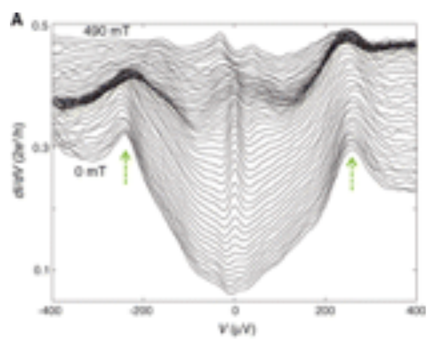
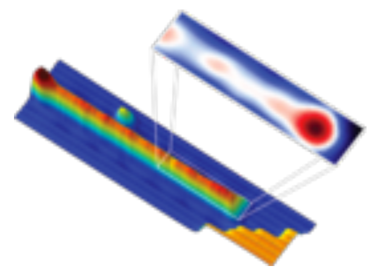
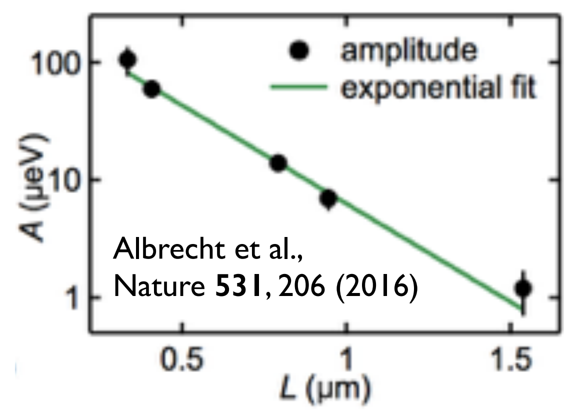
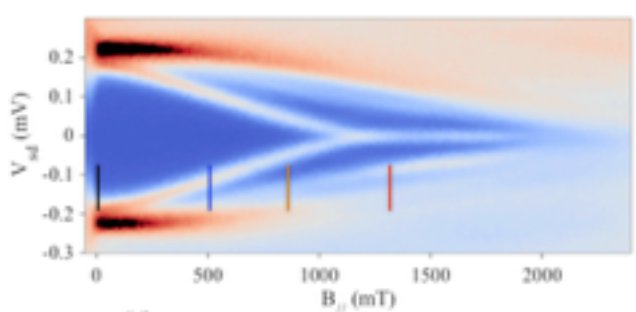
Milestones toward Majorana-based quantum computing

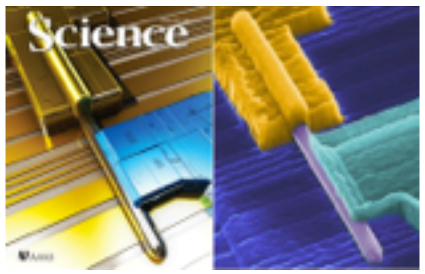


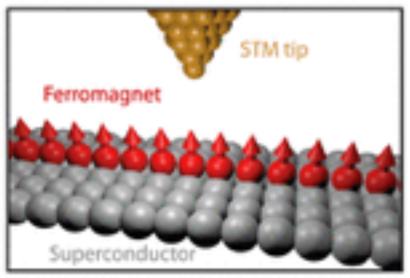


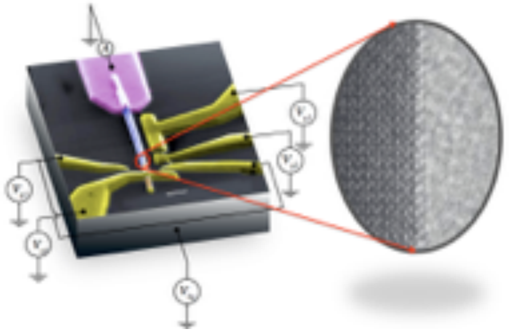


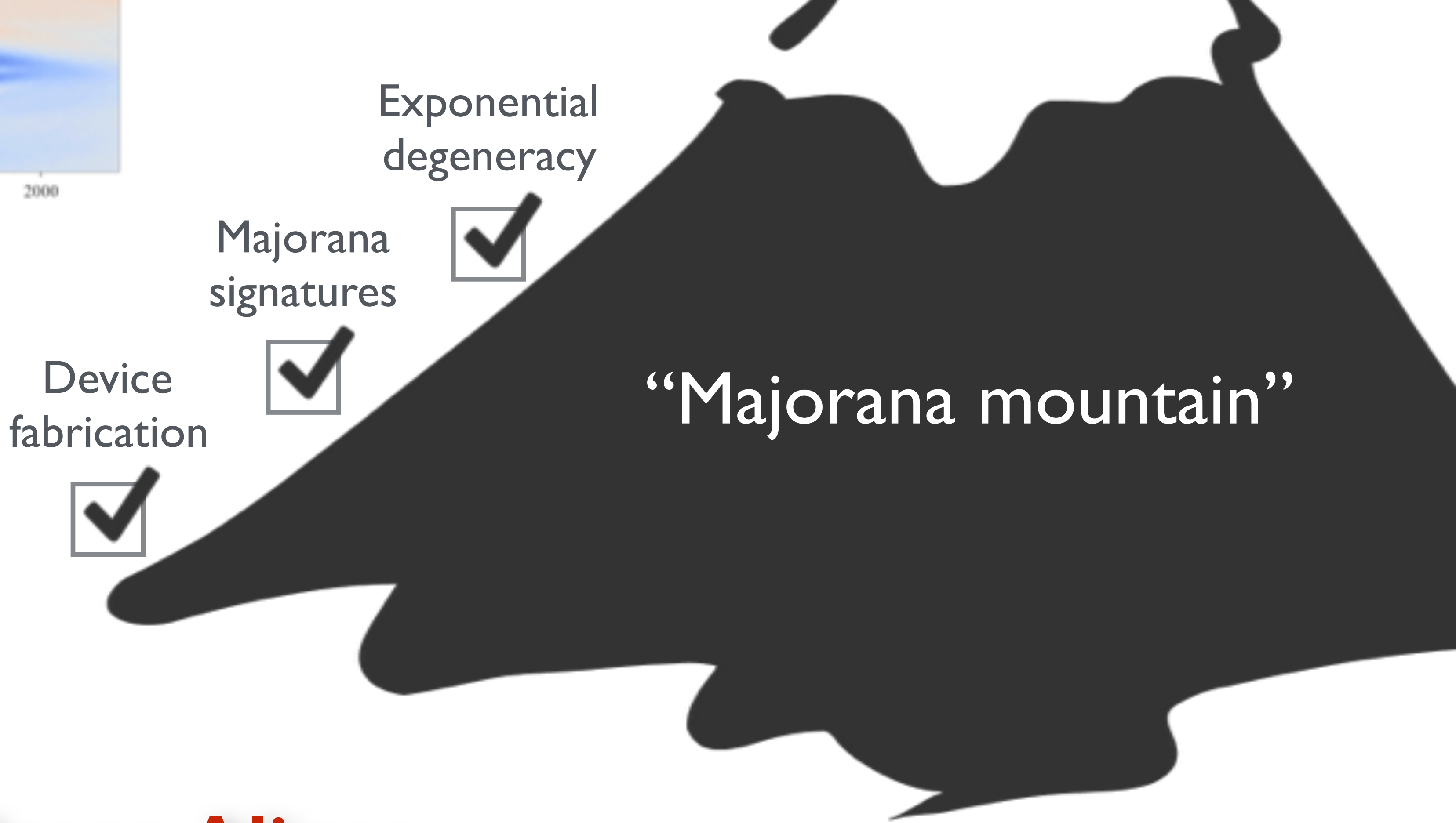
Majorana-based quantum computing







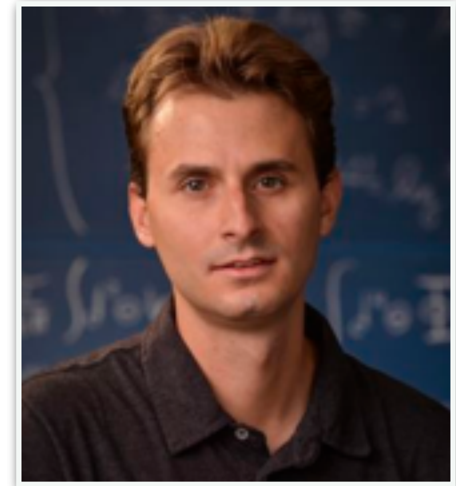




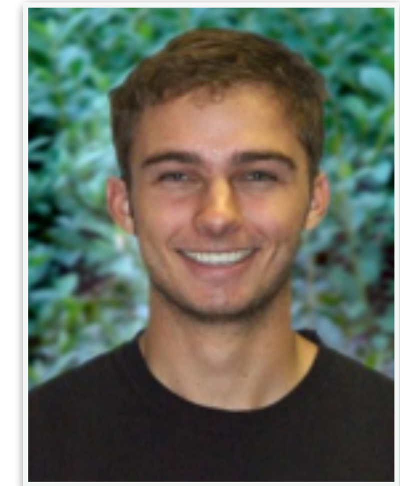
Jason Alicea
(Caltech, IQIM, & Walter Burke Institute)

Dave Aasen
(current KITP grad fellow)

Michael Hell



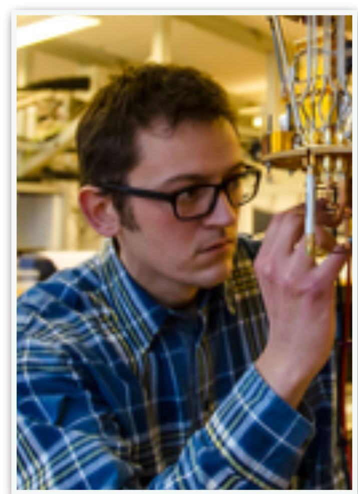
Ryan Mishmash



Andrew Higginbotham

Jeroen Danon

Martin Leijnse



Thomas Jespersen

Josh Folk

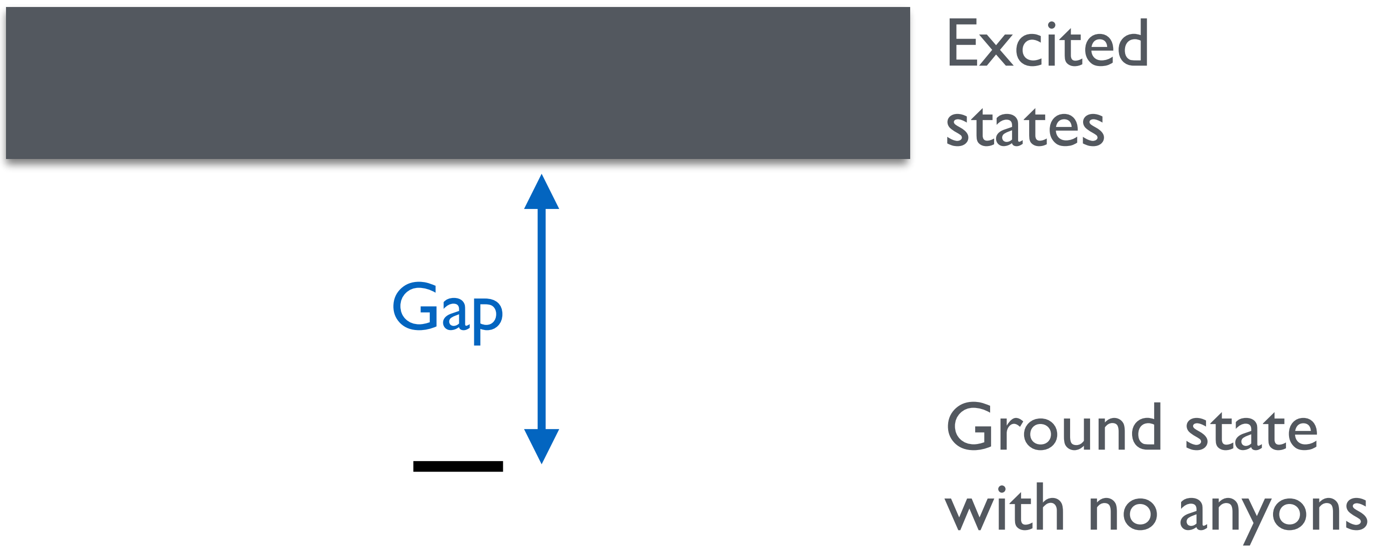
Charlie Marcus

Karsten Flensberg

Physical Review X **6**, 031016 (2016)

NSF
IQIM
INSTITUTE FOR QUANTUM INFORMATION AND MATTER
CALIFORNIA INSTITUTE OF TECHNOLOGY 1891
BURKE INSTITUTE
ALFRED P. SLOAN FOUNDATION 1934

(Ising) non-Abelian anyons



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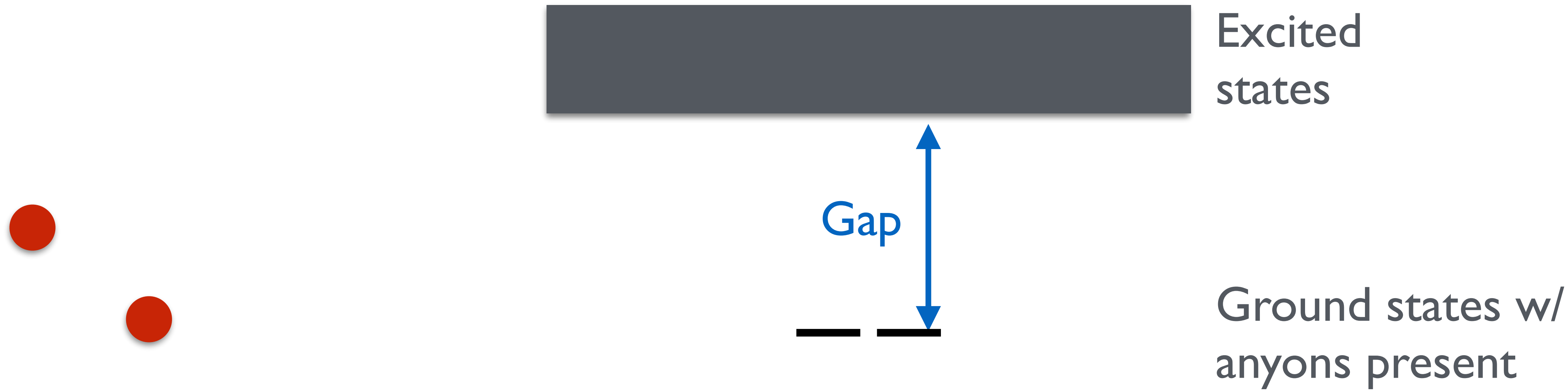

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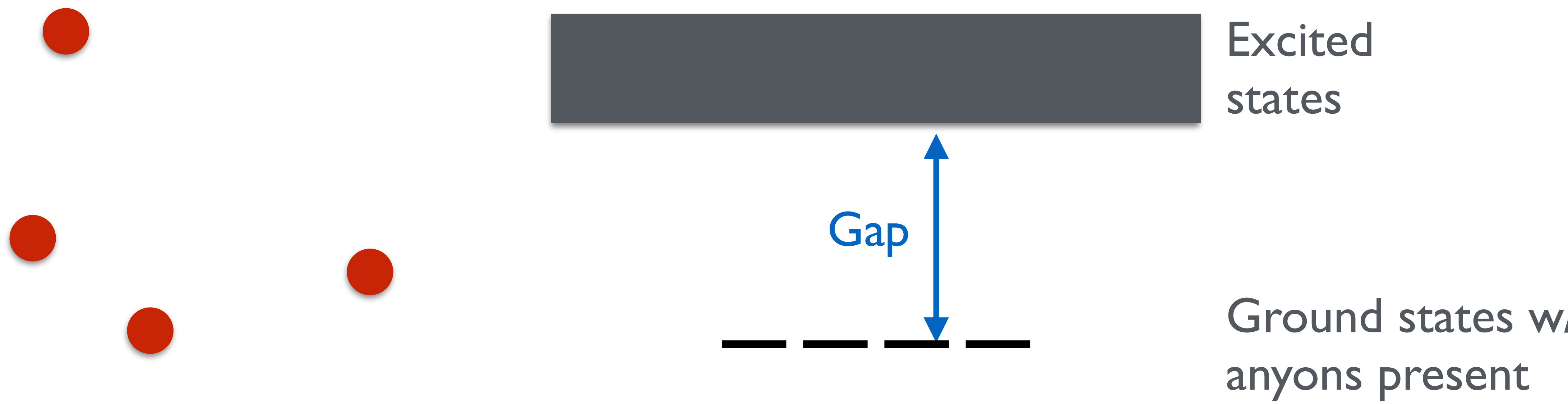

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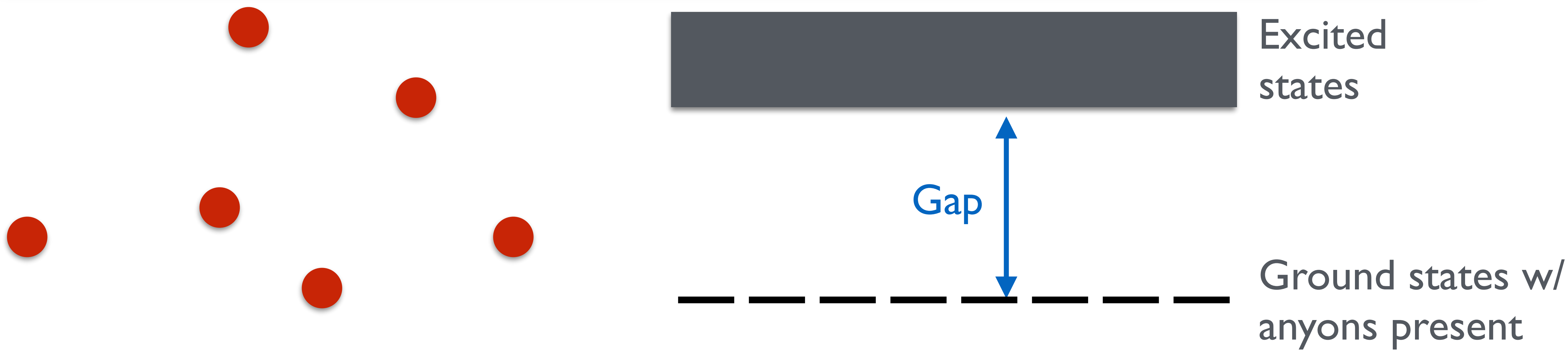

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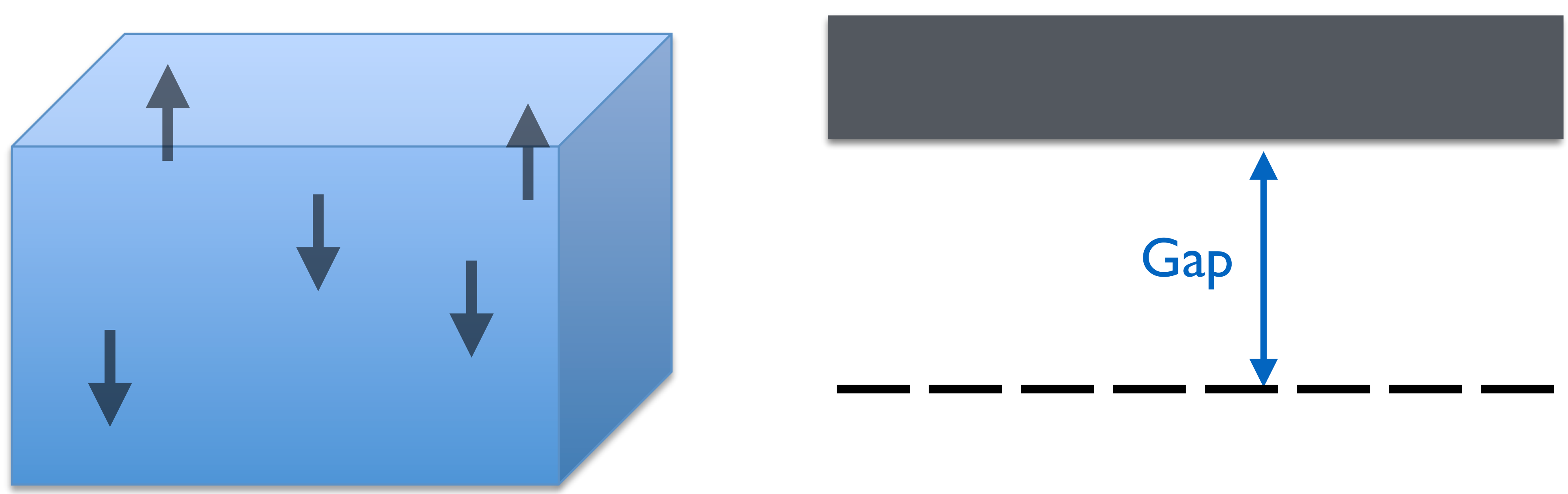
But what about, say, **free spin-1/2's?**



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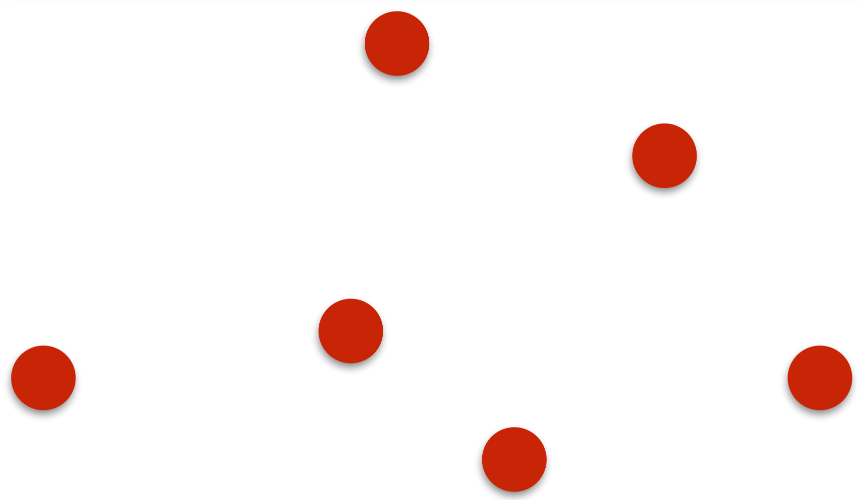

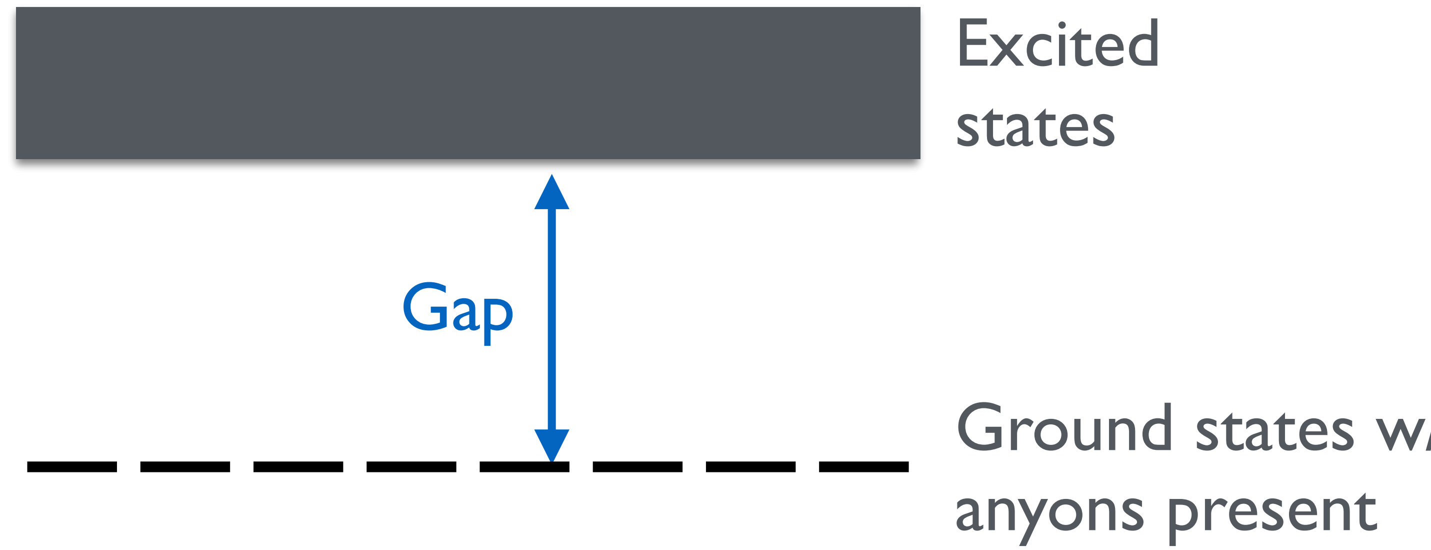

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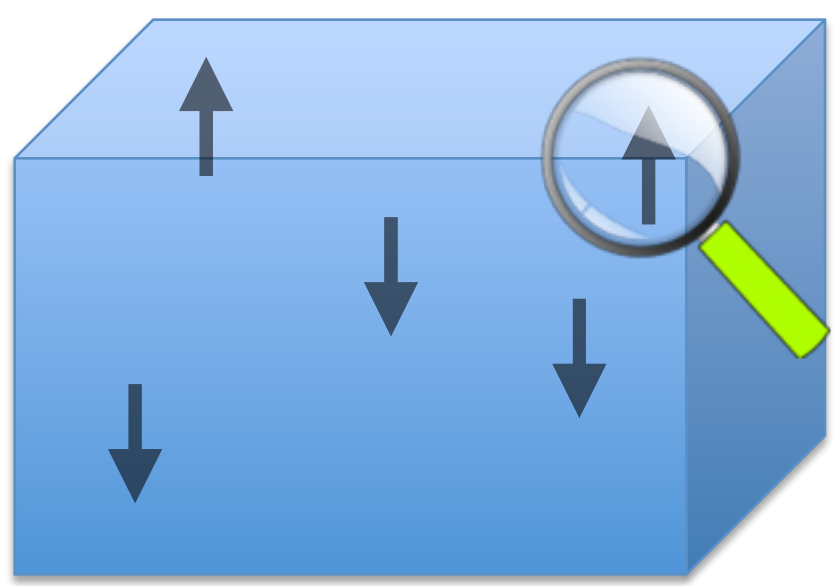

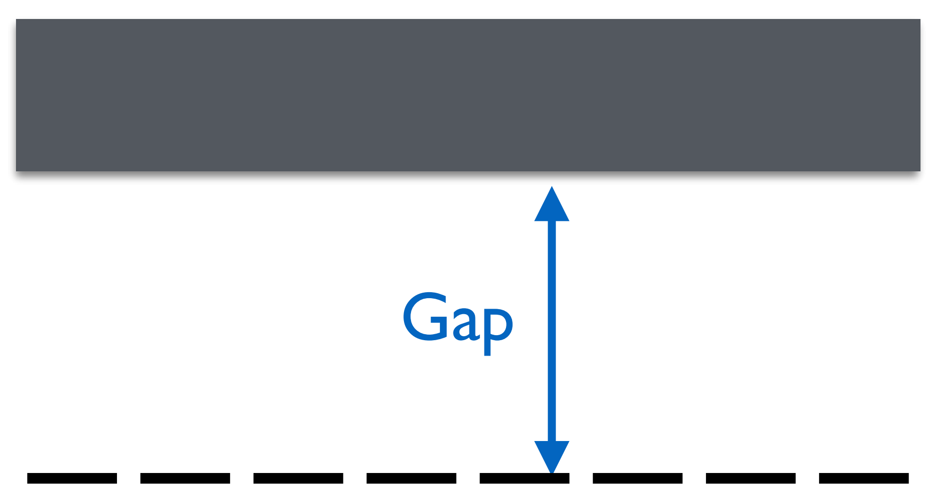

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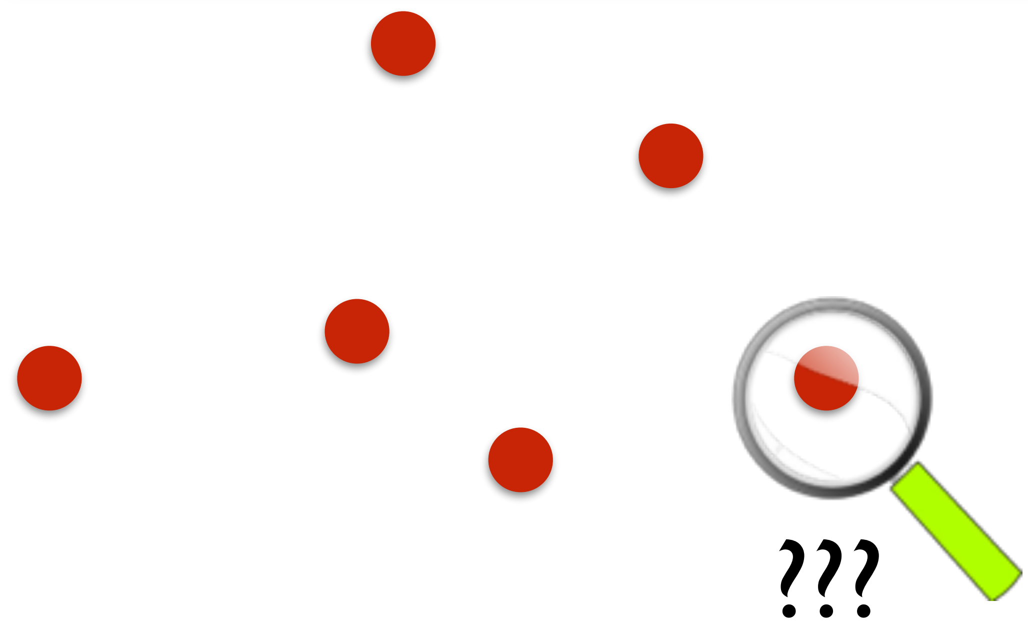

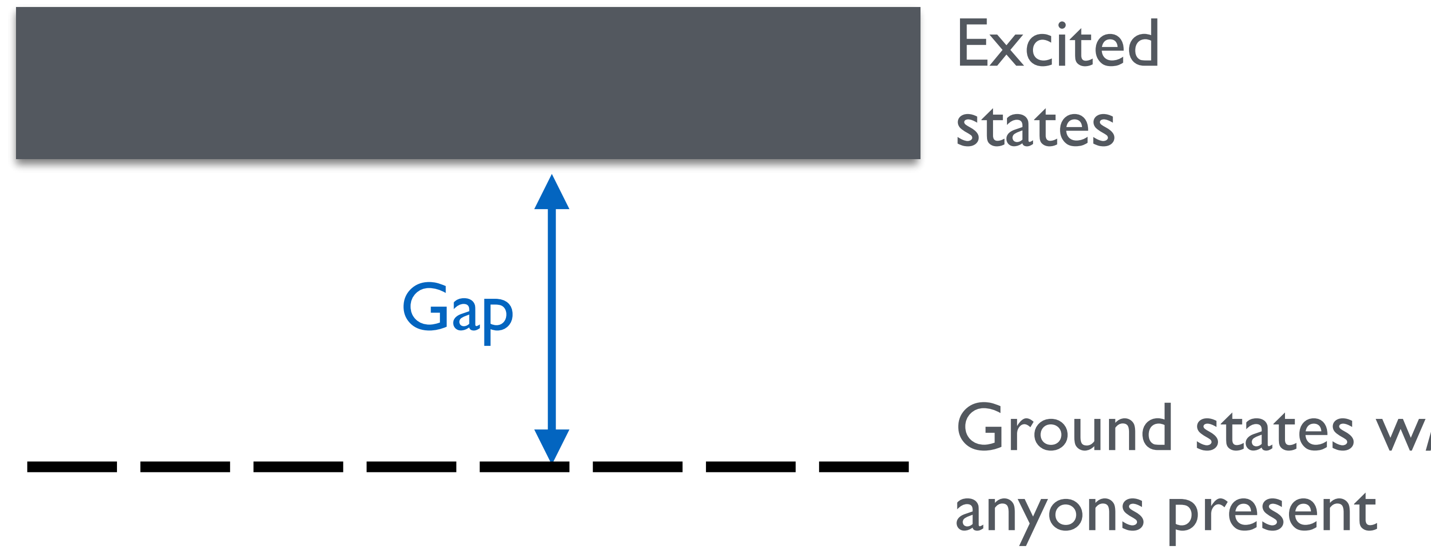

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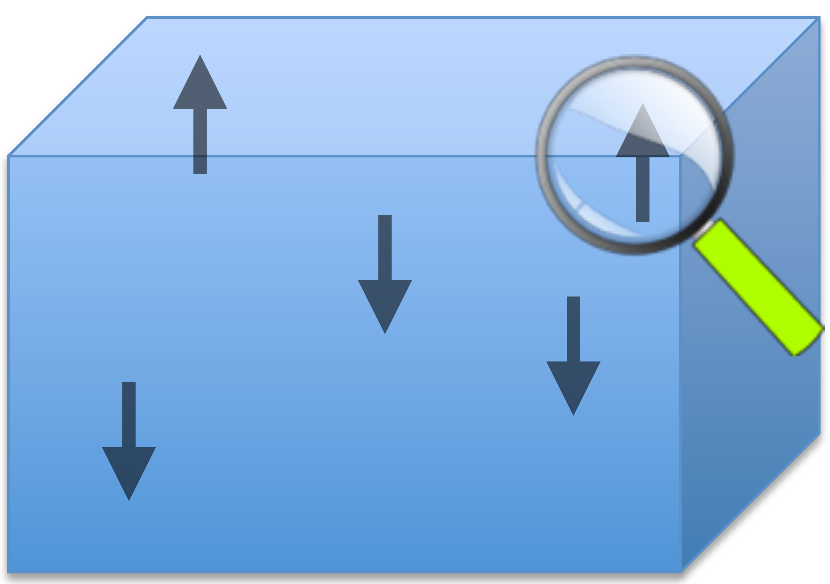

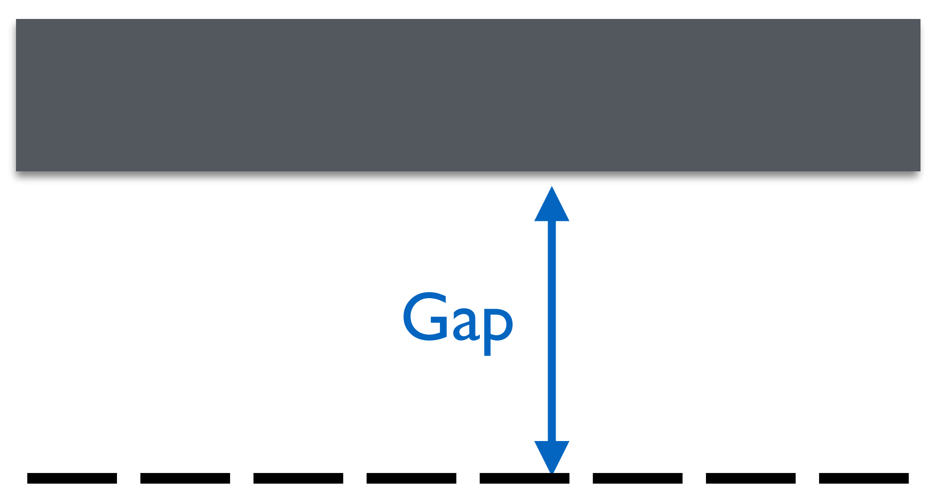

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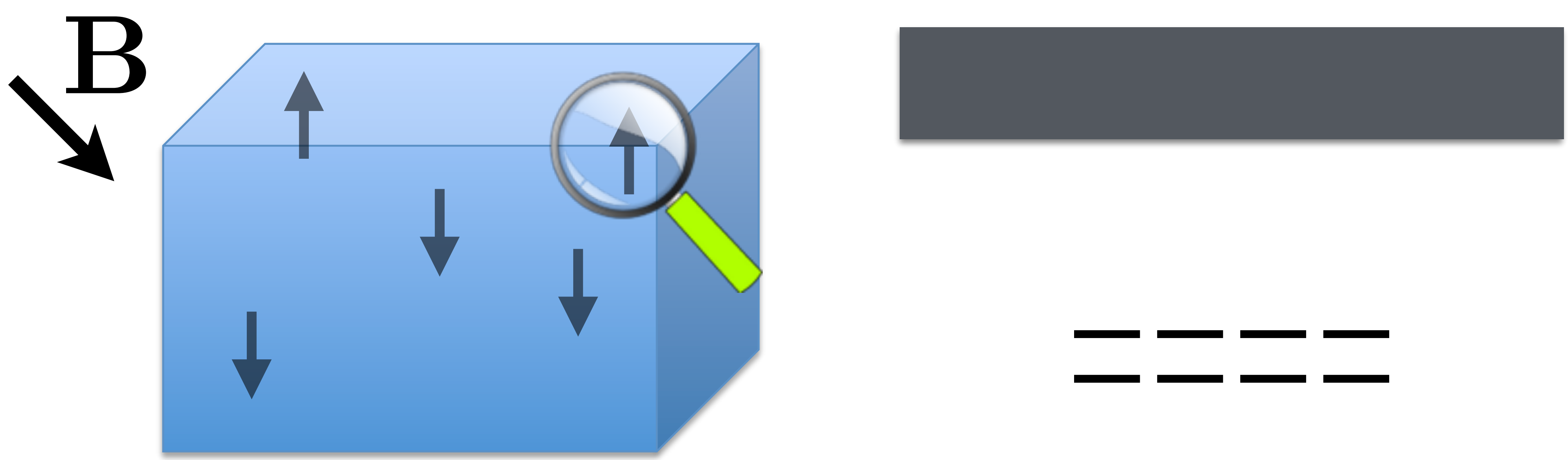

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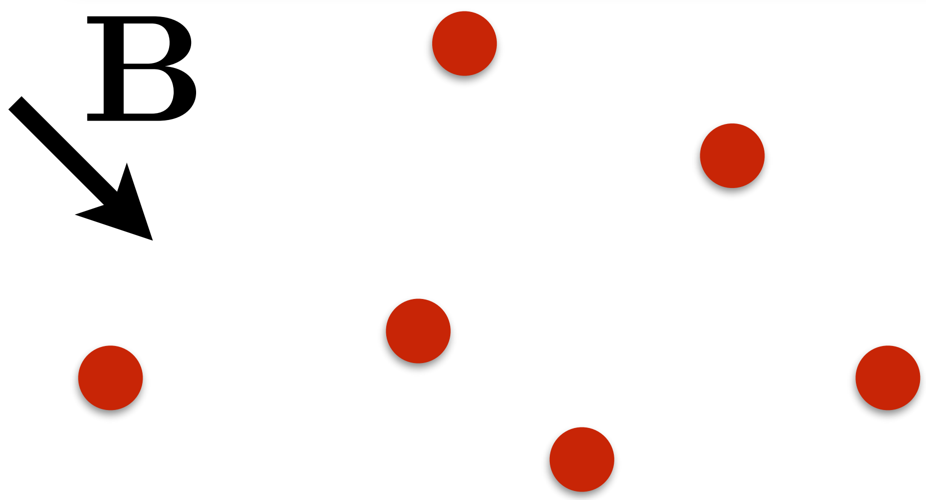

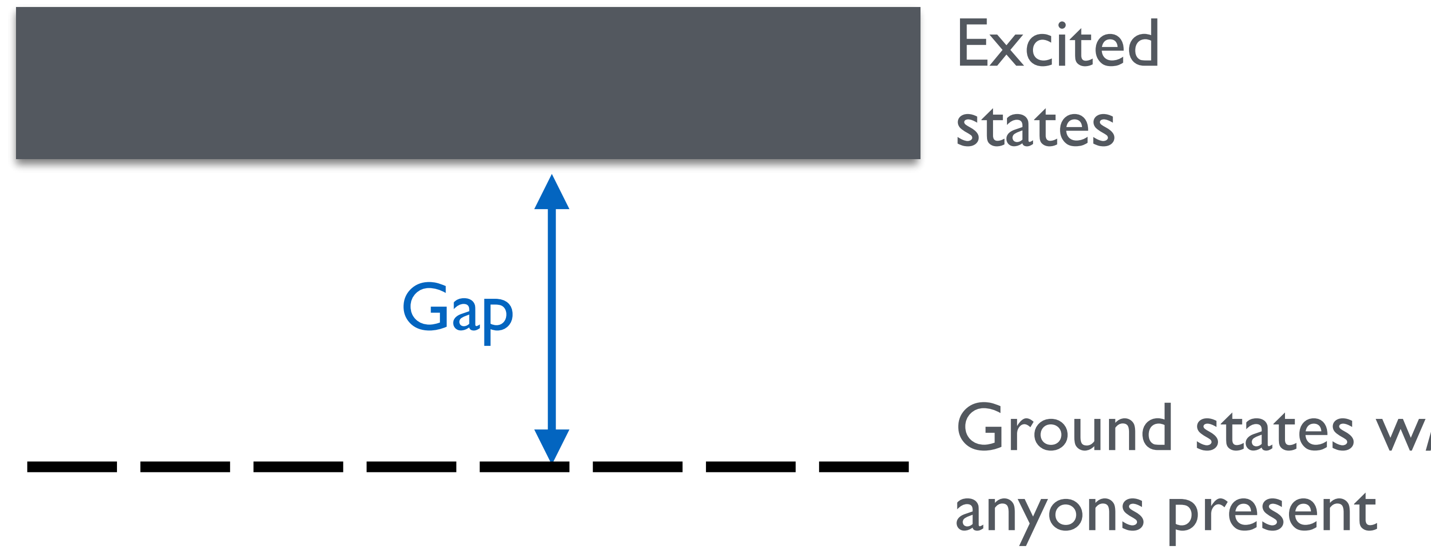

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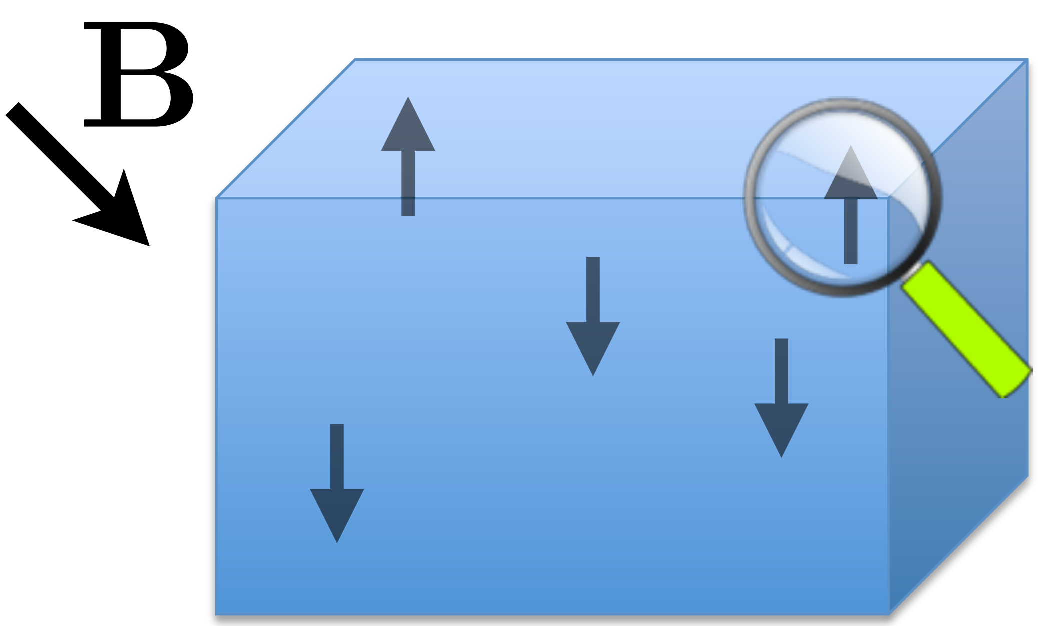

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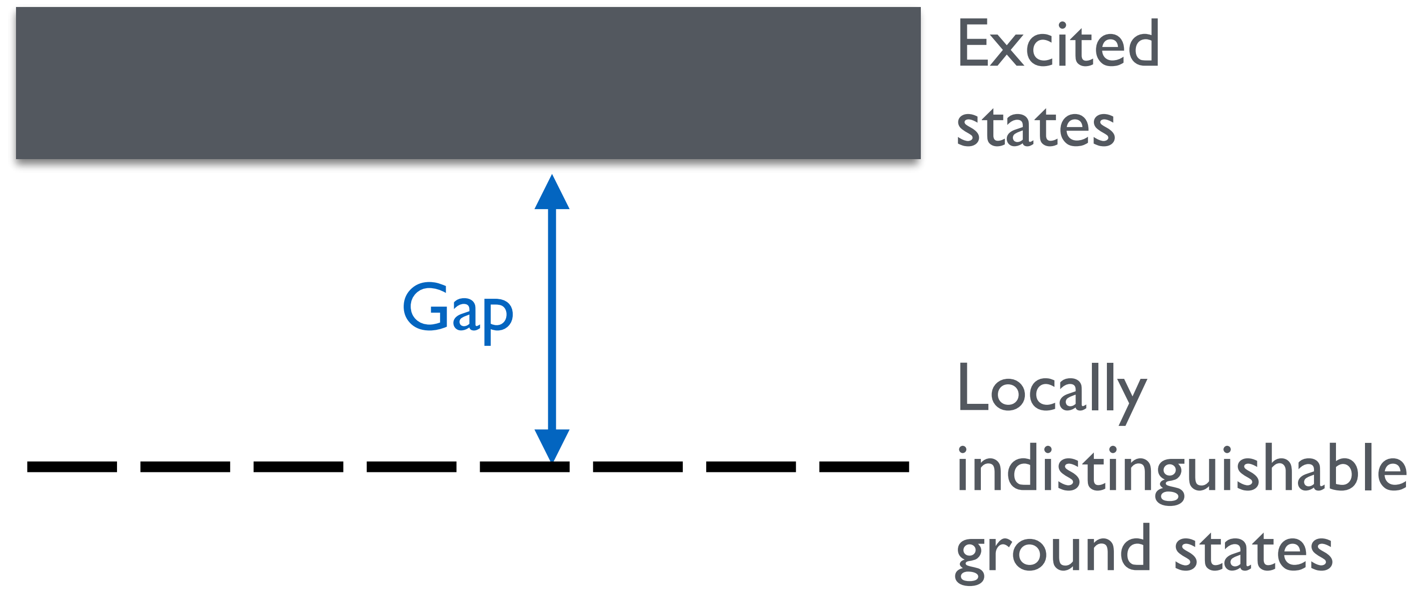

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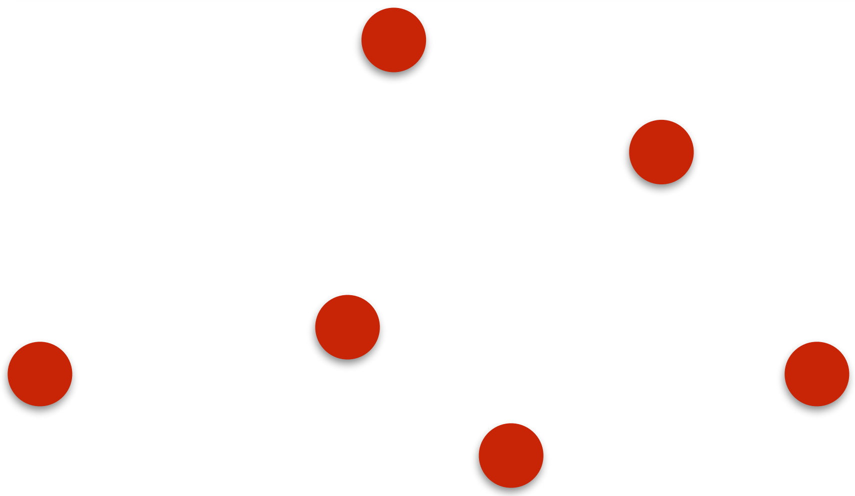
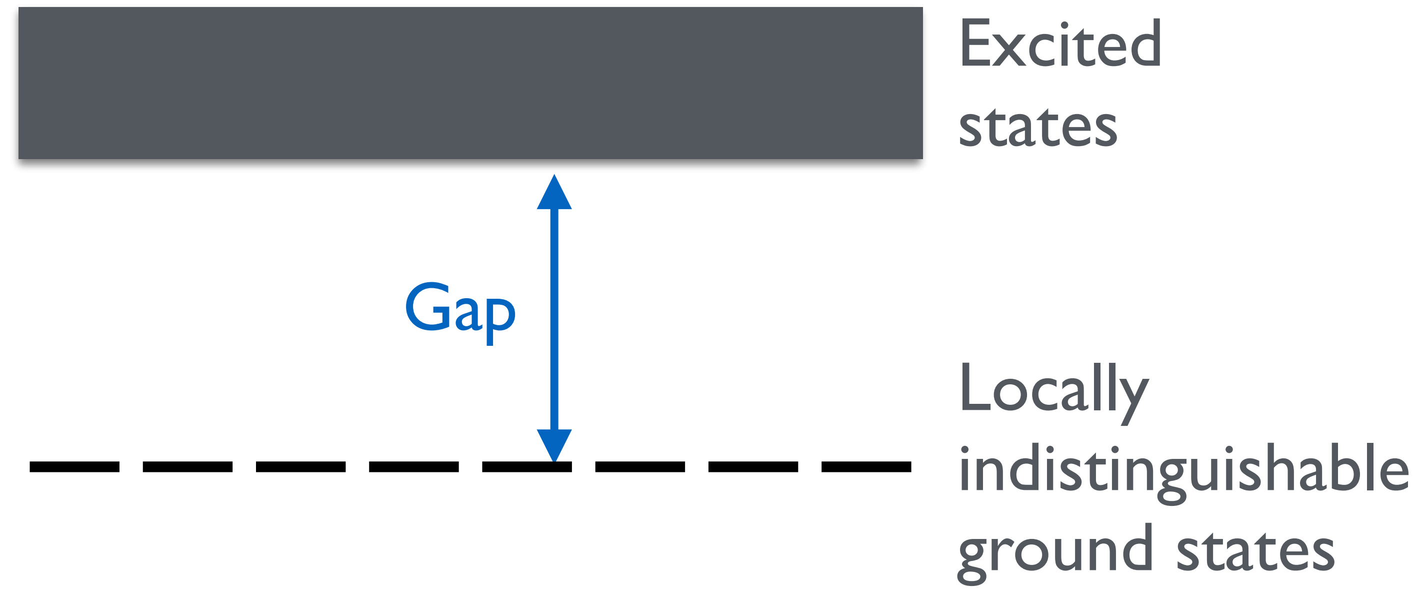
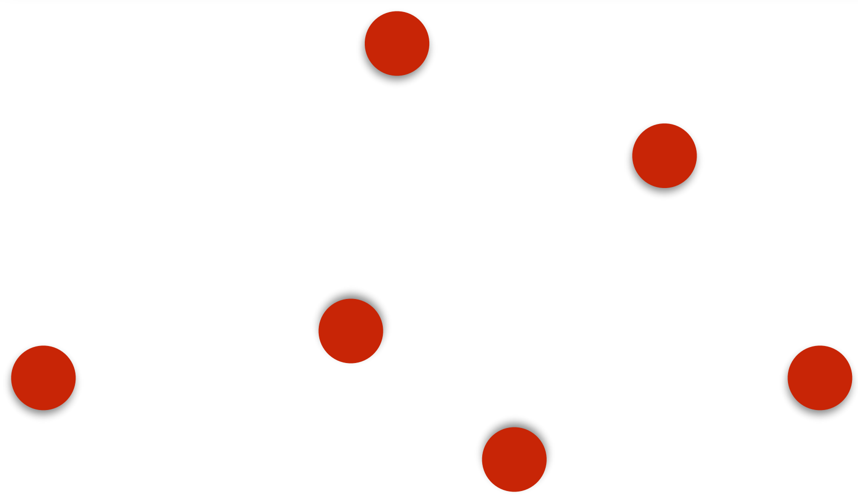
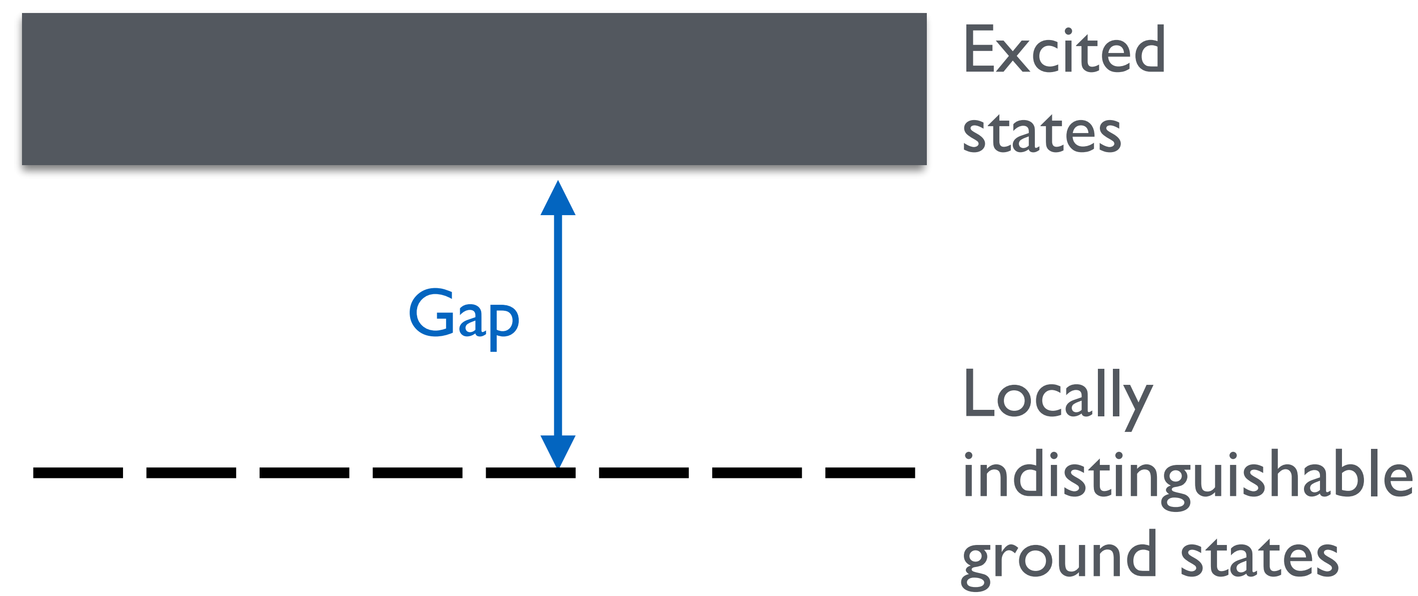




ϕ_i

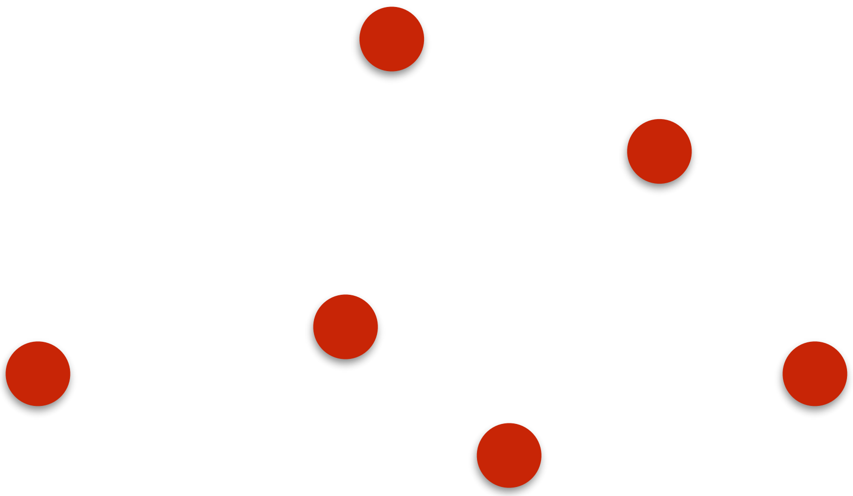
(Ising) non-Abelian anyons

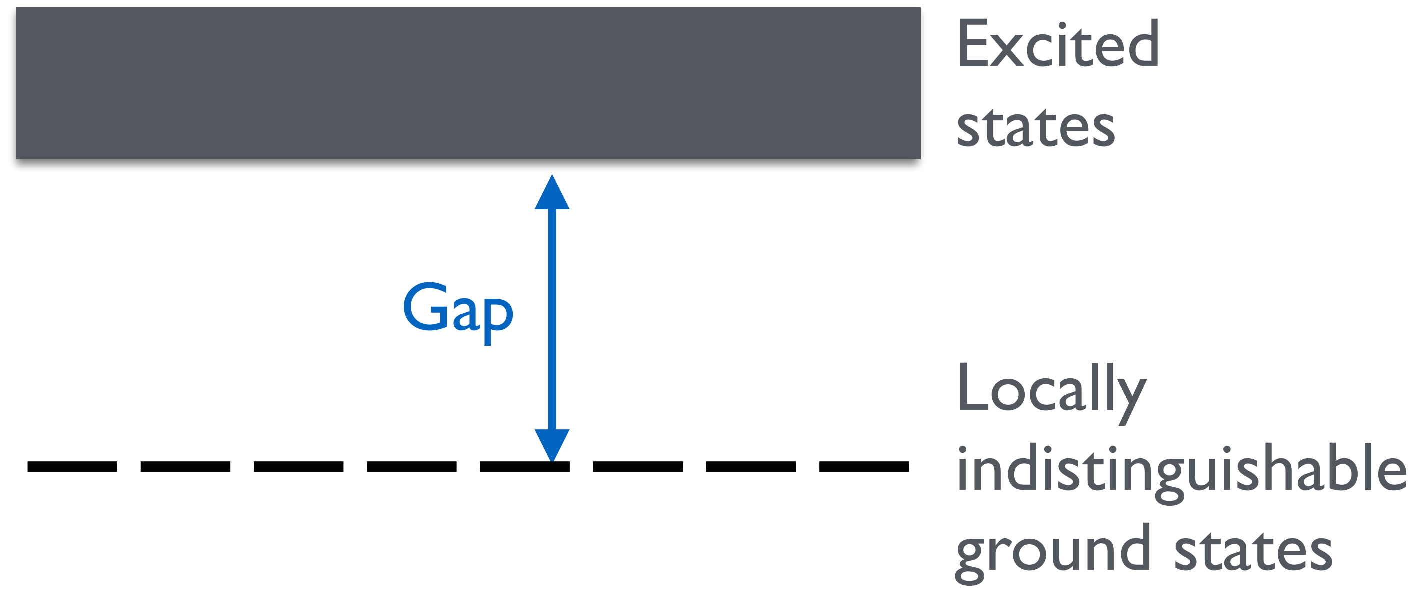




$$\phi_i$$

(Ising) non-Abelian anyons

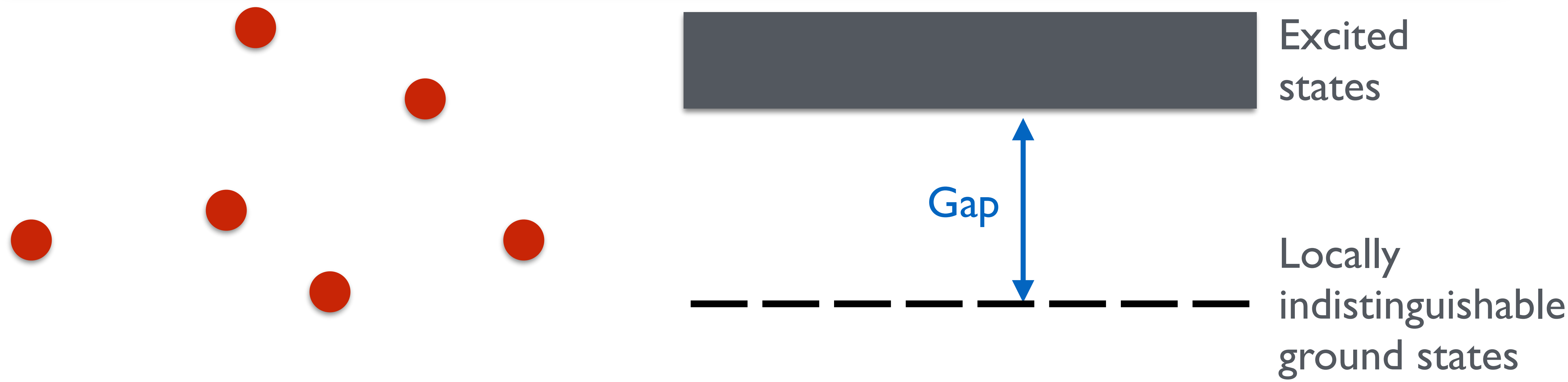




Non-Abelian statistics

$$\phi_i \to U_{ij}\phi_j$$

(Ising) non-Abelian anyons



Non-Abelian statistics

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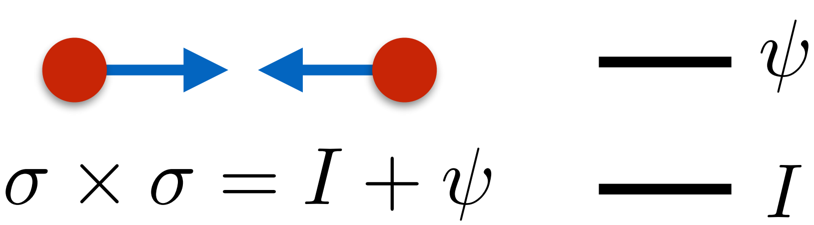
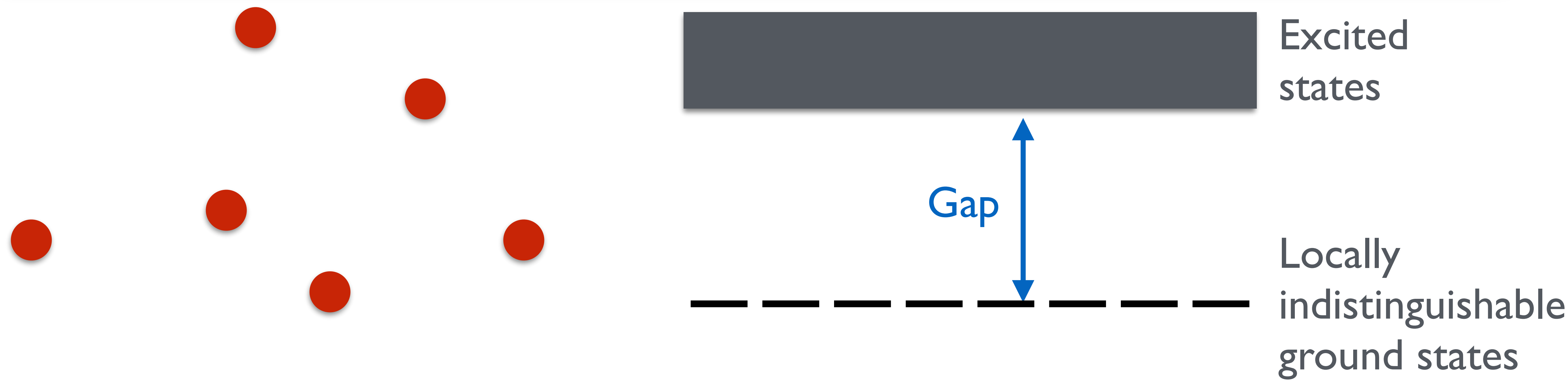
Nontrivial fusion rules



$$\sigma \times \sigma = I + \psi$$

(Ising) non-Abelian anyons



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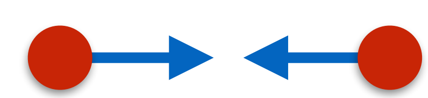

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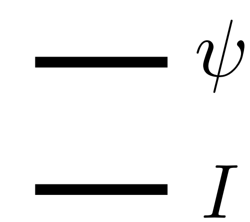

Barkeshli, Bonderson, Cheng, and Wang, arXiv:1410.4540; Rowell and Wang, PRA **93**, 030102(R)

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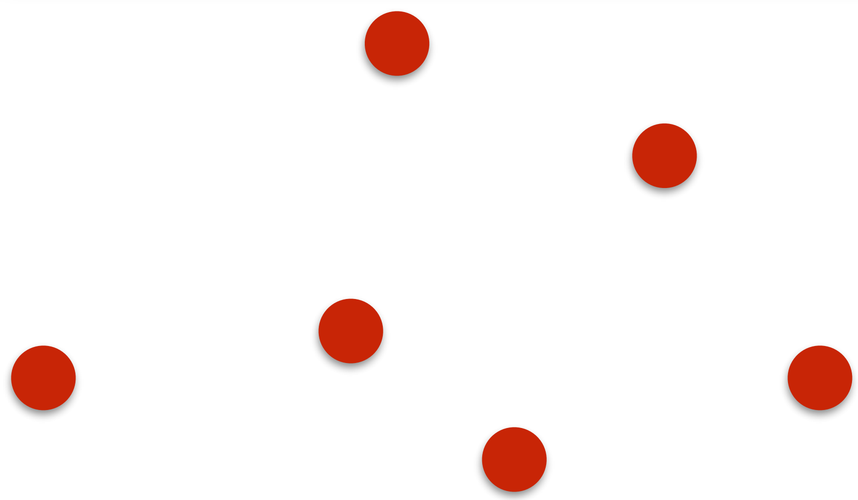

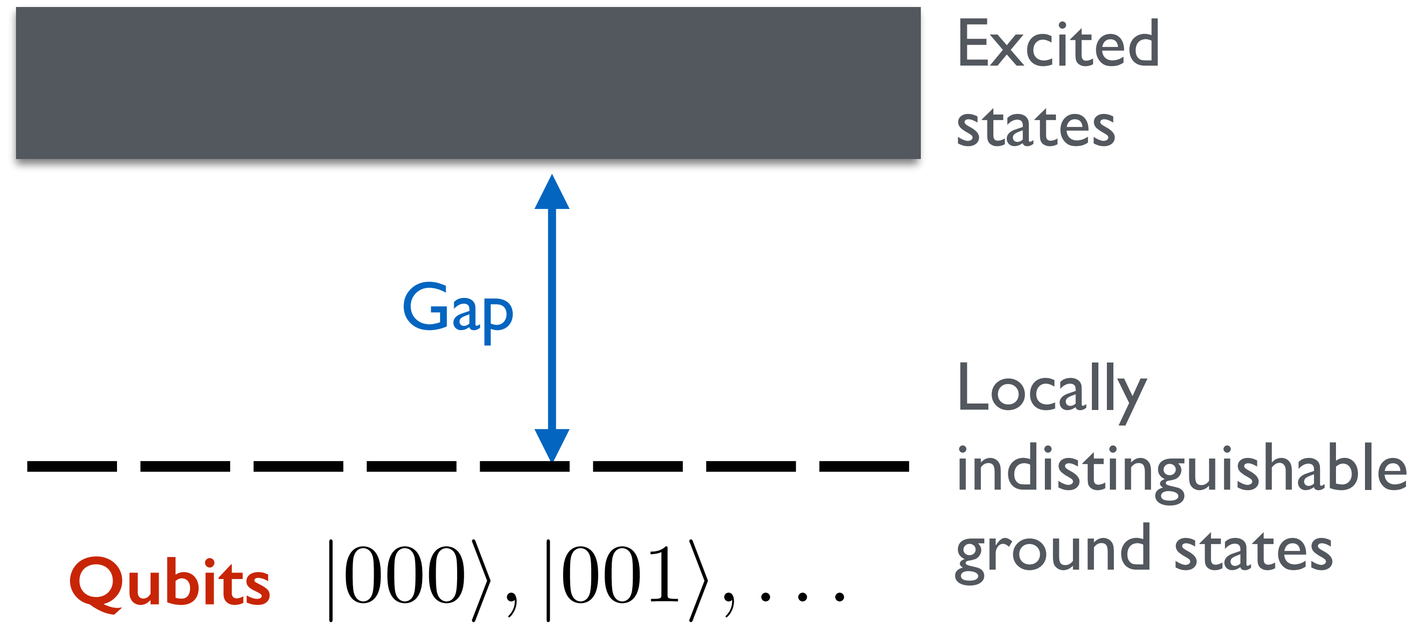

Non-Abelian statistics

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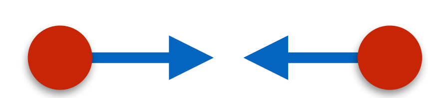
Quantum gates

Nontrivial fusion rules



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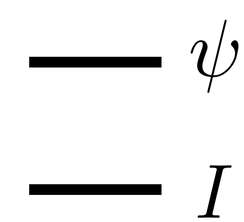
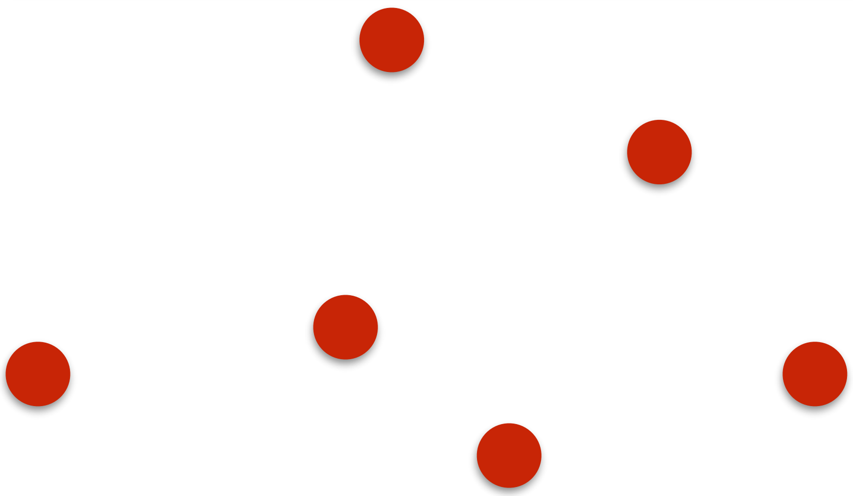


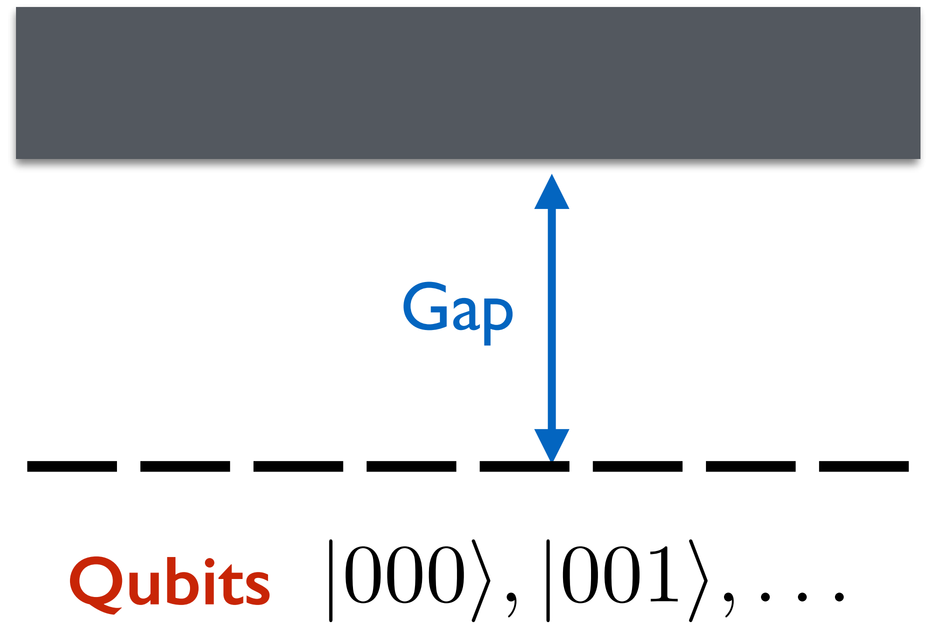
Readout

'$3 million idea': fault-tolerant topological quantum computation!

Alexei Kitaev

(Ising) non-Abelian anyons





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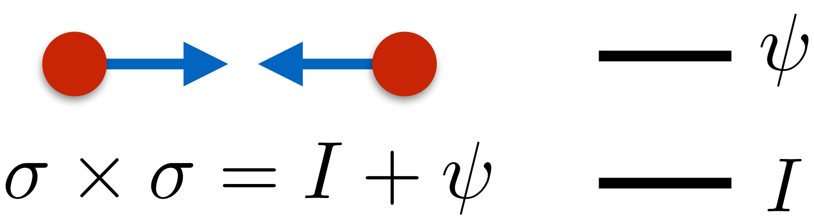

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Readout

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Alexei Kitaev

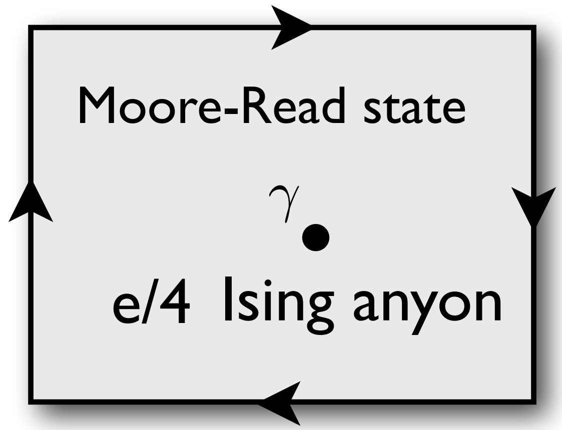
Billion $ question: **how to build the hardware?**

Inception (late 80's)

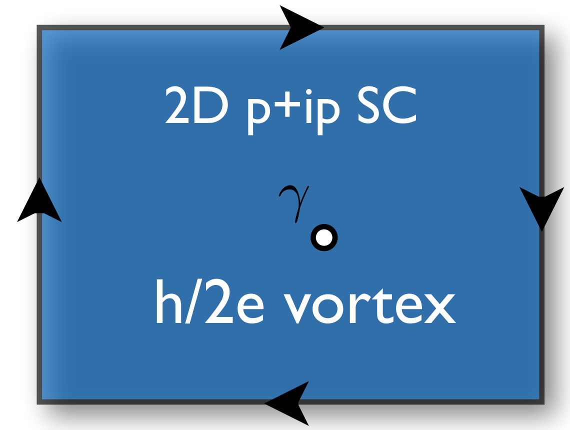
Moore & Seiberg, Witten, …

Inception (late 80's) Moore & Seiberg, Witten, …

Realizations (1991-2000's)



Moore & Read (1991)



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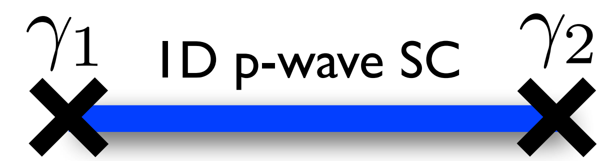

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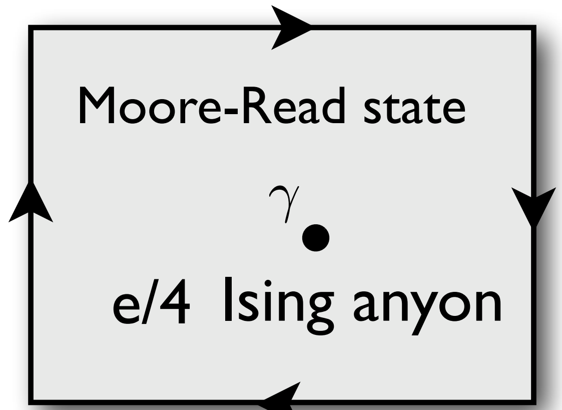

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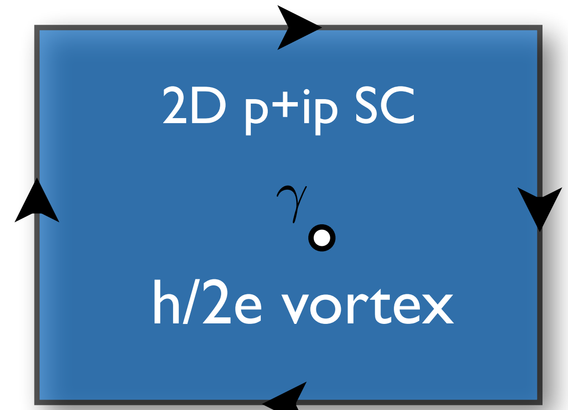

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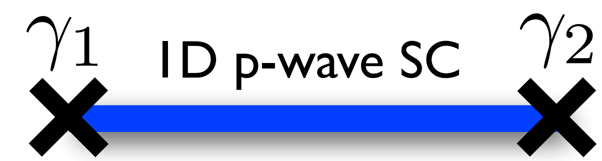
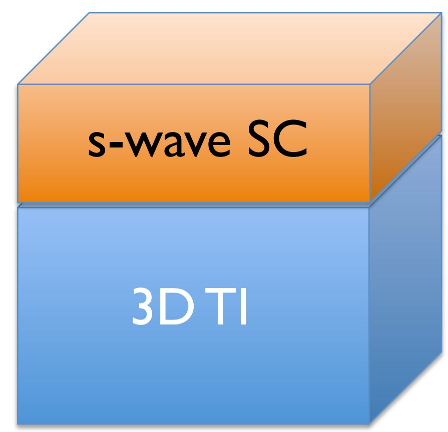


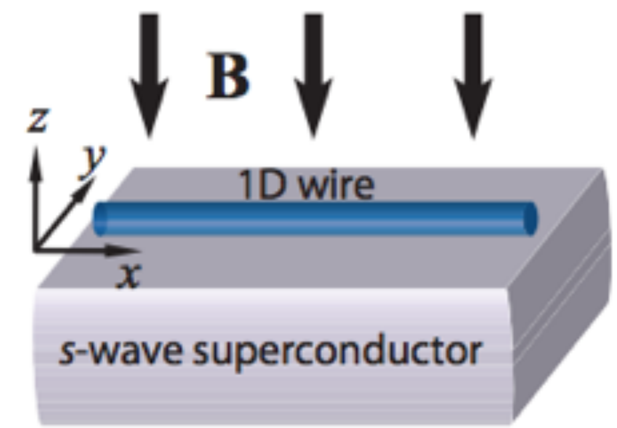
Kitaev (2001)

Design era (2008-2012)

(many others)



Fu & Kane (2008)



Lutchyn et al., Oreg et al. (2010)

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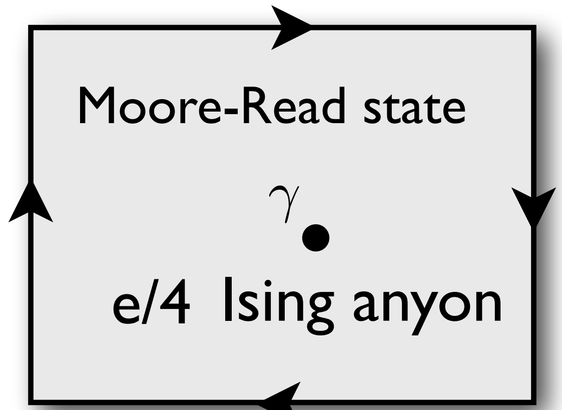

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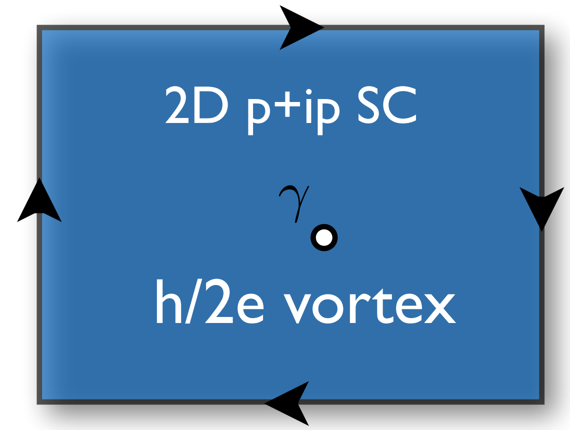

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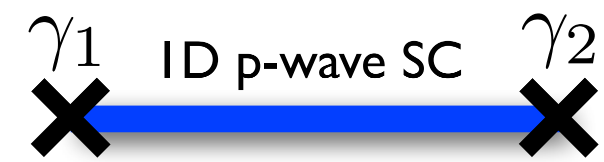

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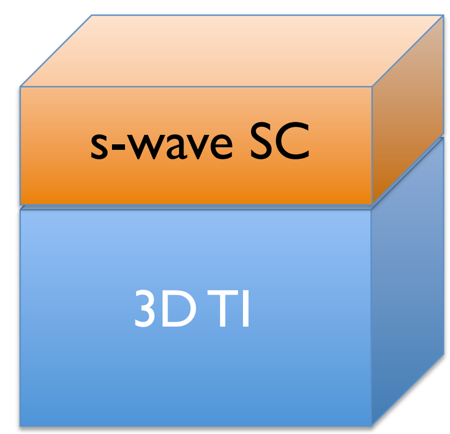

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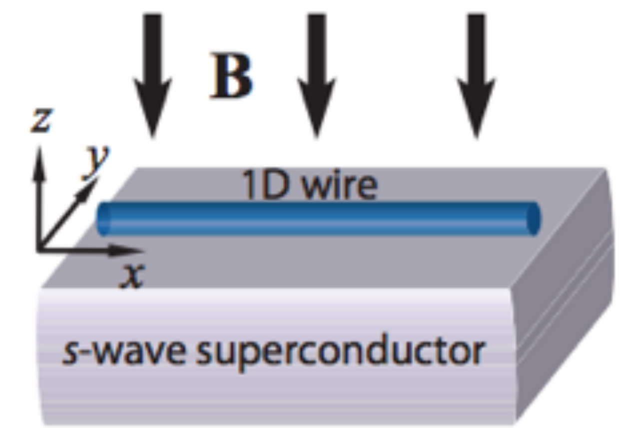
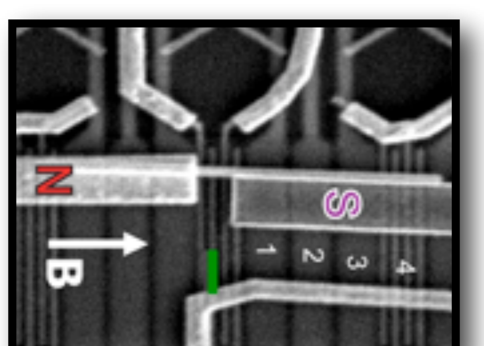
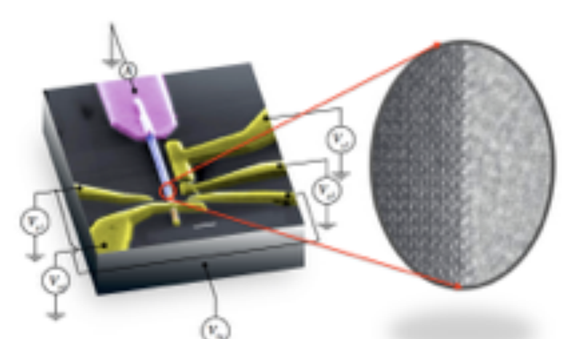


Lutchyn et al., Oreg et al. (2010)

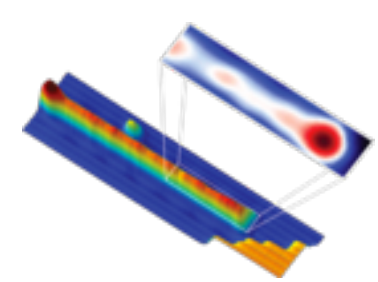
Fabrication & characterization era (2012-present)



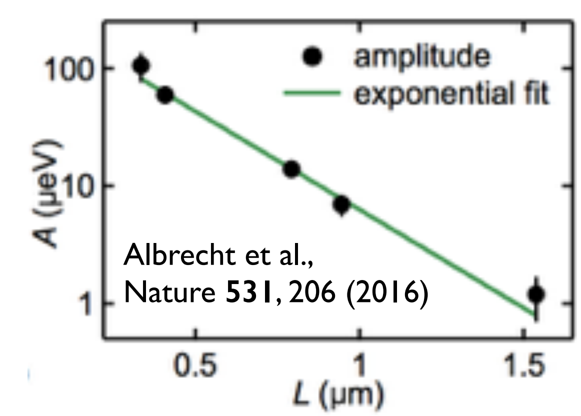
Mourik et al. (2012)



Marcus et al.



Nadj-Perge et al.



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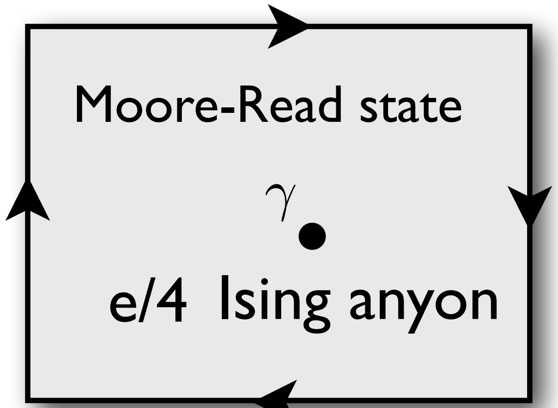

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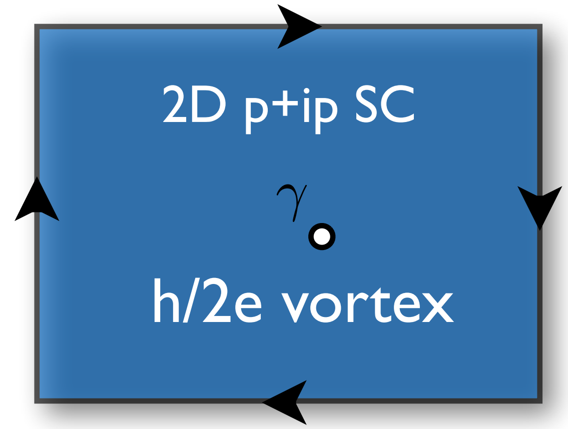
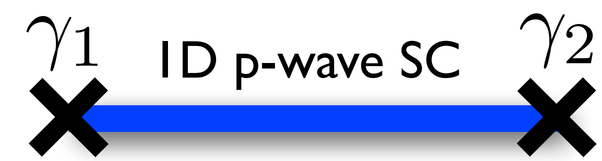


Read & Green (2000)



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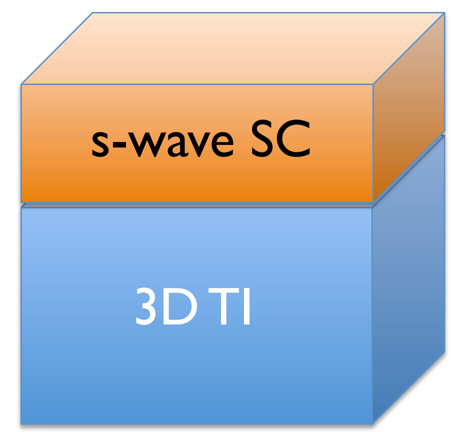
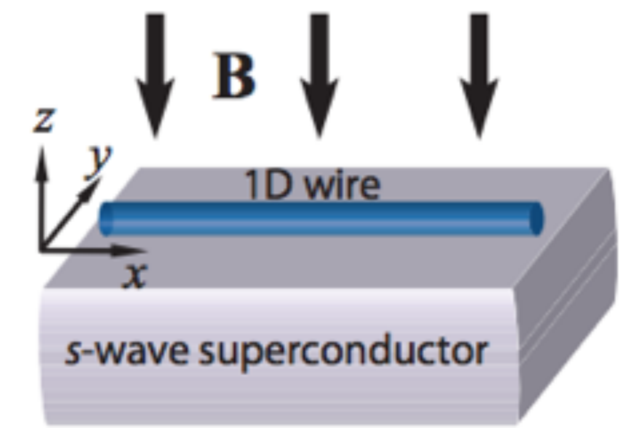
Design era (2008-2012)

(**many** others)

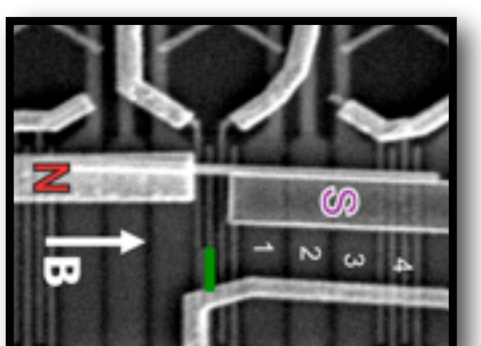


Fu & Kane (2008)

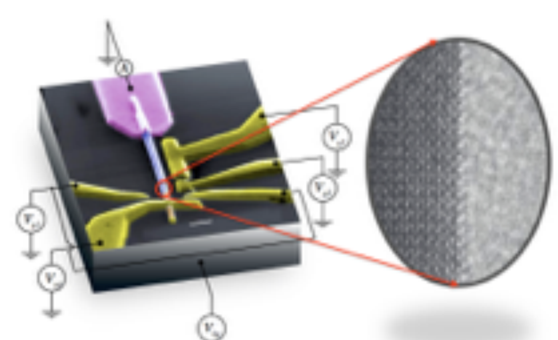


Lutchyn et al., Oreg et al. (2010)

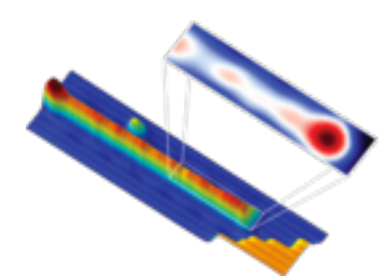
Fabrication & characterization era (2012-present)



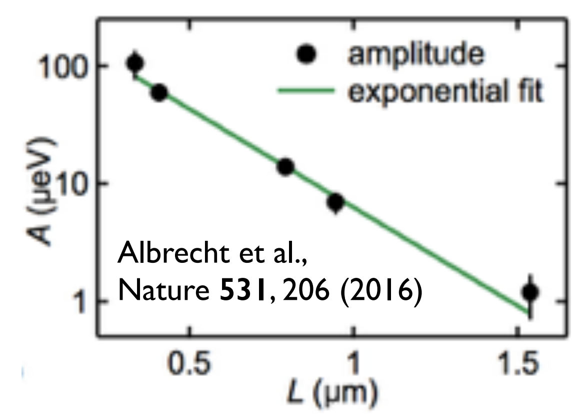
Mourik et al. (2012)



Marcus et al.



Nadj-Perge et al.



(**many** others)

Majorana control era (coming soon?)

I. New all-electrical Majorana control scheme

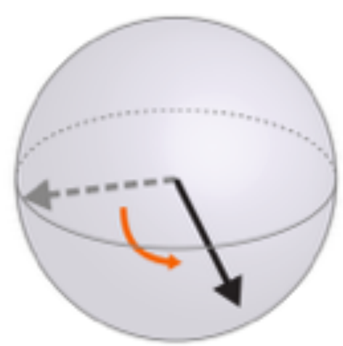
II. Majorana-control milestones

Fusion-rule detection

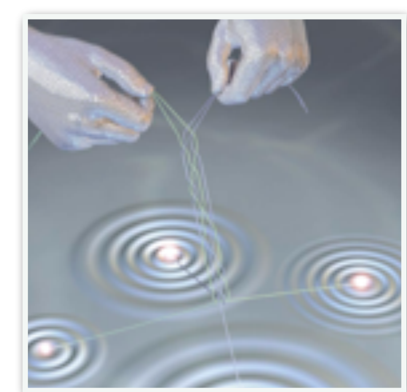
γ_1 γ_2

$$\sigma \times \sigma = I + \psi$$

Topological qubit validation



Braiding

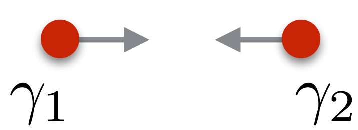


I. New all-electrical Majorana control scheme

Goal: leverage quantum dot/spin qubit tools for experiments below

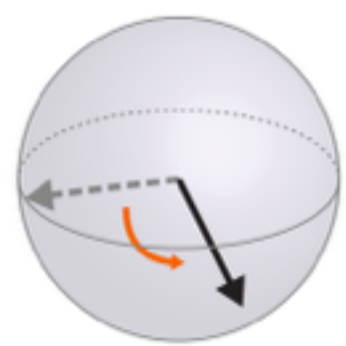
II. Majorana-control milestones

Fusion-rule detection

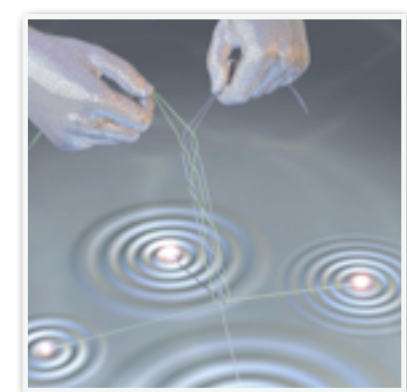


$$\sigma \times \sigma = I + \psi$$

Topological qubit validation

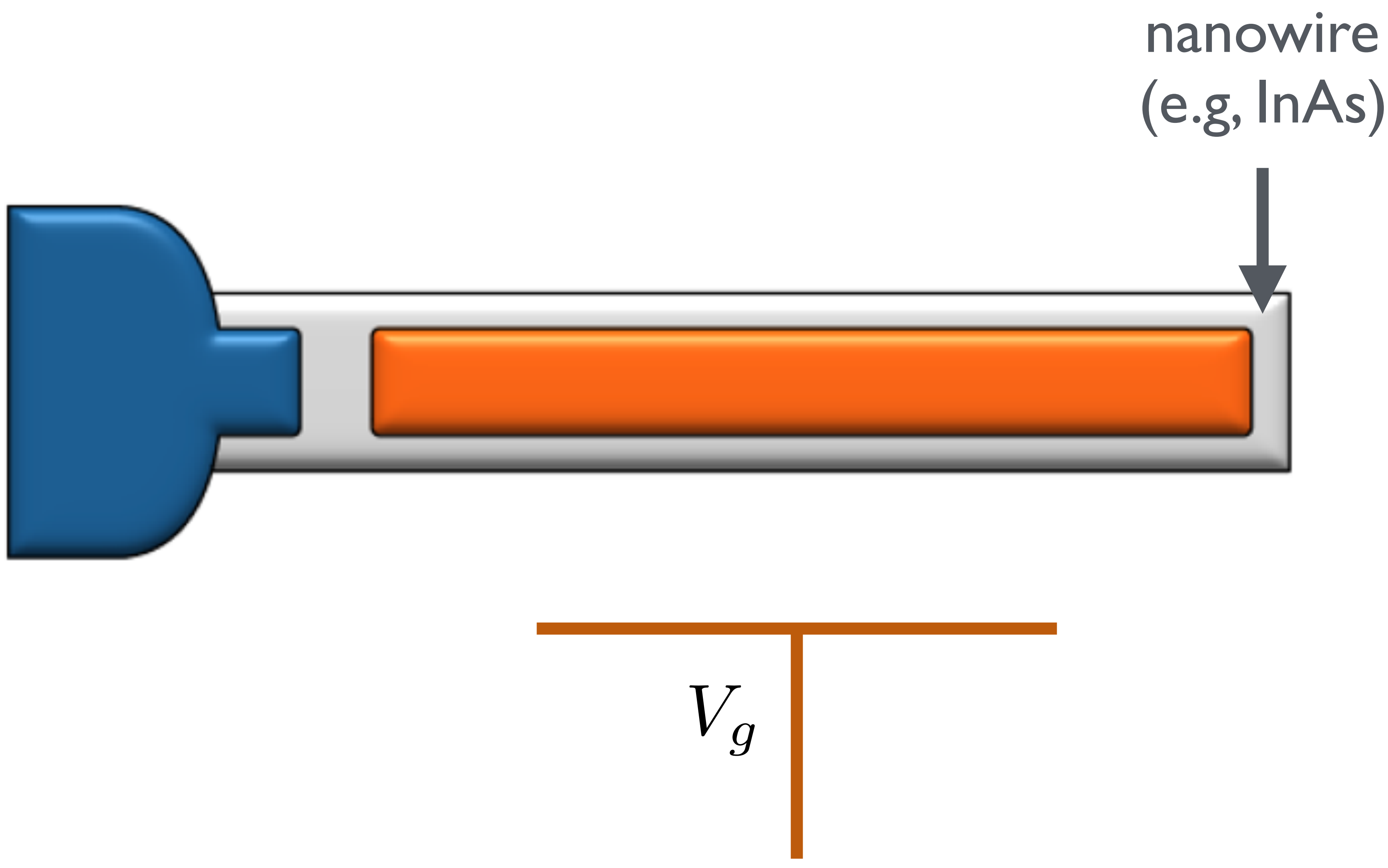


Braiding

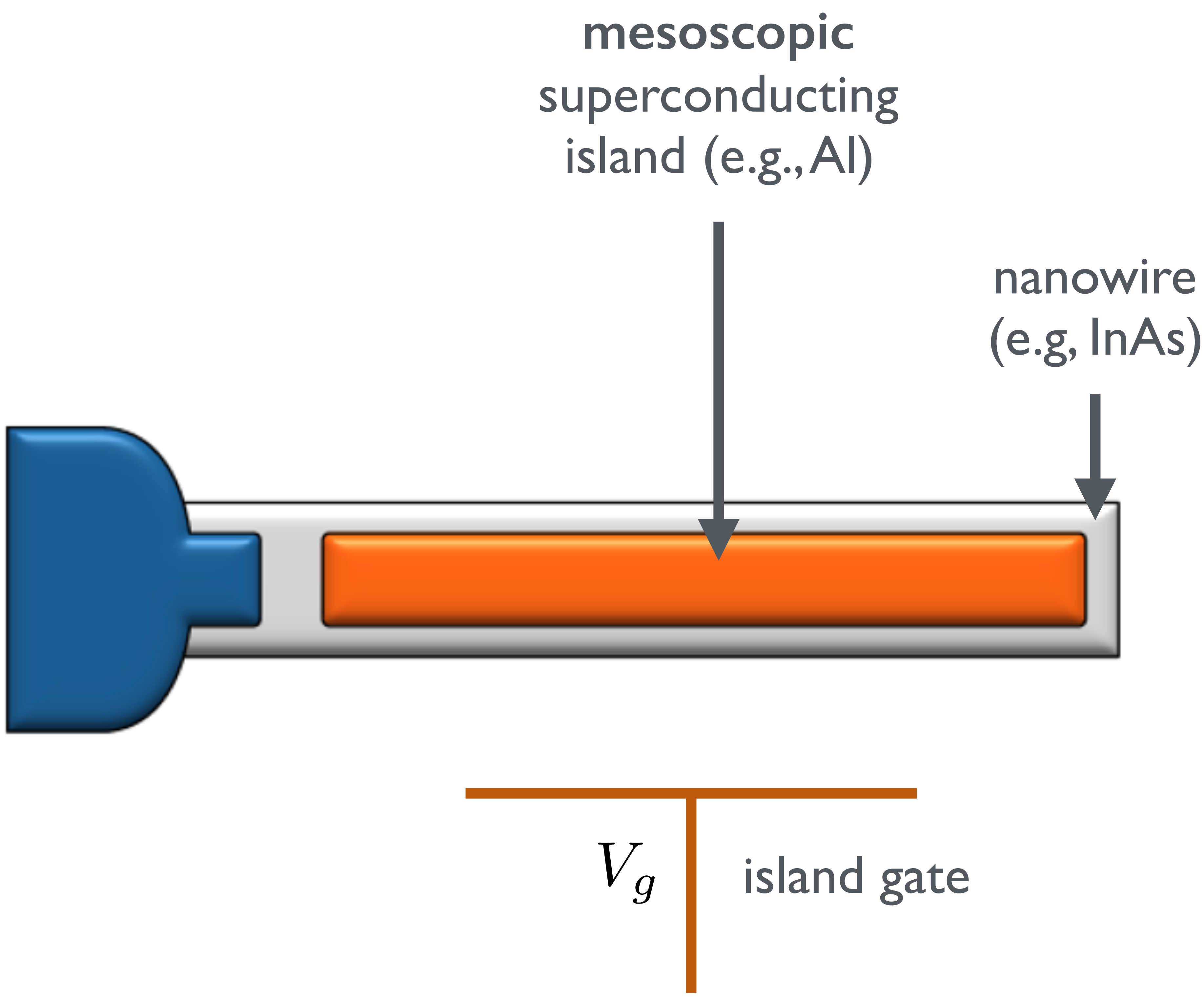


Related to T. W. Larsen, K. D. Petersson, F. Kuemmeth, T. S. Jespersen, P. Krogstrup, J. Nygard, and C. M. Marcus, PRL **115**, 127001 (2015); G. de Lange, B. van Heck, A. Bruno, D. J. van Woerkom, A. Geresdi, S. R. Plissard, E. P. A. M. Bakkers, A. R. Akhmerov, and L. DiCarlo, PRL **115**, 127002 (2015); B. van Heck, A. R. Akhmerov, F. Hassler, M. Burrello, and C. W. J. Beenakker, New Journal of Physics **14**, 035019 (2012); T. Hyart, B. van Heck, I. C. Fulga, M. Burrello, A. R. Akhmerov, and C. W. J. Beenakker, Phys. Rev. B **88**, 035121 (2013).

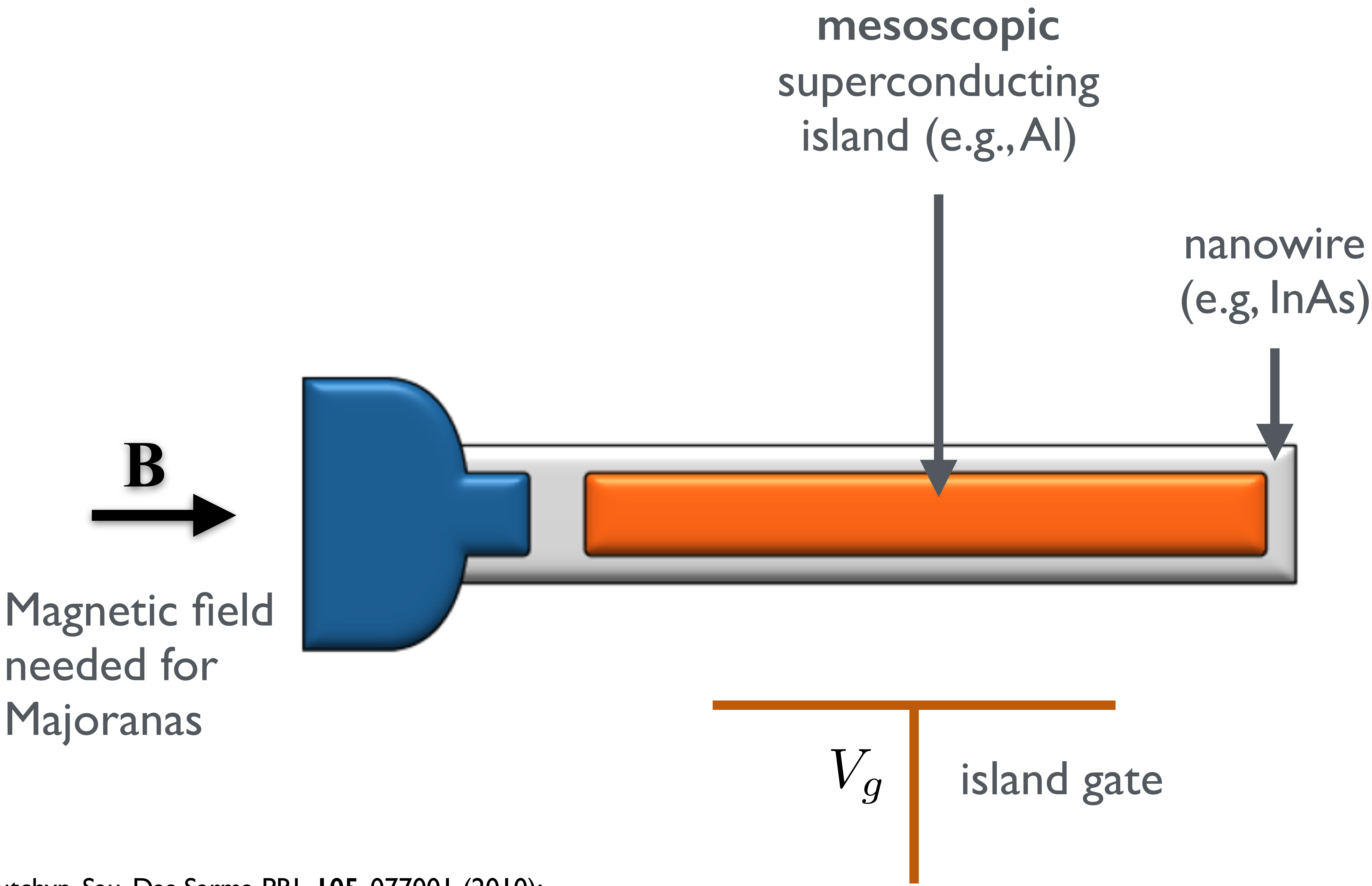
Majorana control scheme: setup



Majorana control scheme: setup

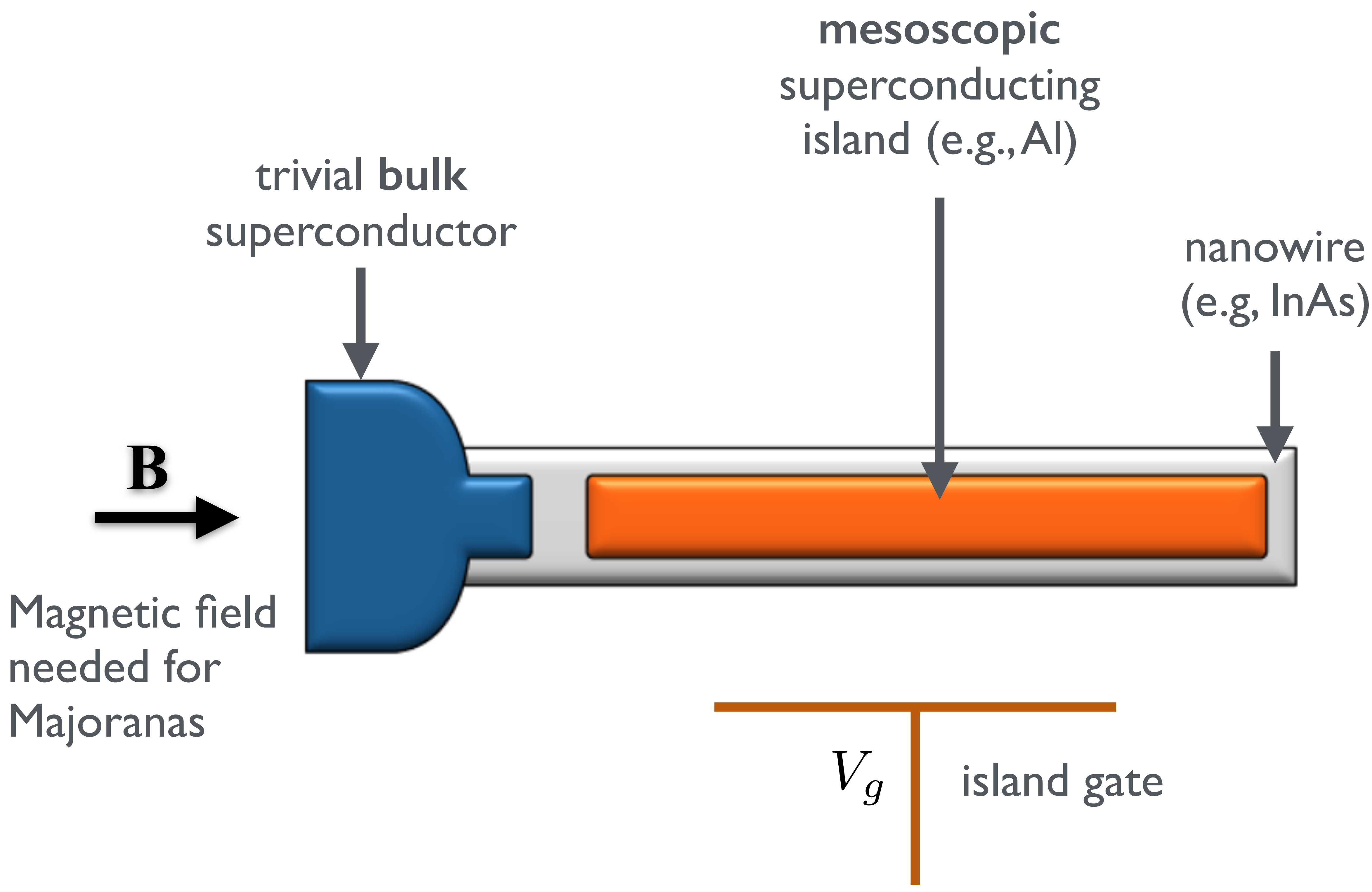


Majorana control scheme: setup



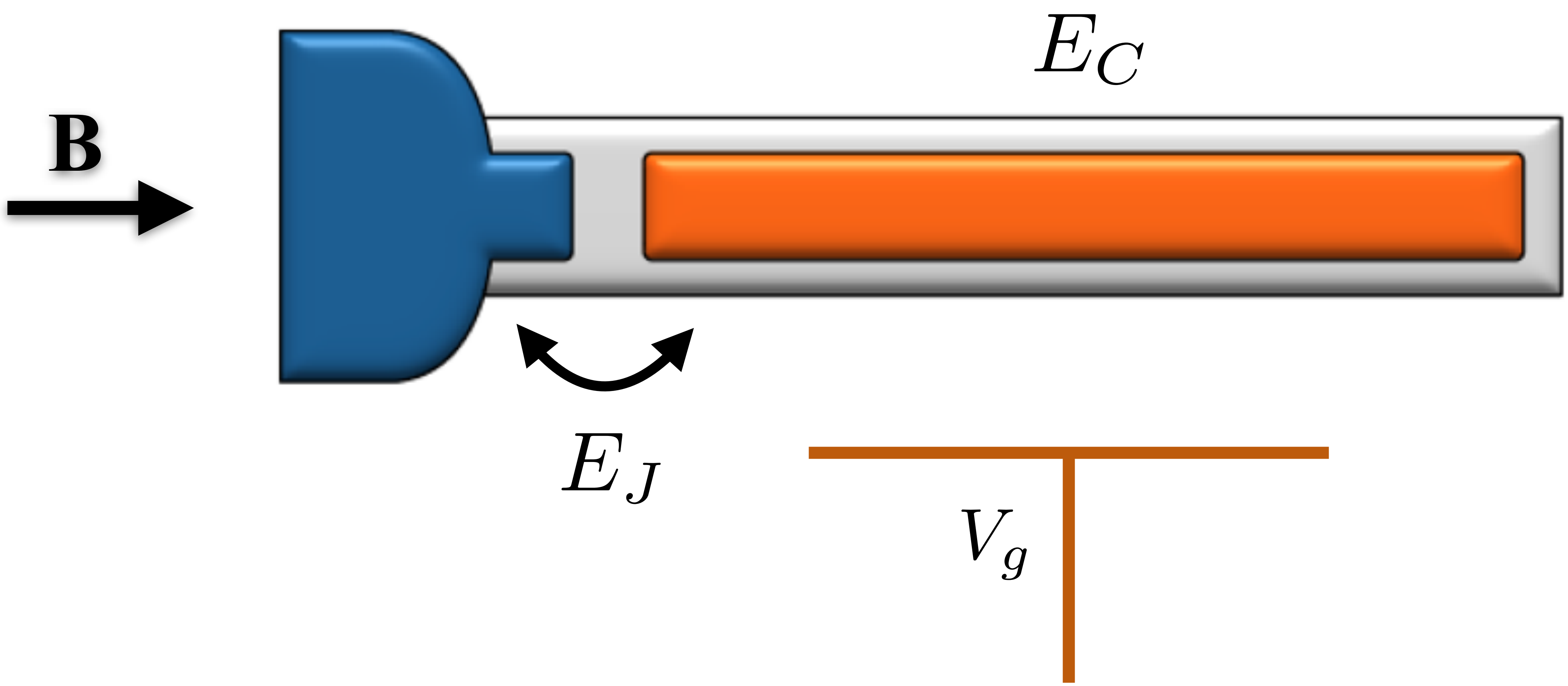
Lutchyn, Sau, Das Sarma PRL **105**, 077001 (2010);
Oreg, Refael, von Oppen PRL **105**, 177002 (2010)

Majorana control scheme: setup



Majorana control scheme: setup

$$H = H_J[\hat{\phi}] + E_C(\hat{n} - n_{\text{offset}})^2$$



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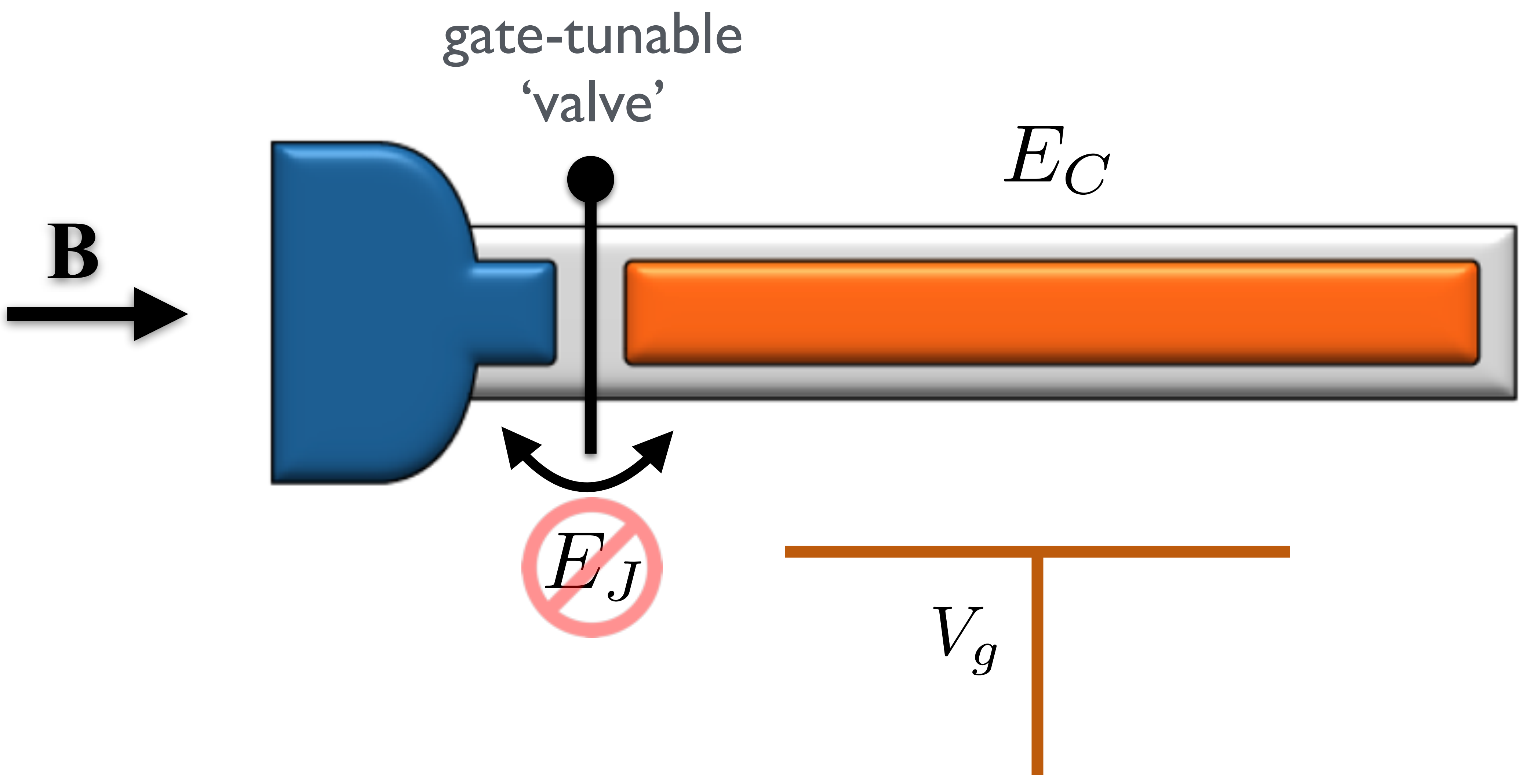

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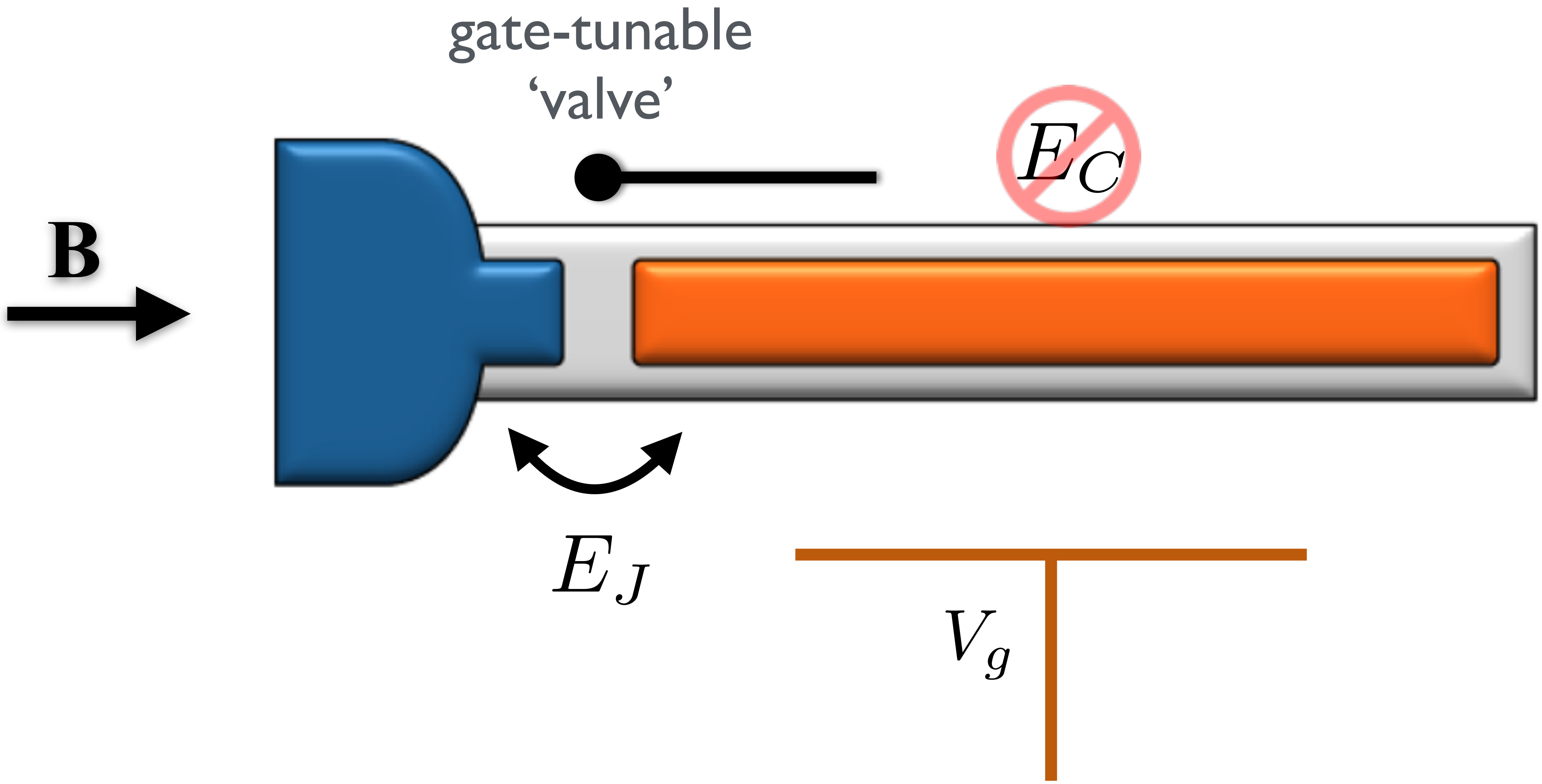

Majorana control scheme: setup

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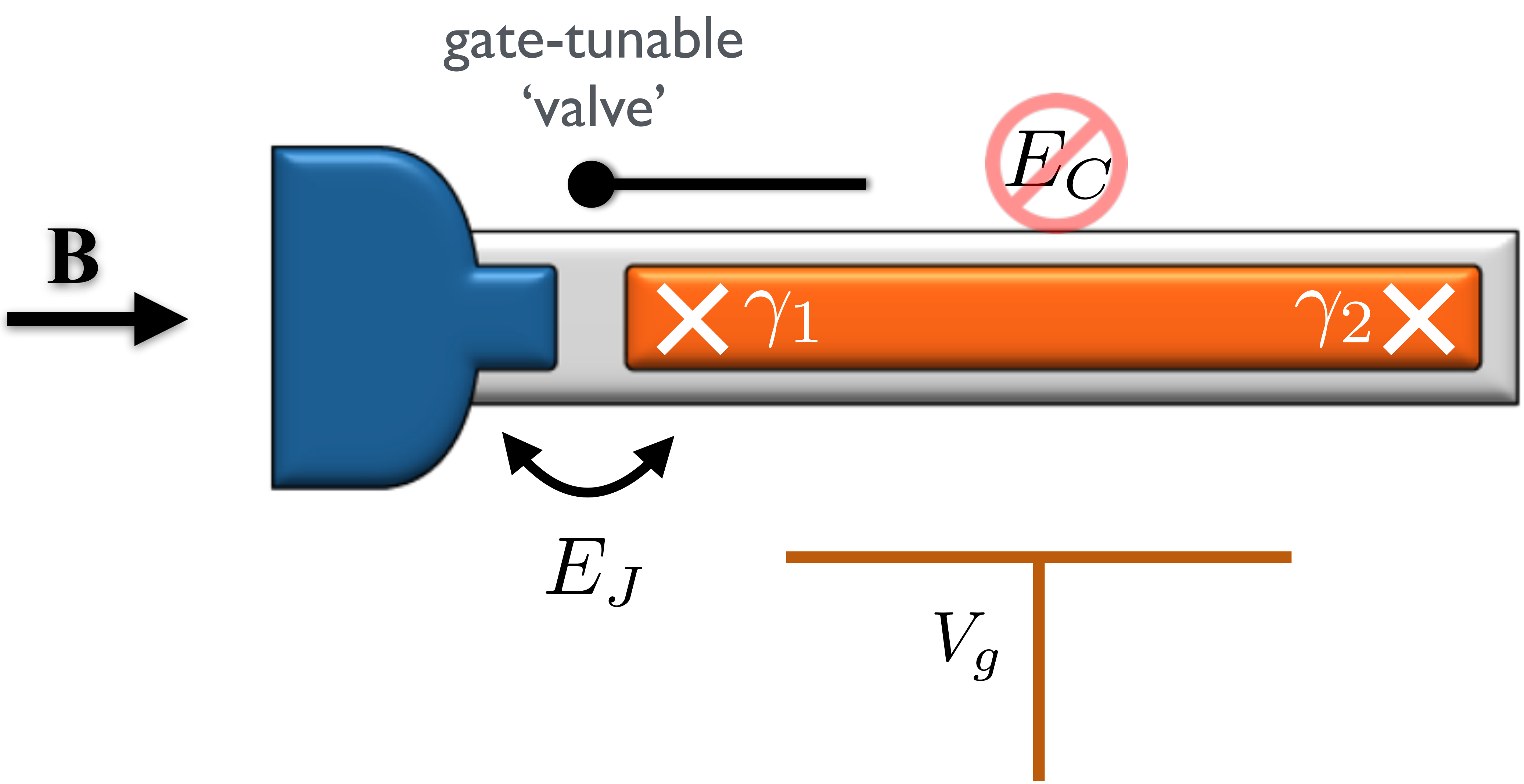
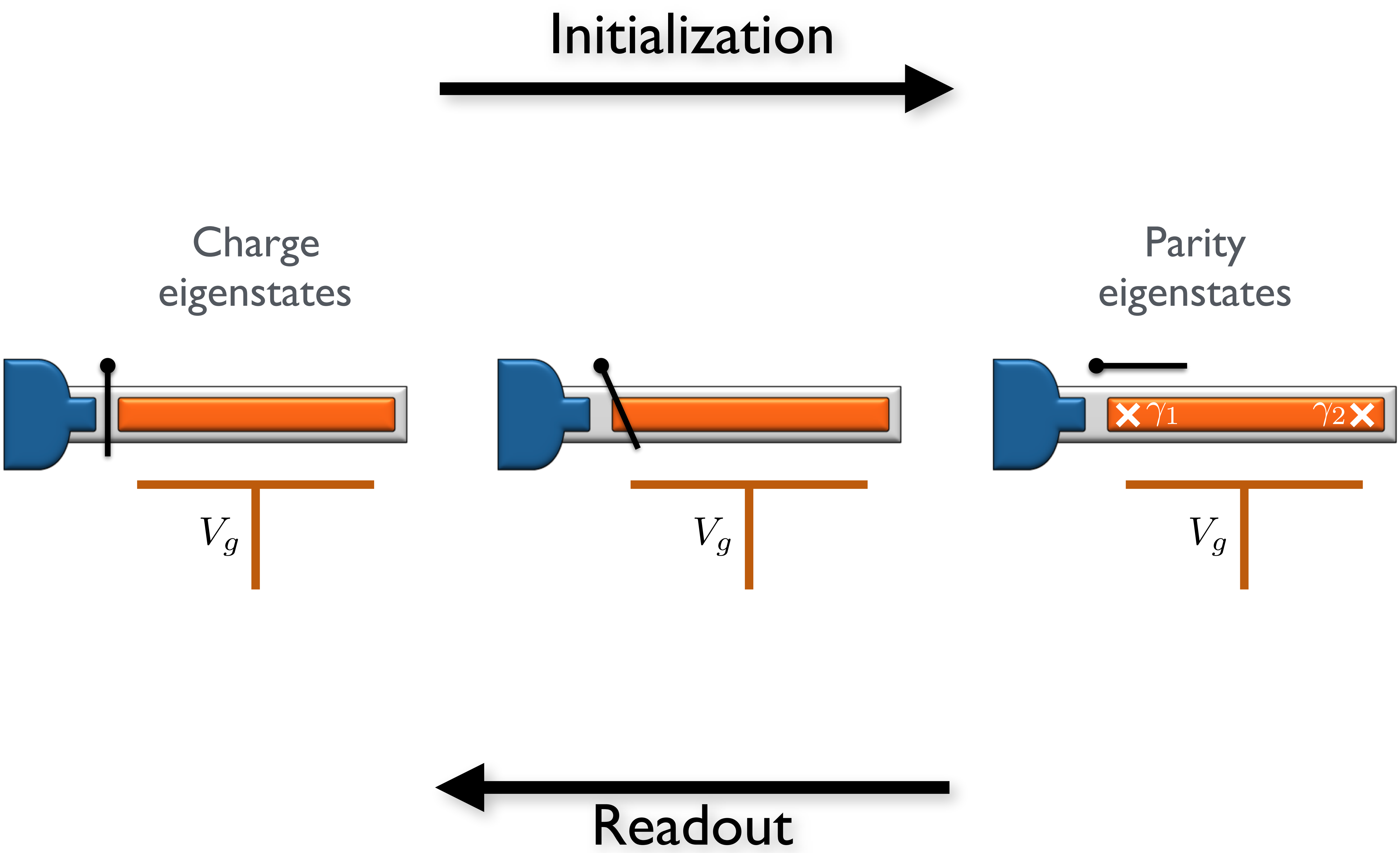
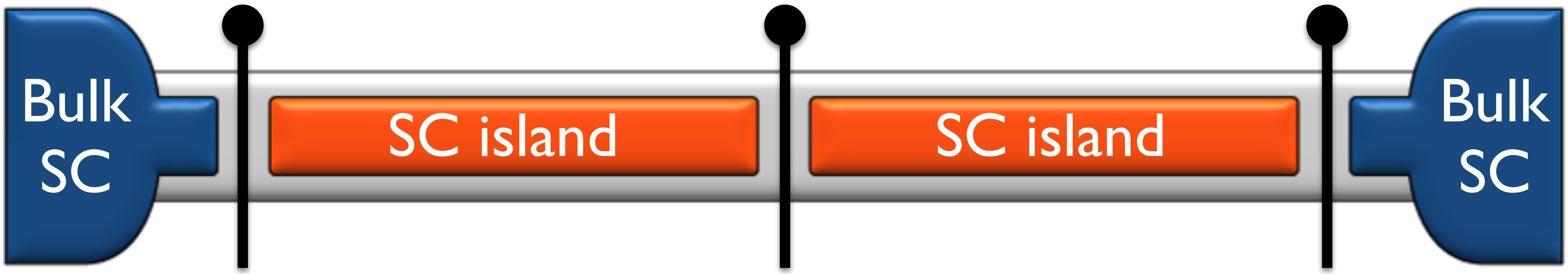


Parity-to-charge conversion

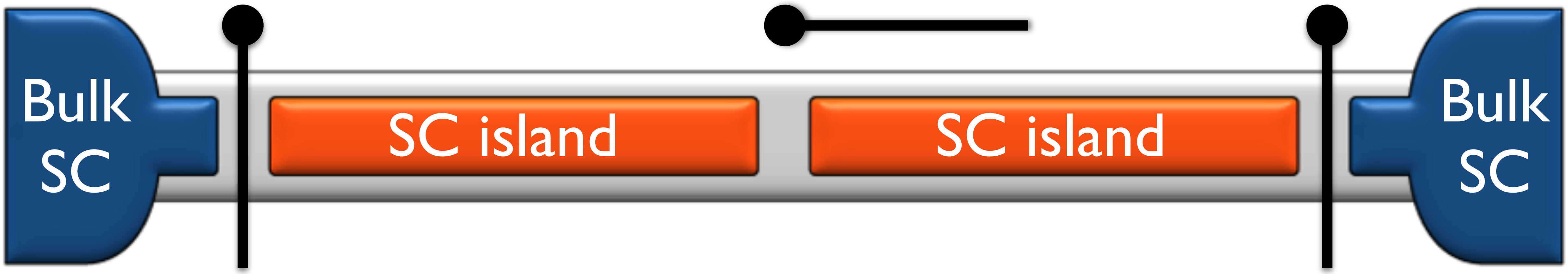


Multi-island extension



Double dot

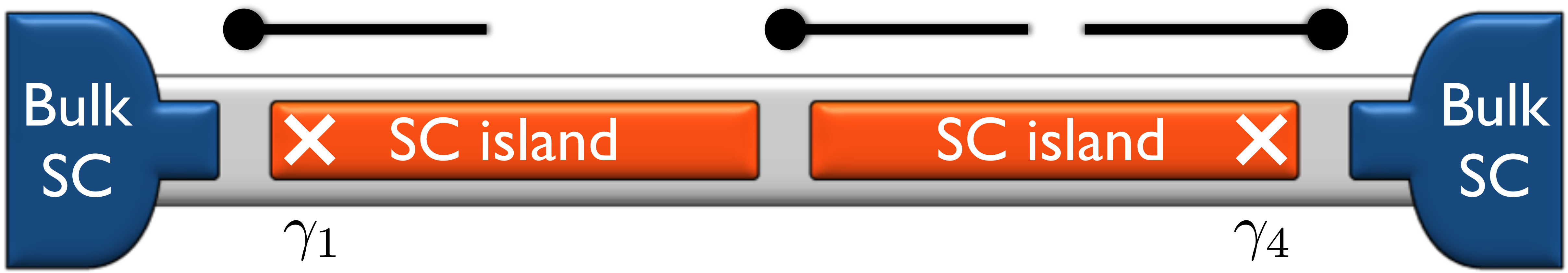
Multi-island extension



Double dot

Single dot

Multi-island extension

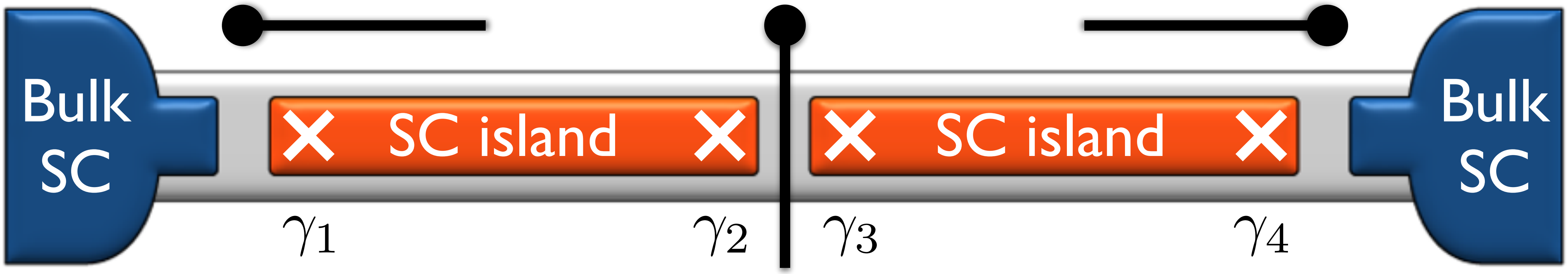


Double dot

Single dot

Topological superconductor

Multi-island extension



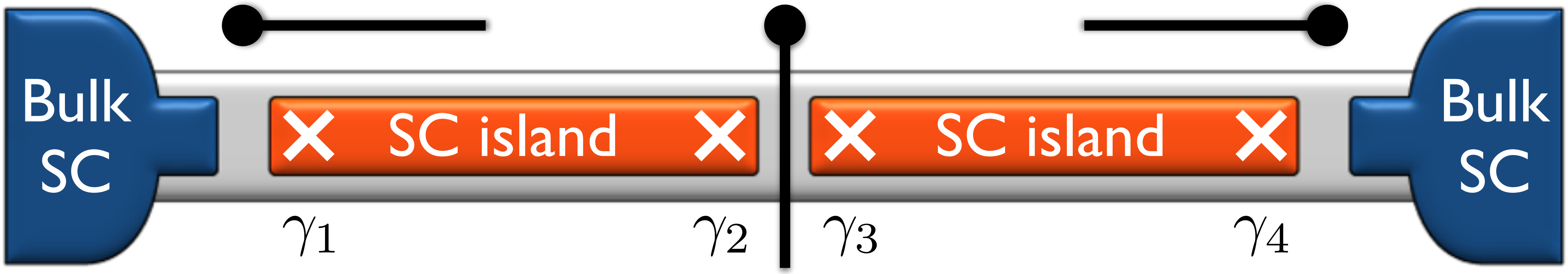
Double dot

Single dot

Topological superconductor

Double topological superconductor

Multi-island extension



Double dot

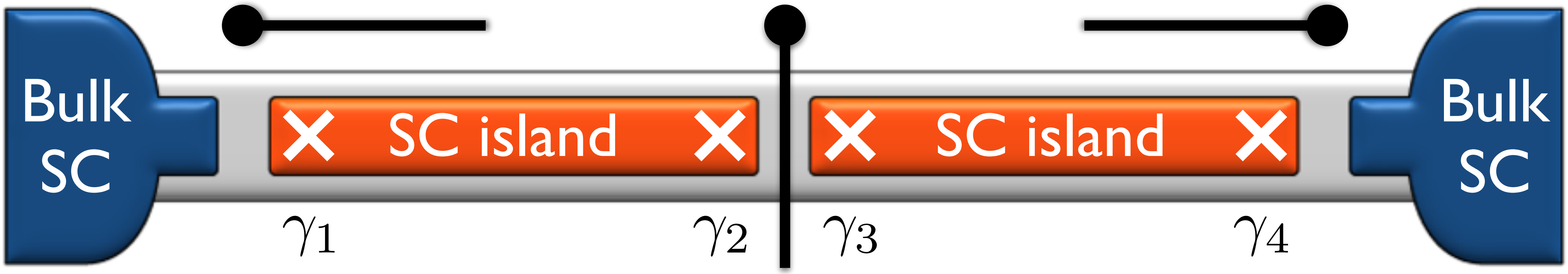
Single dot

Topological superconductor

Double topological superconductor

Suffice for fusion rules,
topological qubit validation.

Multi-island extension



Double dot

Single dot

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Double topological superconductor

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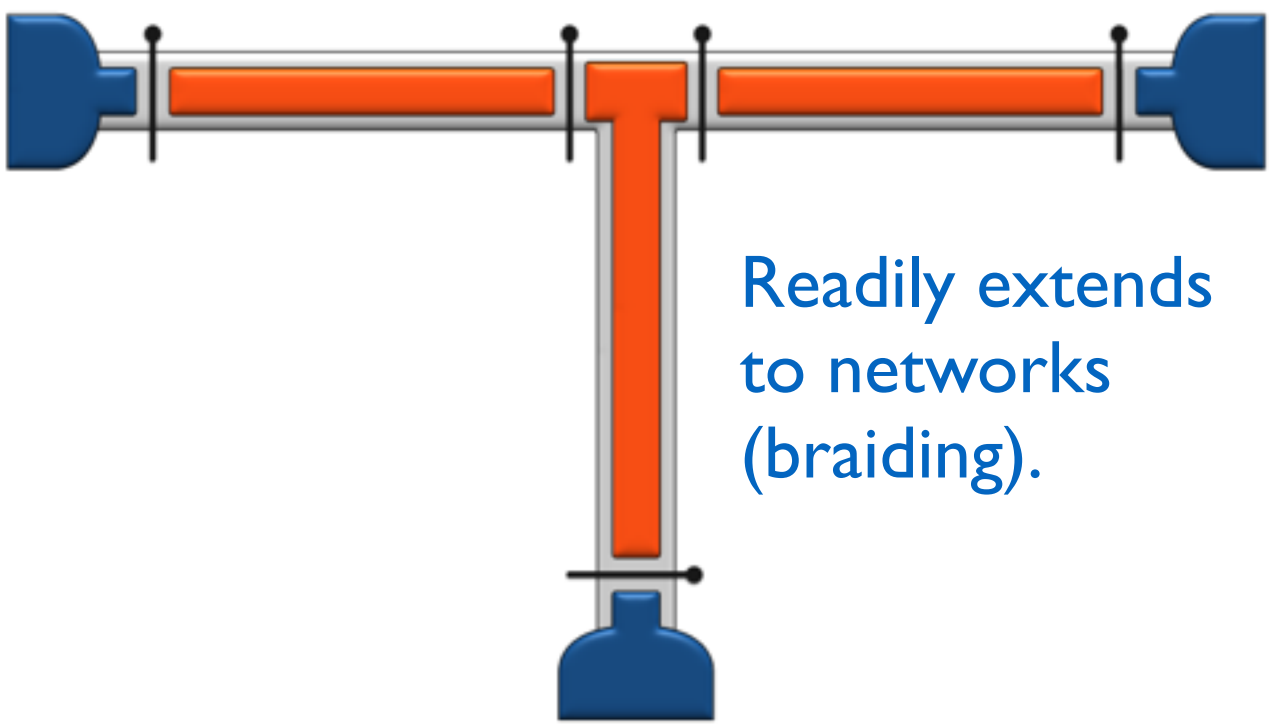


Readily extends to networks (braiding).

I. New all-electrical Majorana control scheme

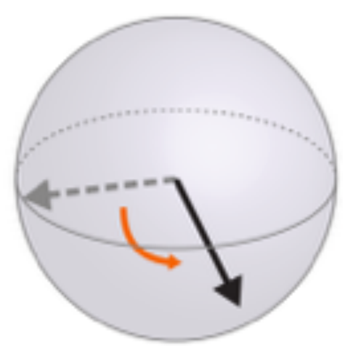
II. Majorana-control milestones

Fusion-rule detection

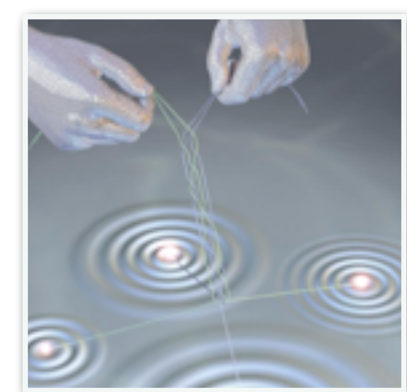
γ_1 γ_2

$$\sigma \times \sigma = I + \psi$$

Topological qubit validation

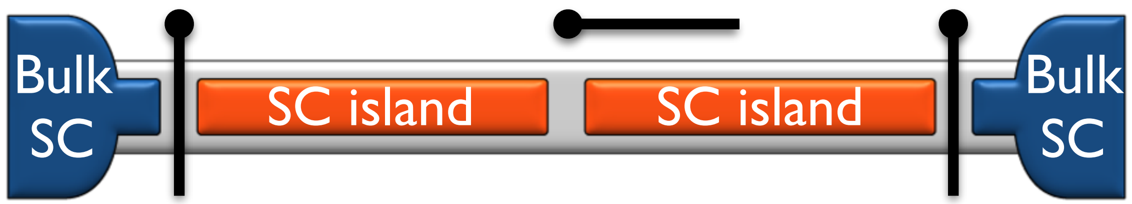


Braiding



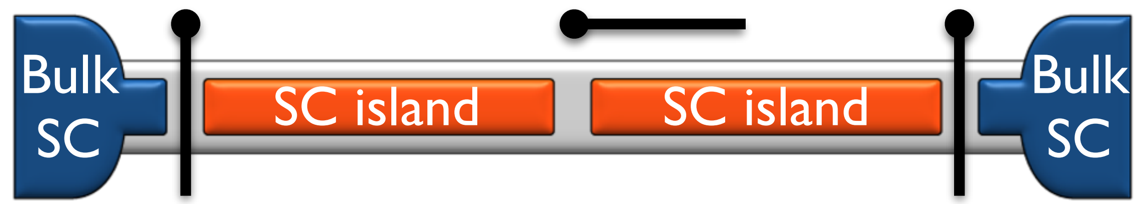
Related to W. Bishara, P. Bonderson, C. Nayak, K. Shtengel, and J. K. Slingerland, PRB **80**, 155303 (2009); JA, Y. Oreg, G. Refael, F. von Oppen, and M. P. A. Fisher, Nat. Phys. **7**, 412 (2011); J. Ruhman, E. Berg, and E. Altman, PRL **114**, 100401 (2015).

Fusion-rule protocol

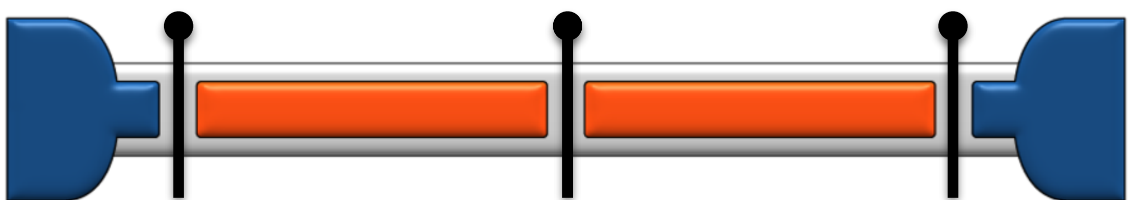


Control (boring)

Fusion-rule protocol

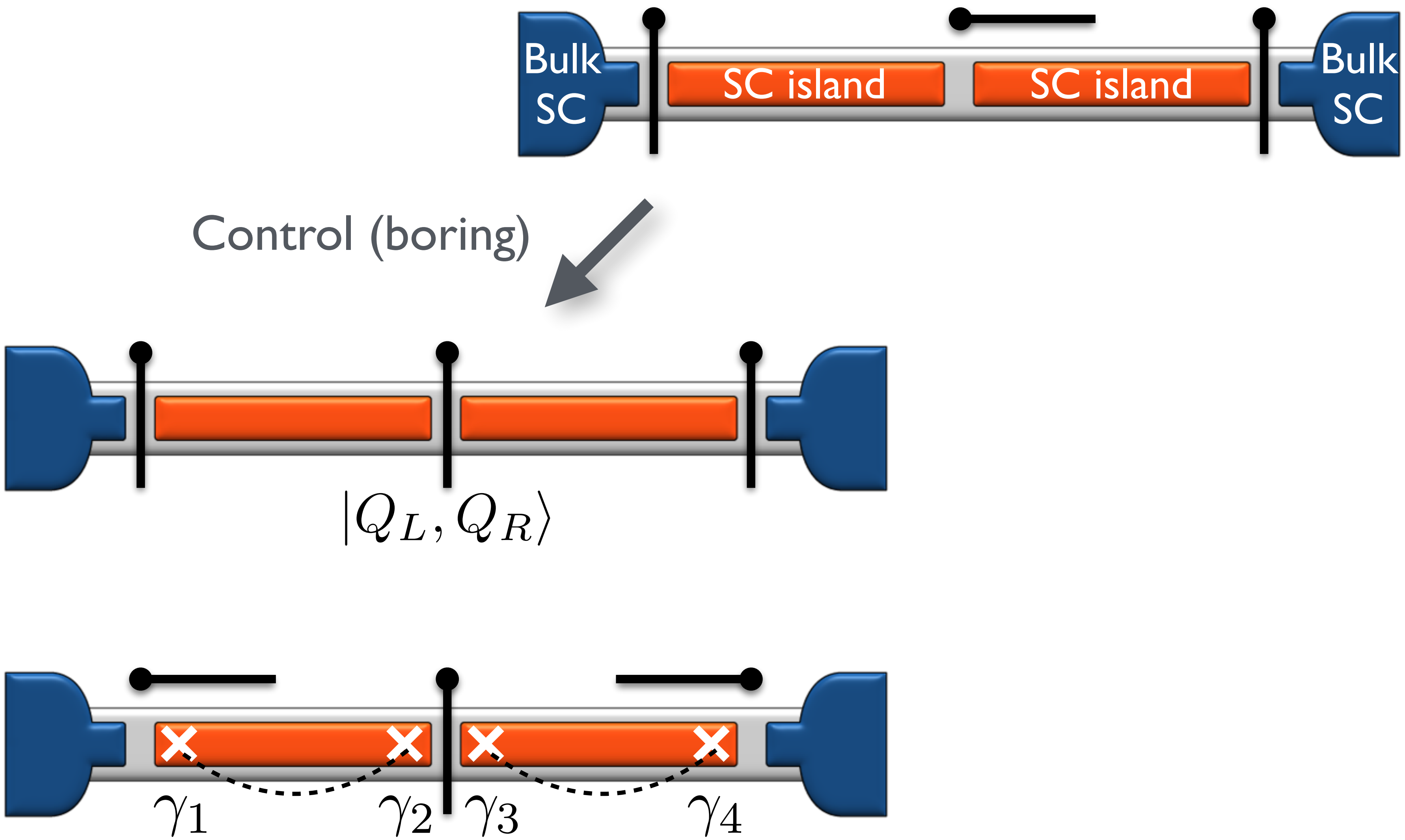


Control (boring)



$|Q_L, Q_R\rangle$

Fusion-rule protocol



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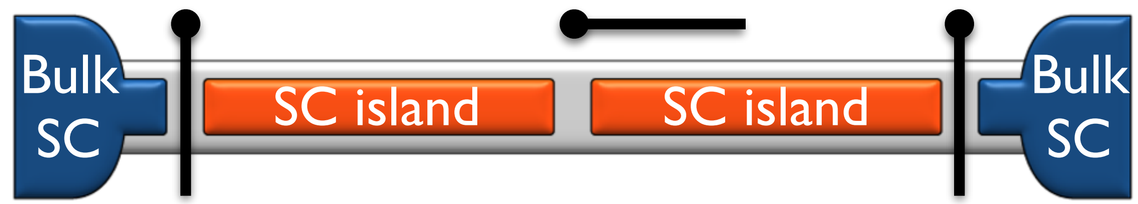

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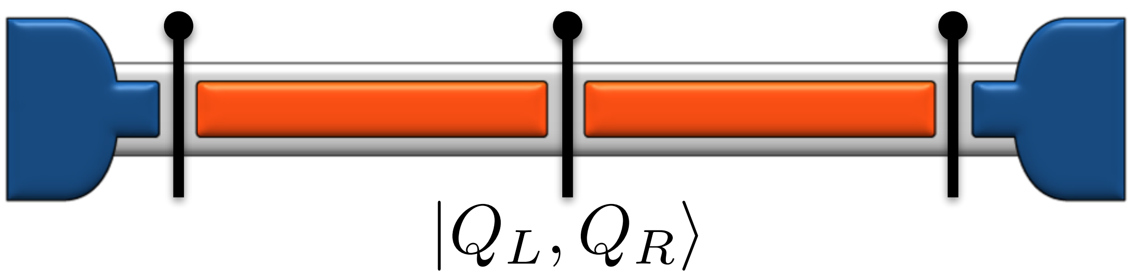
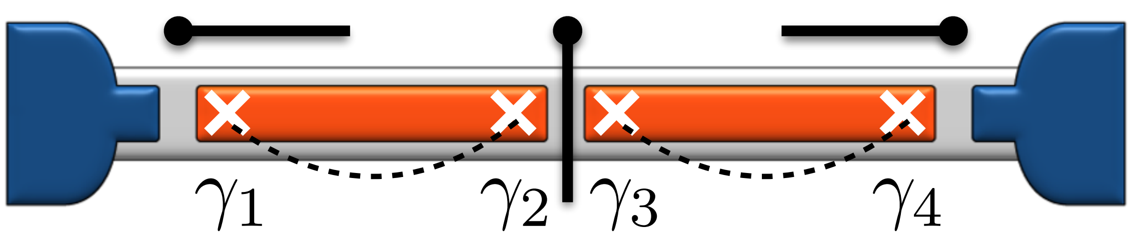
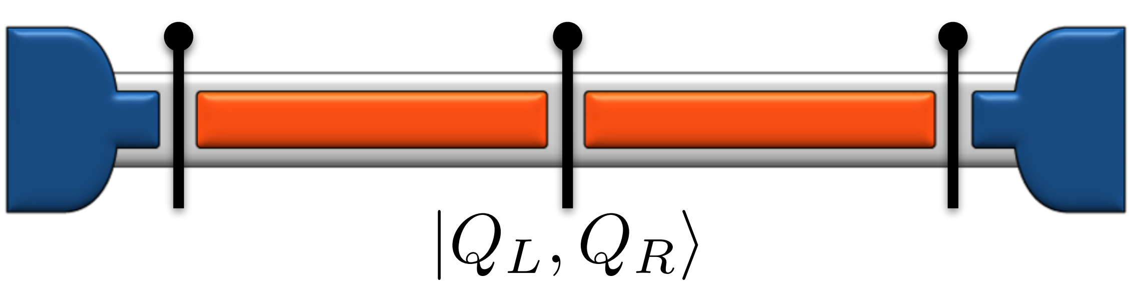




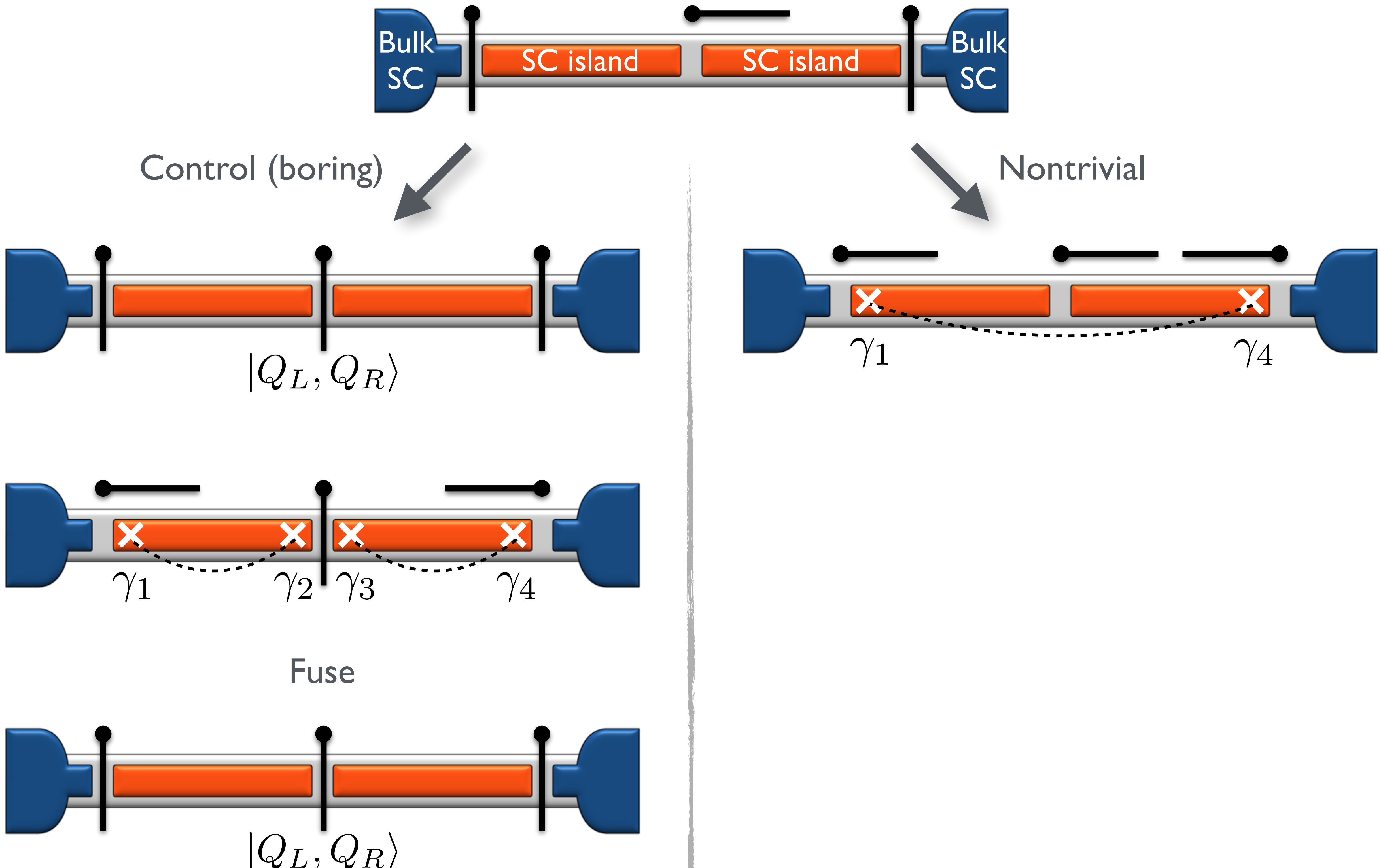
Fuse



Deterministic charge measurement

$$\sigma \times \sigma = I + \cancel{\psi}$$

Fusion-rule protocol



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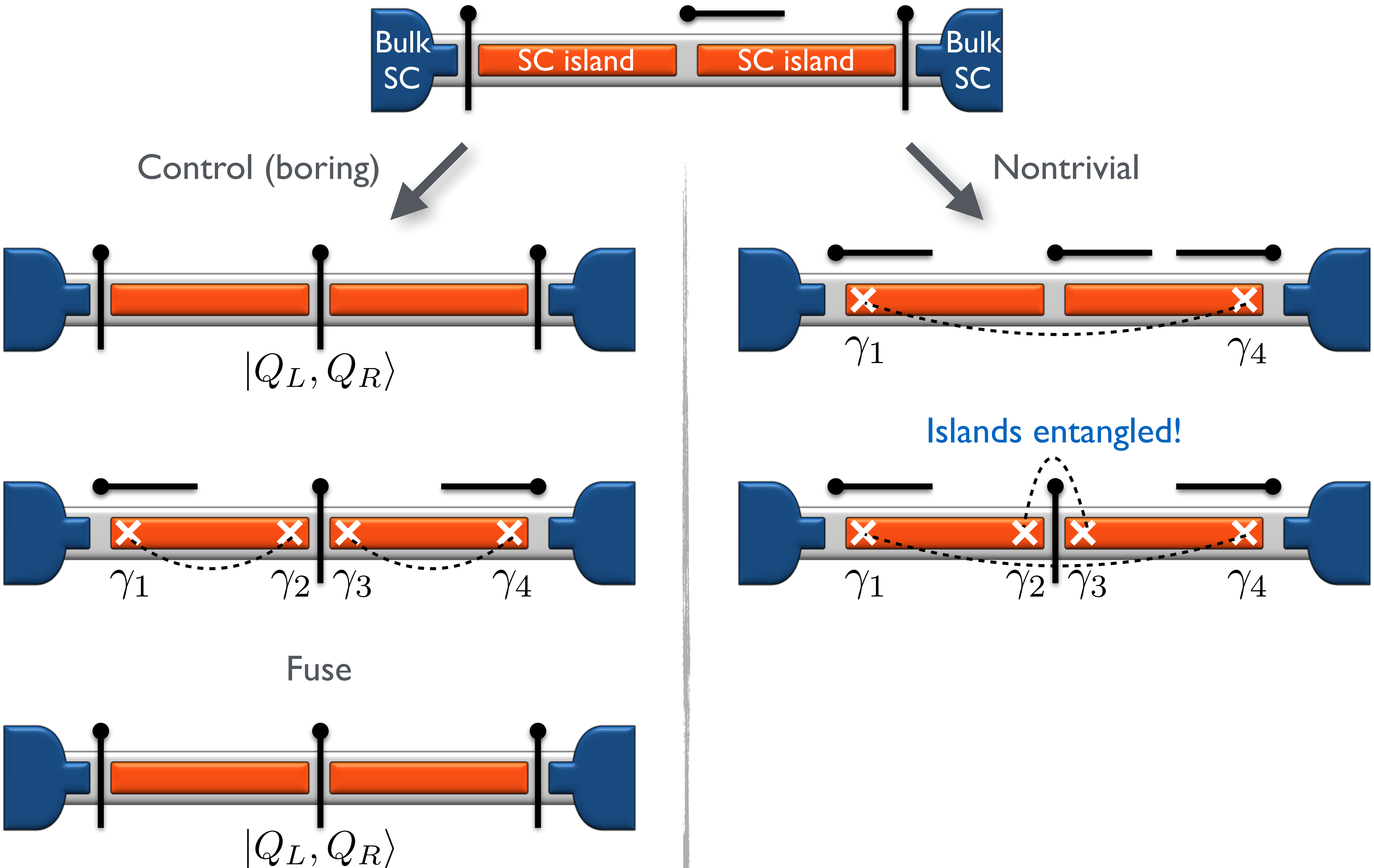

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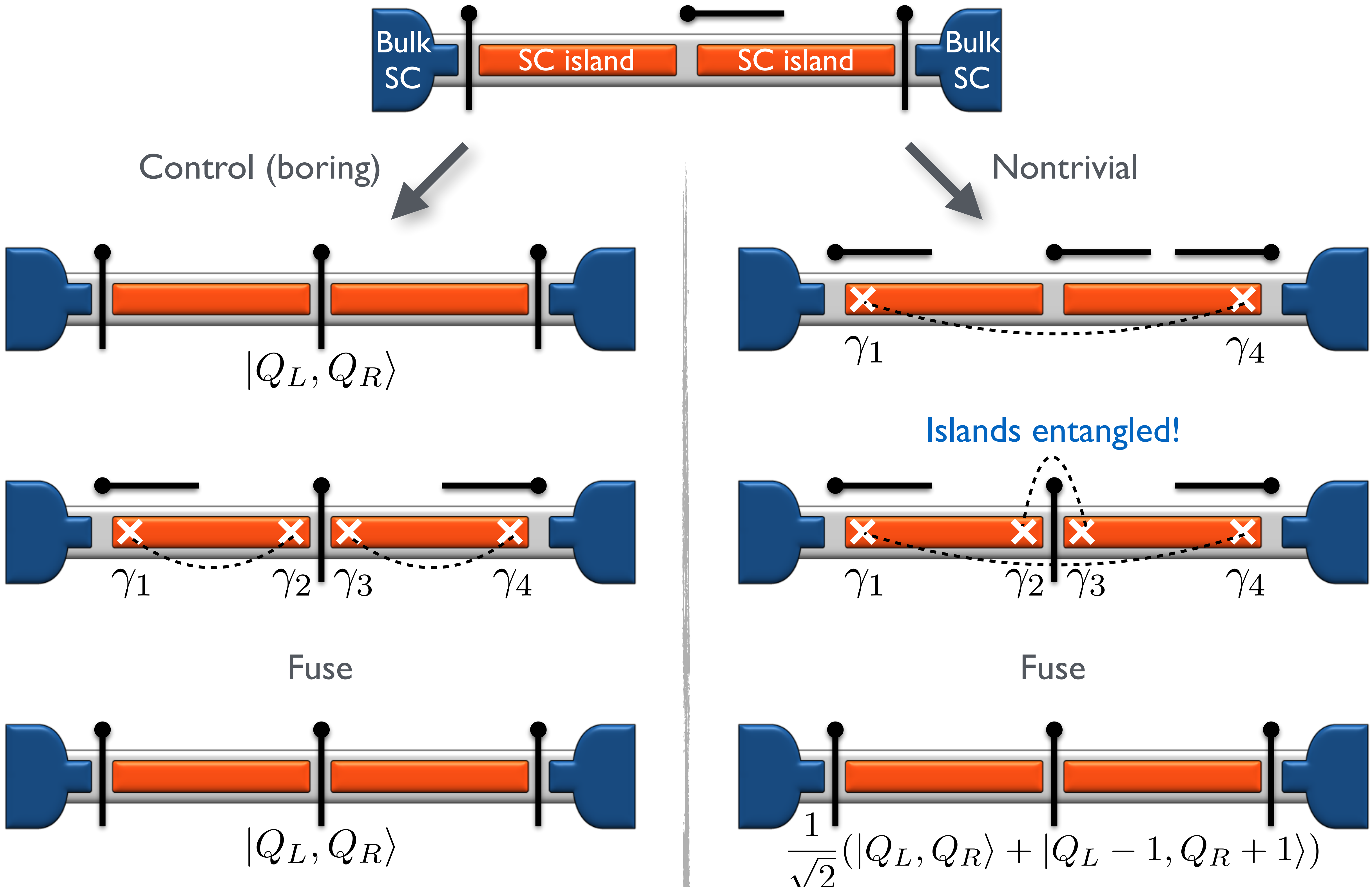
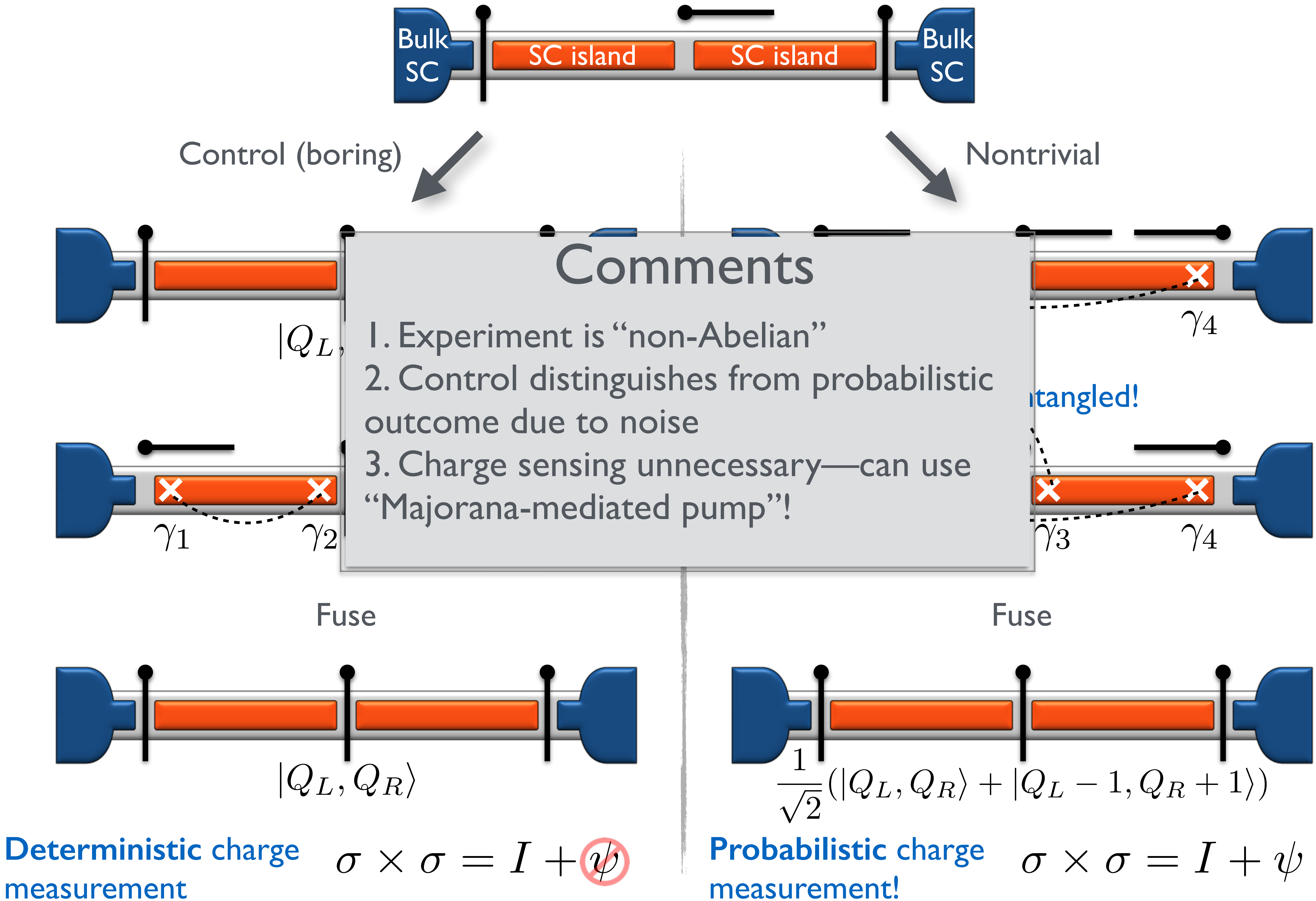
Fusion-rule protocol



Deterministic charge measurement $\sigma \times \sigma = I + \cancel{\psi}$

Probabilistic charge measurement! $\sigma \times \sigma = I + \psi$

Fusion-rule protocol



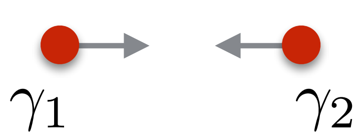
Comments

1. Experiment is "non-Abelian"
2. Control distinguishes from probabilistic outcome due to noise
3. Charge sensing unnecessary—can use "Majorana-mediated pump"!

I. New all-electrical Majorana control scheme

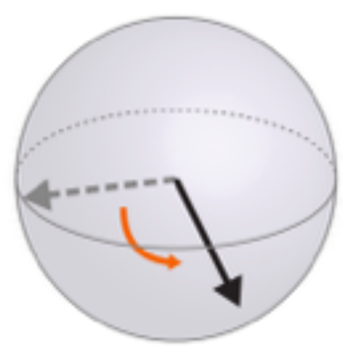
II. Majorana-control milestones

☐ Fusion-rule detection

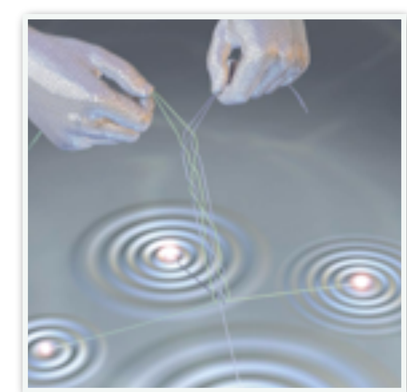


$$\sigma \times \sigma = I + \psi$$

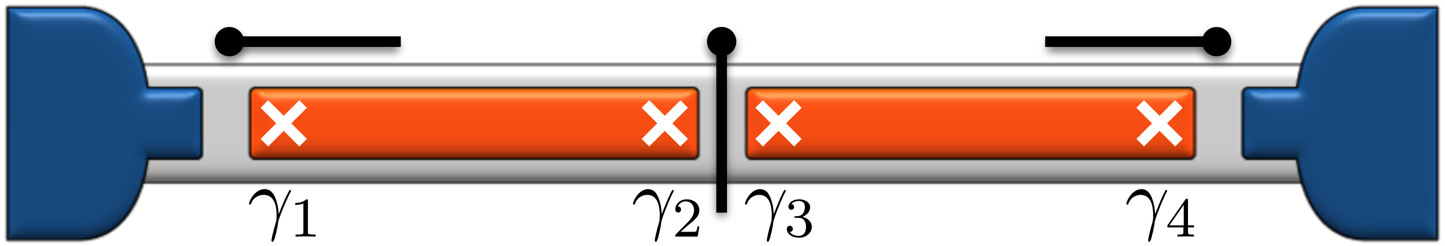
☐ Topological qubit validation



☐ Braiding



Prototype topological qubit



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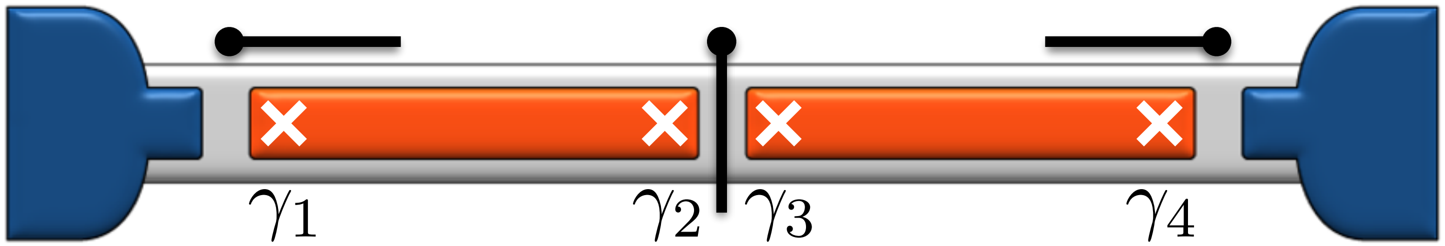

Topological protection requires

1. Time scales << poisoning time
2. System confined to ground states w/high probability (i.e., low T, low frequency noise)

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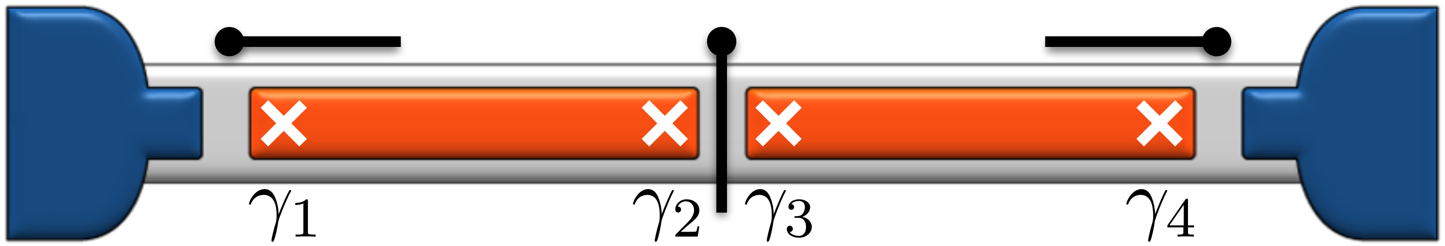

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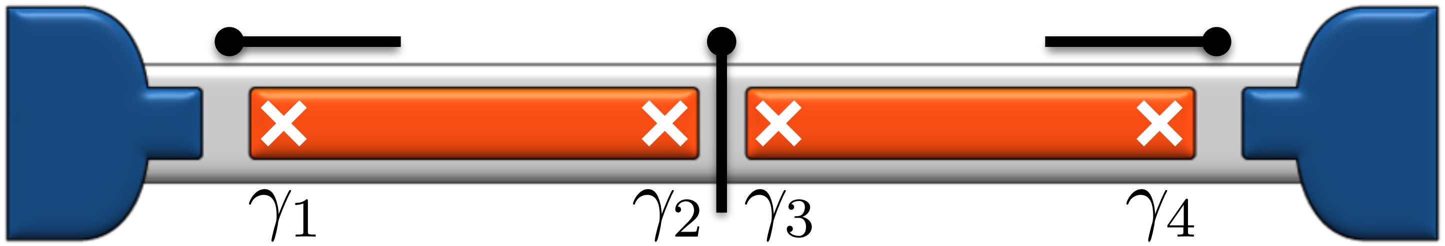
Fundamental question:
Assuming these hold, how to verify topological protection in above device??

Prototype topological qubit



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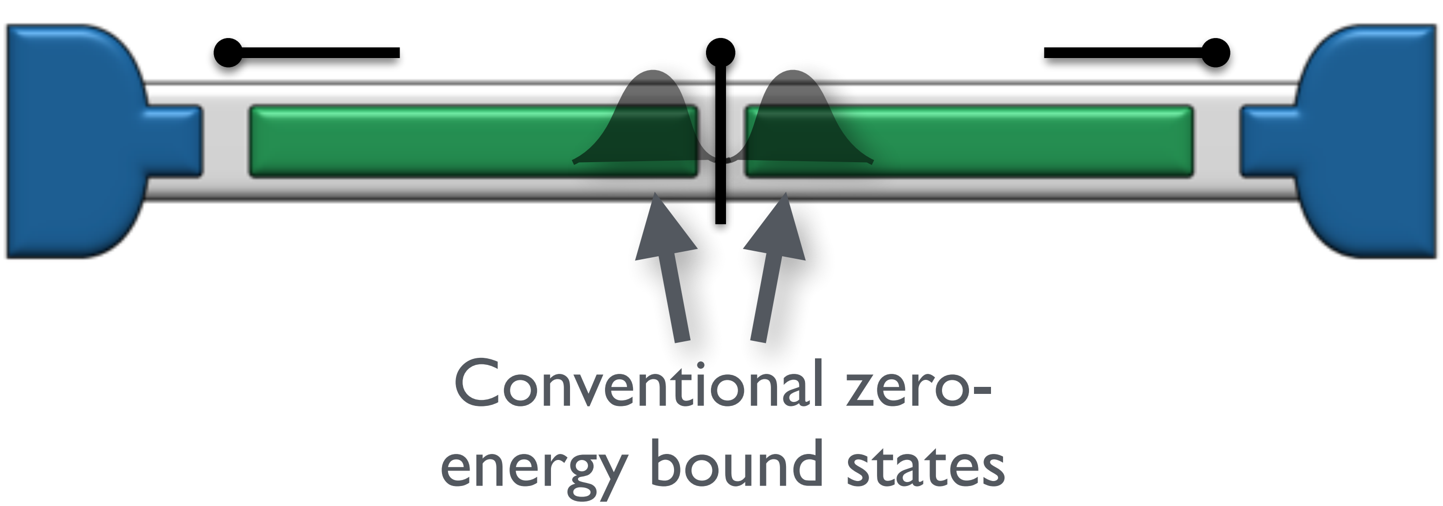

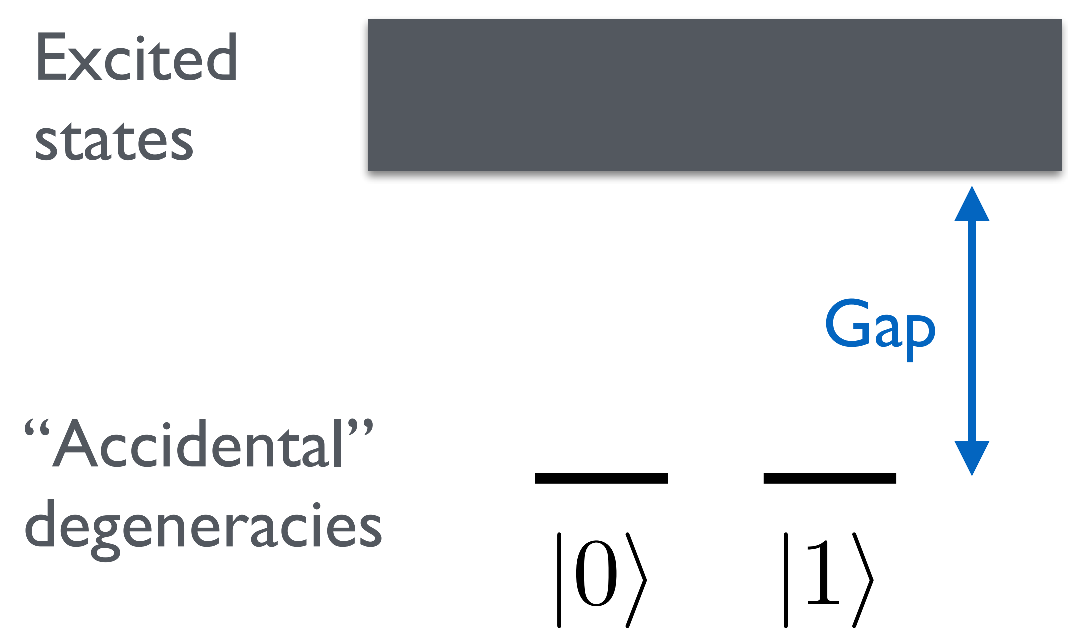

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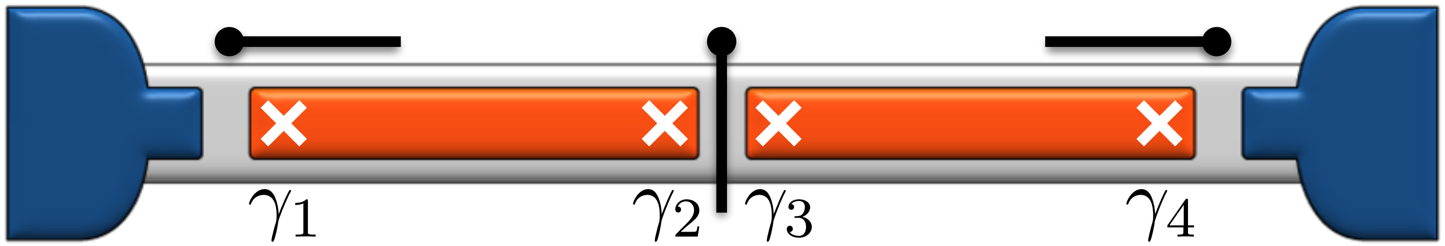

Answer must sharply distinguish these qubits!

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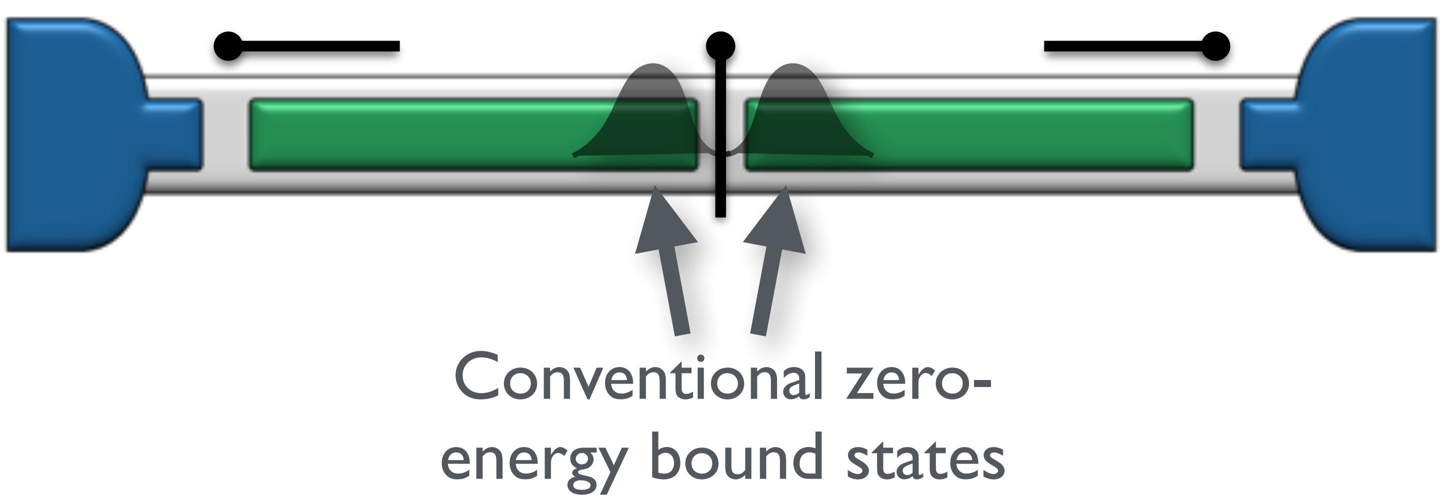

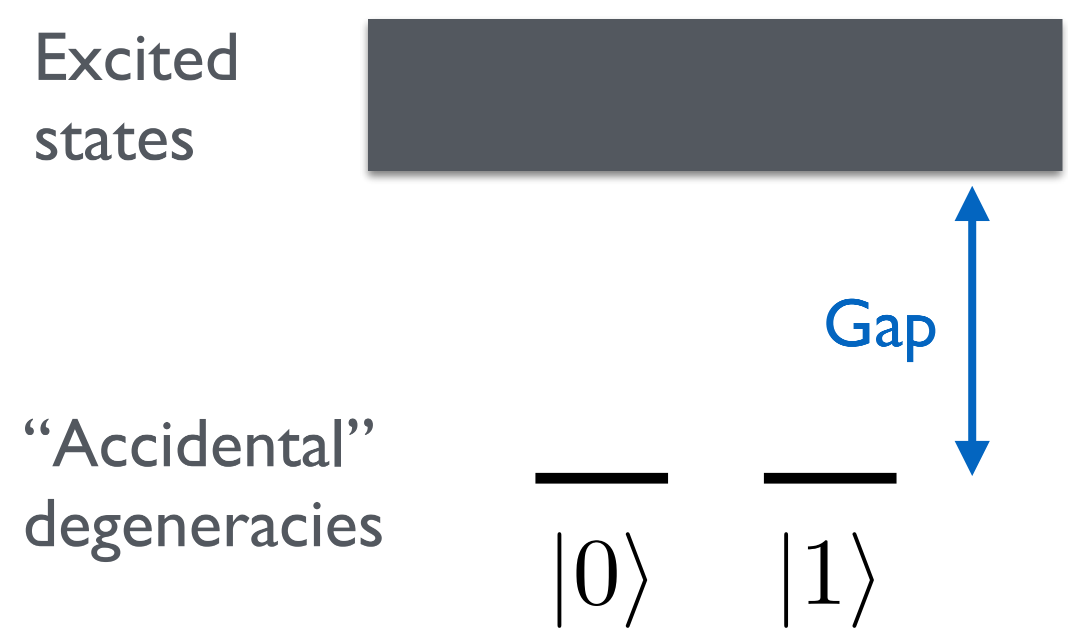

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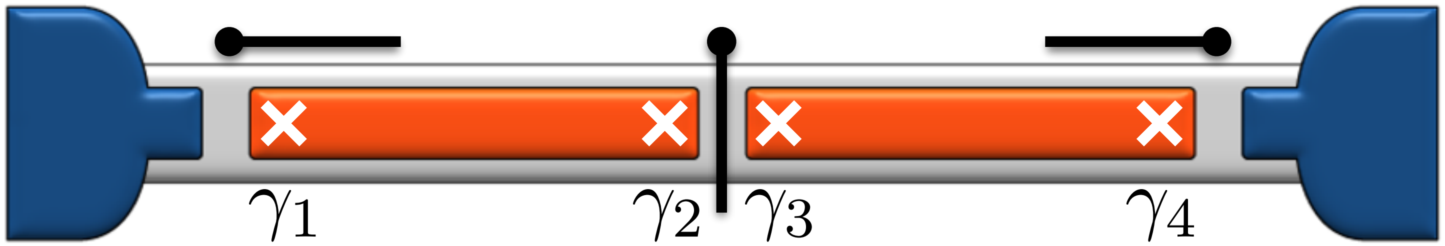

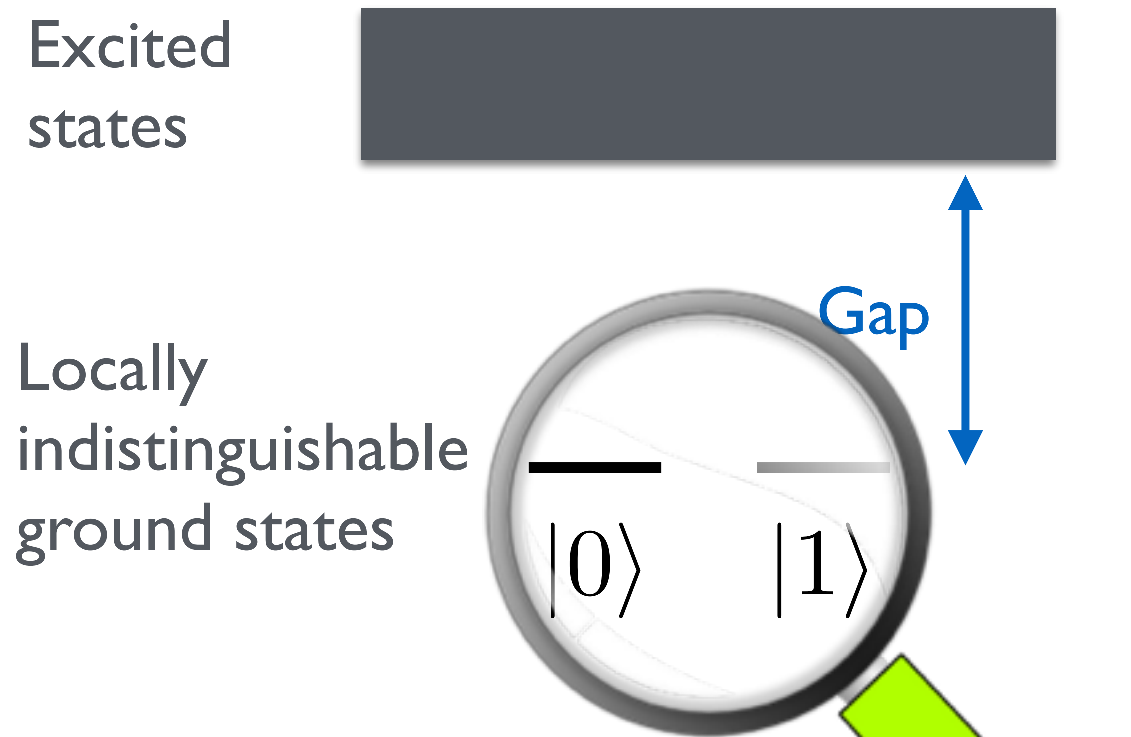

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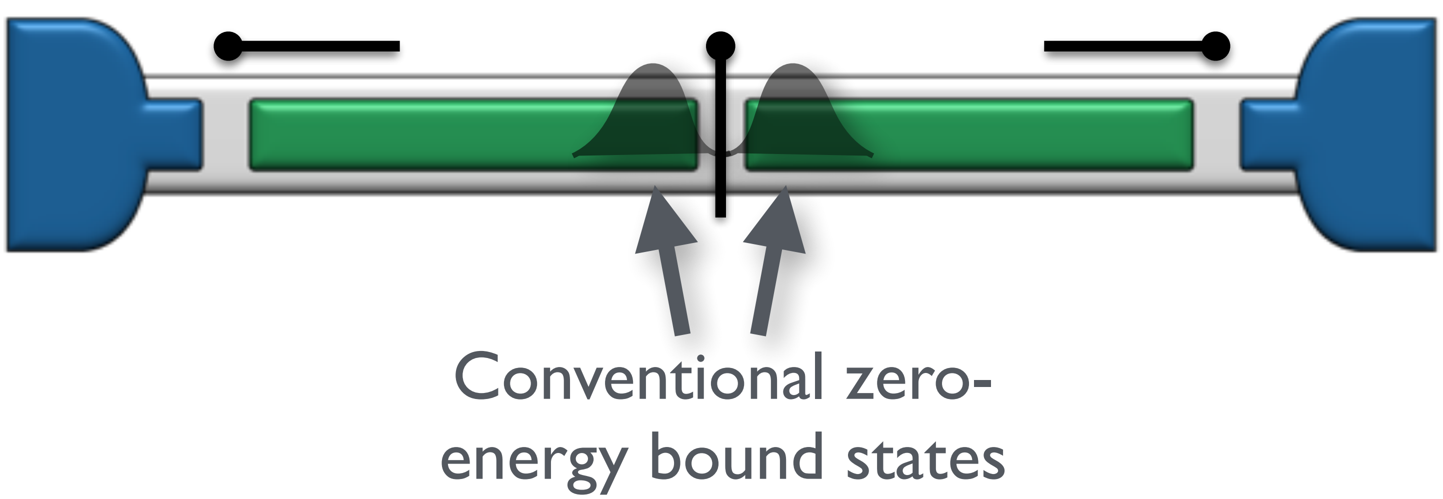
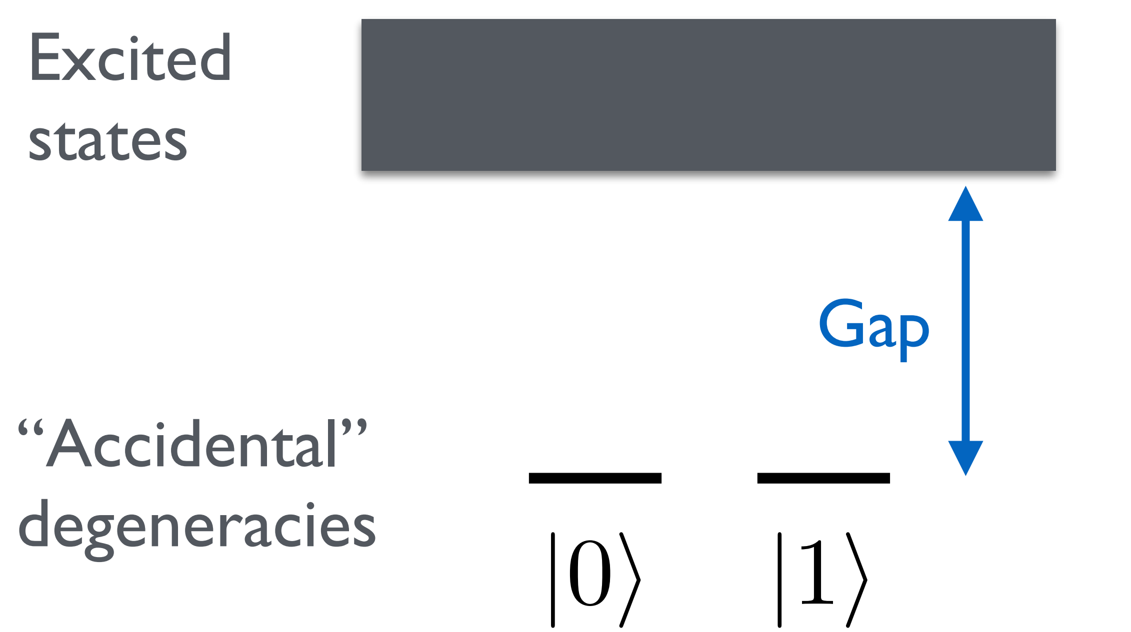
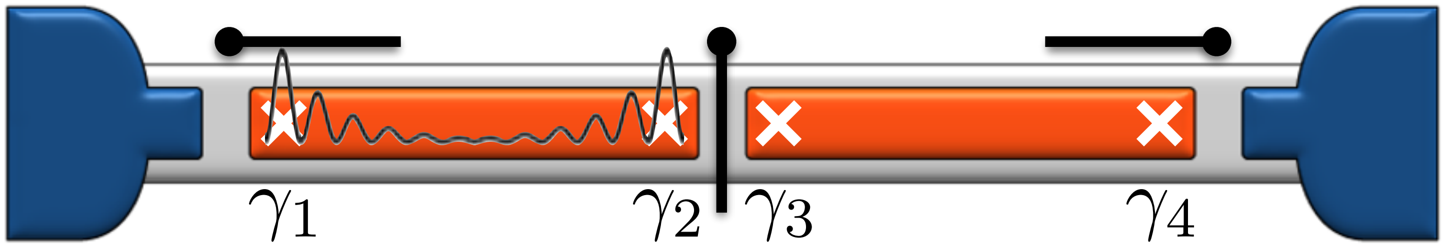
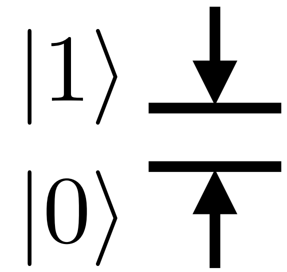


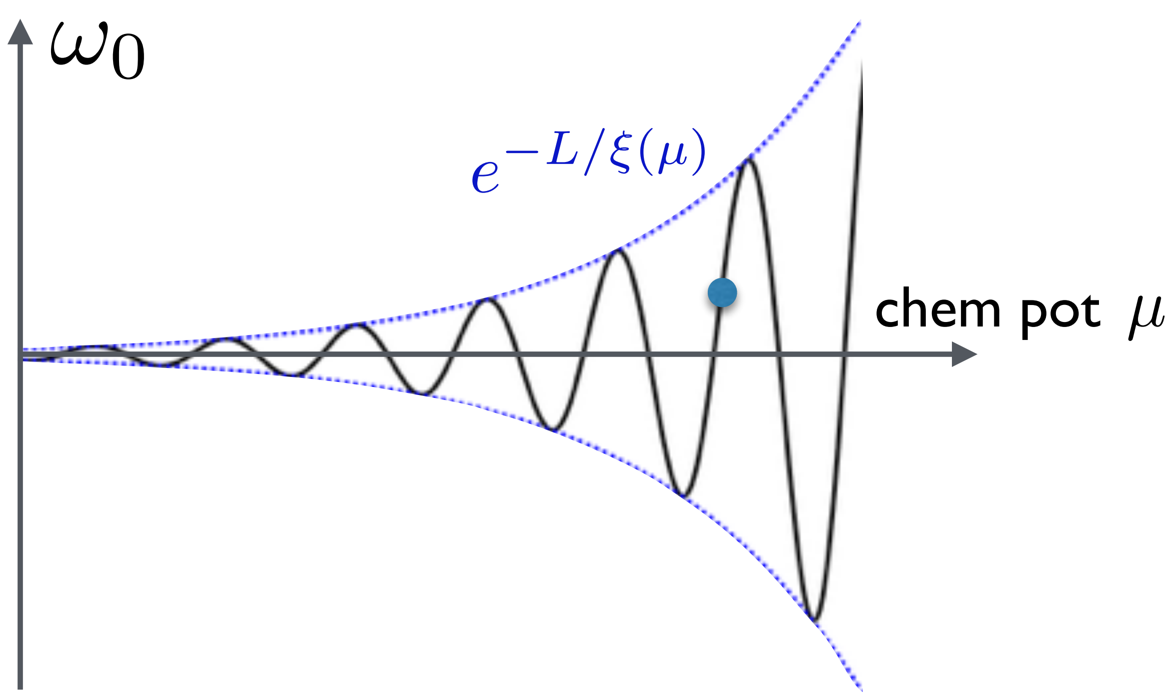


Peculiar noise sensitivity



$$\omega_0 \propto \cos(\kappa L) e^{-L/\xi}$$





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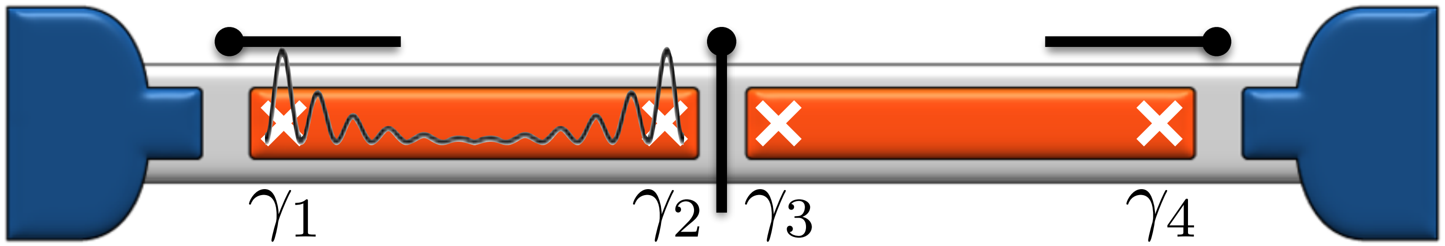

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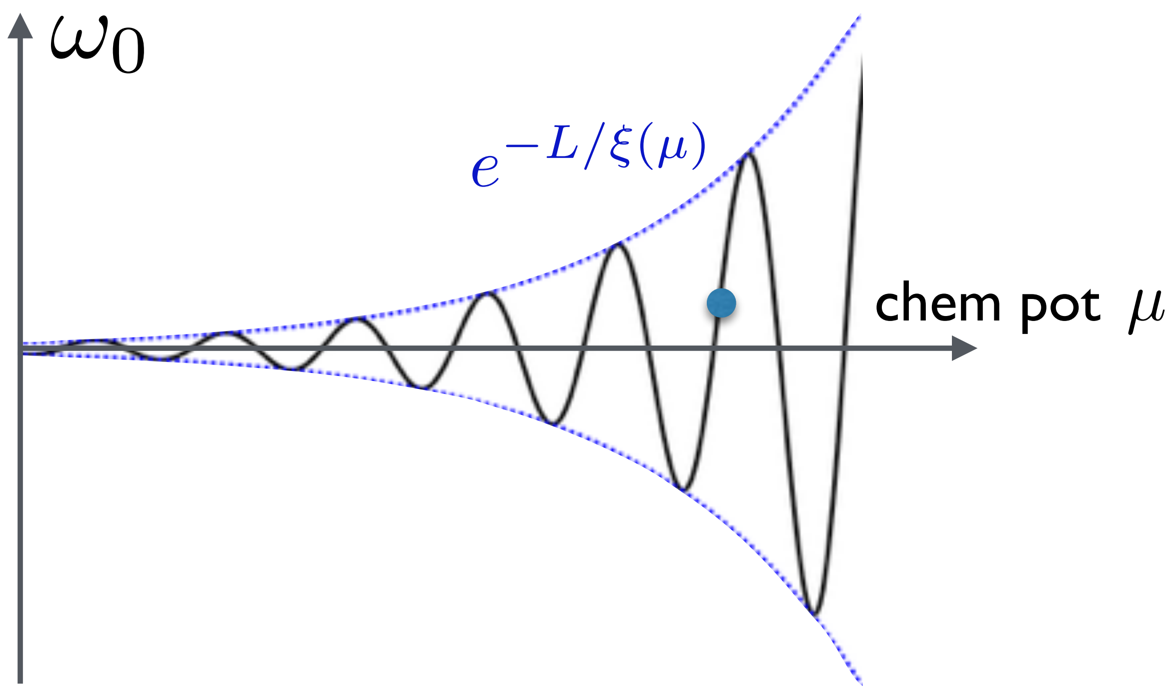
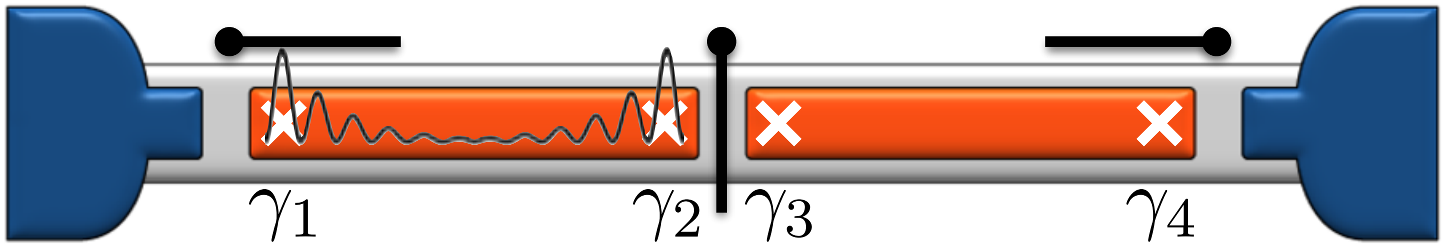
$|1\rangle$

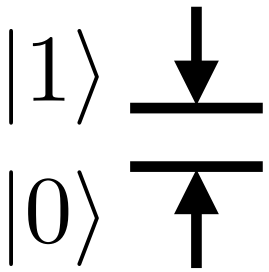
$|0\rangle$

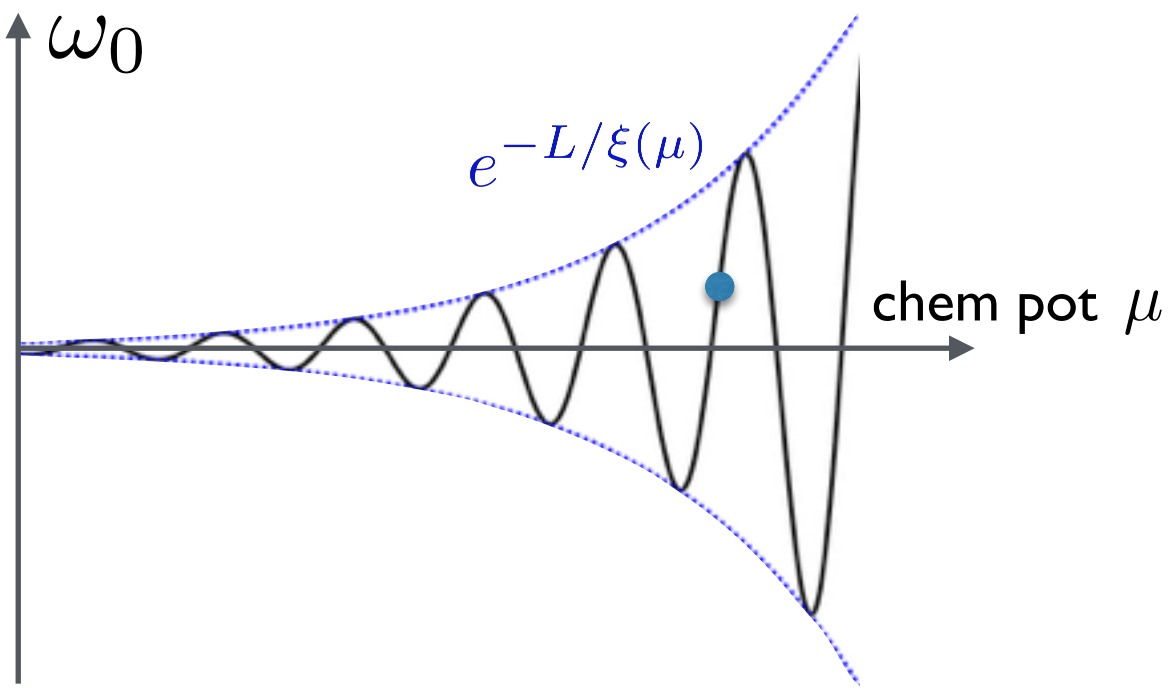


Peculiar noise sensitivity

$$\omega_0 \propto \cos(\kappa L) e^{-L/\xi}$$

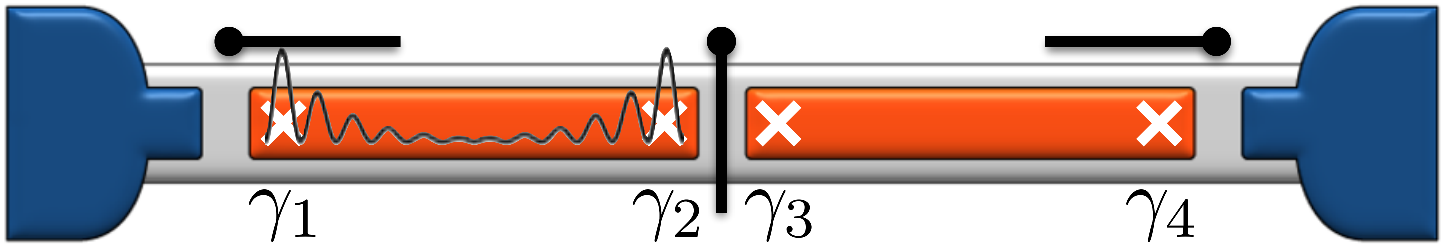




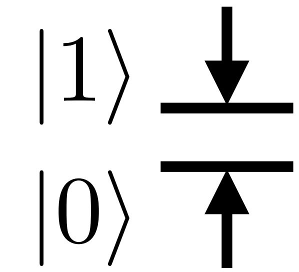


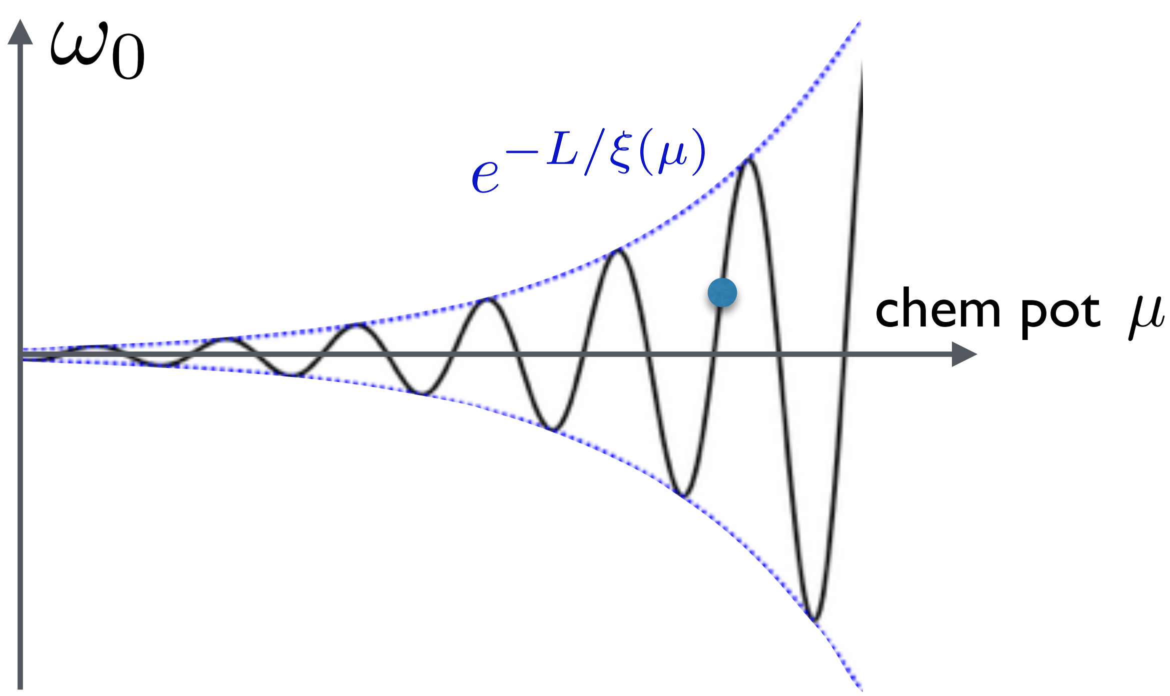
Time-averaged quantities & fluctuations deeply linked for topological qubit!

Peculiar noise sensitivity



$$\omega_0 \propto \cos(\kappa L) e^{-L/\xi}$$





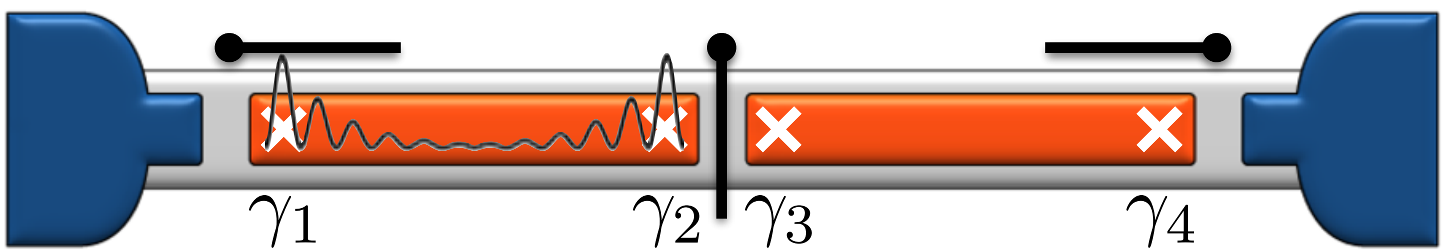
$$\omega_0 \sim \Delta E_{\text{typical}}$$

$$T_2 \sim \hbar/\Delta E_{\text{typical}}$$

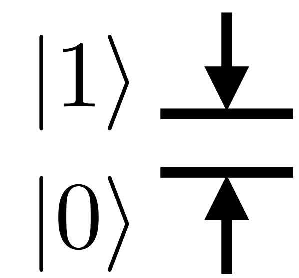
$$1/T_2 \sim \omega_0$$

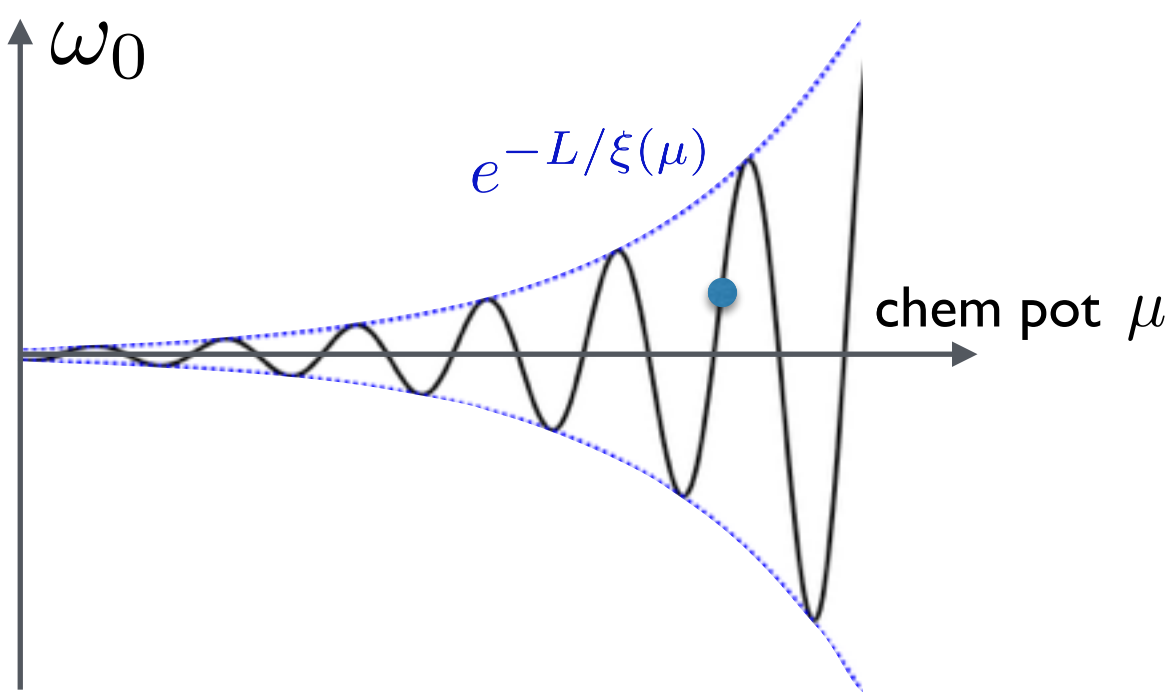
Time-averaged quantities & fluctuations deeply linked for topological qubit!

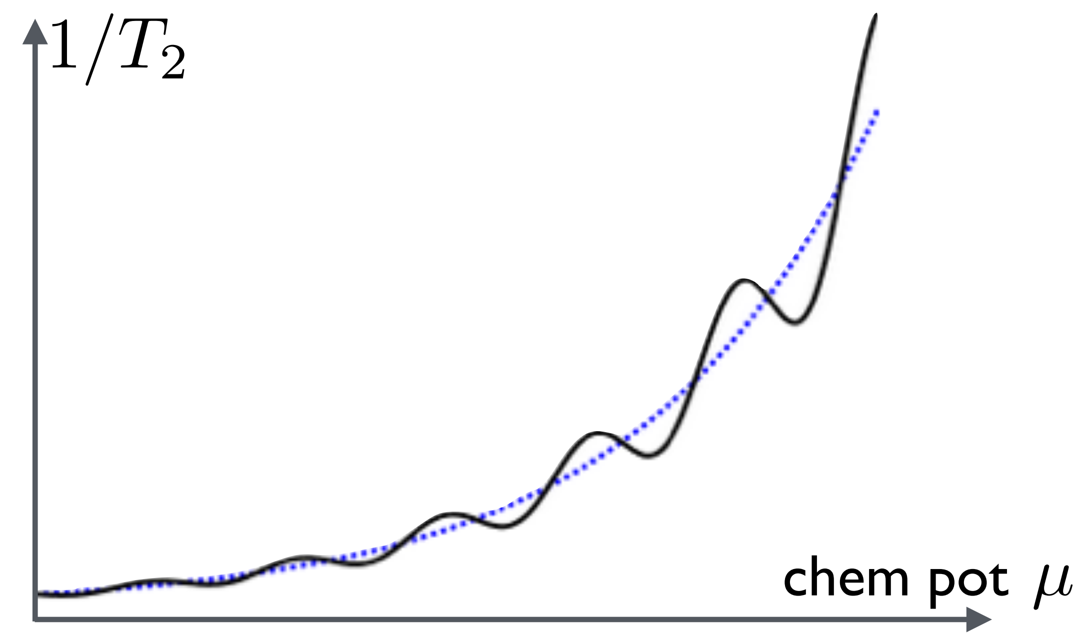
Peculiar noise sensitivity



$$\omega_0 \propto \cos(\kappa L) e^{-L/\xi}$$







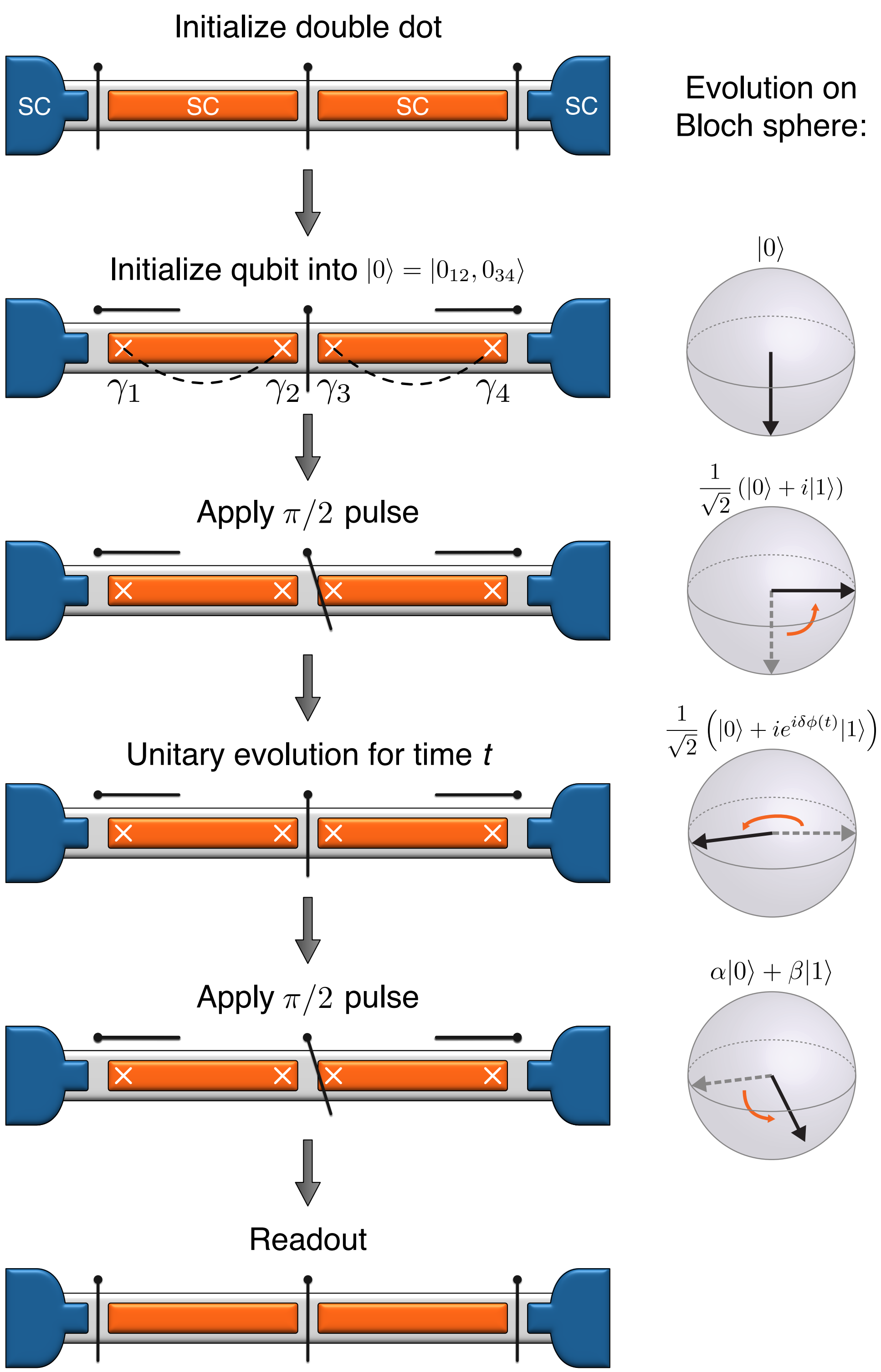
$$\omega_0 \sim \Delta E_{\text{typical}}$$

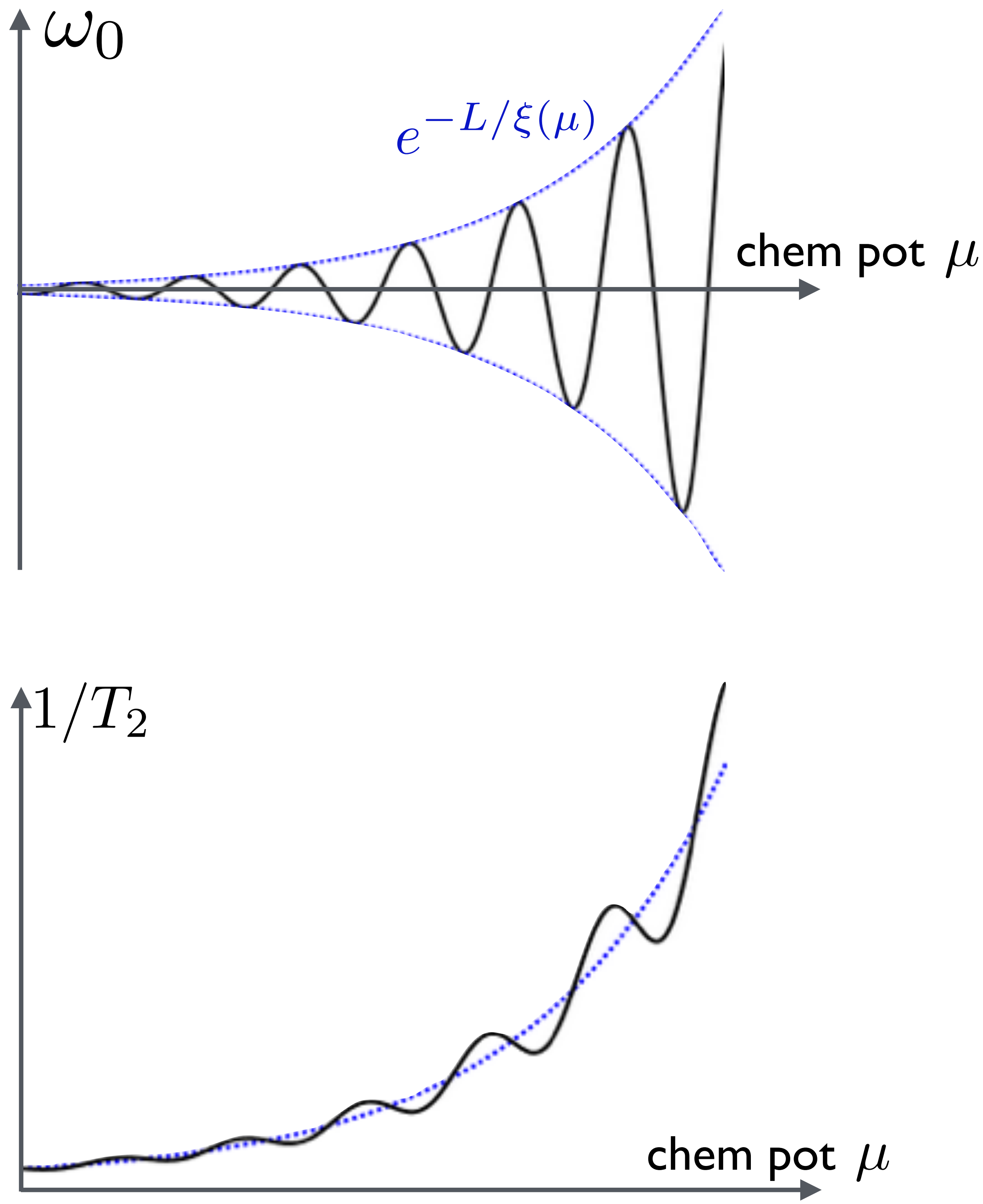
$$T_2 \sim \hbar / \Delta E_{\text{typical}}$$

$$1/T_2 \sim \omega_0$$

Time-averaged quantities & fluctuations deeply linked for topological qubit!

Measuring oscillation frequency & T_2



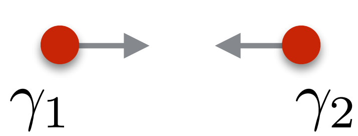


Time-averaged quantities & fluctuations deeply linked for topological qubit!

I. New all-electrical Majorana control scheme

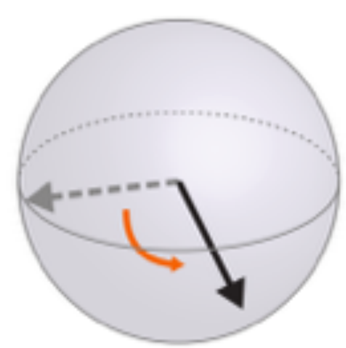
II. Majorana-control milestones

- [ ] Fusion-rule detection

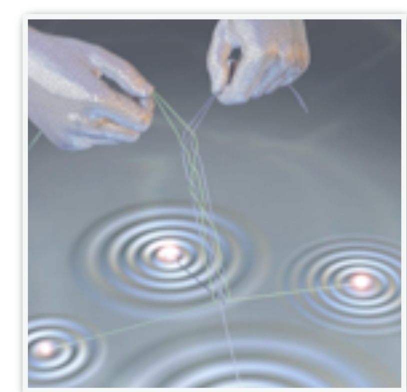


$$\sigma \times \sigma = I + \psi$$

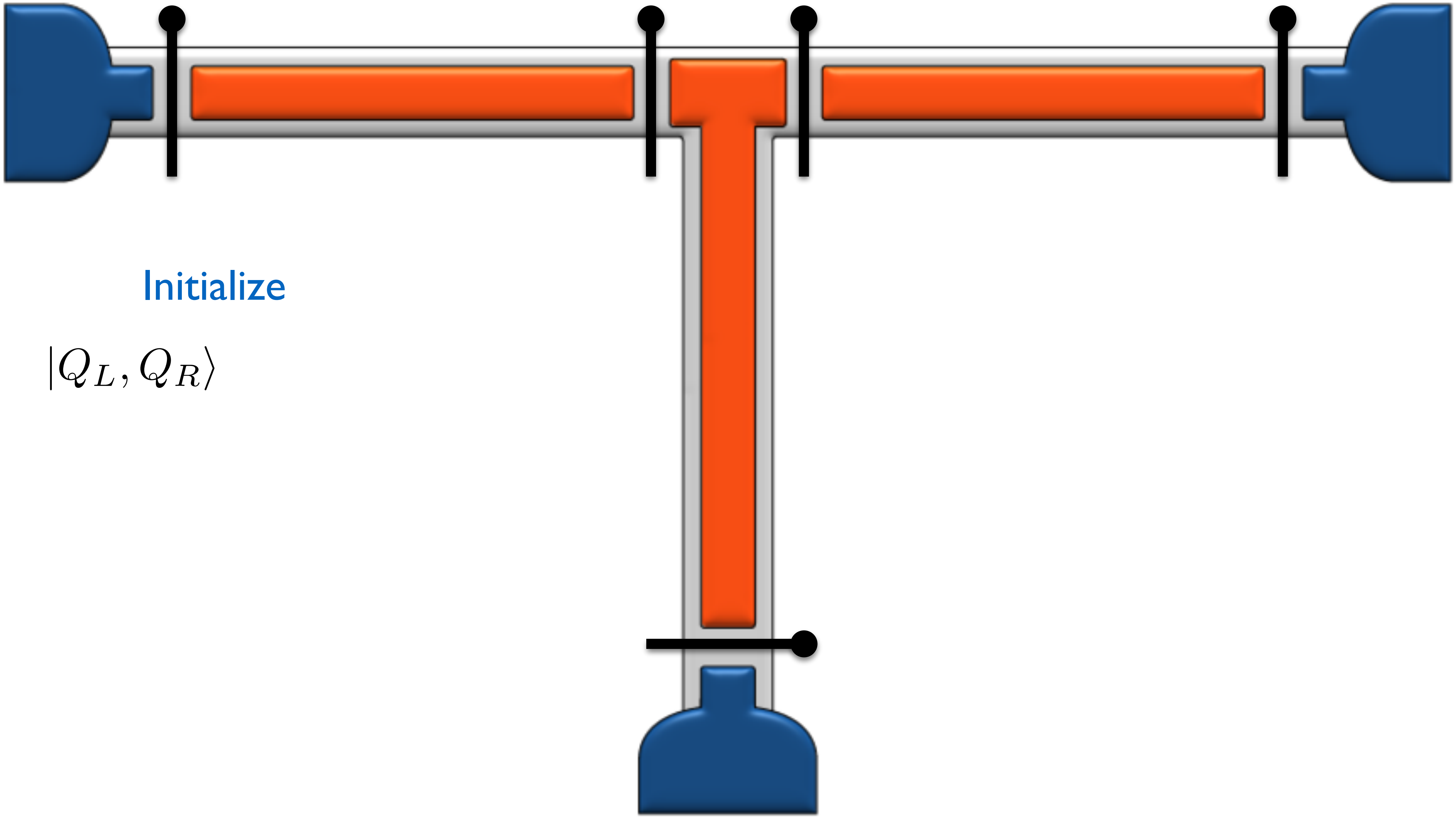
- [ ] Topological qubit validation



- [ ] Braiding



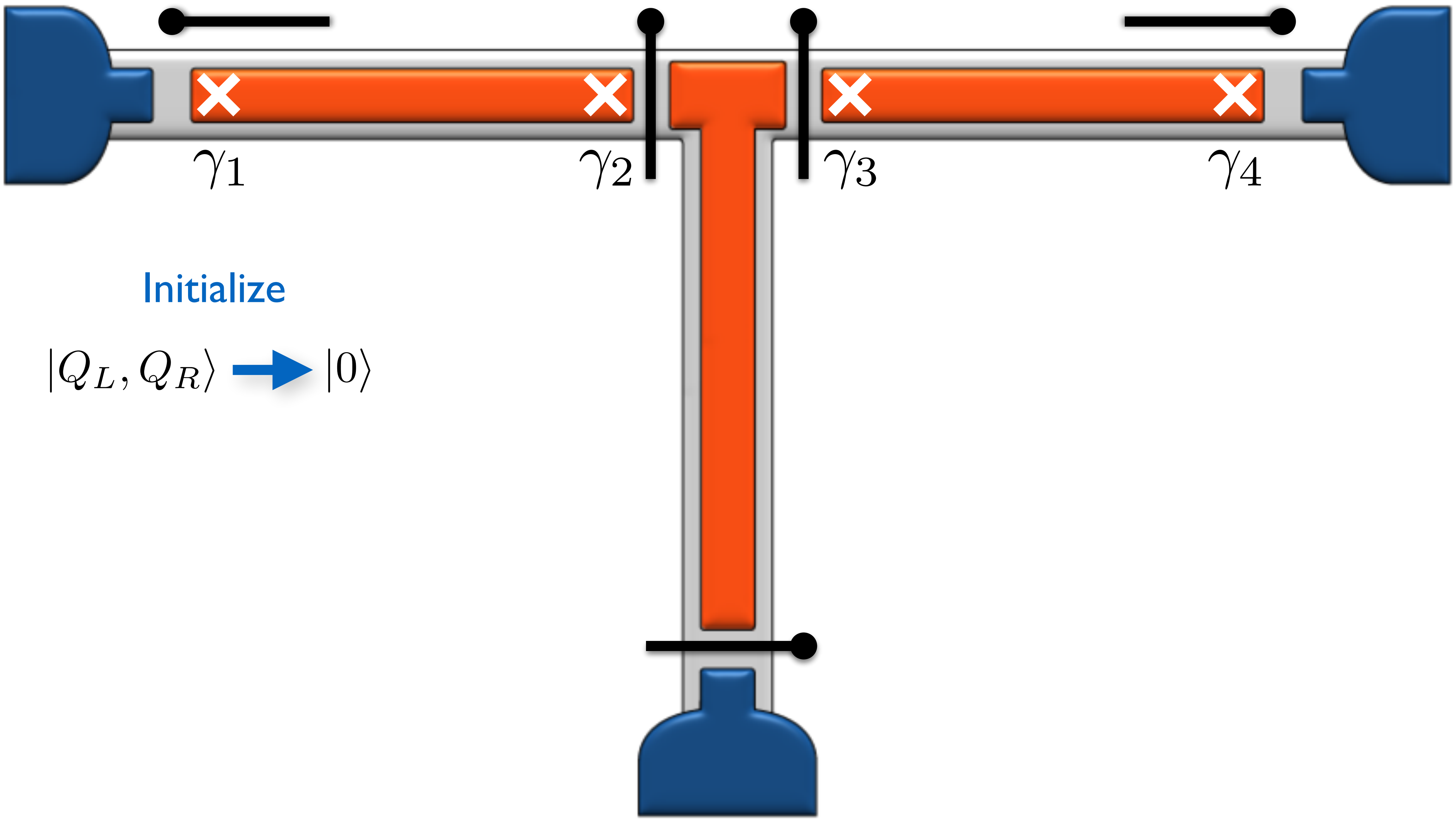
Braiding protocol



Initialize

$|Q_L, Q_R\rangle$

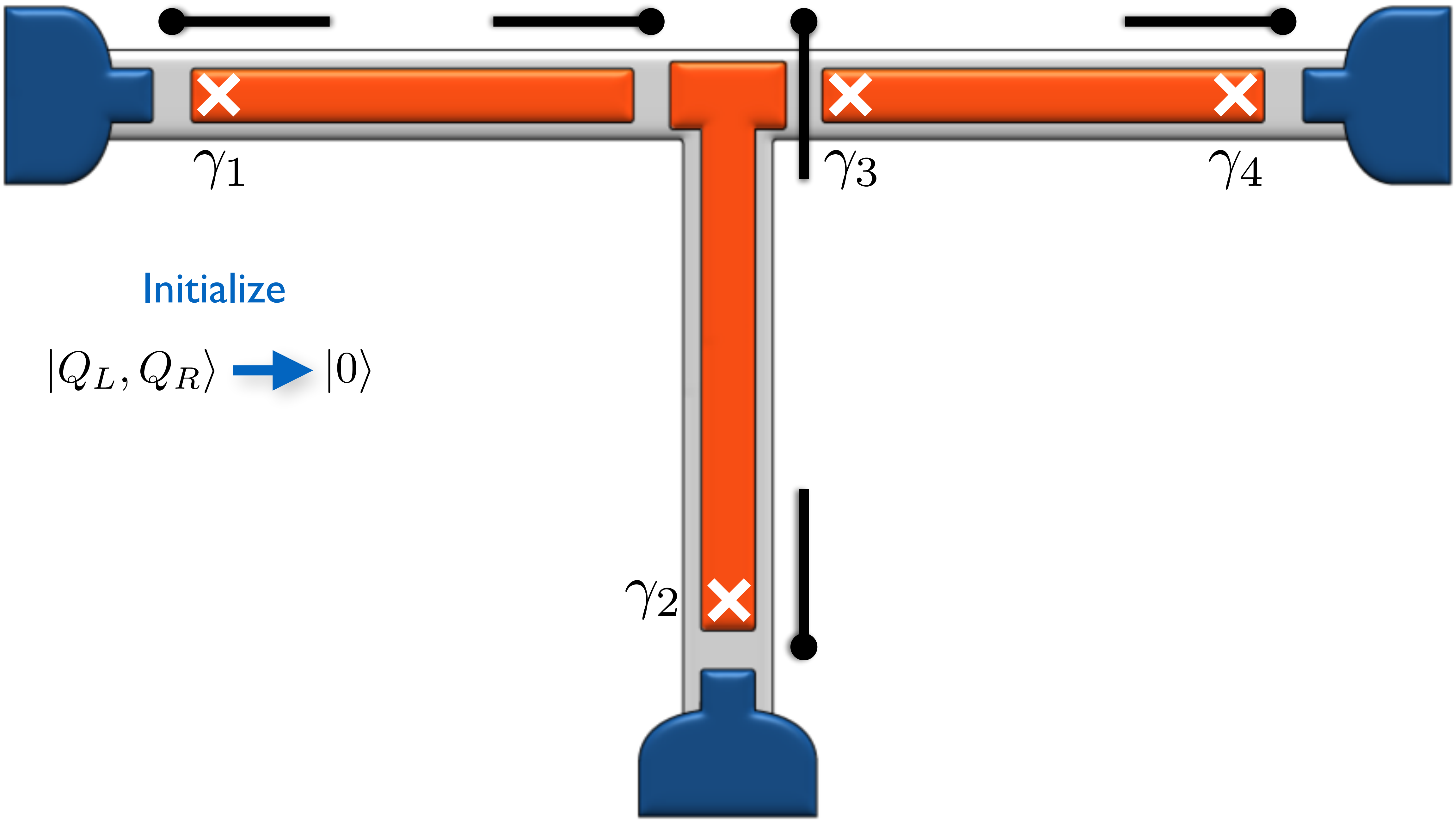
Braiding protocol



Initialize

$|Q_L, Q_R\rangle \rightarrow |0\rangle$

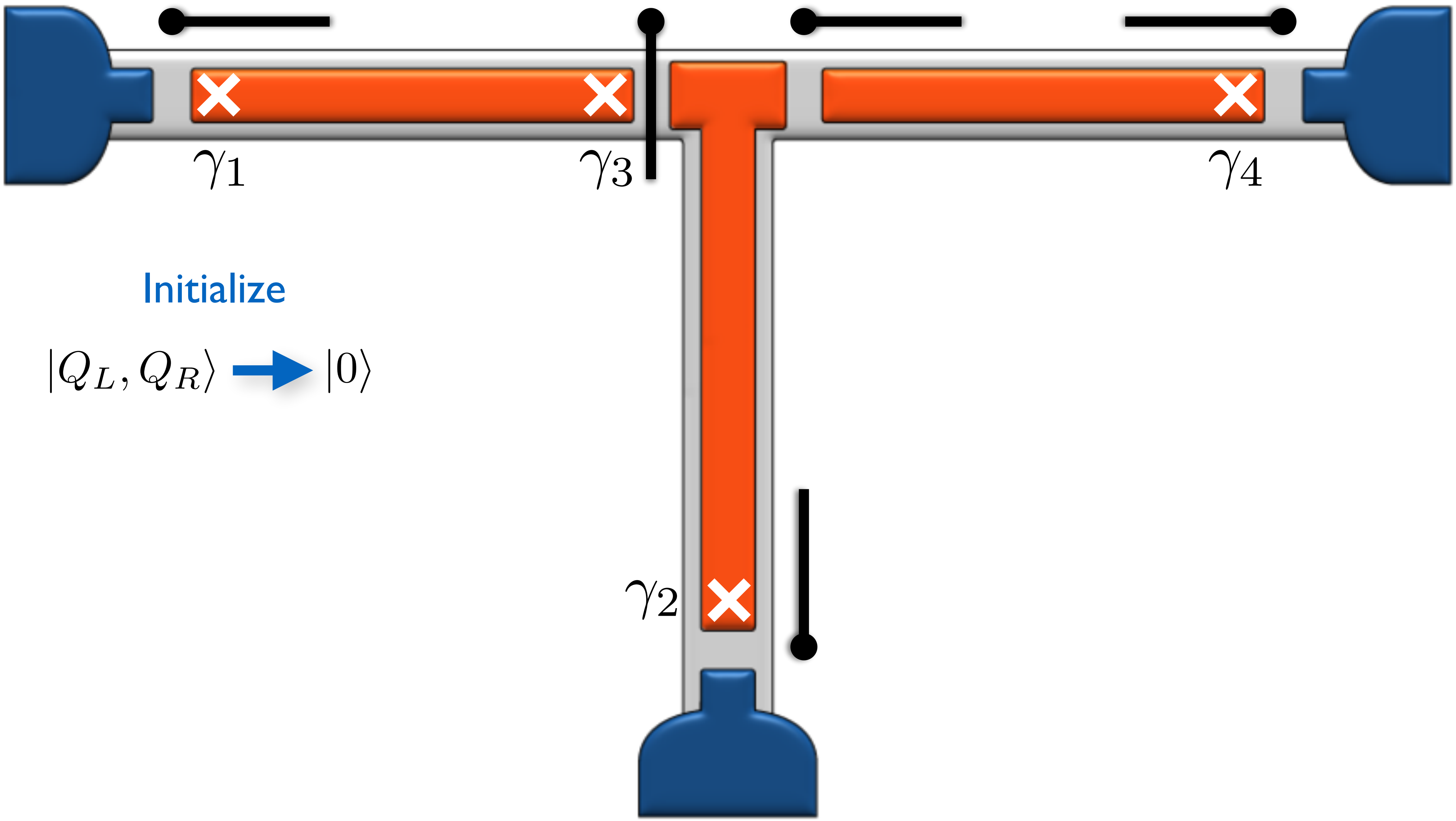
Braiding protocol



Initialize

$|Q_L, Q_R\rangle \rightarrow |0\rangle$

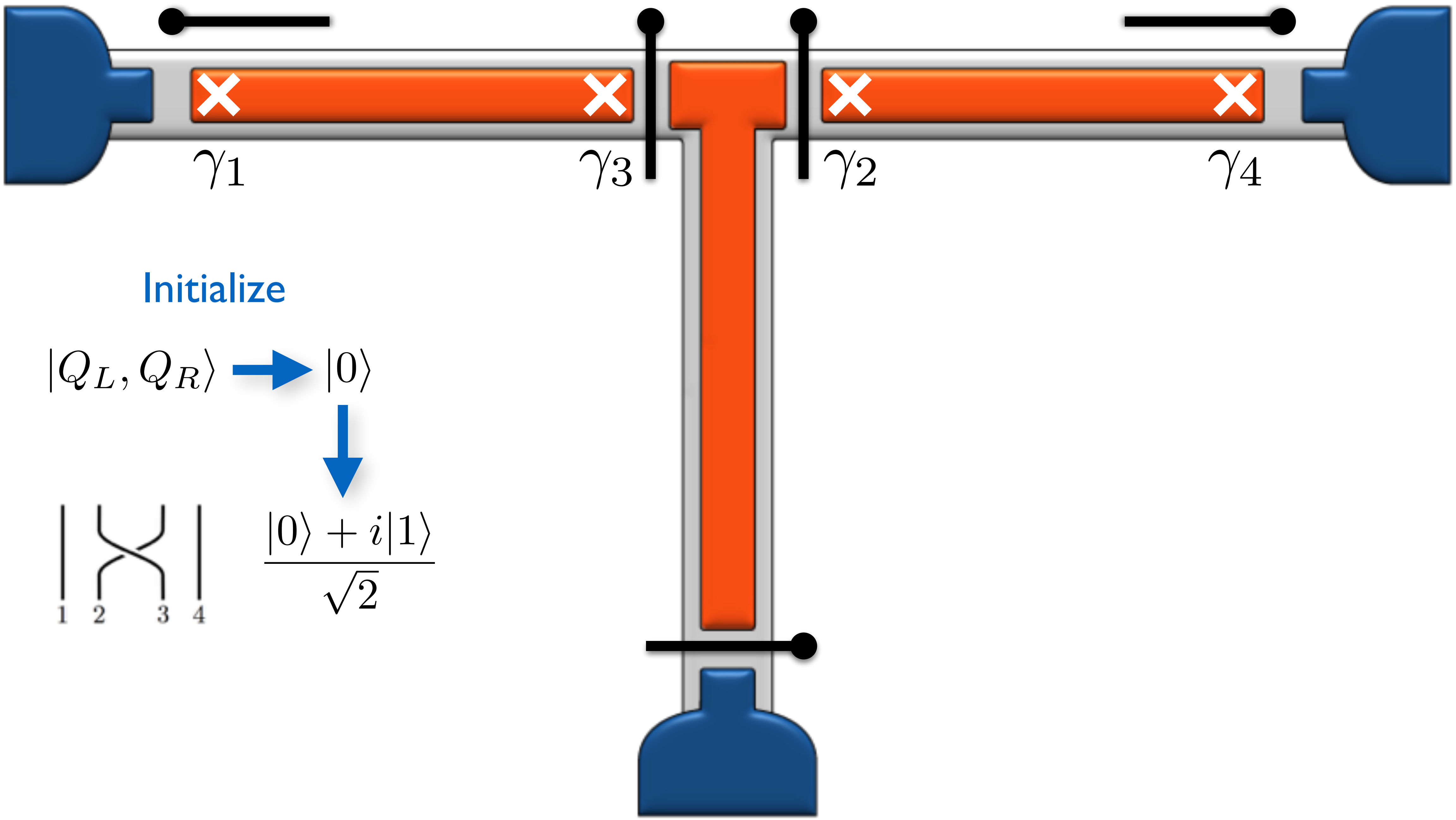
Braiding protocol



Initialize

$|Q_L, Q_R\rangle \rightarrow |0\rangle$

Braiding protocol



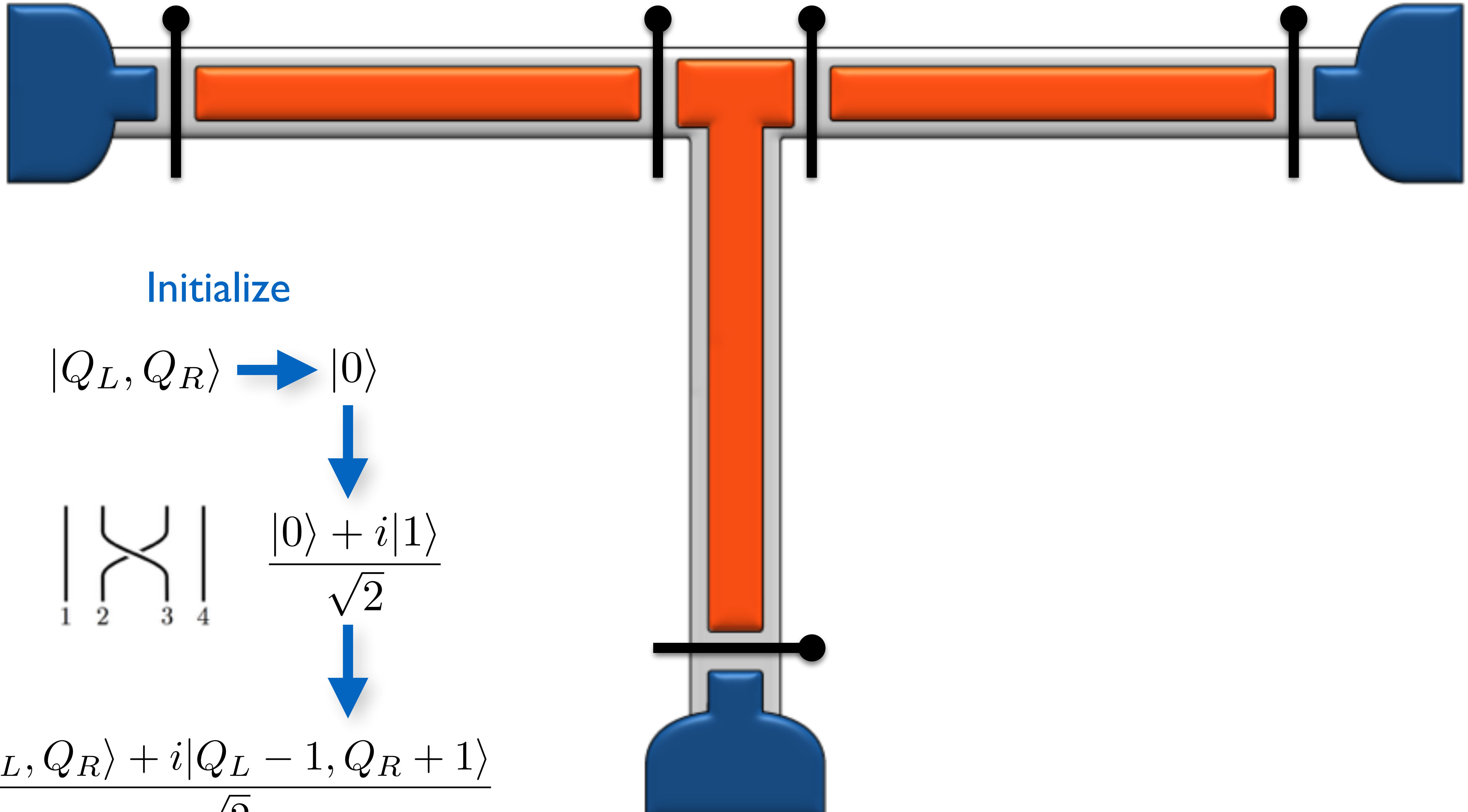
Initialize

$|Q_L, Q_R\rangle \rightarrow |0\rangle$

1 2 3 4

$$\frac{|0\rangle + i|1\rangle}{\sqrt{2}}$$

Braiding protocol



Initialize

$|Q_L, Q_R\rangle \rightarrow |0\rangle$

$$\downarrow$$

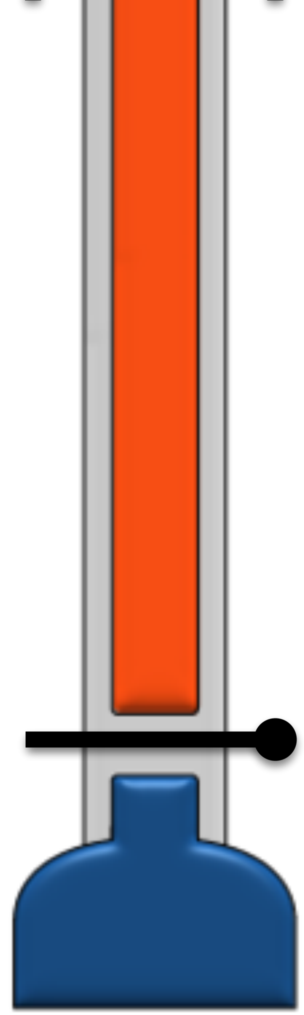
$$\frac{|0\rangle + i|1\rangle}{\sqrt{2}}$$

$$\downarrow$$

$$\frac{|Q_L, Q_R\rangle + i|Q_L - 1, Q_R + 1\rangle}{\sqrt{2}}$$

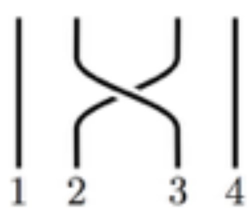
Readout (Probabilistic)

Braiding protocol



Initialize

$$|Q_L, Q_R\rangle \rightarrow |0\rangle$$



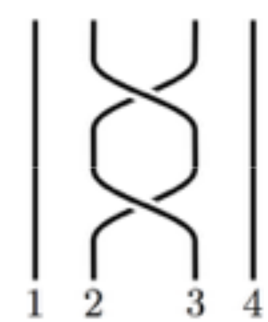
$$\frac{|0\rangle + i|1\rangle}{\sqrt{2}}$$

$$\frac{|Q_L, Q_R\rangle + i|Q_L - 1, Q_R + 1\rangle}{\sqrt{2}}$$

Readout (Probabilistic)

Initialize

$$|Q_L, Q_R\rangle \rightarrow |0\rangle$$



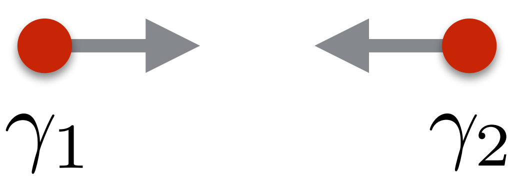
$$i|1\rangle$$

$$|Q_L - 1, Q_R + 1\rangle$$

Readout (Deterministic!)

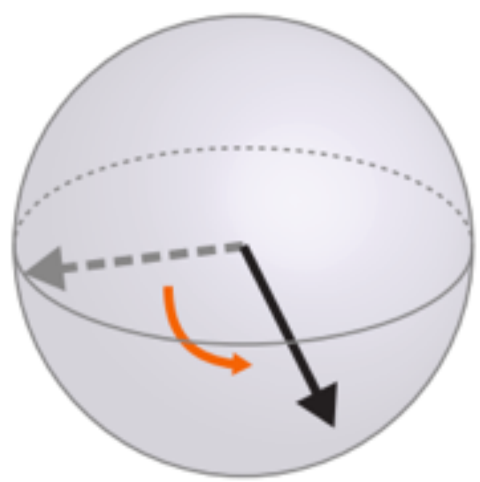
Milestones for the Majorana control era

Fusion-rule detection

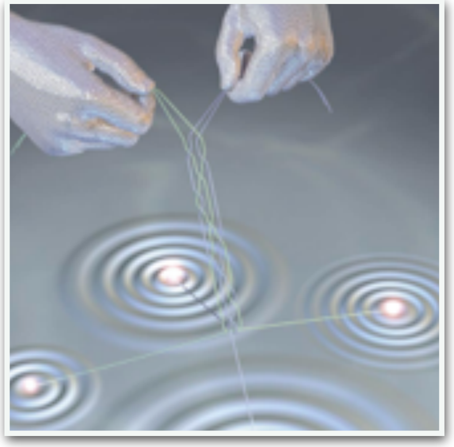


$$\sigma \times \sigma = I + \psi$$

Topological qubit validation



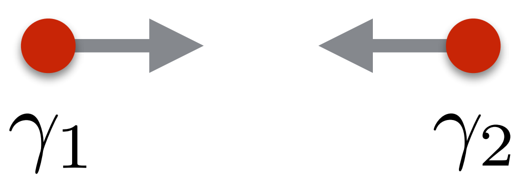
Braiding



Milestones for the Majorana control era

Realizable with **single-wire devices**!
(May generalize to other platforms/schemes)

Fusion-rule detection



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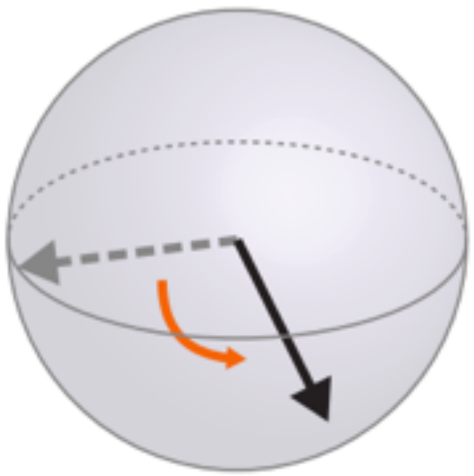
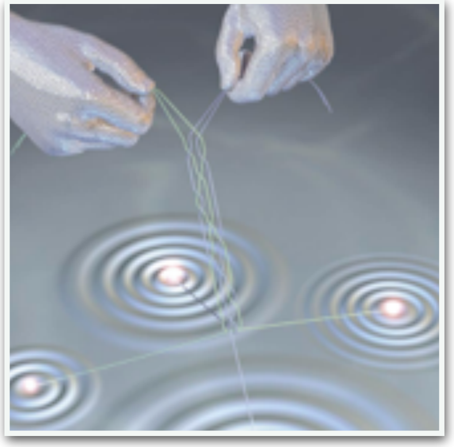
Topological qubit validation



Braiding



Milestones for the Majorana control era

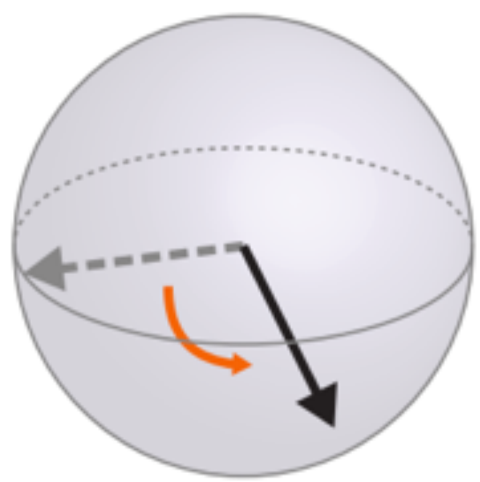
Realizable with **single-wire devices**!
(May generalize to other platforms/schemes)

Fusion-rule detection

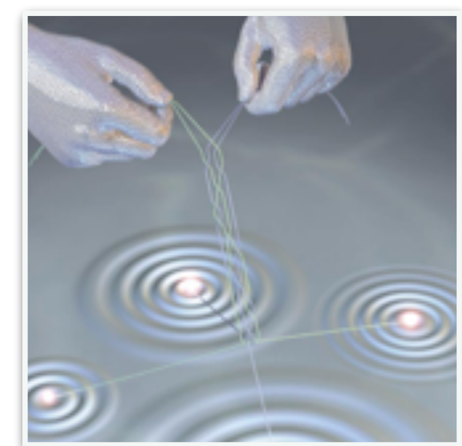
γ_1 γ_2

$$\sigma \times \sigma = I + \psi$$

Topological qubit validation



Braiding

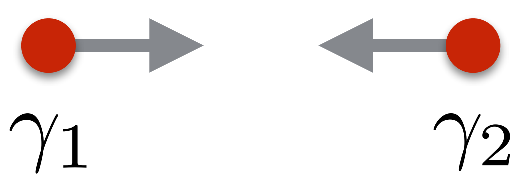


Reveals **defining** property of non-Abelian anyons; natural braiding precursor

Milestones for the Majorana control era

Realizable with **single-wire devices**!
(May generalize to other platforms/schemes)

☐ Fusion-rule detection



$$\sigma \times \sigma = I + \psi$$

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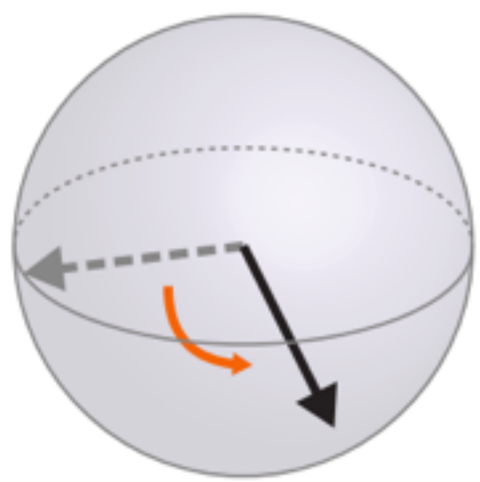
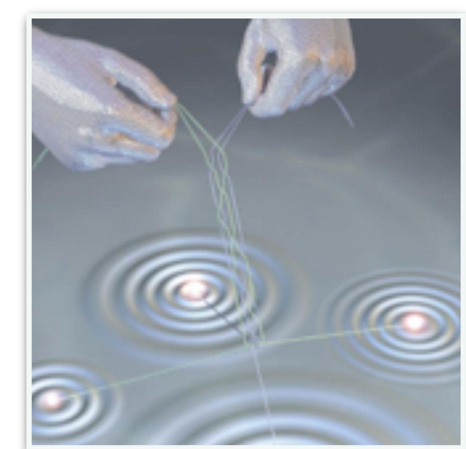


☐ Braiding



Reveals **defining** property of non-Abelian anyons; natural braiding precursor

Verify basic tenets of topological quantum computing

All protocols very difficult to mimic in non-topological setups.