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Electron dynamics at boundaries of quantum many-body systems

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Research Interest

- Experiments
- Condensed matter physics
  - **Mesoscopic physics**

Keywords:

Quantum Hall, Topological materials, Transport measurements, Electronics, etc.

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2023-	Associate Prof. @ISSP
2017-2023	NTT Basic Research Labs.
2009-2017	Assistant Prof. @Tokyo Tech.

Mar. 2009 Ph.D from Kyoto University

KYOTO UNIVERSITY Institute for Chemical Research ICR

東京工業大学 Tokyo Institute of Technology

NTT 物性科学基礎研究所 NTT Basic Research Laboratories

Master, Ph.D. @京大化研

Prof. Ono

Prof. Kobayashi (Supervisor)

Assistant prof. @東工大

Prof. Fujisawa

Reseacher @NTT BRL

Dr. Muraki

Dr. Kumada

◆ Measurement for bulk properties

Reaction from a boundary

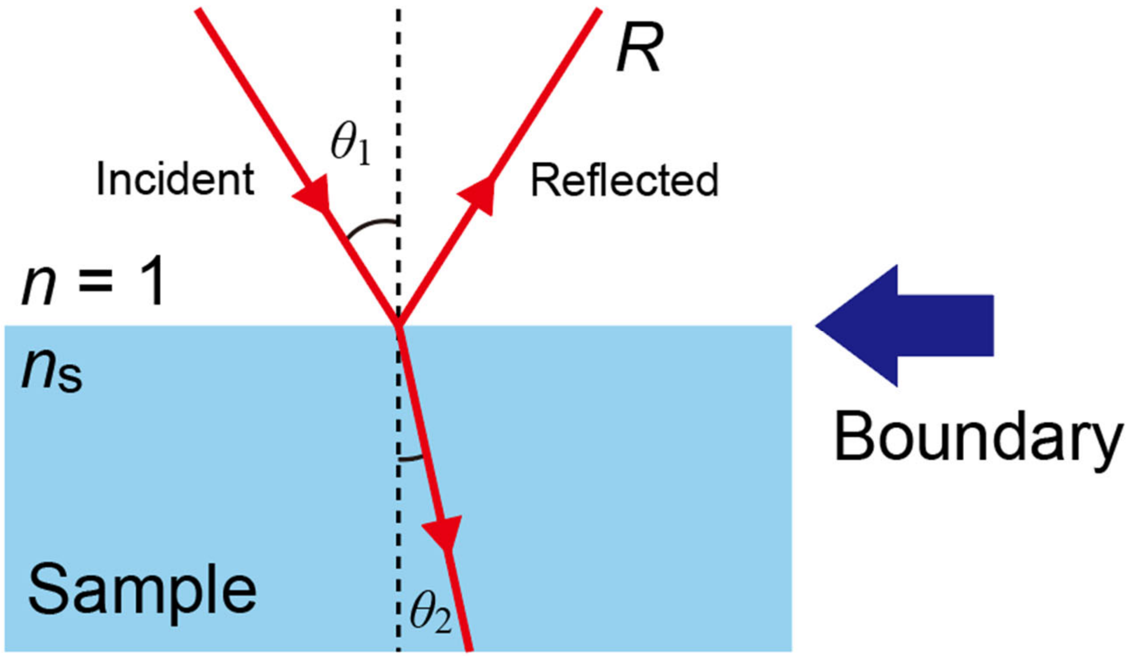
- **Mismatch between systems forming the boundary**

A boundary between a sample and a well-known system

- **Bulk property of the sample**

An example:

Fresnel law $$R = \left| \frac{1 - n_s}{1 + n_s} \right|^2$$



Measurement for a quantum many-body system

An example:

- **Andreev reflection at a Normal metal/Superconductor junction**

Mismatch between carrier charges

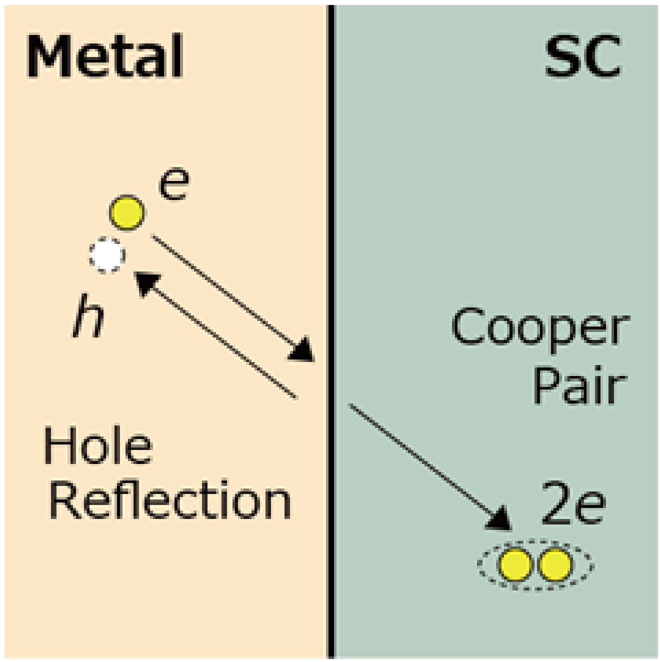
- ✓ Normal metal: single particles (well-known)
- ✓ Superconductor: Cooper pair

Charge conservation

Injection — **Transmission** — **Reflection**

e **(electron) = 2*e* (Cooper pair) - *e* (hole)**

↑ Action — ↑ Bulk property — ↑ Reaction



Quantum many-body systems

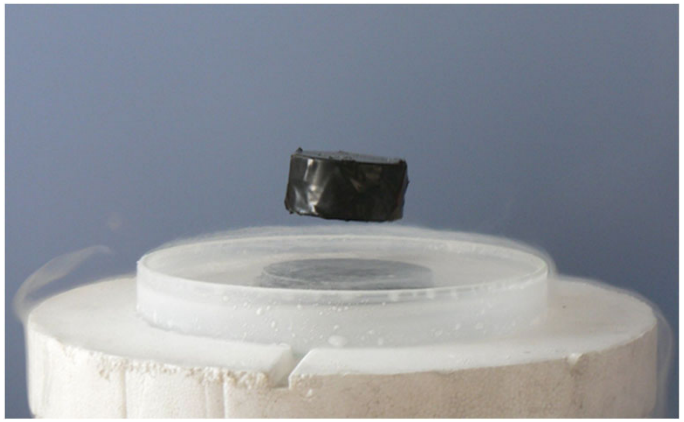
Some analogies appear in electron dynamics at boundaries

- **Superconductor**
- **Fractional quantum Hall state**
- **Tomonga-Luttinger liquid**
- **Kondo effect**
- ・・・

Quantum Hall system

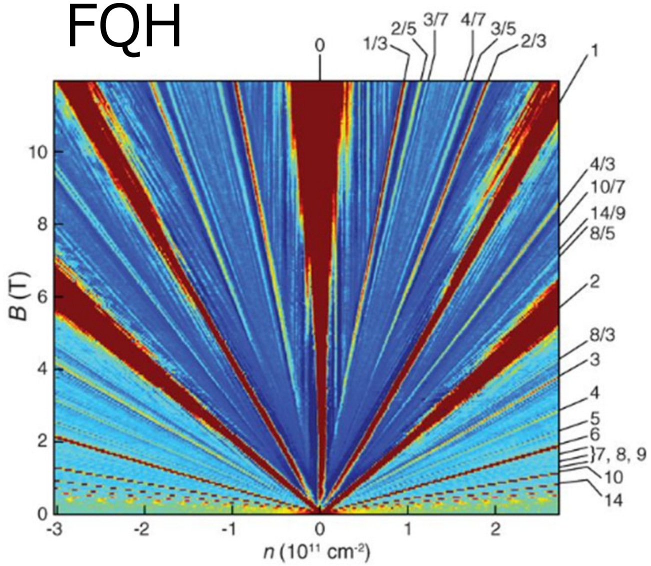
Two-dimensional electron system (2DES) at a high magnetic field

Superconductor



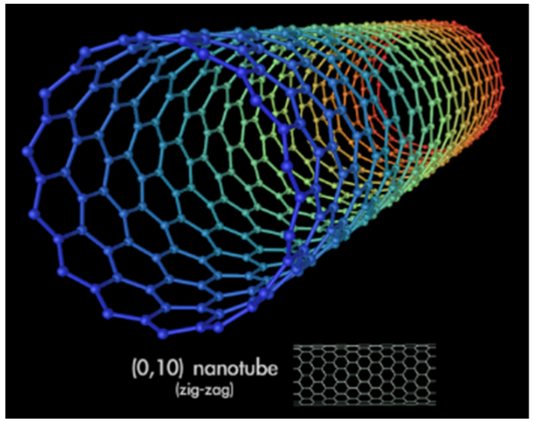
Wikipedia

FQH



Feldman et al., Science 2012.

1D electron system



Wikipedia

Contents

Background

- **Quantum many-body effects in quantum Hall systems**
  - ✓ Fractional quantum Hall (FQH) effect
  - ✓ Tomonaga-Luttinger liquid nature of edge channels

Main

- **Electron dynamics at boundaries of quantum many-body systems**
  - ✓ Fractional-Integer quantum Hall junction

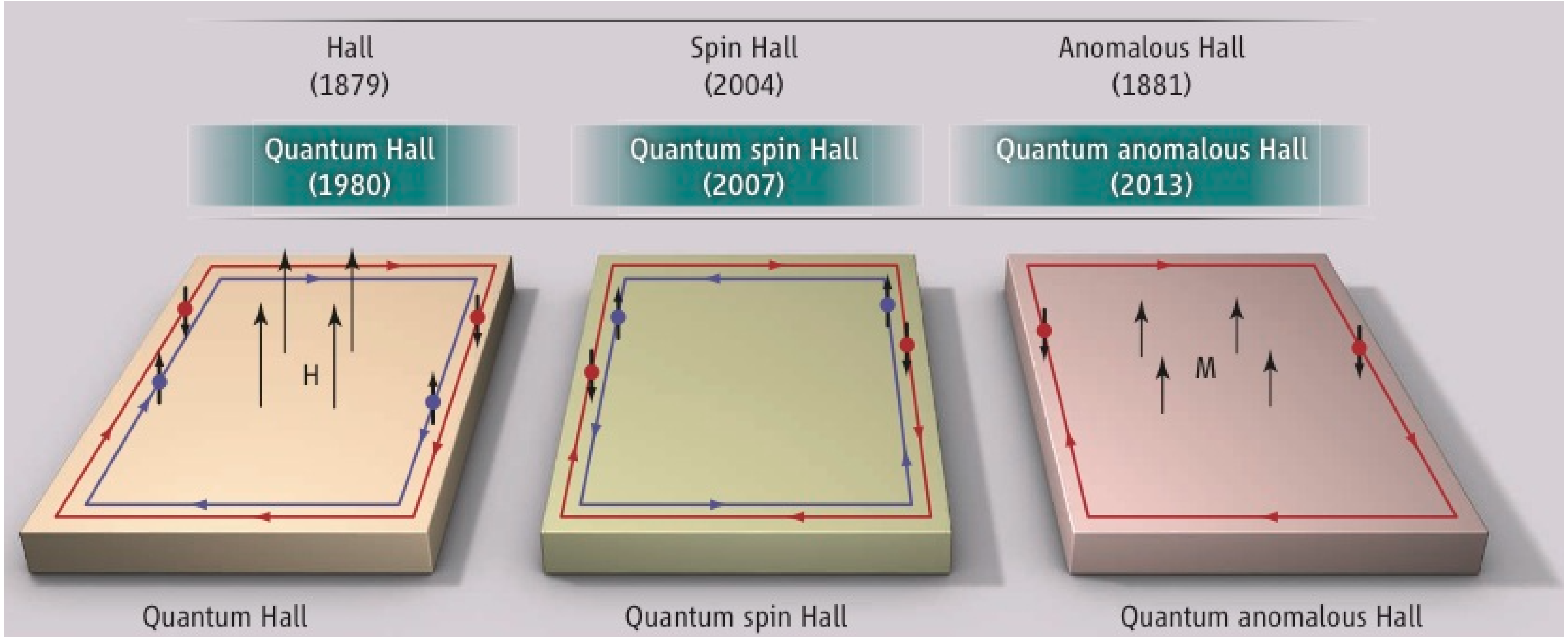
    Hashisaka *et al*., Nat. Commun. **12**, 2794 (2021).

  - ✓ A boundary of a Tomonaga-Luttinger liquid

    Hashisaka *et al*., Nat. Phys. **13**, 559 (2017).

Two-dimensional topological systems

S. Oh, Science 2013.



- **Integer quantum Hall (IQH) effect**

  Klaus von Klitzing 1980. ➡ Nobel prize 1985.

- **Fractional quantum Hall (FQH) effect**

  Tsui, Stomer, Gossard 1982.
  Laughlin 1983. ➡ Nobel prize 1998.

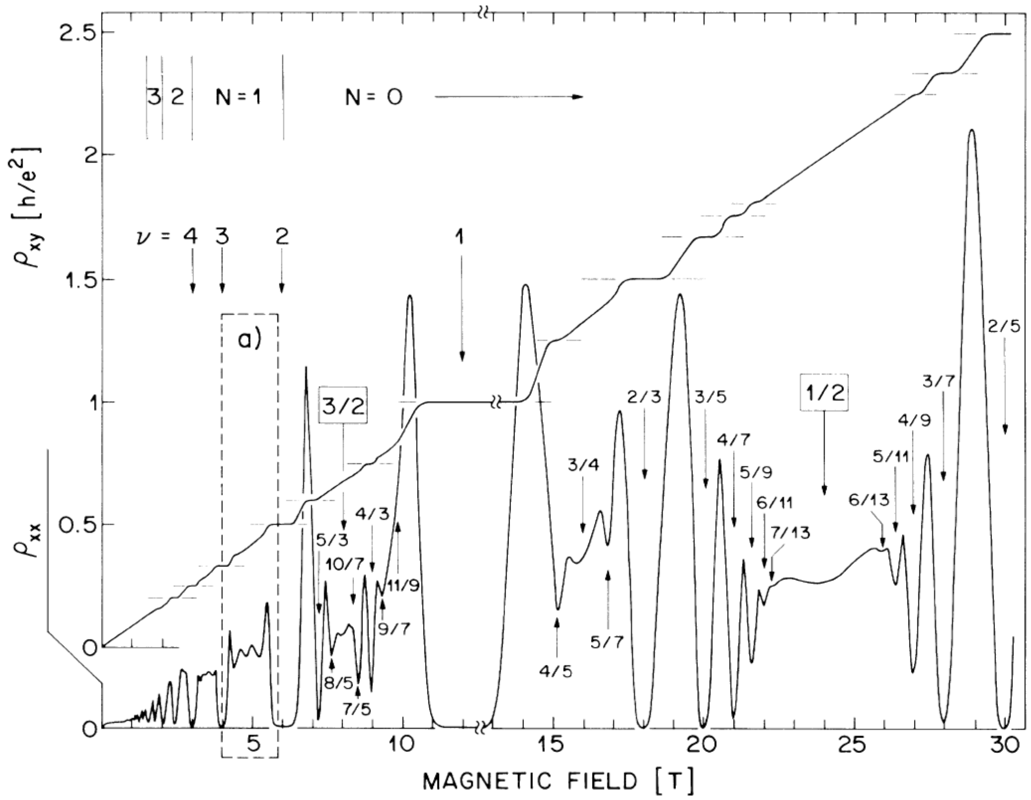
Quantum Hall effect

- **Integer quantum Hall (IQH) effect**

  von Klitzing 1980.

  ✓ Landau-level Filling factor :
  ν = (integer)

  - Charge carrier: $e^* = e$
  - Quantum statistics: $\theta = \pi$ (Fermion)



R. Willett et al.,
Phys. Rev. Lett. **59**, 1776 (1987).

Quantum many-body state

- **Fractional QH (FQH) effect**

  Tsui, Stomer, Gossard 1982.

  ✓ Laughlin state: ν = 1/3, etc.

  - Charge carrier: $e^* = e/3$
  - Quantum statistics: $\theta = \pi/3$ (Abelian)

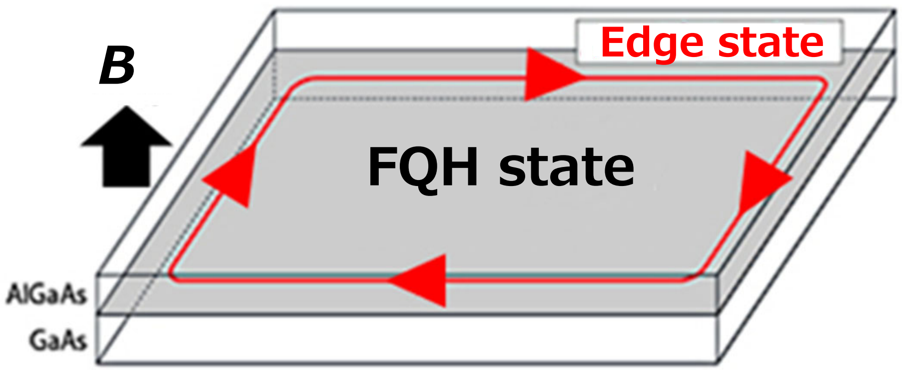
  ✓ Moore-Read Pfaffian state: ν = 5/2

  - Charge carrier: $e^* = e/4$
  - Quantum statistics: Non-abelian (Ising)

Fractional quasiparticles

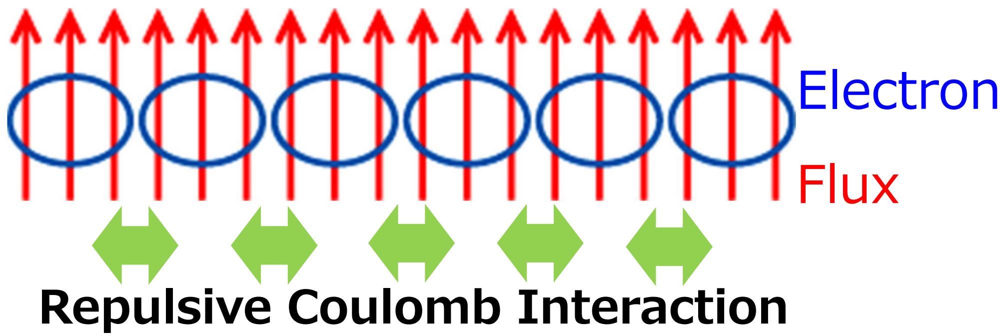
FQH state

Bulk: incompressible (insulating)
Edge: compressible (metallic)



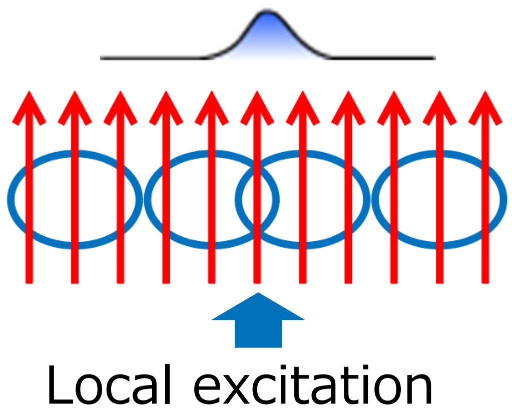
- **Laughlin state: ν = 1/3, etc.**
  - ✓ Charge carrier: $e^* = e/3$
  - ✓ Quantum statistics: $\theta = \pi/3$

Ground state（ν = 1/3）



Uniform electron density:
Three flux quanta per an electron.

Elementary excitation (quasiparticle)



Minimal electron-density modulation

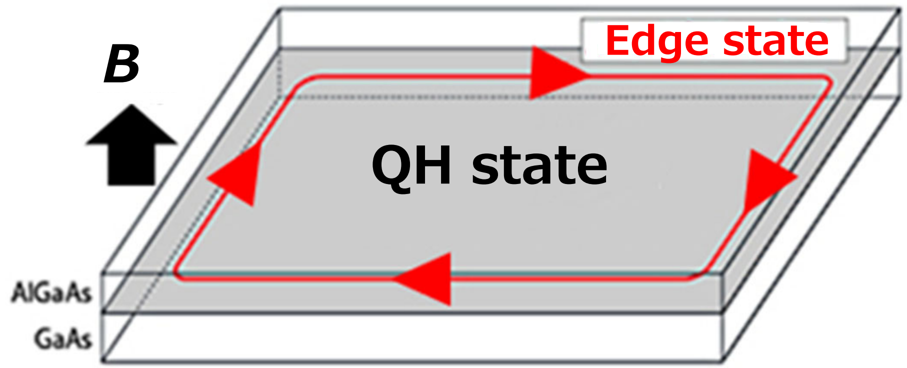
Fractional charge

$e^* = e/3$

Edge channels

Integer quantum Hall edge:
Chiral 1D channels

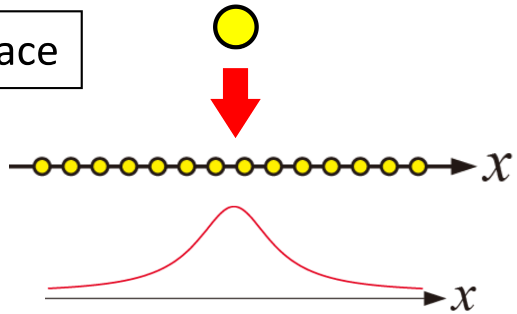
Fractional quantum Hall edge:
Chiral or helical 1D channels



➢ **Tomonaga-Luttinger liquid**

Interacting 1D electron system

Real space

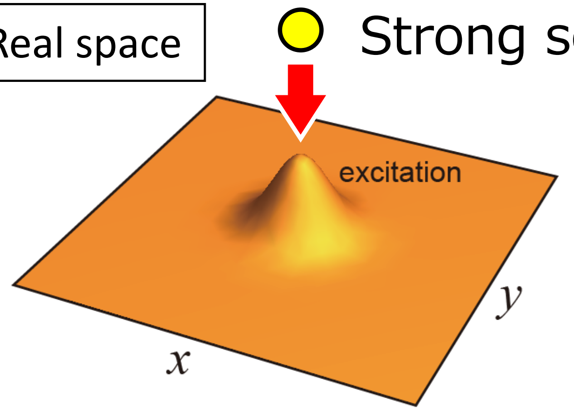


Correlation function:
Long range (**power law**)

c.f. **Fermi liquid**

Real space

Strong screening



Correlation function:
Local (**exp.** decay)

Luttinger-liquid nature of edge channels

Quantum many-body state

- **Fractional QH edge channel**

  Chiral Luttinger liquid

  (Short-range interaction)

  ✓ **Power-law behaviors.** →

- **Integer QH edge channel**

  Non-interacting 1D system

  (Short-range interaction)

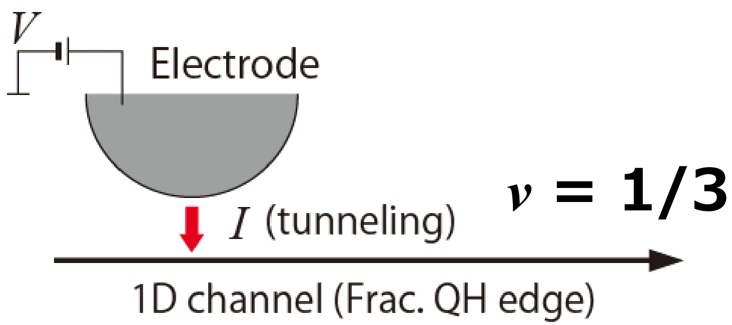
  Artificial Luttinger liquid

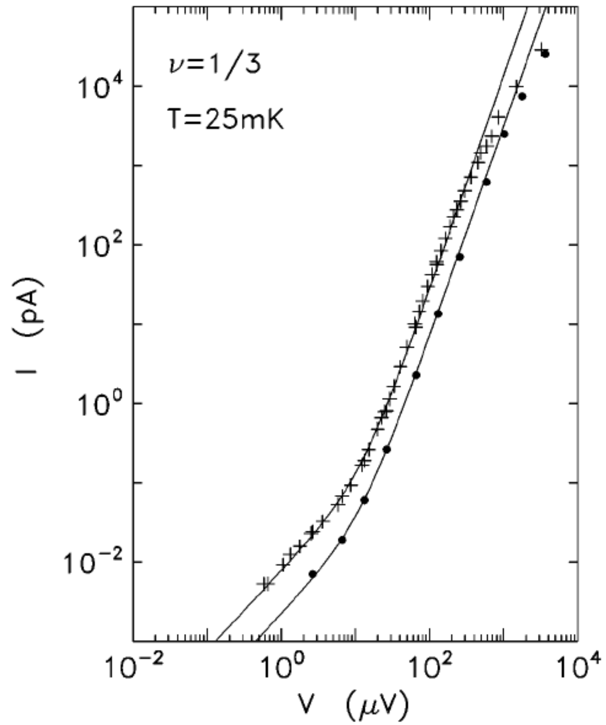
  (Long-range interaction)

  ✓ **Charge fractionalization**

  ✓ **Spin-charge separation**

  (Discussions later)





Power-law behavior
Phys.Rev. Lett. **77**, 2538 (1996).

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  - Fractional-Integer quantum Hall junction

    Hashisaka *et al*., Nat. Commun. **12**, 2794 (2021).

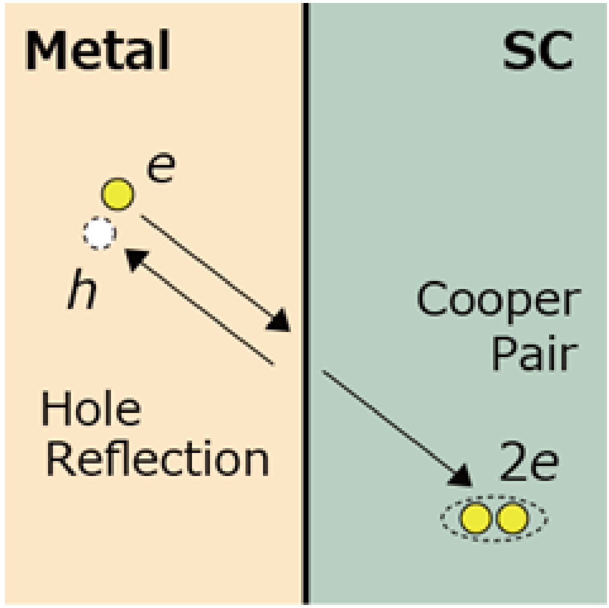
  - A boundary of a Tomonaga-Luttinger liquid

    Hashisaka *et al*., Nat. Phys. **13**, 559 (2017).

Andreev-reflection-like scatterings

Electron dynamics at boundaries of quantum many-body systems

Electron scattering reflects the mismatch between systems forming the boundary.



1. Fractional-Integer quantum Hall junction

(Q Many-body) (Normal)

Hashisaka *et al*., Nat. Commun. **12**, 2794 (2021).

2. A boundary of a Tomonaga-Luttinger liquid

Hashisaka *et al*., Nat. Phys. **13**, 559 (2017).

Fractional-Integer QH junction

Andreev reflection of fractional quantum Hall quasiparticles

M. Hashisaka, T. Jonckheere, T. Akiho, S. Sasaki, J. Rech, T. Martin, K. Muraki

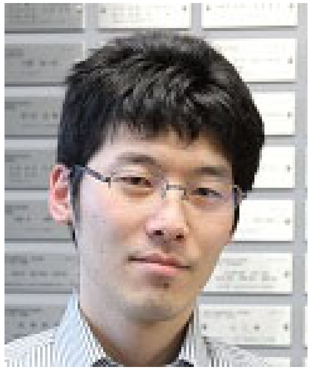
Nature Communications, **12**, 2794 (2021).

NTT members

Experiments

CPT, CNRS

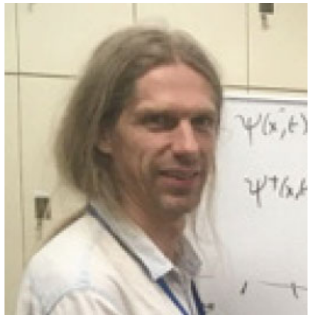
Calculations



T. Akiho

S. Sasaki

K. Muraki



T. Jonckheere

J. Rech

T. Martin

Acknowledgements

N. Kumada, T. Ito,
N. Shibata T. Fujisawa,
H. Murofushi, & M. Imai

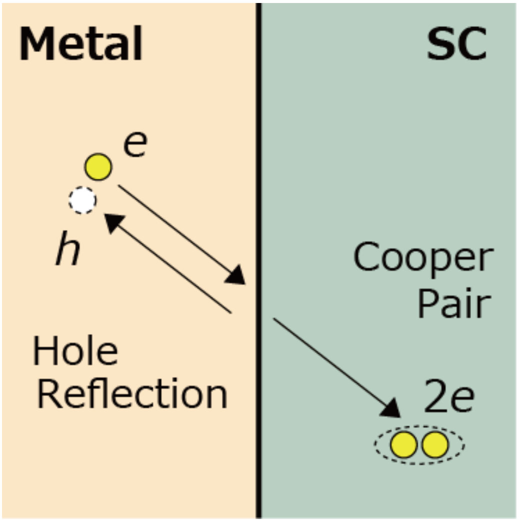
Fractional-Integer QH junction

My first thought:

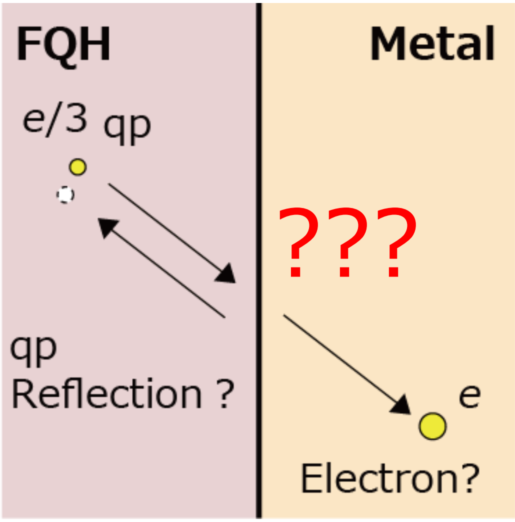
Charge conservation at a FQH／normal metal interface.

Fractionally-charged carrier dynamics

Andreev reflection



Fractional AR?



Conventional Andreev reflection at a Metal/Superconductor interface

Injection **Transmission** **Reflection**

e **(electron) = *2e* (Cooper pair) - *e* (hole)**

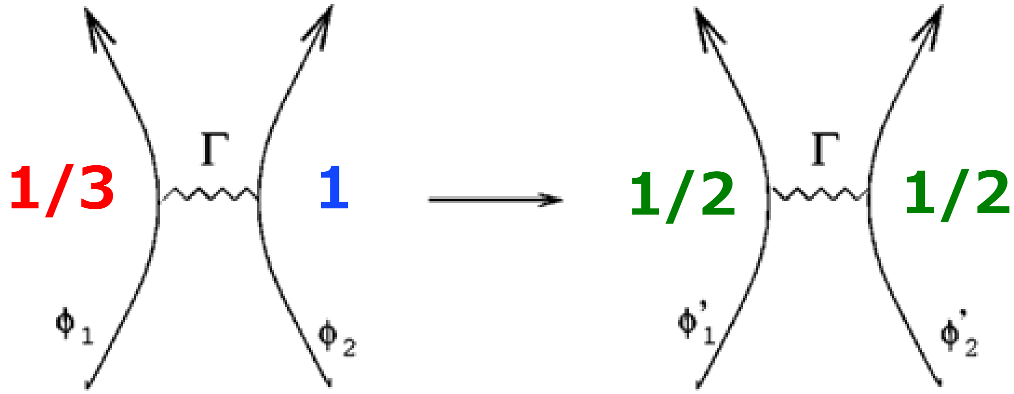
Similar scattering process at an FQH/Metal interface (?)

Injection **Transmission** **Reflection**

e/3 **(quasiparticle) = *e* (electron) - *2e/3* (quasihole)**

Theoretical proposals

Conductance through the 1/3-1 junction:
tunneling between Luttinger liquids.



➡ Analytical result of the single-impurity case:

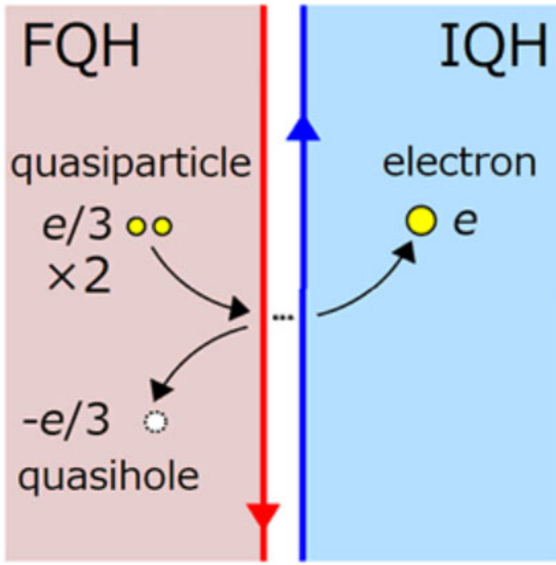
$G = \mathbf{1.5} \times e^2/3h$ (Strong coupling)

Safi & Schulz, PRB **52**, R17040 (1995).
Chamon & Fradkin, PRB **56**, 20120(1997).
Chklovskii & Halperin, PRB **57**, 3781 (1998).
Sandler, Chamon & Fradlkin, PRB **59**, 12521 (1999).

Conductance exceeding $e^2/3h$:

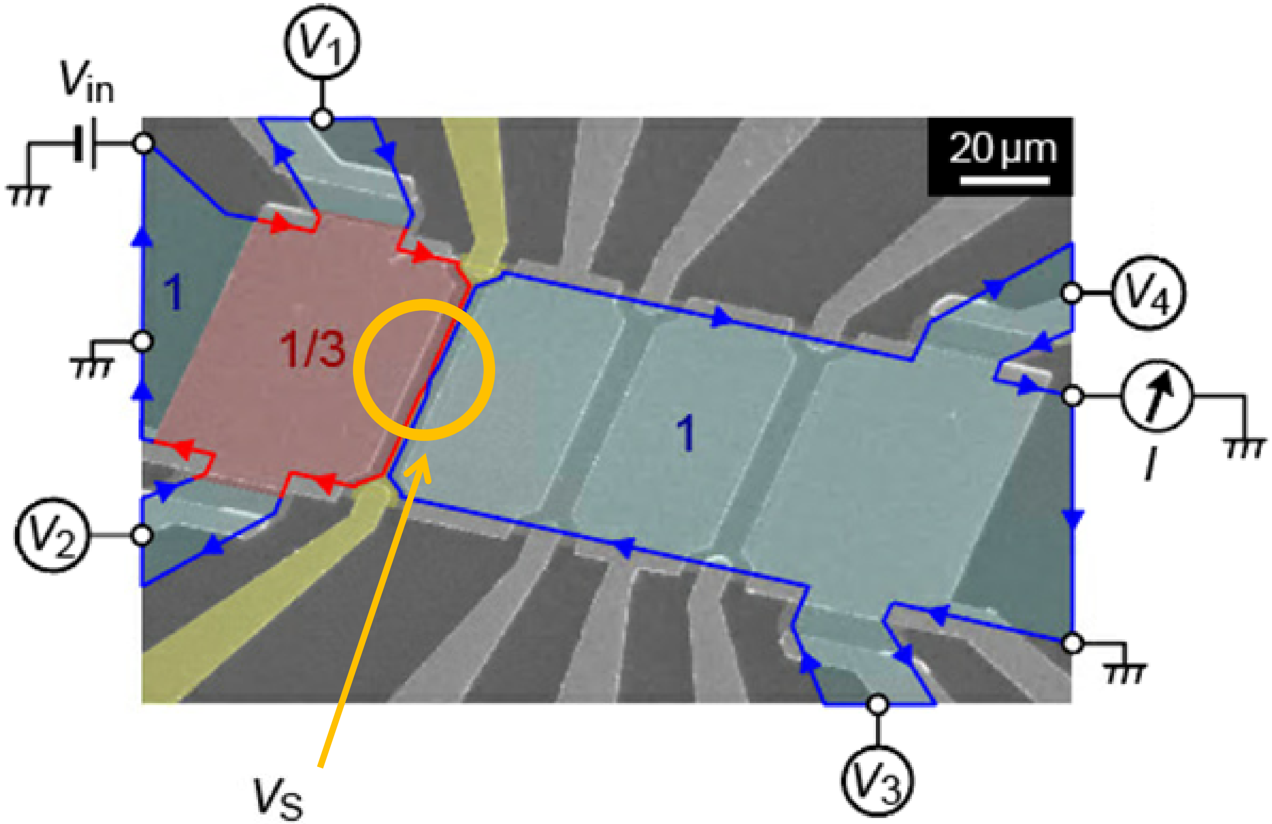
➡ Interpretation:
Andreev reflection of fractional quasiparticles.

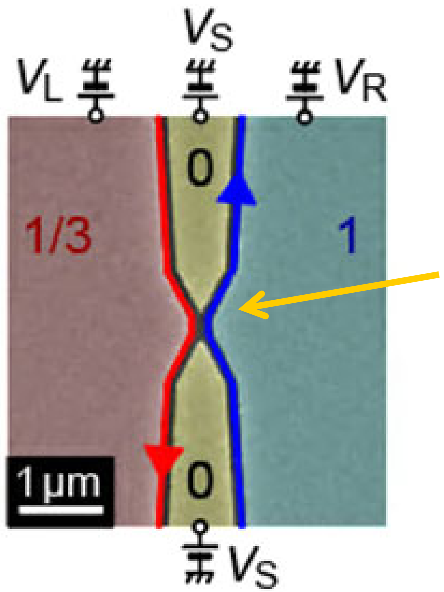
Sandler, Chamon, Fradkin PRB **57**, 12324 (1998).



No experimental demonstration since the theoretical prediction in the 1990s.

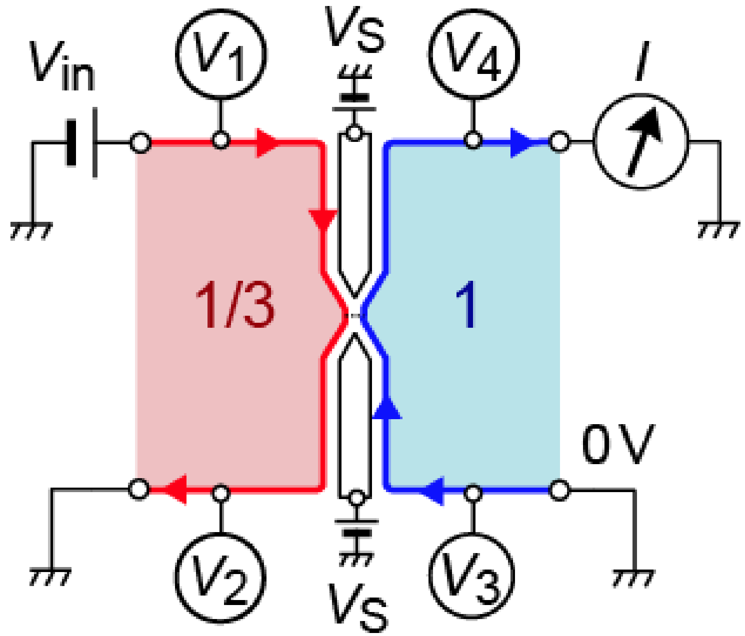
Sample





Split-gate aperture:

300 nm
600 nm
900 nm

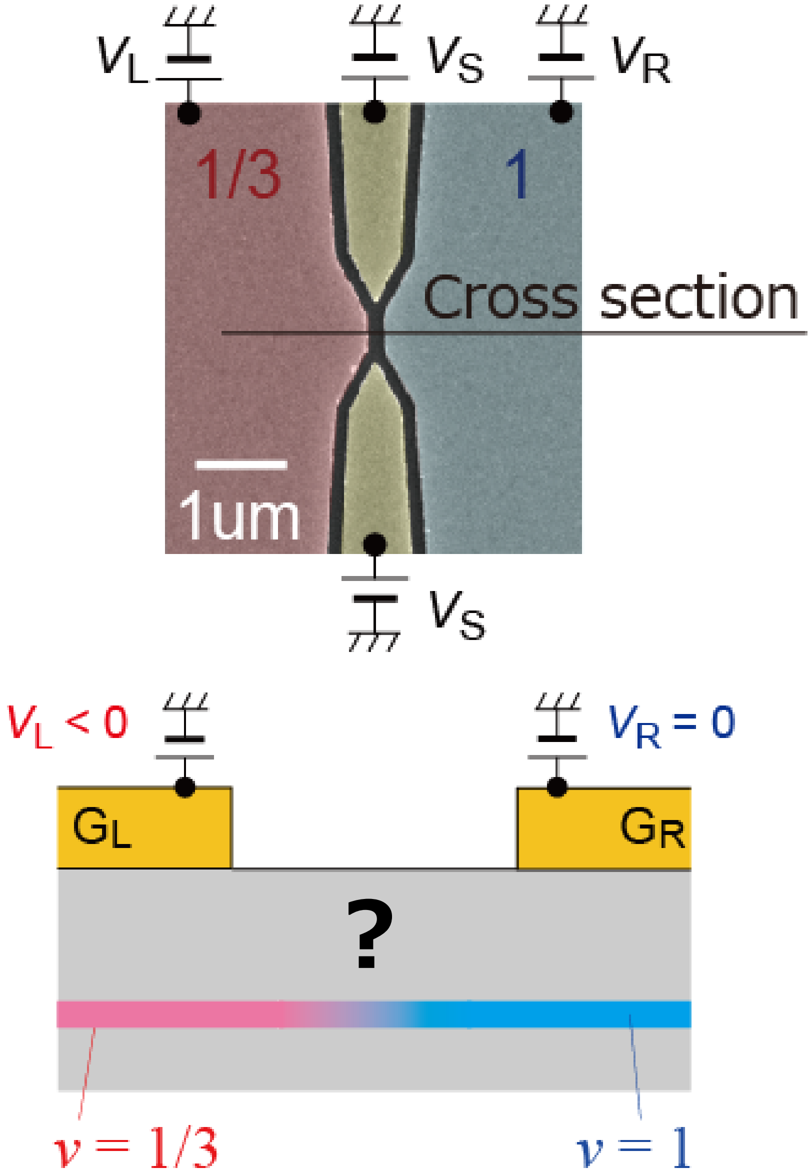


2DES in a GaAs quantum well
(with a back gate: V_{BG})
Electron density ∼ 1.8 x 10^{11} cm^{-2}

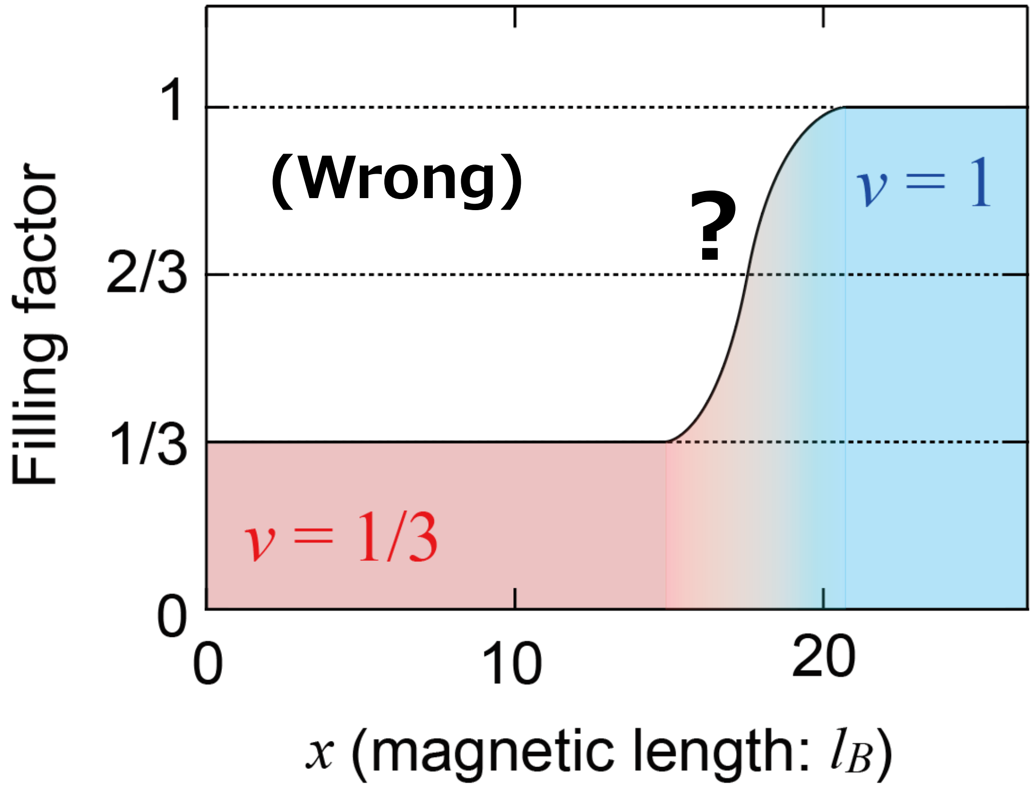
Magnetic field B = 9.0T
(Bulk filling: ν= 1 @ V_{BG} = +1.29 V)
Electron temperature ~10 mK

Boundary of the FQH and IQH systems

Hashisaka et al., Phys. Rev. X **13**, 031024 (2023).



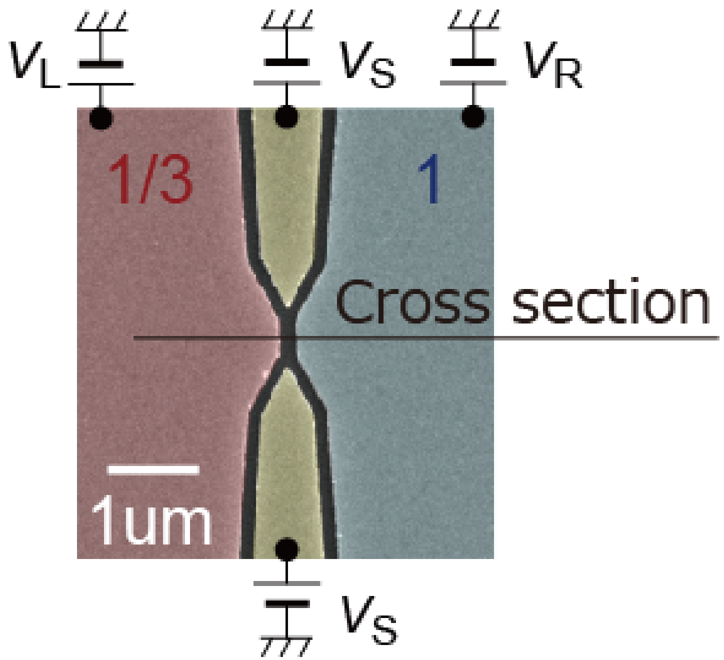
Electron-density profile

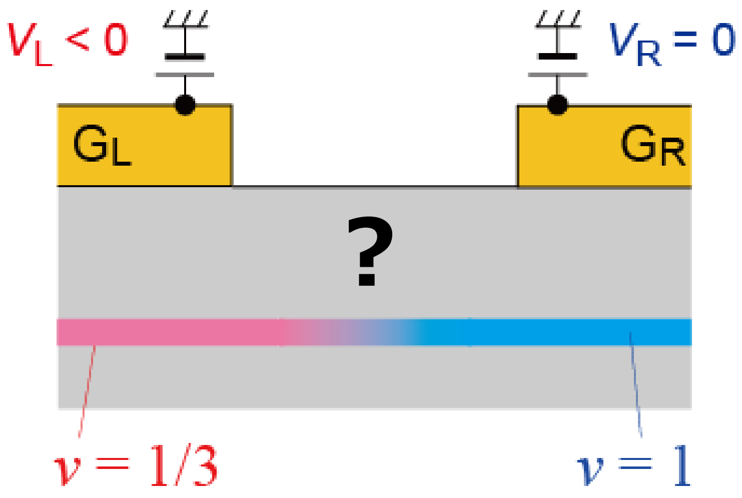


We need to consider
electron correlation in the ν = 1/3 region.

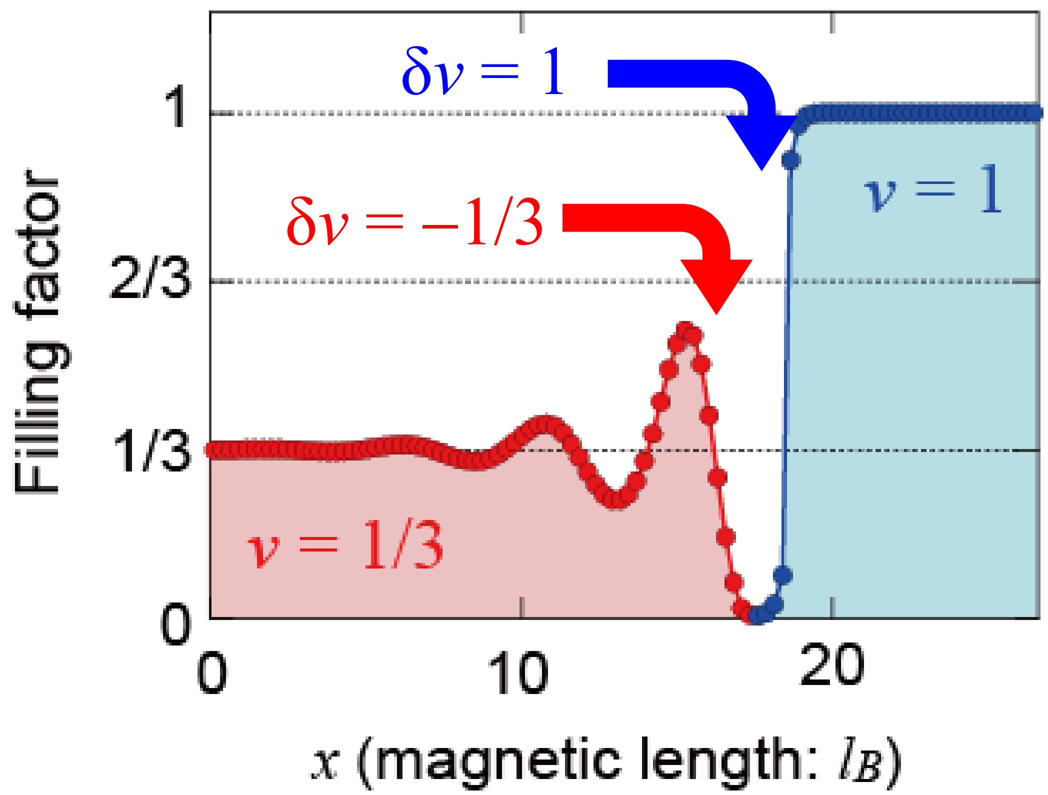
Boundary of the FQH and IQH systems

Hashisaka et al., Phys. Rev. X **13**, 031024 (2023).





Electron-density profile



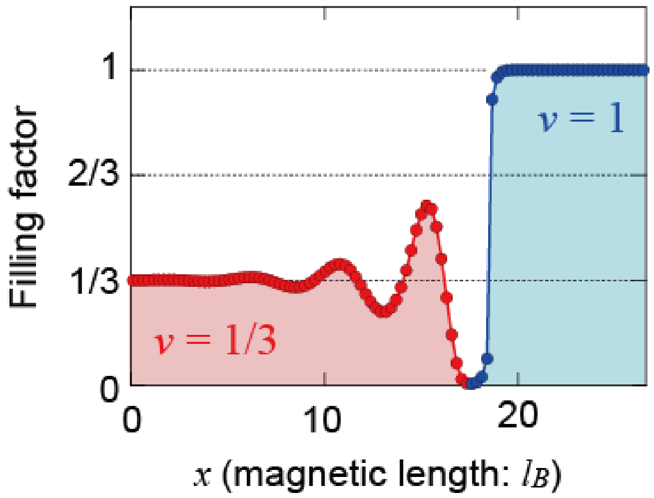
Density-Matrix Renormalization Group (DMRG) calculation

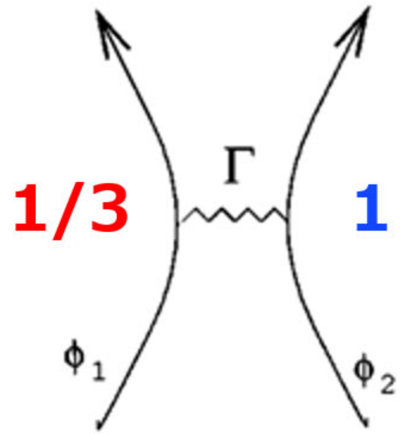
Ito & Shibata (Tohoku Univ.)

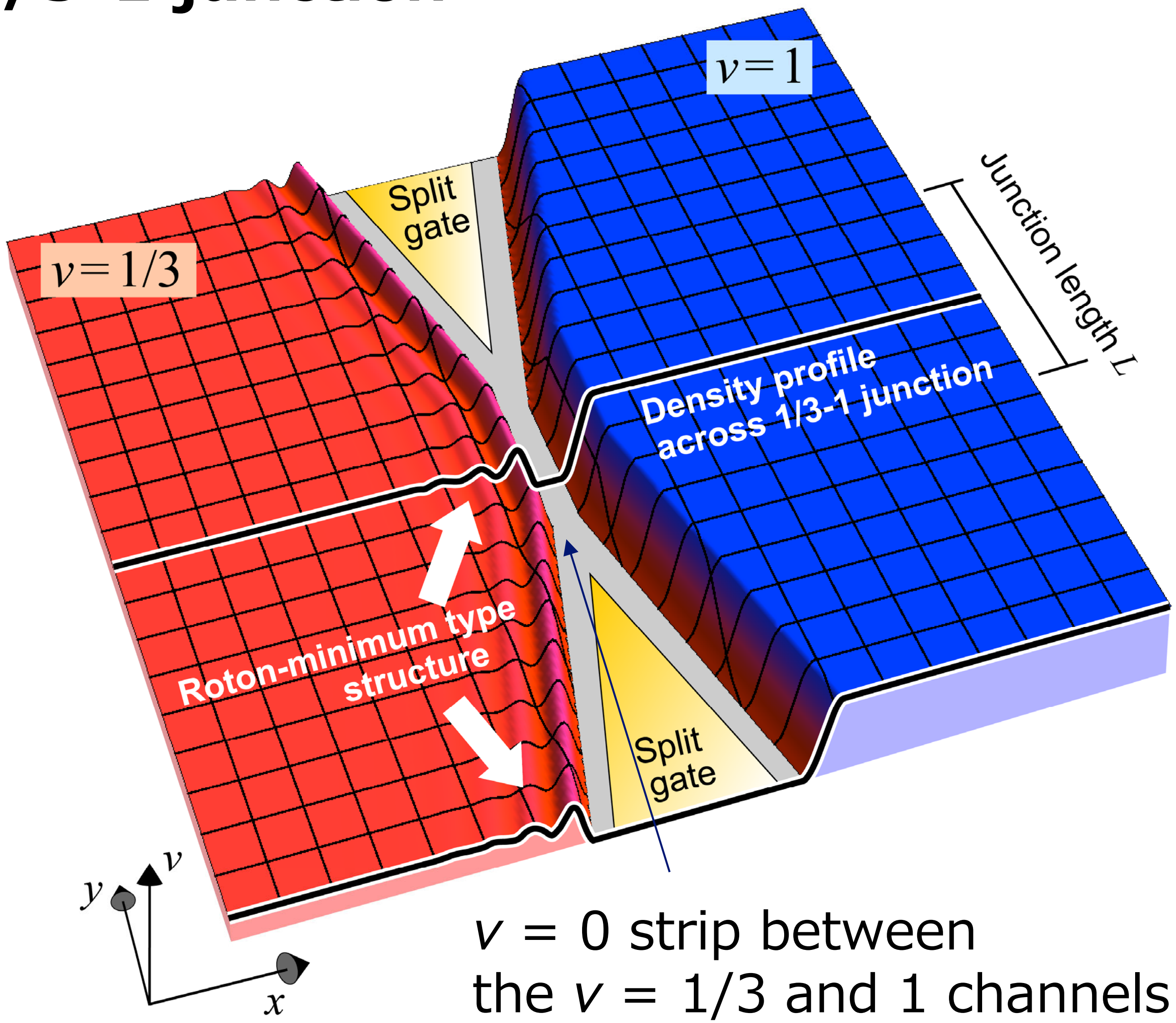
c.f. Ito, T. & Shibata, PRB **103**, 115107 (2021).

Hashisaka et al., Phys. Rev. X **13**, 031024 (2023).

Schematic of the 1/3-1 junction



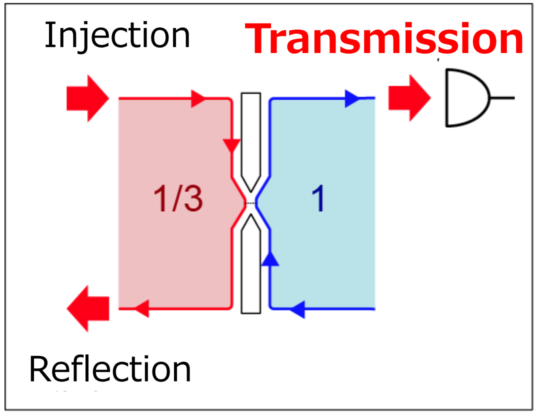


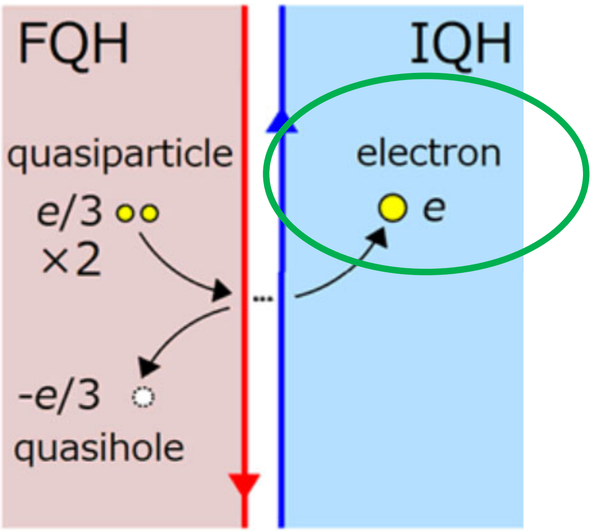


ν = 0 strip between the ν = 1/3 and 1 channels.

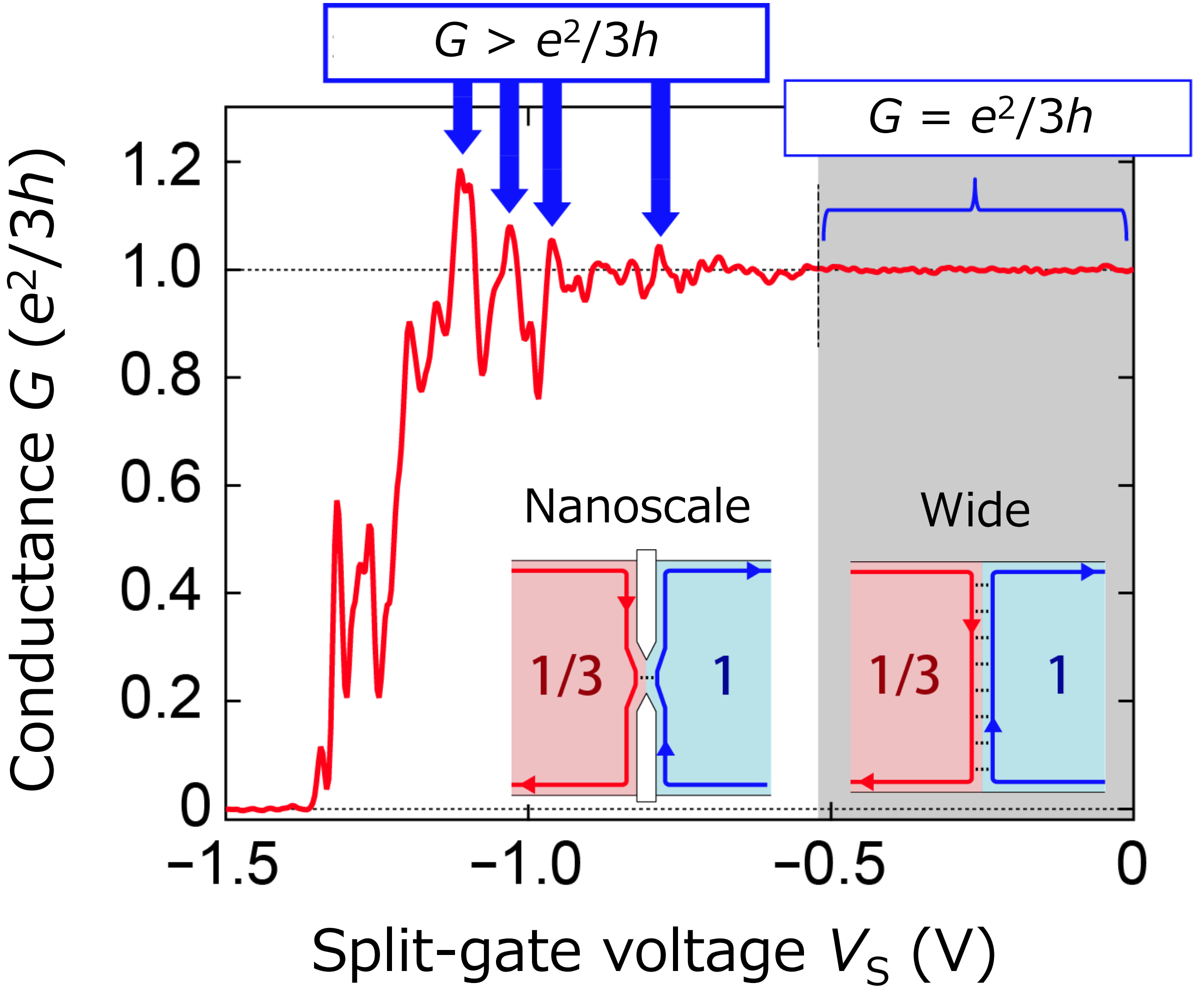
Experimental result 1:
Conductance oscillations with $G > e^2/3h$

Maximum conductance: ~ 1.2 × $e^2/3h$ (1.5$e^2/3h$: strong coupling limit)
Oscillation amplitude increases with decreasing the junction width.





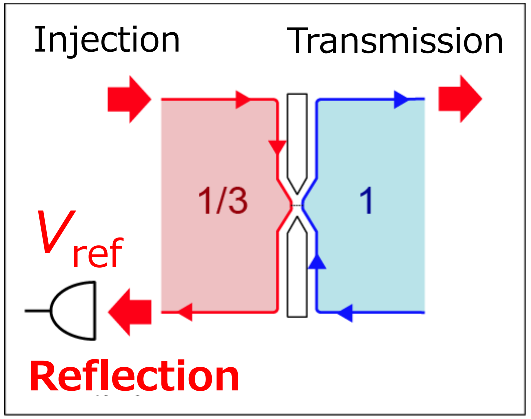
Evidence of the Andreev process

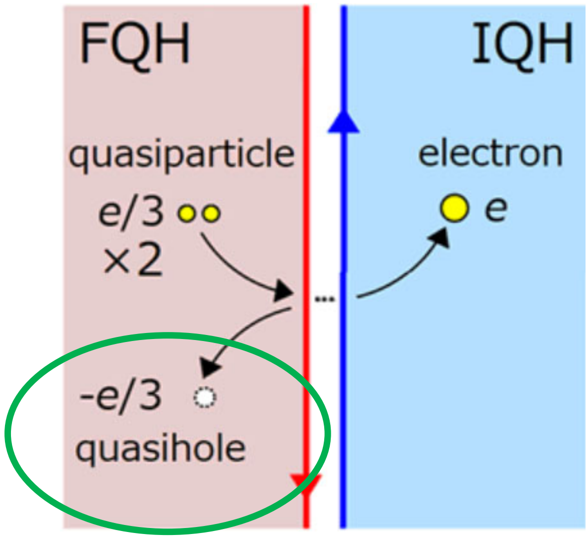


Negative reflection signal

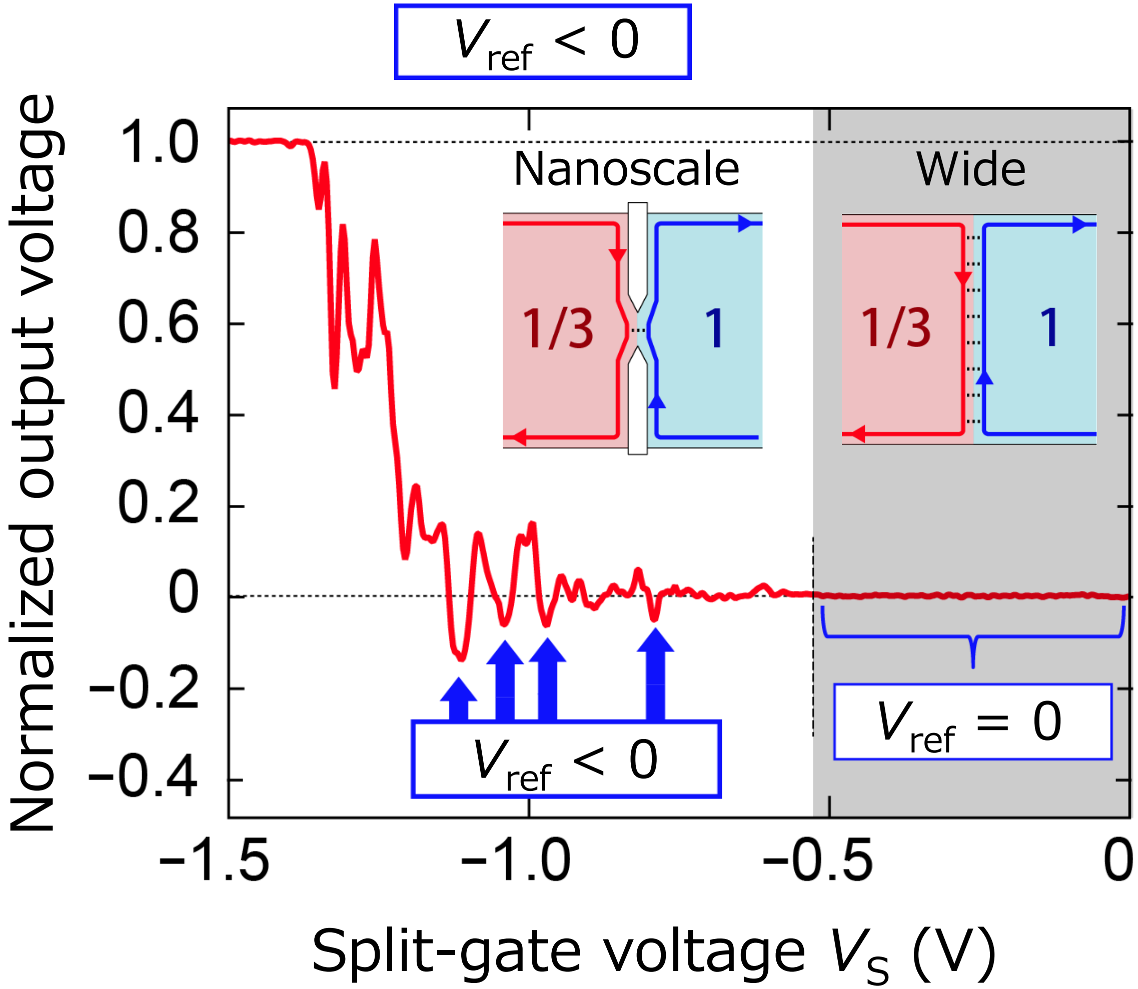
Negative output voltage of the reflected channel.

Similar oscillations are observed as a function of V_S.





Evidence of the Andreev process



Conductance oscillations

Why does the conductance oscillate?

Multiple impurities

G oscillates between 0 and 1.5 x $e^2/3h$.

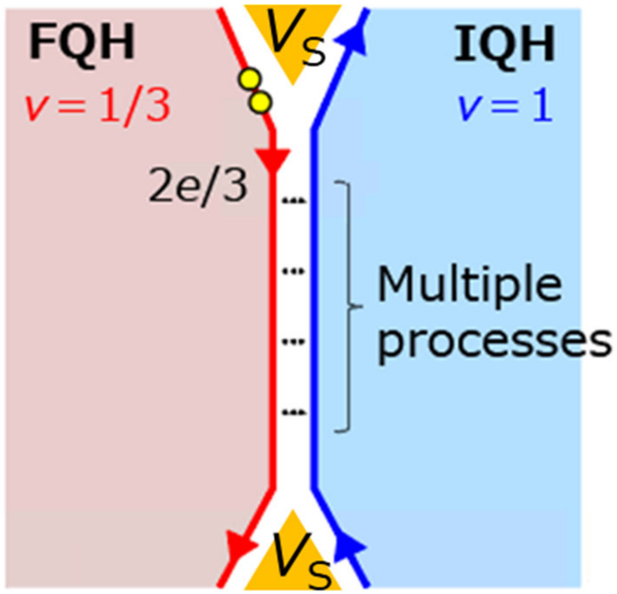
Theory:

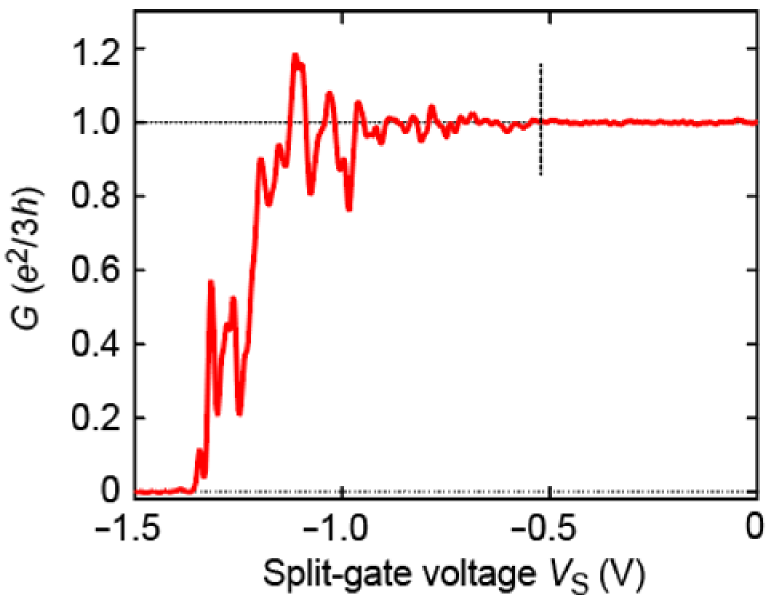
Chamon, Fradlkin PRB **56**, 20120(1997).
Ponomarenko et al., PRB **67**, 035314 (2003).
Zülicke and Shimshoni, PRB **69**, 085307 (2004).

Our Experiment:

(GaAs 2DES) Hashisaka *et al*., Nat. Commun. 2021.

Multiple impurities





Single impurity

G = **1.5** x $e^2/3h$ (Strong coupling)

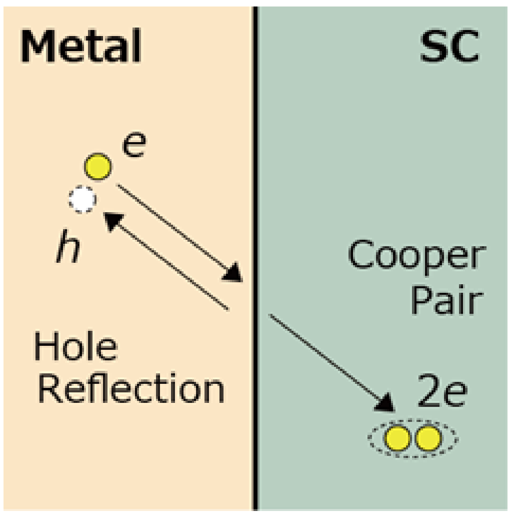
Recent Experiment:

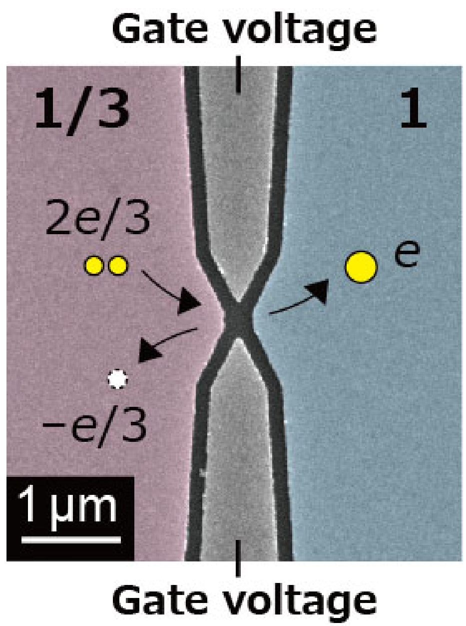
(Graphene) Cohen et al., Science 2023.

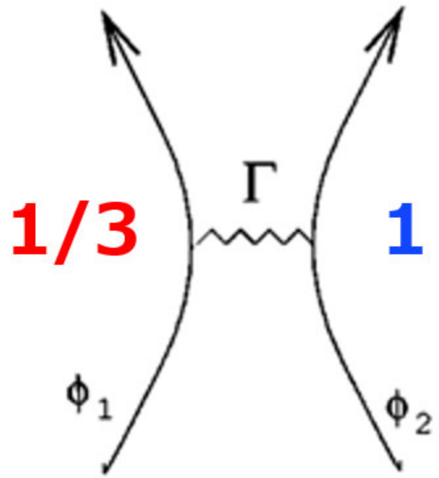
Andreev-reflection-like scatterings at an FQH-IQH interface

Nature Communications, **12**, 2794 (2021).

Theory: Safi & Schulz, PRB **52**, R17040 (1995).
Chamon & Fradkin, PRB **56**, 20120(1997).
Sandler, Chamon, Fradkin PRB **57**, 12324 (1998).
Chklovskii & Halperin, PRB **57**, 3781 (1998).
Sandler, Chamon & Fradlkin, PRB **59**, 12521 (1999).







c.f. Hashisaka et al., Phys. Rev. X **13**, 031024 (2023).
Cohen et al., Science **382**, 542 (2023).

Contents

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- **Quantum many-body effects in quantum Hall systems**

  Fractional quantum Hall (FQH) effect

  Edge channel (Tomonaga-Luttinger liquid)

Main

- **Electron dynamics at boundaries of quantum many-body systems**

  - ✓ Fractional-Integer quantum Hall junction

    Hashisaka *et al*., Nat. Commun. **12**, 2794 (2021).

  - ✓ A boundary of a Tomonaga-Luttinger liquid

    Hashisaka *et al*., Nat. Phys. **13**, 559 (2017).

Boundary of a Tomonaga-Luttinger liquid

Waveform measurement of charge- and spin-density wavepackets in a chiral Tomonaga-Luttinger liquid

M. Hashisaka, N. Hiyama, T. Akiho, K. Muraki, and T. Fujisawa

Nature Physics **13**, 559 (2017).

Tokyo Tech.

Measurements

NTT members

Crystal growth

Acknowledgements

H. Kamata, N. Kumada, Y. Tokura

N. Hiyama

T. Fujisawa

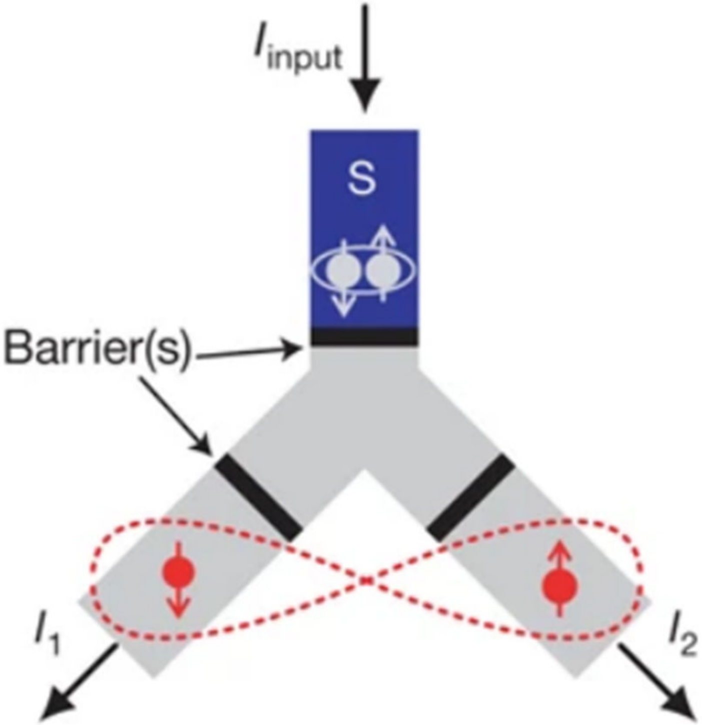
T. Akiho

K. Muraki

Cooper-pair splitting

Andreev reflection at a
Y-shaped Metal-Superconductor junction

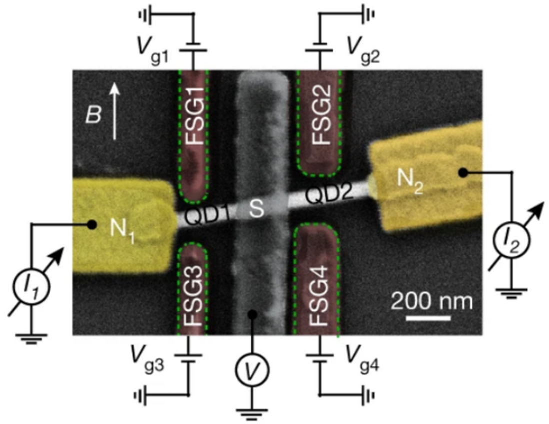
A promising device for generating pairwise entangled electrons in solids.



Hofstetter et al., Nature 2009.

Experiments:

Das *et al*., Nat. Commun. 2012.
Deacon *et al*., Nat. Commun. 2015.
Rani *et al*., Nat. Commun. 2021.
Bordoloi *et al*., Nature 2022.
etc.



Mode transformation at a boundary of a Tomonaga-Luttinger liquid

Electron fractionalization (Spin-Charge separation)

Hashisaka *et al*., Nat. Phys. **13**, 559 (2017).

Artificial Luttinger liquid

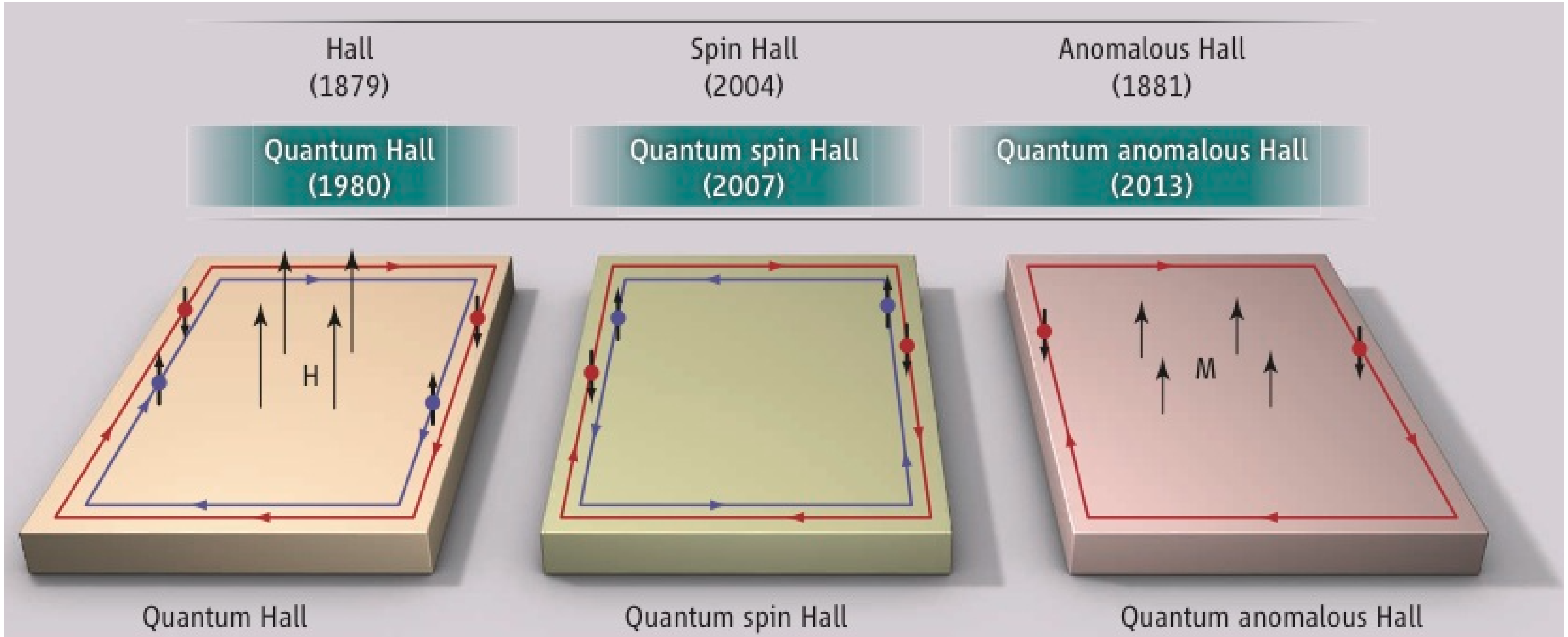
- **Integer QH edge channel**

(Short-range interaction) Non-interacting 1D system

(Long-range interaction) Artificial Luttinger liquid

- ✓ **Charge fractionalization**
- ✓ **Spin-charge separation**

} RF transport



S. Oh, Science 2013.

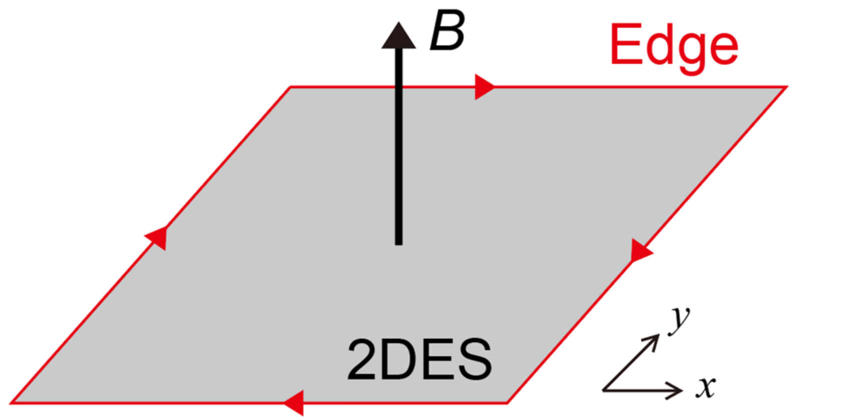
Low-energy charge dynamics

Quantum Hall system

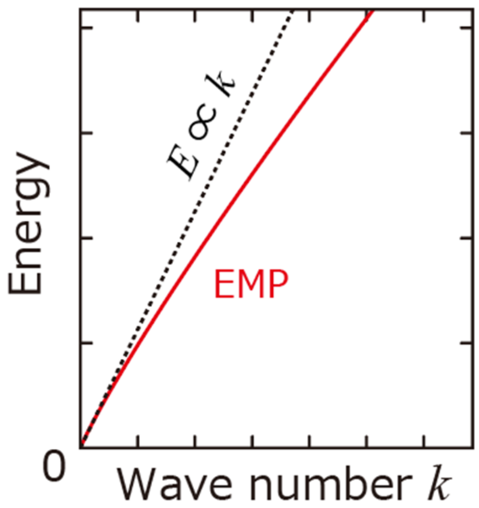
- ✓ Bulk: (Energy gap) > ~100 GHz
- ✓ Edge: gapless

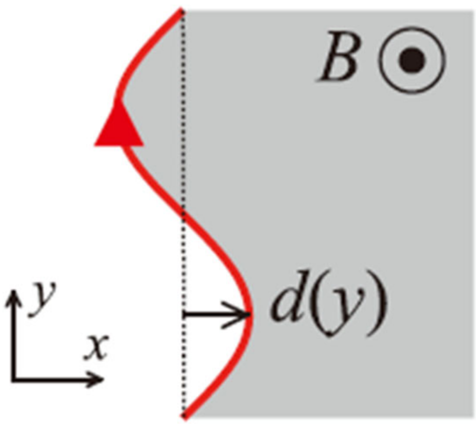
➢ **Edge magneto-plasmon (EMP)**

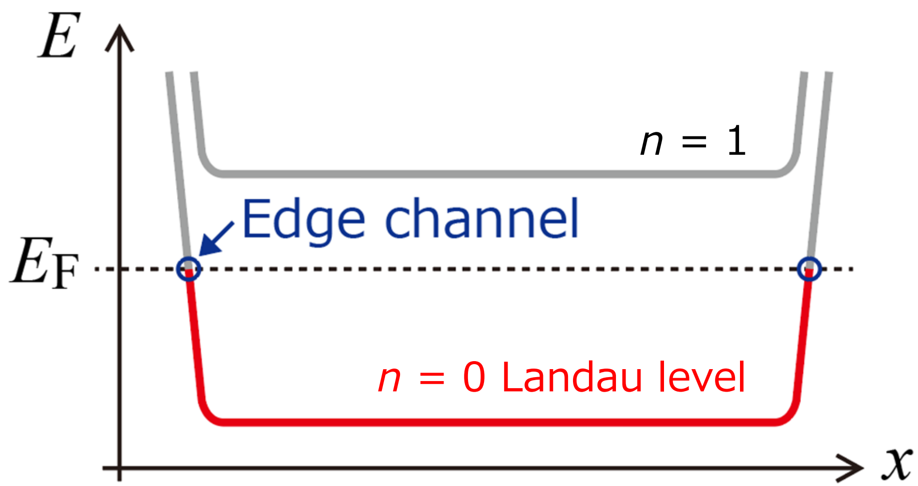
- Change in the boundary shape
- Almost linear dispersion relation



2-dimensional electron system(2DES)







Inter-channel interaction

➢ Circuit model of edge magnetoplasmons

Hashisaka *et al*., PRB 2012; PRB 2013.

- 1D continuity equation ➡ $\frac{\partial I}{\partial x} = -\frac{\partial \rho}{\partial t}$
- Electron correlation ➡ $\rho = c_{ch} V$
- Equation of motion ➡ $I(x,t) = \sigma_{xy} V(x,t)$

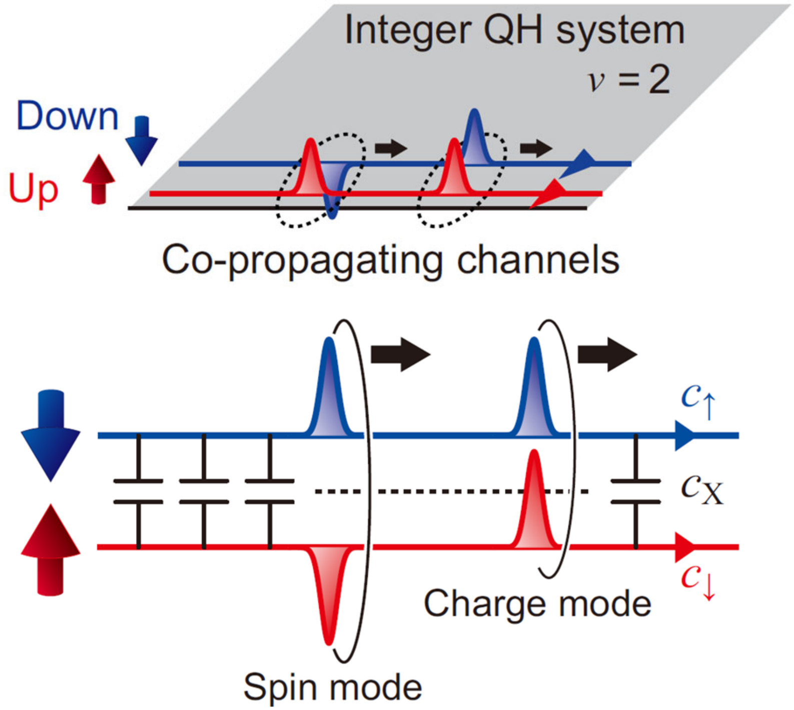
Inter-channel Coulomb interaction

✓ 1D wave equation:

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_\uparrow \\ \rho_\downarrow\end{pmatrix} = -\begin{pmatrix} v_\uparrow & U_X \\ U_X & v_\downarrow \end{pmatrix}\frac{\partial}{\partial y}\begin{pmatrix}\rho_\uparrow \\ \rho_\downarrow\end{pmatrix}$$

$$v_\uparrow = \frac{\sigma_{xy}(c_\downarrow + c_X)}{c_\uparrow c_\downarrow + c_\uparrow c_X + c_\downarrow c_X}, \quad v_\downarrow = \ldots, U_X = \ldots$$

Hashisaka & Fujisawa, Rev. Phys. 2018.



Artificial Luttinger liquid

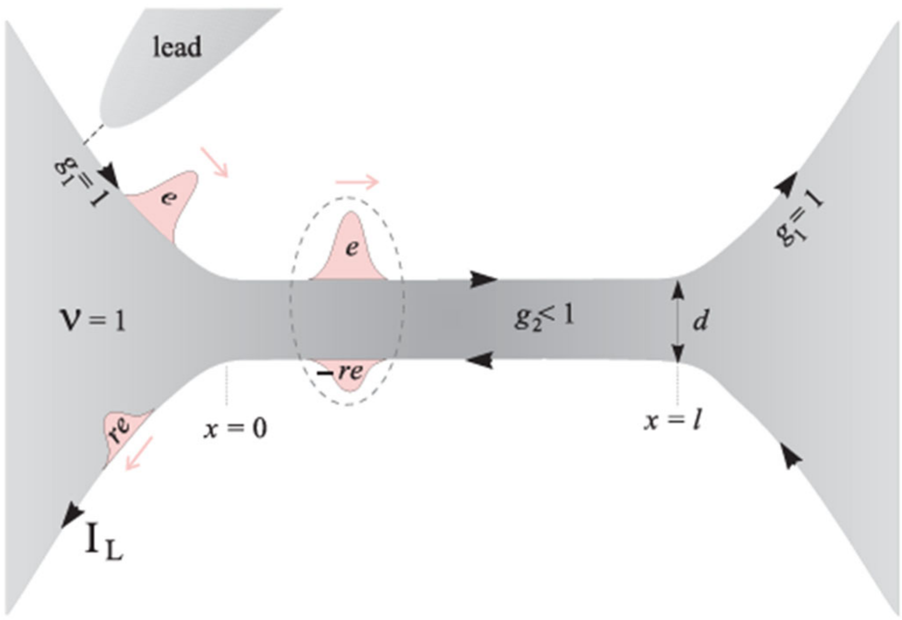
Interacting integer edge channels show Luttinger-liquid-like behaviors

Theory: Berg, Oreg, Kim, von Oppen, Phys. Rev. Lett. **102**, 236409 (2009).

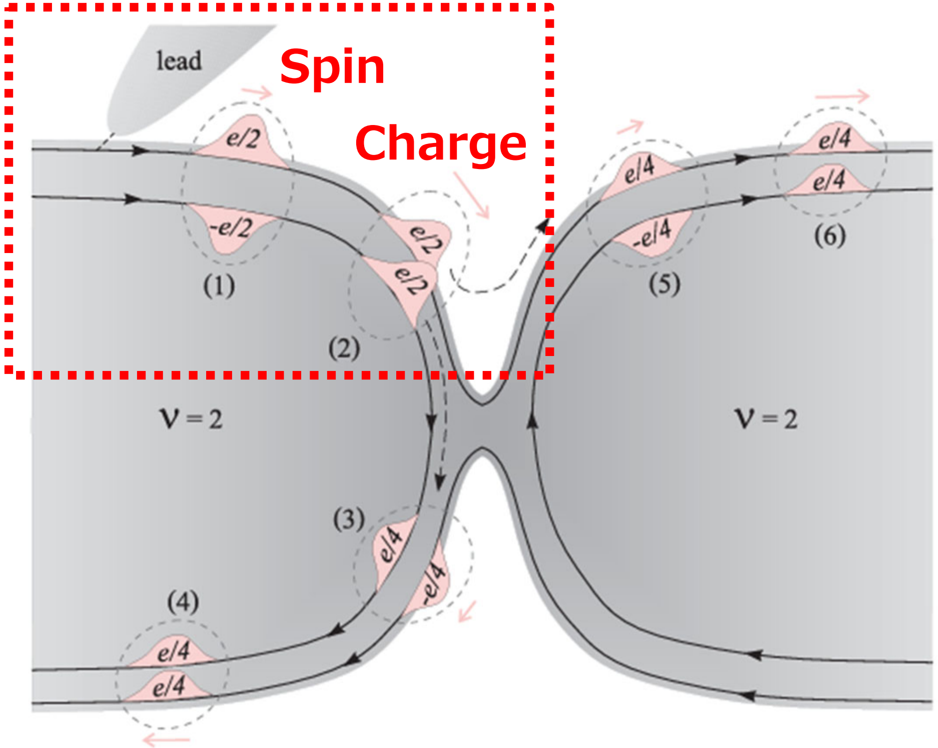
Charge conservation: $e = er + e(1-r)$

electron   Mode A + Mode B

Charge fractionalization



Spin-Charge separation

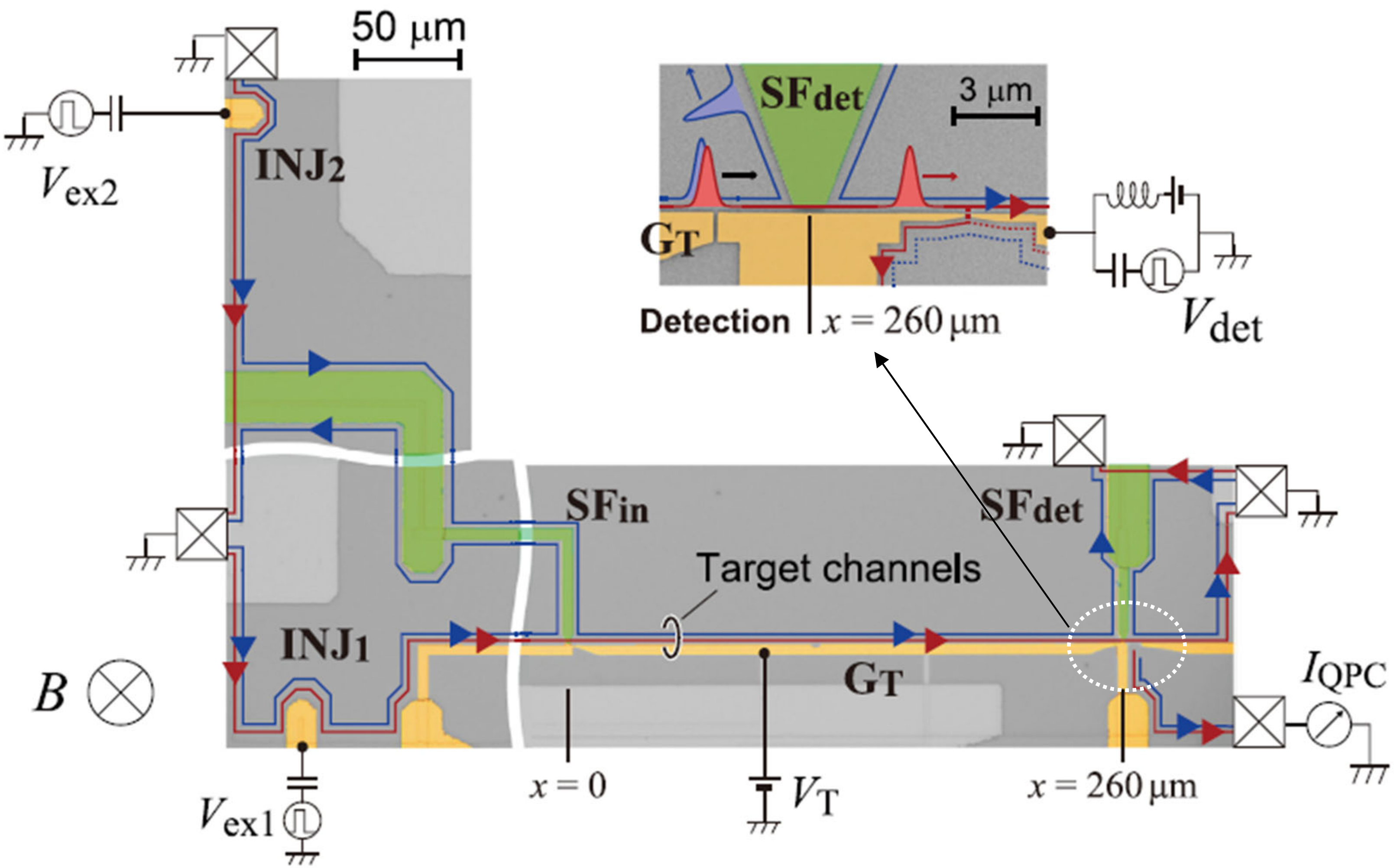


Kamata, Hashisaka, *et al*., Nat. Nanotechnol. 2014.
Hashisaka *et al*., PRB 2012.

Waveforms of charge & spin excitations

Direct time-domain measurement of the spin-charge separation in a Tomonaga-Luttinger liquid.

Hashisaka et al., Nat. Phys. **13**, 559 (2017).

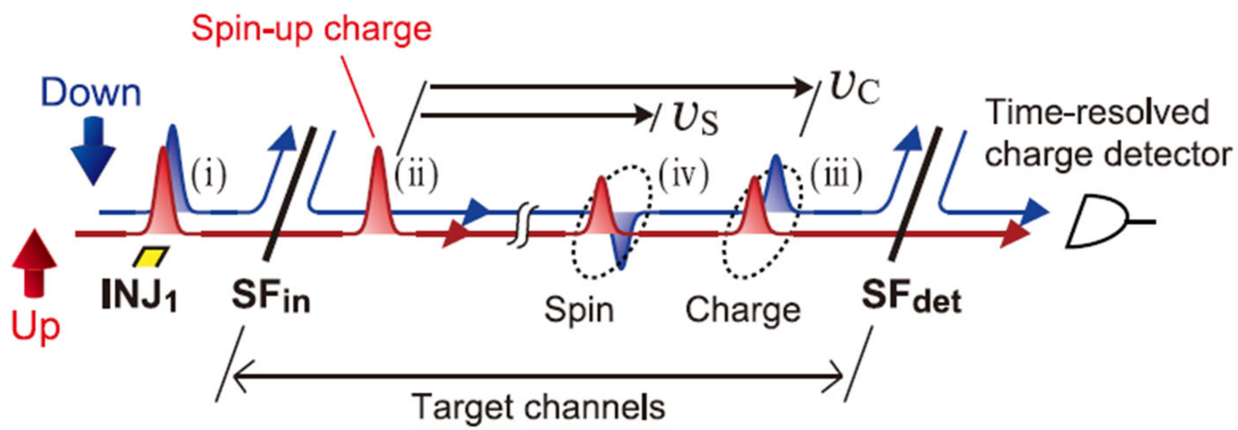


Optical micrograph of the sample (**ν = 2 IQH system in a GaAs quantum well**).

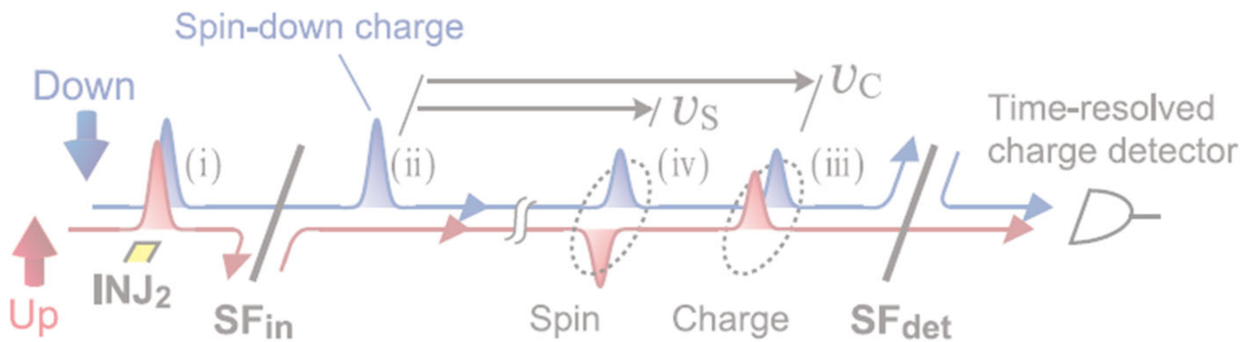
Spin-charge separation

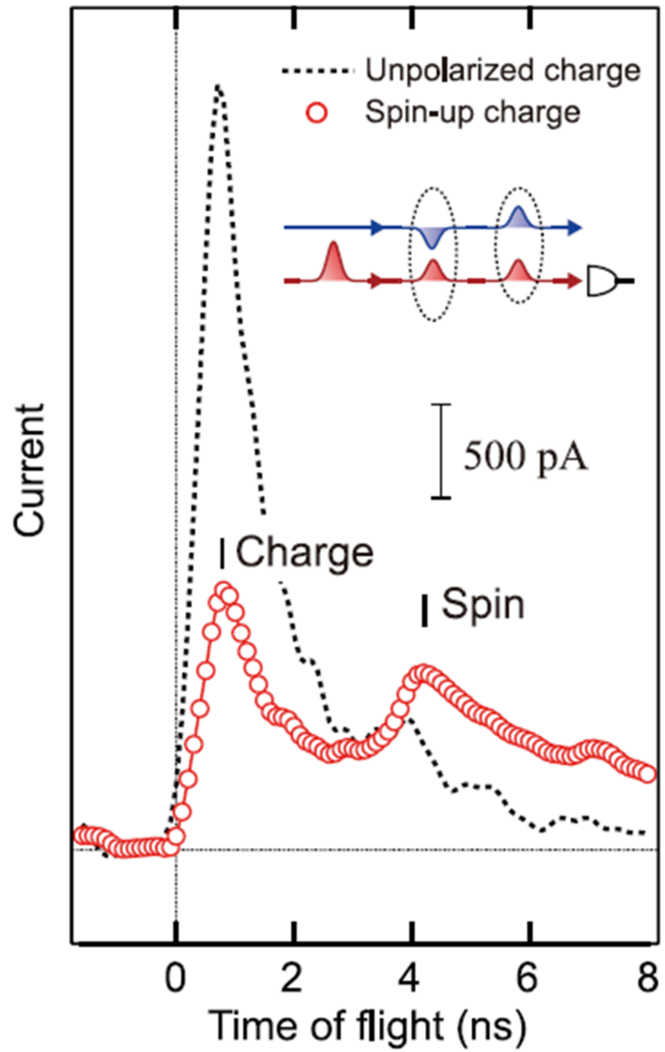
Hashisaka et al., Nat. Phys. **13**, 559 (2017).

- **Spin-up charge injection**



- Spin-down charge injection

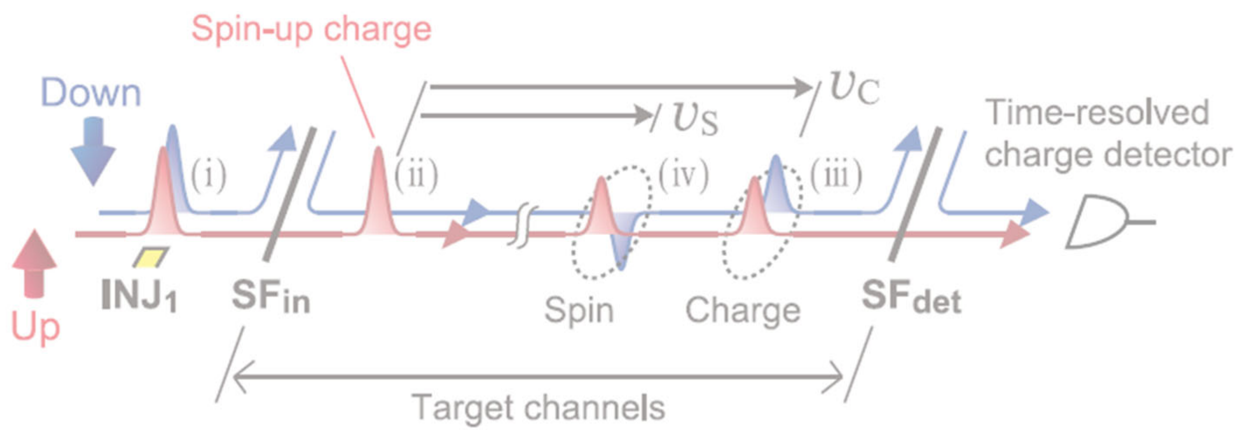




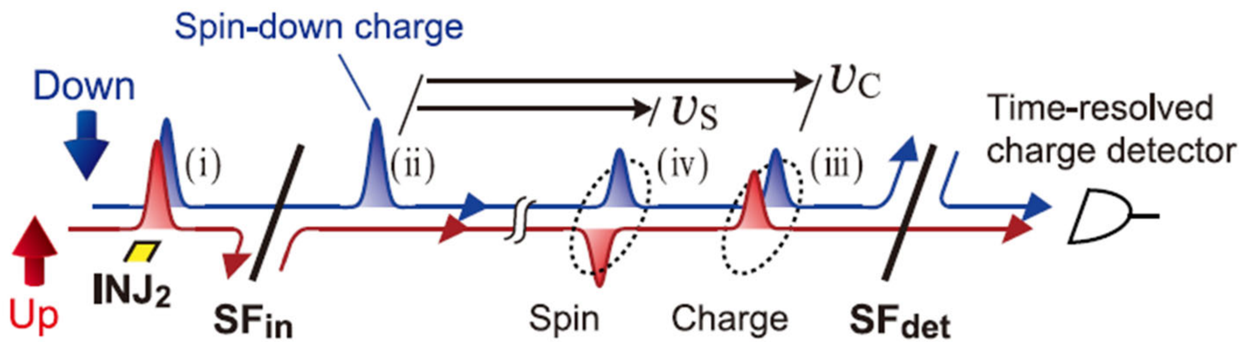
Spin-charge separation

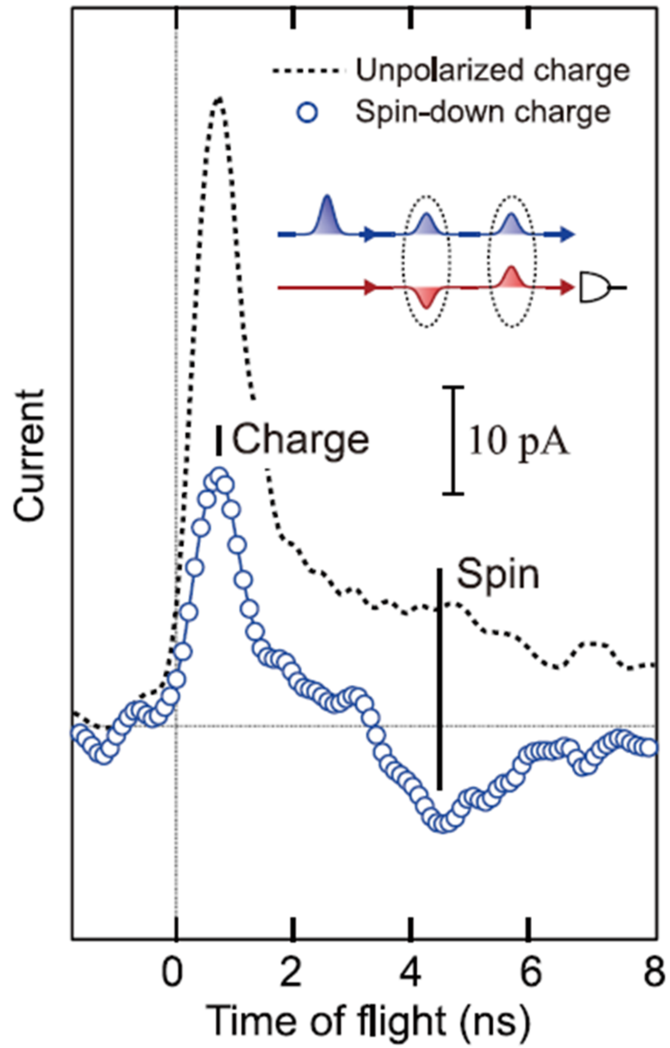
Hashisaka et al., Nat. Phys. **13**, 559 (2017).

- Spin-up charge injection



- **Spin-down charge injection**





Summary of the second topic

Waveform measurement of charge- and spin-density wavepackets in a chiral Tomonaga-Luttinger liquid

Nature Physics **13**, 559 (2017).

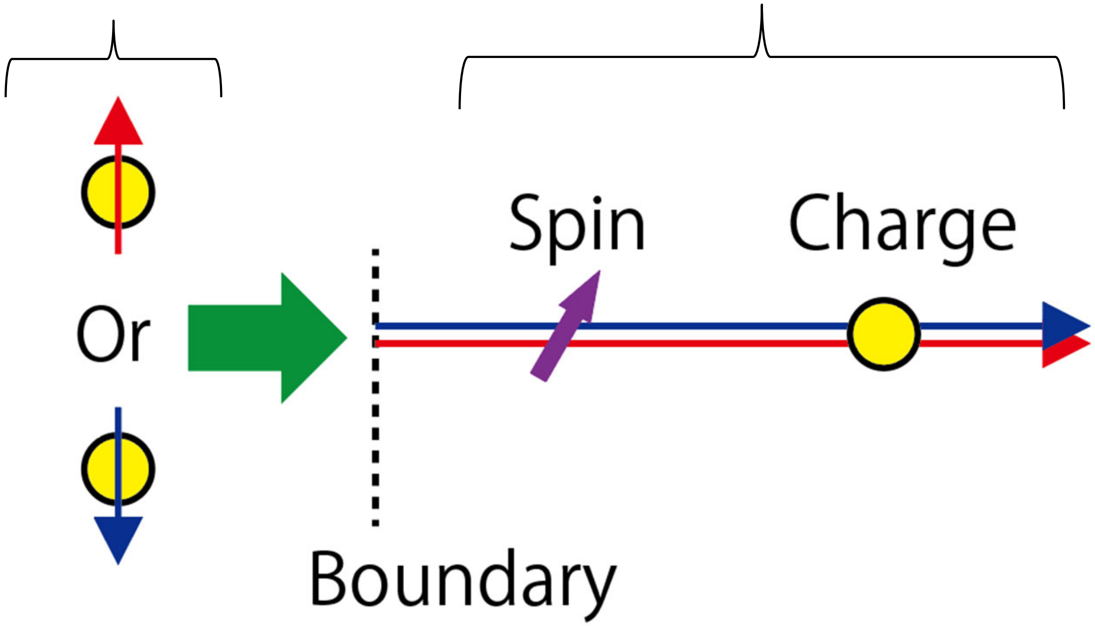
Theory: Berg, Oreg, Kim, von Oppen, Phys. Rev. Lett. **102**, 236409 (2009).

Mode transformations at boundaries

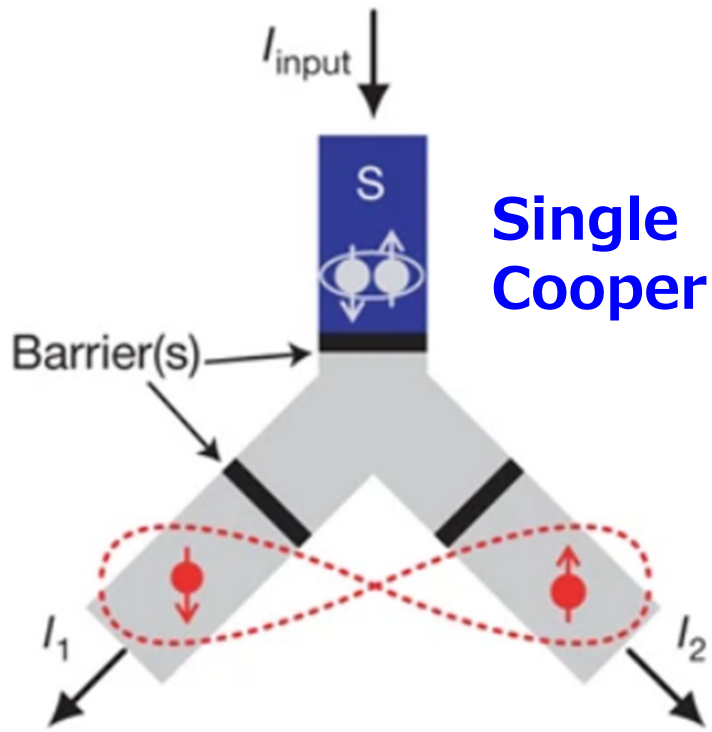
Single electron

Multiple modes

(Fractionalization)



Hashisaka et al., Nat. Phys. **13**, 559 (2017).



Single Cooper pair

Multiple electrons

Hofstetter et al., Nature 2009.

Summary

Background

- **Quantum many-body effects in quantum Hall systems**

Fractional quantum Hall (FQH) effect

Edge channel (Tomonaga-Luttinger liquid)

Main

- **Electron dynamics at boundaries of quantum many-body systems**
  - ✓ Fractional-Integer quantum Hall junction

    Hashisaka *et al*., Nat. Commun. **12**, 2794 (2021).
  - ✓ A boundary of a Tomonaga-Luttinger liquid

    Hashisaka *et al*., Nat. Phys. **13**, 559 (2017).

Appendix

- **Quantum many-body phase of interacting 1D channels**

Hashisaka et al., Phys. Rev. X **13**, 031024 (2023).

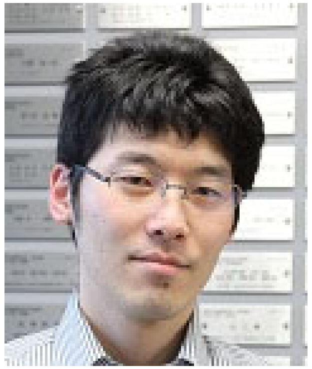
Edge-mode transformation

Coherent-Incoherent Crossover of Charge and Neutral Mode Transport as Evidence for the Disorder-Dominated Fractional Edge Phase

Hashisaka et al., Phys. Rev. X **13**, 031024 (2023).

NTT members

Experiments



T. Akiho

S. Sasaki

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Tohoku Univ.

Calculations

T. Ito

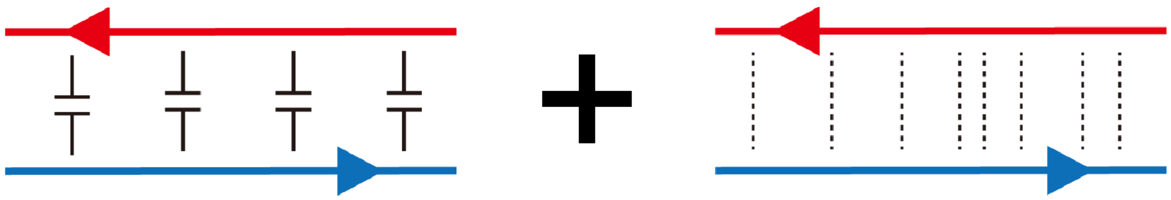
N. Shibata

Acknowledgements

T. Jonckheere, J. Rech,
T. Martin, T. Fujisawa,
H. Murofushi, & M. Imai

Appendix: Coulomb interaction & Tunnel couplings

➢ Helical edge channels



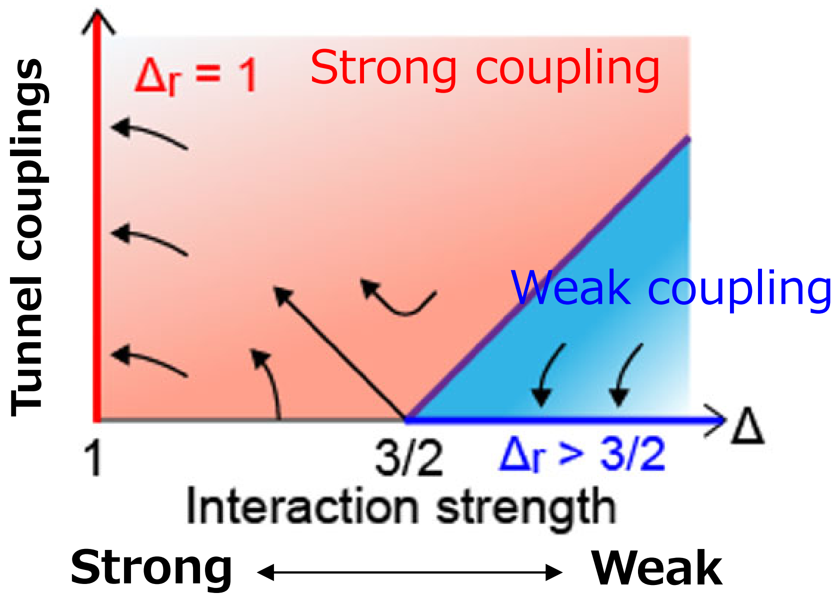
Coulomb interaction + Tunnel couplings

Example:

✓ 2D topological insulator (HgTe, etc.)

Quantized electrical conductance (?)

➢ Equilibration in the coupled helical channels.



Phase diagram of the coupled helical channels (from renormalization group theory)

The 1D phase can be identified by the **Electrical and thermal transport meas.**

MacDonald, PRL 1990.
Kane, Fisher, Polchinski, PRL 1994.
Kane, Fisher, PRB 1995.
Protopopov, Gefen, Mirlin, Ann. Phys. 2017.

Appendix: Coulomb interaction

Mechanism: How do the charge and charge-neutral modes emerge?

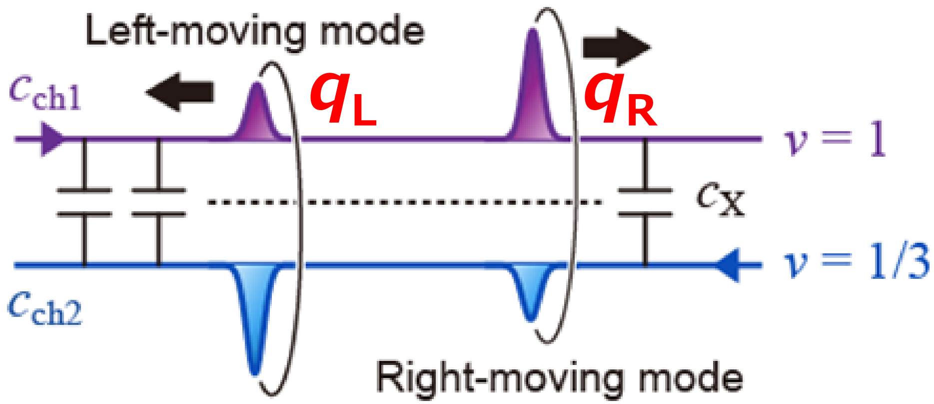
Wave equation:
(Coulomb interaction only)

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_1\\ \rho_{1/3}\end{pmatrix} = \begin{pmatrix}\nu_1 & U_X\\ -U_X & -\nu_{1/3}\end{pmatrix}\frac{\partial}{\partial x}\begin{pmatrix}\rho_1\\ \rho_{1/3}\end{pmatrix}$$

Hashisaka & Fujisawa, Rev. Phys. **3**, 32 (2018).

Coulomb interaction only

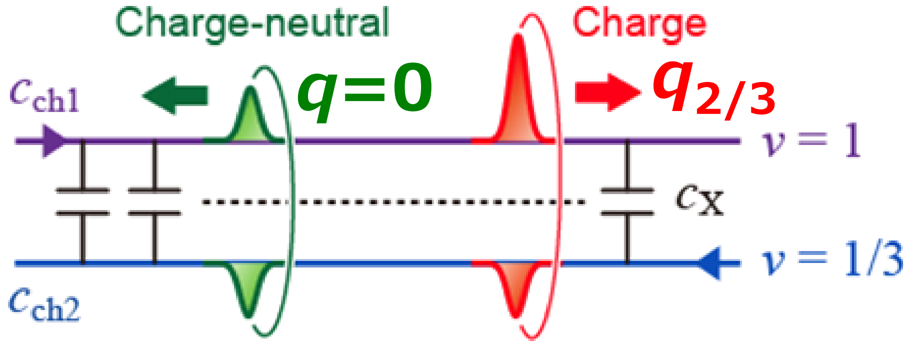
Right- and left-moving modes carrying finite charges.



Renormalization toward
the strong coupling limit

Coulomb + Tunnel couplings

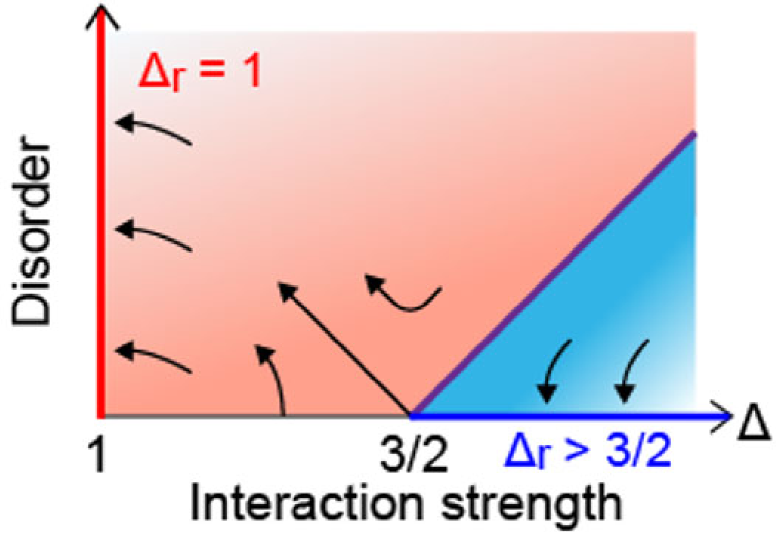
Downstream charge and
upstream charge-neutral modes

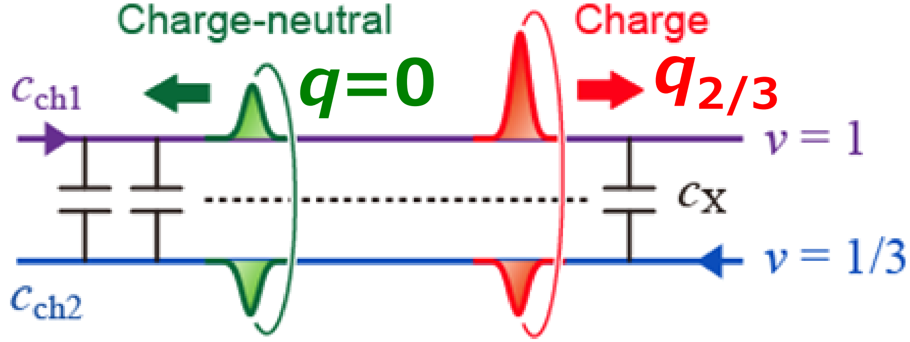


Kane, Fisher, Polchinski 1994.
Kane, Fisher 1995.
Protopopov, Gefen, Mirlin 2017.

Appendix: Renormalization

Disorder-dominated FQH edge phase

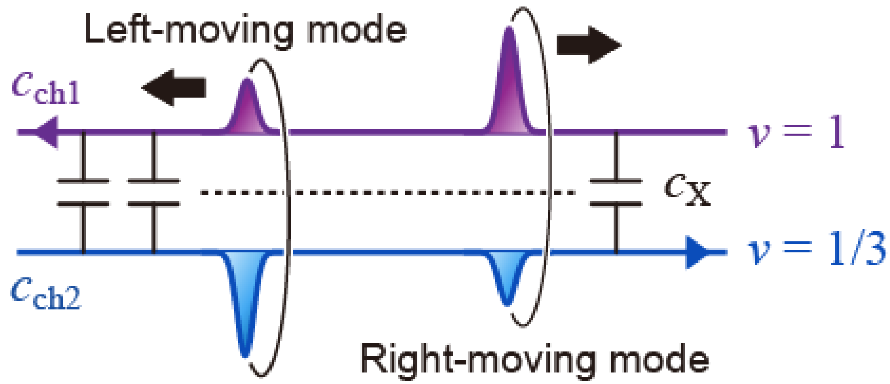




Charge and neutral modes.

Weak coupling phase (Δ > 3/2)

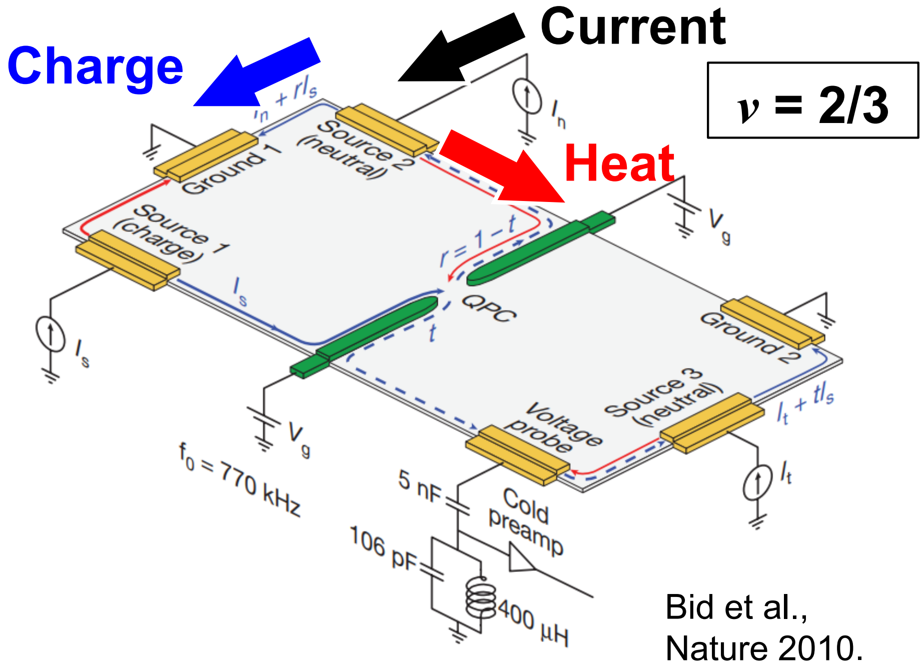
Right- and left-moving modes both carrying charges.



Kane, Fisher, Polchinski 1994.
Kane, Fisher 1995.
Protopopov, Gefen, Mirlin 2017.

Experimental evidence (?) of the strong coupling phase

✓ Electrical conductance: $2e^2/3h$
✓ Upstream heat transport
(Charge-neutral mode)



Bid et al., Nature 2010.

"Standard model" for fractional QH edge transport

- Downstream charge mode
- Upstream neutral mode

Banerjee *et al*., Nature **545**, 75 (2017).
Banerjee *et al*., Nature **559**, 205 (2018).
Nakamura *et al*., Nat. Phys. **15**, 563 (2019).
Dutta *et al*., Science **375**, 193 (2022).
Dutta *et al*., Science **377**, 1198 (2022). etc.

Bid *et al*., Nature **466**, 585 (2010).
Venkatachalam *et al*., Nat. Phys. **8**, 676 (2012).
Altimiras *et al*., PRL **109**, 026803 (2012).
Inoue *et al*., Nat. Commun. **5**, 4067 (2014).
Sabo *et al*., Nat. Phys. **13**, 491 (2017).
Kumar *et al*., Nat. Commun. **13**, 213 (2022).
Melcer *et al*., Nat. Commun. **13**, 376 (2022).
Breton *et al*., PRL **129**, 116803 (2022).
Srivastav *et al*., Nat. Commun. **13**, 5185 (2022).
Nakamura *et al*., PRL **130**, 076205 (2023). etc.

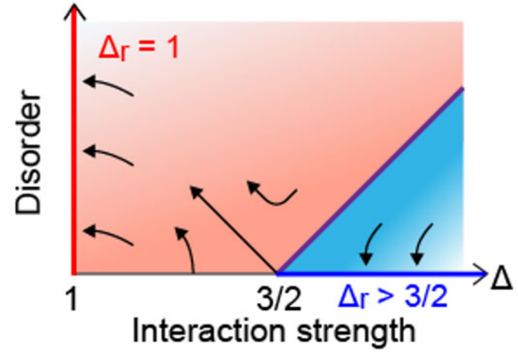
Appendix: Problems in experiments and theories

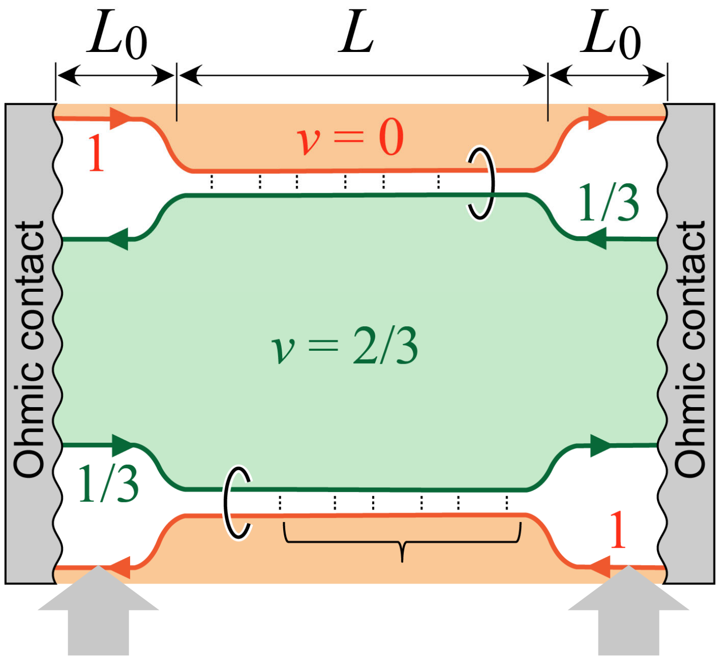
◆ Non-interacting "leads" near ohmic contacts

Protopopov, Gefen, Mirlin, Ann. Phys. **385**, 287 (2017).

"Strong" and "Weak" coupling phases have
very similar electrical & thermal transport properties
except for **the mesoscopic regime.**

$$l \ll \min(L_0, L_T) \ll L \ll L_{in}$$





Non-interacting "leads"

Interaction	Strong $\Delta_r \simeq 1$	Weak $\Delta_r > 3/2$
Eigenmode	DS charge and US neutral modes	DS and US charged modes
Coherent	$G_E^{(2)} = 4/3$ $G_T^{(2)} = 2$	$G_E^{(2)} = 4/3$ $G_T^{(2)} = 2$
Mesoscopic	$1/3 \leq G_E^{(2)} \leq 4/3$ (fluctuating) $G_T^{(2)} = 1$	$2/3 \leq G_E^{(2)} \leq 4/3$ (monotonic) $1.88 \leq G_T^{(2)} \leq 2$
Incoherent	$G_E^{(2)} = 2/3$ $G_T^{(2)} \propto 1/L$	$G_E^{(2)} = 2/3$ $G_T^{(2)} \propto 1/L$

short ↑ L ↓ long

Appendix: Coherence in a disordered system

Protopopov, Gefen, Mirlin, Ann. Phys. **385**, 287 (2017).

Previous experiments:

Long counter-propagating channels with **inelastic scatterings**.

Bid *et al.*, Nature 2010, etc.

This study: crossover between long and short channel regimes.

Short counter-propagating channels with **only elastic scatterings**.

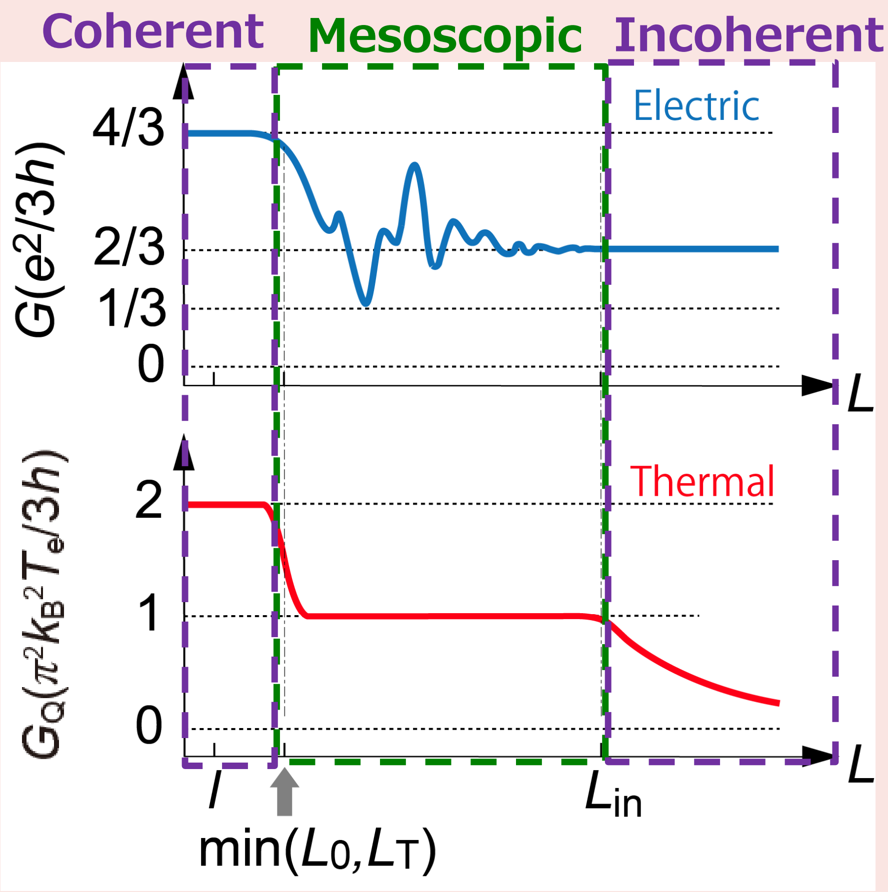
Mesoscopic regime

$L < L_{in}$

L: 1/3-1 channel length
L_{in}: Inelastic scattering length

Cocurrence of
- ✓ Electrical conductance fluctuations
- ✓ Quantized thermal conductance

c.f.
Cohen *et al.*, Nat. Commun. 2019.
Kumar *et al.*, Nat. Commun. 2022.
Melcer *et al.*, Nat. Commun. 2022.



Appendix: Half-quantized thermal conductance

- **Strong coupling phase**
  - ✓ Electrical conductance: $2e^2/3h$
  - ✓ **Upstream heat transport**

Bid *et al*., Nature 2010.
Inoue *et al*., Nat. Commun. 2014.
・・・

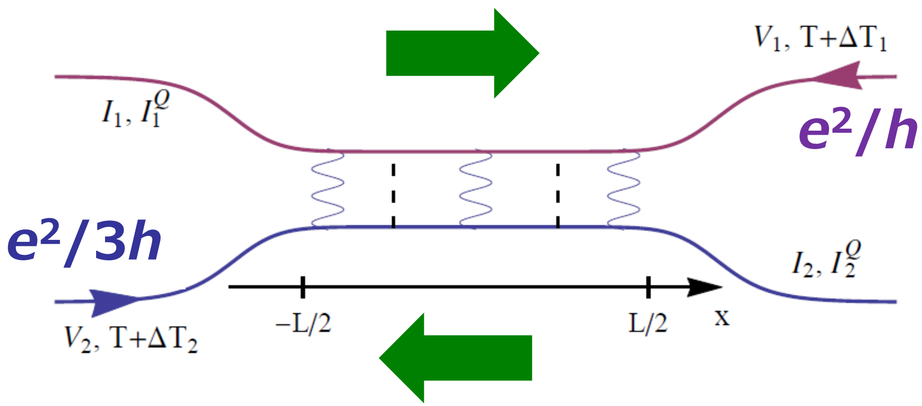
Experimental hallmark

$$G_Q = 0.5\frac{\pi^2 k_B^2 T}{3h}$$

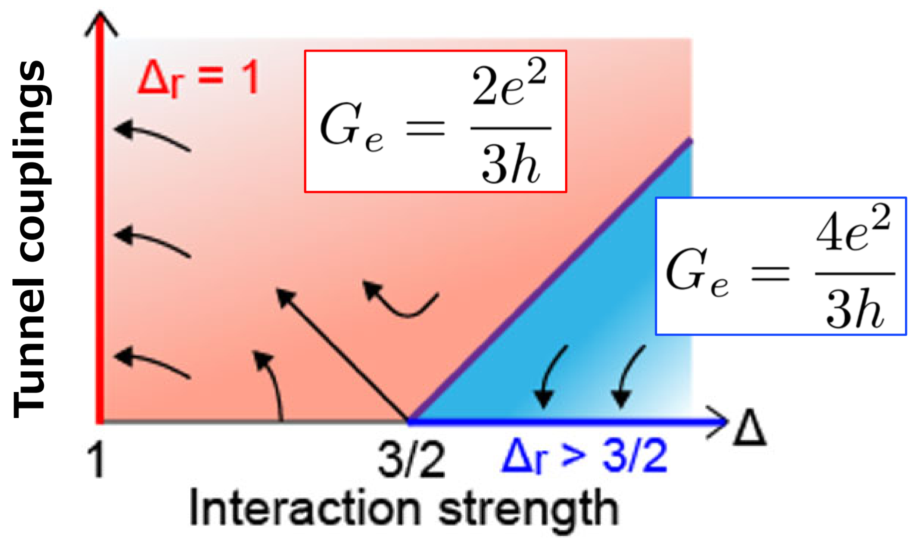
Half-quantized thermal conductance
in the dissipationless transport regime.

Protopopov, Gefen, Mirlin 2017.

Upstream heat transport

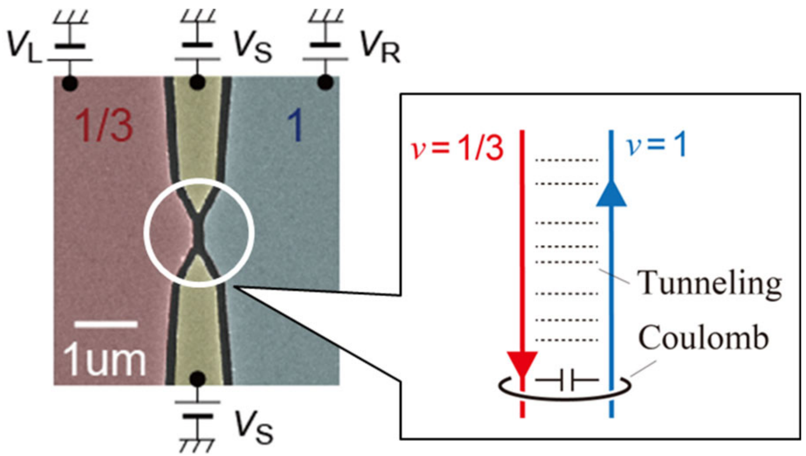


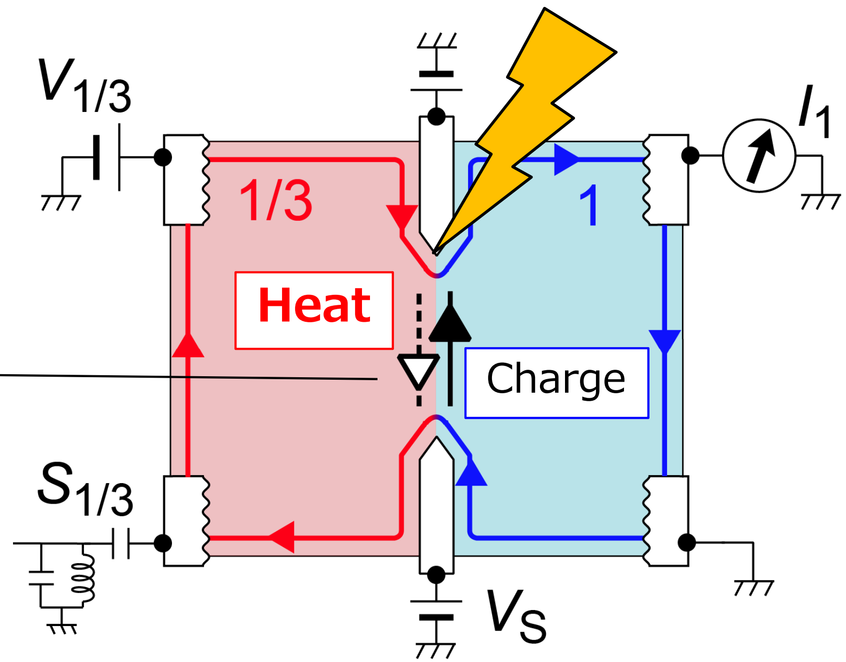
Electrical transport $2e^2/3h$
(1 − 1/3)



Appendix: Thermal conductance measurement

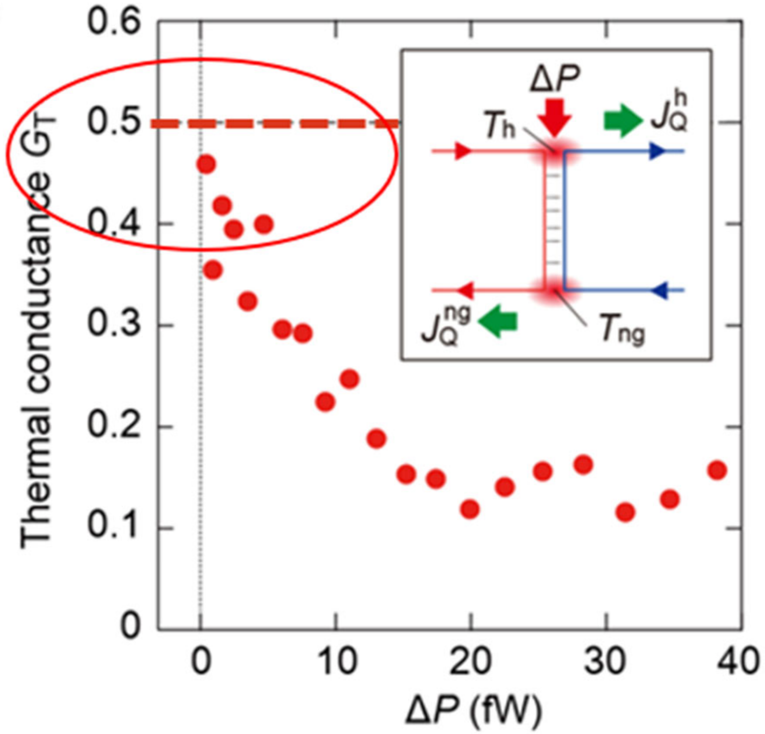
2DES in a GaAs quantum well





Thermal Noise

(Thermal conductance from top to bottom)



Half-quantized thermal conductance $G_Q/2$:

Evidence of the strong coupling phase

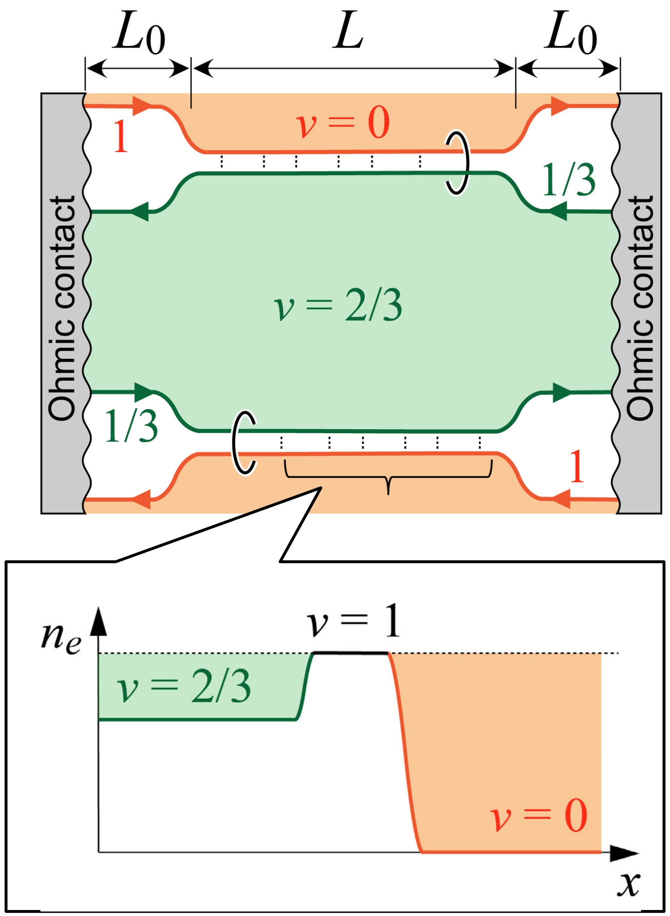
Appendix: Particle-hole symmetry

Coulomb interaction + Tunneling

M. Hashisaka et al., PRX **13**, 031024 (2023).

Generalized quantum Hall (QH) edge system

Conventional ν = 2/3 device

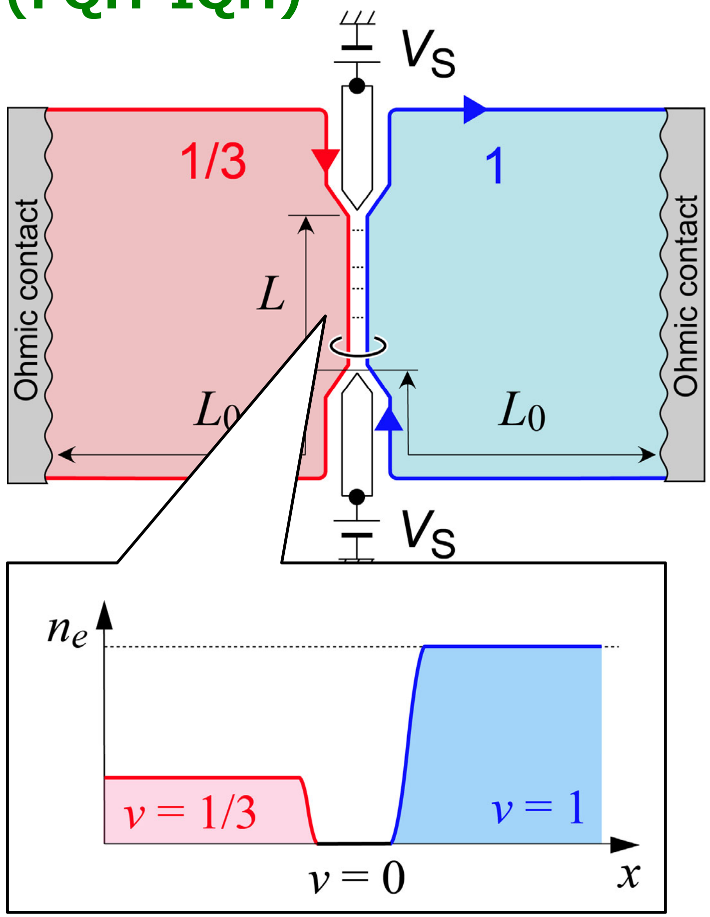


$\nu(x) \leftrightarrow 1 - \nu(x)$

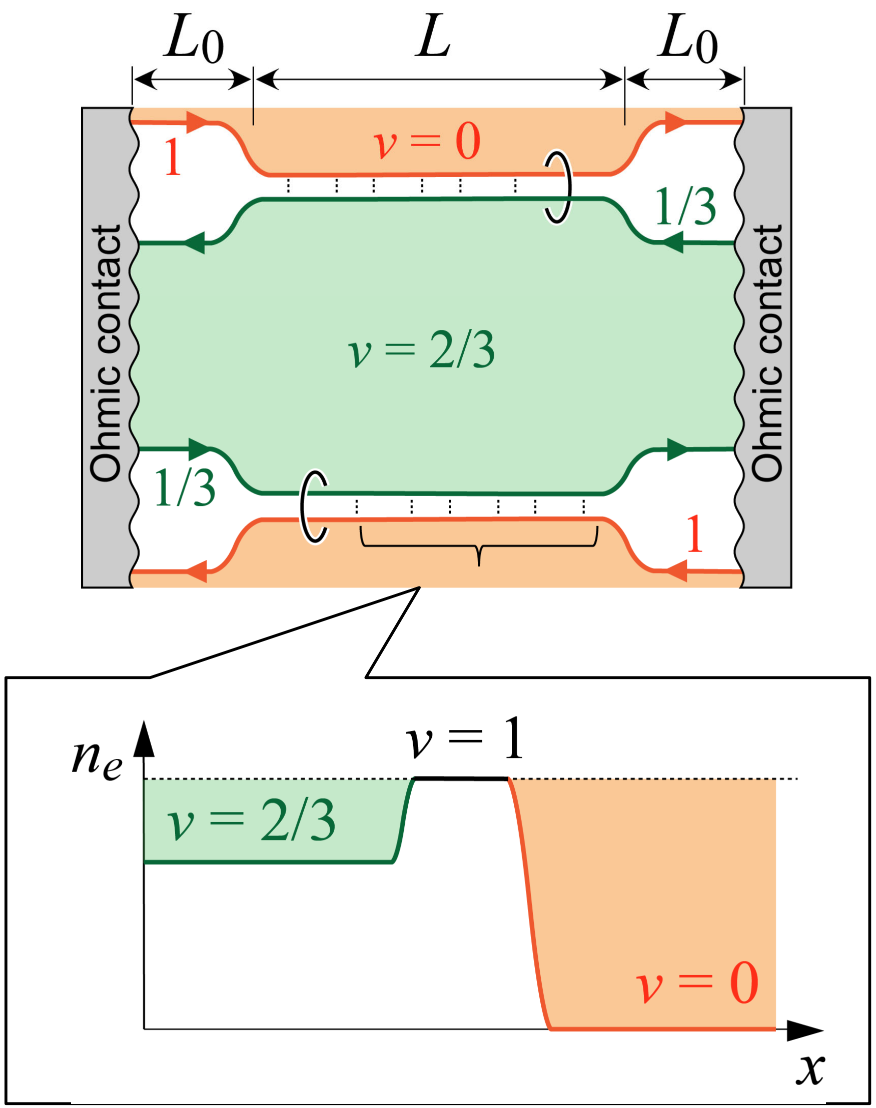
Particle-hole symmetry

Spontaneously appeared 1/3-1 channels

Fractional-Integer QH junction (FQH-IQH)



◆ Counter-propagating ν = 1/3 and ν = 1 edge channels



Bulk

Spin-polarized ν = 2/3 state:

ν_h = 1/3 fractional quantum Hall state

(ν = 2/3 = 1 – 1/3)

Bulk-Edge correspondence

Edge

Counter-propagating 1/3 and 1 channels

(MacDonald's model: 1-1/3 channels)

MacDonald, PRL **64**, 220 (1990).
Johnson, MacDonald, PRL **67**, 2060 (1991).
Meir, PRL **72**, 2624 (1994).
Chamon, Wen, PRB **49**, 8227 (1994).
…

Summary of the Appendix part

Experiment:

Coherent-Incoherent Crossover of Charge and Neutral Mode Transport as Evidence for the Disorder-Dominated Fractional Edge Phase

M. Hashisaka, T. Ito, T. Akiho, S. Sasaki, K. Kumada, N. Shibata, K. Muraki
Physical Review X **13**, 031024 (2023).

Theory:

Transport in a disordered *ν* = 2/3 fractional quantum Hall junction

I. V. Protopopov, Y. Gefen, A. D. Mirlin
Annals of Physics **385**, 287 (2017).

Key background theory:

Neutral modes in fractional QH systems.

Kane, Fisher, Polchinski, PRL **72**, 4129 (1994).
Kane, Fisher, PRB **51**, 13449 (1995).