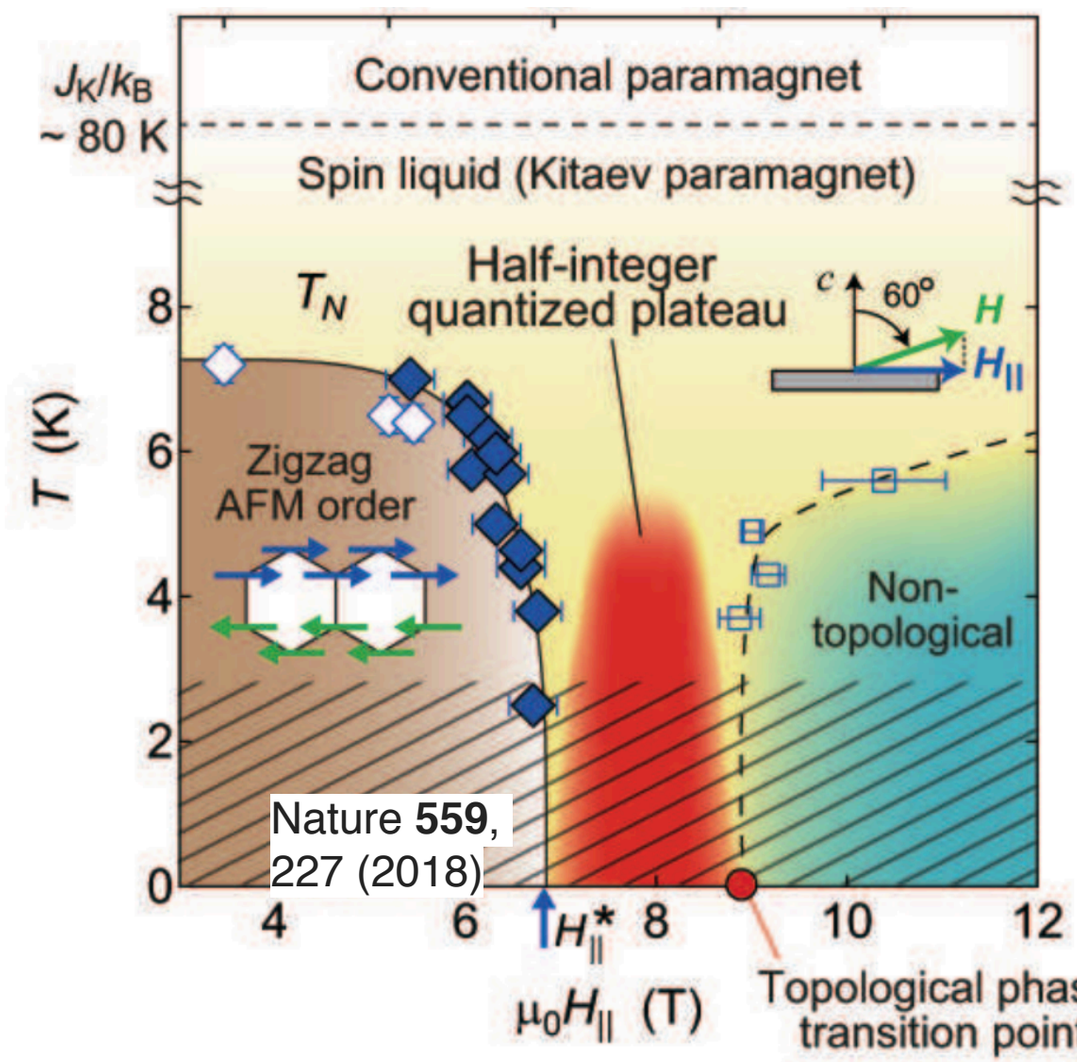
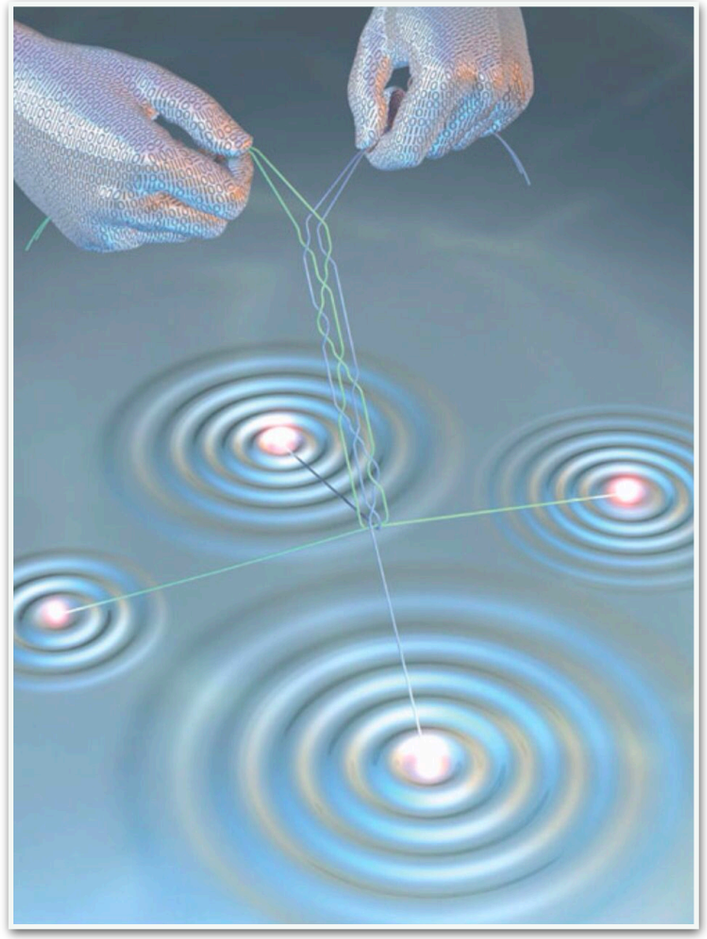
Towards topological quantum computing with Kitaev materials



Nature **559**, 227 (2018)



Jason Alicea, Caltech

INSTITUTE FOR QUANTUM INFORMATION AND MATTER

GORDON AND BETTY MOORE FOUNDATION

BURKE INSTITUTE

Topological quantum computation overview

Non-Abelian anyons

Anyons carry exotic
zero-energy modes

Locally indistinguishable ground states

Inherently fault-tolerant qubits!

$$|000\rangle, |001\rangle, \ldots$$

Alexei Kitaev

Non-Abelian anyons

Anyons carry exotic
zero-energy modes

Locally indistinguishable ground states

$$|000\rangle, |001\rangle, \ldots$$

Inherently fault-tolerant qubits!

Non-Abelian statistics

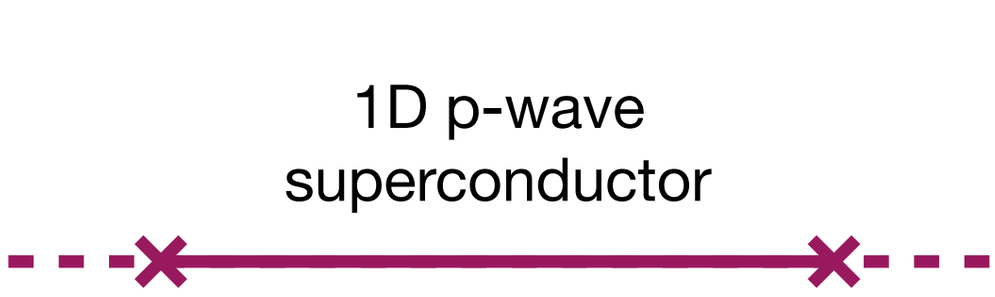
$$\psi_i$$

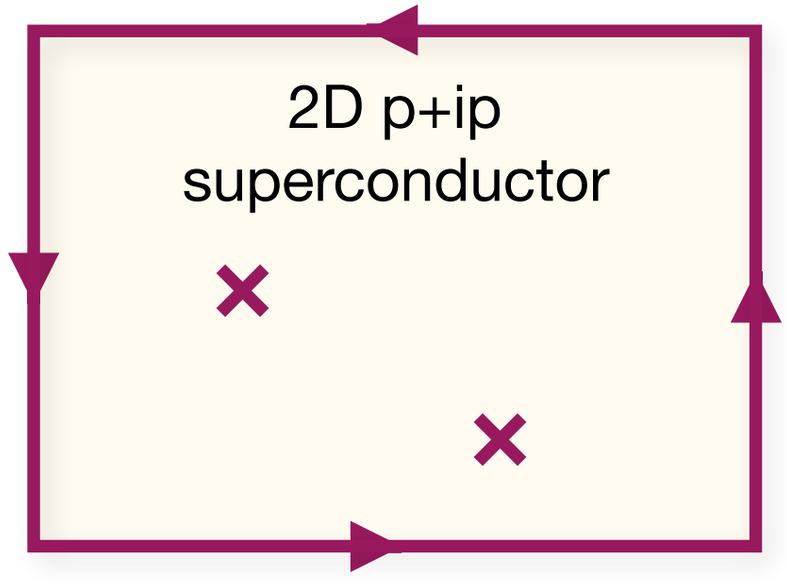
Inherently fault-tolerant gates!

Alexei Kitaev

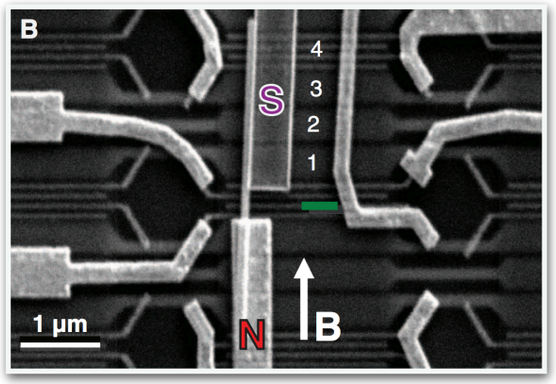
How to build the hardware?

“Designer” realizations

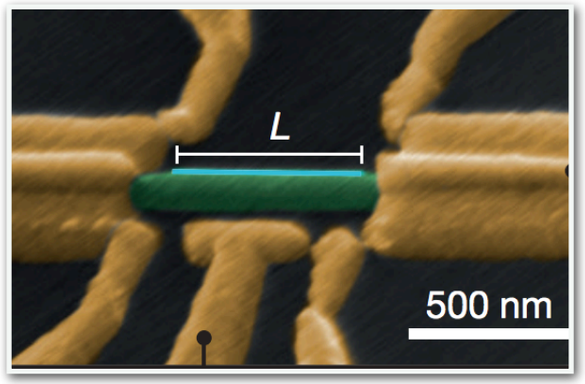




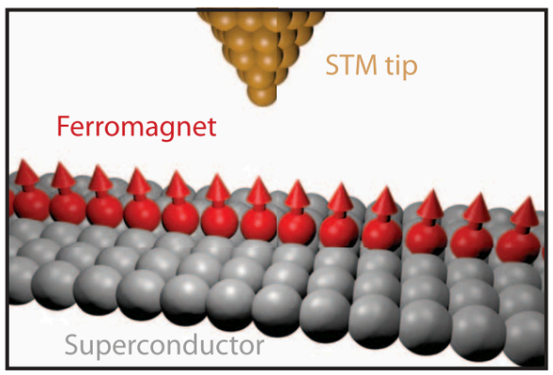
“Designer” realizations



Mourik et al. Science **336**, 1003 (2012)

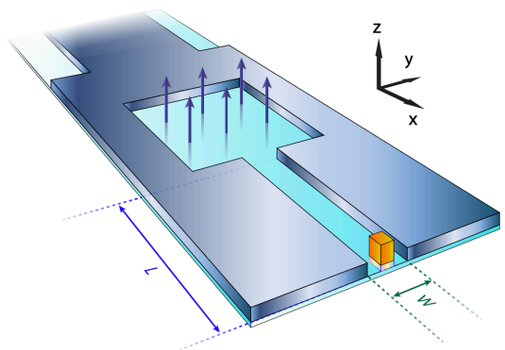


Albrecht et al. Nature **531**, 206 (2016)



Nadj-Perge et al. Science **346**, 602 (2014)

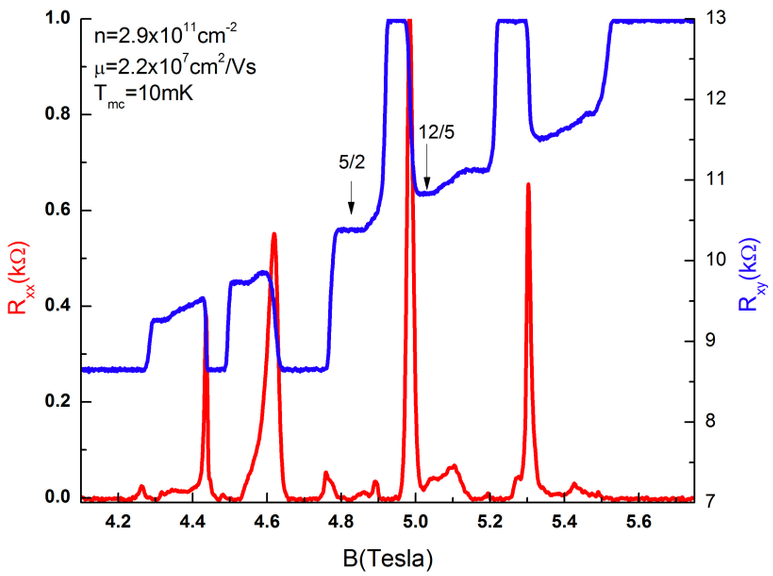
..and many more



Ren et al. arXiv:1809.03076

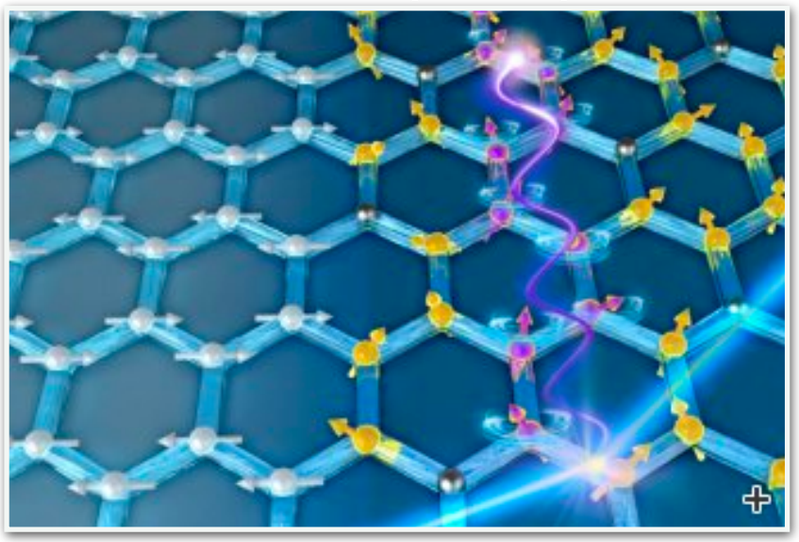
“Intrinsic” realizations

Fractional quantum Hall



http://manfragroup.org/non-abelian-phases-in-the-fractional-quantum-hall-regime/

Quantum spin liquids



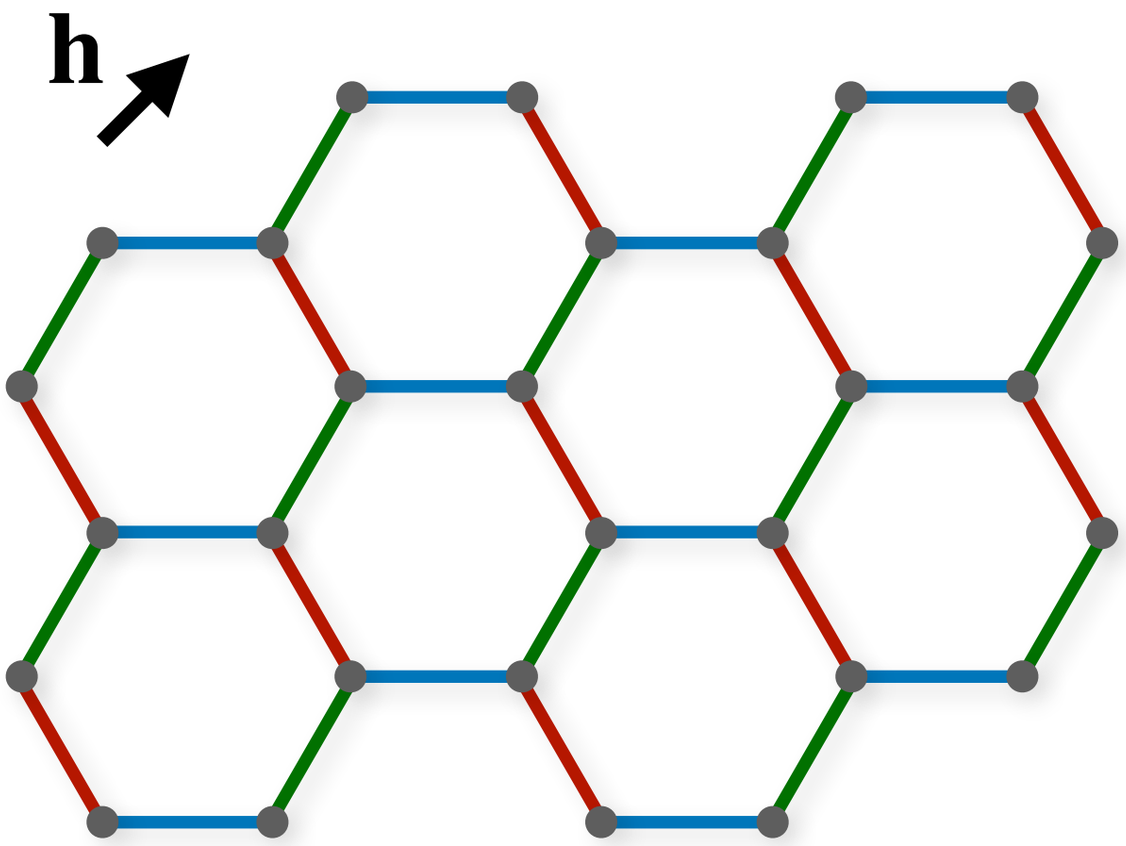
https://neutronsources.org/news/scientific-highlights/neutrons-exotic-particles.html

Non-Abelian spin liquids & “Kitaev materials”

Annals of Physics 321 (2006) 2–111

Anyons in an exactly solved model and beyond

Alexei Kitaev *

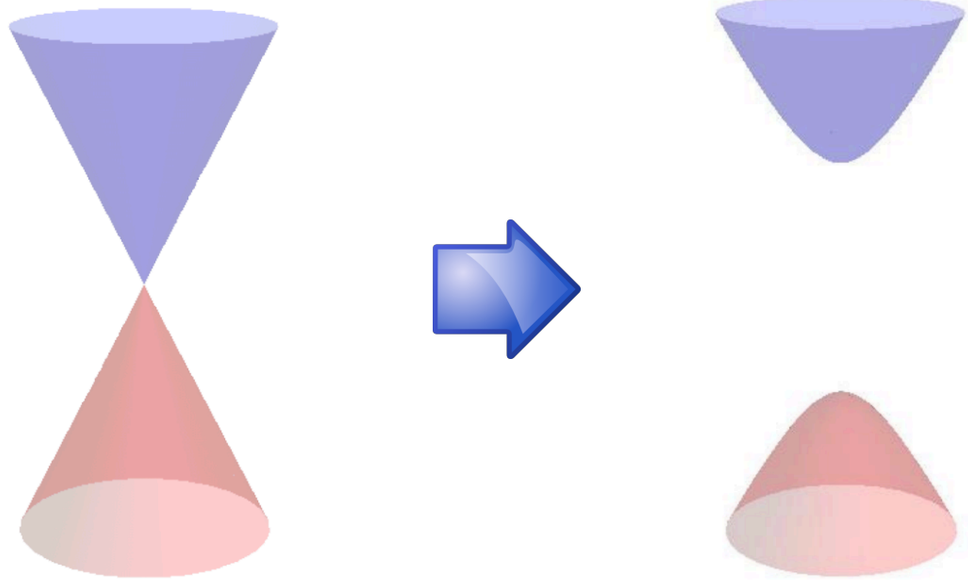


$$\mathbf{S}_\mathbf{r} = i\gamma_\mathbf{r}^0\vec{\gamma}_\mathbf{r} \rightarrow$$

~free Majorana fermions

Frustration

$$H = -J\left(\sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^x_\mathbf{r} S^x_{\mathbf{r}'} + \sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^y_\mathbf{r} S^y_{\mathbf{r}'} + \sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^z_\mathbf{r} S^z_{\mathbf{r}'}\right) - \sum_\mathbf{r} \mathbf{h}\cdot\mathbf{S}_\mathbf{r}$$



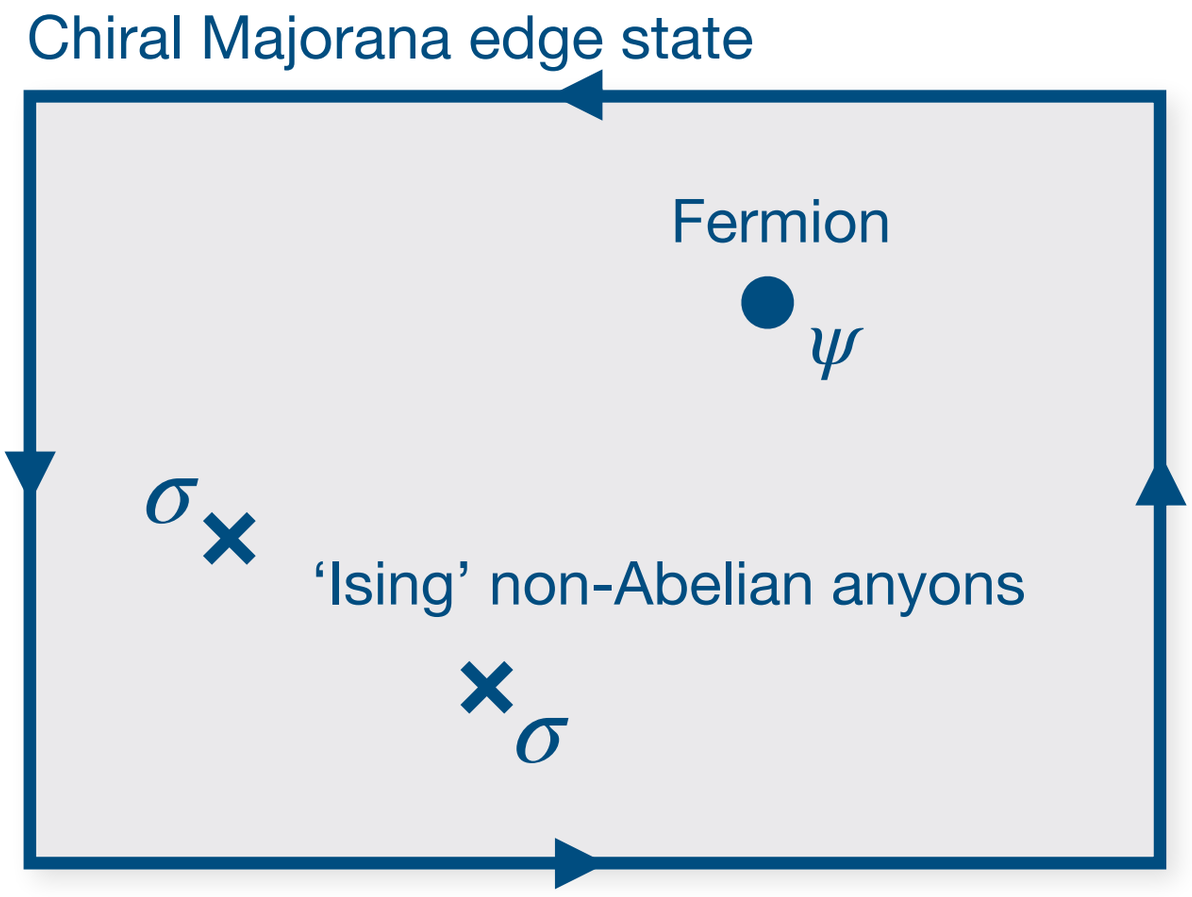
Gapless spin liquid

Gapped, **non-Abelian** spin liquid!

Annals of Physics 321 (2006) 2–111

Anyons in an exactly solved model and beyond

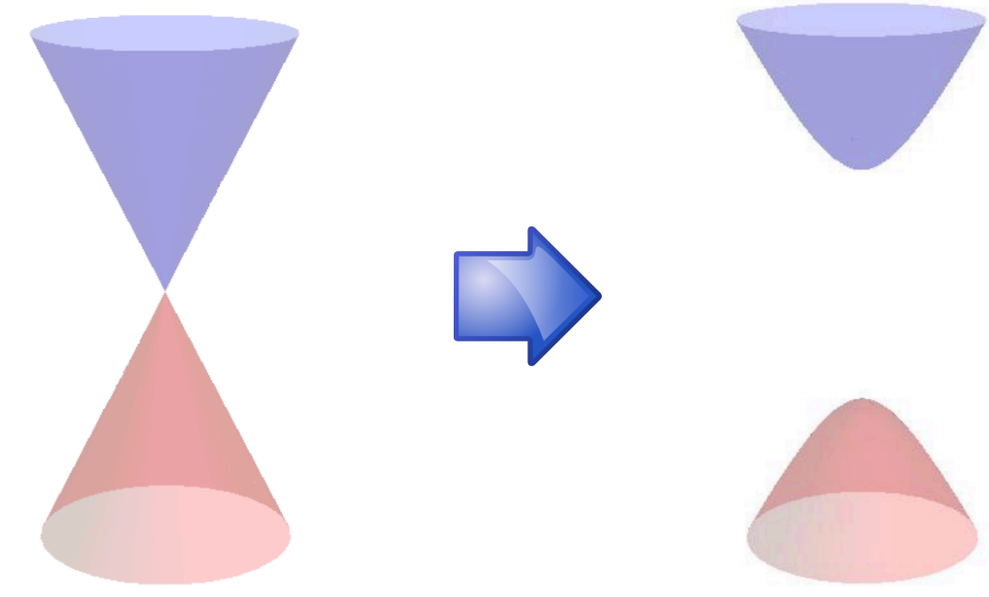
Alexei Kitaev *



$$H = -J\left(\sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^x_{\mathbf{r}} S^x_{\mathbf{r}'} + \sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^y_{\mathbf{r}} S^y_{\mathbf{r}'} + \sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^z_{\mathbf{r}} S^z_{\mathbf{r}'}\right) - \sum_{\mathbf{r}} \mathbf{h}\cdot\mathbf{S}_{\mathbf{r}}$$

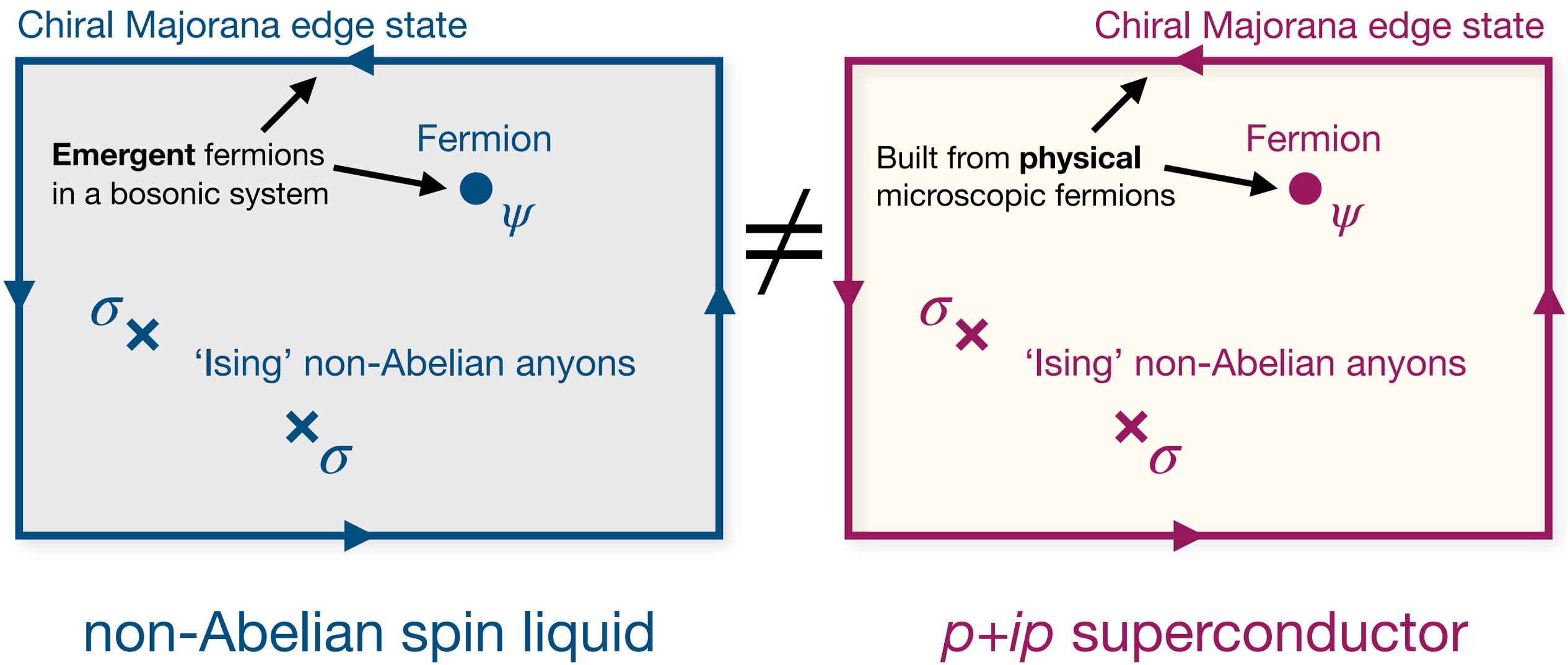
$$\mathbf{S}_{\mathbf{r}} = i\gamma^0_{\mathbf{r}}\vec{\gamma}_{\mathbf{r}} \rightarrow$$

~free Majorana fermions



Gapless spin liquid

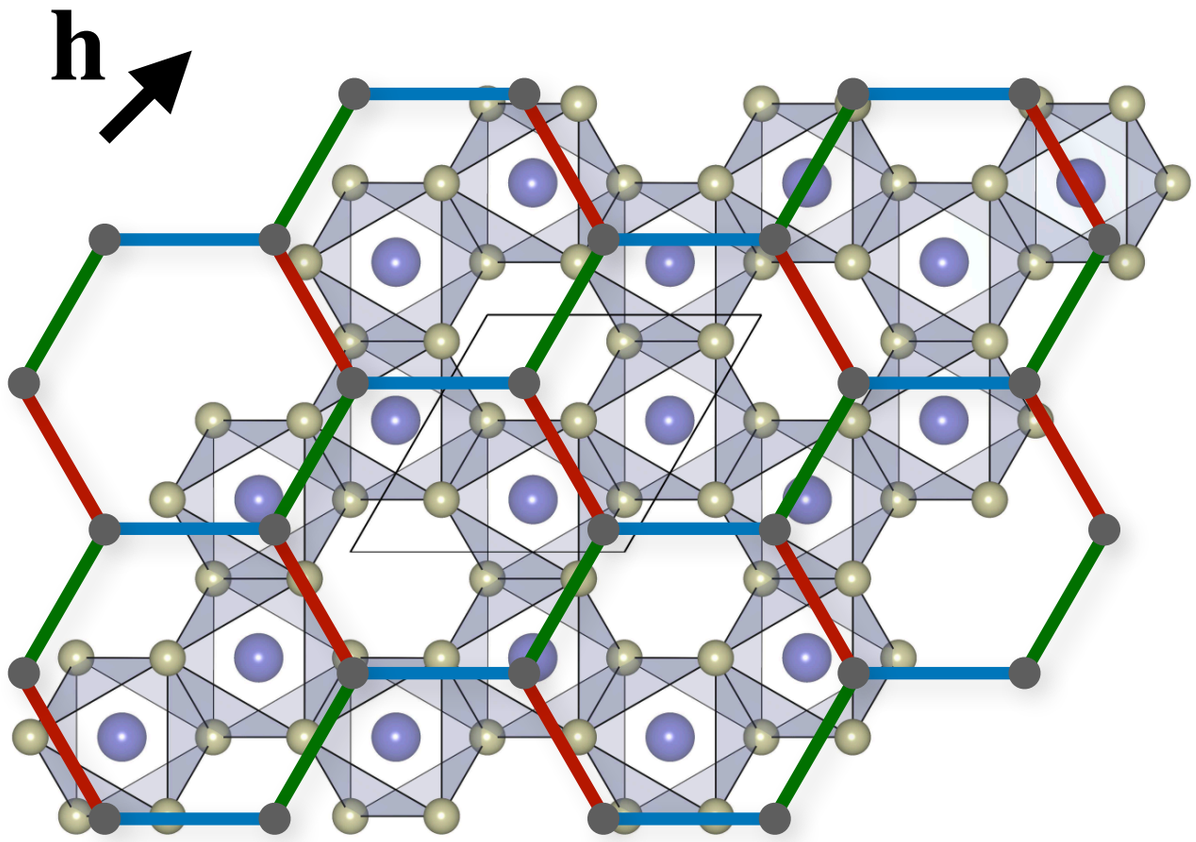
Gapped, **non-Abelian** spin liquid!



non-Abelian spin liquid

p+*ip* superconductor

Towards experimental reality



Plumb et al., PRB **90**, 041112 (2014)

$$H = -J\left(\sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^x_{\mathbf{r}} S^x_{\mathbf{r}'} + \sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^y_{\mathbf{r}} S^y_{\mathbf{r}'} + \sum_{\langle \mathbf{r}\mathbf{r}'\rangle} S^z_{\mathbf{r}} S^z_{\mathbf{r}'}\right) - \sum_{\mathbf{r}} \mathbf{h}\cdot\mathbf{S}_{\mathbf{r}} \quad +\cdots$$

Focus here: α-$RuCl_3$

PRL **102,** 017205 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

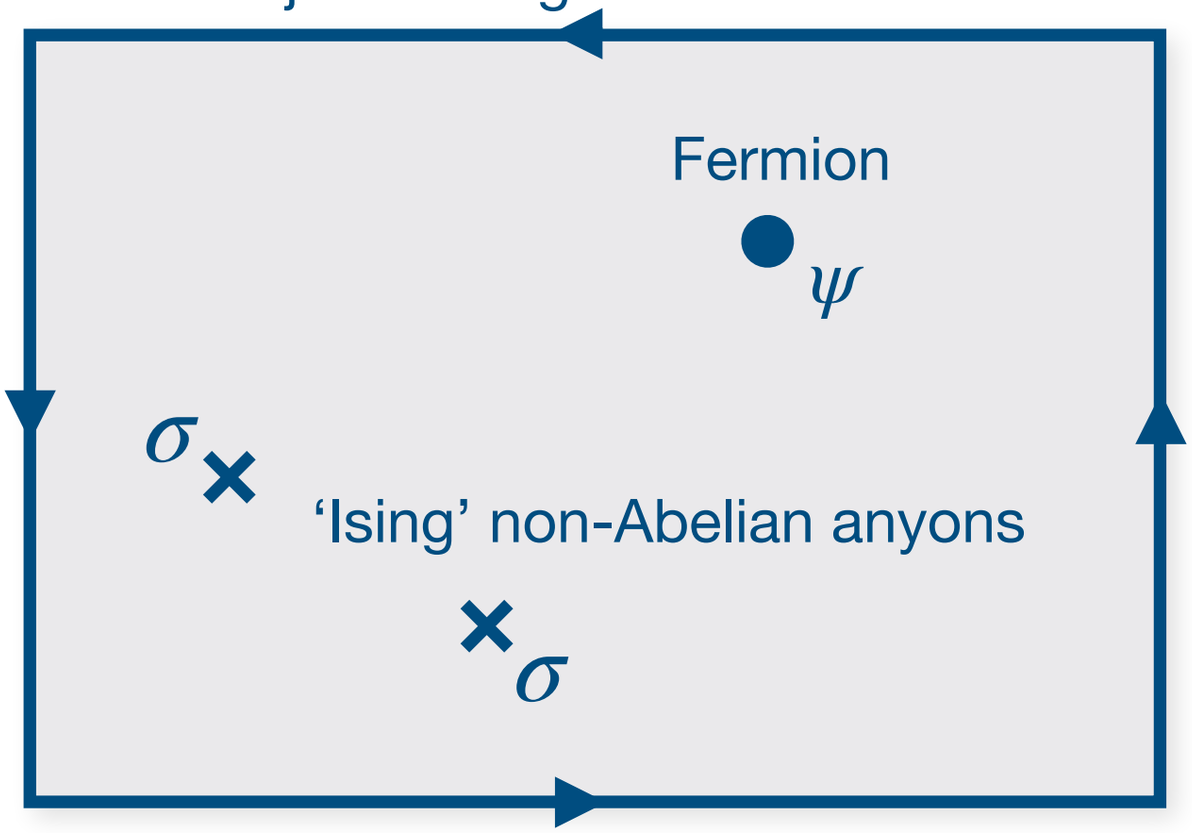
Mott Insulators in the Strong Spin-Orbit Coupling Limit: From Heisenberg to a Quantum Compass and Kitaev Models

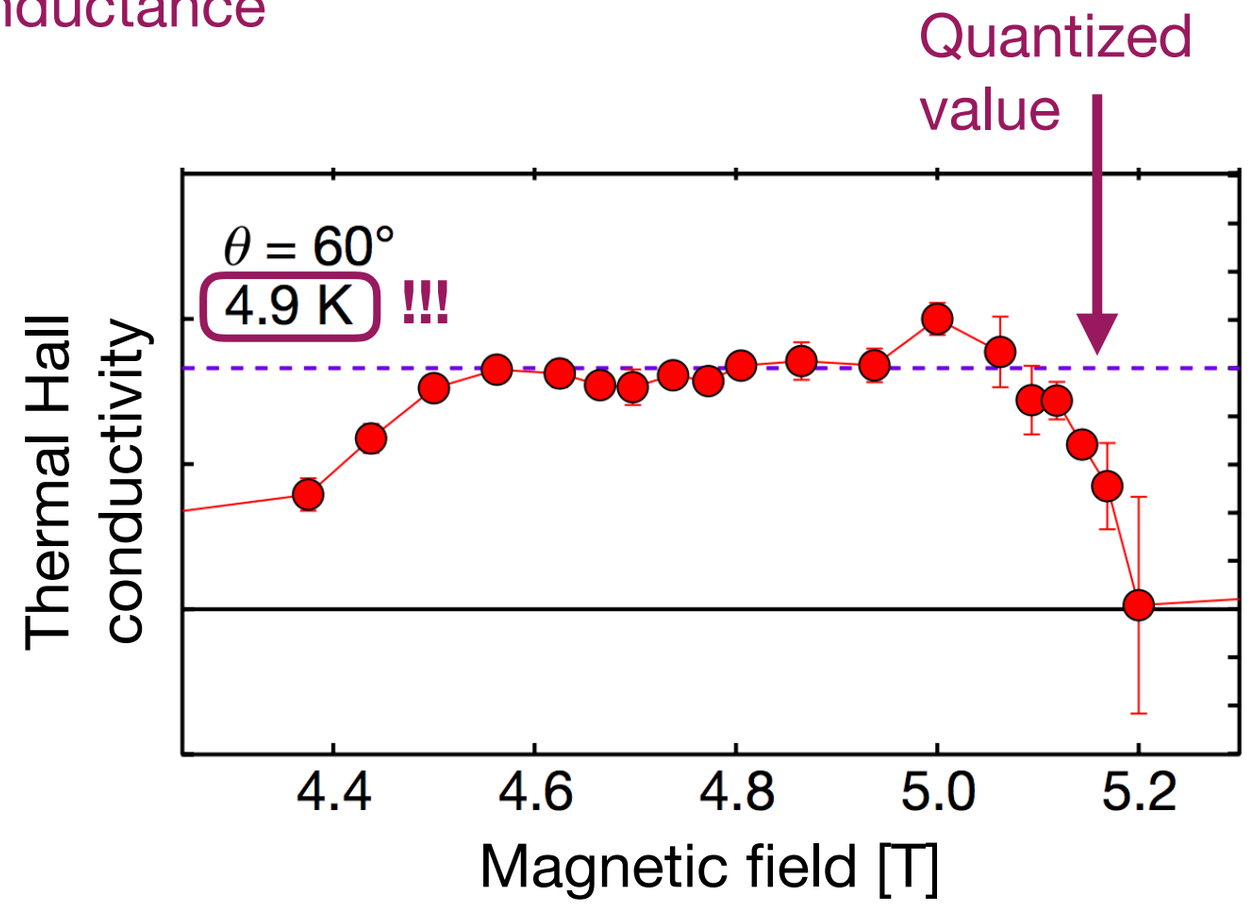
G. Jackeli[1,*] and G. Khaliullin[1]

Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

Y. Kasahara[1], T. Ohnishi[1], Y. Mizukami[2], O. Tanaka[2], Sixiao Ma[1], K. Sugii[3], N. Kurita[4], H. Tanaka[4], J. Nasu[4], Y. Motome[5], T. Shibauchi[2] & Y. Matsuda[1]*

Yields **quantized** thermal Hall conductance





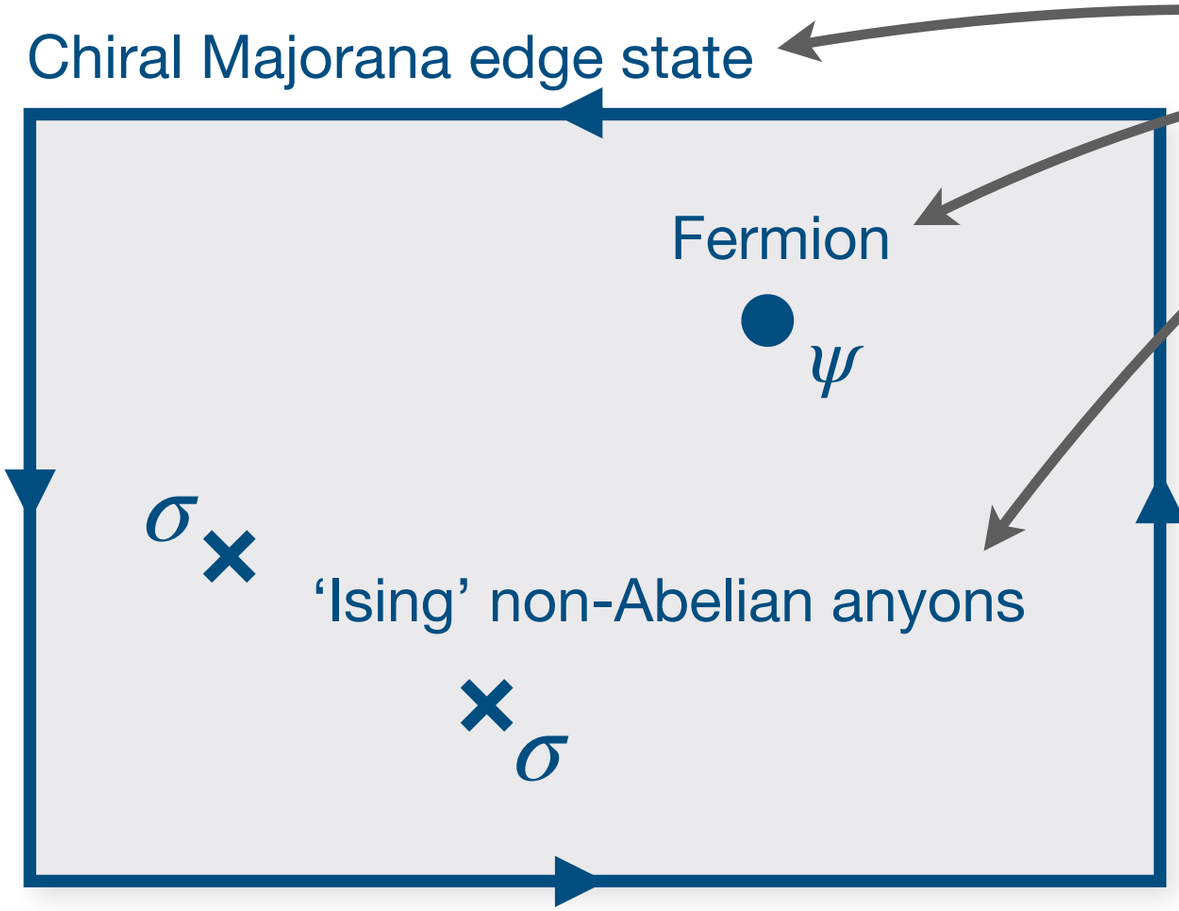
First experimental evidence of a **non-Abelian** spin liquid!

Contender for topological quantum computing hardware?
Virtues: energy scales, fabrication flexibility
Challenges: manipulation & detection of anyons

Nature **559**, 227 (2018)

So far withstood theoretical scrutiny! Vinkler-Aviv & Rosch PRX; Ye, Halasz, Savary, Balents PRL

Punchline I



Detectable with **electrical** probes—even though $RuCl_3$ is an electrical insulator!

Dave Aasen

Roger Mong

Ben Hunt

David Mandrus

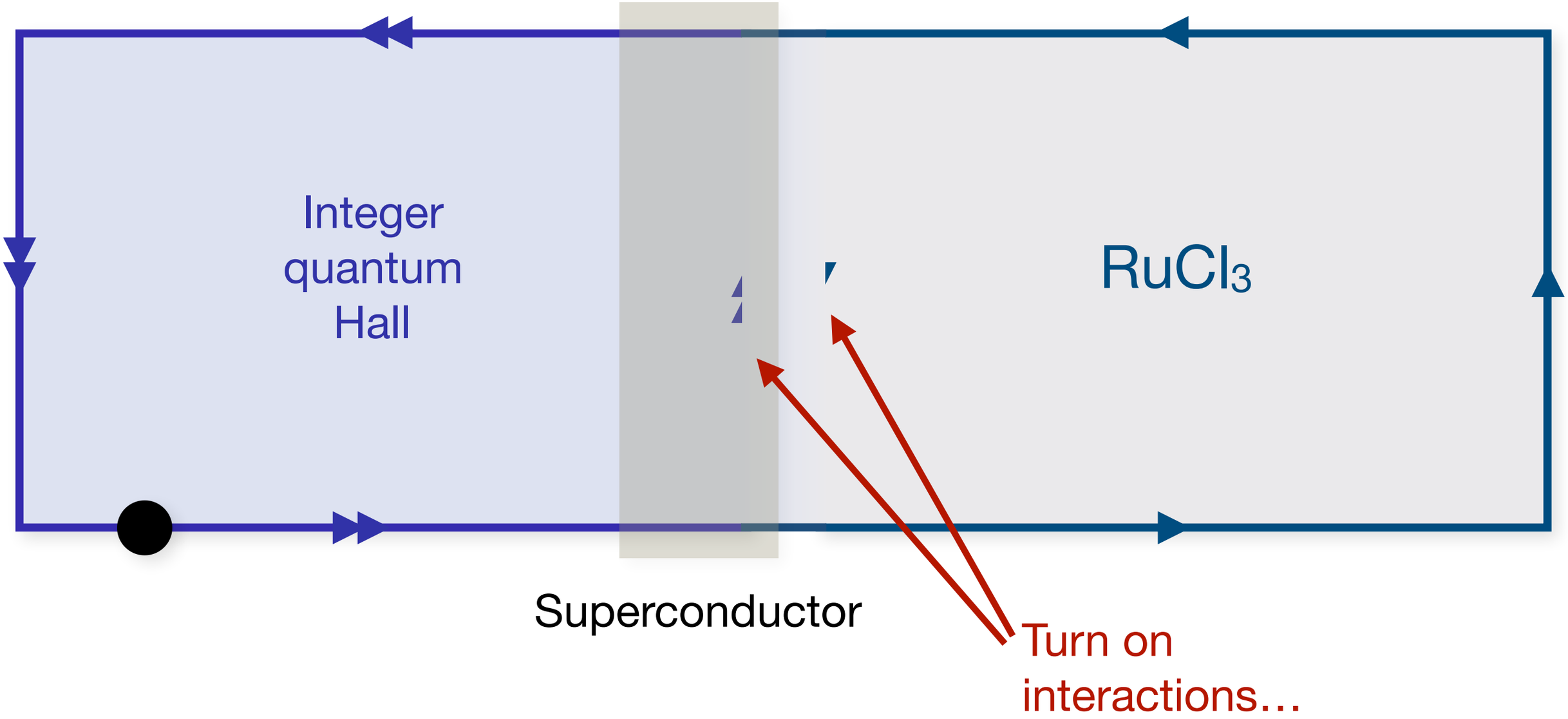
Phys. Rev. X **10**, 031014 (2020)

Coherent Transmutation of Electrons into Fractionalized Anyons

Maissam Barkeshli,[1] Erez Berg,[2] and Steven Kivelson[3]

Electrical probes of non-Abelian spin liquids

Converting physical and emergent fermions



Fermion condensation and super pivotal categories

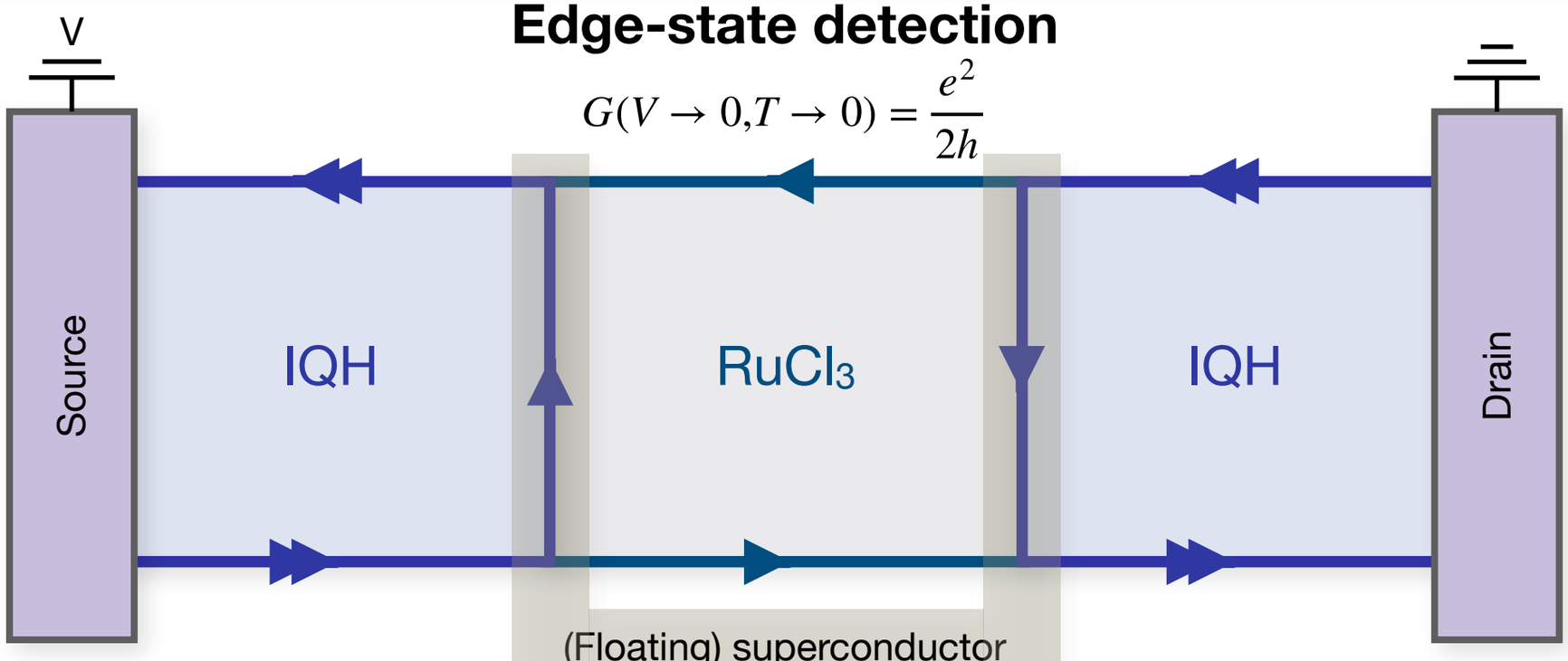
David Aasen[12], Ethan Lake[3], and Kevin Walker[4]

arXiv:1709.01941

Circuit designs

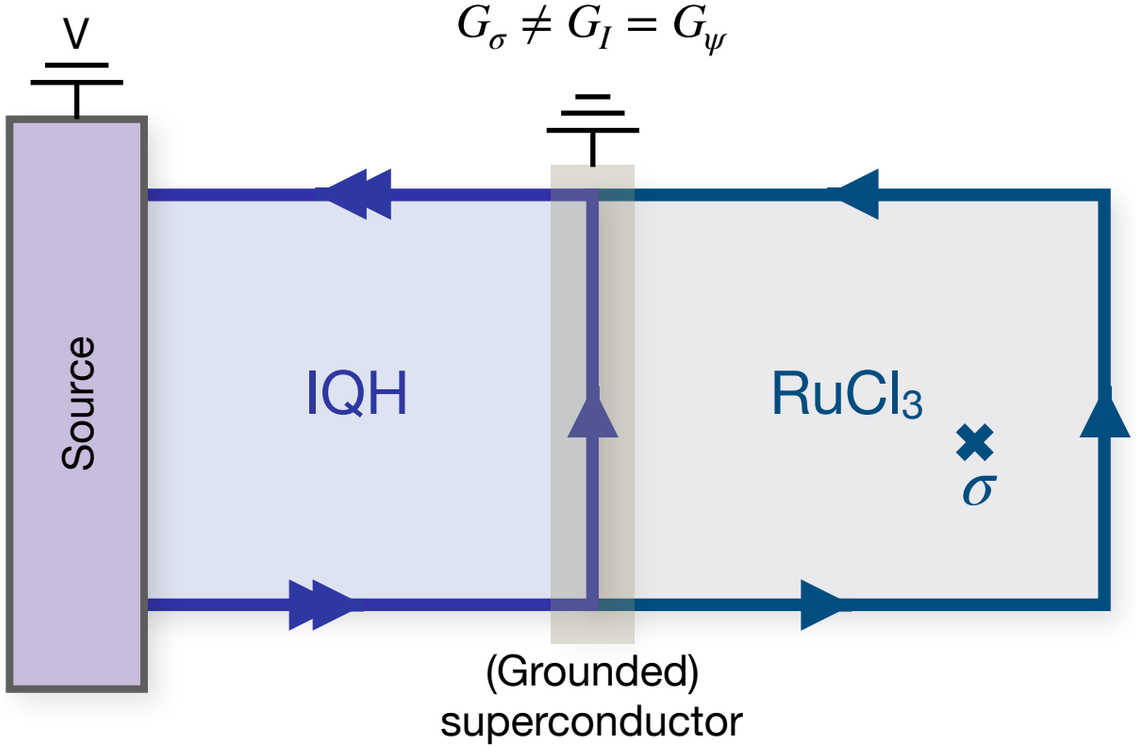
Edge-state detection

$$G(V \to 0, T \to 0) = \frac{e^2}{2h}$$



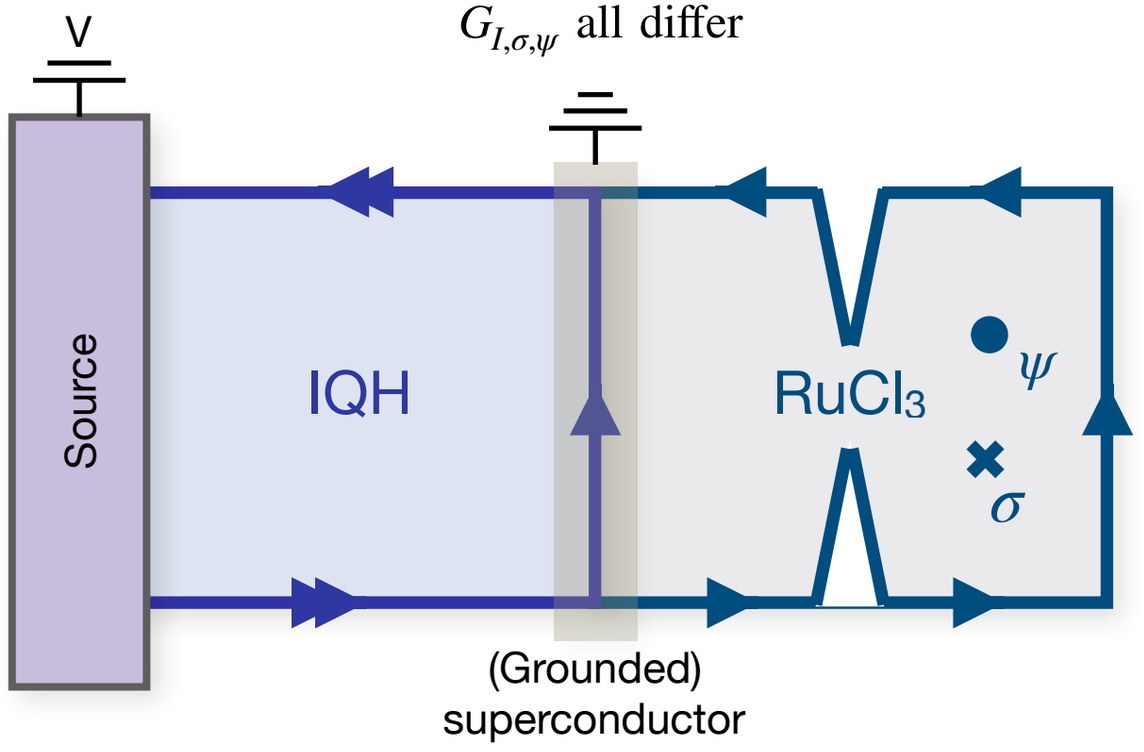
Ising-anyon detection

$$G_\sigma \neq G_I = G_\psi$$



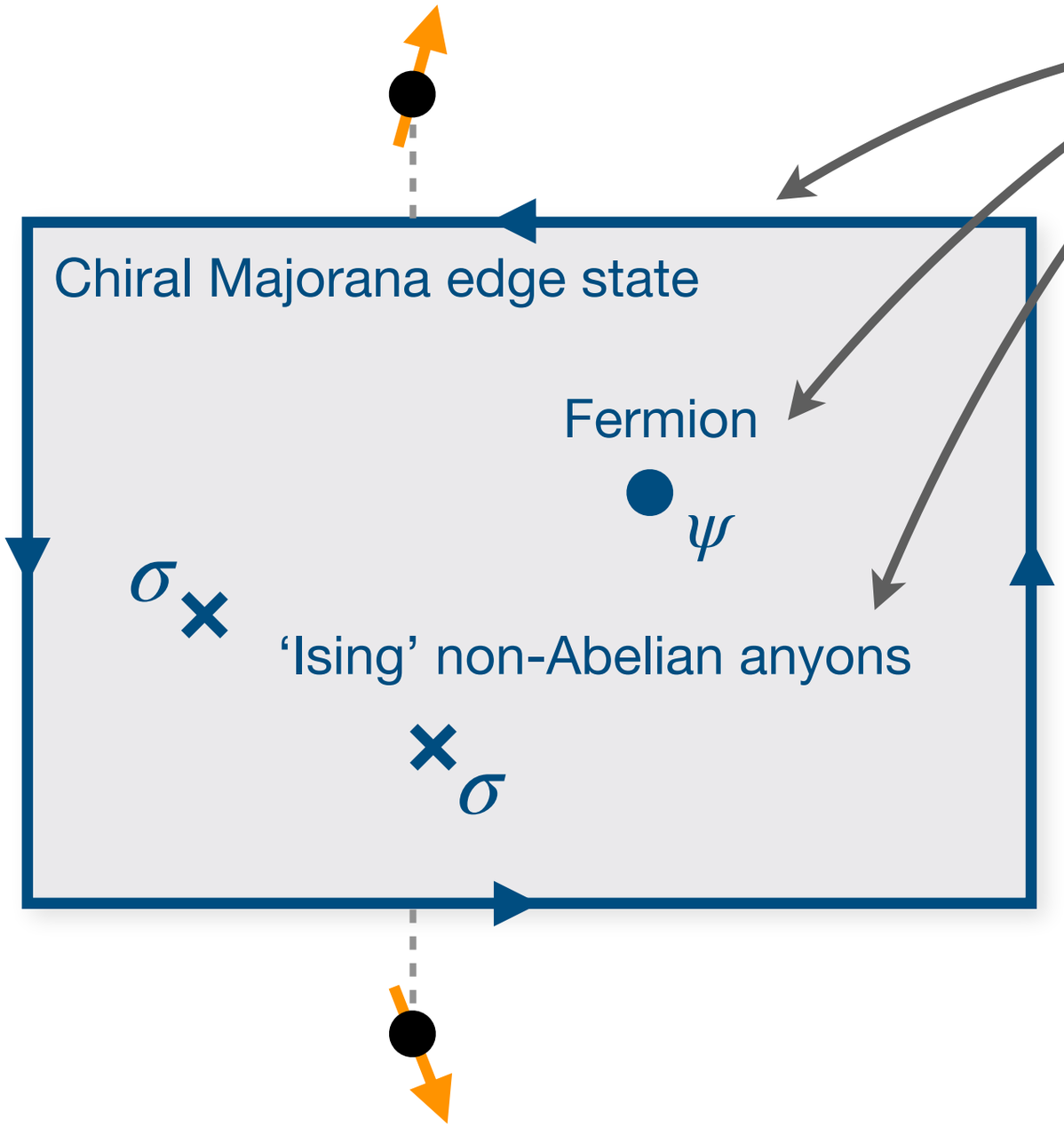
Ising-anyon/fermion detection

$$G_{I,\sigma,\psi} \text{ all differ}$$



Experimental status

Punchline II



Detectable with simpler **time-domain** probes—no QH/SC needed!

Kai Klocke

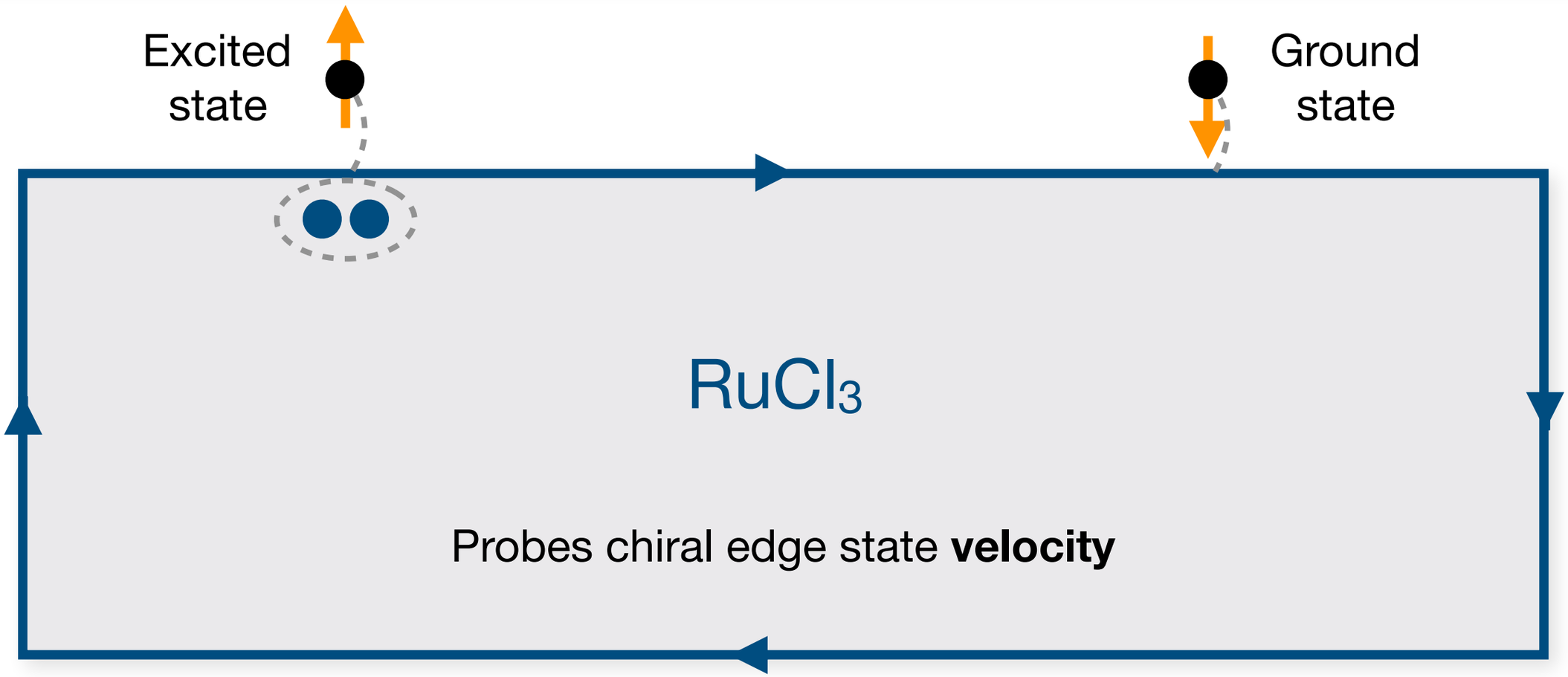
Dave Aasen

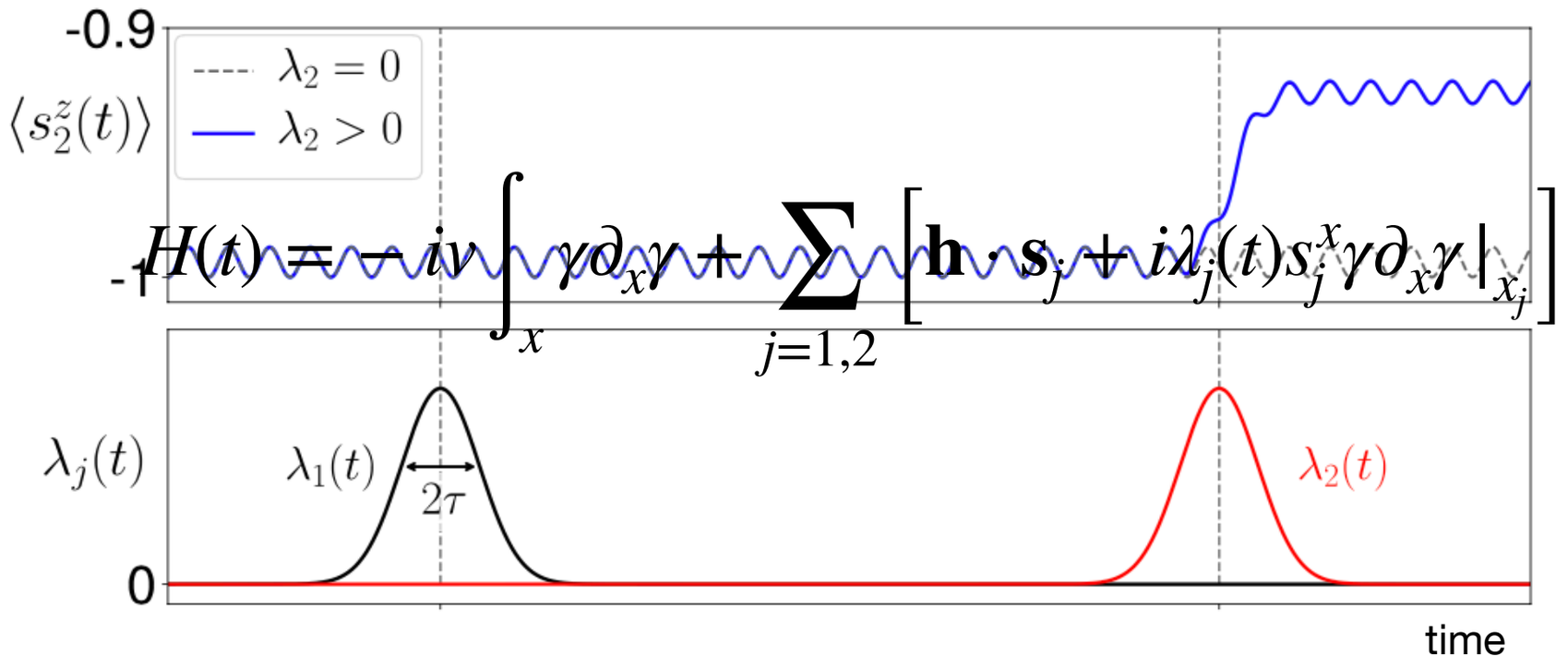
Roger Mong

Eugene Demler

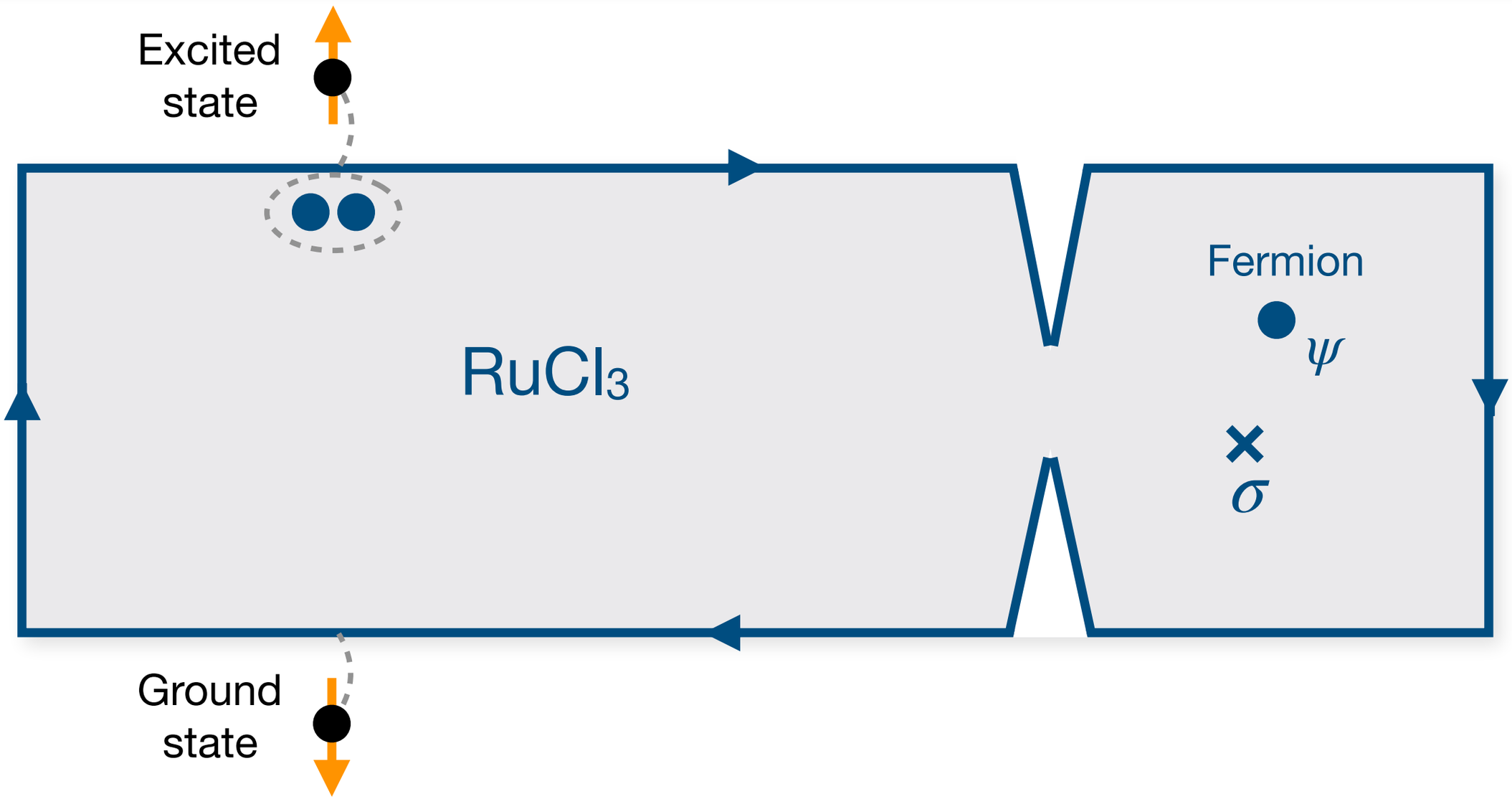
Available soon…

Majorana edge-mode detection

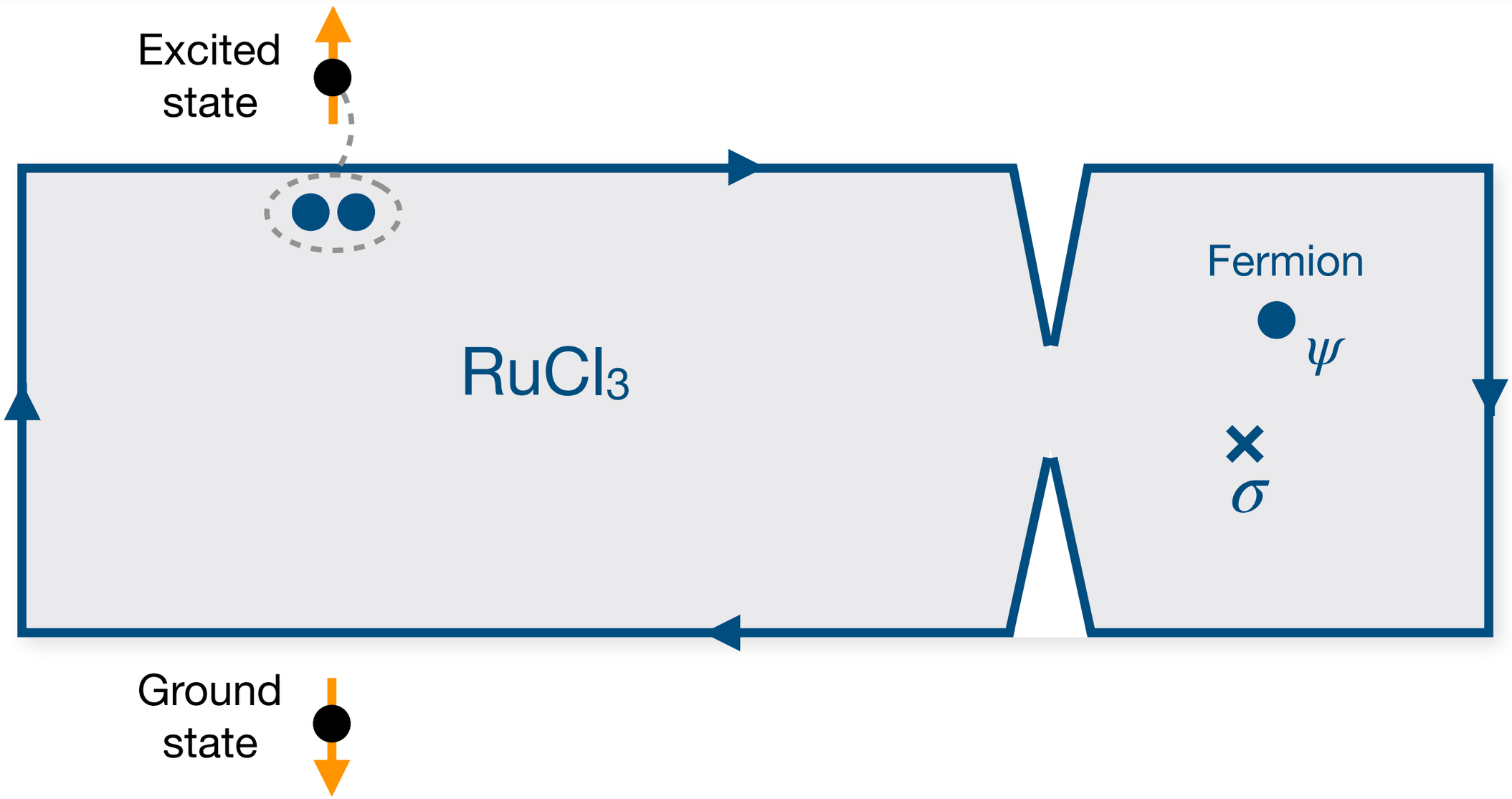




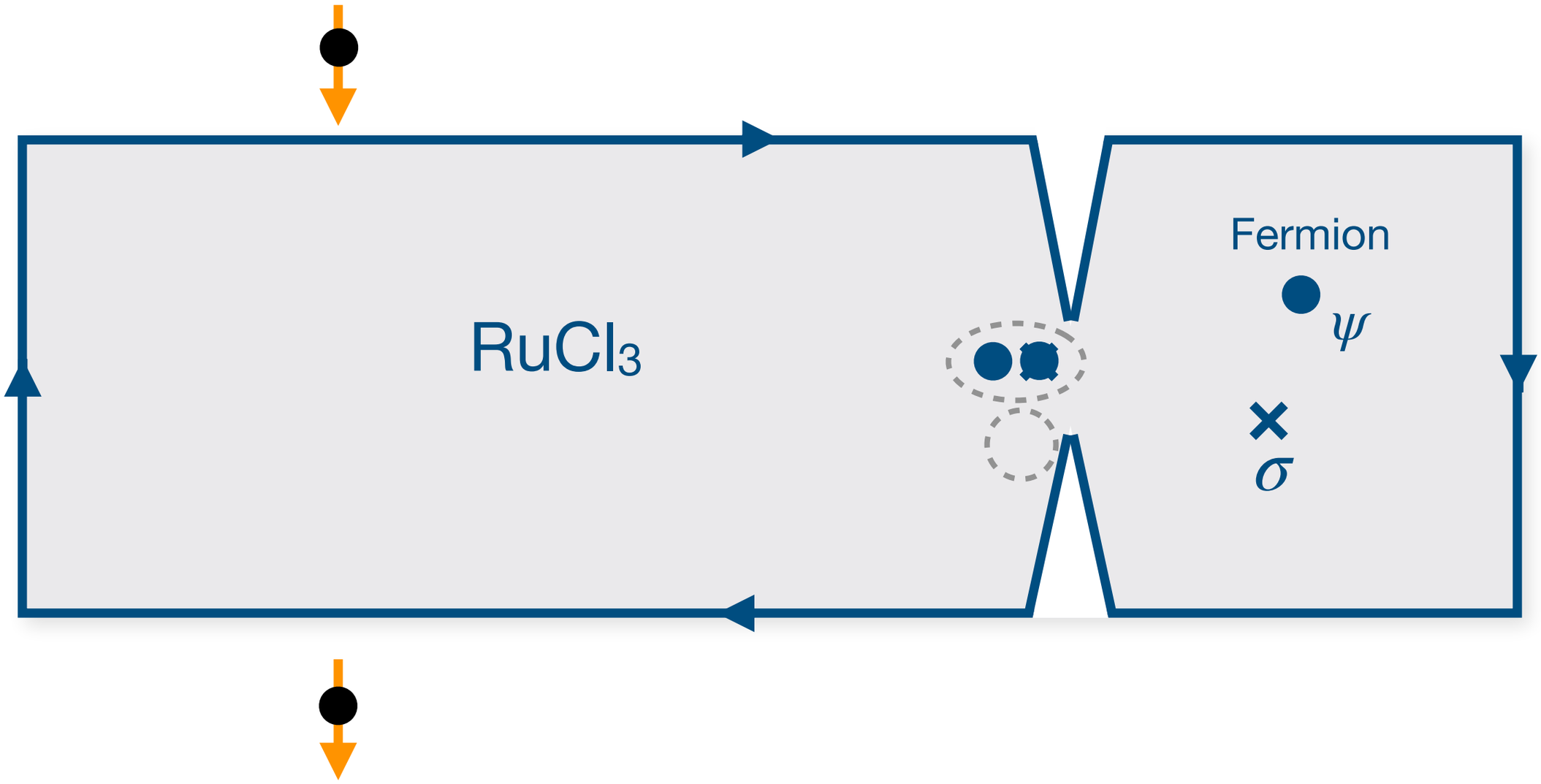
Time-domain anyon interferometry



Time-domain anyon interferometry

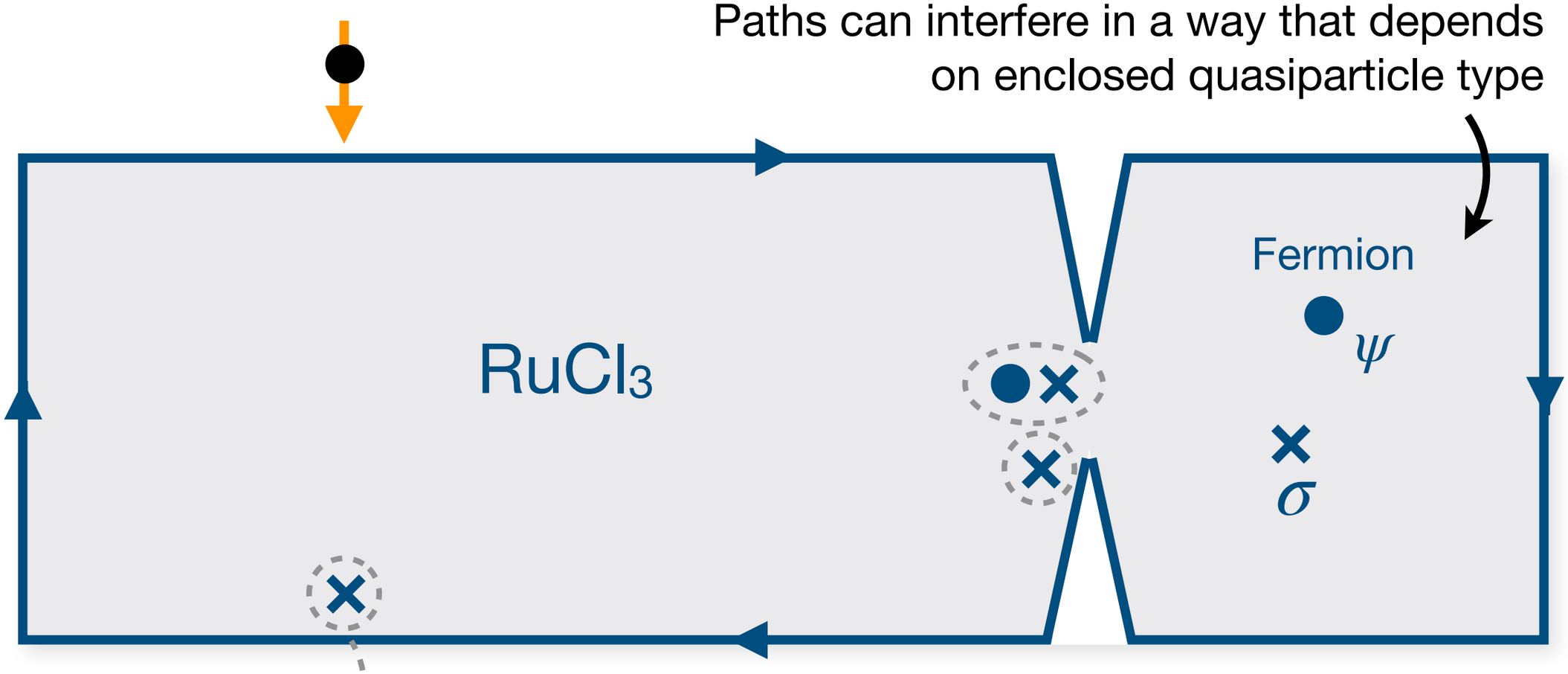


Time-domain anyon interferometry

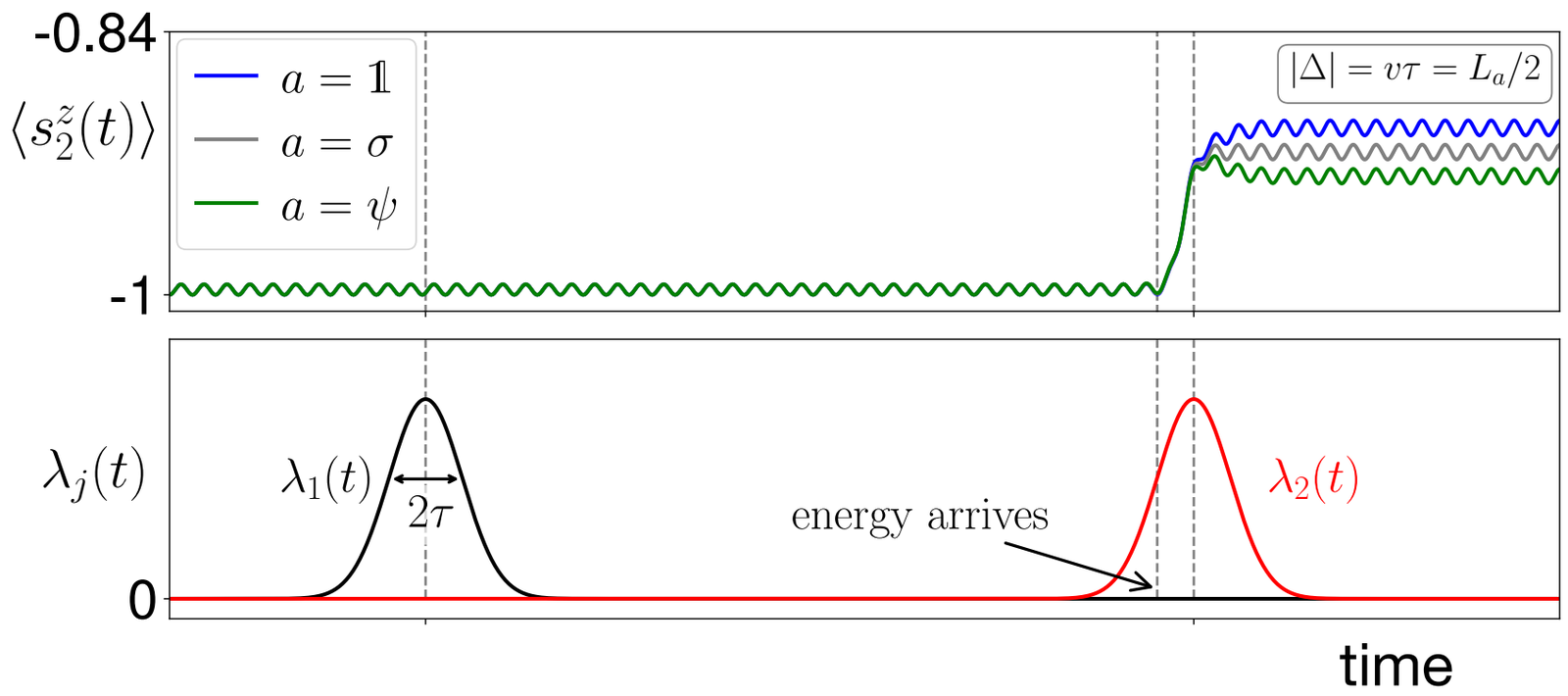


Time-domain anyon interferometry

Paths can interfere in a way that depends on enclosed quasiparticle type

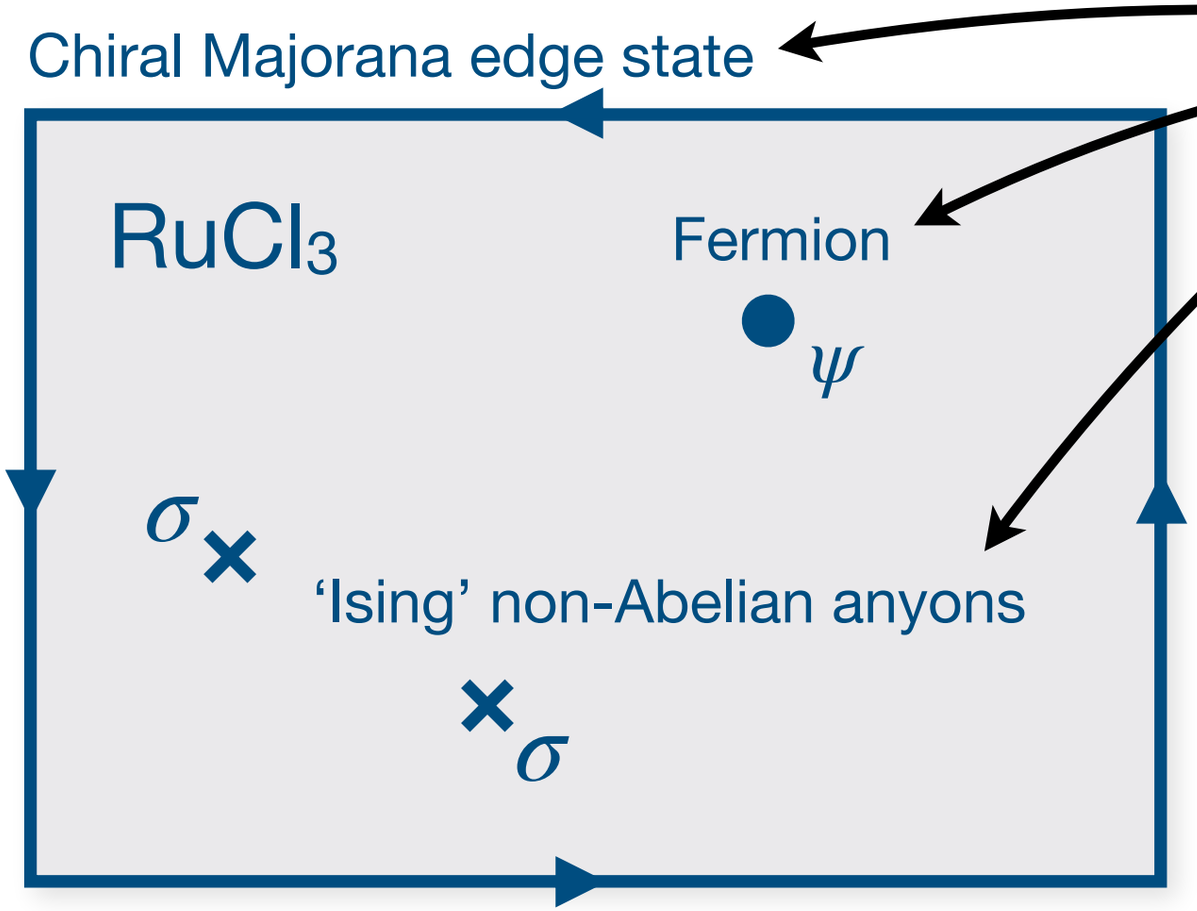


Detects individual bulk anyons and their exotic statistics!

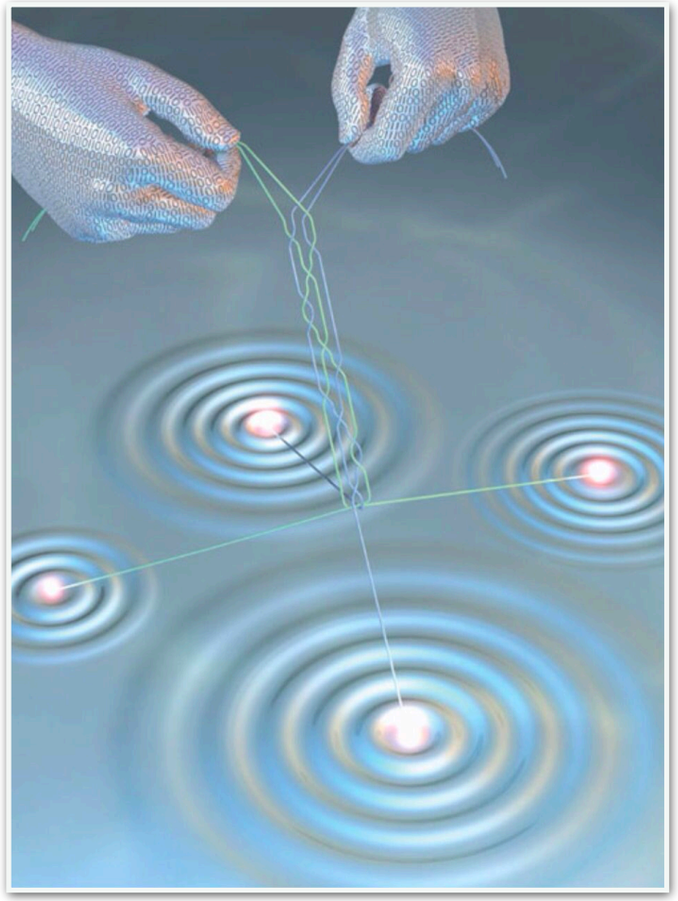


Summary & Outlook

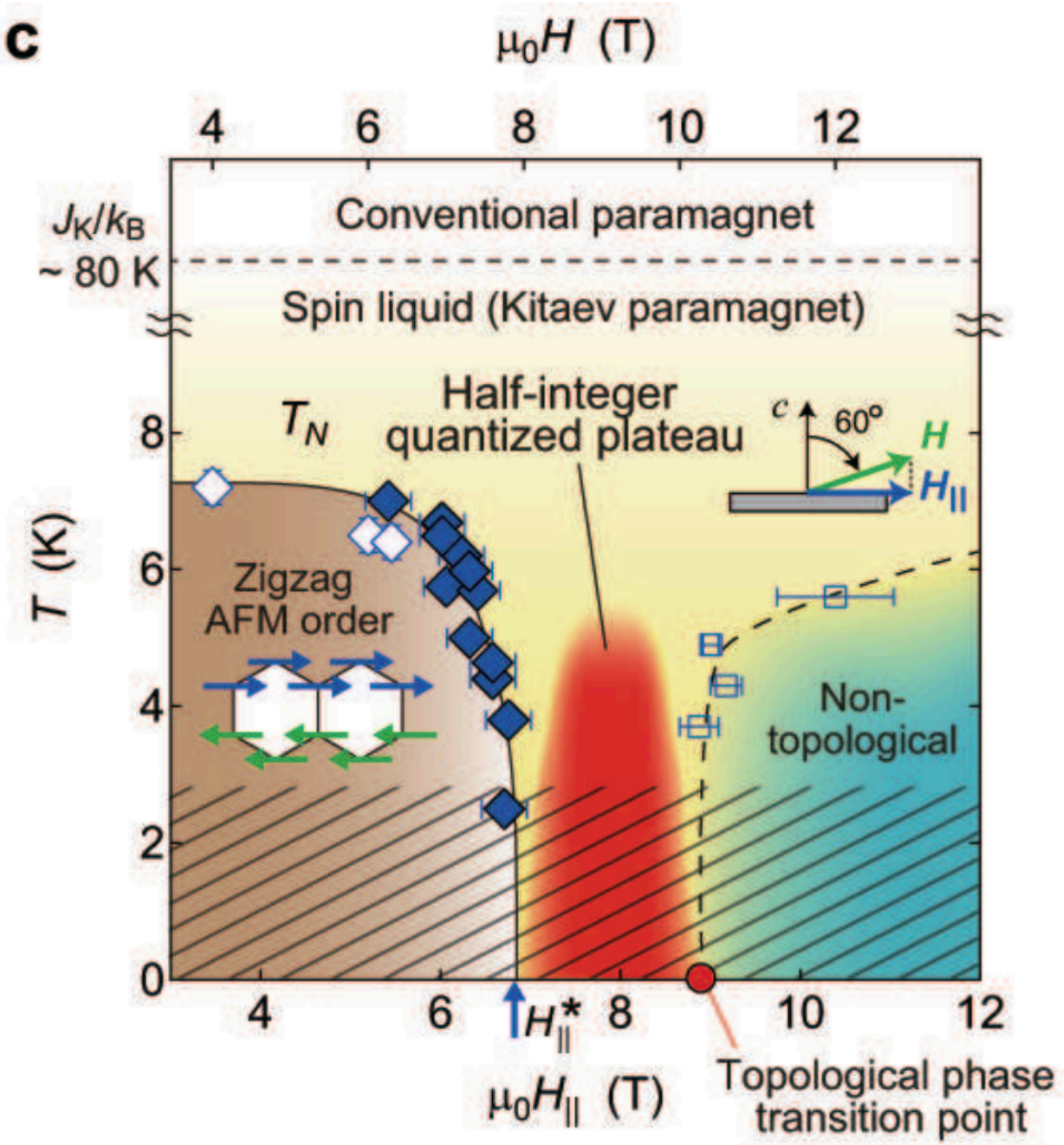
Non-Abelian spin liquids in “Kitaev materials” appear to be experimental reality, providing new horizon in topological quantum computation.



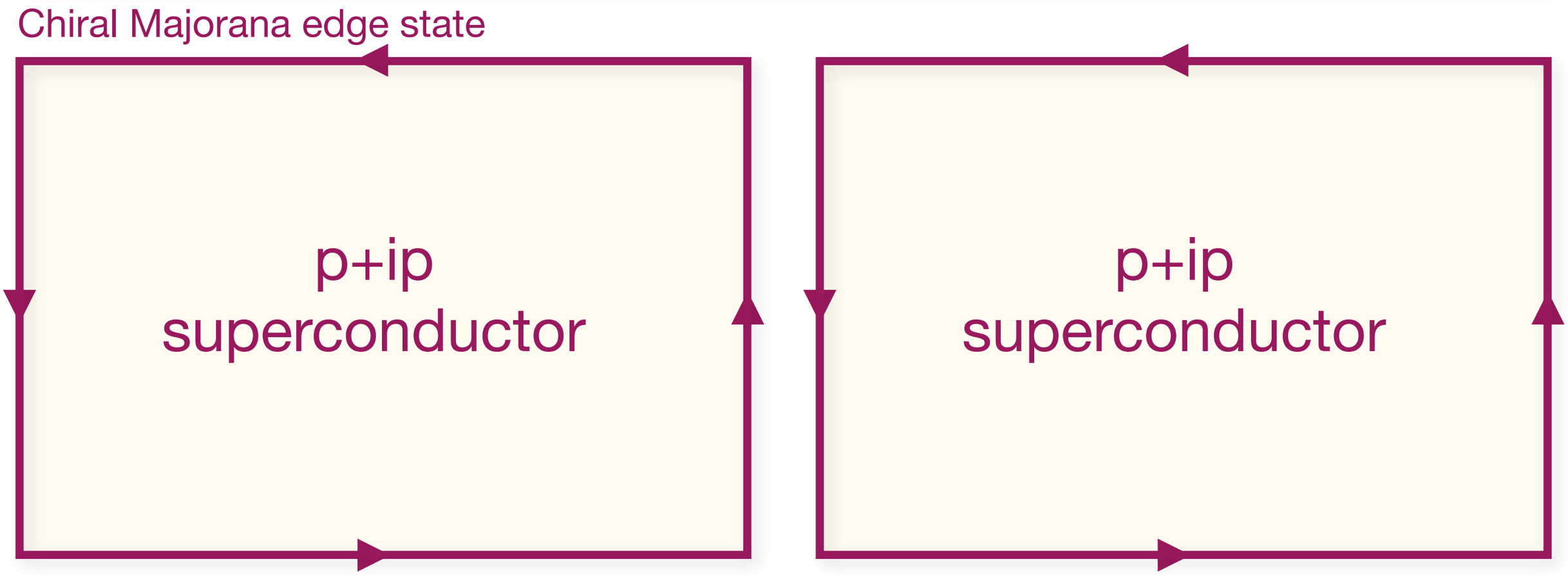
Key features detectable with **electrical** probes and simpler **time-domain** measurements!



Practical anyon manipulation schemes needed (Ising anyons particularly subtle).

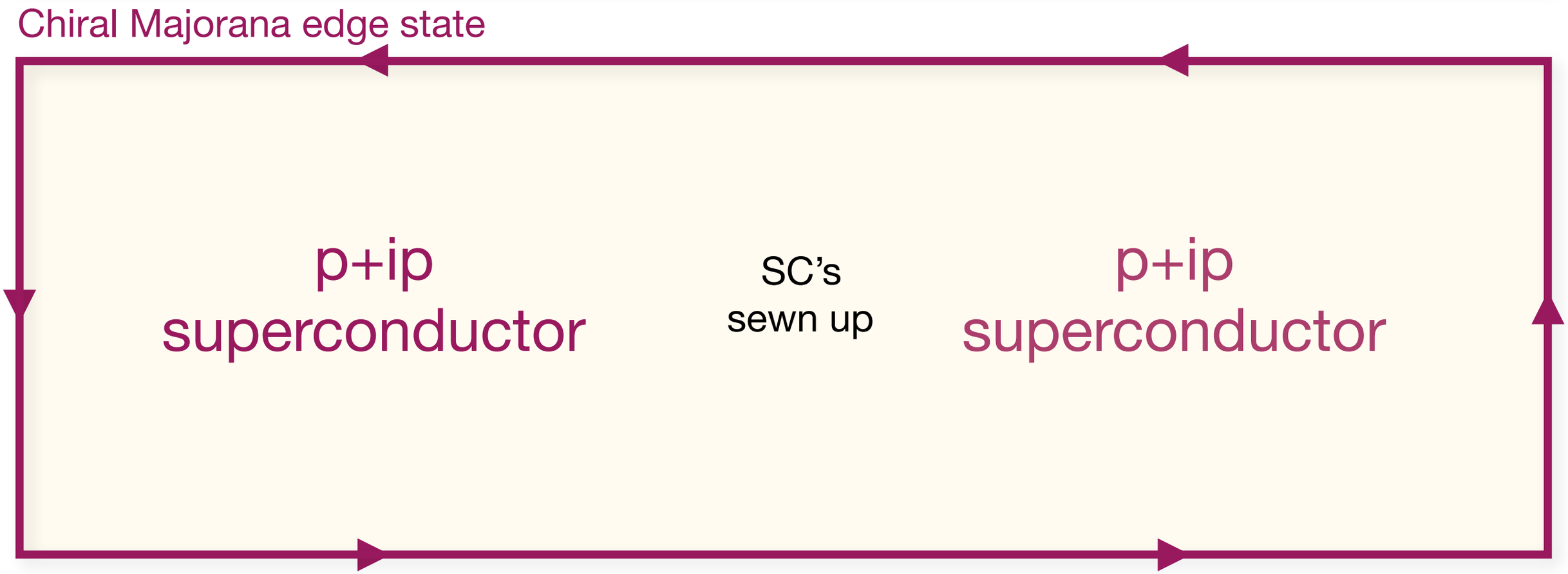

c
$\mu_0 H$ (T)
4
6
8
10
12
J_K/k_B
~ 80 K
Conventional paramagnet
Spin liquid (Kitaev paramagnet)
T_N
Half-integer
quantized plateau
c
60°
H
H_{II}
Zigzag
AFM order
Non-
topological
T (K)
8
6
4
2
0
4
6
H_{II}^*
8
10
12
$\mu_0 H_{II}$ (T)
Topological phase
transition point

Warm-up: stitching p+ip superconductors



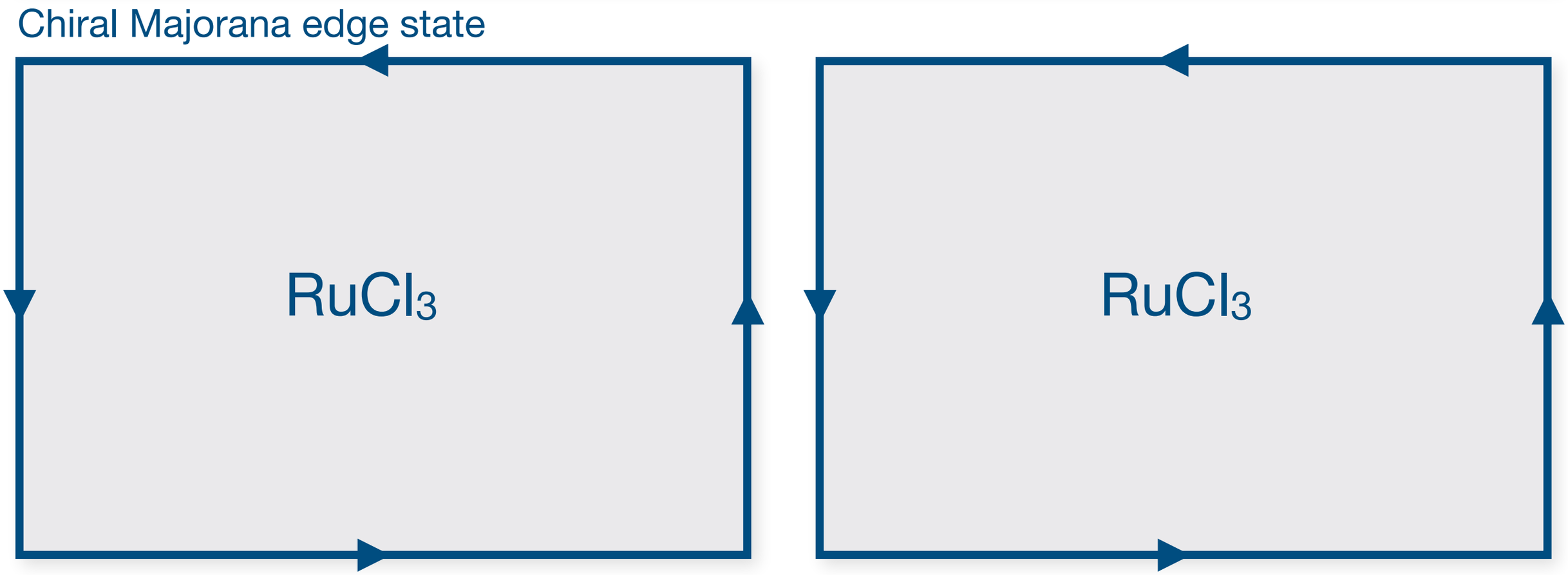
$$\mathscr{H} = -iv\gamma_R\partial_x\gamma_R + iv\gamma_L\partial_x\gamma_L + im\gamma_R\gamma_L$$

Warm-up: stitching p+ip superconductors



$$\mathscr{H} = -iv\gamma_R\partial_x\gamma_R + iv\gamma_L\partial_x\gamma_L + im\gamma_R\gamma_L$$

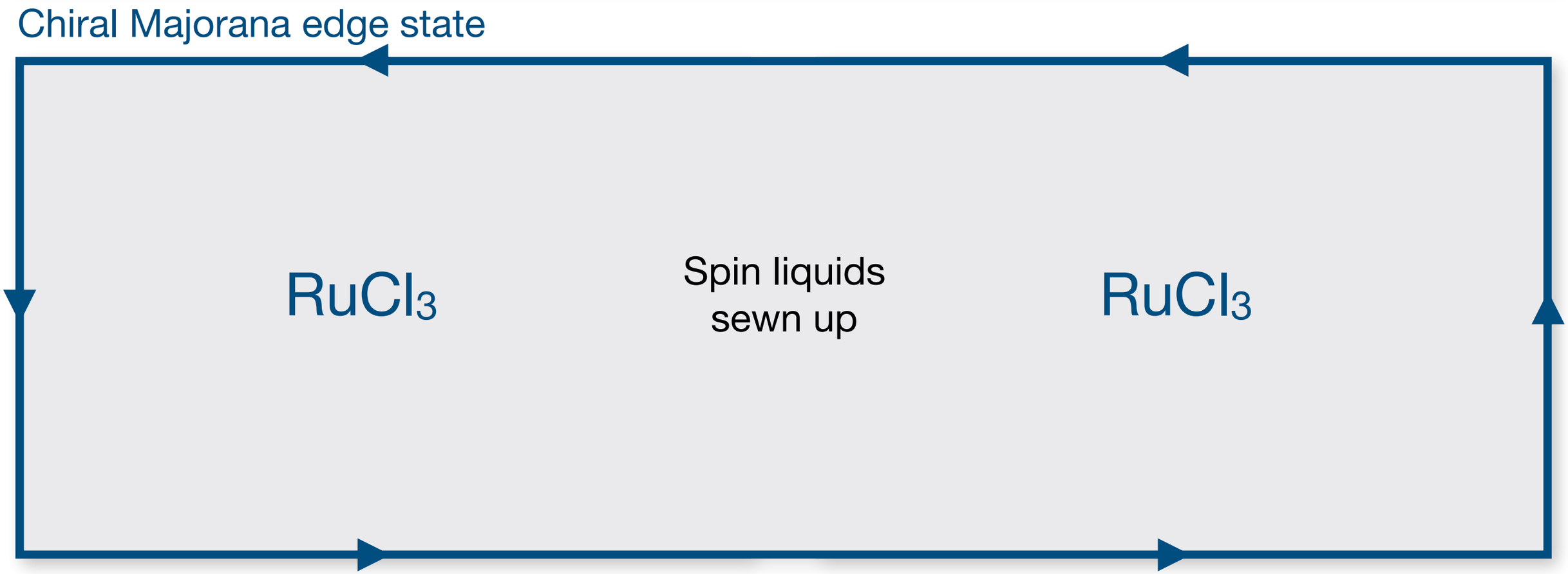
Warm-up: stitching non-Abelian spin liquids



$$\mathscr{H} = -iv\gamma_R\partial_x\gamma_R + iv\gamma_L\partial_x\gamma_L \boxed{+im\gamma_R\gamma_L}$$

Unphysical! (because fermions are emergent)

Warm-up: stitching non-Abelian spin liquids



Assume “large”…

$$\mathscr{H} = -iv\gamma_R\partial_x\gamma_R + iv\gamma_L\partial_x\gamma_L + \lambda\gamma_R\gamma_R\gamma_L\gamma_L$$

$$\rightarrow \lambda\langle i\gamma_R\gamma_L\rangle i\gamma_R\gamma_L$$

$$\equiv im_{\text{eff}}\gamma_R\gamma_L$$

…mass generated **spontaneously!**