Title: The Story of Anyons

Speakers: Steve Simon

Series: Colloquium

Date: December 15, 2021 - 2:00 PM

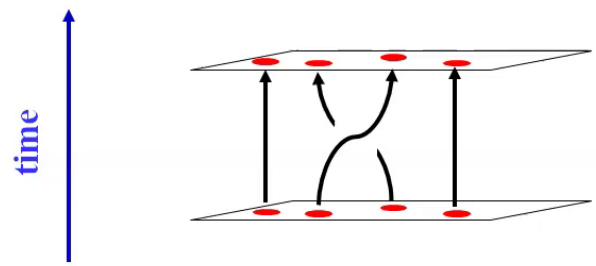
URL: https://pirsa.org/21120030

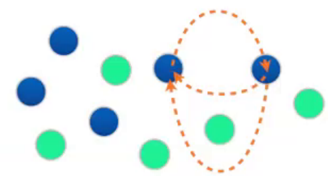
Abstract: I will review the history of anyons, particles that are neither bosons nor fermions, starting with their theoretical proposal all the way to their definitive experimental observation over 40 years later. I will further discuss why the more general idea of non-abelian anyons is of intense interest for quantum computation. If time permits I will give a status report on some of the current non-abelian anyon experiments.

Zoom Link: https://pitp.zoom.us/j/98698779123?pwd=SWIyak9OZ0dud2ZGcWdoazdkVURHQT09

The Story of Anyons

Caution: This is a selective history





Steve Simon

EPSRC

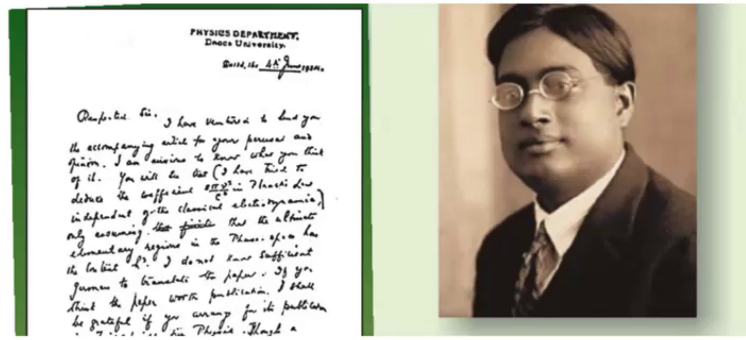
UNIVERSITY OF OXFORD

What happens when you exchange two identical particles?

BOSONS ●

1924: **Bose-Einstein Statistics**

"Respected Sir,
I have ventured to send you
the accompanying article
for your perusal and opinion..."



FERMIONS

1925: **Pauli Exclusion**

Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren.

Von **W. Pauli** jr. in Hamburg.

(Eingegangen am 16. Januar 1925.)

Resulting in **Fermi-Dirac Statistics** ... discovered first by Jordan 1925..
... then Fermi and Dirac 1926

1930: **Basics of Quantum Mechanics Finished** (QFT by ~1948)

Are there other types of particles besides bosons and fermions?

There *were* attempts to define "parastatistics" but eventually these were found to be essentially bosons and fermions in disguise. (Doplicher, Haag, Roberts ~ 1970)

No one asked about lower dimensions until...

IL NUOVO CIMENTO Vol. 37 B, N. 1 11 Gennaio 1977

"...in one and two dimensions a continuum of possible intermediate cases connects the boson and fermion cases..."

On the Theory of Identical Particles.

J. M. Leinaas and J. Myrheim
Department of Physics, University of Oslo - Oslo

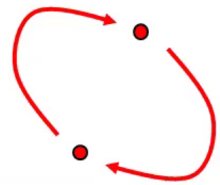
(ricevuto il 16 Agosto 1976)

Clockwise exchange gets phase

$e^{i\theta}$

Counterclockwise exchange gets phase

$e^{-i\theta}$



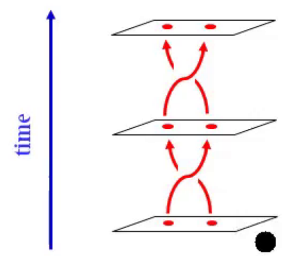
Dogma:

Exchanging twice should be identity $\sqrt{1} = \pm 1$

- Bosons $\Psi(r_1, r_2) = \Psi(r_2, r_1)$
- Fermions $\Psi(r_1, r_2) = -\Psi(r_2, r_1)$

And That's All ?

In 2+1 Dimensions: Two Exchanges $\neq$ Ide[redacted]



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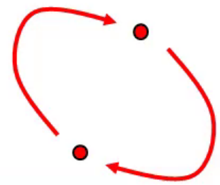

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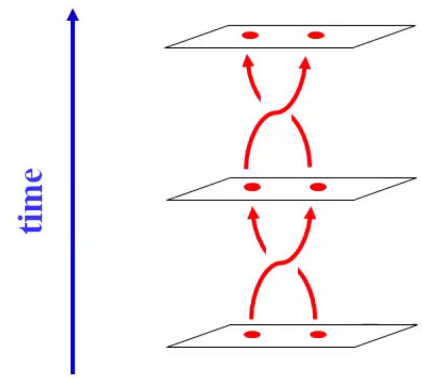
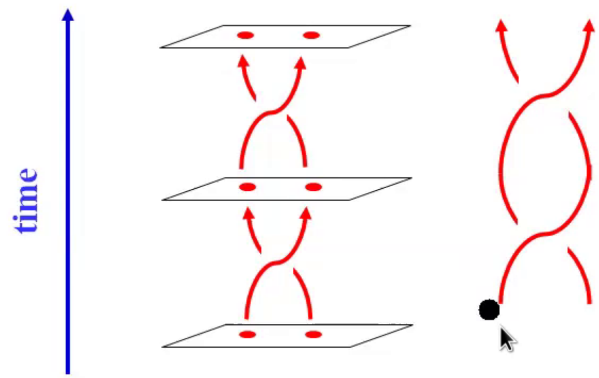


In 2+1 Dimensions: Two Exchanges ≠ Identity



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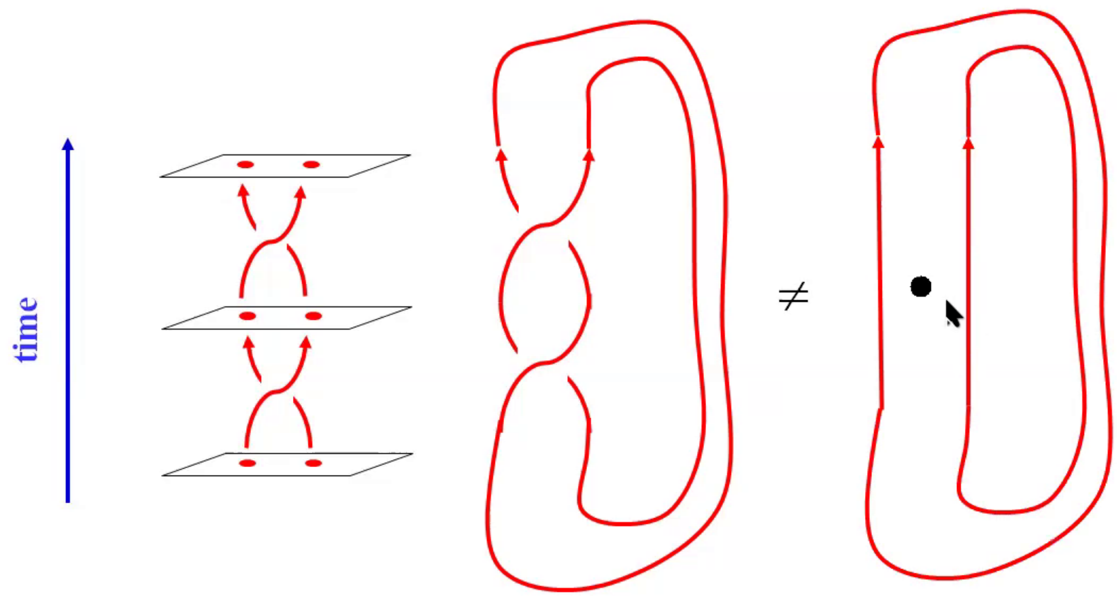

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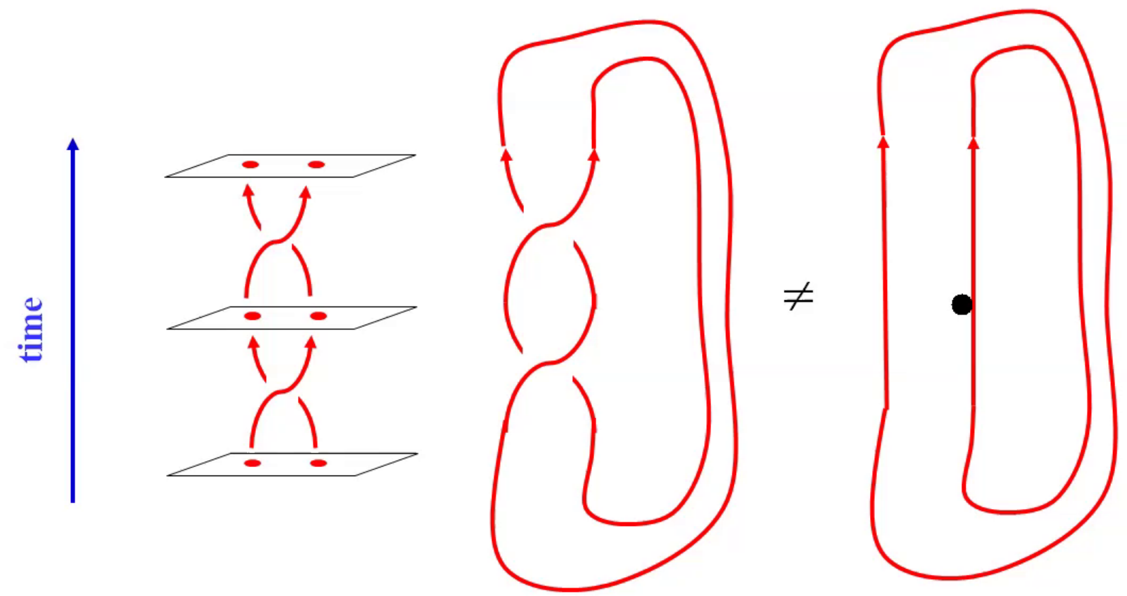


In 3+1 Dimensions: Two Exchanges = Identity

No Knots in (one dimensional) World Lines in 3+1 D !

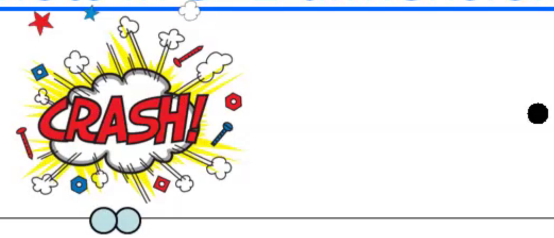
Why are there no knots in 3+1 dimensions?

1+1 d point particles

No way to cross without crashing

Why are there no knots in 3+1 dimensions?

1+1 d point particles



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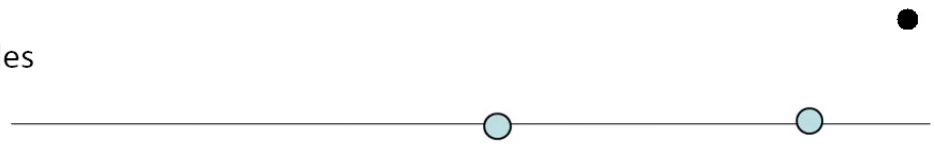
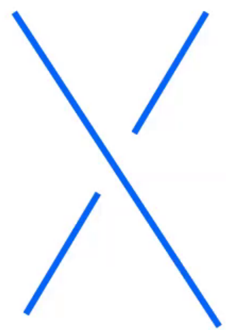


Why are there no knots in 3+1 dimensions?

2+1 d point particles

Can get to the other side without touching

2+1 d world lines



No way to change over-crossing to under-crossing without crashing

Why are there no knots in 3+1 dimensions?

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Can get to the other side without touching

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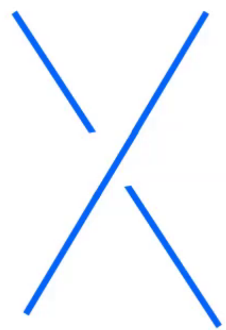

No way to change over-crossing to under-crossing without crashing

But in 3+1d, can get to other side without touching

1977 J. M. LEINAAS and J. MYRHEIM

1982 **Quantum Mechanics of Fractional-Spin Particles**
Frank Wilczek

coins word "Anyon"
5th citation of Leinaas + Myrheim

1982 **Two-Dimensional Magnetotransport in the Extreme Quantum Limit**
D. C. Tsui,[a),(b)] H. L. Stormer,[(a)] and A. C. Gossard

Discovery of FQHE!

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R. B. Laughlin

Laughlin Theory

Nobel Prize 1998

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FQHE quasiparticles are anyons!

: .....
: ....
2020

(Fractional) Quantum Hall Primer

- Occurs in 2D electron systems in strong B-field when filling $\nu \approx p/q$

$$\nu = \frac{\text{electron density}}{\text{flux density}} \approx p/q$$

- We consider ν=1/3 :

Low energy excitations:

Charge $e^* = e/3$

Statistics $\theta = 2\pi/3$

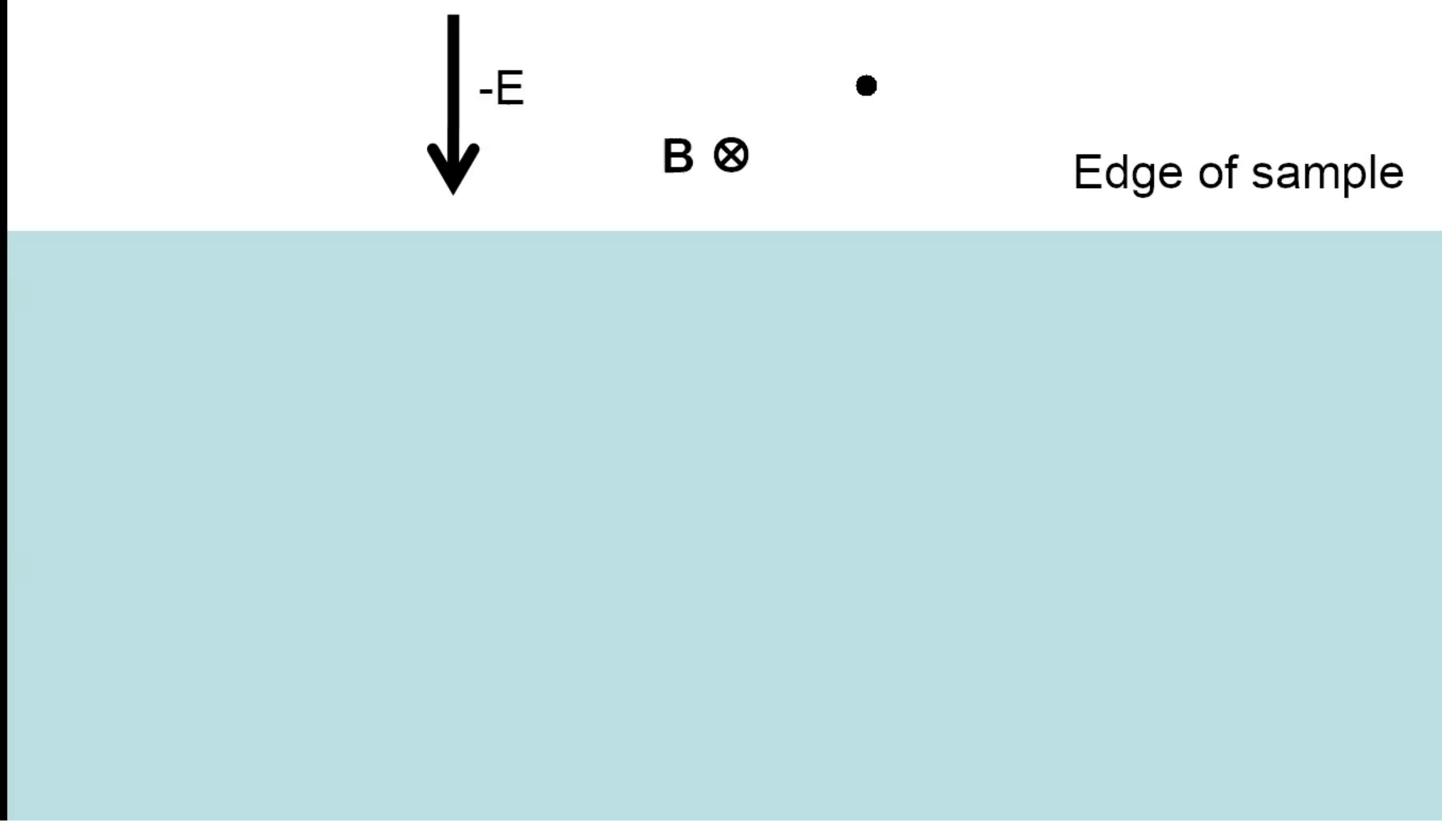
Clockwise exchange gets phase

$e^{i\theta}$

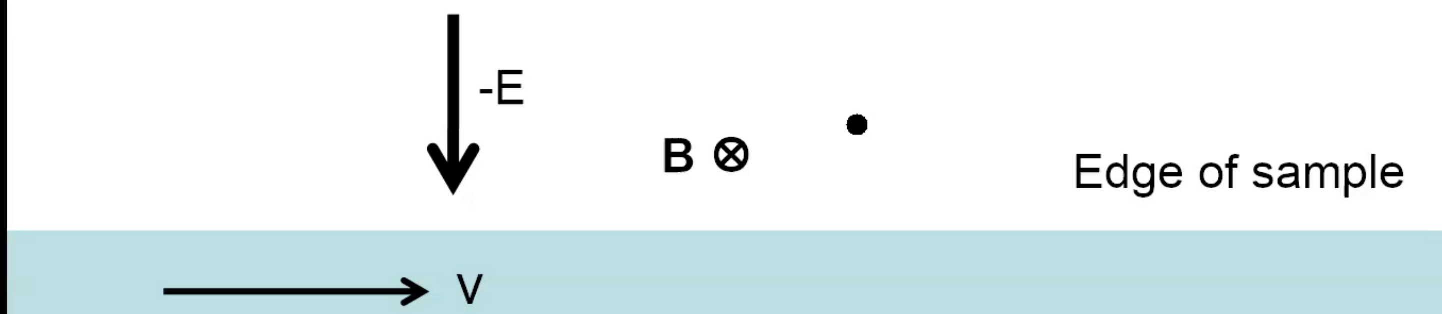
Counterclockwise exchange gets phase

$e^{-i\theta}$

Quantum Hall Edge States

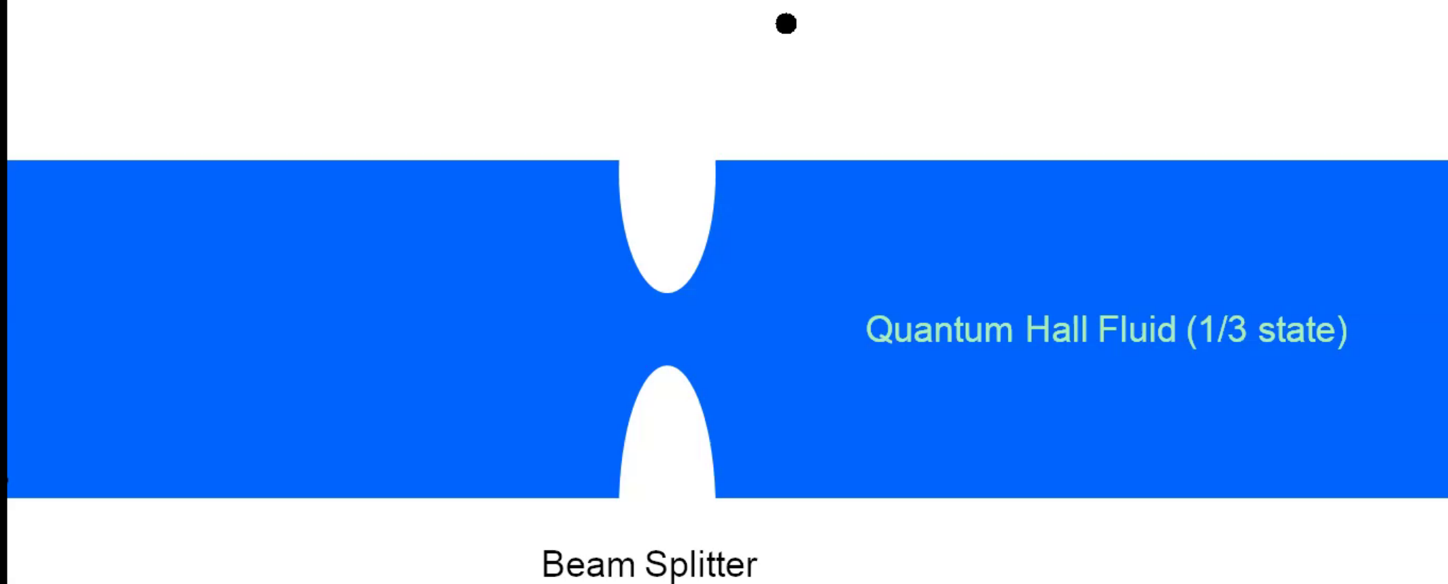


Quantum Hall Edge States



Edge States Carry Electrical Current

QPC=Quantum Point Contact = Half-Silvered Mirror



Two Successful Observation of Anyons in 2020

RESEARCH

MESOSCOPIC PHYSICS

Bartolomei *et al.*, *Science* **368**, 173–177 (2020) 10 April 2020

Fractional statistics in anyon collisions

H. Bartolomei[1*], M. Kumar[1*†], R. Bisognin[1], A. Marguerite[1‡], J.-M. Berroir[1], E. Bocquillon[1], B. Plaçais[1], A. Cavanna[2], Q. Dong[2], U. Gennser[2], Y. Jin[2], G. Fève[1§]

nature physics ARTICLES
https://doi.org/10.1038/s41567-020-1019-1

NATURE PHYSICS | VOL 16 | SEPTEMBER 2020 | 931–936

Direct observation of anyonic braiding statistics

J. Nakamura[1,2], S. Liang[1,2], G. C. Gardner[2,3] and M. J. Manfra[1,2,3,4,5]

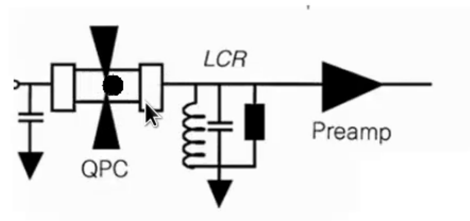
... Plus I will report on progress observing nonabelions

VOLUME 72, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1994

Nonequilibrium Noise and Fractional Charge in the Quantum Hall Effect

C. L. Kane Matthew P. A. Fisher

Shot noise measurements of fractional charge



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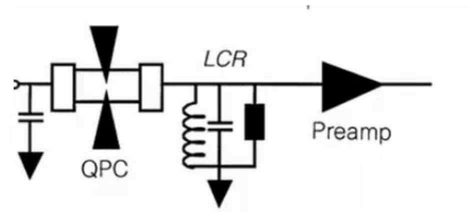

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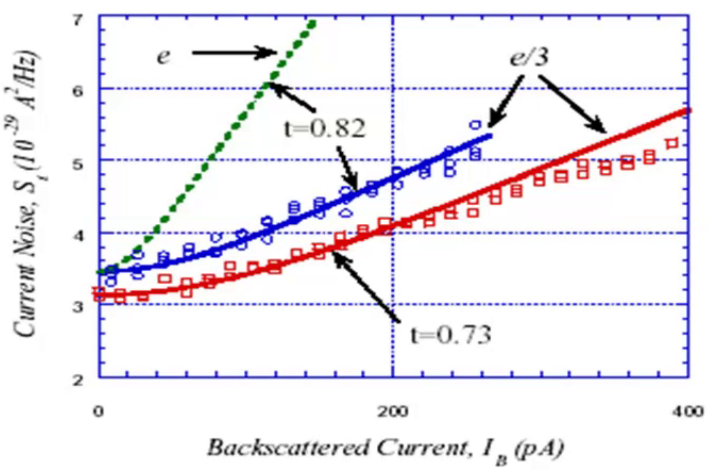
NATURE | VOL 389 | 11 SEPTEMBER 1997



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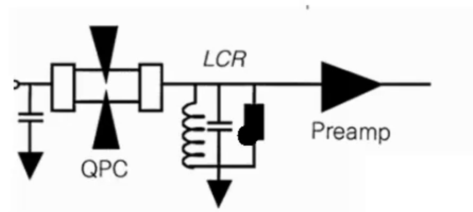

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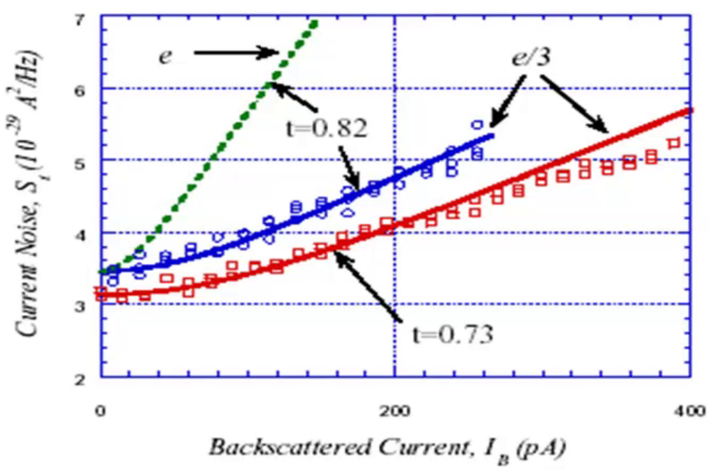
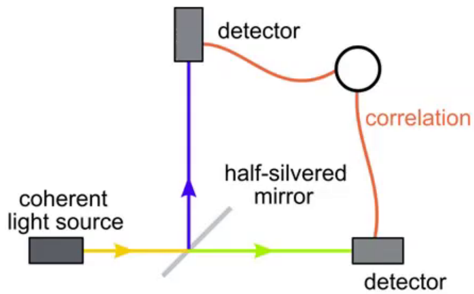
NATURE | VOL 389 | 11 SEPTEMBER 1997

This became a technology!



Bosons bunch...
Fermions antibunch...

Hanbury Brown and Twiss (1954)



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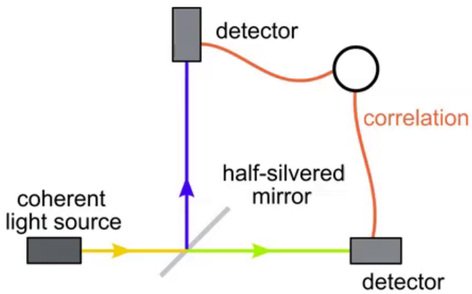
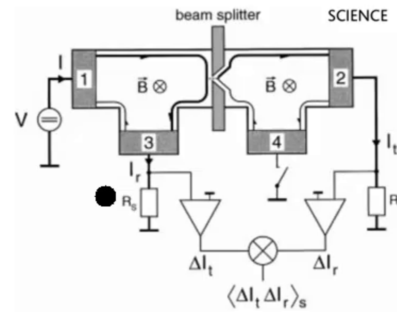


The Fermionic Hanbury Brown and Twiss Experiment

M. Henny,[1] S. Oberholzer,[1] C. Strunk,[1] T. Heinzel,[2] K. Ensslin,[2]
M. Holland,[3] C. Schönenberger[1*]

SCIENCE VOL 284 9 APRIL 1999



PHYSICAL REVIEW B VOLUME 46, NUMBER 19 15 NOVEMBER 1992-I

Scattering theory of current and intensity noise correlations in conductors and wave guides

M. Büttiker

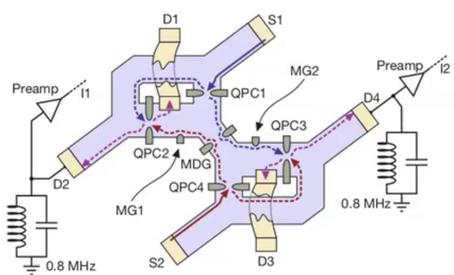
Bosons bunch...
Fermions antibunch...

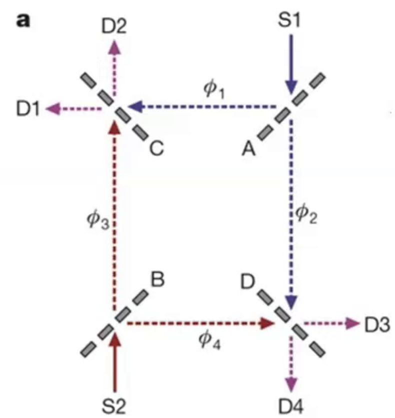
Hanbury Brown and Twiss (1956)

VOLUME 92, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2004

Two-Particle Aharonov-Bohm Effect and Entanglement in the Electronic Hanbury Brown–Twiss Setup

P. Samuelsson, E.V. Sukhorukov, and M. Büttiker



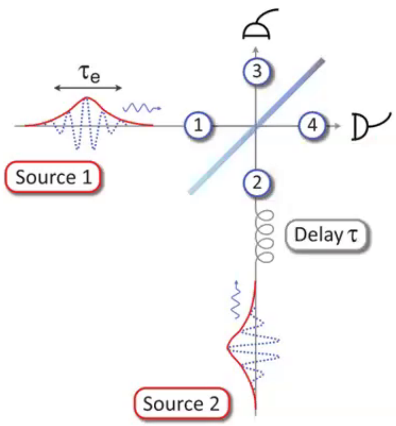


Interference between two indistinguishable electrons from independent sources

I. Neder[1], N. Ofek[1], Y. Chung[2], M. Heiblum[1], D. Mahalu[1] & V. Umansky[1] 2007 **Nature**

Bosons bunch...
Fermions antibunch...

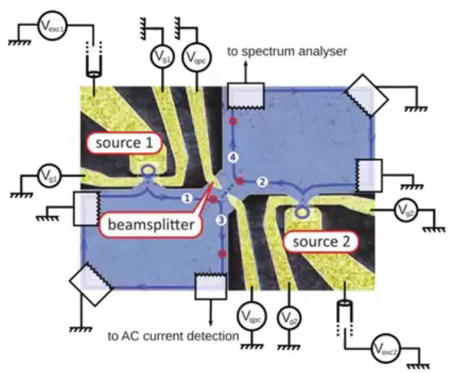
Hong-Ou-Mandel (1987)

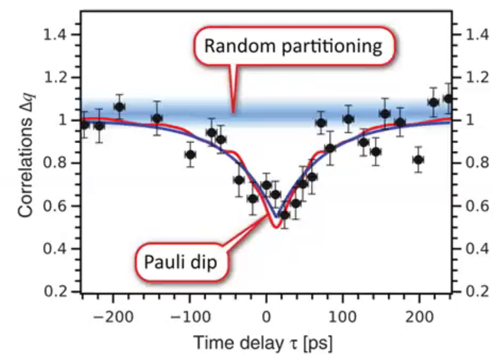


Coherence and Indistinguishability of Single Electrons Emitted by Independent Sources

SCIENCE VOL 339 1 MARCH 2013

E. Bocquillon,[1] V. Freulon,[1] J.-M Berroir,[1] P. Degiovanni,[2] B. Plaçais,[1] A. Cavanna,[3] Y. Jin,[3] G. Fève[1*]



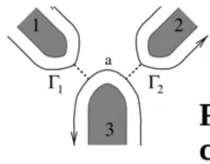


VOLUME 86, NUMBER 20 PHYSICAL REVIEW LETTERS 14 MAY 2001

Partition Noise and Statistics in the Fractional Quantum Hall Effect

I. Safi,[1] P. Devillard,[1,2] and T. Martin[1,3]

Fractional Statistics has important effects on current correlation (noise) measurements



Fractional statistics, Hanbury-Brown and Twiss correlations and the quantum Hall effect

Rodolphe Guyon[a,b], Thierry Martin[a,b*], Inès Safi[a,c], Pierre Devillard[a,d]

C. R. Physique 3 (2002)

VOLUME 91, NUMBER 19 PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2003

Revisiting the Hanbury Brown–Twiss Setup for Fractional Statistics

Smitha Vishveshwara

PRL **95,** 176402 (2005) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2005

Signatures of Fractional Statistics in Noise Experiments in Quantum Hall Fluids

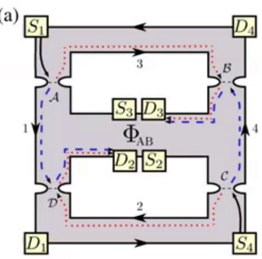
Eun-Ah Kim, Michael Lawler, Smitha Vishveshwara, and Eduardo Fradkin

PRL **109,** 106802 (2012) PHYSICAL REVIEW LETTERS week ending 7 SEPTEMBER 2012

Hanbury Brown–Twiss Interference of Anyons

Gabriele Campagnano,[1] Oded Zilberberg,[1] Igor V. Gornyi,[2,3] Dmitri E. Feldman,[4] Andrew C. Potter,[5] and Yuval Gefen[1]

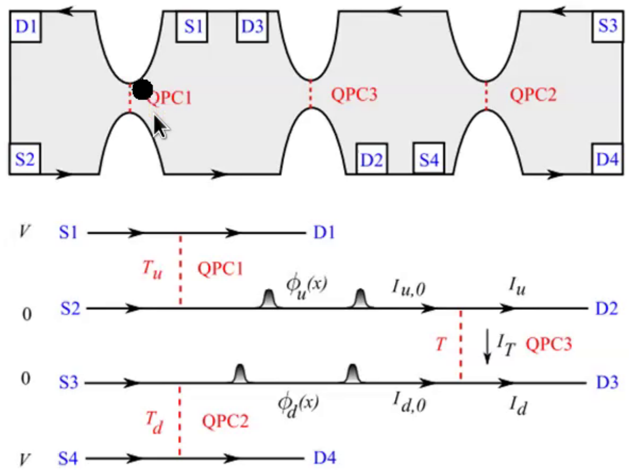
(a)



PRL 116, 156802 (2016) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2016

Current Correlations from a Mesoscopic Anyon Collider

Bernd Rosenow,[1,2] Ivan P. Levkivskyi,[3,2] and Bertrand I. Halperin[2]



Steven Simon

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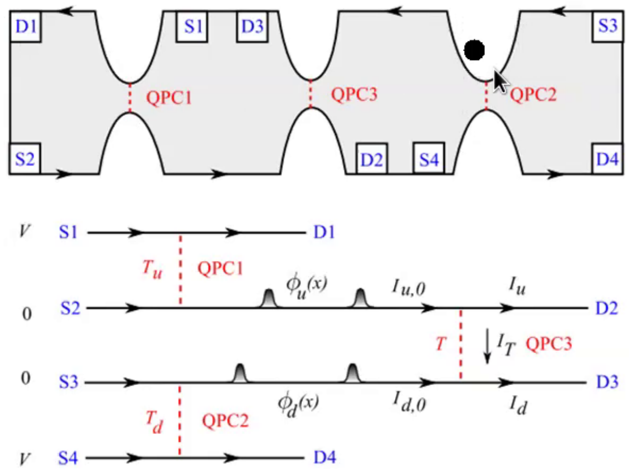


$\langle \delta I_d \delta I_u \rangle_{\omega=0}$ = (appropriately normalized and with $T_u = T_d$)

$$= 1 - \frac{\tan \pi\lambda}{\tan \pi\delta} \frac{1}{1-2\delta} \xrightarrow{\lambda = \delta = 1/3} -2$$

Negative correlations = Bunching Behavior

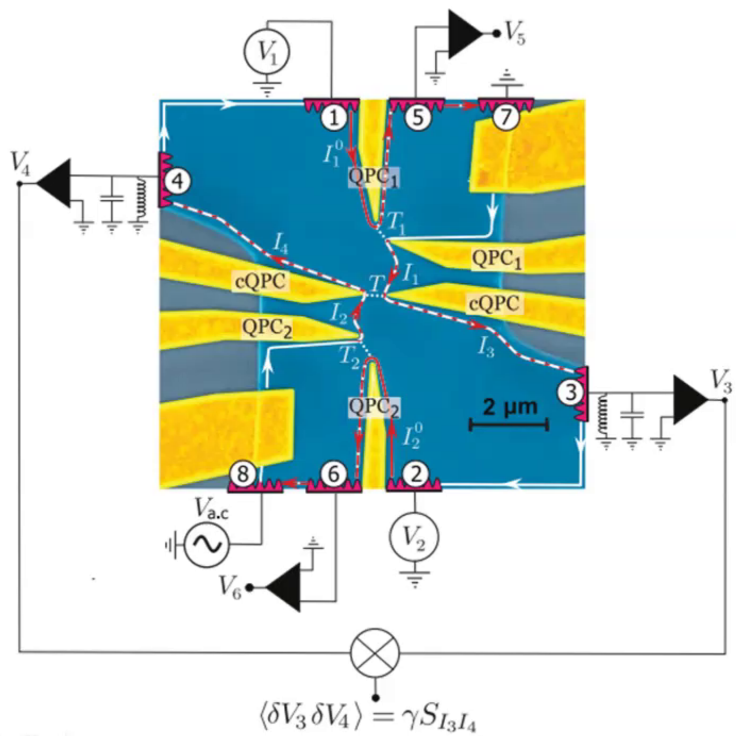
$\lambda =$ Edge "screening parameter" (noninteracting anyons = 1/3)

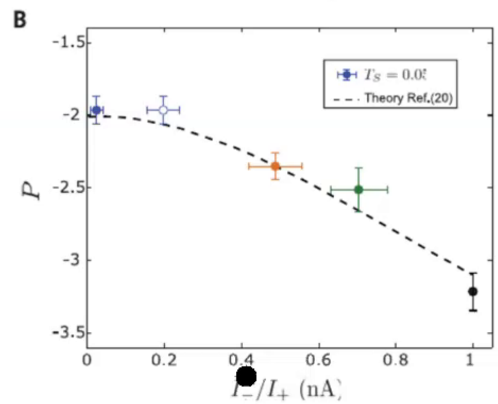
$\delta =$ Statistical angle (noninteracting anyons = 1/3)

Fractional statistics in anyon collisions

H. Bartolomei[1]*, M. Kumar[1]*†, R. Bisognin[1], A. Marguerite[1]‡, J.-M. Berroir[1], E. Bocquillon[1], B. Plaçais[1], A. Cavanna[2], Q. Dong[2], U. Gennser[2], Y. Jin[2], G. Fève[1]§

Bartolomei *et al.*, *Science* **368**, 173–177 (2020)   10 April 2020





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nature physics

ARTICLES

https://doi.org/10.1038/s41567-020-1019-1

NATURE PHYSICS | VOL 16 | SEPTEMBER 2020 | 931–936

Direct observation of anyonic braiding statistics

J. Nakamura[1,2], S. Liang[1,2], G. C. Gardner[2,3] and M. J. Manfra[1,2,3,4,5] ✉

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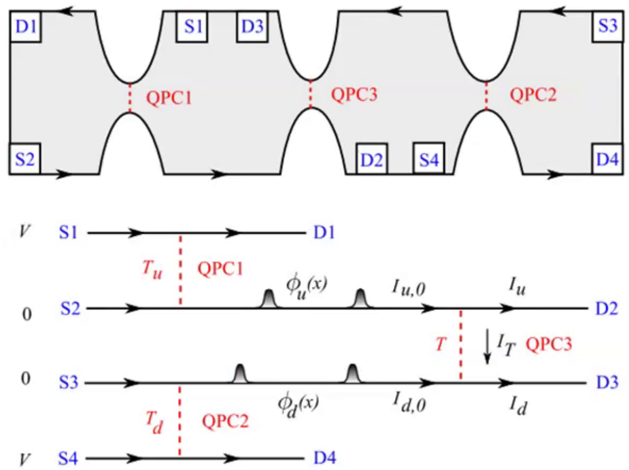


$\langle \delta I_d \delta I_u \rangle_{\omega=0}$ = (appropriately normalized and with $T_u = T_d$)

$$= 1 - \frac{\tan \pi\lambda}{\tan \pi\delta} \frac{1}{1-2\delta} \xrightarrow{\lambda = \delta = 1/3} -2$$

$\lambda =$ Edge "screening parameter" (noninteracting anyons = 1/3)

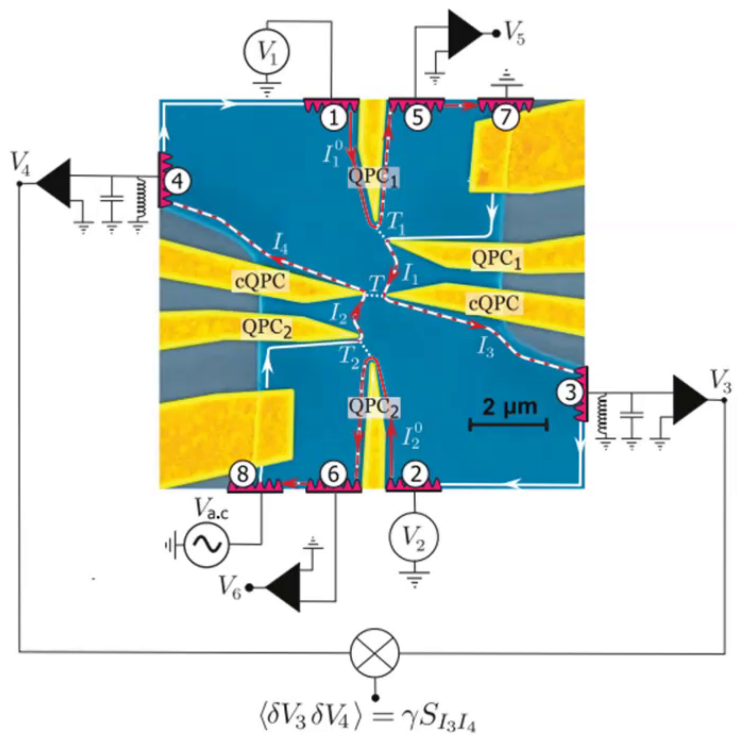
Negative correlations = Bunching Behavior

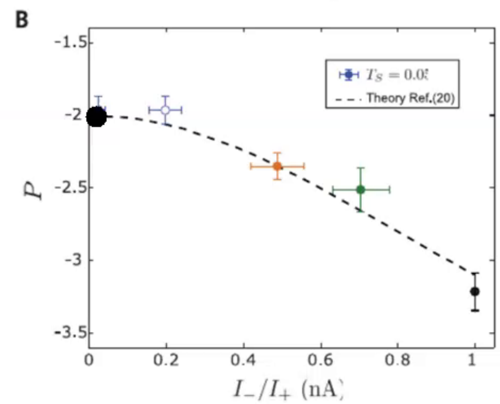
$\delta =$ Statistical angle (noninteracting anyons = 1/3)

Fractional statistics in anyon collisions

H. Bartolomei[1]*, M. Kumar[1]*†, R. Bisognin[1], A. Marguerite[1]‡, J.-M. Berroir[1], E. Bocquillon[1], B. Plaçais[1], A. Cavanna[2], Q. Dong[2], U. Gennser[2], Y. Jin[2], G. Fève[1]§

Bartolomei *et al.*, *Science* **368**, 173–177 (2020)   10 April 2020





Two Successful Observation of Anyons in 2020

RESEARCH

MESOSCOPIC PHYSICS

Bartolomei *et al.*, *Science* **368**, 173–177 (2020) 10 April 2020

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nature physics

ARTICLES

https://doi.org/10.1038/s41567-020-1019-1

NATURE PHYSICS | VOL 16 | SEPTEMBER 2020 | 931–936

Direct observation of anyonic braiding statistics

J. Nakamura[1,2], S. Liang[1,2], G. C. Gardner[2,3] and M. J. Manfra[1,2,3,4,5] ✉

Interferometry:

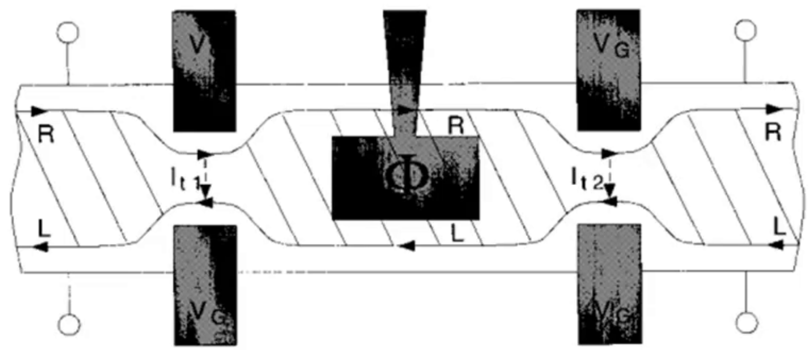
1990: **Semiclassical Theory of Localized Many-Anyon States**

Steven Kivelson

Interference around a dot can measure statistics

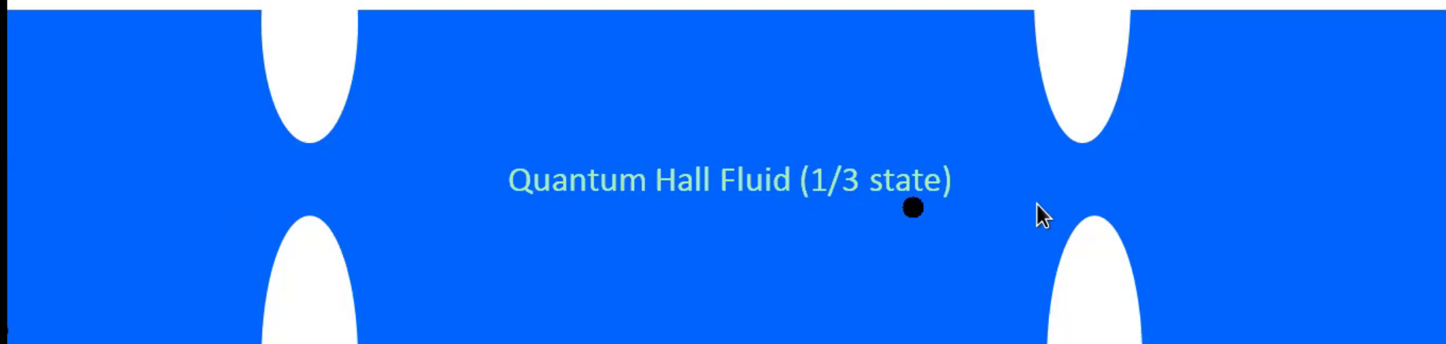
1997: **Two point-contact interferometer for quantum Hall systems**

C. de C. Chamon, D. E. Freed, S. A. Kivelson, S. L. Sondhi, and X. G. Wen



Fabry-Perot Interferometer

Interference between two paths = Fabry Perot Interferometer



Beam Splitter

Mirror

Interference of two partial waves

Fabry-Perot Interferometer

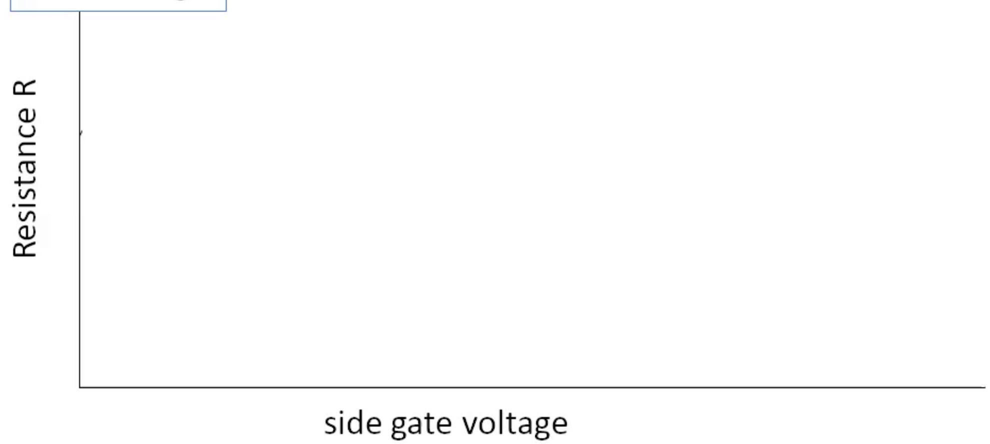
Side gate changes phase

$$R = R_0 + R_1 \cos(\theta)$$

$$\theta = 2\pi e^*(\Phi + \beta V_G)$$

Flux

Gate voltage



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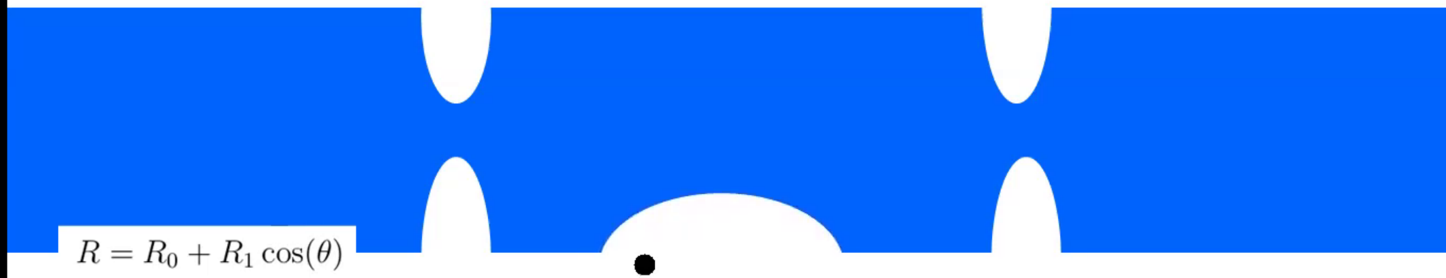

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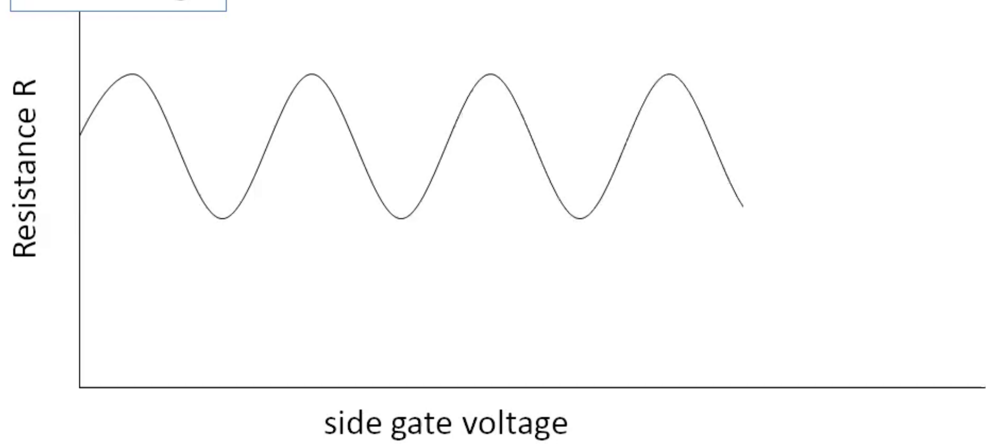

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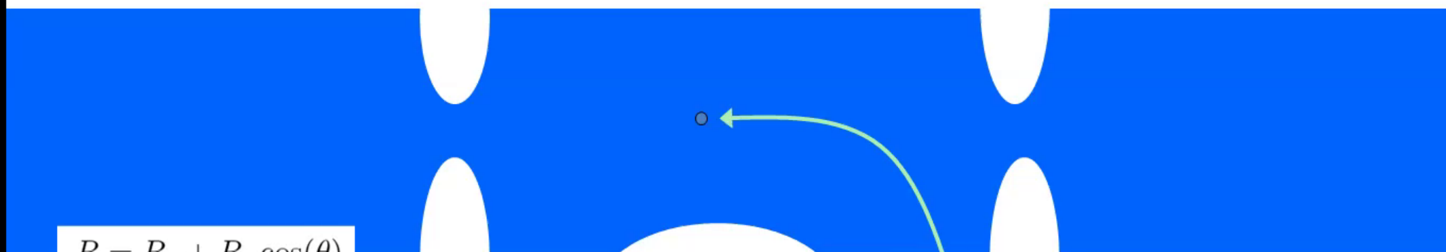
Side gate changes phase

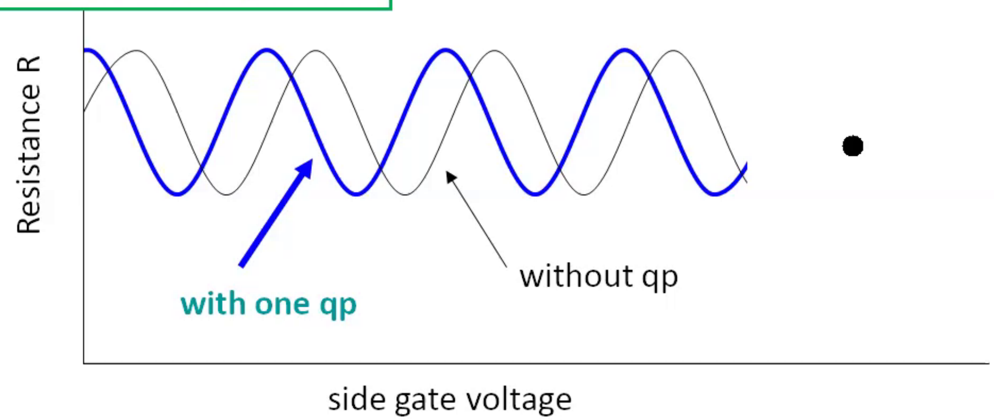


$$R = R_0 + R_1 \cos(\theta)$$

$$\theta = 2\pi e^*(\Phi + \beta V_G) + N\theta_{anyon}$$

Number of quasiparticles

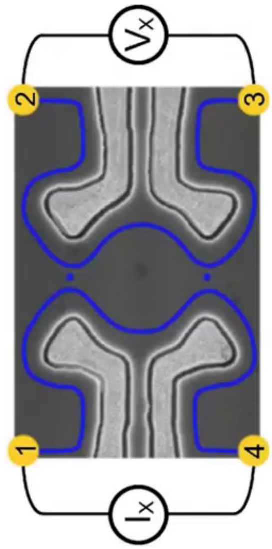
Adding 1 quasiparticle shifts interference pattern by $\theta_{anyon} = 2\pi / 3$

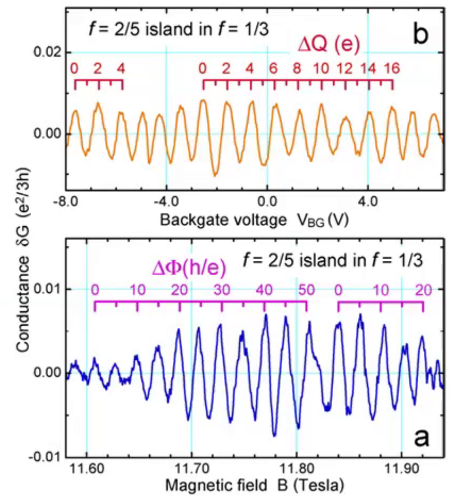


PHYSICAL REVIEW B **72**, 075342 (2005)

Realization of a Laughlin quasiparticle interferometer: Observation of fractional statistics

F. E. Camino, Wei Zhou, and V. J. Goldman





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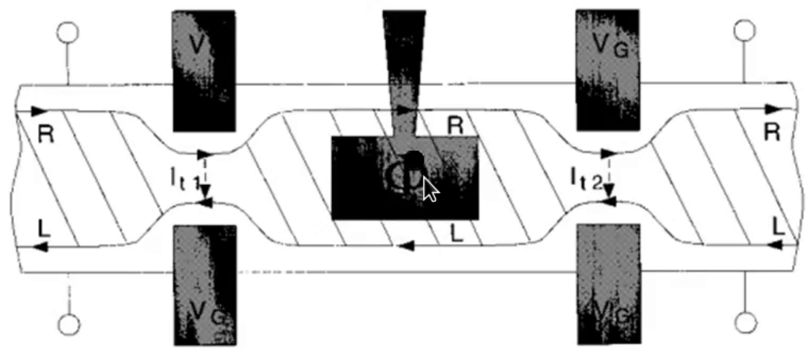

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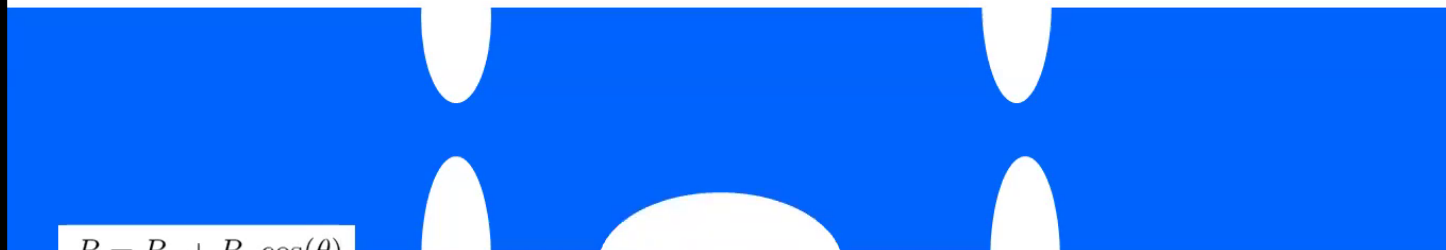

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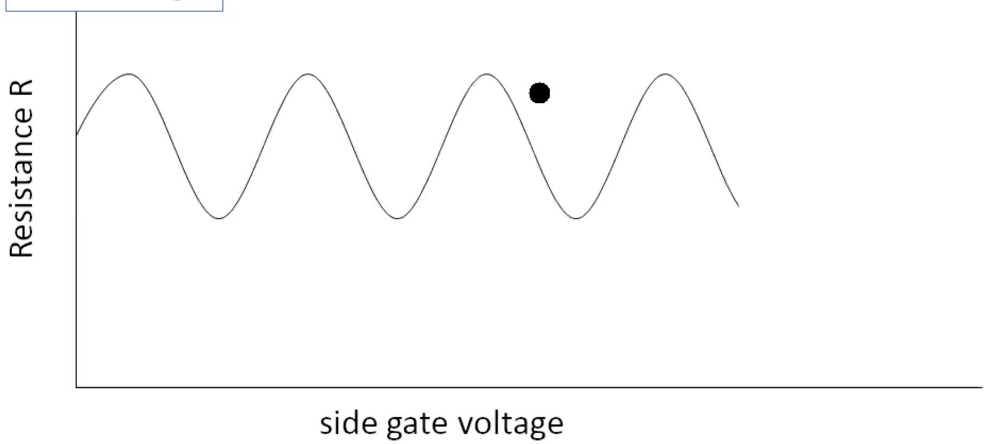

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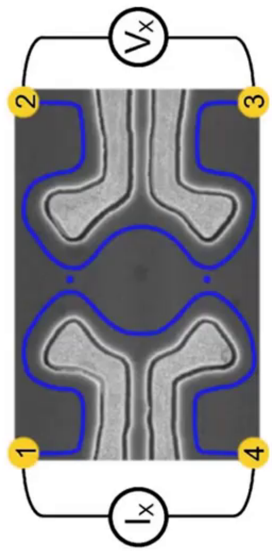
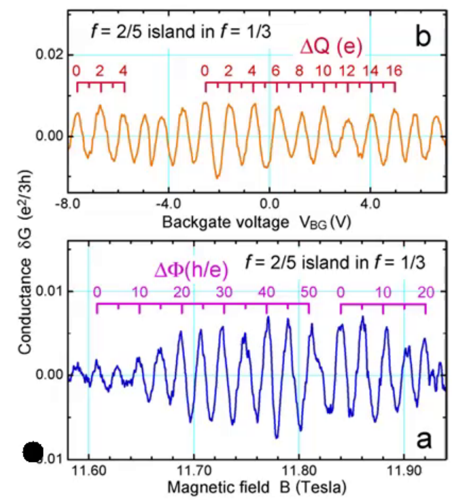




Lots of confusion....

PRL 98, 106801 (2007) PHYSICAL REVIEW LETTERS week ending 9 MARCH 2007

Influence of Interactions on Flux and Back-Gate Period of Quantum Hall Interferometers

B. Rosenow* and B. I. Halperin

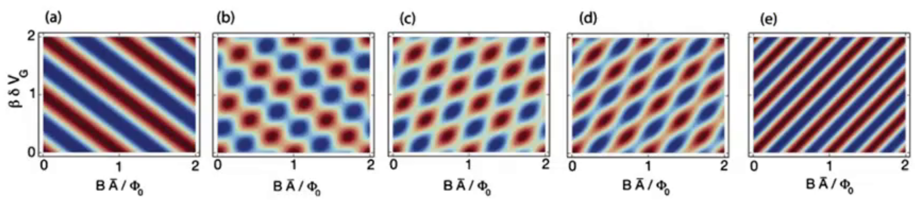
PHYSICAL REVIEW B 83, 155440 (2011)

Theory of the Fabry-Pérot quantum Hall interferometer

Bertrand I. Halperin,[1] Ady Stern,[2] Izhar Neder,[3] and Bernd Rosenow[3]

Charging effects of the enclosed dot can be crucial!

"Pajama Patterns"



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Coulomb Dominated (strong charging effects)

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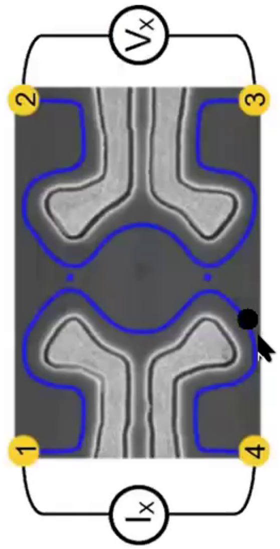

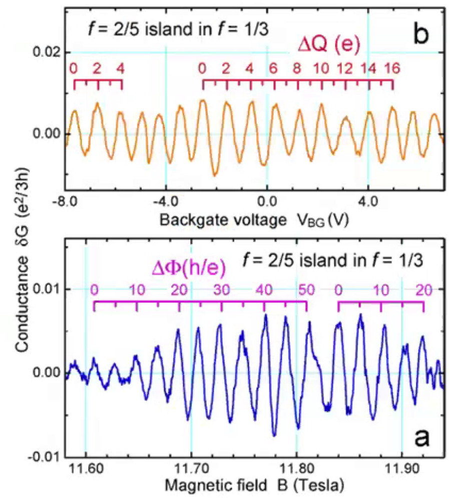

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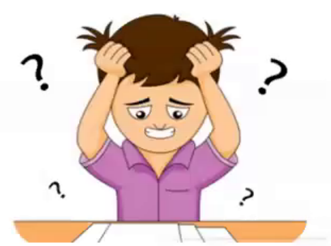

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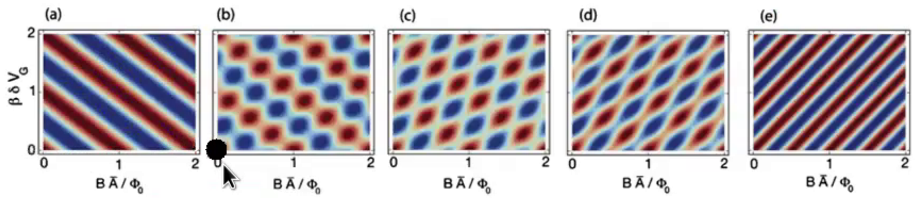

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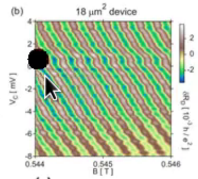
Coulomb correction

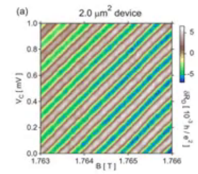
PHYSICAL REVIEW B **79**, 241304(R) (2009)

Distinct signatures for Coulomb blockade and Aharonov-Bohm interference in electronic Fabry-Perot interferometers

Yiming Zhang, D. T. McClure, E. M. Levenson-Falk, and C. M. Marcus L. N. Pfeiffer and K. W. West

Large dot = small charging





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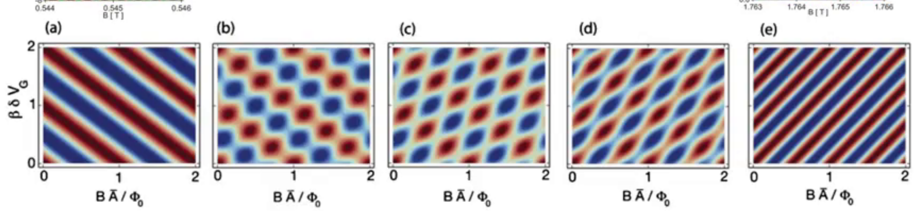

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PHYSICAL REVIEW B **80**, 125310 (2009)

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Ping V. Lin,[1] F. E. Camino,[2] and V. J. Goldman[1]

Aharonov-Bohm-Like Oscillations in Quantum Hall Corrals

M.D. Godfrey[1], P. Jiang[1], W. Kang[1], S.H. Simon[2], K.W. Baldwin[2], L.N. Pfeiffer[2], and K.W. West[2]

Role of interactions in an electronic Fabry–Perot interferometer operating in the quantum Hall effect regime 5276–5281 | PNAS | March 23, 2010 | vol. 107 | no. 12

Nissim Ofek[1], Aveek Bid, Moty Heiblum, Ady Stern, Vladimir Umansky, and Diana Mahalu

PRL **108,** 256804 (2012) PHYSICAL REVIEW LETTERS week ending 22 JUNE 2012

Fabry-Perot Interferometry with Fractional Charges

D. T. McClure,[1] W. Chang,[1] C. M. Marcus,[1] L. N. Pfeiffer,[2] and K. W. West[2]

But No Aharanov-Bohm Pajama-Patterns in Fractional Quantum Hall Regime

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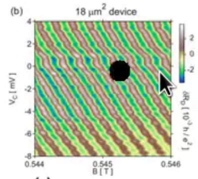

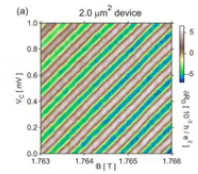

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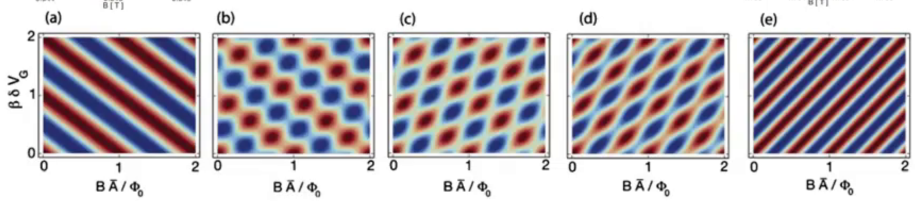

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PLUS: Mach-Zehnder interferometry never saw interference of fractional quantum Hall

letters to nature

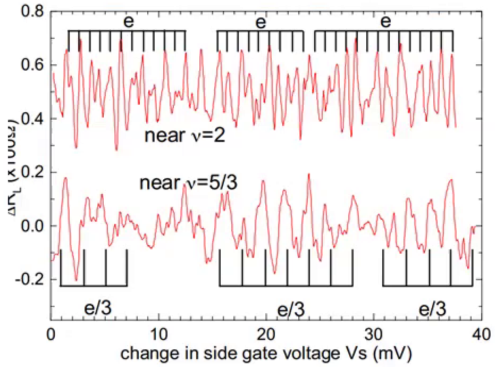
An electronic Mach–Zehnder interferometer

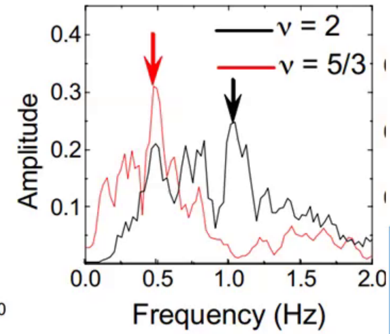
Yang Ji, Yunchul Chung, D. Sprinzak, M. Heiblum, D. Mahalu & Hadas Shtrikman

NATURE | VOL 422 | 27 MARCH 2003 | www.nature.com/nature

Some rays of hope (or confusion?)

Data from Willett – suggesting Aharanov-Bohm Regime (even in very small dots)





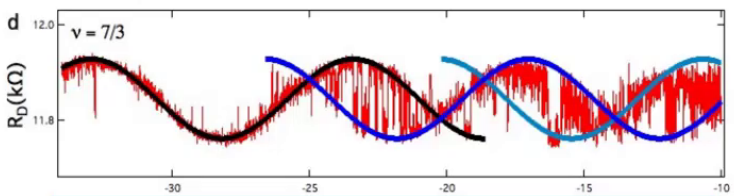
Problems:
- Not pajama patterns
- Not very periodic even
- Not measuring statistics (yet)

Measurement of filling factor 5/2 quasiparticle interference with observation of charge e/4 and e/2 period oscillations

R. L. Willett, L. N. Pfeiffer, and K. W. West

PNAS | June 2, 2009 | vol. 106 | no. 22 | 8853–8858

Data from Kang – suggesting fractional phase slips



Braiding of Abelian and Non-Abelian Anyons in the Fractional Quantum Hall Effect

Sanghun An[1], P. Jiang[1,2], H. Choi[1], W. Kang[1], S.H. Simon[3], L.N. Pfeiffer[4], K.W. West[4], and K.W. Baldwin[4]

Problem:
- Coulomb Dominated Regime

Telegraph noise and the Fabry-Perot quantum Hall interferometer

PHYSICAL REVIEW B **85**, 201302(R) (2012)

B. Rosenow[1] and Steven H. Simon[2]

Gives a scenario that phase slips could still be close to quantized

Problem:
- Data did not reproduce...

The big breakthrough:

nature physics

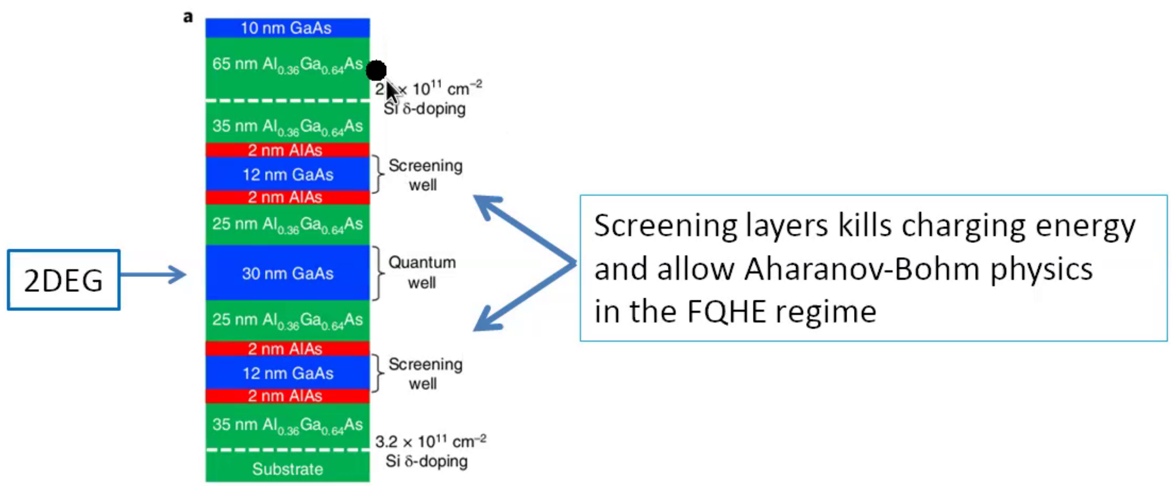
ARTICLES

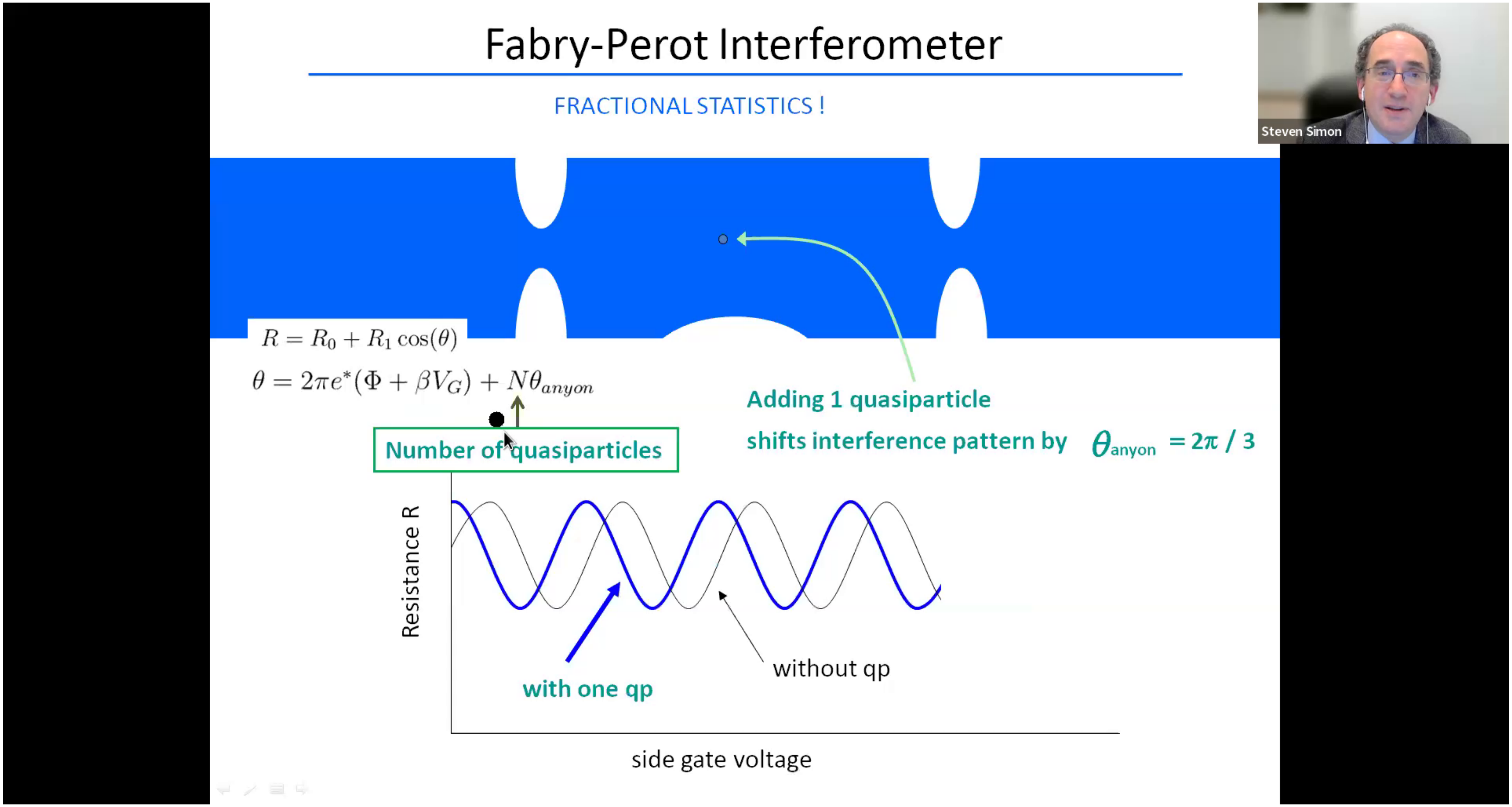
https://doi.org/10.1038/s41567-019-0441-8

NATURE PHYSICS | VOL 15 | JUNE 2019 | 563-569 |

Aharonov–Bohm interference of fractional quantum Hall edge modes

J. Nakamura[1,2], S. Fallahi[1,2], H. Sahasrabudhe[1], R. Rahman[3], S. Liang[1,2], G. C. Gardner[2,4] and M. J. Manfra[1,2,3,4,5]*




Fabry-Perot Interferometer
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Steven Simon
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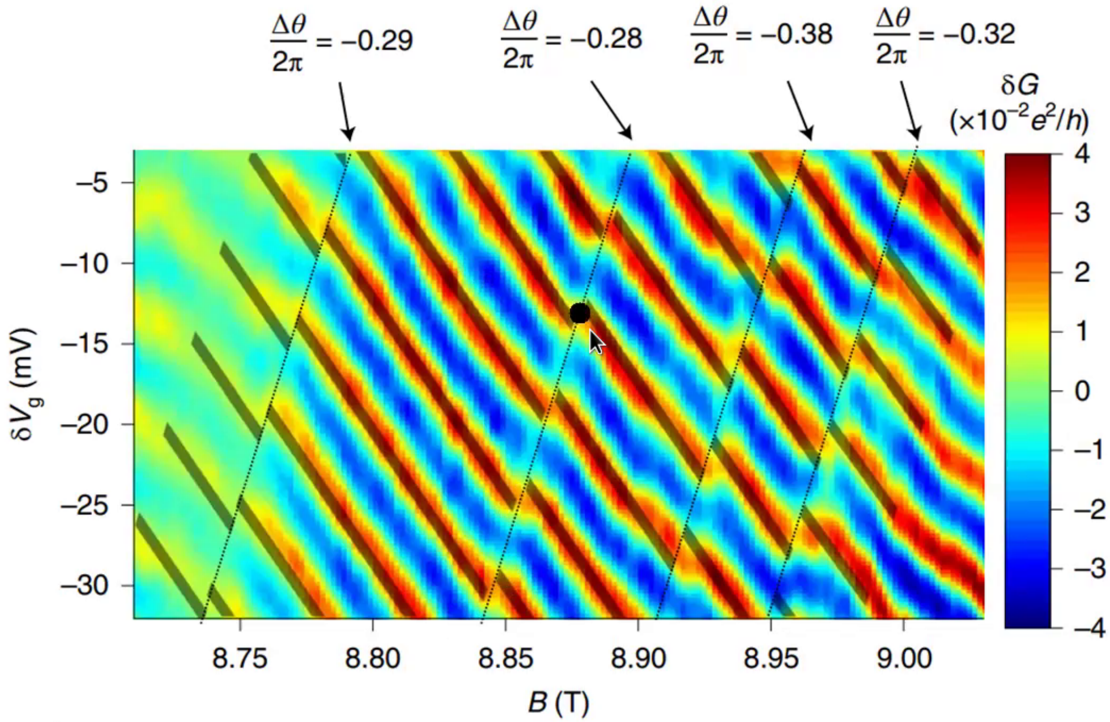
Resistance R
with one qp
without qp
side gate voltage

Direct observation of anyonic braiding statistics

J. Nakamura[1,2], S. Liang[1,2], G. C. Gardner[2,3] and M. J. Manfra[1,2,3,4,5]

NATURE PHYSICS | VOL 16 | SEPTEMBER 2020 | 931–936 | www.nature.com/naturephysics



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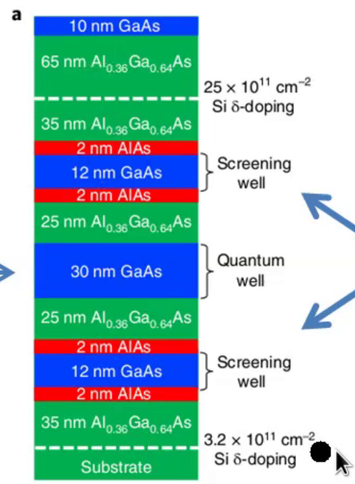

2DEG

Screening layers kills charging energy and allow Aharanov-Bohm physics in the FQHE regime

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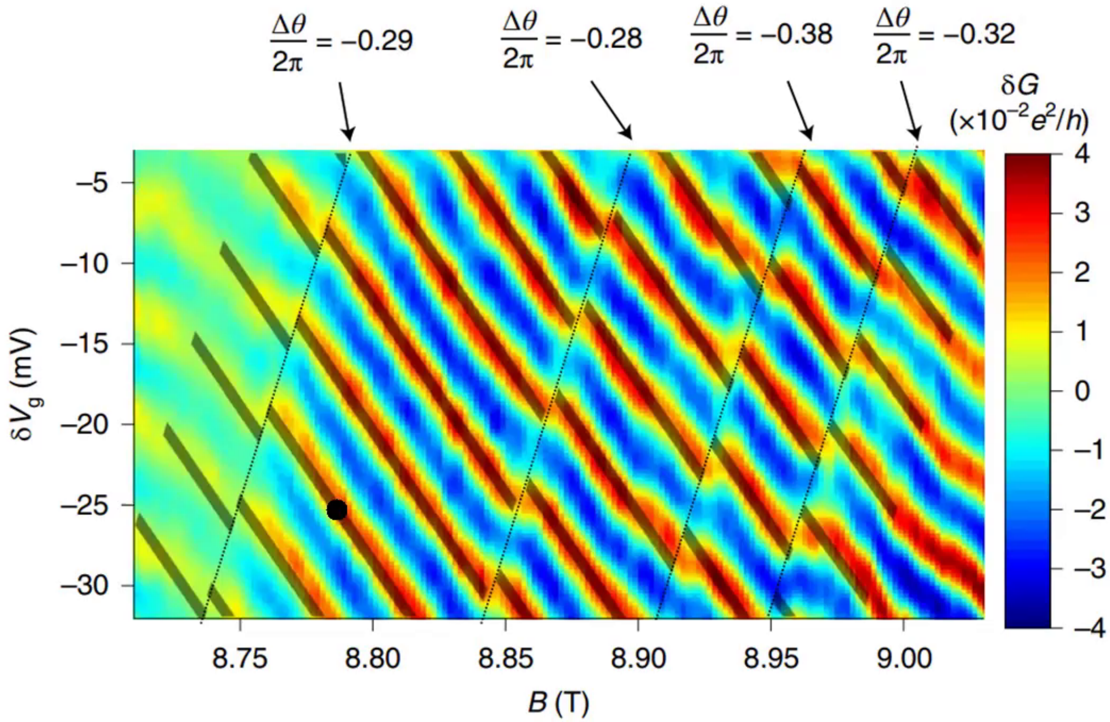

Impact of bulk-edge coupling on observation of anyonic braiding statistics in quantum Hall interferometers

J. Nakamura,[1,2] S. Liang,[1,2] G. C. Gardner,[2,3] and M. J. Manfra[1,2,3,4,5,*]

arXiv:2107.02136v1

Quantum Hall interferometers have been used to probe fractional charge, and more recently, fractional statistics of quasiparticles. Theoretical predictions have been made regarding the effect of electrostatic coupling on interferometer behavior and observation of anyonic phases. Here we present measurements of a small Fabry-Perot interferometer in which these electrostatic coupling constants can be determined experimentally, facilitating quantitative comparison with theory. At the $\nu = 1/3$ fractional quantum Hall state, this device exhibits Aharonov-Bohm interference near the center of the conductance plateau interrupted by a few discrete phase jumps, and Φ_0 oscillations at higher and lower magnetic fields, consistent with theoretical predictions for detection of anyonic statistics. We estimate the electrostatic parameters K_I and K_{IL} by two methods: by the ratio of oscillation periods in compressible versus incompressible regions, and from finite-bias conductance measurements, and these two methods yield consistent results. We find that the extracted K_I and K_{IL} can account for the deviation of the values of the discrete phase jumps from the theoretically predicted anyonic phase $\theta_a = 2\pi/3$. In the integer quantum Hall regime, we find that the experimental values of K_I and K_{IL} can account for the the observed Aharonov-Bohm and Coulomb dominated behavior of different edge states.

What next?

- All of these experiments are on $\nu=1/3$.

- There is a zoo of other FQHE states

  $\nu = 2/3, 2/5, 3/5, 3/7, 4/7, \ldots$

- None of these have shown the expected results (yet)

- And of course the rare non-abelian FQHE

  $\nu = 5/2, 7/2, 12/5$

Two Successful Observation of Anyons in 2020

RESEARCH

MESOSCOPIC PHYSICS

Bartolomei *et al.*, *Science* **368**, 173–177 (2020)   10 April 2020

Fractional statistics in anyon collisions

H. Bartolomei[1*], M. Kumar[1*†], R. Bisognin[1], A. Marguerite[1‡], J.-M. Berroir[1], E. Bocquillon[1], B. Plaçais[1], A. Cavanna[2], Q. Dong[2], U. Gennser[2], Y. Jin[2], G. Fève[1§]

nature physics

ARTICLES

https://doi.org/10.1038/s41567-020-1019-1

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Direct observation of anyonic braiding statistics

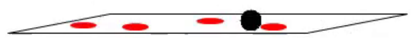
J. Nakamura[1,2], S. Liang[1,2], G. C. Gardner[2,3] and M. J. Manfra[1,2,3,4,5]

... Plus I will report on progress observing nonabelions

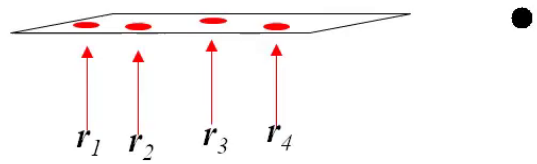
The idea of Nonabelian Anyons

<u>Nonabelion</u> = A Particle Obeying *Nonabelian Statistics*

NonAbelian Statistics

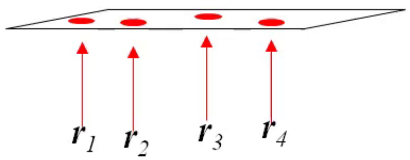


NonAbelian Statistics



NonAbelian Statistics

Suppose 2 Degenerate Orthogonal States $|\psi_a\rangle \; , \; |\psi_b\rangle$



Vector Represents State

$$\Psi_i = a_i|\psi_a\rangle + b_i|\psi_b\rangle = \begin{pmatrix} a_i \\ b_i \end{pmatrix}$$

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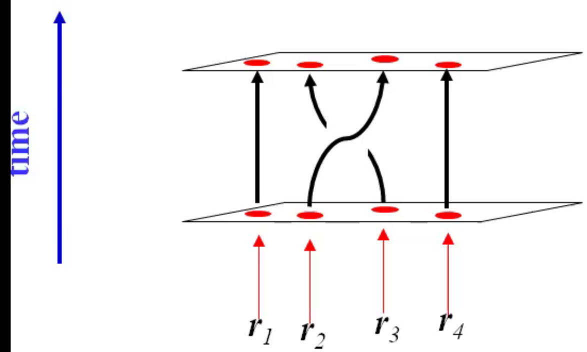

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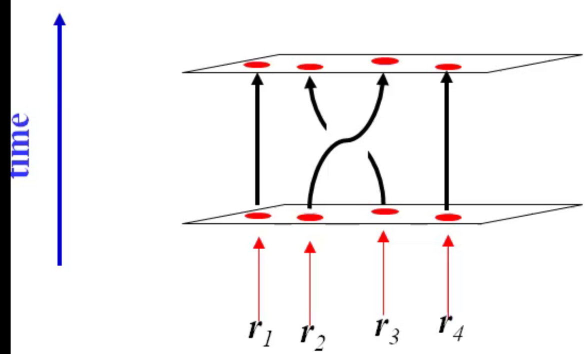

Vector Represents State

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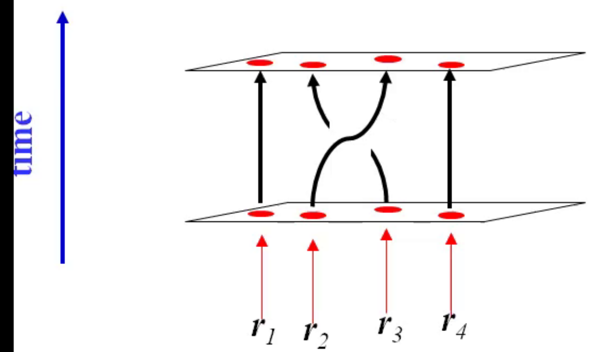
$$\Psi_f = a_f|\psi_a\rangle + b_f|\psi_b\rangle = \begin{pmatrix} a_f \\ b_f \end{pmatrix}$$

$$\begin{pmatrix} a_f \\ b_f \end{pmatrix} = U \begin{pmatrix} a_i \\ b_i \end{pmatrix}$$

Unitary Matrix From Braid Operation
Depends only on the Topology of the braid

NonAbelian Statistics

Suppose 2 Degenerate Orthogonal States $|\psi_a\rangle \ , \ |\psi_b\rangle$



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Makes a great Qubit !!

$$\begin{pmatrix} a_f \\ b_f \end{pmatrix} = U \begin{pmatrix} a_i \\ b_i \end{pmatrix}$$

Unitary Matrix From Braid Operation
Depends only on the Topology of the braid

- In Nonabelian Topological Theories, the ground state in the presence of quasiparticles/quasiholes is degenerate (multiple ground states).

  - The *ONLY* "dynamics" in bulk is that braiding quasiparticles makes transitions between degenerate ground states
  - No *Local* operator can mix the multiple ground states

Almost all noise processes are local !

Qubits are *HIGHLY* protected from decoherence/error

Nonabelian Anyons?

1980: Bais (in context of gauge theories)
1989: Moore+Seiberg (in context of CFTs)
1989: Witten (in context of Chern-Simons theories)
1989: Fredenhagen, Rehren, Schroer
1989: Froelich + Gabbiani
1989: Chen, Wilczek, Witten, Halperin

1990: Moore+Read: How Nonabelions can arise in FQHE
....

1998: Morf: 5/2 FQHE is Nonabelian
1997: Kitaev "Fault-Tolerant Quantum Computation by Anyons"
2000: Kitaev "Unpaired Majorana Fermions in Quantum Wires"
...

~2004: Microsoft Station Q formed... > 10^8 $ Spent

1987: Discovery of 5/2 FQHE
Willett, Eisenstein, Tsui
Gossard, and English

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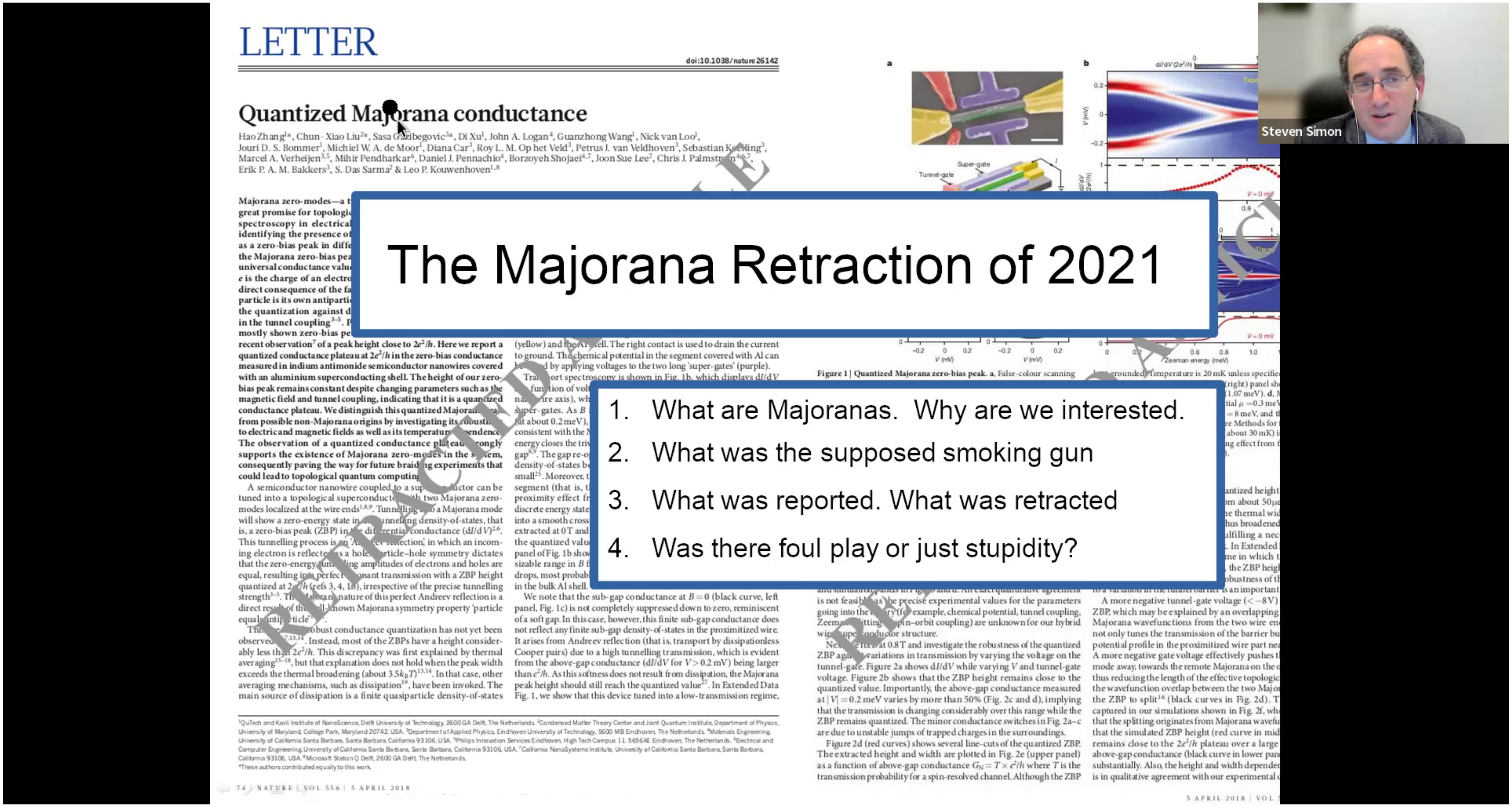
Research in several different systems thought to (maybe) have nonabelions

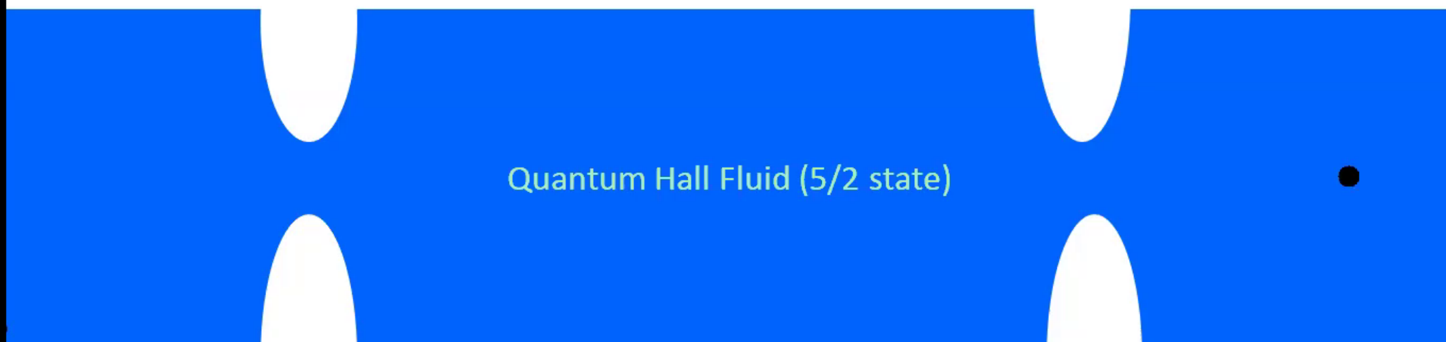

LETTER
doi:10.1038/nature26142
Quantized Majorana conductance
The Majorana Retraction of 2021
1. What are Majoranas. Why are we interested.
2. What was the supposed smoking gun
3. What was reported. What was retracted
4. Was there foul play or just stupidity?
Steven Simon

Nonabelian Interferometer and the ν=5/2 FQHE

Theory: Stern, Halperin; Bonderson, Shtengel, Kitaev; Das Sarma, Nayak, Freedman; Chamon, Wen, et al; Nayak, Wilczek, et al ... and many others.

Experiment: Willett Group (Also Kang Group, Marcus Group, Heiblum Group)

The Quantum Hall Fabry-Pérot Interferometer



Beam Splitter

Mirror

interference of two partial waves