Mesoscopic transport with ultracold atomic gases

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科研費 KAKENHI

卓越研究員事業
Leading Initiative for Excellent Young Researchers (LEADER)

Matsuo Foundation
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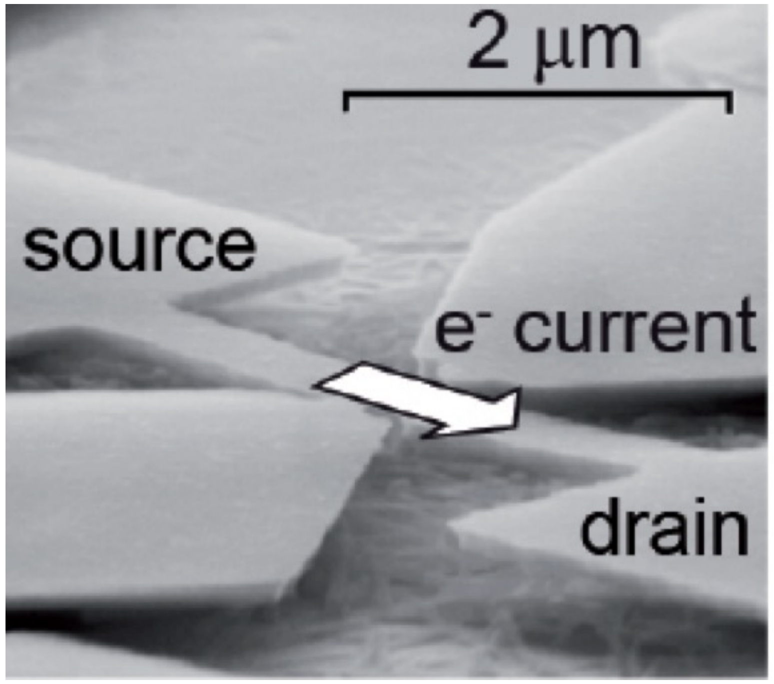
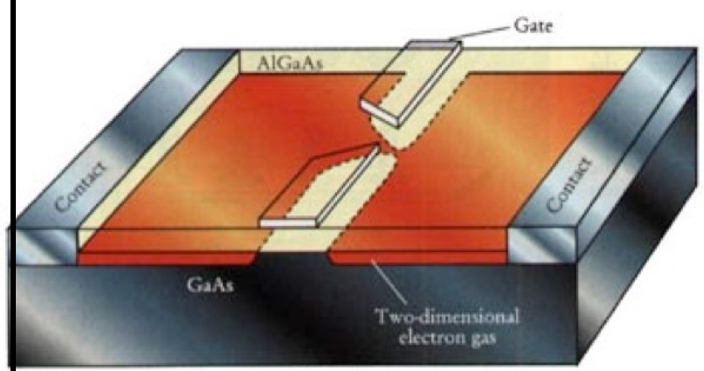
Mesoscopic systems in condensed matter

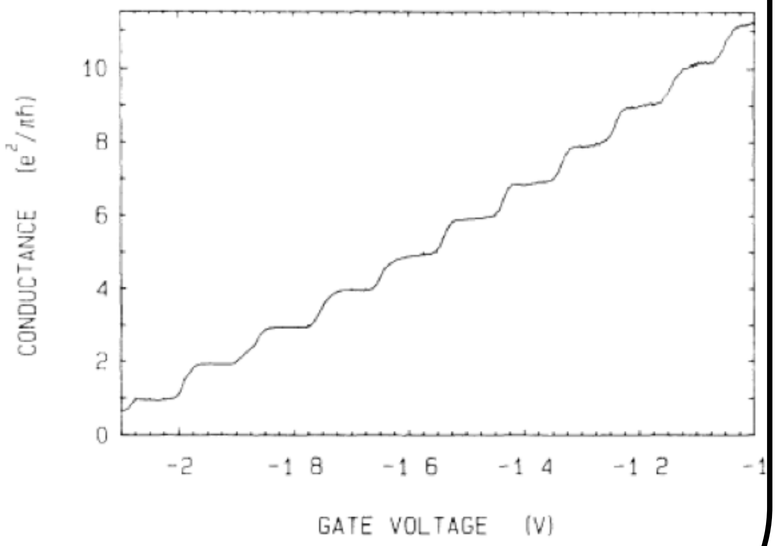
- Small sample (conduction channel) attached to macroscopic reservoirs
- Electric current induced by external bias voltage



C. Rossler et al., APL **93**, 071107 (2008)

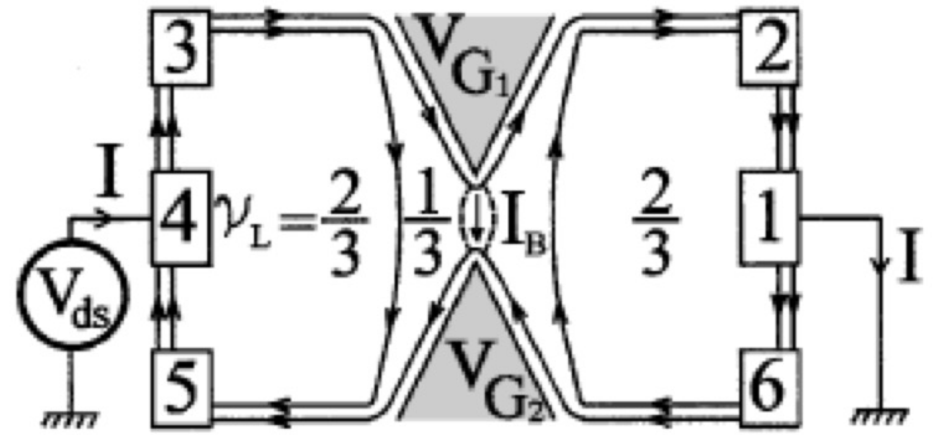
Conductance quantization in quantum point contact





B. J. van Wees et al., PRL **60**, 848 (1988).

Fractional charge measurement in FQHE

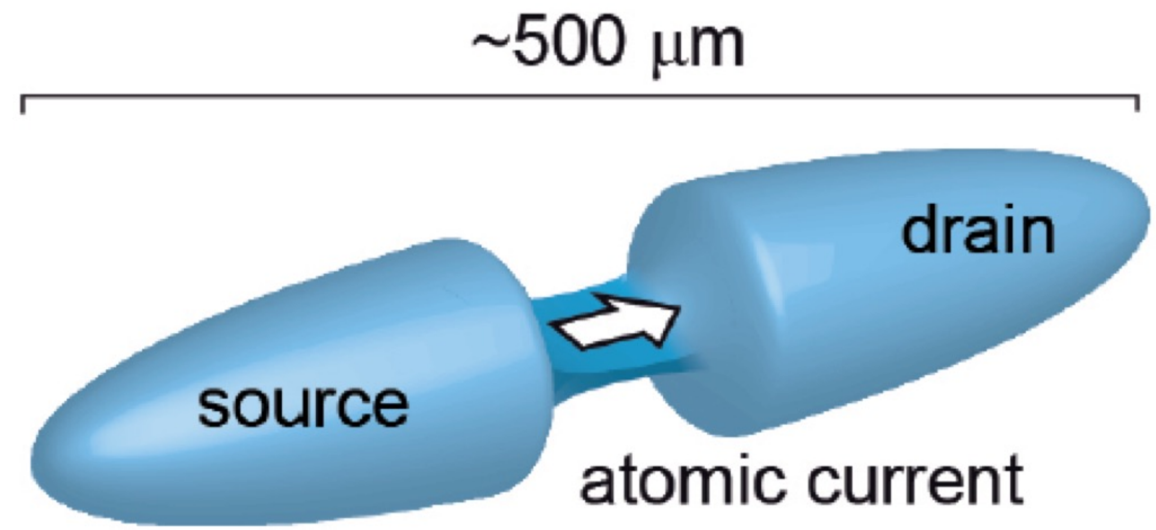


R. de-Picciotto et al., Nature **389**, 162 (1997); L. Saminadyar et al., PRL **79**, 2526 (1997).

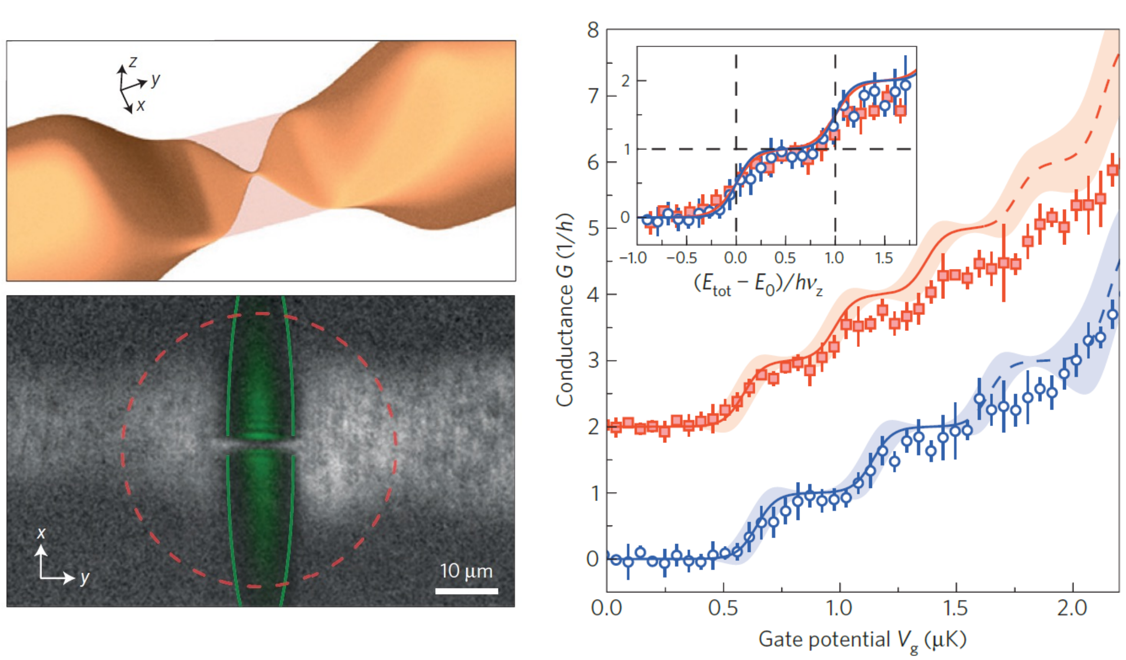
Mesoscopic system w/ cold atoms

Two-terminal setup realized by Esslinger's group at ETH

- Atomic current (charge neutral)
- Current induced by biases on thermodynamic quantities (chemical potential, temperature)

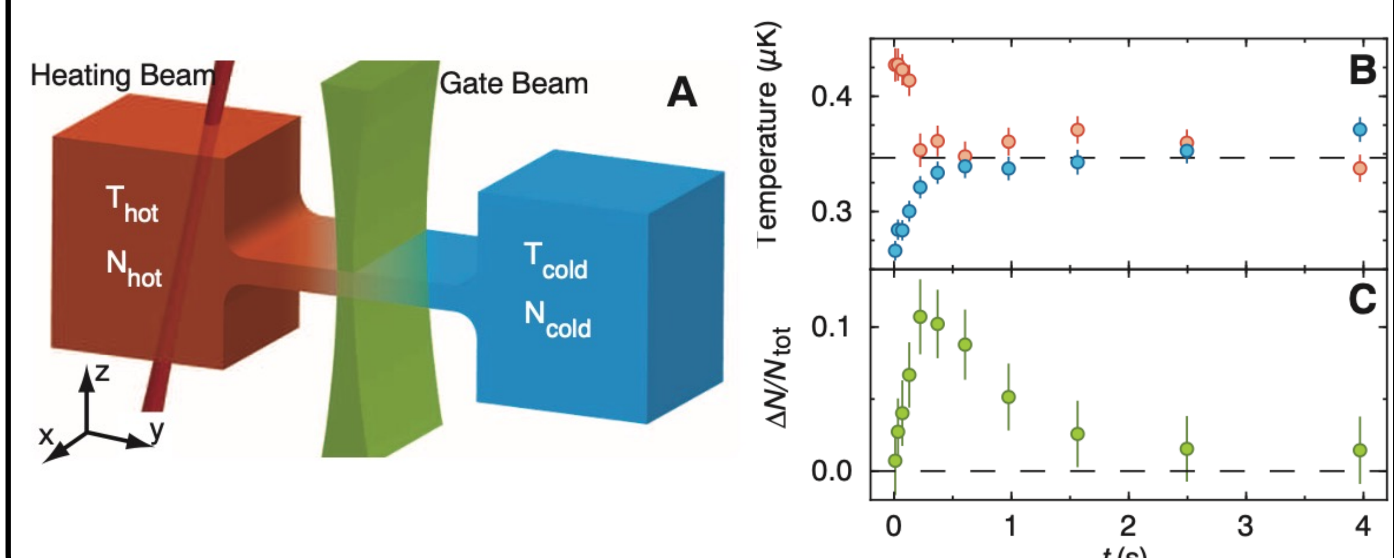


Conductance quantization in quantum point contact



S. Kriner et al., Nature **517,** 6467 (2015).

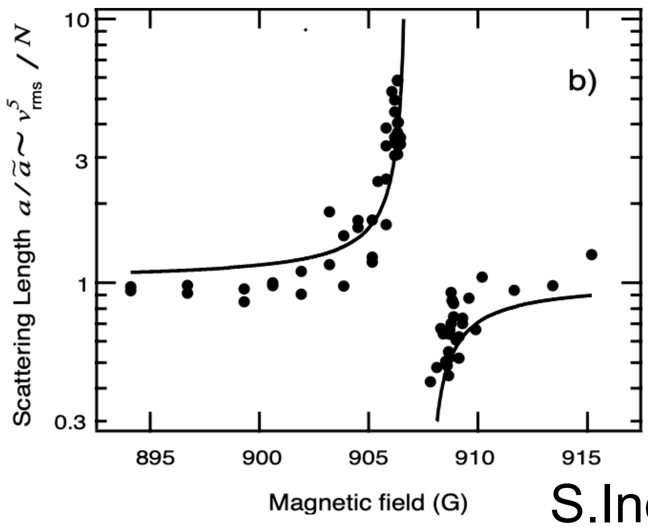
Heat transport



J.-P. Brantut et al., Science **342**, 713 (2013).

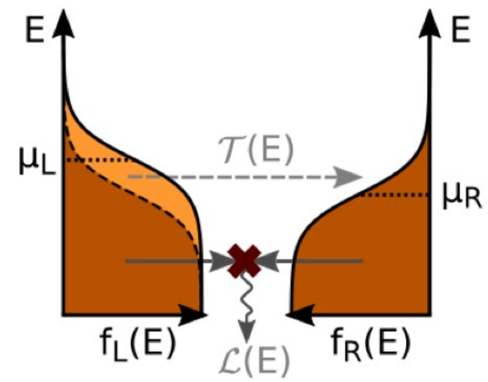
Why cold atoms?

- Control of interaction



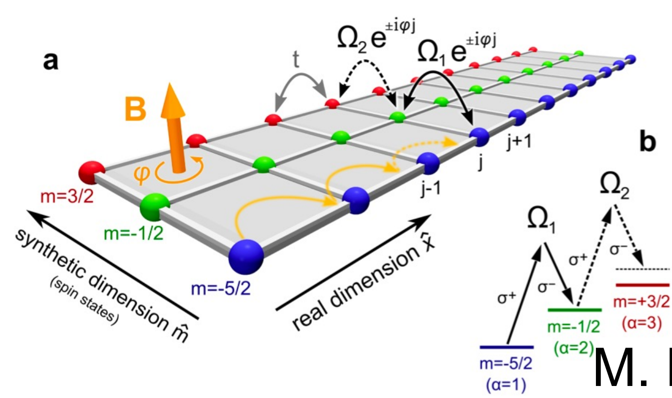
S.Inouye et al., Nature **392**, 151 (1998).

- control of dissipation



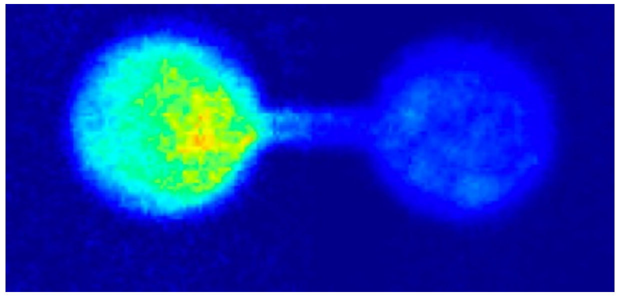
L. Corman et al., PRA **103**, 059902 (2021).

- Synthetic dimensions



M. Mancini et al., Science **349**, 1510 (2015).

- Control of quantum statistics

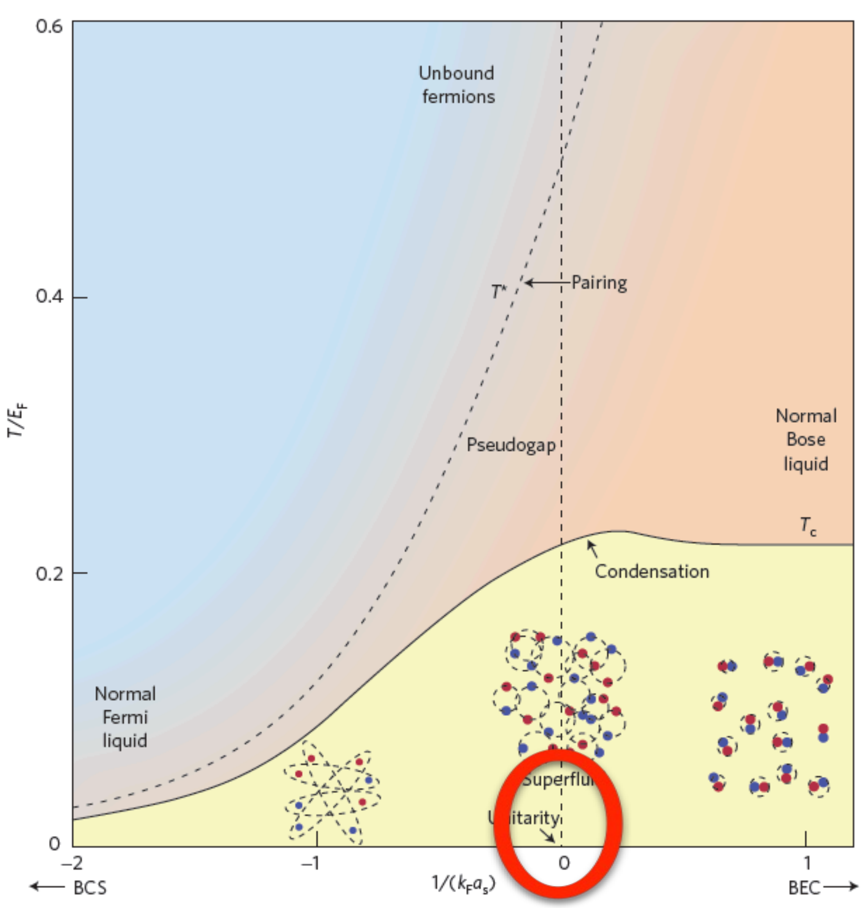


S. Eckel et al., PRA **93**, 063619 (2016).

Transport in strongly-interacting Fermi gases

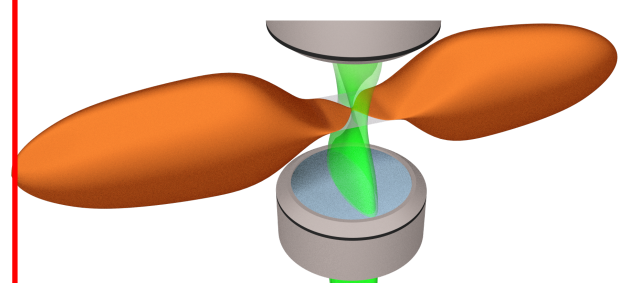
$$\mathcal{H} = \int d^3r \Big[\sum_{\sigma=\uparrow,\downarrow} \psi_\sigma^\dagger \Big\{ -\frac{\hbar^2\nabla^2}{2m} + V(\mathbf{r}) \Big\} \psi_\sigma - g\psi_\uparrow^\dagger \psi_\downarrow^\dagger \psi_\downarrow \psi_\uparrow \Big]$$

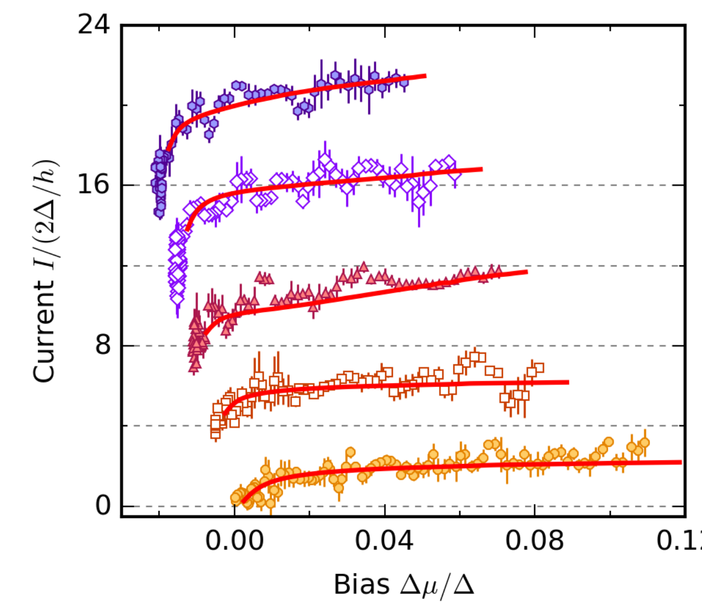
Phase diagram



M. Randeria, E. Taylor, Annual Review of Condensed matter physics **5,** 209 (2014).

Point contact transport in unitary Fermi gas





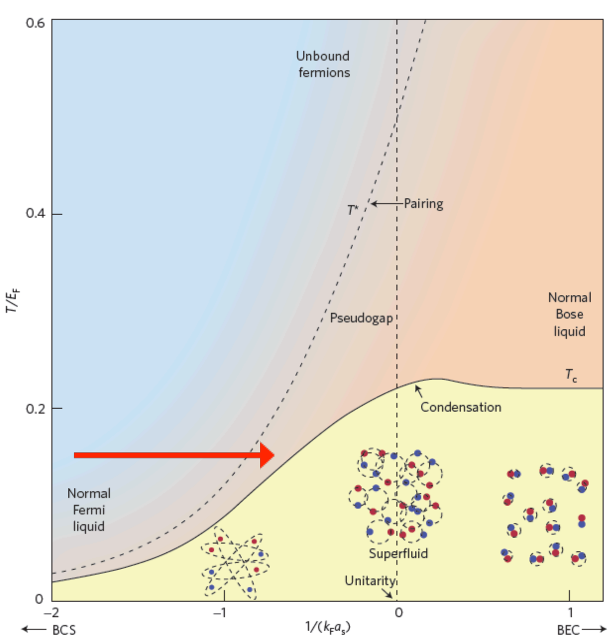
D. Husmann et al., Science **350**, 1498 (2015).

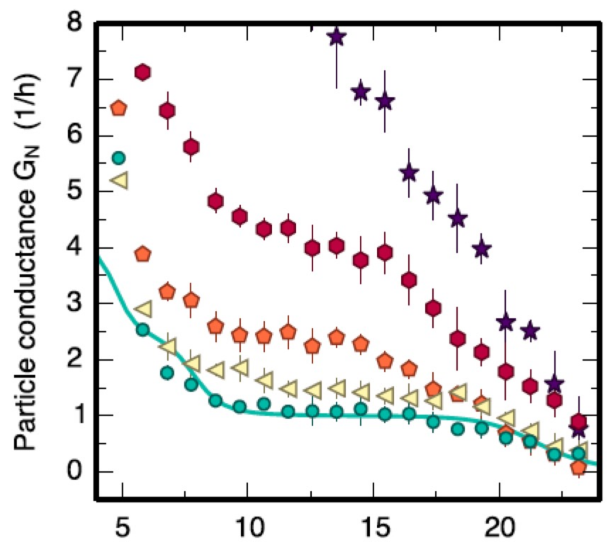
Nonlinear current-bias characteristics stemming from multiple Andreev reflections

Transport in strongly-interacting Fermi gases

$$\mathcal{H} = \int d^3r \Big[\sum_{\sigma=\uparrow,\downarrow} \psi_\sigma^\dagger \Big\{ -\frac{\hbar^2\nabla^2}{2m} + V(\mathbf{r}) \Big\} \psi_\sigma - g\psi_\uparrow^\dagger \psi_\downarrow^\dagger \psi_\downarrow \psi_\uparrow \Big]$$

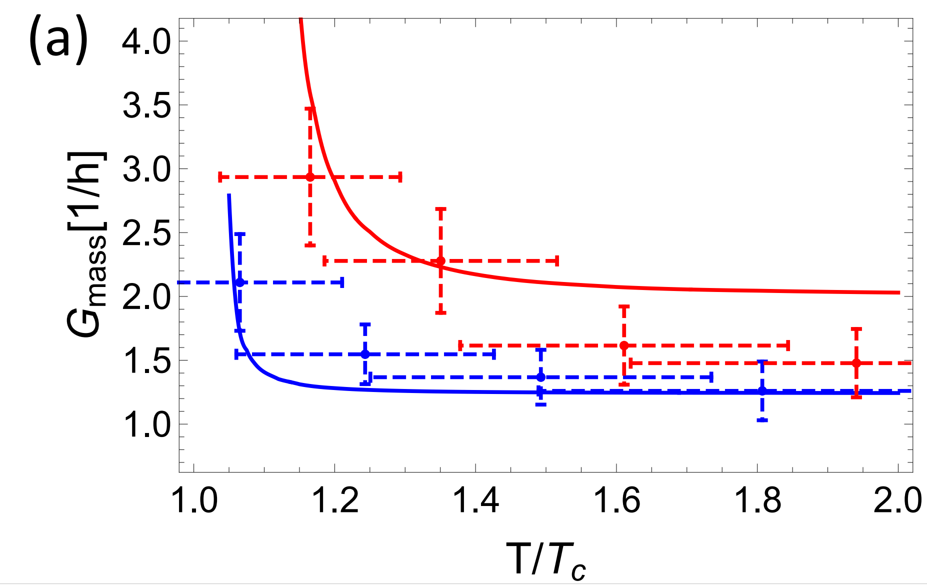
Breakdown of conductance quantization

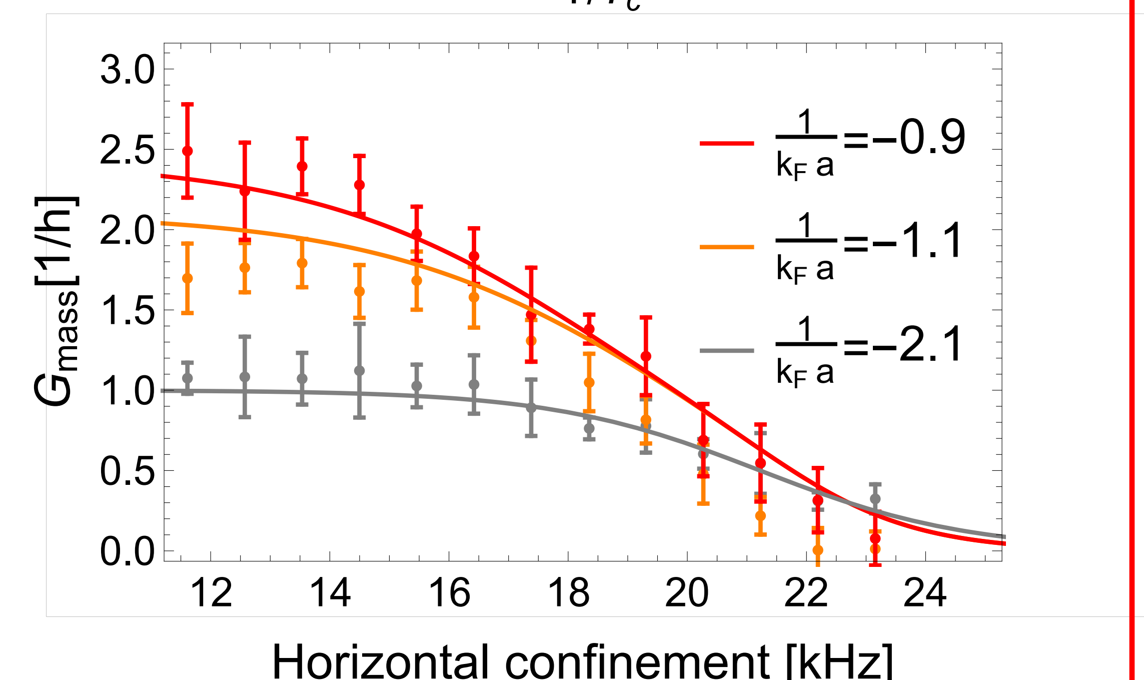




S. Krinner et al., PNAS **13**, 8144 (2016).

Theory with preformed pairs

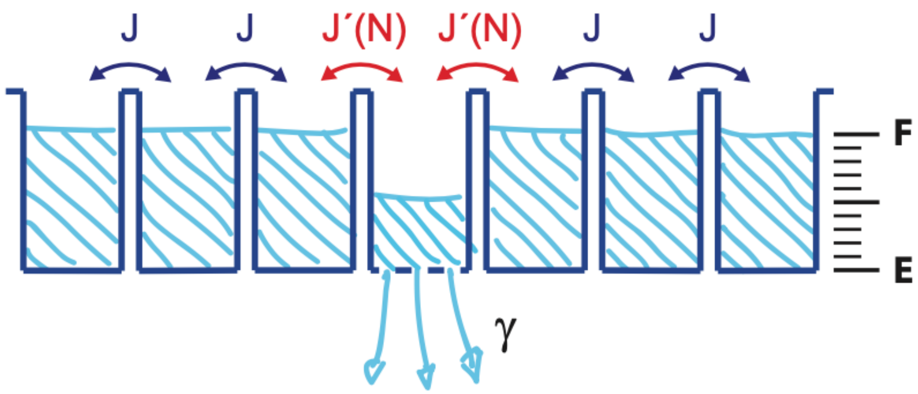




SU and M. Ueda, PRL **118**, 105303 (2017).

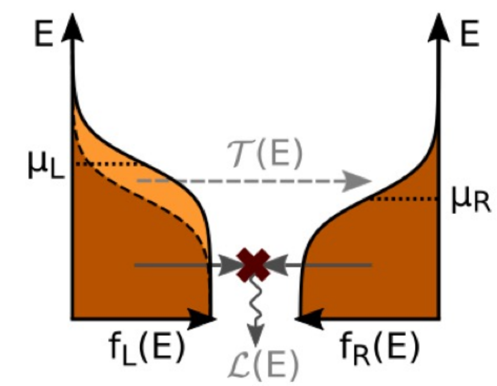
Mesoscopic system + dissipation (atom loss)

Jesephson junction array of Bose-Einstein condensates

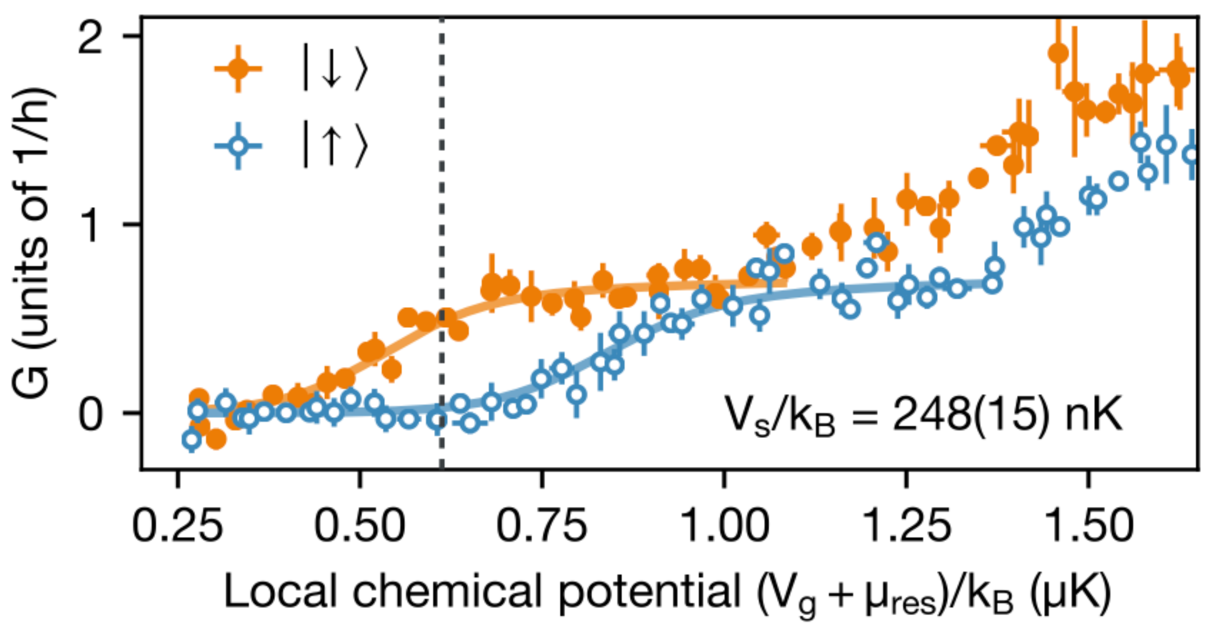


R. Labouvie et al., PRL**116**, 235302 (2016).

Point contact transport in noninteracting Fermi gases



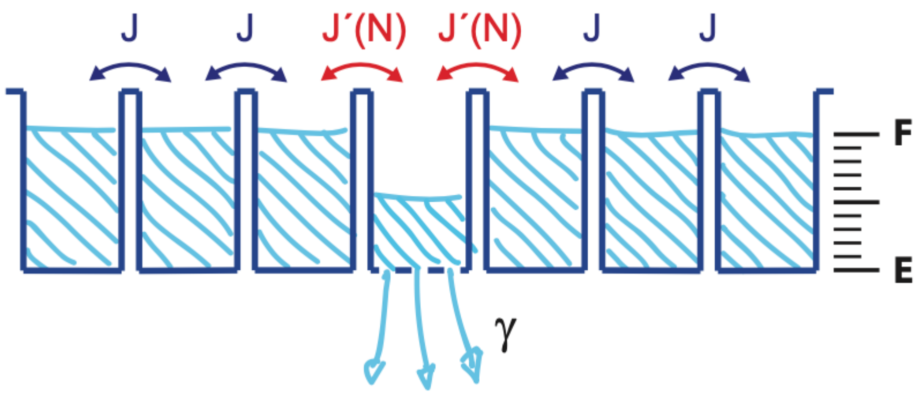
L. Corman et al., PRA **103**, 059902 (2021).



Experimental results were interpreted with a phenomenological non-Hermitian Landauer-Büttiker analysis

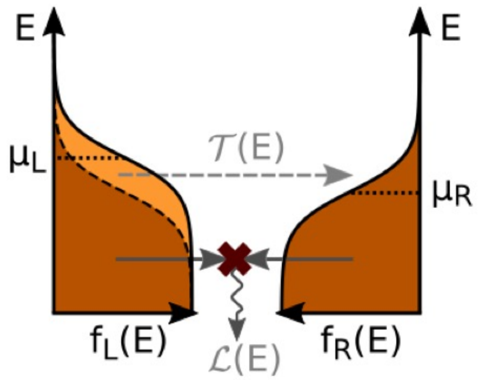
Mesoscopic system + dissipation (atom loss)

Jesephson junction array of Bose-Einstein condensates



R. Labouvie et al., PRL**116**, 235302 (2016).

Point contact transport in noninteracting Fermi gases



L. Corman et al., PRA **103**, 059902 (2021).

Current formula of lossy point contact

SU, arXiv:2206.09088 (PRA in press)

$$I = \int \frac{d\omega}{2\pi}\left[\mathcal{T}(\omega) + \frac{\mathcal{L}(\omega)}{2}\right][n_L(\omega) - n_R(\omega)]$$

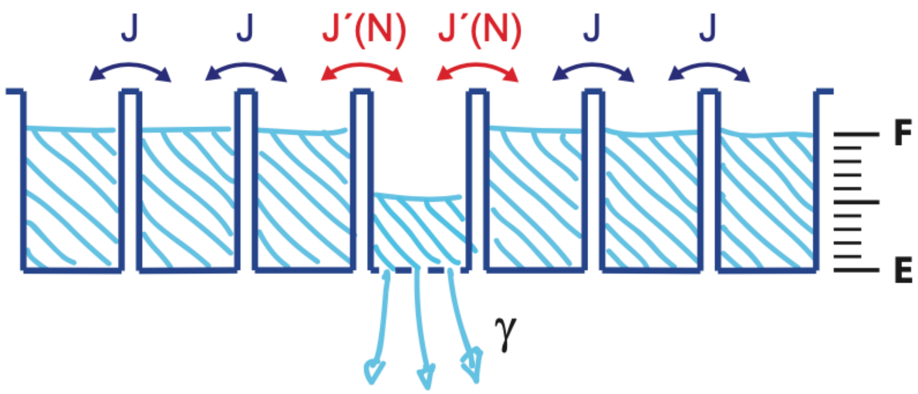
$\mathcal{T}(\omega)$: transmittance

$\mathcal{L}(\omega)$: loss probability

- Obtained with an analysis based on Keldysh+ Lindblad formalism or three-terminal Landauer-Büttiker analysis
- Consistent with the non-Hermitian Landauer-Büttiker analysis

Strongly-interacting Fermi gas + dissipation

Jesephson junction array of Bose-Einstein condensates



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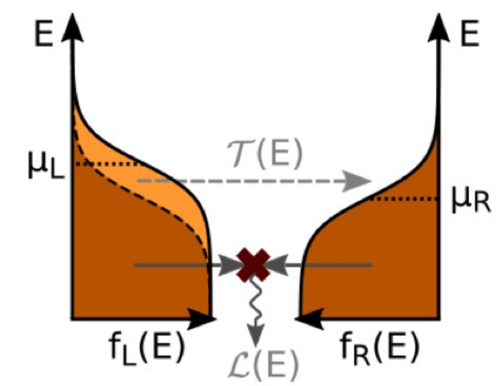
Point contact transport in noninteracting Fermi gases

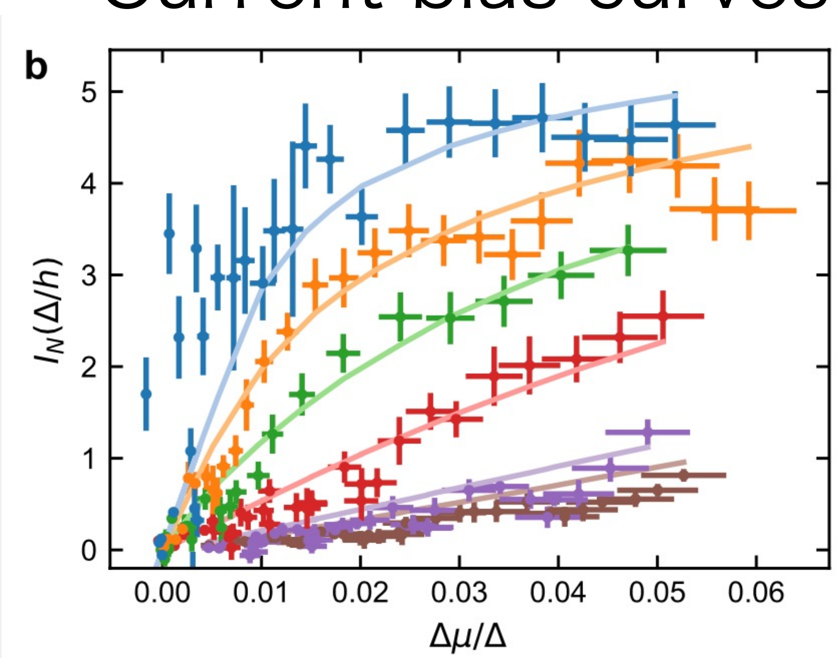


L. Corman et al., PRA **103**, 059902 (2021).

Point contact transport in strongly-interacting Fermi superfluids

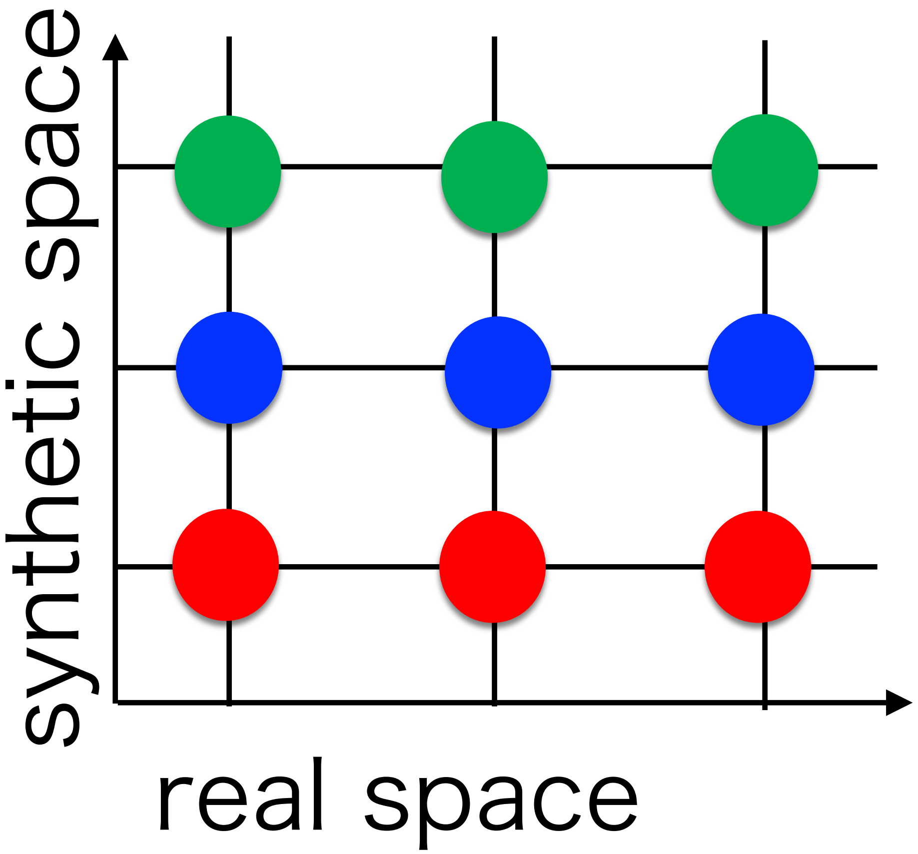
M.-Z. Huang et al., arXiv:2210.03371

Current-bias curves

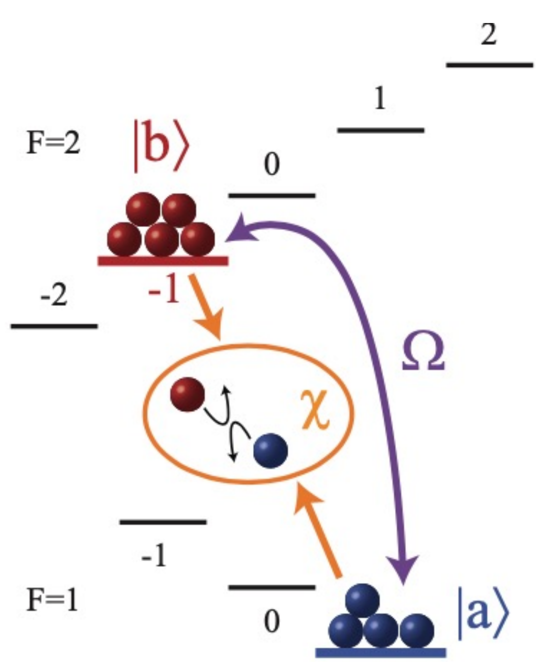


Agreement with a theory based on Lindblad + Keldysh formalism

Synthetic dimensions

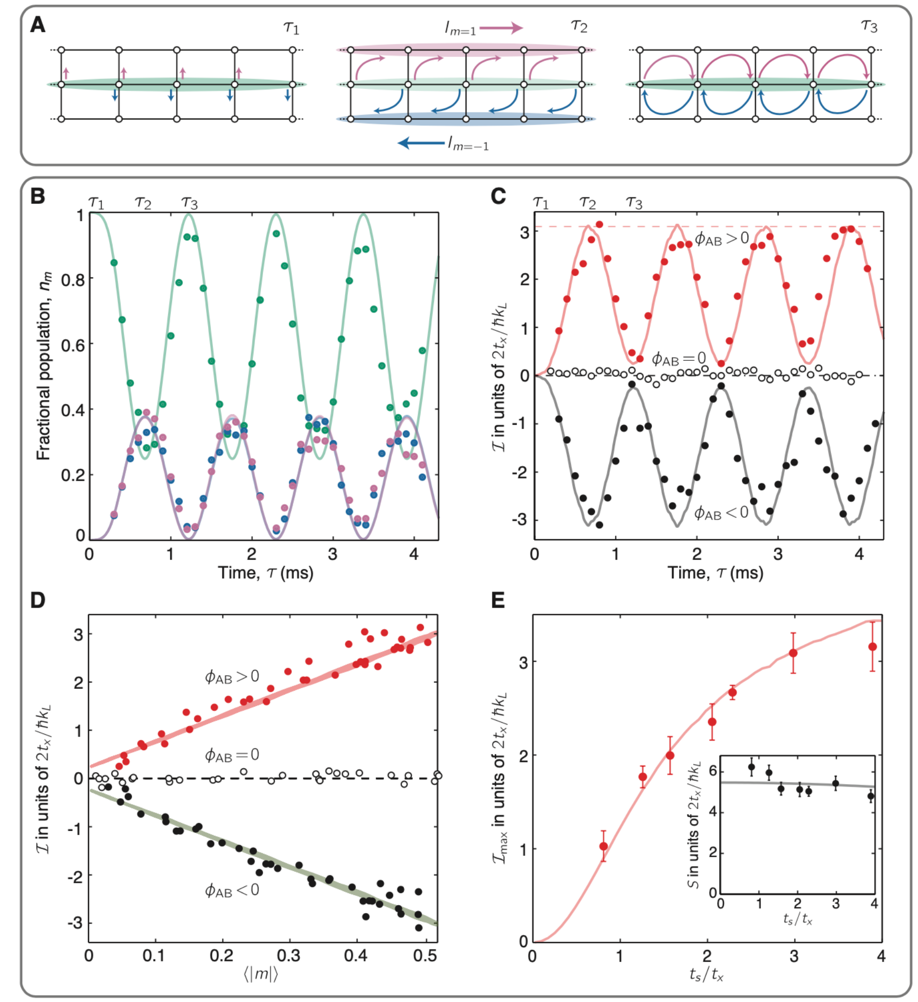


Internal Josephson effect



T. Zibold et al., PRL **105**, 204101 (2010).

Edge current



M. Mancini et al., Science **349**, 1510 (2015);
B. K. Stuhl et al., Science **349,** 1514 (2015).

Mesoscopic transport via magnetic impurity

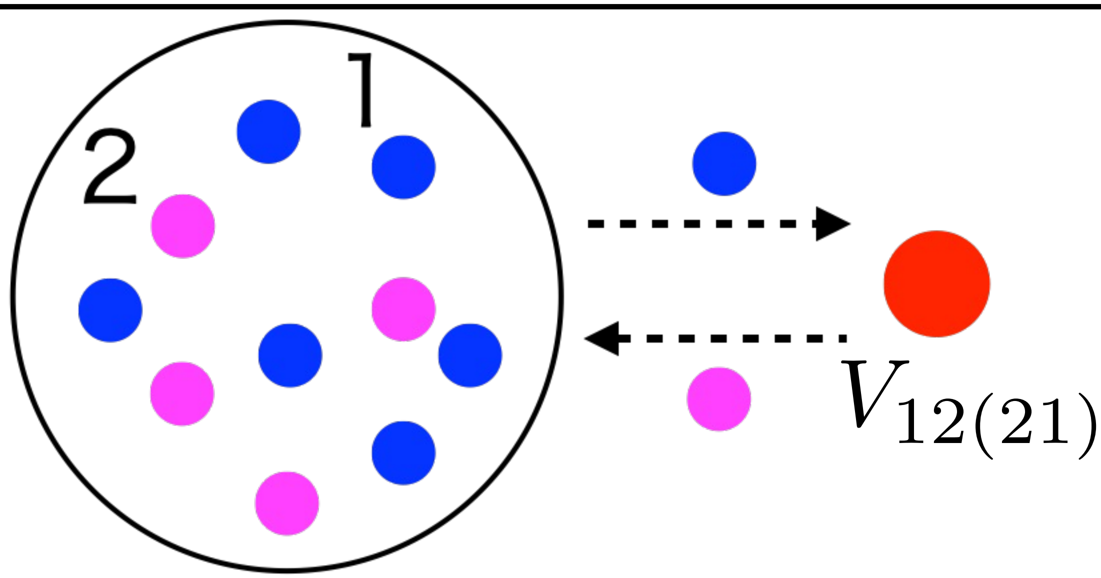
M. Knap et al., PRX 2, 041020 (2012);
J. You et al., PRB 99, 214505 (2019);
S. Nakada et al., PRA 102, 031302(R) (2020).

$$\mathcal{H} = \int d^3r \Big[\sum_{\sigma=\uparrow,\downarrow} \psi_\sigma^\dagger \Big\{ -\frac{\hbar^2\nabla^2}{2m} + V(\mathbf{r}) \Big\} \psi_\sigma - g\psi_\uparrow^\dagger \psi_\downarrow^\dagger \psi_\downarrow \psi_\uparrow \Big] + \sum_\sigma V_\sigma \psi_\sigma^\dagger \psi_\sigma(\mathbf{0})$$

spin rotation $|\sigma\rangle \to |\alpha\rangle = \sum_\sigma |\sigma\rangle U_{\sigma\alpha}^\dagger$

$$\mathcal{H} = \int d^3r \Big[\sum_{\alpha=1,2} \psi_\alpha^\dagger \Big\{ -\frac{\hbar^2\nabla^2}{2m} + V(\mathbf{r}) \Big\} \psi_\alpha - g\psi_1^\dagger \psi_2^\dagger \psi_2 \psi_1 \Big] + \sum_{\alpha,\beta=1,2} \psi^\dagger V_{\alpha\beta} \psi_\beta(\mathbf{0})$$

$$V_{12(21)} \neq 0 \quad \text{if } V_\uparrow \neq V_\downarrow$$



Landauer-Büttiker formula

$$I = \int \frac{d\epsilon}{h} \mathcal{T}(\epsilon)[f_1(\epsilon) - f_2(\epsilon)]$$

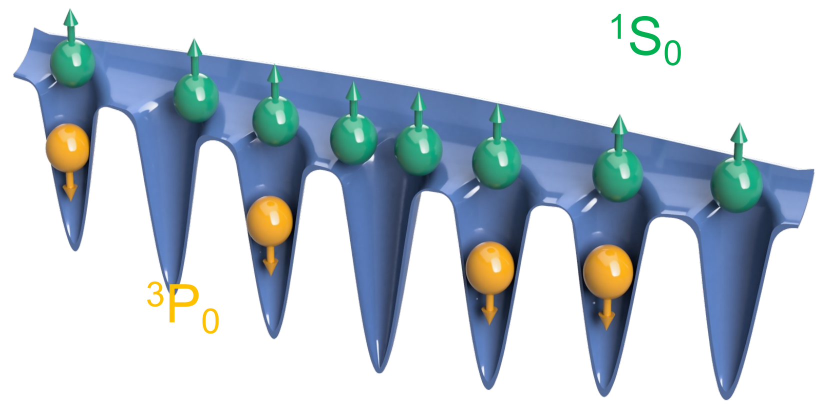
Realization with Yb atoms

K. Ono et al., Nat. Commun. **12,** 6724 (2021).

- Two-orbital lattice system with ^{173}Yb

$^1S_0$ atoms: itinerant fermions

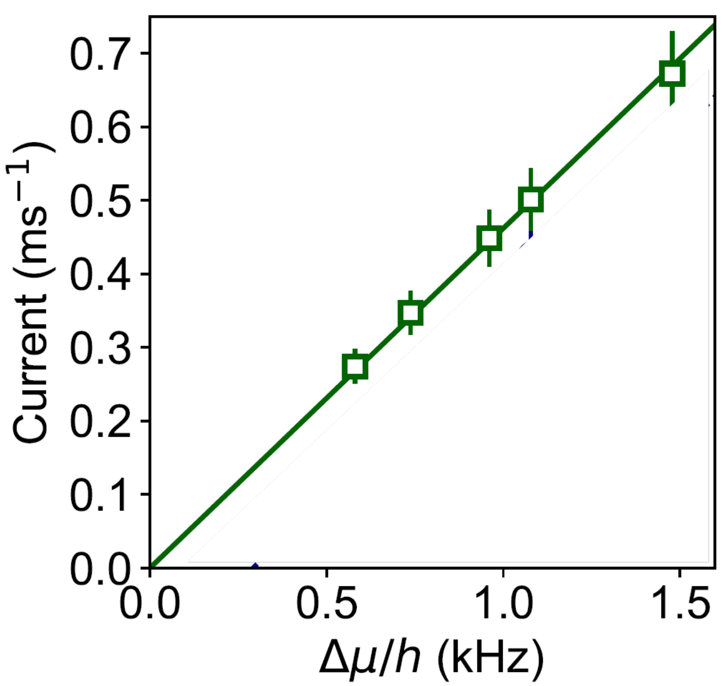
$^3P_0$ atom: localized impurity



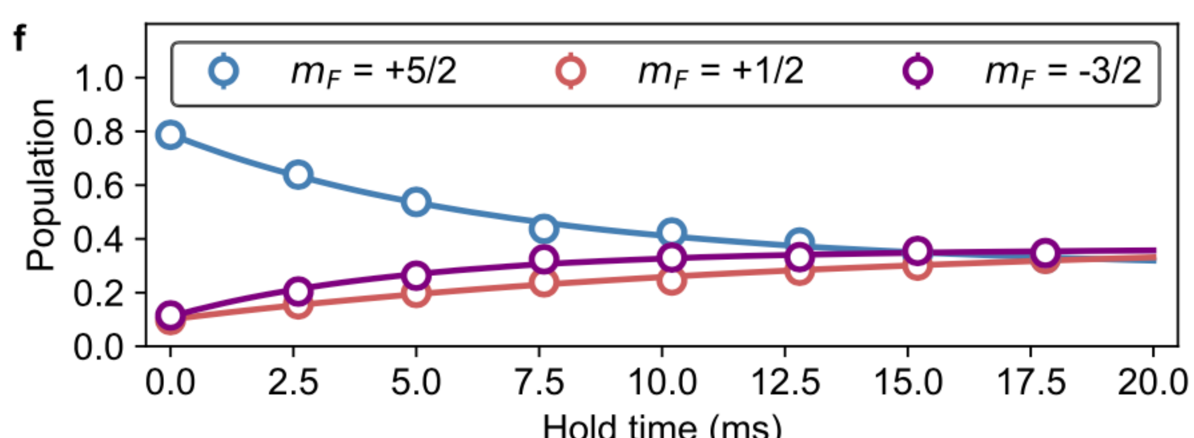
Spin-dependent potential can be tuned with the orbital Feshbach resonance

G. Pagano et al., PRL **115**, 265301 (2015);
M. Hofer et al., PRL **115**, 265302 (2015).

Ohmic current

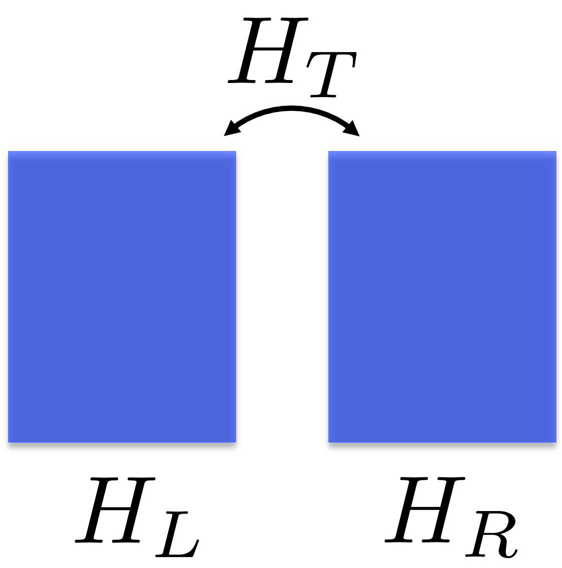


Three-terminal transport



Mesoscopic transport of Bose superfluid

- Tunneling Hamiltonian formalism



$$H = H_L + H_R + H_T$$

$$I = -\dot{N}_L = i[N_L, H_T]$$

$$H_T = \sum_{\mathbf{k},\mathbf{p}} \left(e^{-i\Delta\mu\tau} t_{\mathbf{k},\mathbf{p}} b^\dagger_{\mathbf{k},L} b_{\mathbf{p},R} + h.c. \right)$$

absence of the momentum conservation

There must be the conversion process
between condensation and normal elements.

Linear response theory: F. Meier & W. Zwerger PRA **64** 033610 (2001).
Beyond linear response effect: SU & J.P. Brantut, PRR **2**, 023284 (2020);
SU, PRR **2**, 023340 (2020).

Experiment: G. Del Pace et al., PRL **126**, 055301 (2021).

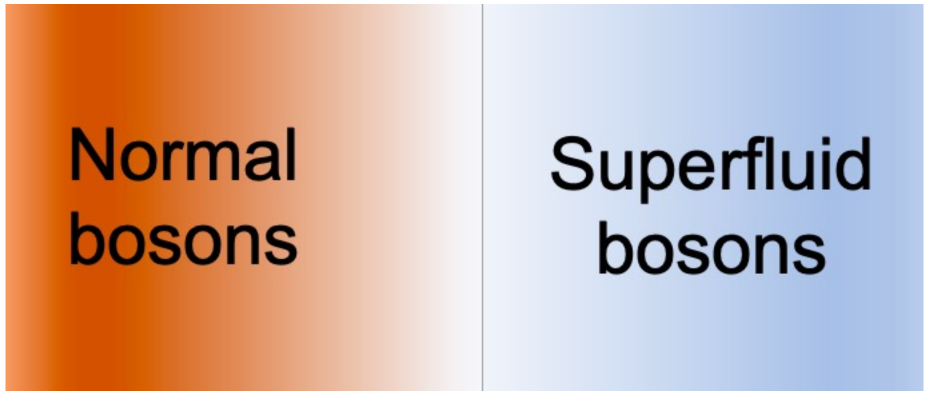
Superfluid-normal state junction

PHYSICAL REVIEW A **106**, L011303 (2022)

Letter | Editors' Suggestion

Asymmetry and nonlinearity of current-bias characteristics in superfluid–normal-state junctions of weakly interacting Bose gases

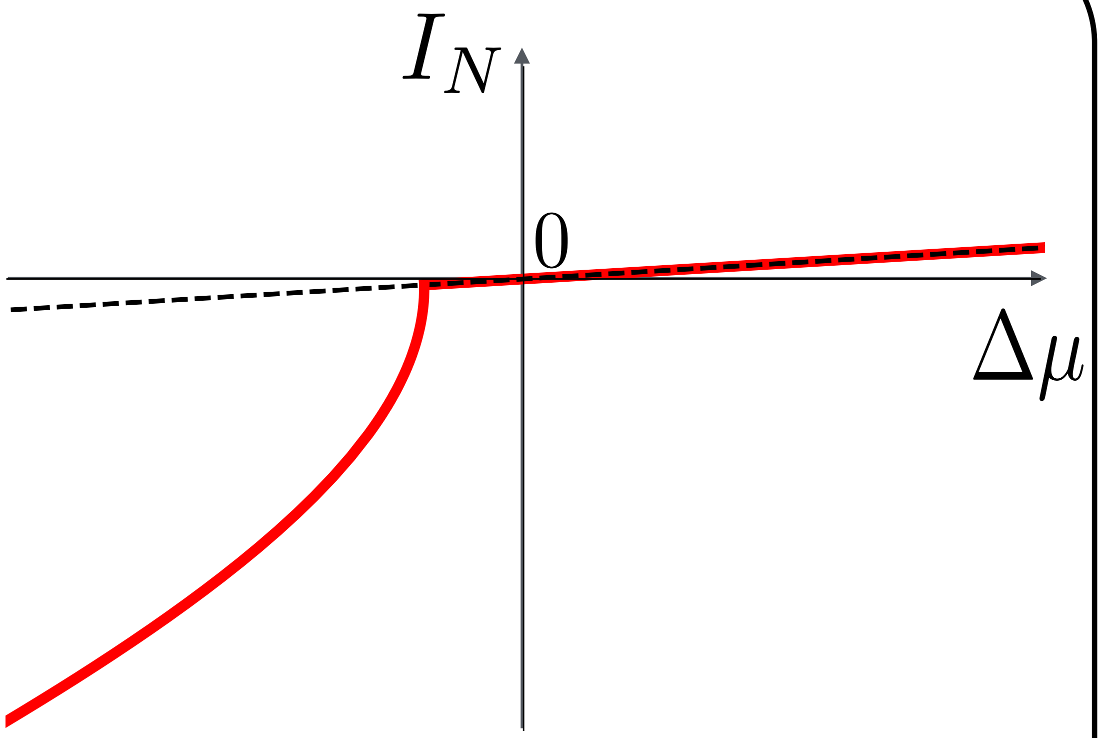
Shun Uchino



Normal bosons: Hartree-Fock theory

Superfluid bosons: Bogoliubov theory

Current-bias curve



- Asymmetry arises from the conversion process between condensation and normal elements, and the bosonic Andreev reflection.
- Quasiparticle current shows a symmetric response and is suppressed with decreasing T.

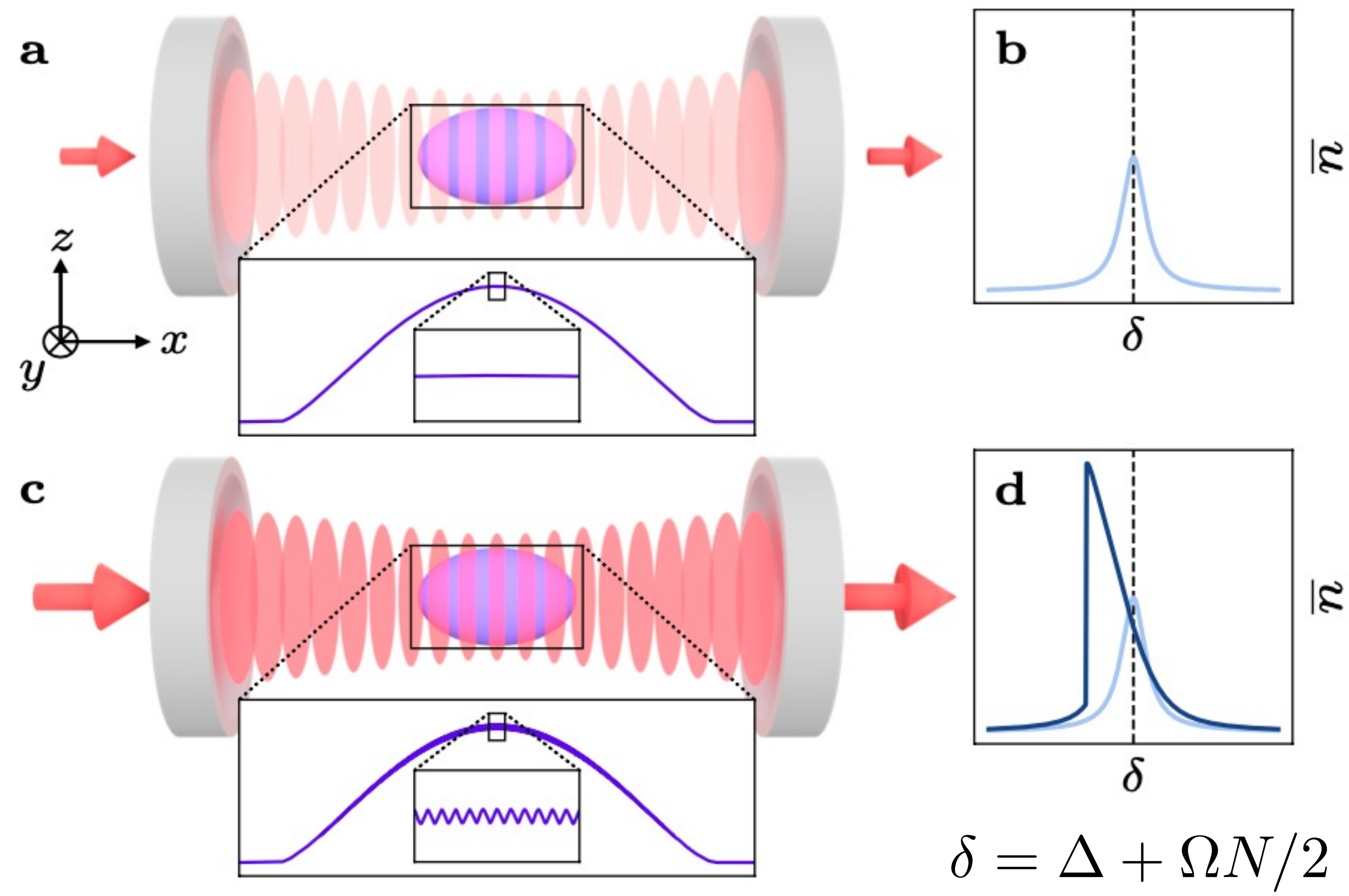
Strongly interacting Fermi gas in a cavity

V. Helson et al., PRR **4**, 133199 (2022)

$$H = H_{\text{atom}} + H_c + H_{\text{int}}$$

$$H_c = \Delta a^\dagger a$$

$$H_{\text{int}} = \Omega a^\dagger a \int d^3 r n(\mathbf{r}) \cos^2 \mathbf{k}_c \cdot \mathbf{r}$$

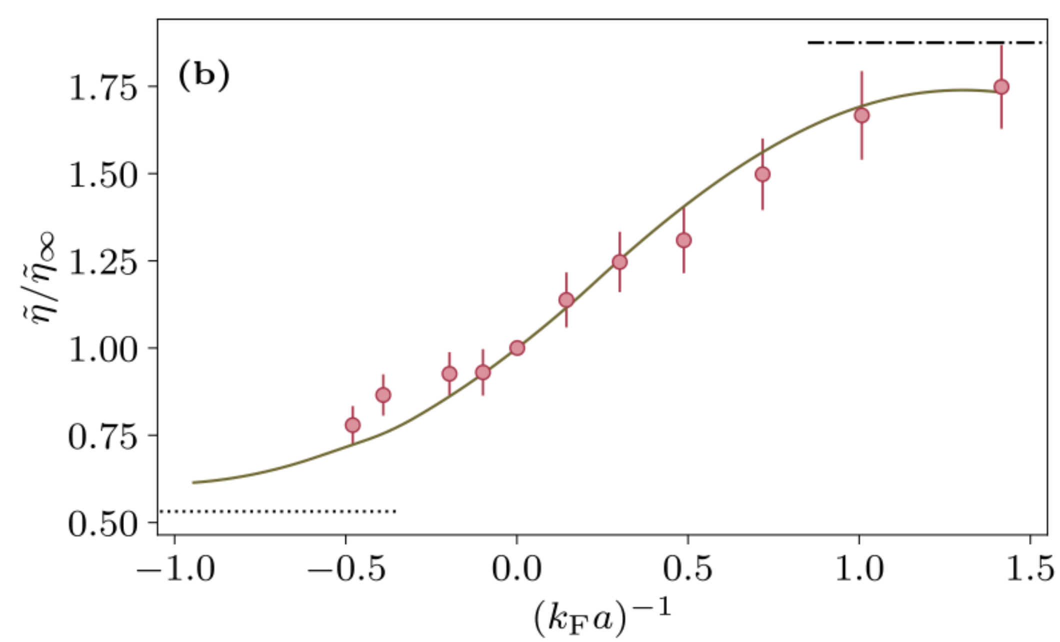


$$\delta = \Delta + \Omega N/2$$

- Photon measurement reflects density-density correlation of atoms

$$\chi^R(\mathbf{q}, \omega = 0) = -\int d\omega \left[\frac{S(\mathbf{q}, \omega) + S(-\mathbf{q}, \omega)}{\omega} \right]$$

compressibility sum rule



- Agreement with a theory with the operator product expansion

Summary

- Two-terminal transport of Fermi gases

  Nonlinear current-bias characteristics D. Husmann et al., Science **350**, 1498 (2015).

  Breakdown of conductance quantization

  SU and M. Ueda, PRL **118**, 105303 (2017).

  Particle loss effect in mesoscopic transport

  SU, arXiv:2206.09088
  M.-Z. Huang et al., arXiv:2210.03371

- Transport with synthetic junctions

  Realization of two and three terminal transport

  S. Nakada et al., PRA 102, 031302(R) (2020).
  K. Ono et al., Nat. Commun. **12,** 6724 (2021).

- Transport of bosons

  Asymmetry and nonlinearity in SN junction

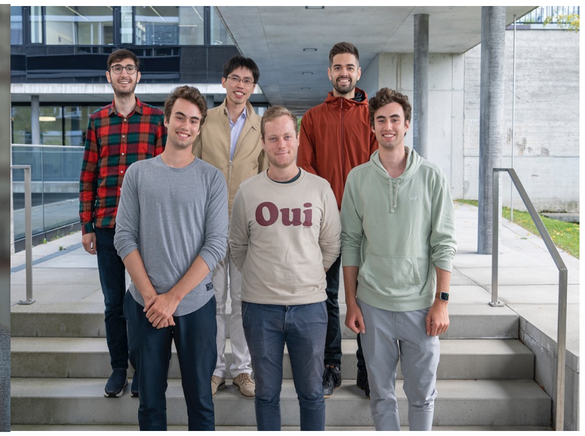
  SU, PRA **106**, L011303 (2022).

  Compressibility sum rule via optical cavity

  V. Helson et al., PRR **4**, 133199 (2022).

Collaborators

- Transport of Fermi gases

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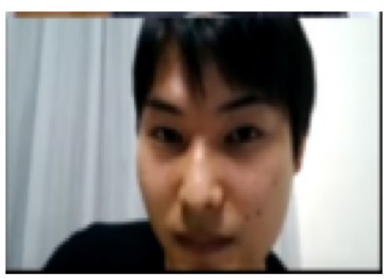
M. Ueda
Univ. Tokyo

- Transport with synthetic dimensions



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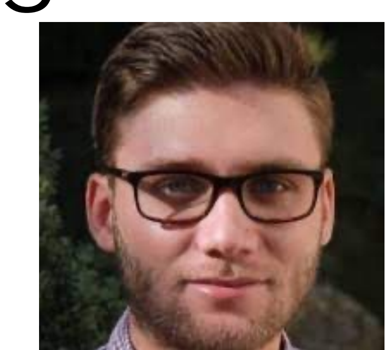
Y. Nishida
TITECH

- Strongly-interacting Fermi gas inside a cavity

Brantut group @ EPFL
J.P. Brnatut, V. Helson,
T. Zwettler



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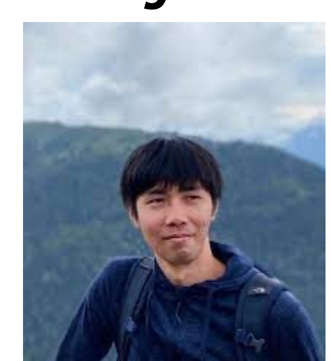
UGA



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