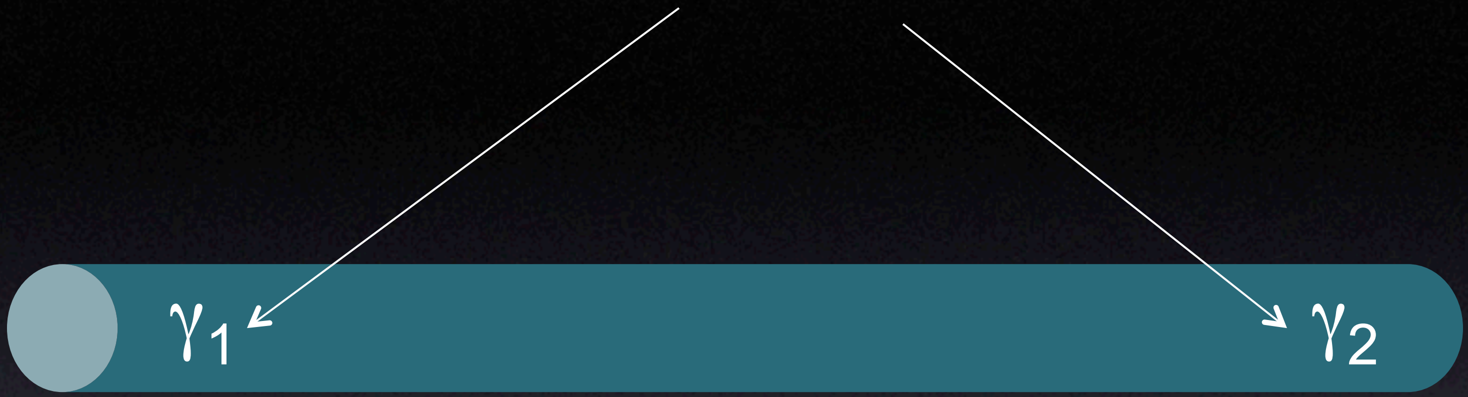
EMERGING QUASI-PARTICLES & TOPOLOGY

$$c^\dagger = \gamma_1 + i\gamma_2$$



non-local separation provides topological protection

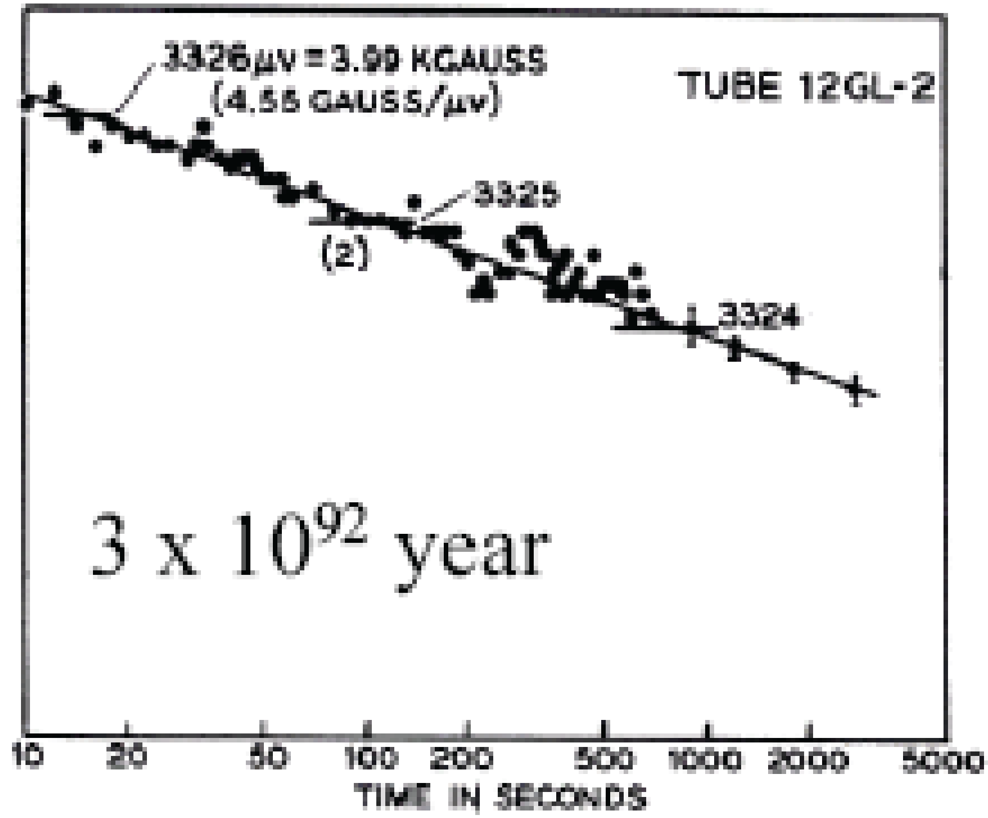
NEW: design and create a Majorana as a quasi-particle in solid state.

=> *emerging state arising from collective behaviour.*

...,Kitaev, Read, Fu, Kane, Das Sarma, Beenakker, Alicea,....
(see review Nick Read, Physics Today July 2012.)

Fundamental physics in collective phenomena

Supergeleiders



Kim ea PRL 9 (1962) 306

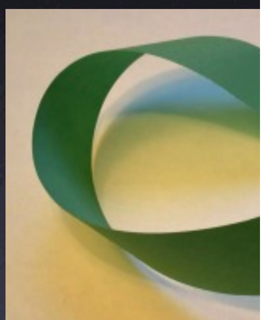
“If this rate of decay continues indefinitely, we estimate that the persistent current in this SC sample will die out after 3 x10^{92} years. In any practical sense then, the persistent current is persistent.”

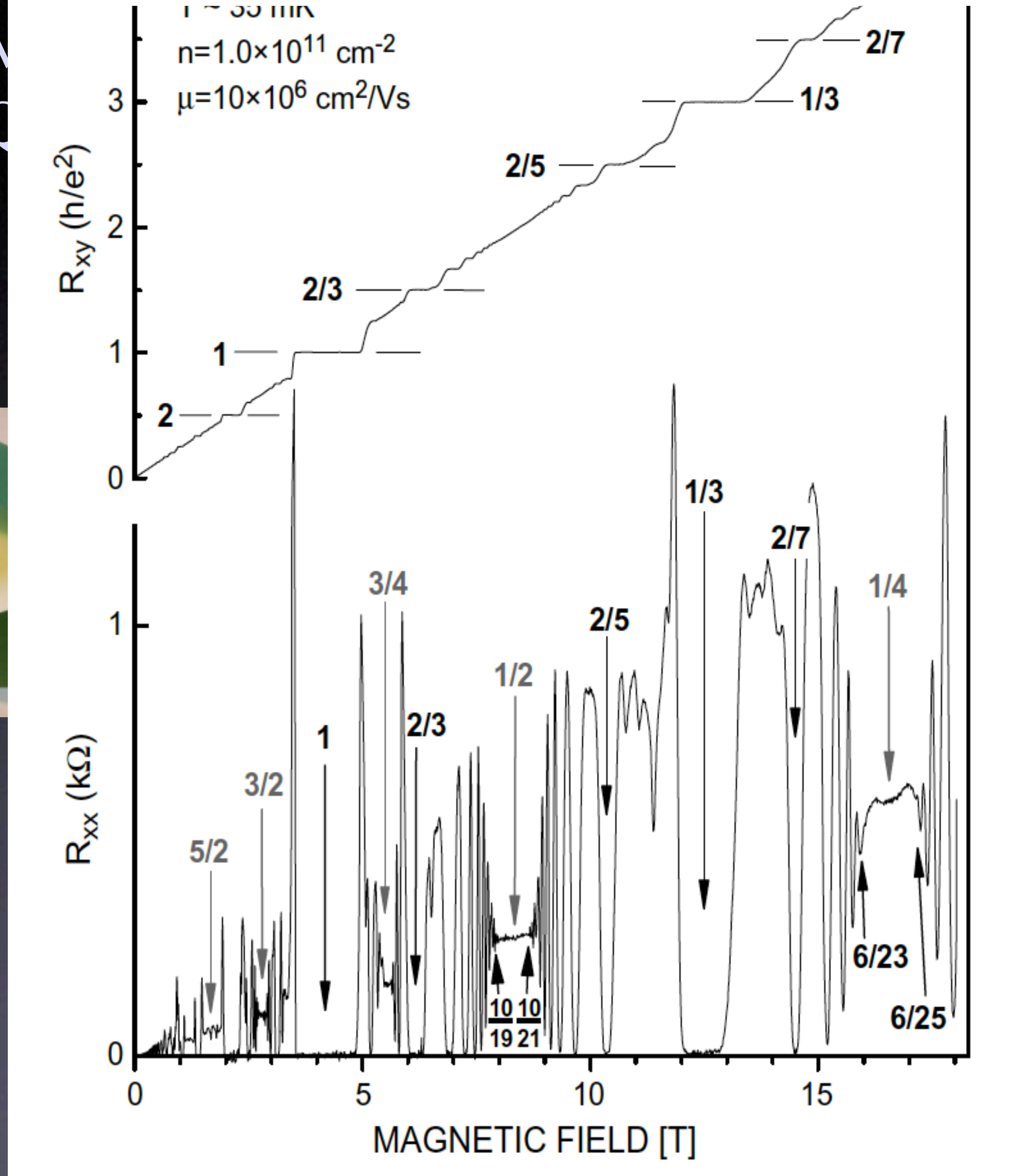
Topological

=> M

=> Q ... ing

sample size and shape doesn't matter

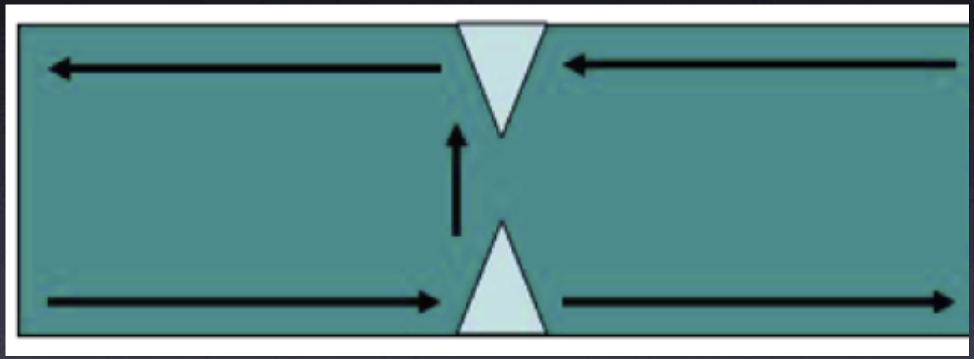


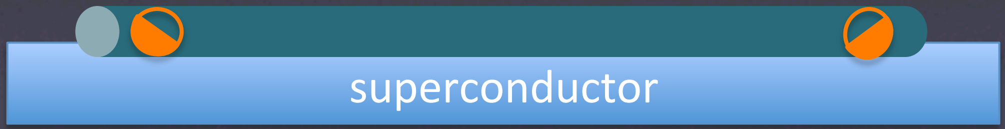


Topological protection

=> Möbius strip against twists

=> QHE chiral edge states against backscattering



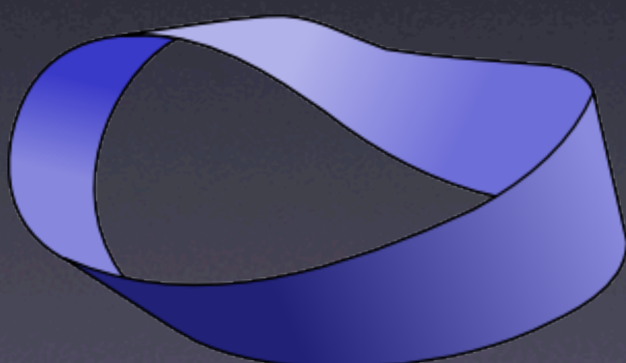


Two physically separated degenerate quantum states

TOPOLOGICAL QUBITS

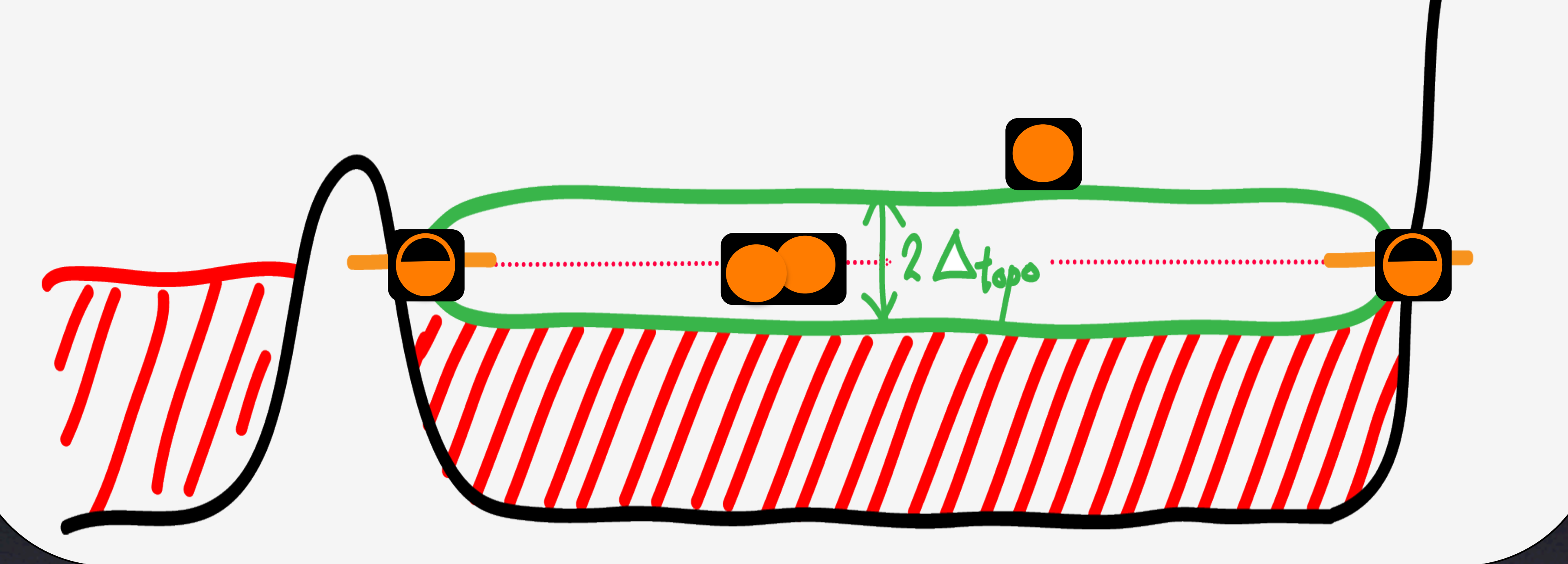
Quantum bits

"analog" qubit
(decoherence)

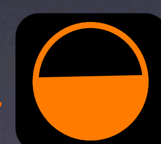


topologically
protected
"digital" qubit

(Kitaev, Freedman,...)



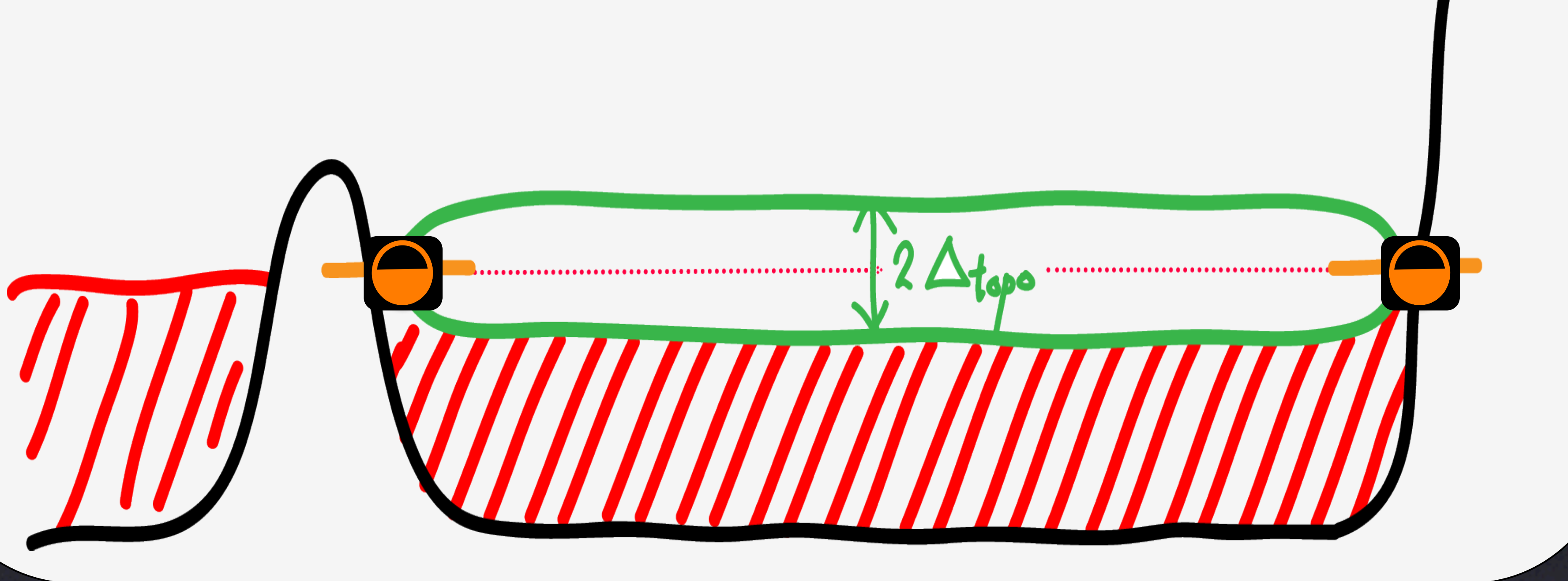
$N =$ even 

$N =$ odd  + 2 

$\Big\}\ E = 0$

$N =$ odd  + 

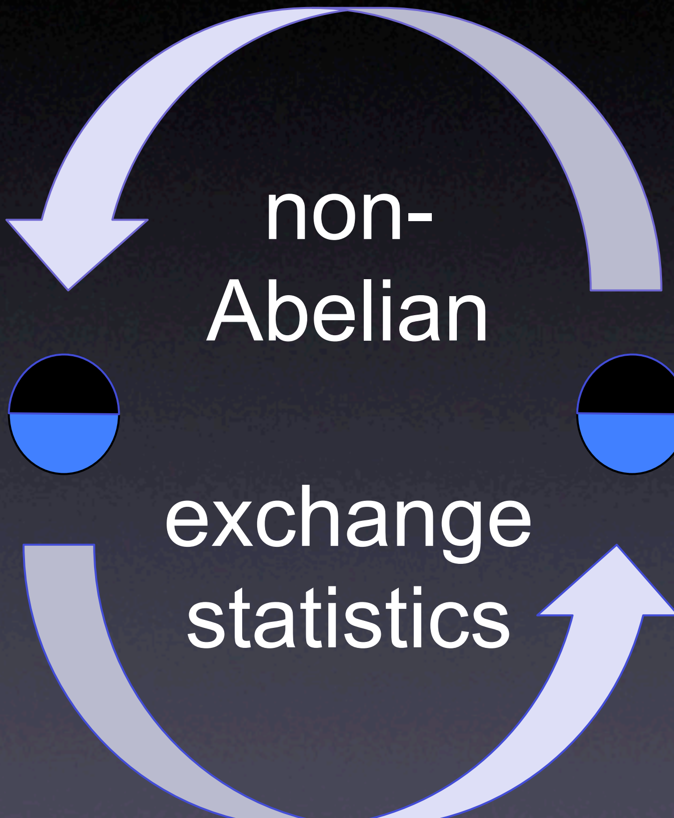
$E = \Delta$

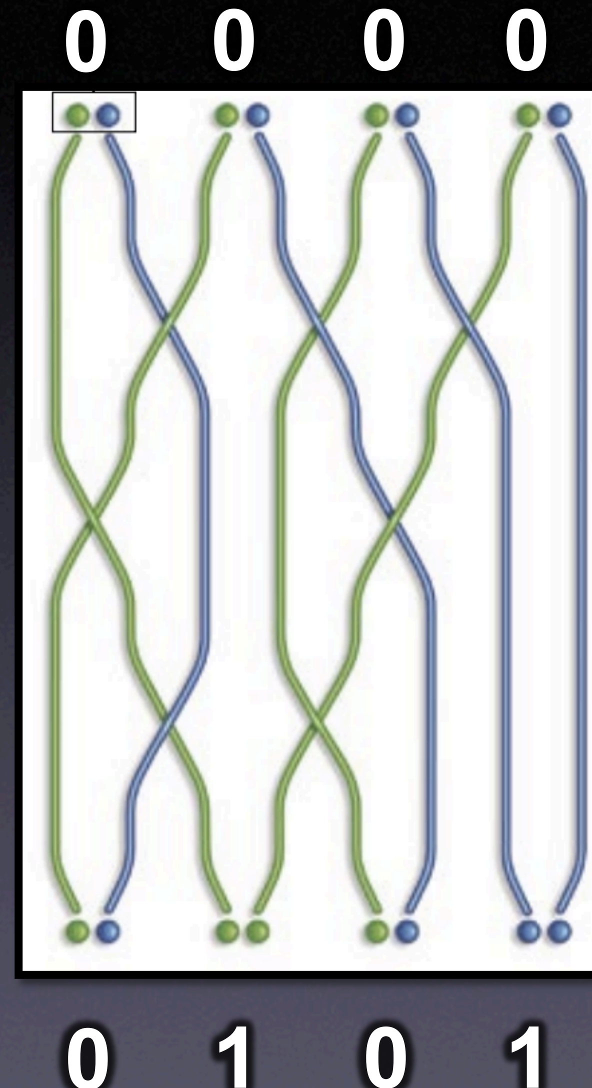


E(even parity) = E(odd parity) = 0

parity qubit
with qubit states
stored non-locally

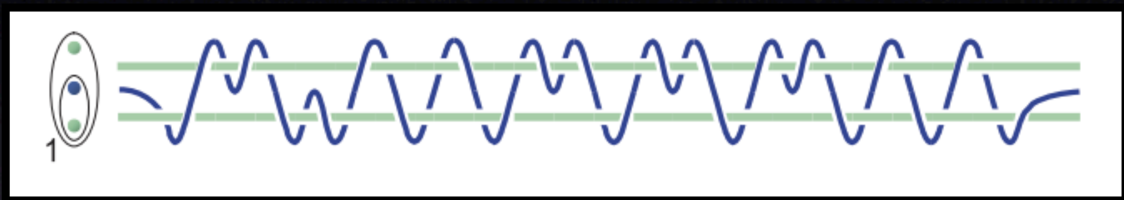
Topological Quantum Computing

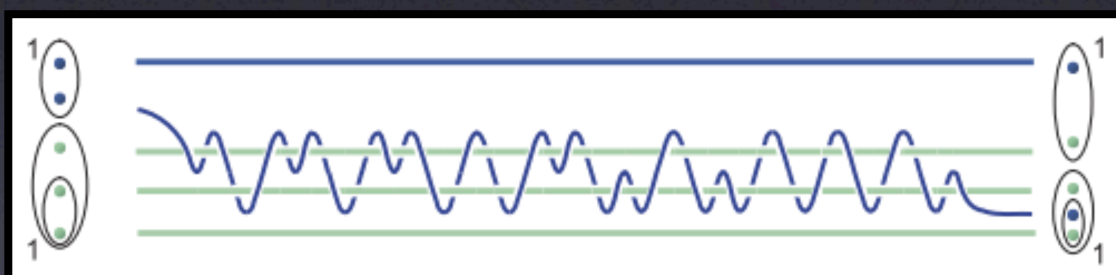


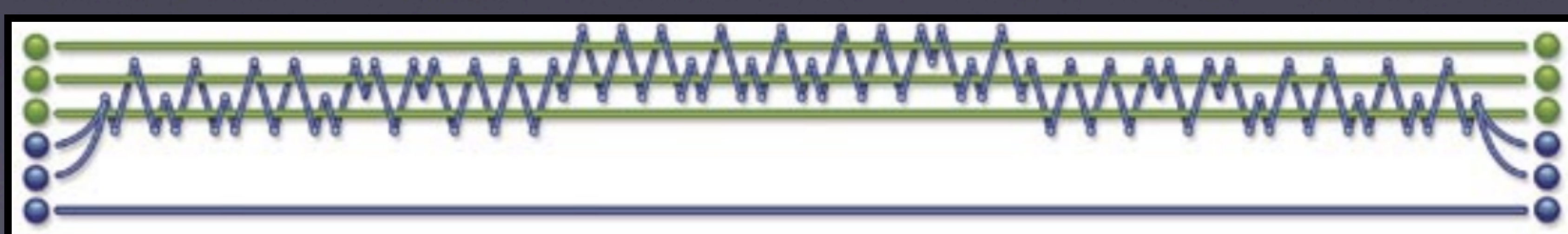


Microsoft®

Majorana braiding

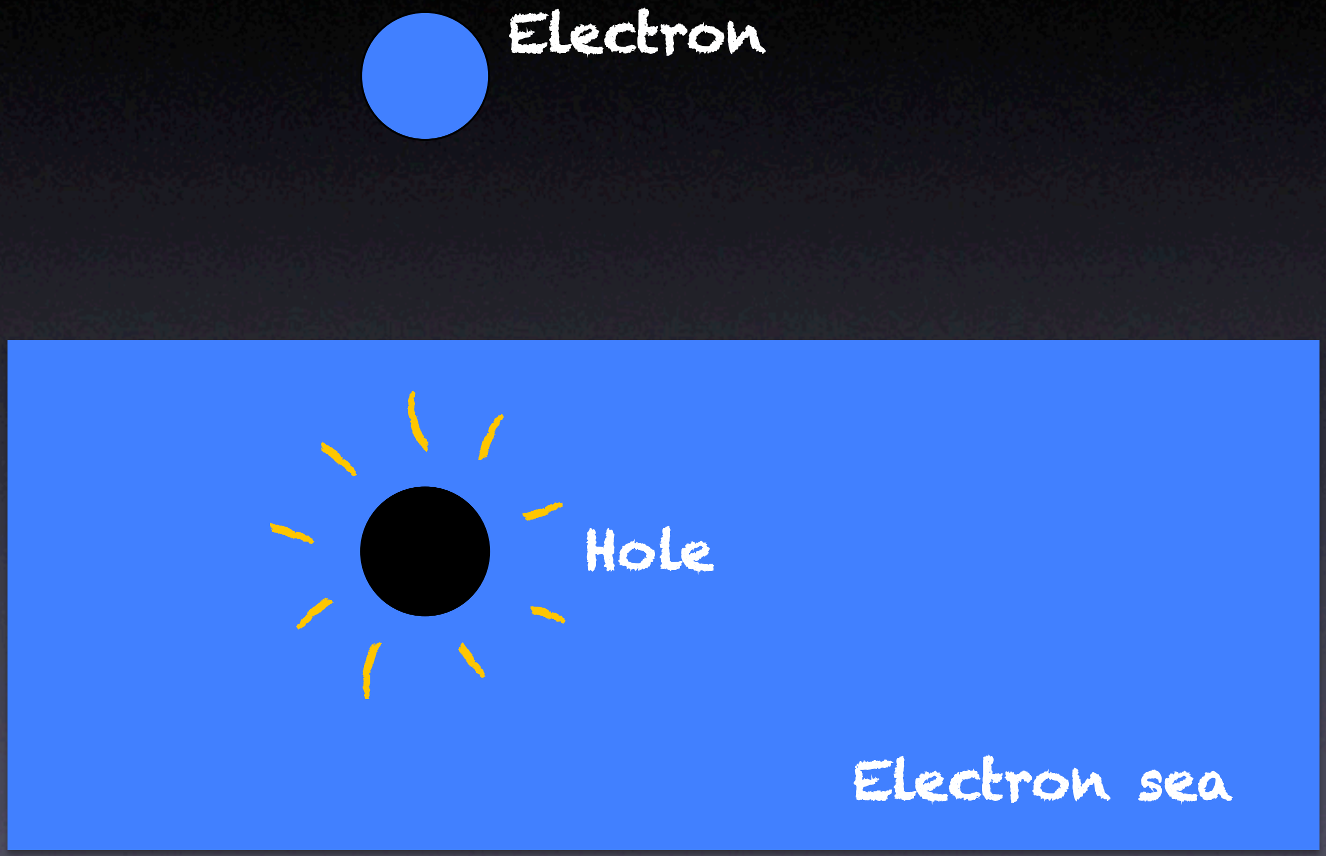






Fusion

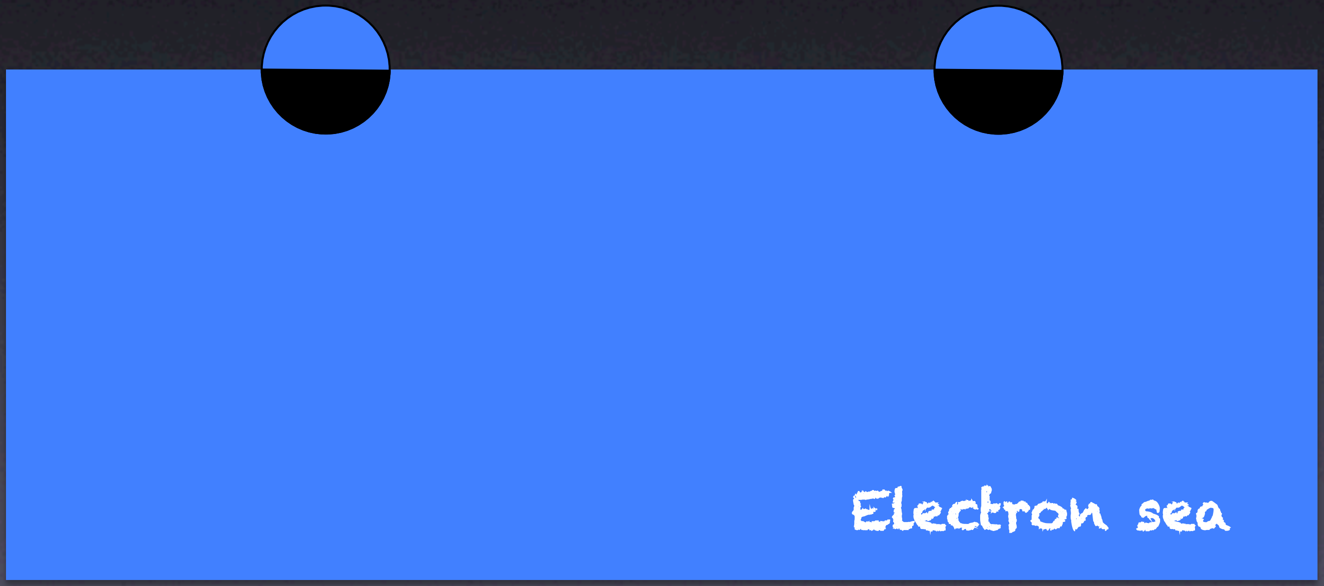
Electron-Hole annihilation



Majorana annihilation

First result:

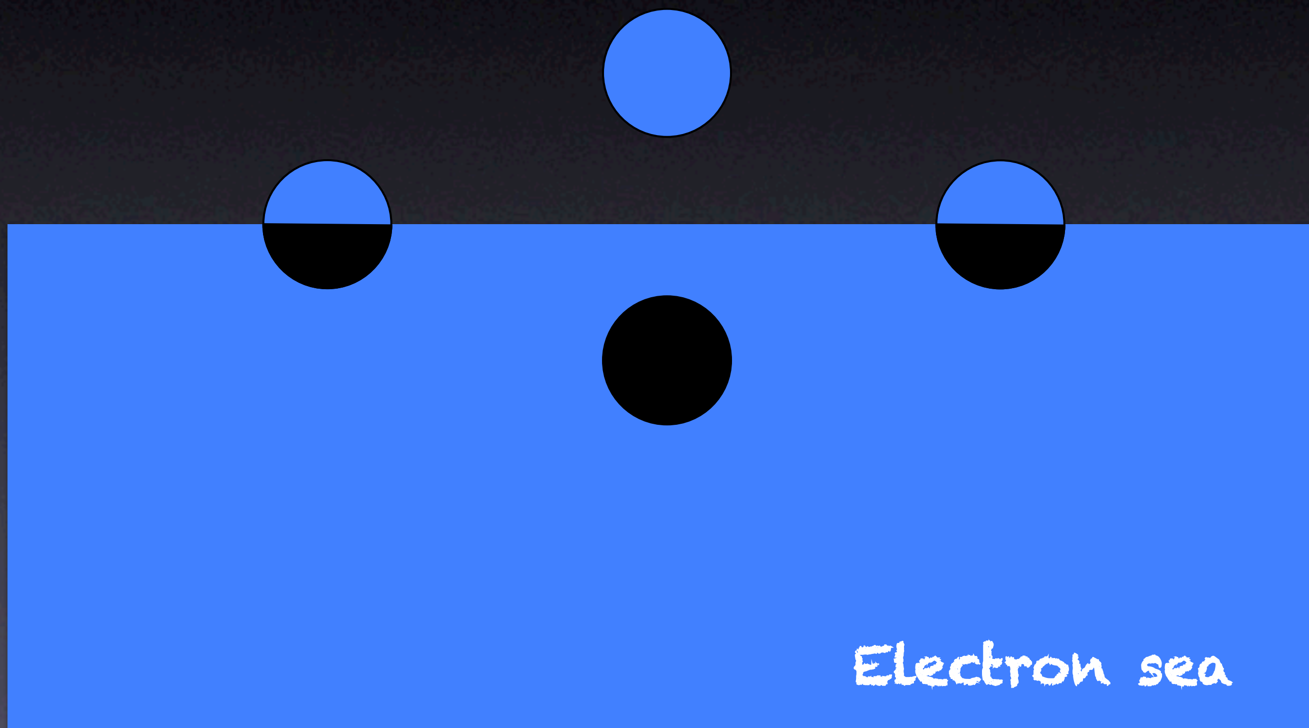
2 x (½ electron ± ½ hole) = 0



Majorana annihilatie

Second result:

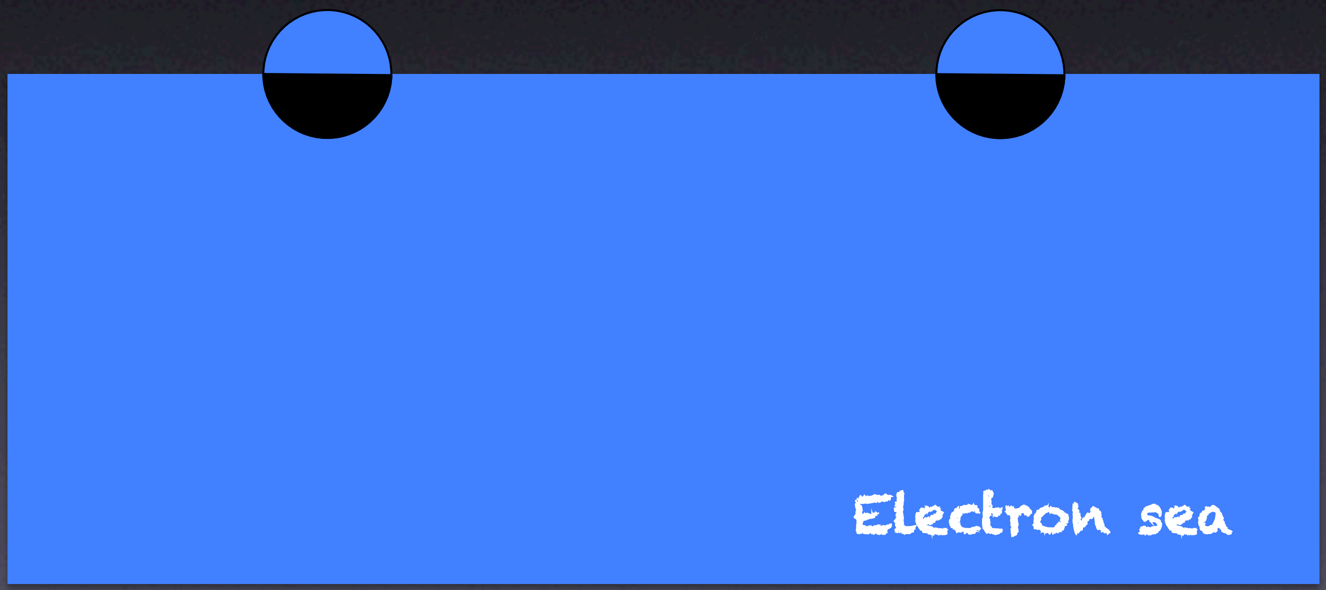
2 x (½ electron ± ½ hole) = electron + hole



Fusion Rules

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

Fusion by:
- Distance
- Interaction



uires fast gate operation

In the present context the ends of 1D topological su-

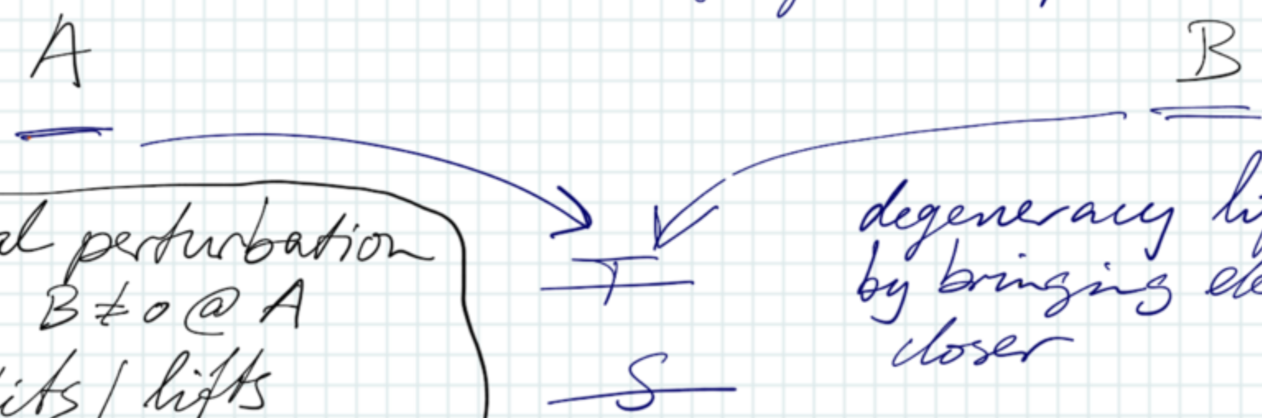
pair of anyons hybridizes the associated Majorana modes and splits the twofold ground-state degeneracy. The lower and upper states correspond to the Ising anyons coalescing into the identity (I) and fermion (ψ) fusion channels. While fusion and braiding are intimately linked, establishing the former experimentally is expected to be much simpler; see Figs. 5 and 6

* single electron has internal degrees-of-freedom
* 2 spin states, degenerate at $B=0$

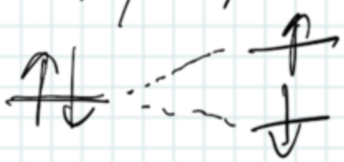
$S=\frac{1}{2}$ @ $B=0$ ↑ ↓

- fusion of two electrons forms a single 2-particle state with 4 internal degrees-of-freedom.
- fusion rule $\frac{1}{2} \times \frac{1}{2} = 0 + 1$

= singlet + triplet

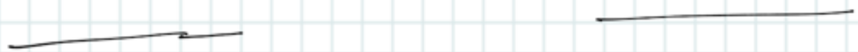


local perturbation e.g. $B \neq 0$ @ A splits / lifts



degeneracy lifted by bringing electrons closer

2 majo's   2 degenerate levels



local perturbation has no effect.

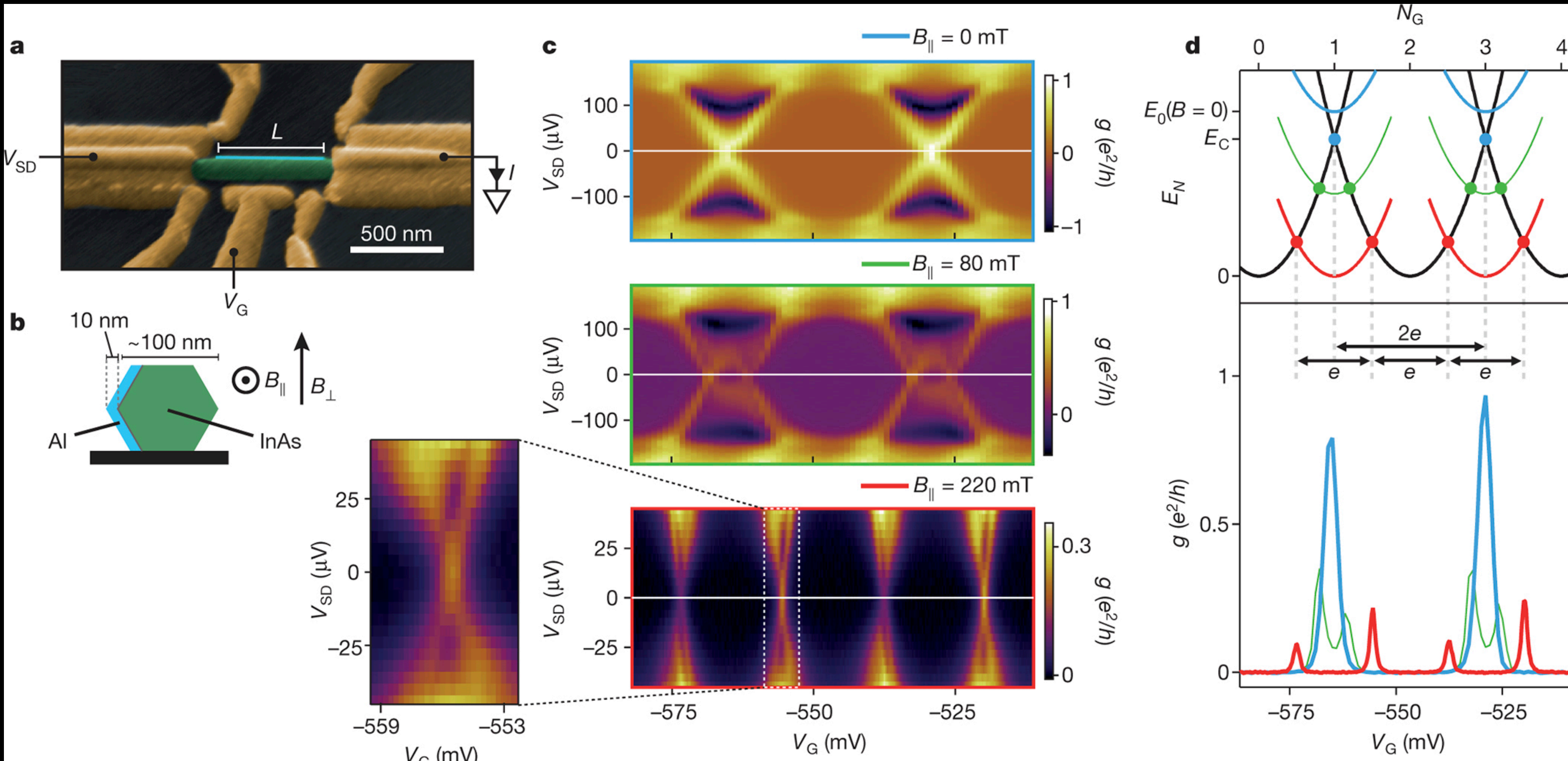
degeneracy lifted when bringing together

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

I = identity $\Rightarrow$ even state

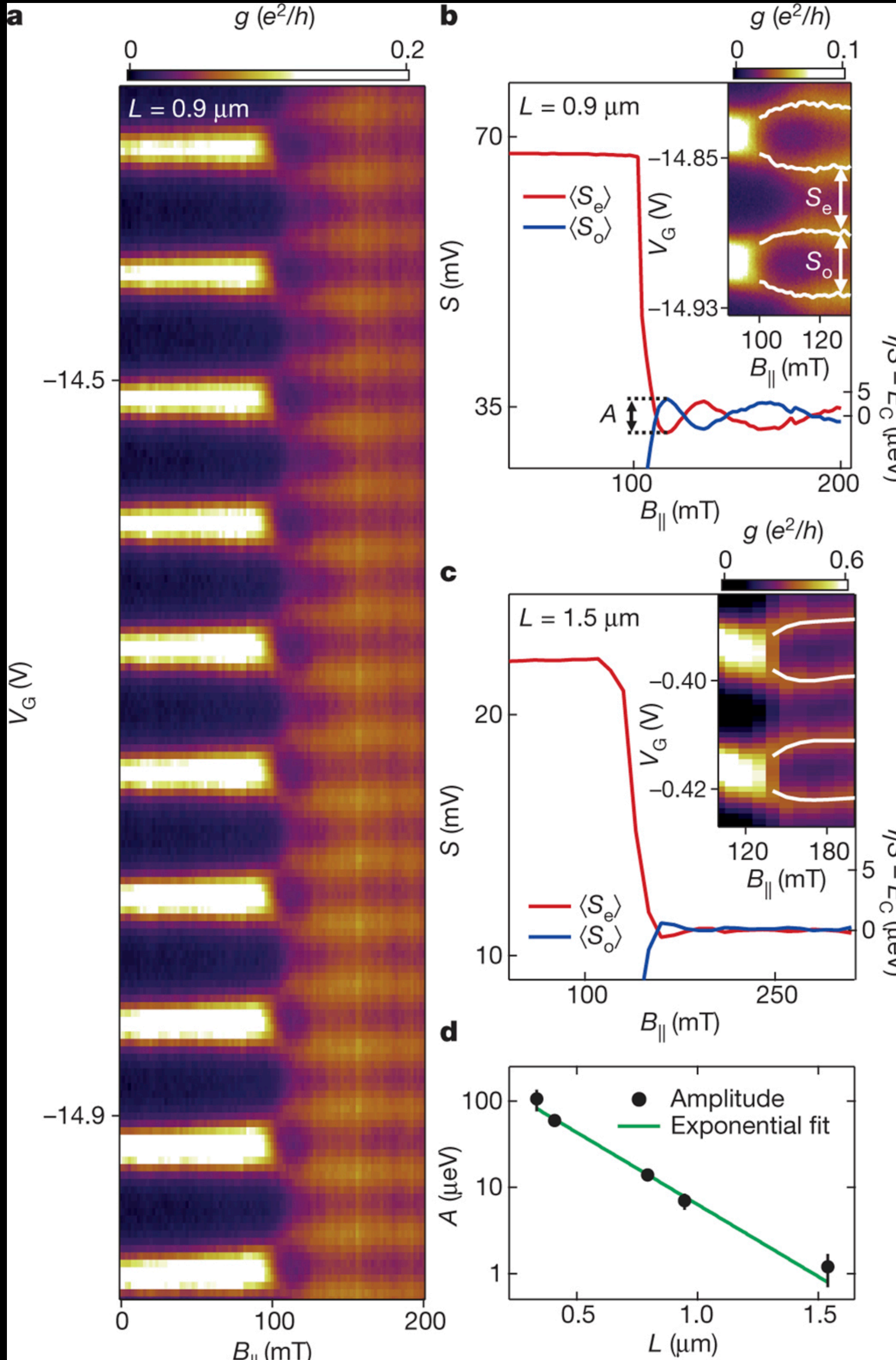
ψ = fermion channel $\Rightarrow$ odd state

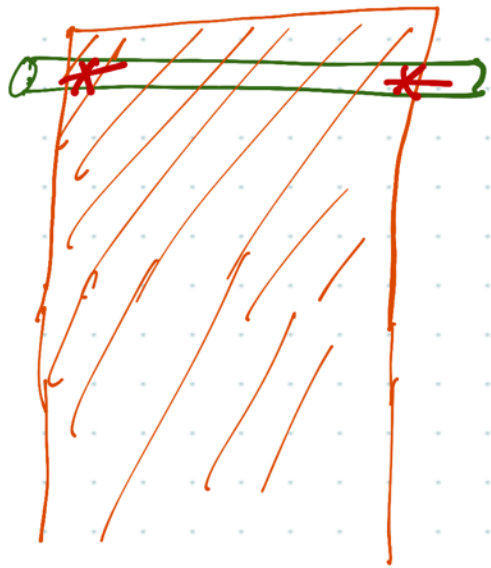
Majorana island device



S M Albrecht *et al.* *Nature* **531**, 206–209 (2016) doi:10.1038/nature17162

nature

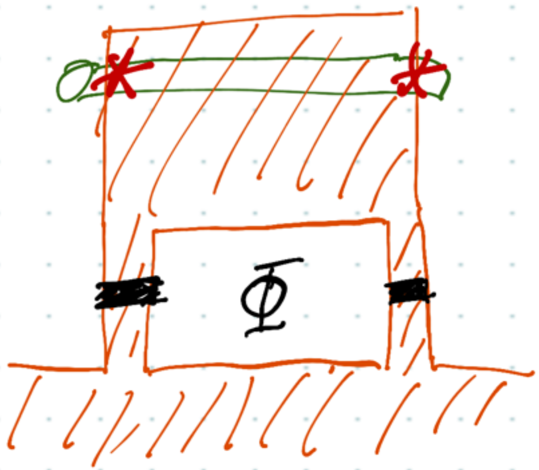

a
g (e²/h)
0
0.2
L = 0.9 μm
−14.5
−14.9
V_G (V)
0
100
200
B_|| (mT)
b
g (e²/h)
0
0.1
L = 0.9 μm
70
35
S (mV)
⟨S_e⟩
⟨S_o⟩
−14.85
−14.93
V_G (V)
S_e
S_o
100
120
B_|| (mT)
A
5
0
ηS − E_C (μeV)
100
200
B_|| (mT)
c
g (e²/h)
0
0.6
L = 1.5 μm
20
10
S (mV)
−0.40
−0.42
V_G (V)
120
180
B_|| (mT)
5
0
ηS − E_C (μeV)
⟨S_e⟩
⟨S_o⟩
100
250
B_|| (mT)
d
100
10
1
A (μeV)
Amplitude
Exponential fit
0.5
1.0
1.5
L (μm)



$E_c = 0$

N = undefined

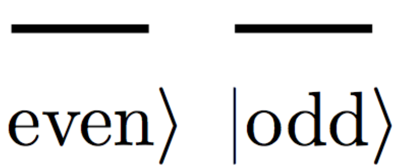
$\rightarrow E_{even} = E_{odd}$

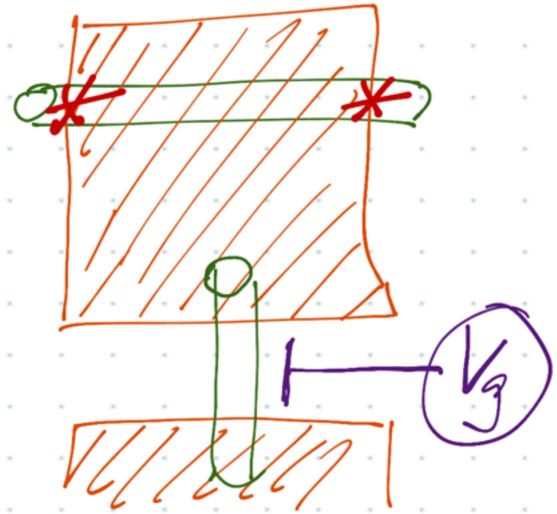


$E_J = E_{J0} \cos \Phi$

tuning: $\frac{E_J}{E_C}(\Phi)$

$$E_J \gg E_C$$

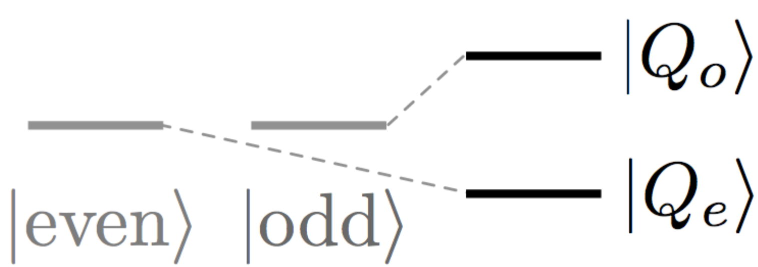




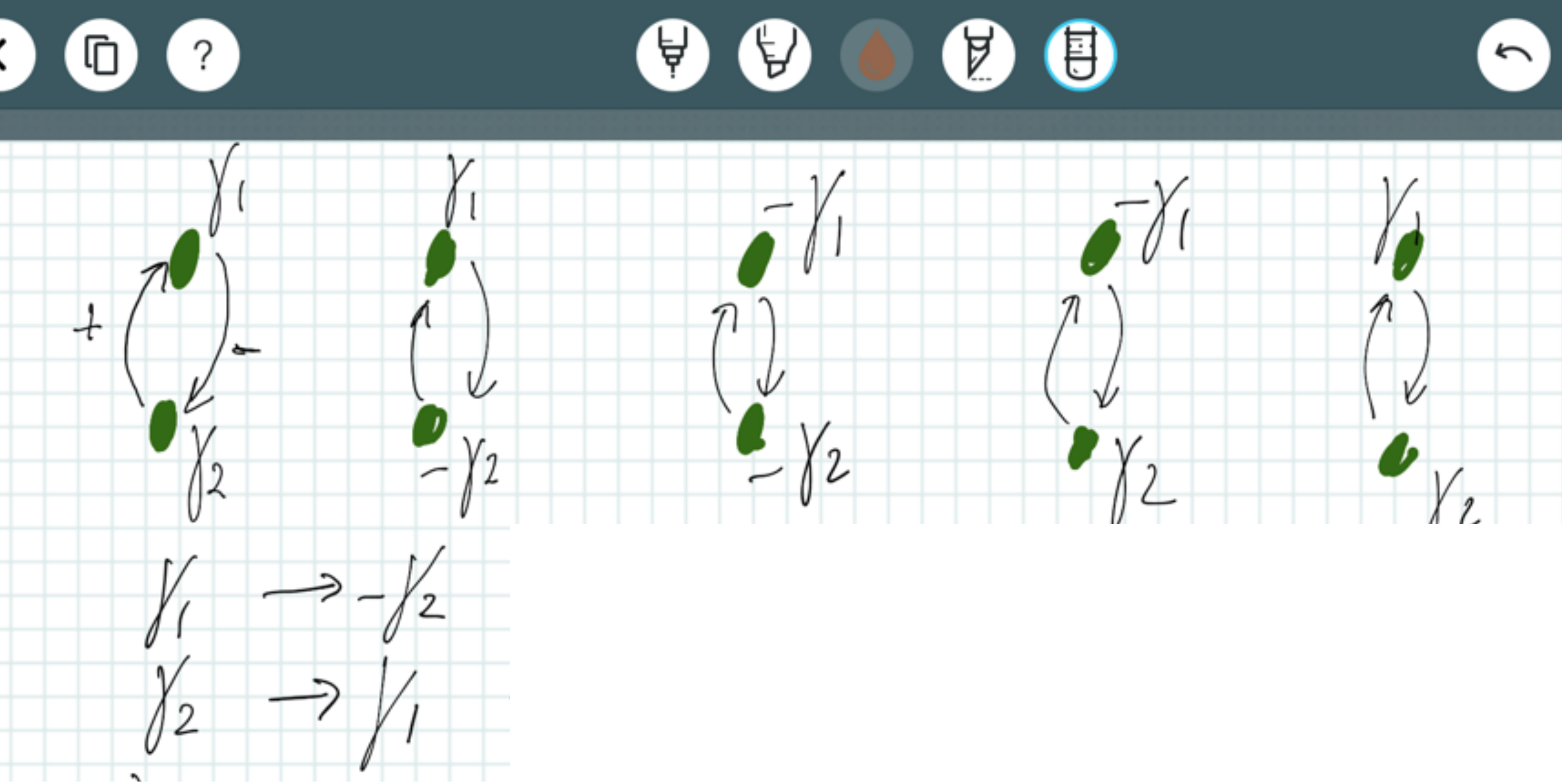
$E_J(V_g)$

tuning: $\frac{E_J}{E_C}(V_g)$

$$E_J \ll E_C$$



Braiding



It takes two full rotations to come back to initial state

$$B_{23}|00\rangle = \frac{1}{\sqrt{2}}(1+\gamma_2\gamma_3)|00\rangle$$

$$= \frac{1}{\sqrt{2}}(|00\rangle + \gamma_2|01\rangle)$$

$$\gamma_2 = i(f_1^{+} - f_1)$$

$$\gamma_3 = f_2^{+} + f_2$$

$$B|00\rangle = \frac{1}{\sqrt{2}}(|00\rangle + i|11\rangle)$$

$\gamma_3\gamma_2$ or

$$B_{23}|00\rangle = \frac{1}{\sqrt{2}}(1+\gamma_2\gamma_3)|00\rangle$$

$$\gamma_2 = i(f_1^+ - f_1)$$

$$\gamma_3 = f_2^+ + f_2$$

$$= \frac{1}{\sqrt{2}}(|00\rangle + \gamma_2|01\rangle)$$

$$B|00\rangle = \frac{1}{\sqrt{2}}(|00\rangle + i|11\rangle)$$

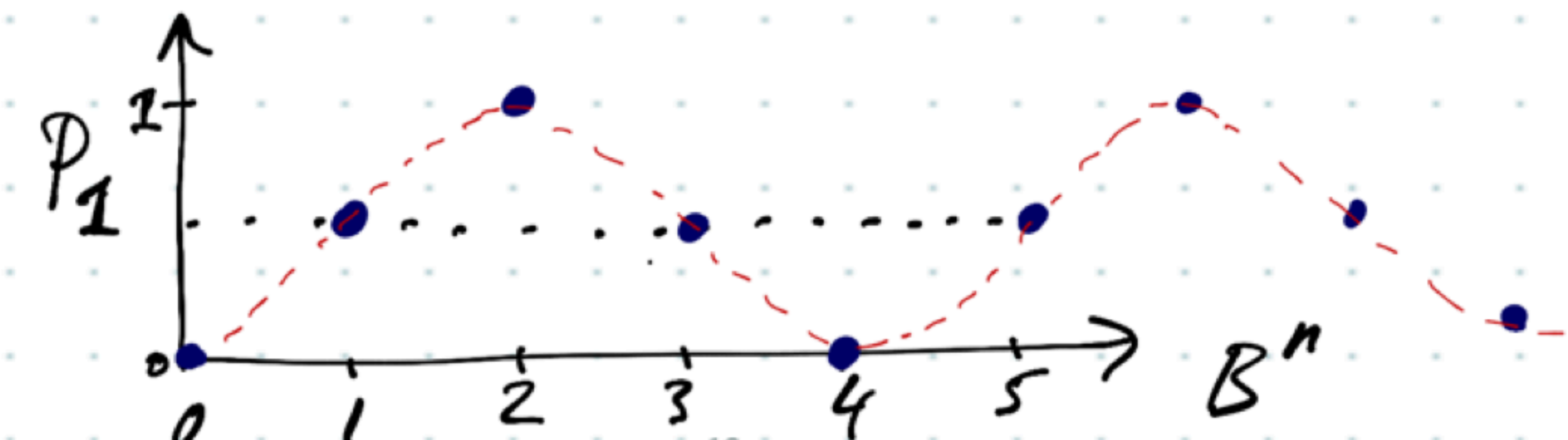
$\gamma_3\gamma_2$ or

$$B^2|00\rangle = \frac{1}{2}(1+\gamma_3\gamma_2)(|00\rangle + i|11\rangle) =$$

$$\frac{1}{2}(|00\rangle + i|11\rangle - \gamma_2\gamma_3|00\rangle - i\gamma_2\gamma_3|11\rangle)$$

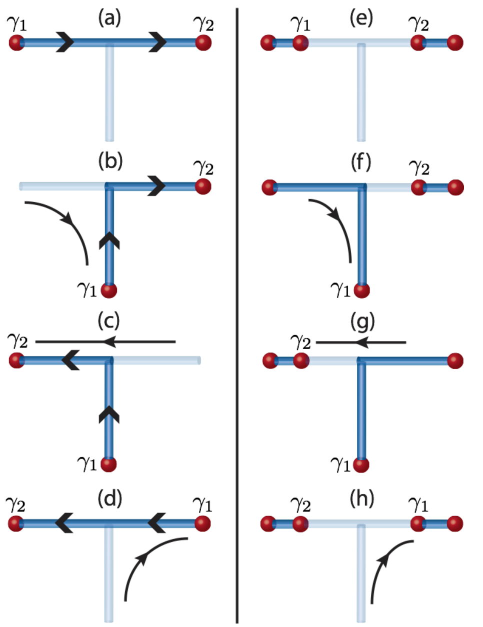
$$+i|11\rangle \qquad -|00\rangle$$

$$B^2|00\rangle = ?\,i|11\rangle$$



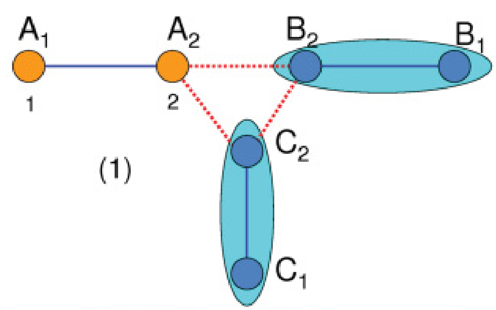
Proposals for braiding Majoranas

Position



Alicea *et. al*, N. Phys (2011)

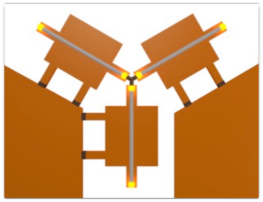
Tunnel coupling



Sau *et. al*, PRB (2011)

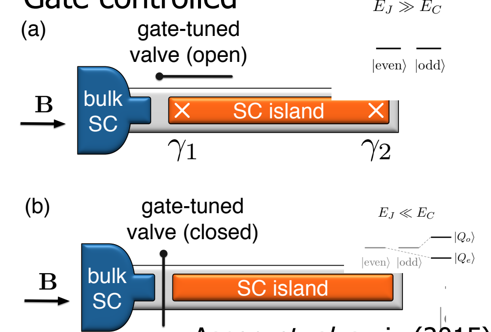
Coulomb coupling

Flux controlled



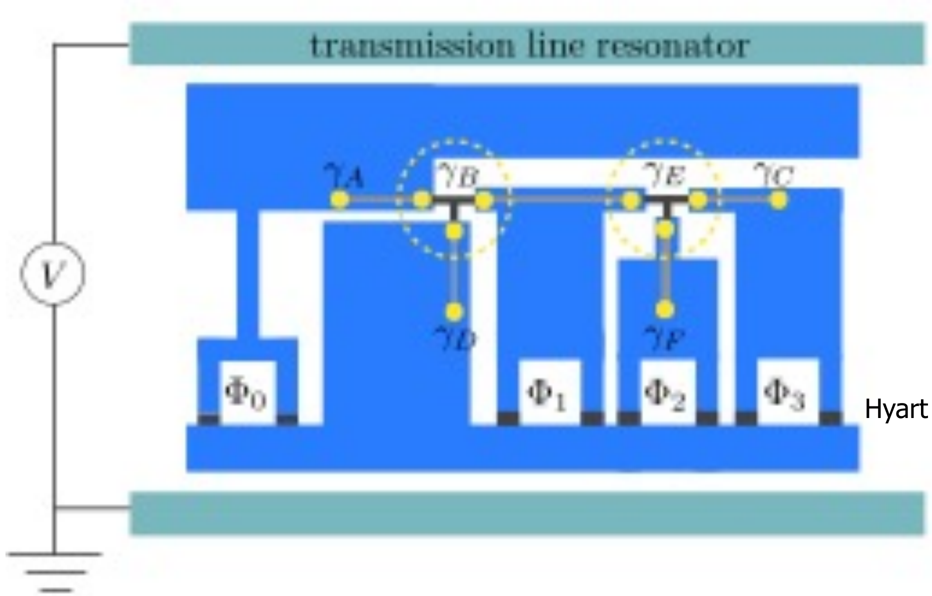
van Heck *et. al*, PRB (2011)

Gate controlled



Aasen *et. al*, arxiv (2015)

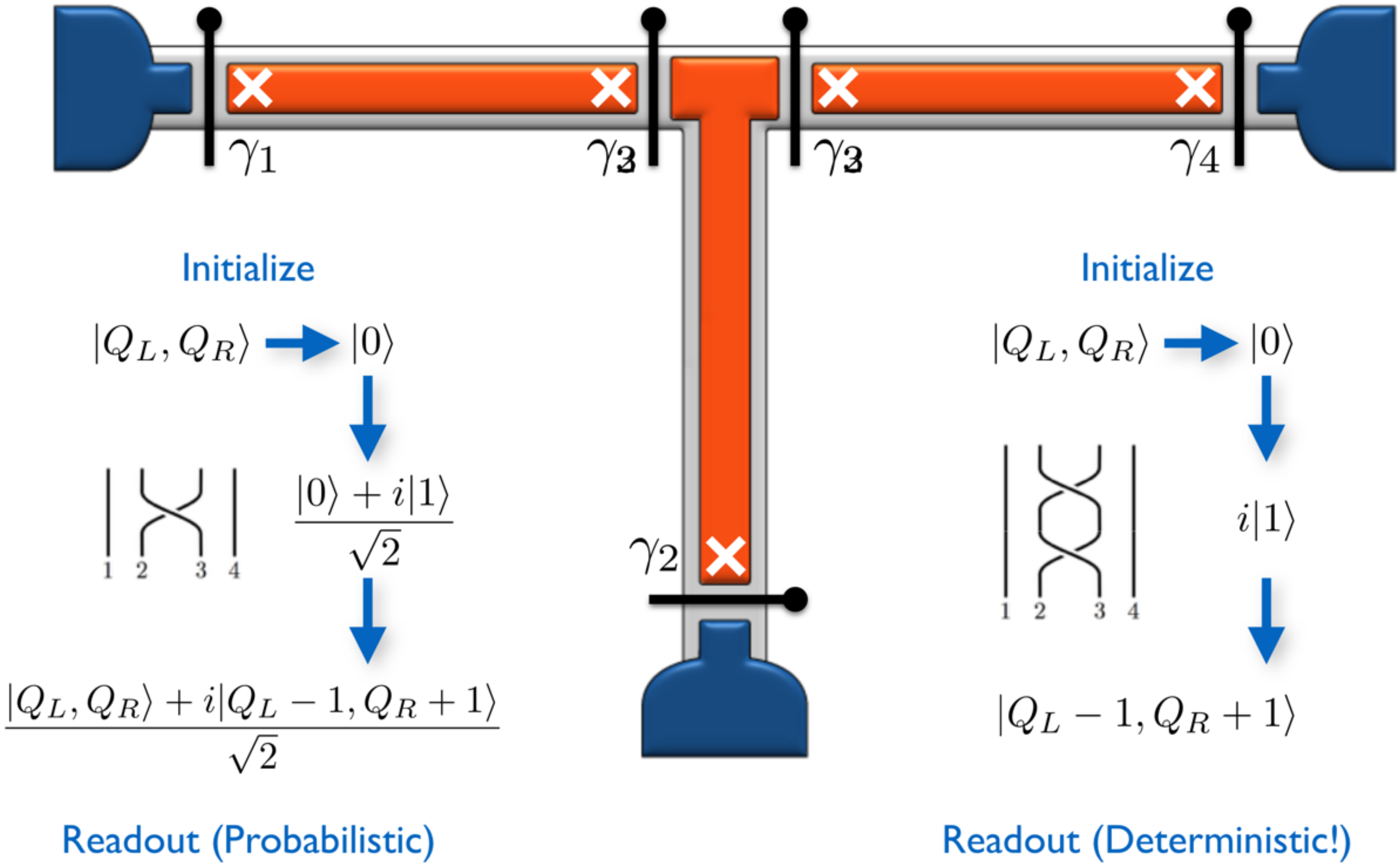
Transmon as a charge parity sensor

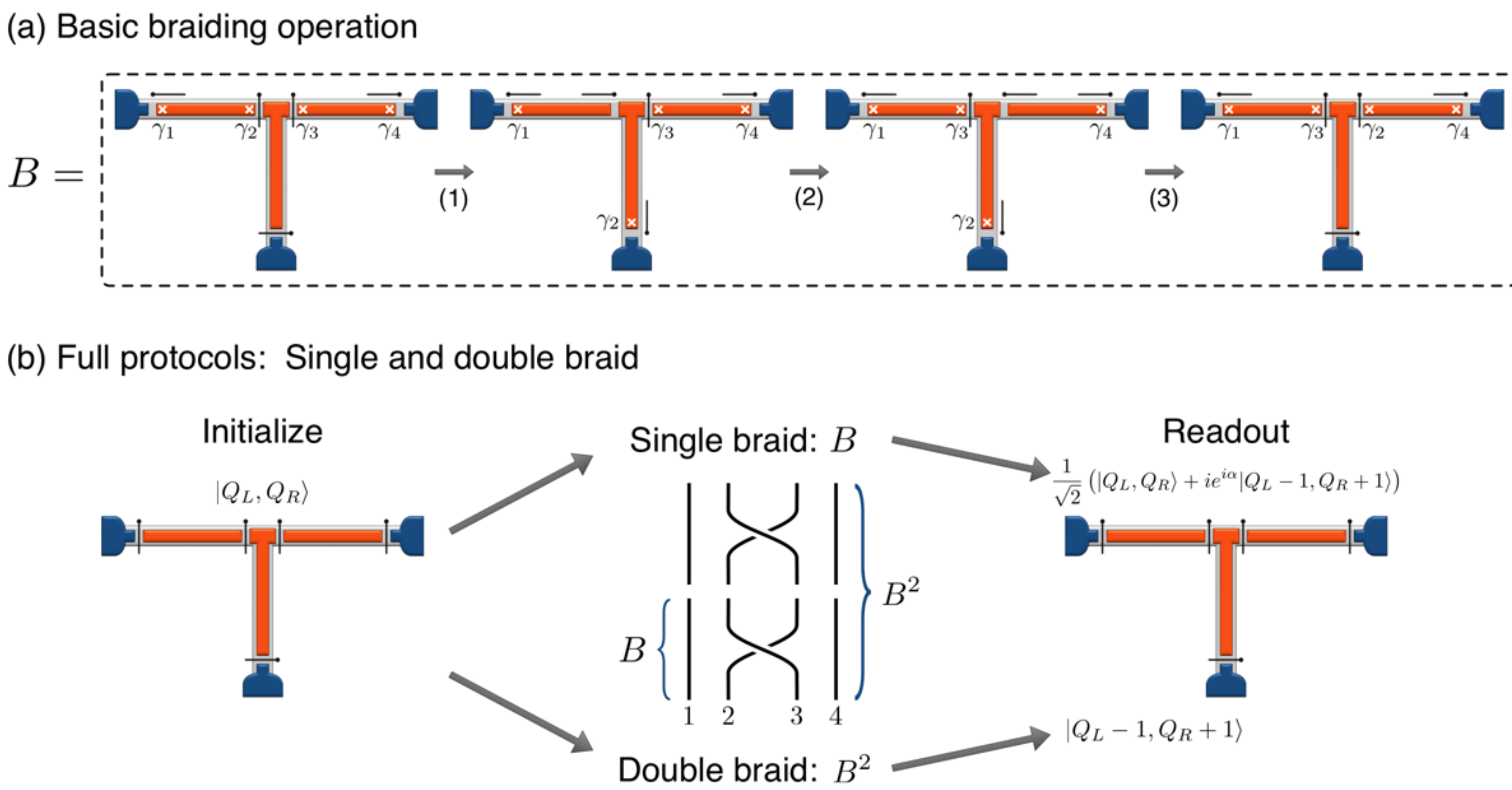


Hyart *et. al,* PRB (2013)

- Readout via parity to charge conversion by changing E_J/E_C
- Operation + readout must be carried out before quasiparticle poisoning disturbs parity
- Superconducting circuit elements must survive B > 0.5 T Majorana conditions

Braiding protocol





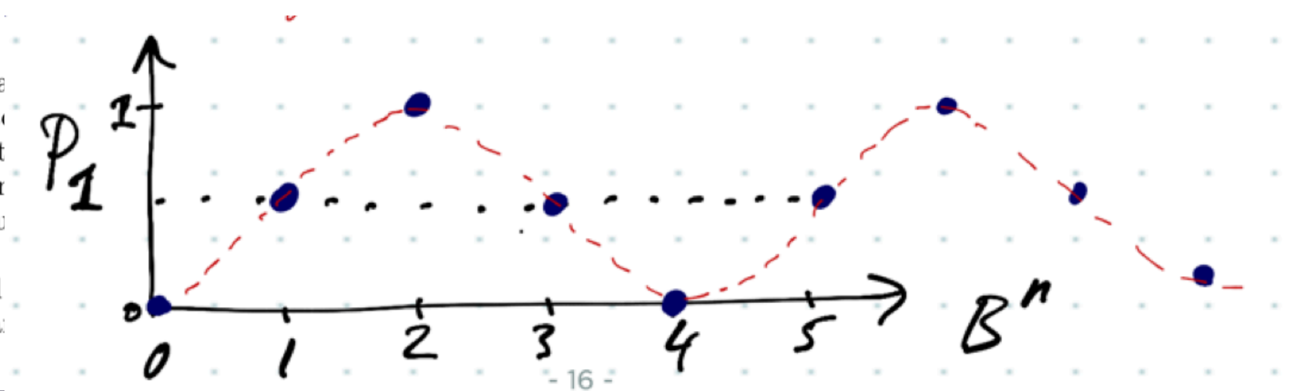


FIG. 10. (a) … lodulating the
three valves a… ng topological
superconducto… us nontrivially
rotating the t… erifying 'rigid'
qubit rotation… ed islands, the
topological qu… le braid (lower
path) rotates … e qubit rotates
into an equal … braid flips the
qubit to $|1\rangle$ a…

PARITY CONSERVATION
OR
QUASI-PARTICLE
POISONING

Kitaev

Lutchyn et al.
Oreg et al.

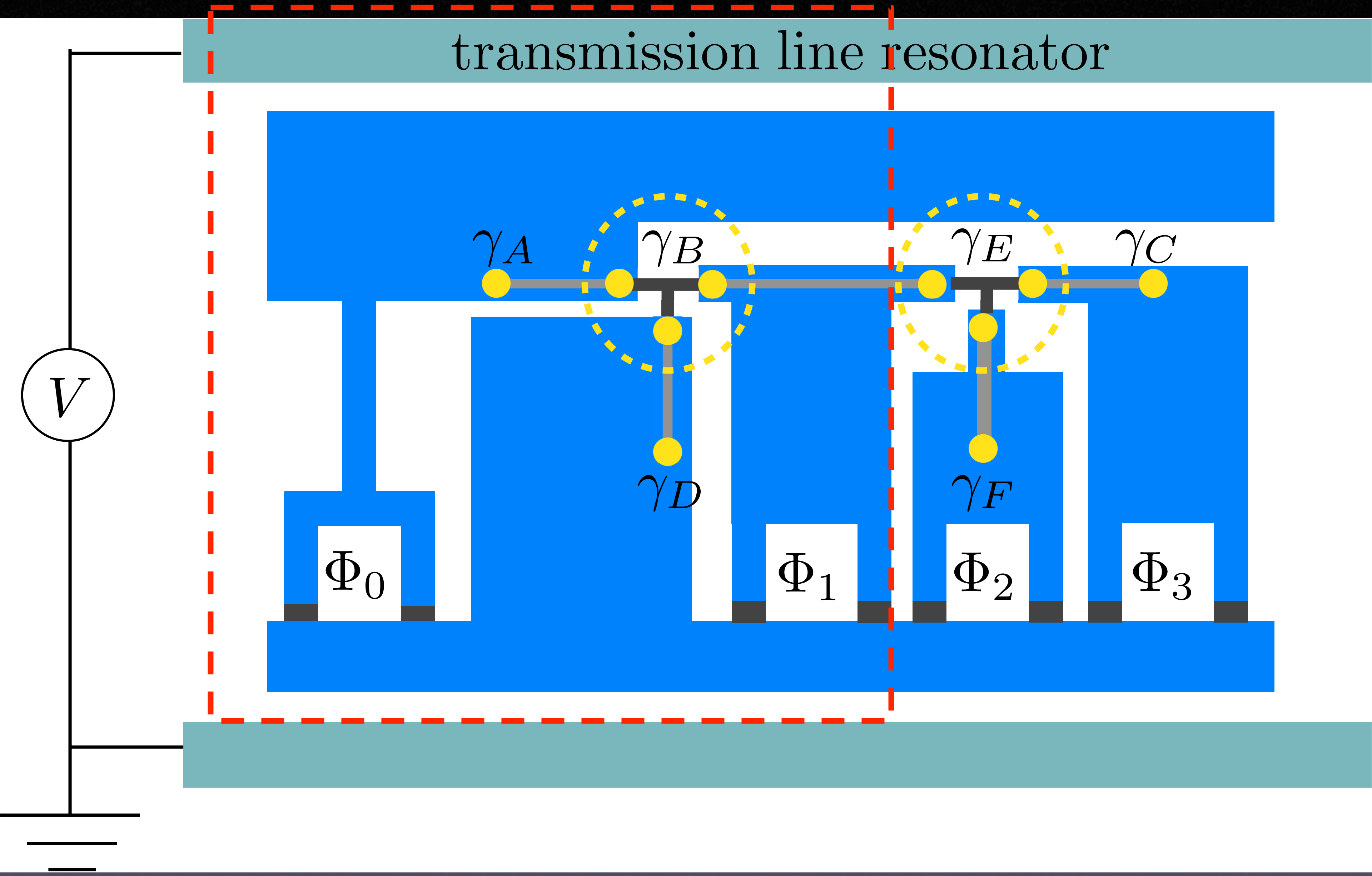
numerical work
advanced device proposals

"Majorana
zero mode"
⇒ ZBP
Xu-Lund
Harlingen-Illinios
Marcus-Copenhagen

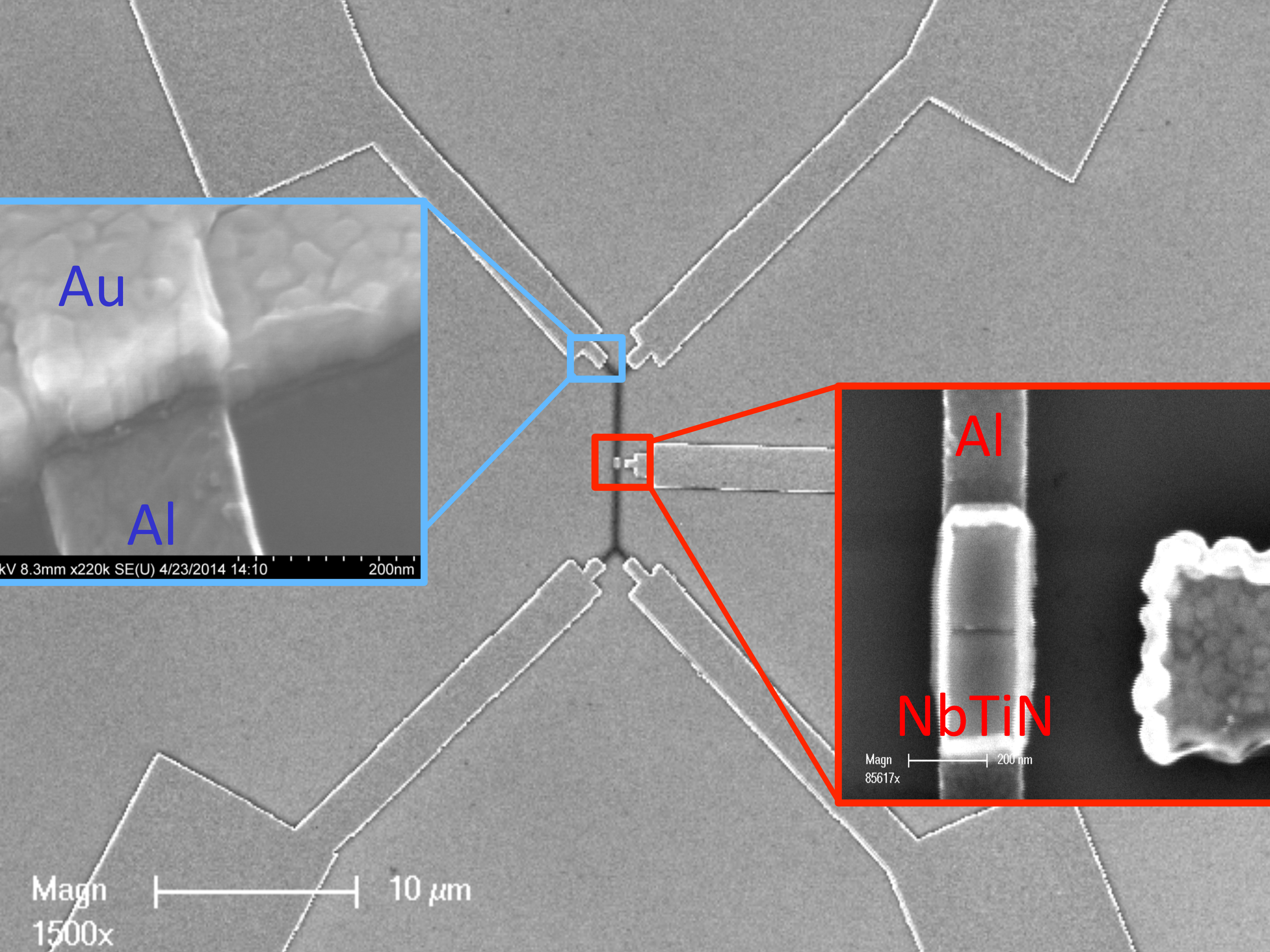
"Majorana state"
parity qubit
topological aspects

Braiding,
non-Abelian

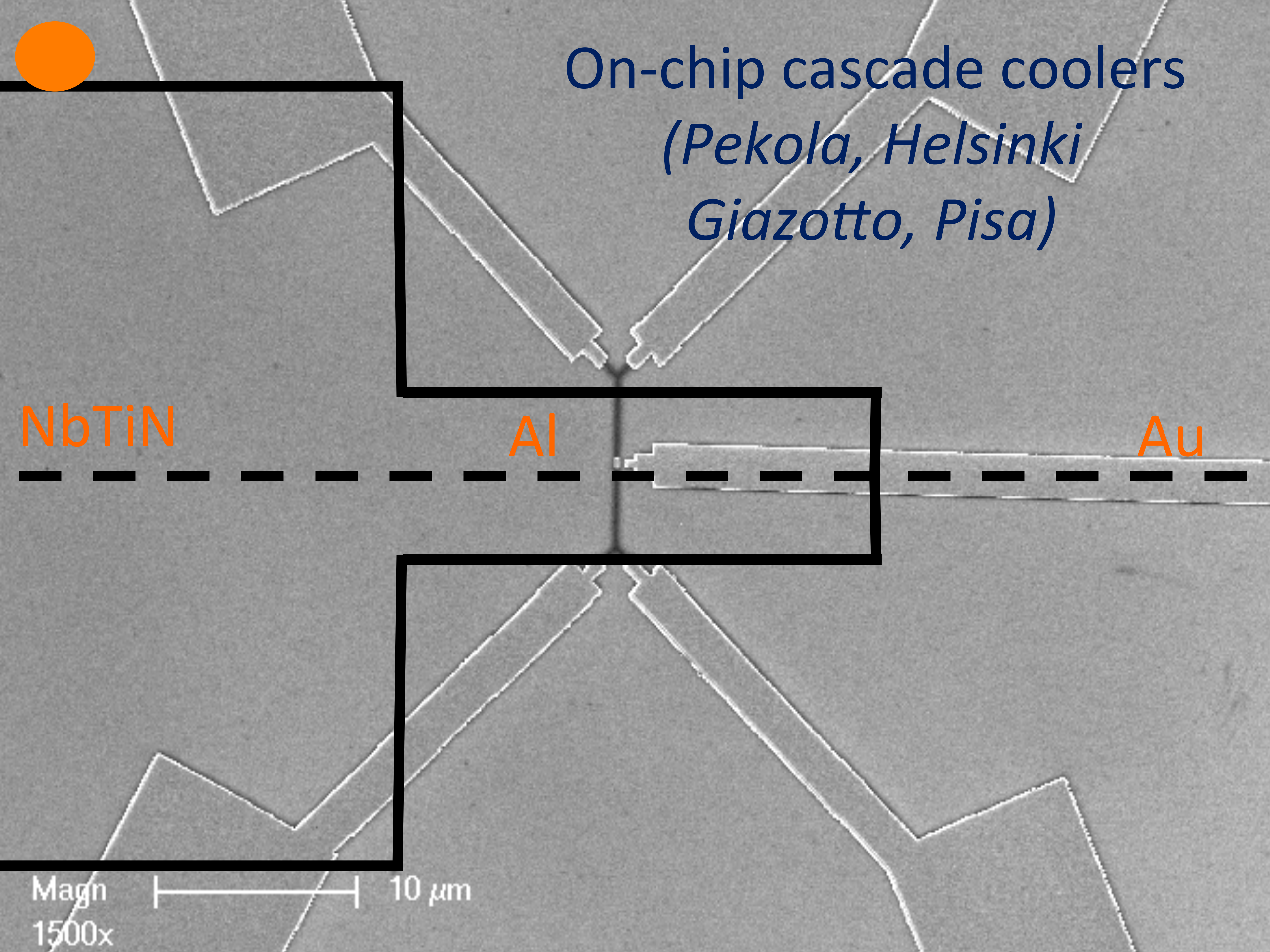
⇒ control even-odd occupation in an ~ open system

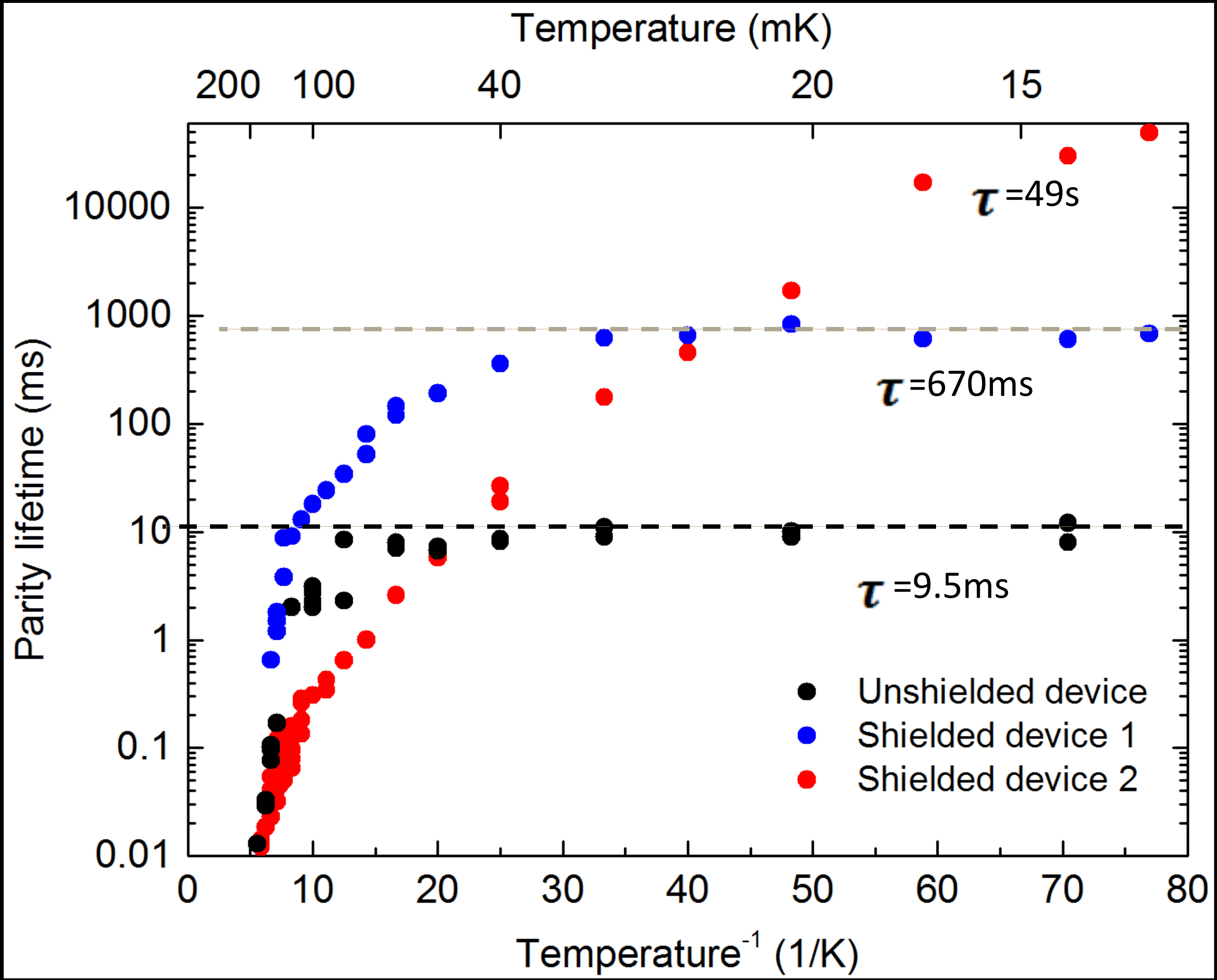


Hyart, van Heck, Fulga, Burrello, Akhmerov & Beenakker, PRB (2013)


Au
Al
kV 8.3mm x220k SE(U) 4/23/2014 14:10
200nm
Al
NbTiN
Magn
85617x
200 nm
Magn
1500x
10 µm

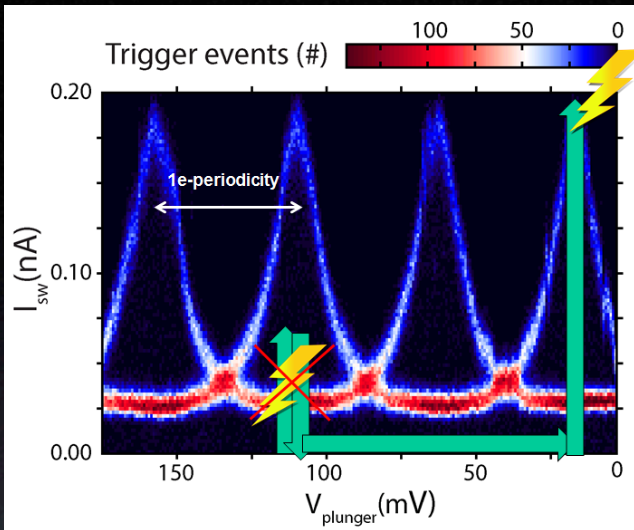
On-chip cascade coolers
(Pekola, Helsinki
Giazotto, Pisa)



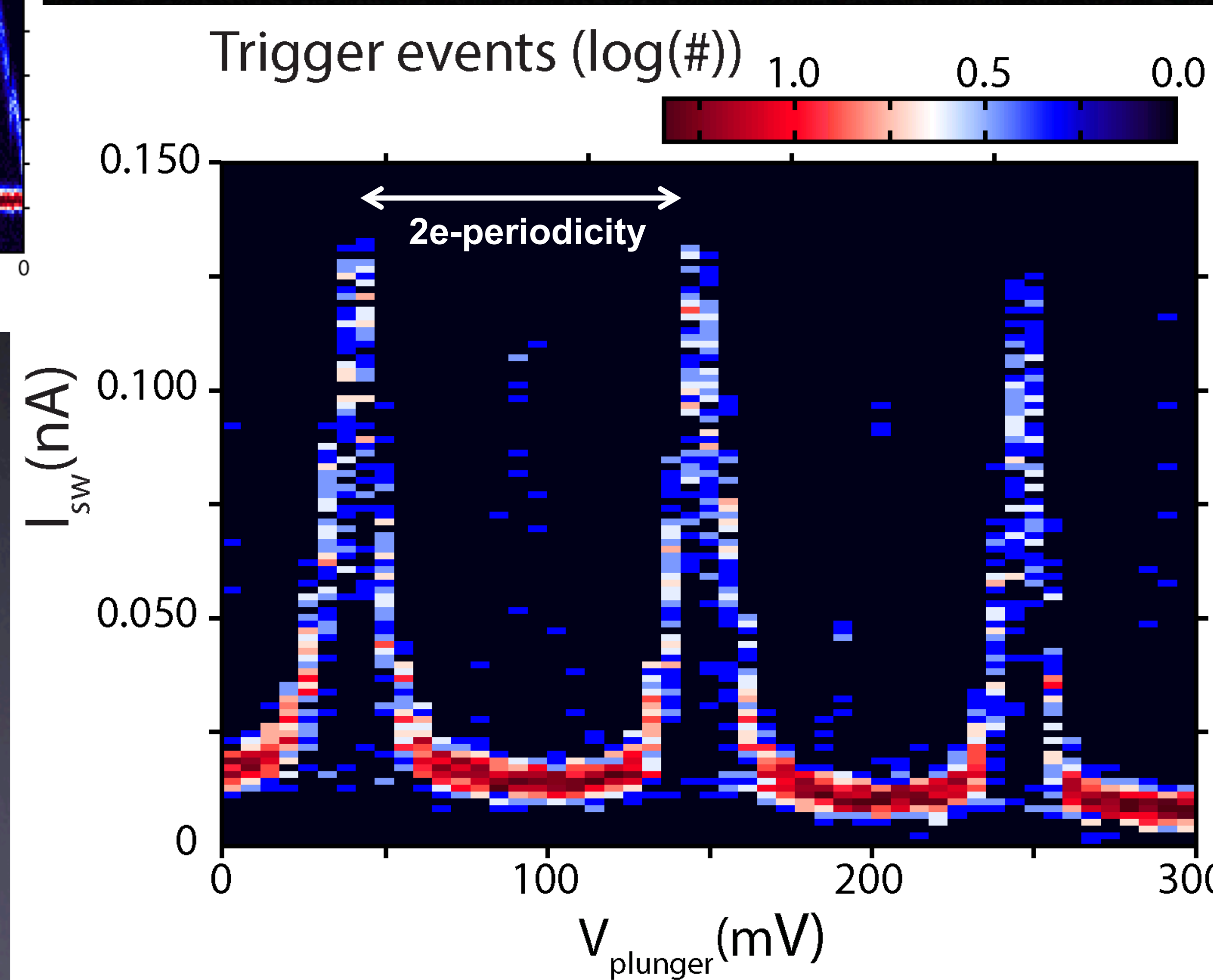


Temperature (mK)
200
100
40
20
15
Parity lifetime (ms)
10000
1000
100
10
1
0.1
0.01
τ =49s
τ =670ms
τ =9.5ms
Unshielded device
Shielded device 1
Shielded device 2
0
10
20
30
40
50
60
70
80
Temperature-1 (1/K)

Explicit demonstration of parity conservatioin



QP-time ~ minute



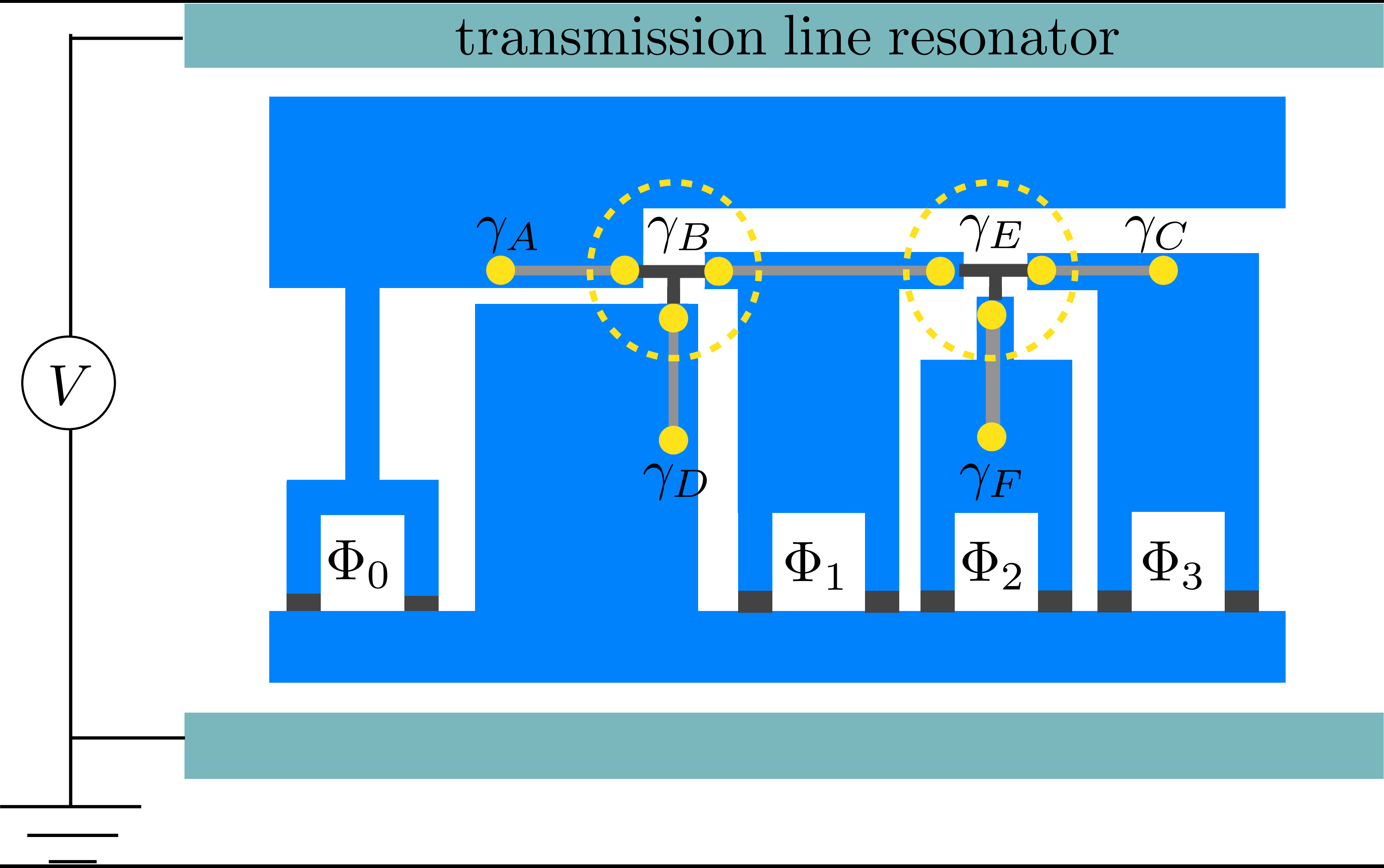
Our best (QP) parity relaxation time:
~1 minute

Note: E_J = 50 μeV, => f_J = 25 GHz

ratio of 12 orders of magnitude
(between parity change over tunneling)

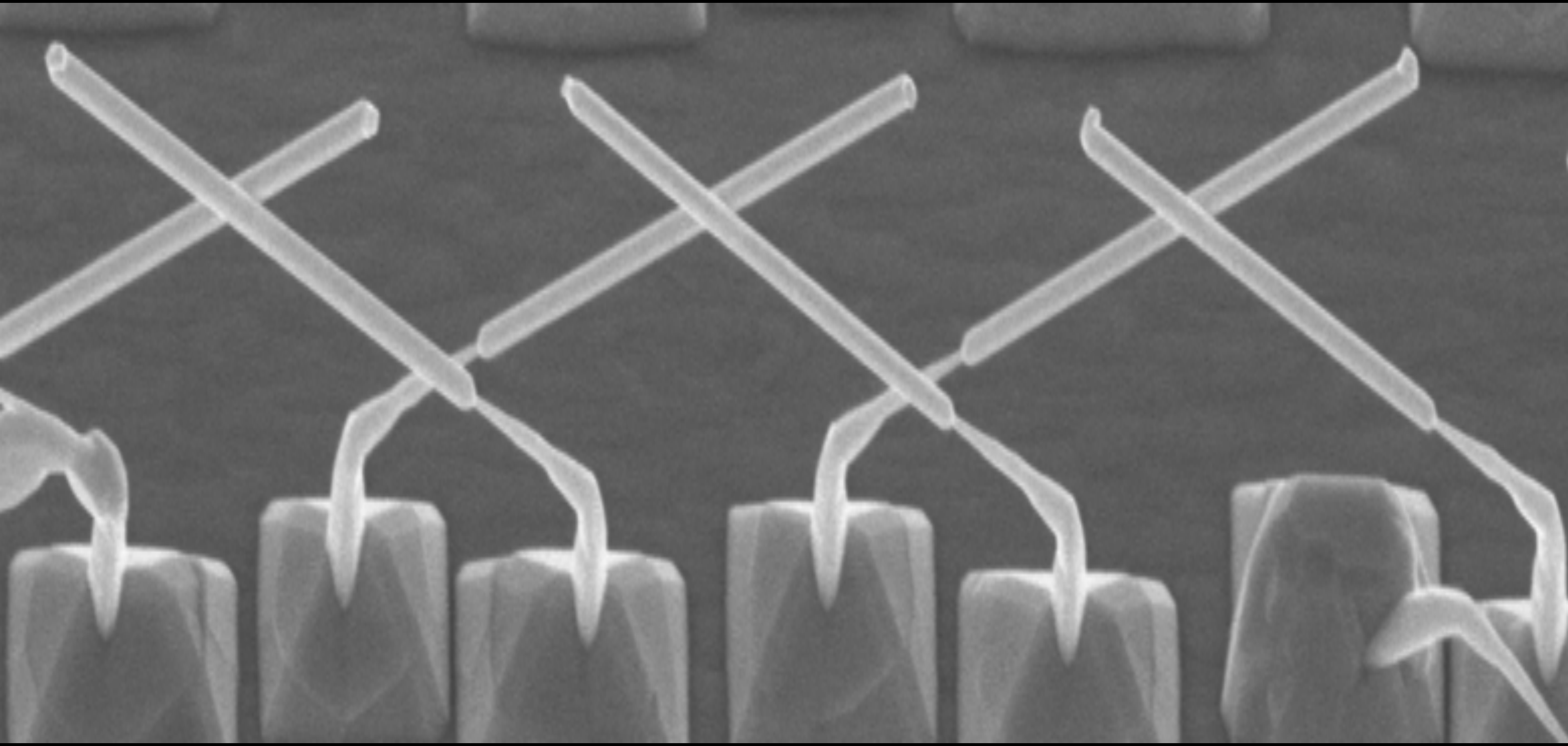
van Woerkom, Geresdi, LK, Nature Physics (2015)

NANOWIRE CROSSES

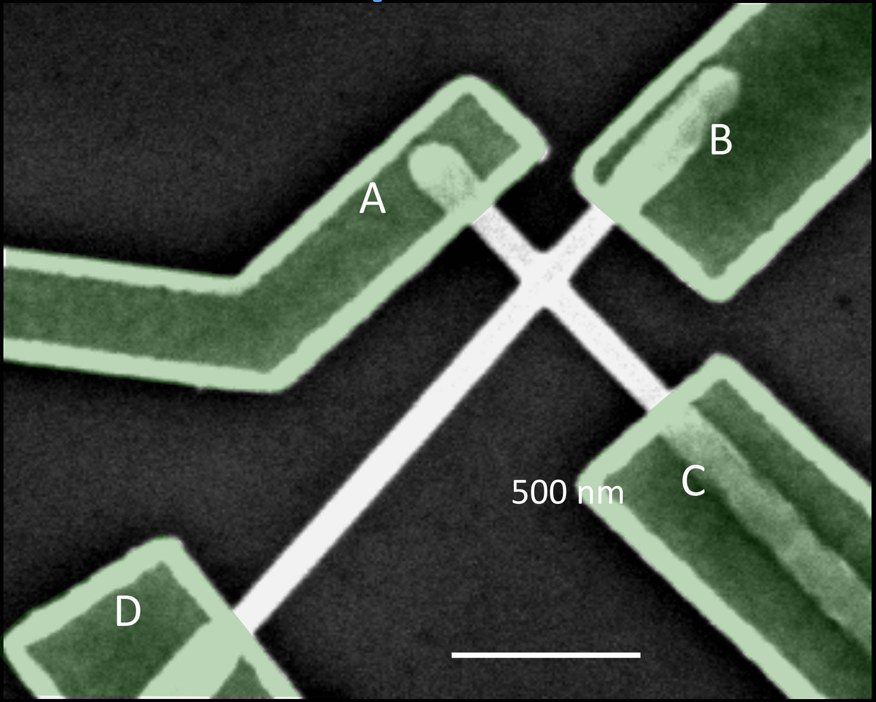


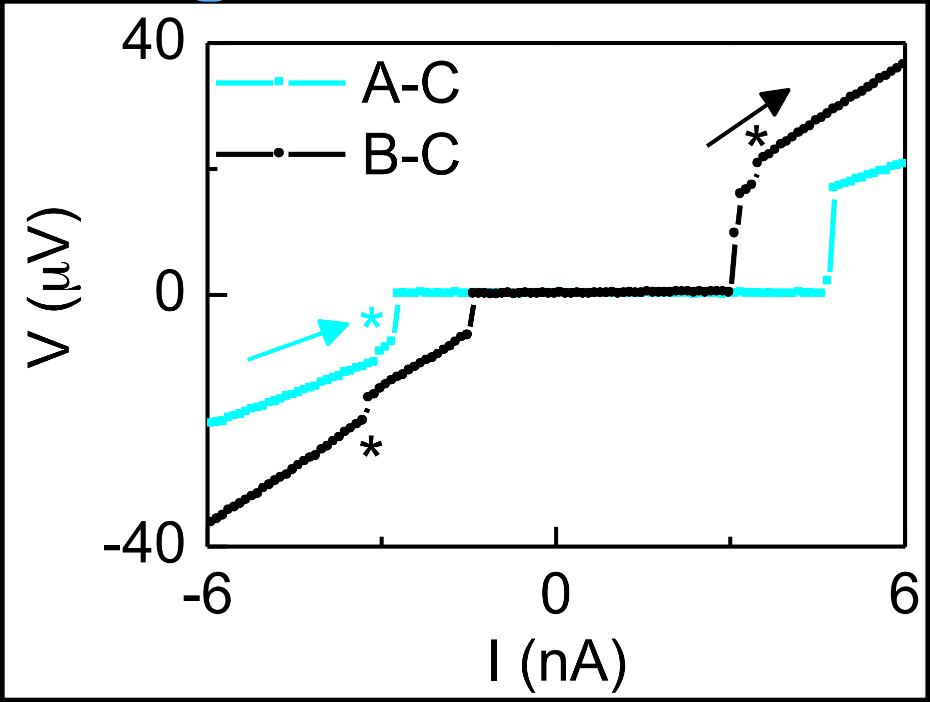
Hyart, van Heck, Fulga, Burrello, Akhmerov & Beenakker, PRB (2013)

Growth by Diana Car,
Sébastien Plissard and Erik Bakkers

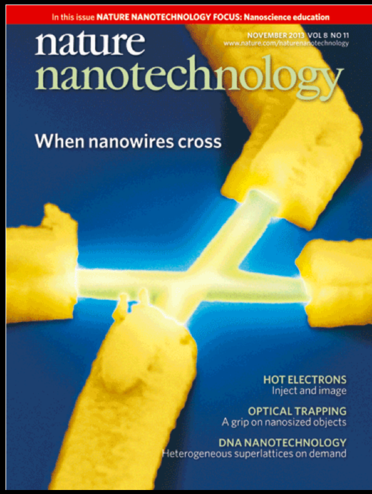


Supercurrent through nanocross





⇒ Transparent epitaxial (!) interface between wires



Plissard, Bakkers et al., *Nature Nanotech.* (2013)