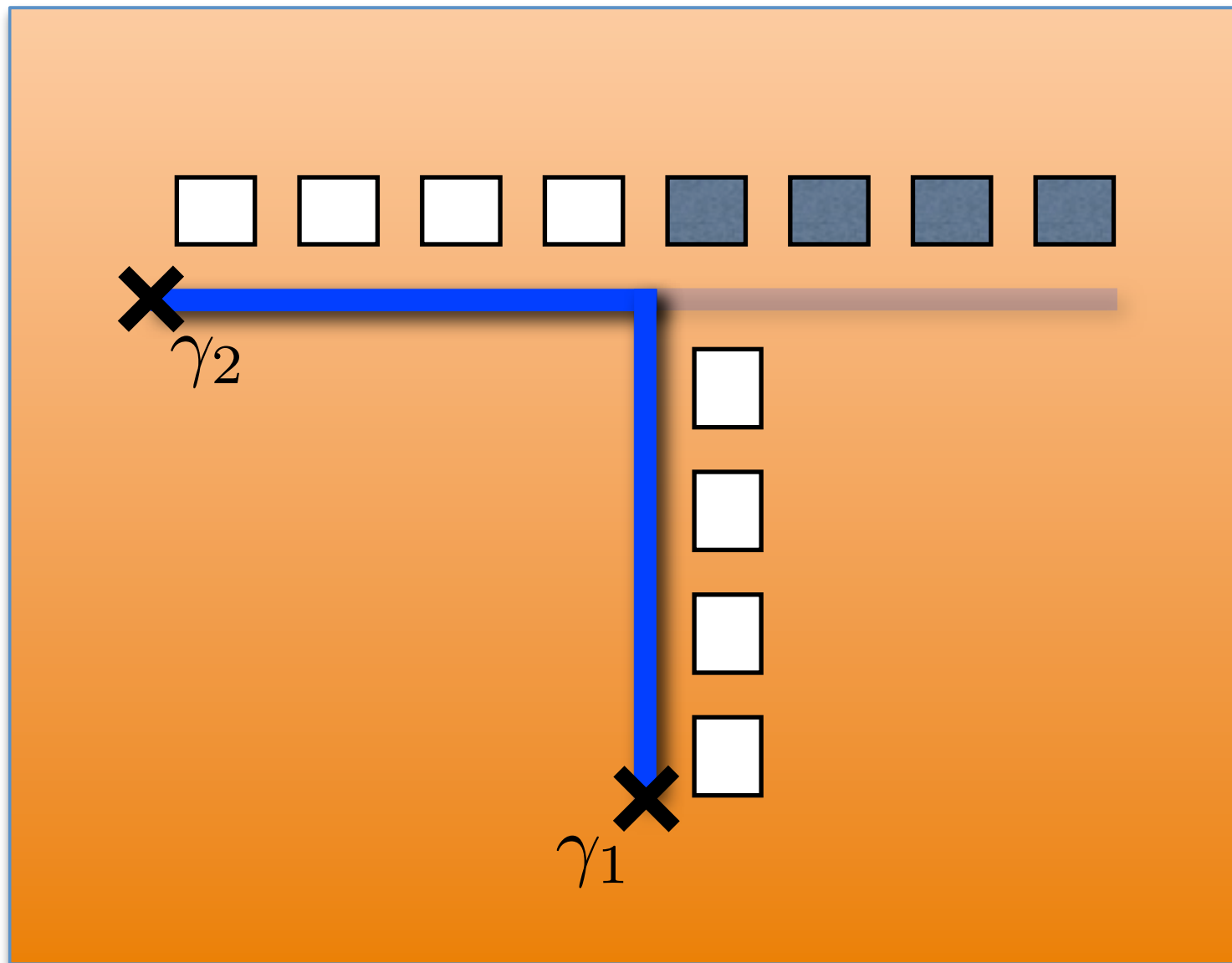
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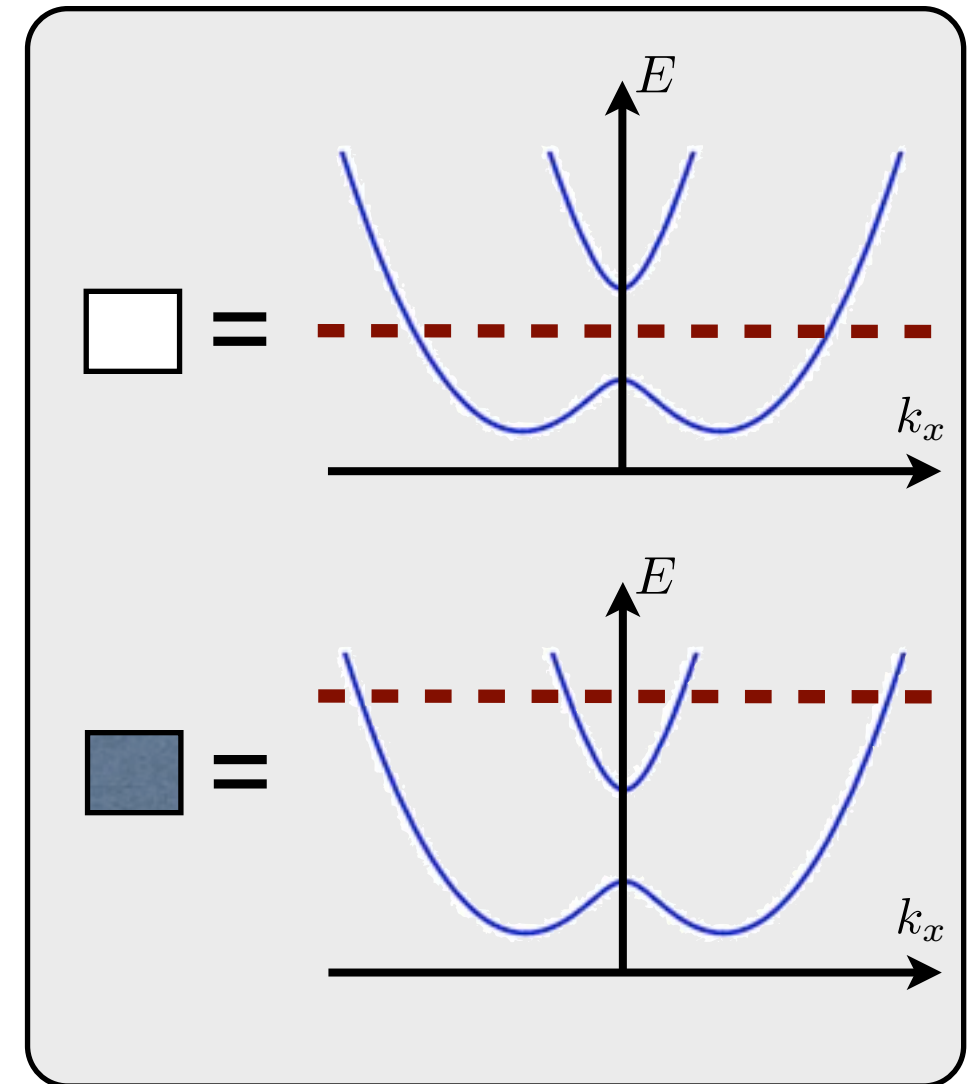
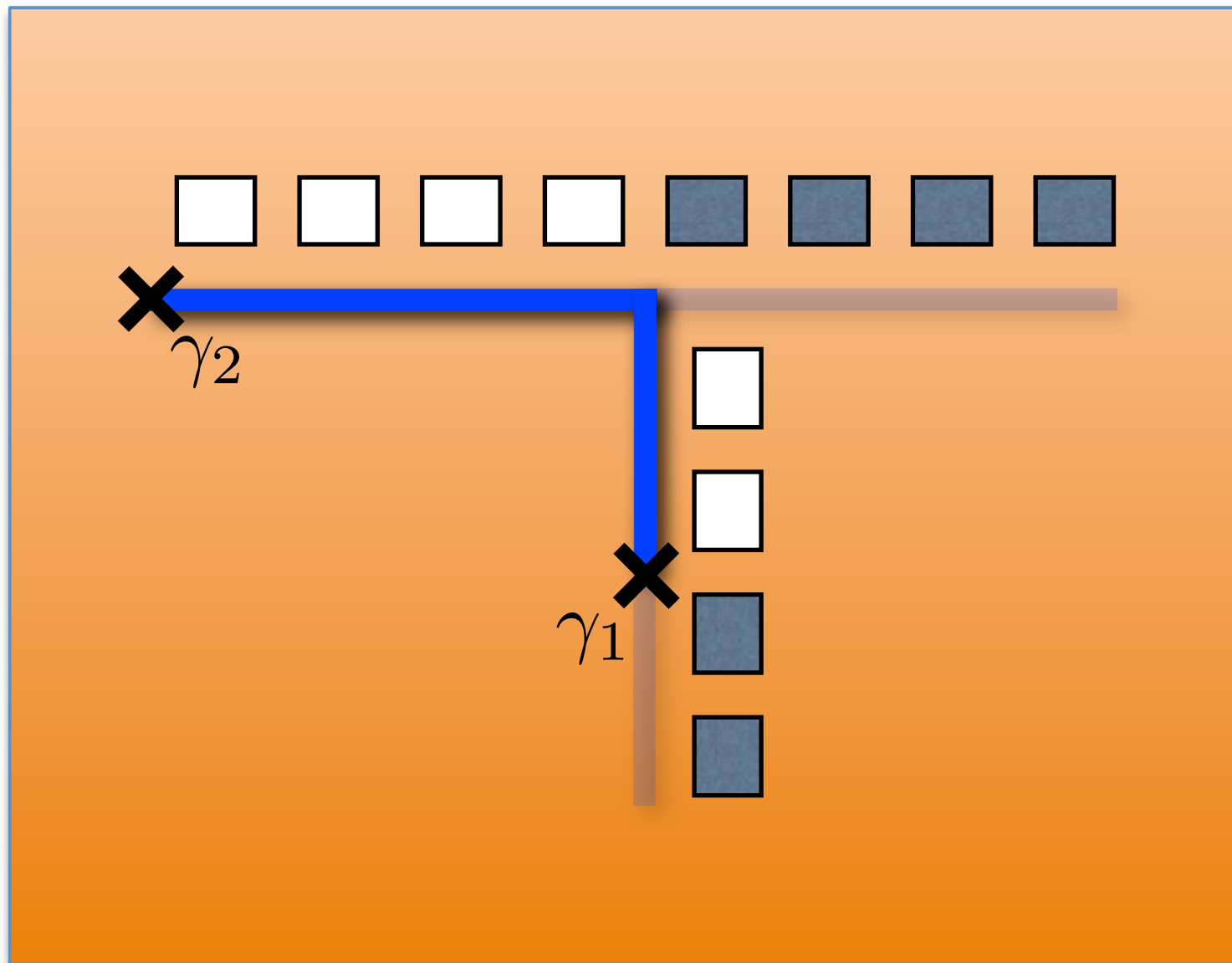
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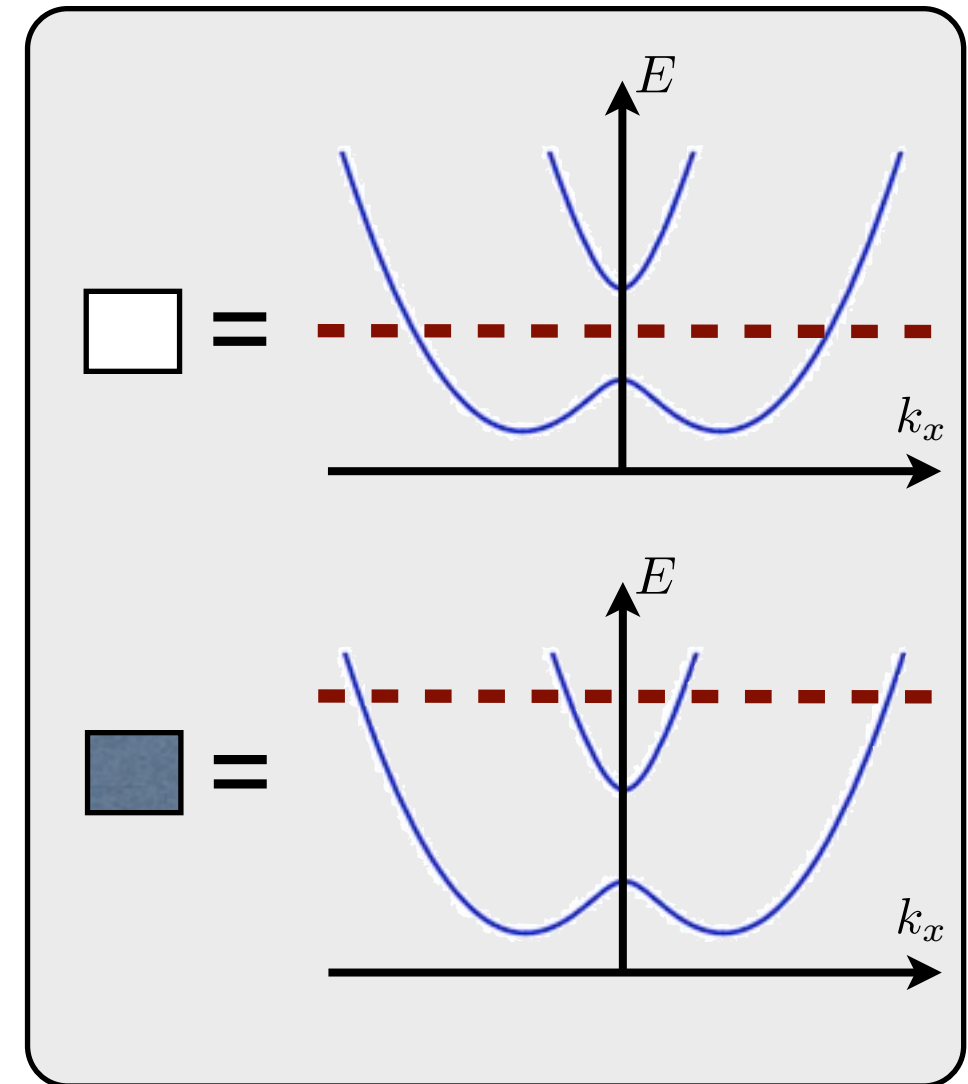
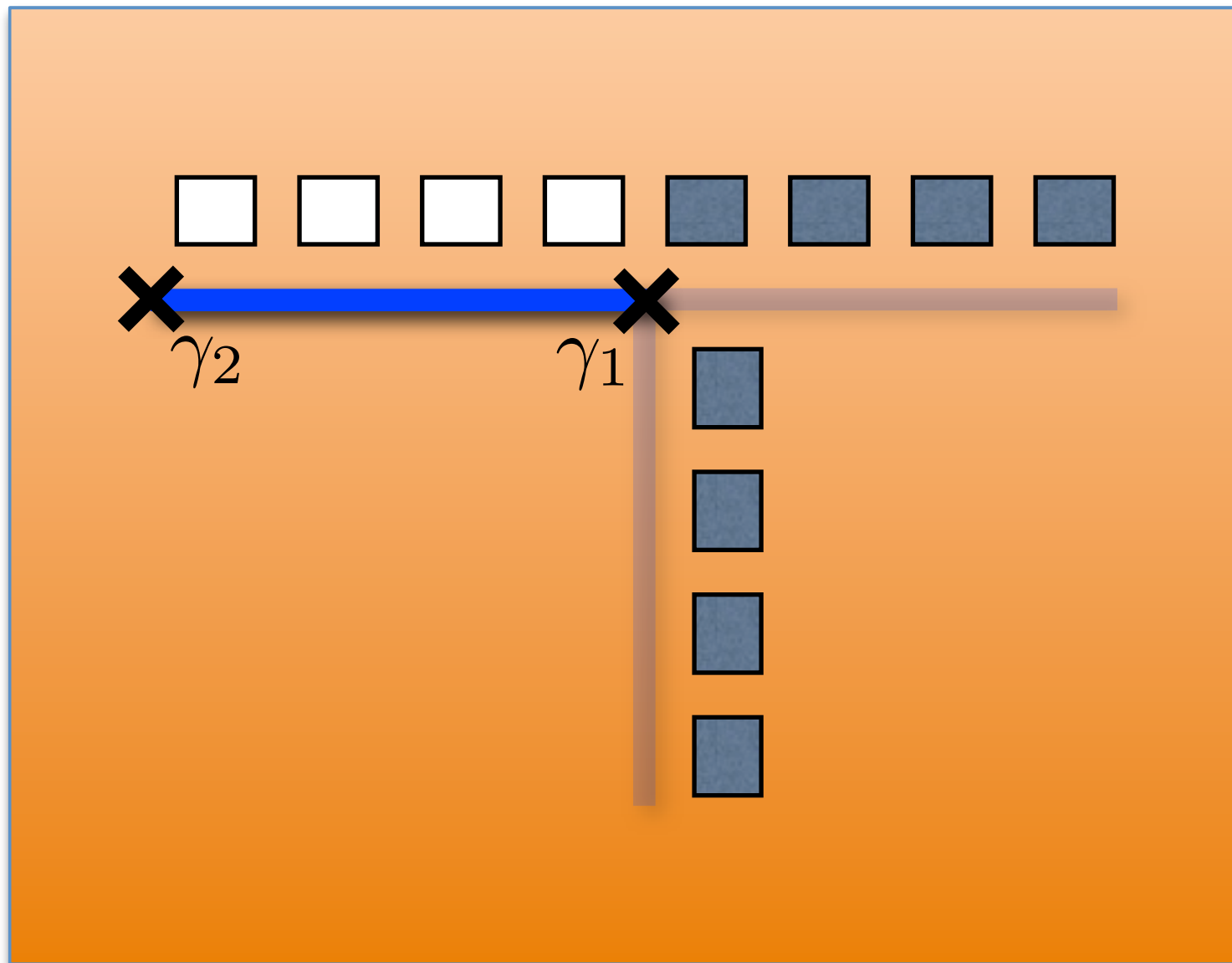
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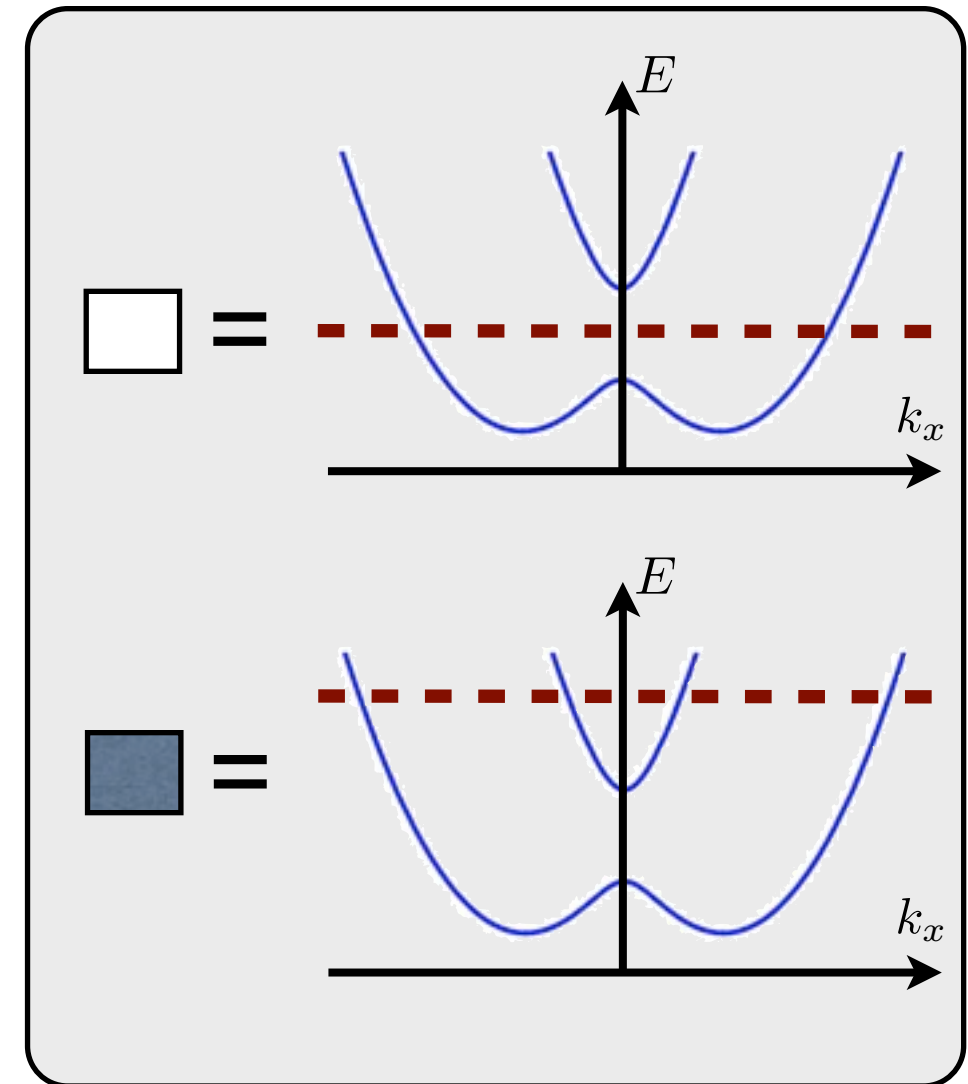
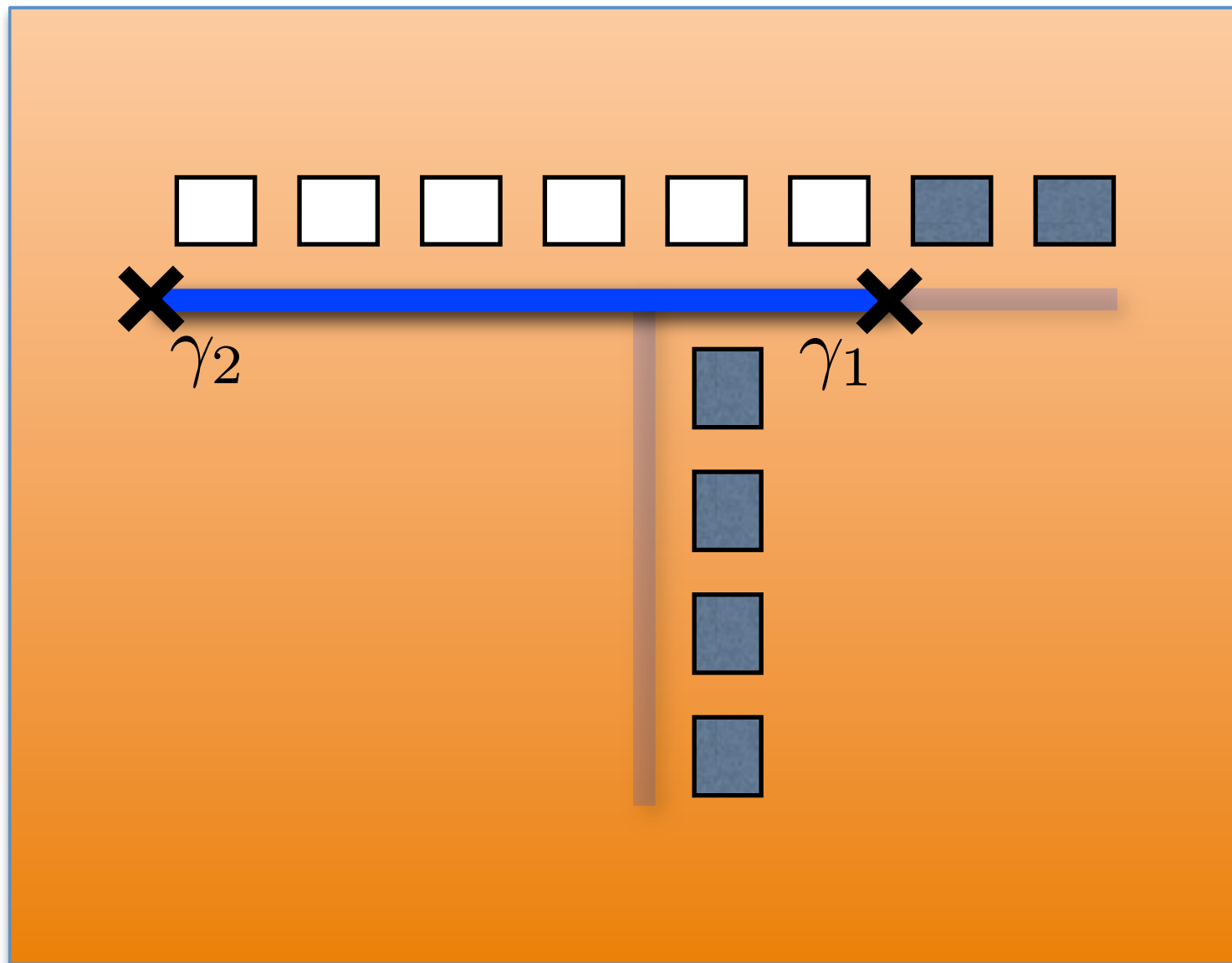
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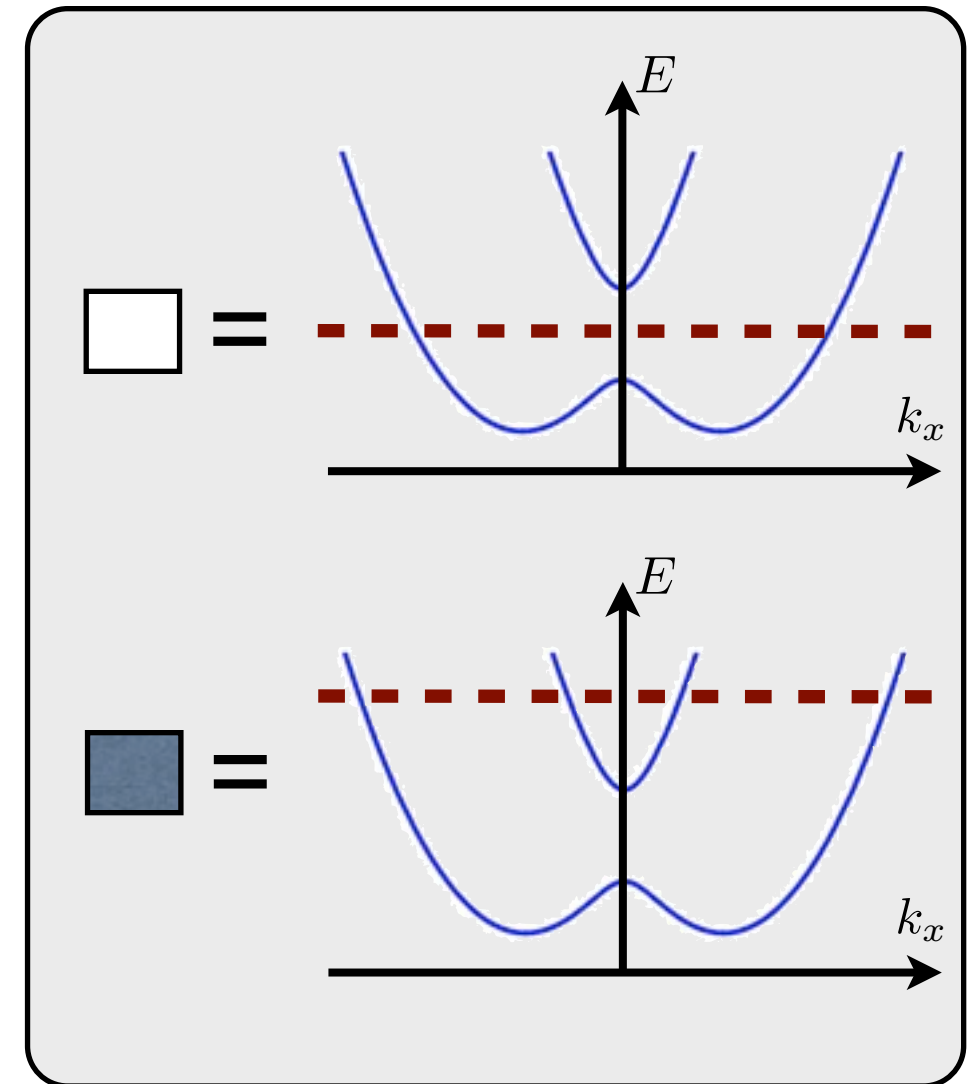
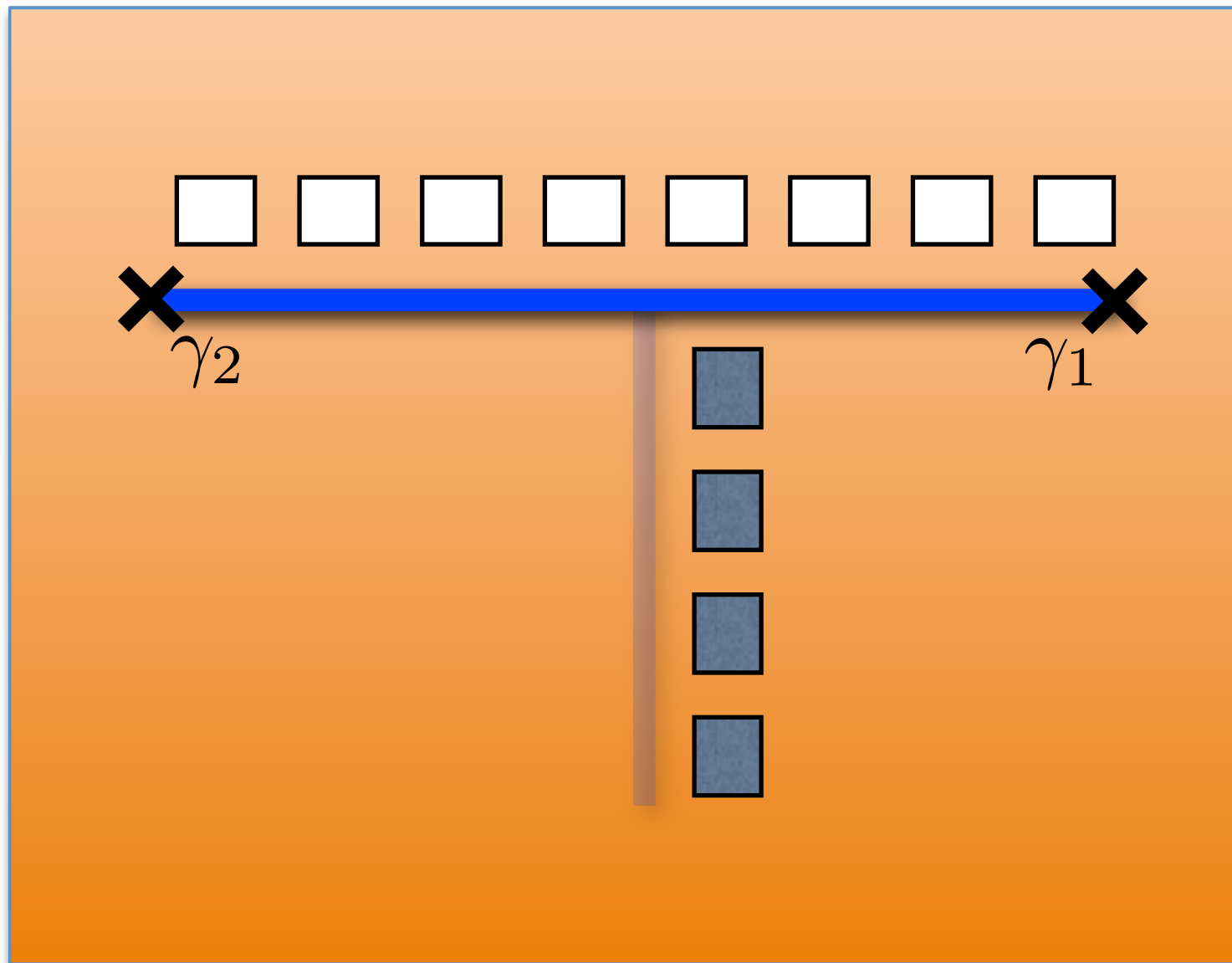
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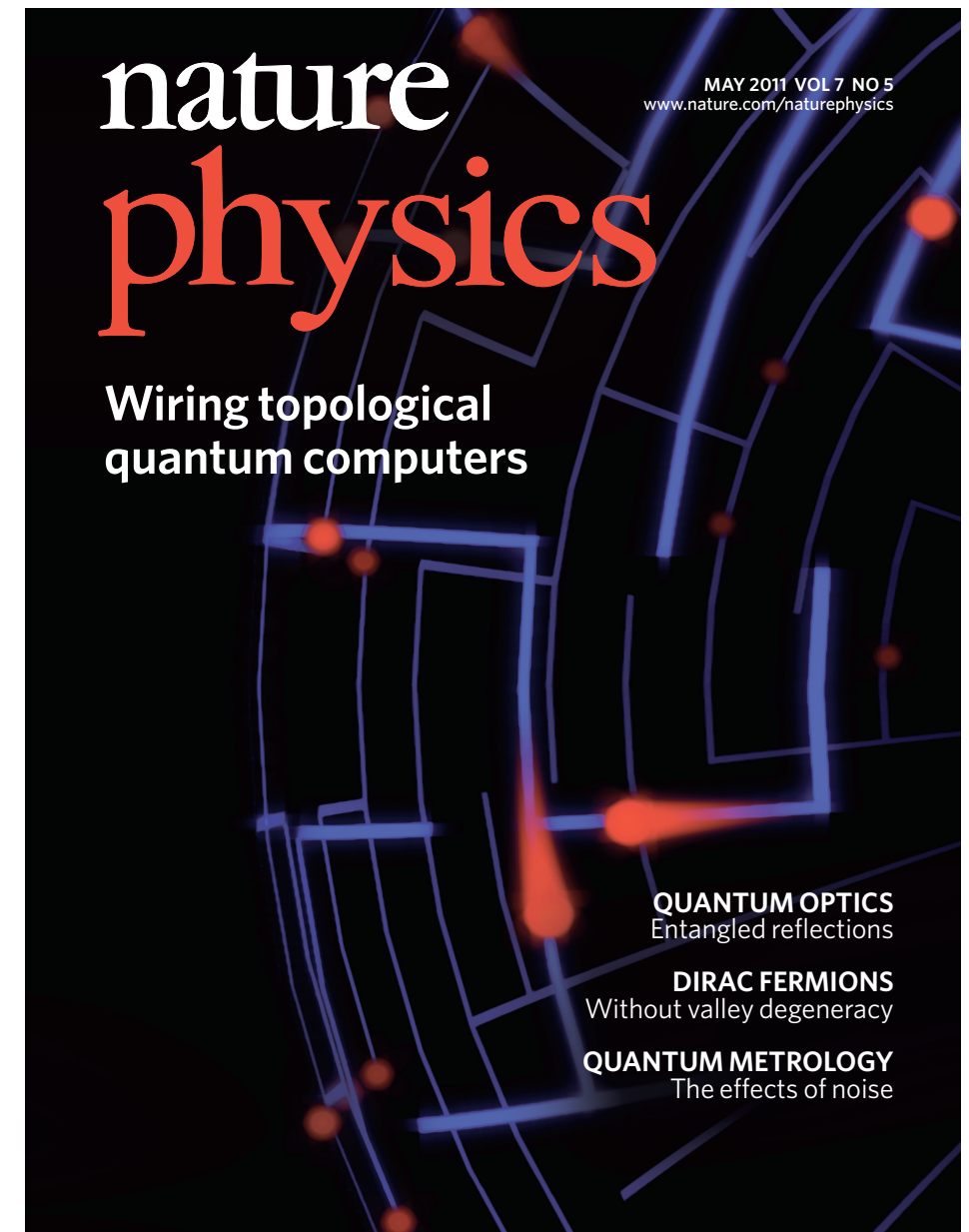
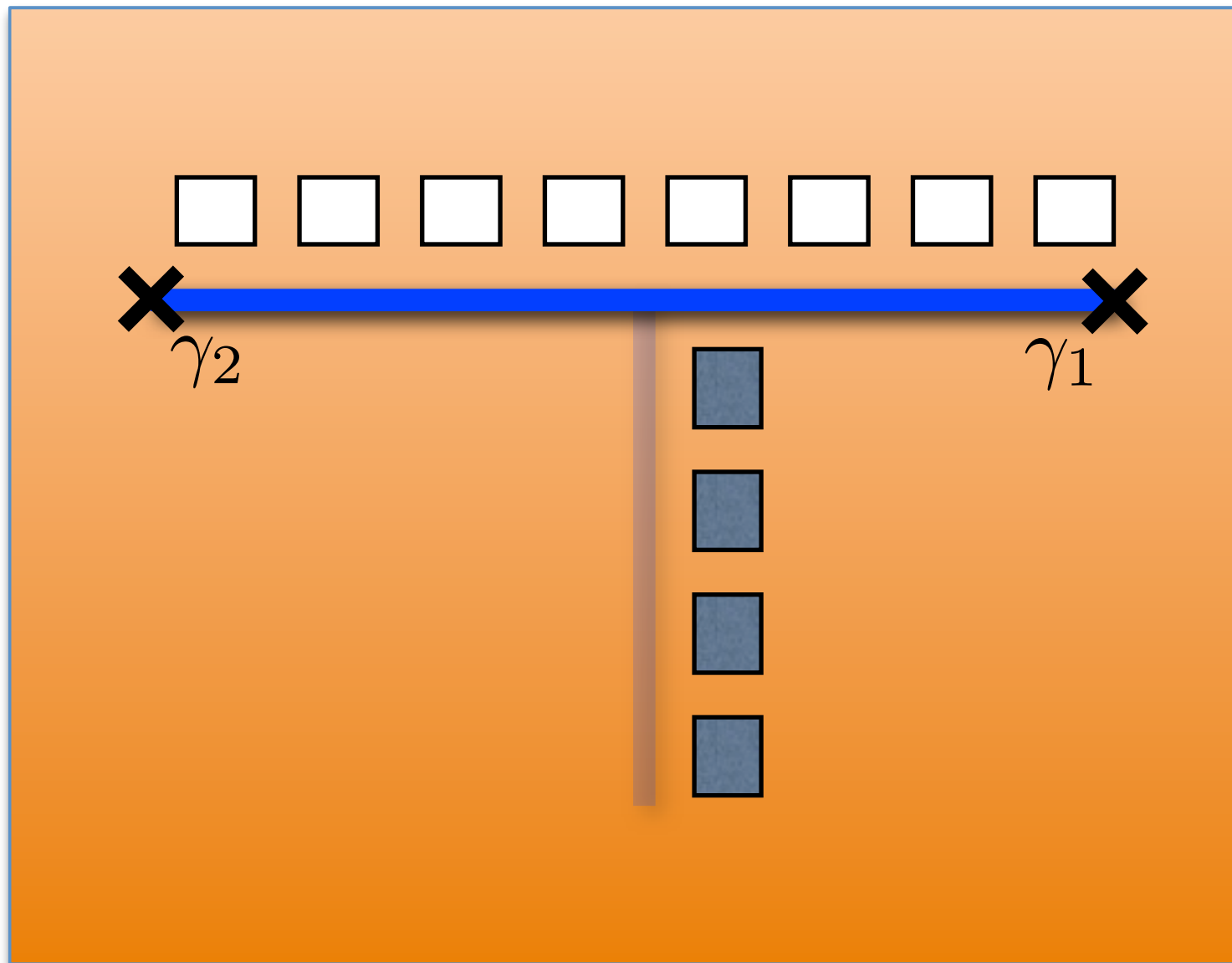
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Non-Abelian statistics
possible using 1D wires!

Harnessing non-Abelian statistics

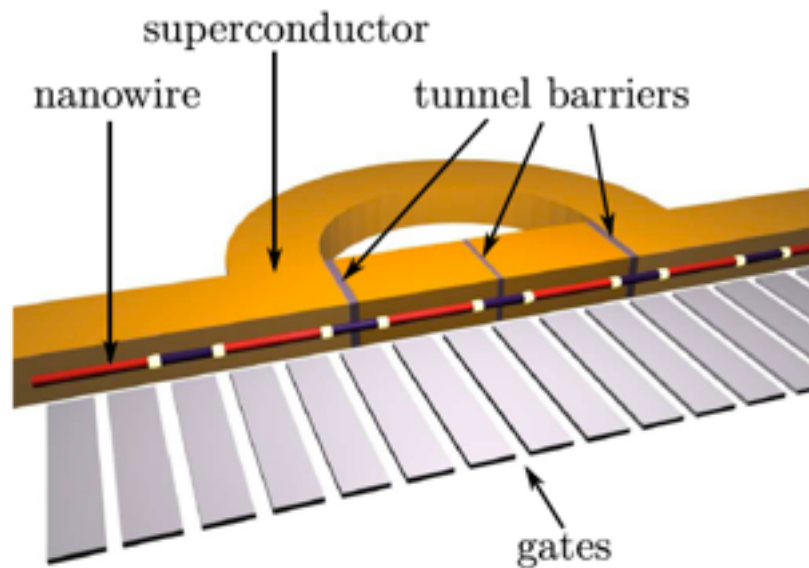


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Blueprints for quantum computers

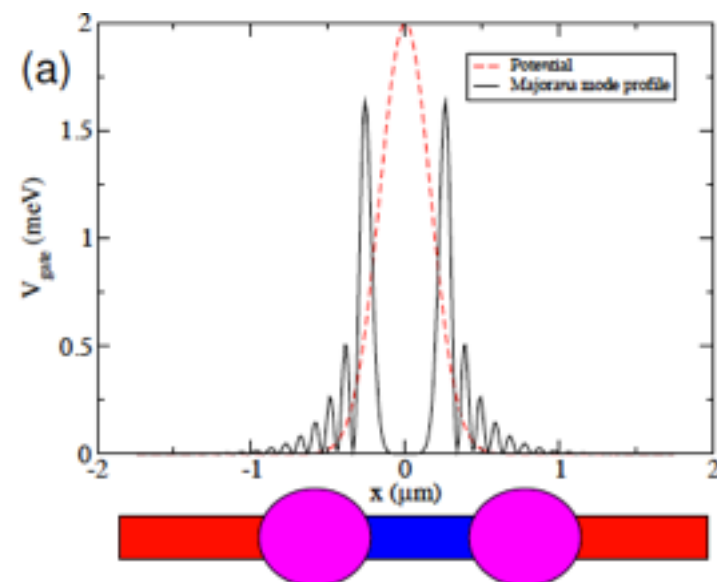
Need to supplement braiding with additional operations...



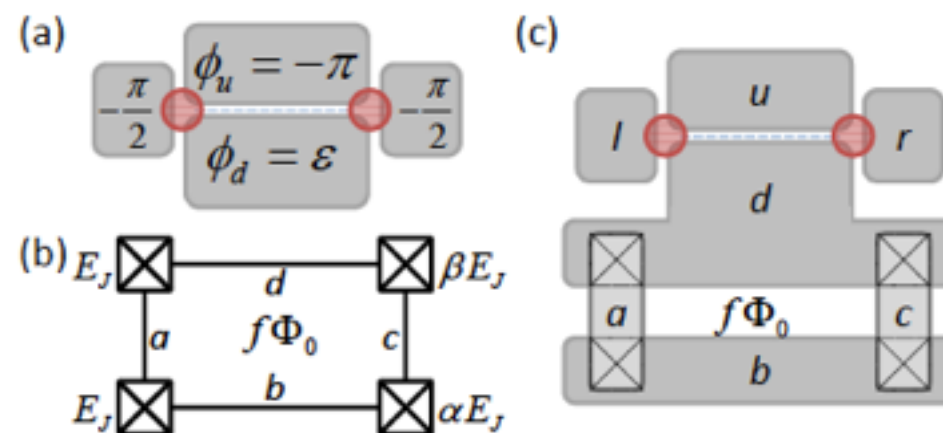
Hassler, Akhmerov,
Hou, Beenakker (2010)



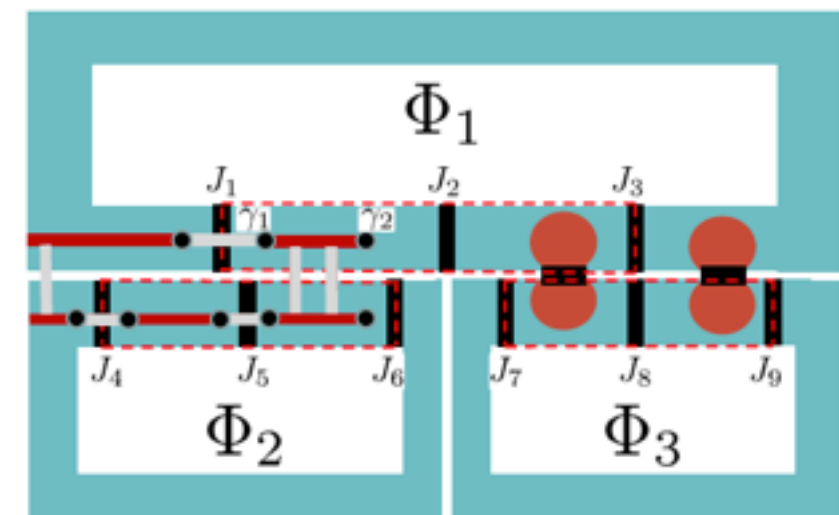
Hassler, Akhmerov, Beenakker (2011)



Sau, Tewari, Das Sarma (2010)



Jiang, Kane, Preskill (2010)



Bonderson and Lutchyn (2010)

Outline

- Majorana fermions: what they are & why they're interesting
- The quest for Majorana in the solid state
- Getting the most out of Majorana fermions
- **Experimental status & closing remarks**

Signatures of Majorana Fermions in Hybrid Superconductor-Topological Insulator Devices

J. R. Williams,¹ A. J. Bestwick,¹ P. Gallagher,¹ Seung Sae Hong,² Y. Cui,^{3,4}
Andrew S. Bleich,⁵ J. G. Analytis,^{2,4} I. R. Fisher,^{2,4} and D. Goldhaber-Gordon¹



Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices



V. Mourik,^{1*} K. Zuo,^{1*} S. M. Frolov,¹ S. R. Plissard,² E. P. A. M. Bakkers,^{1,2} L. P. Kouwenhoven^{1†}

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Anindya Das*, Yuval Ronen*, Yonatan Most, Yuval Oreg, Moty Heiblum[#], and Hadas Shtrikman

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M. T. Deng,¹ C. L. Yu,¹ G. Y. Huang,¹ M. Larsson,¹ P. Caroff,² and H. Q. Xu^{1,3,*}

Observation of the fractional ac Josephson effect: the signature of Majorana particles

Leonid P. Rokhinson,^{1,2,*} Xinyu Liu,³ and Jacek K. Furdyna³

Anomalous Modulation of a Zero-Bias Peak in a Hybrid Nanowire-Superconductor Device

A. D. K. Finck, D. J. Van Harlingen, P. K. Mohseni, K. Jung, and X. Li

Phys. Rev. Lett. **110**, 126406 (2013)



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Superconductor-Nanowire Devices from Tunneling to the Multichannel Regime: Zero-Bias Oscillations and Magnetoconductance Crossover

H. O. H. Churchill,^{1,2} V. Fatemi,² K. Grove-Rasmussen,³ M. T. Deng,⁴ P. Caroff,⁴ H. Q. Xu,^{4,5} and C. M. Marcus¹



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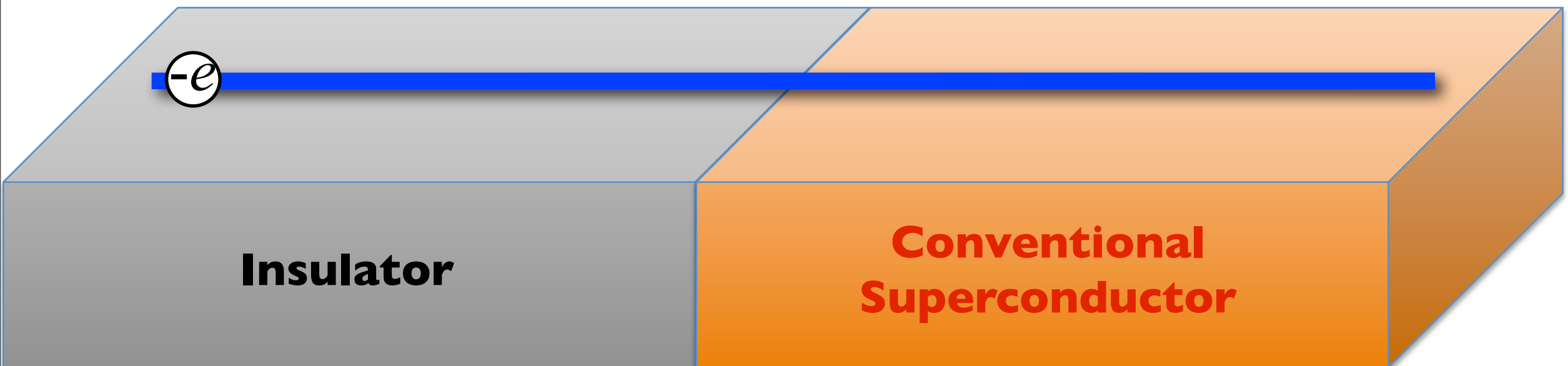
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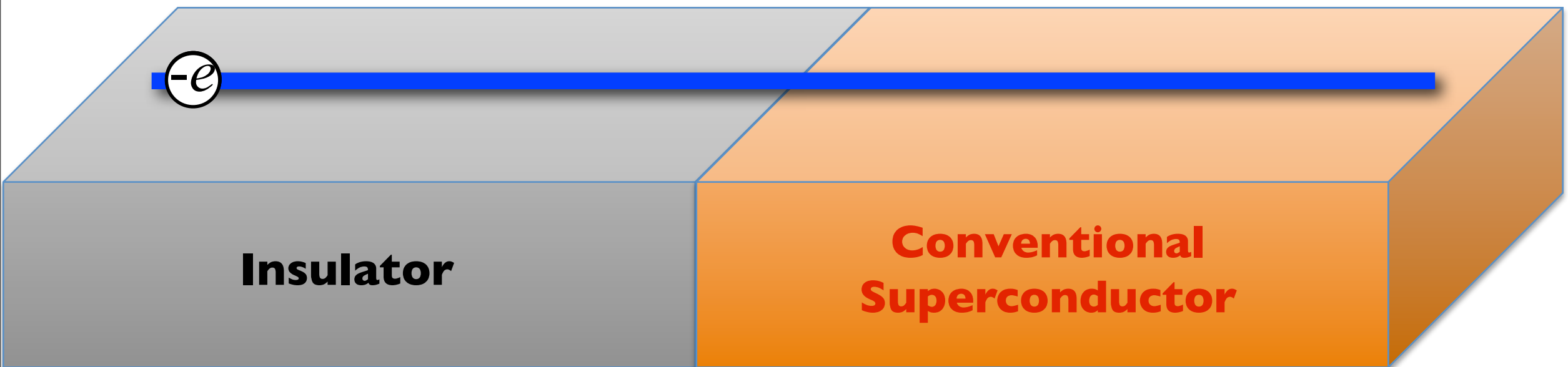
Detection via transport

Normal reflection



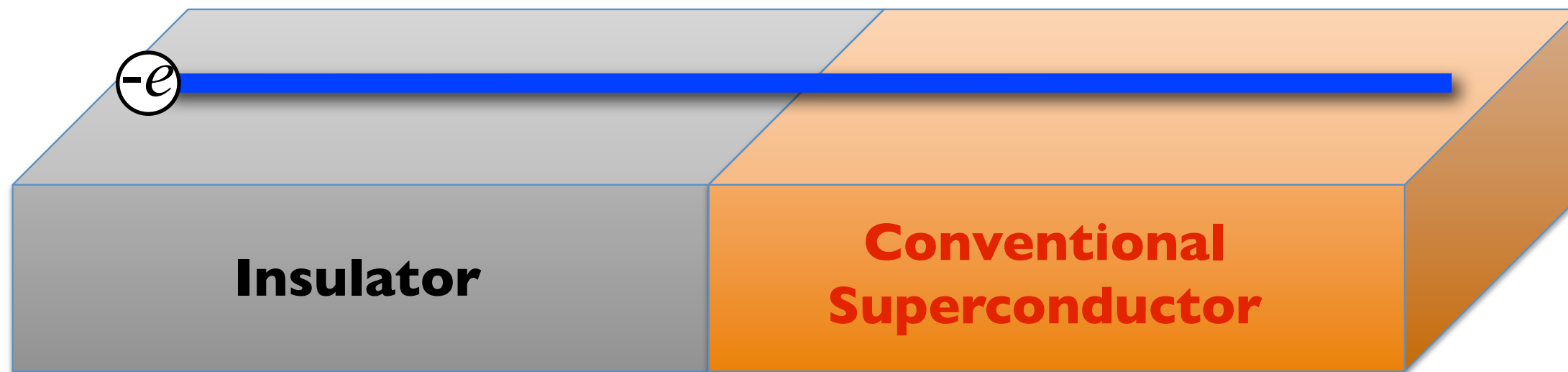
Detection via transport

Andreev reflection

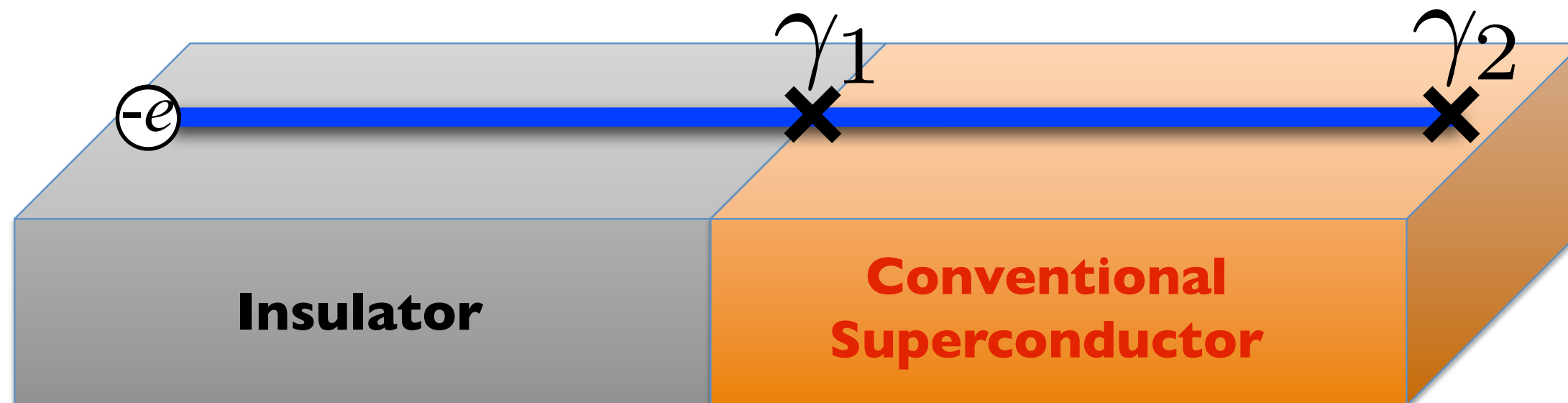


Detection via transport

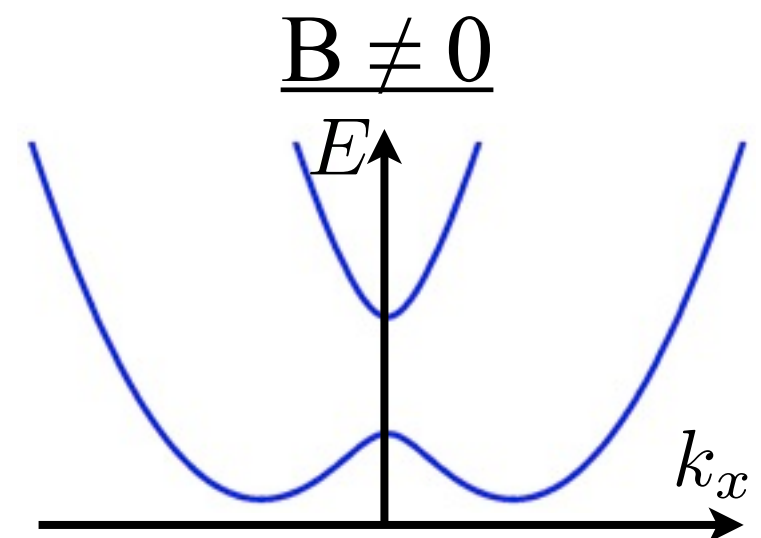
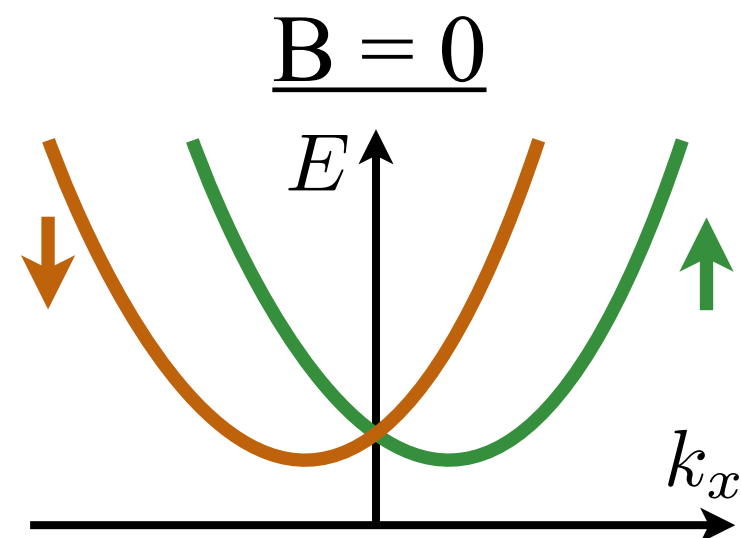
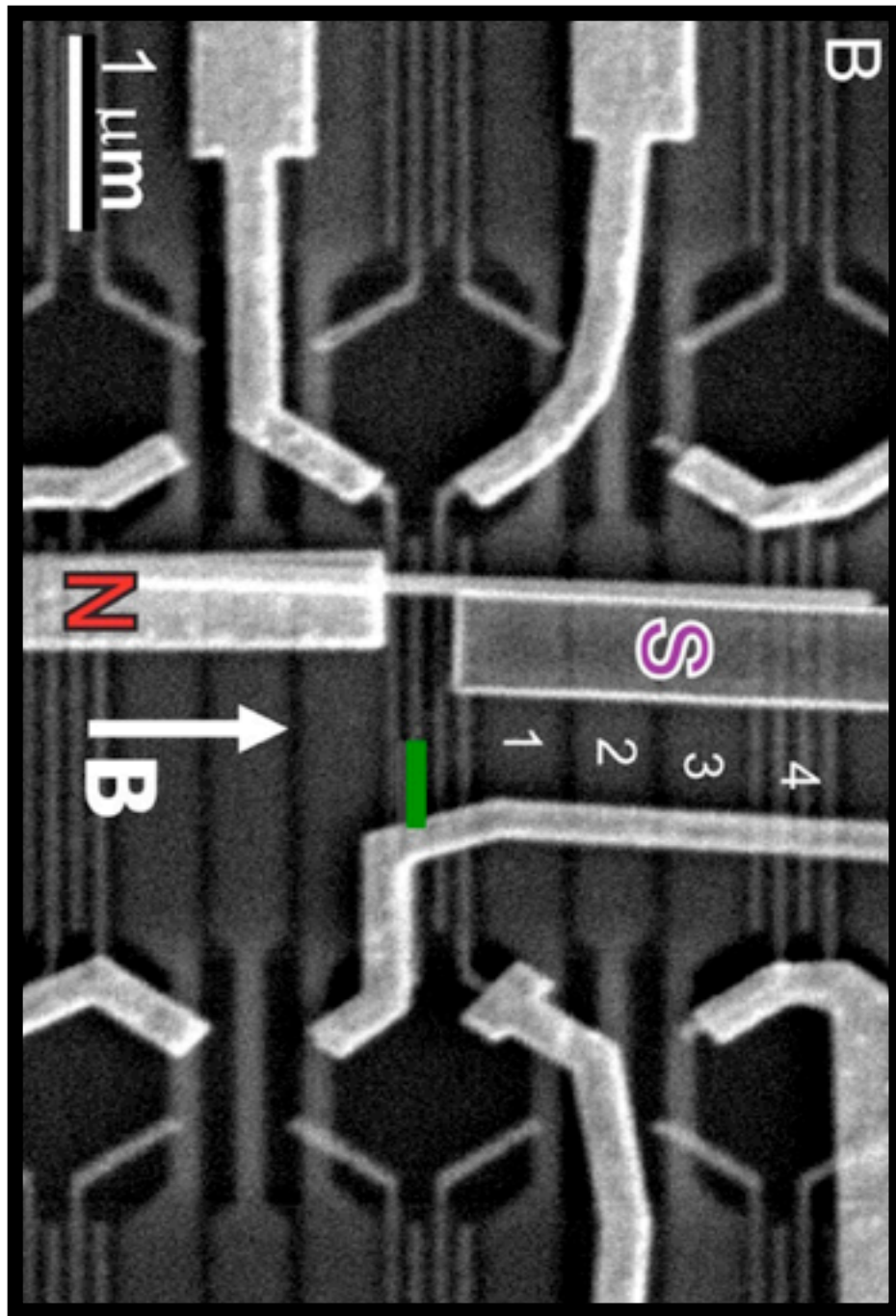
No Majoranas \Rightarrow Perfect normal reflection $\Rightarrow G = 0$



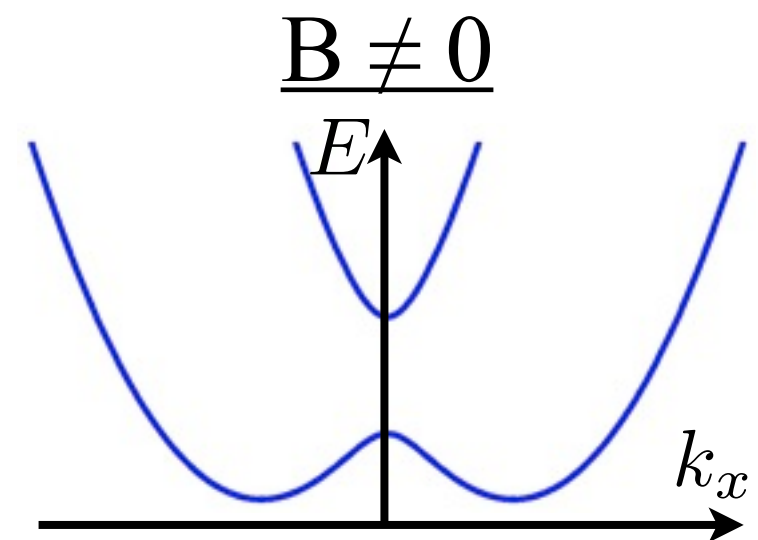
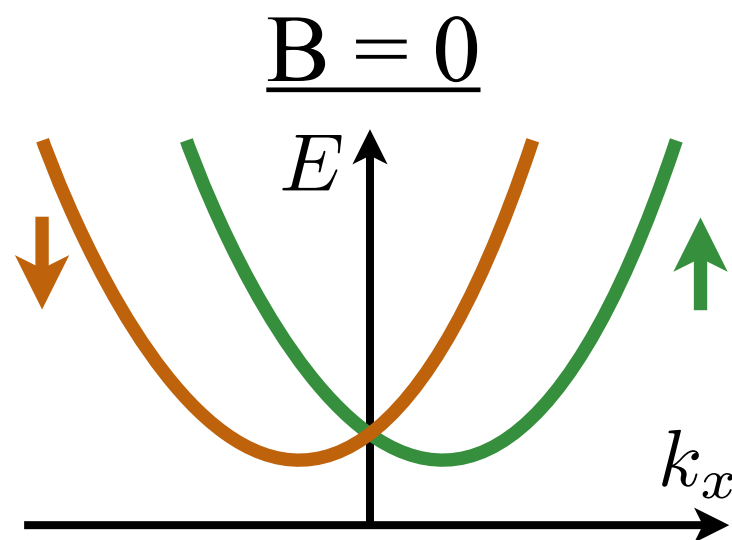
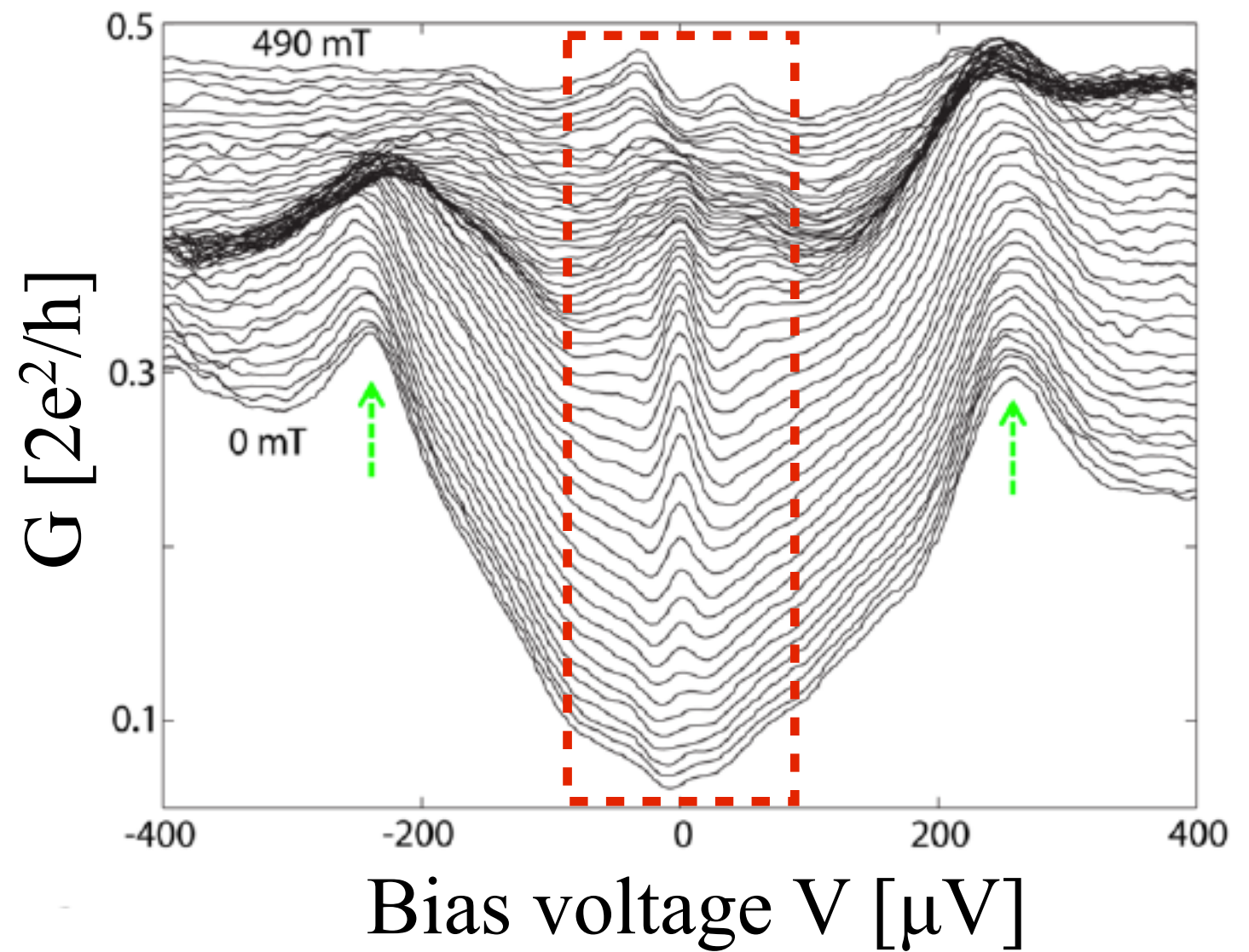
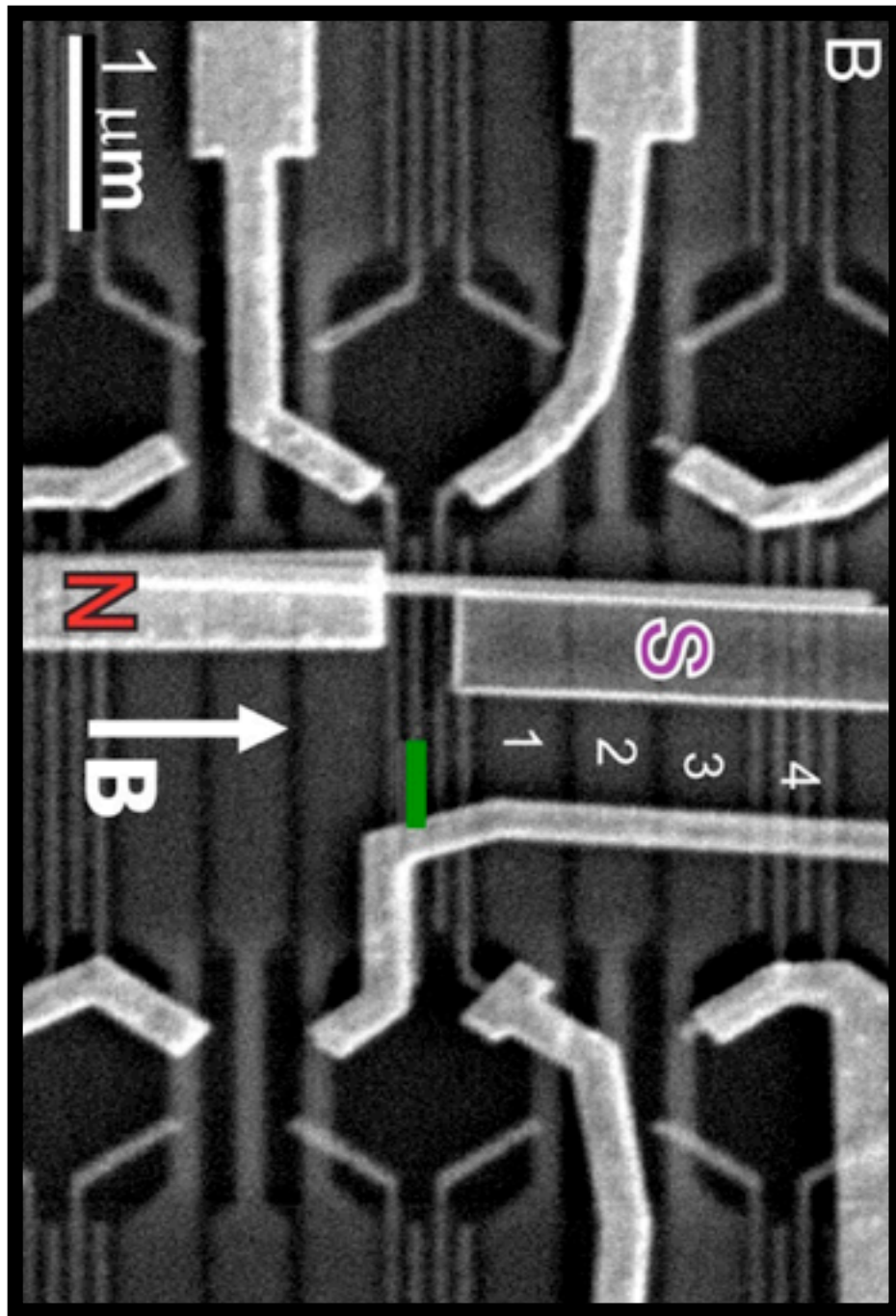
With Majoranas \Rightarrow Perfect Andreev reflection $\Rightarrow G = 2e^2/h$



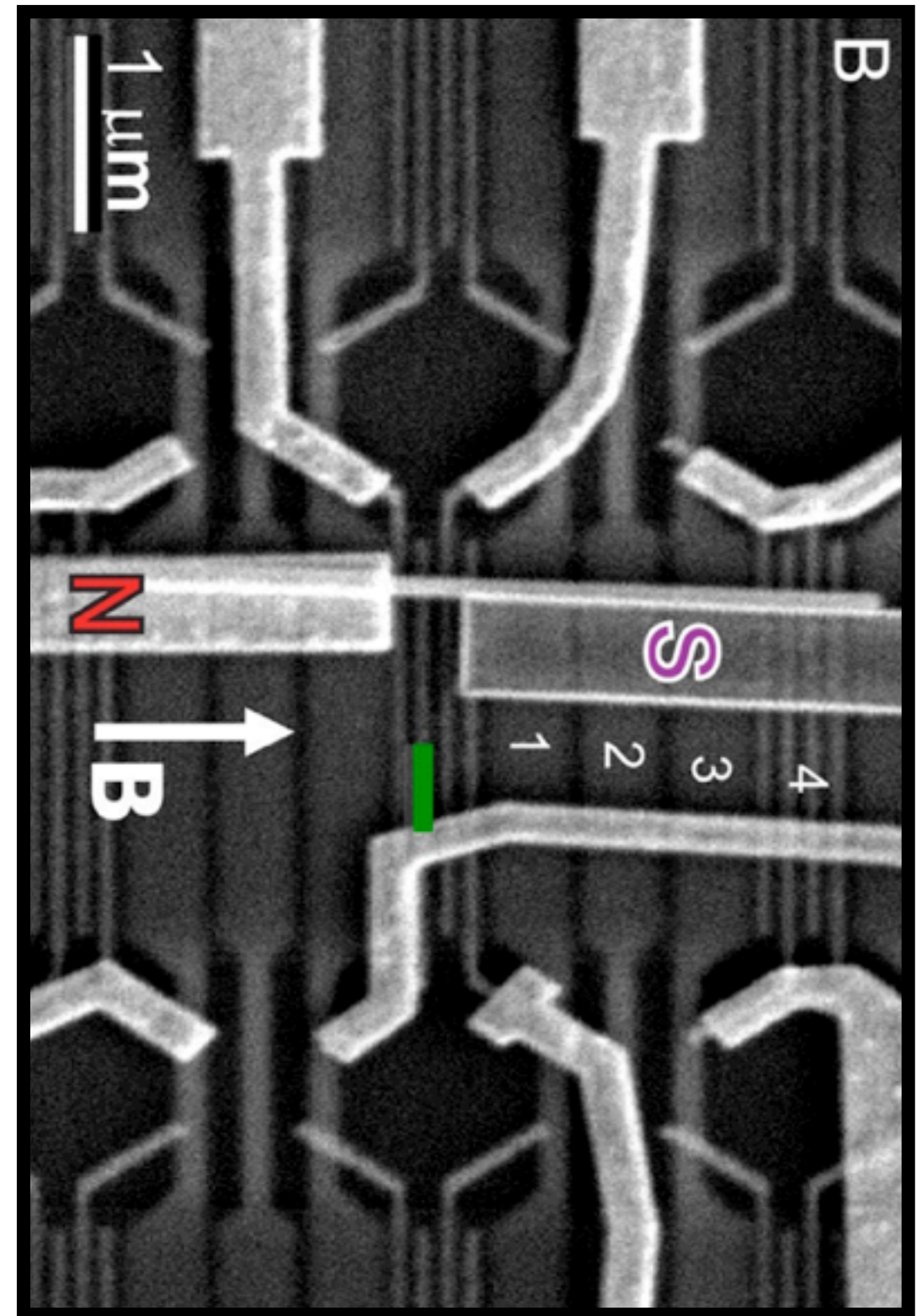
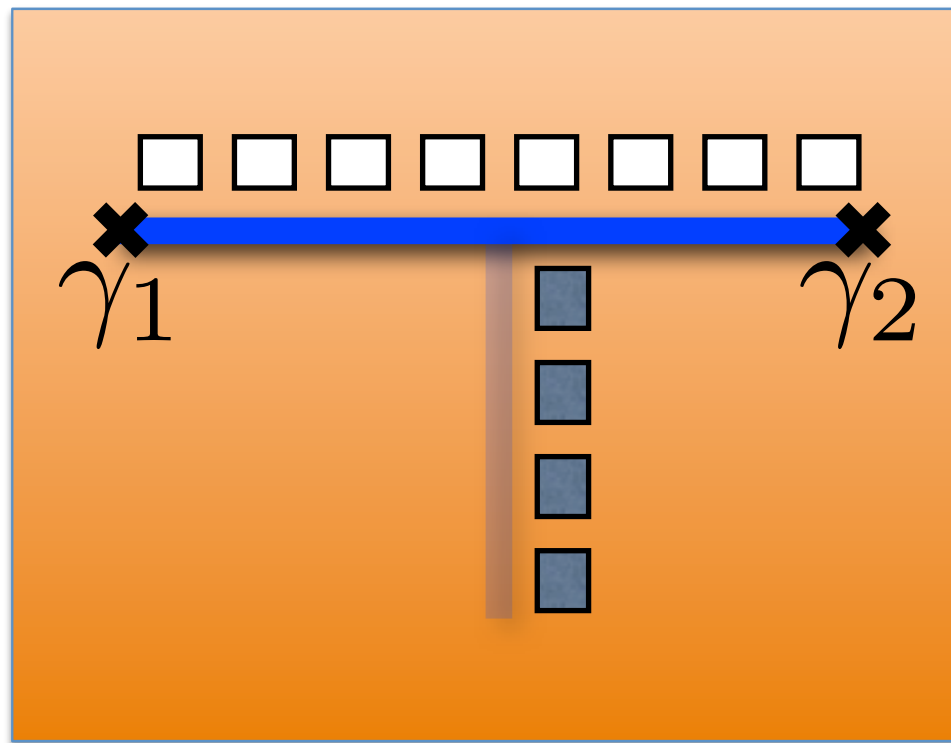
Experimental results



Experimental results



Braiding on the horizon?

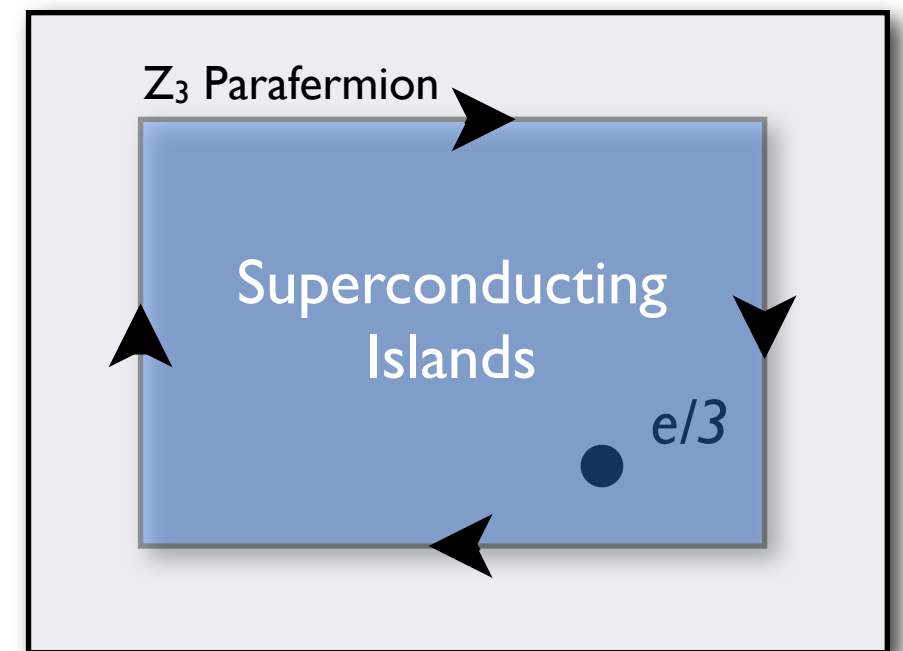




“More is different”...
...even at the **macroscale**

Topological insulators
Non-Abelian anyons
Majorana fermions
Parafermions
Fibonacci

can be “engineered” by
combining simple ingredients



Mong, Clarke, JA, Lindner, Fendley, Nayak, Oreg,
Stern, Berg, Shtengel, Fisher, arXiv:1307.4403

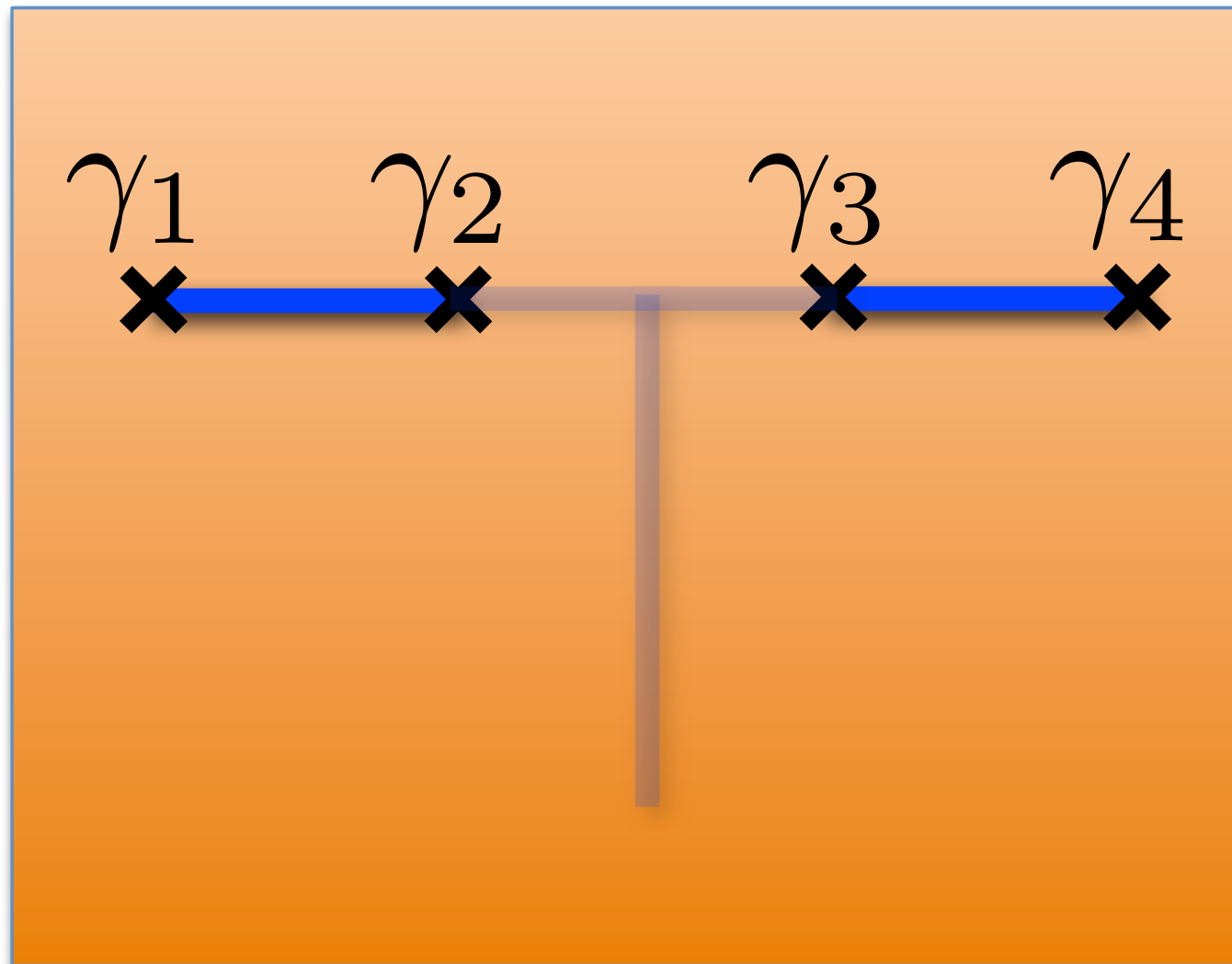
Thanks for your attention!

**Recent
reviews:**

1. Beenakker, Annual Review of
Condensed Matter Physics **4**,
113 (2013)

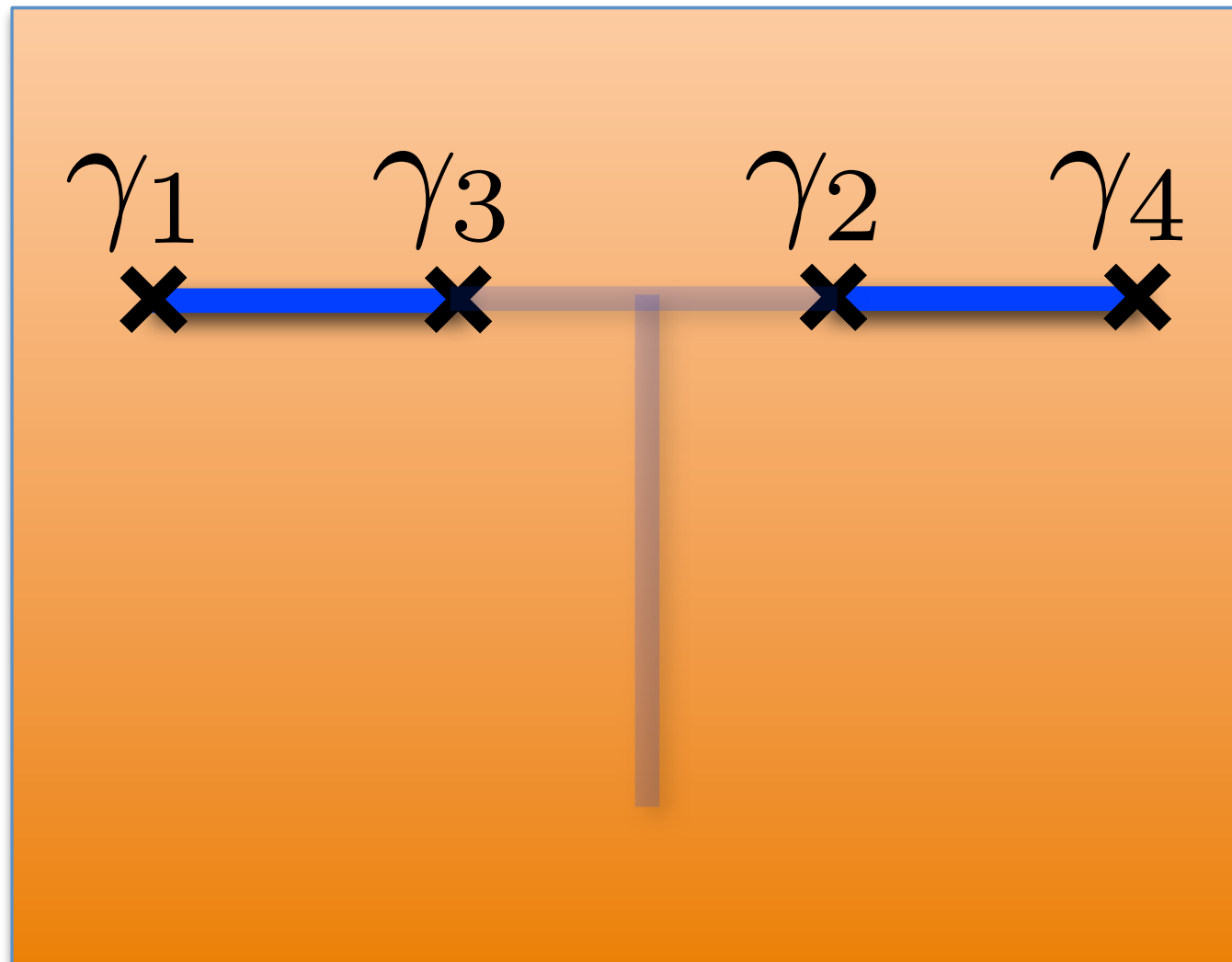
2. Alicea, Reports on Progress
in Physics **75**, 076501 (2012)

Confirming non-Abelian statistics



1. Nucleate Majoranas from the vacuum
2. Check that fusing pairs you created returns the ground state
3. Exchange Majoranas

Confirming non-Abelian statistics



5. Can detect excitation using Josephson measurements

1. Nucleate Majoranas from the vacuum

2. Check that fusing pairs you created returns the ground state

3. Exchange Majoranas

4. Fusing pairs in same way as in 2 should now yield excited state with 50% probability