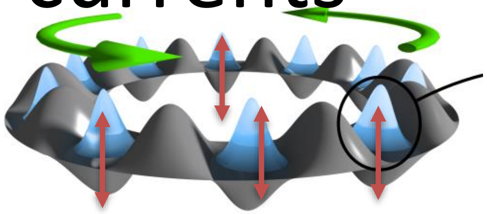
Atomtronic multi-terminal Aharonov-Bohm interferometer

J. Lau, K.S. Gan, R. Dumke, L. Amico,
L.C. Kwek, Tobias Haug

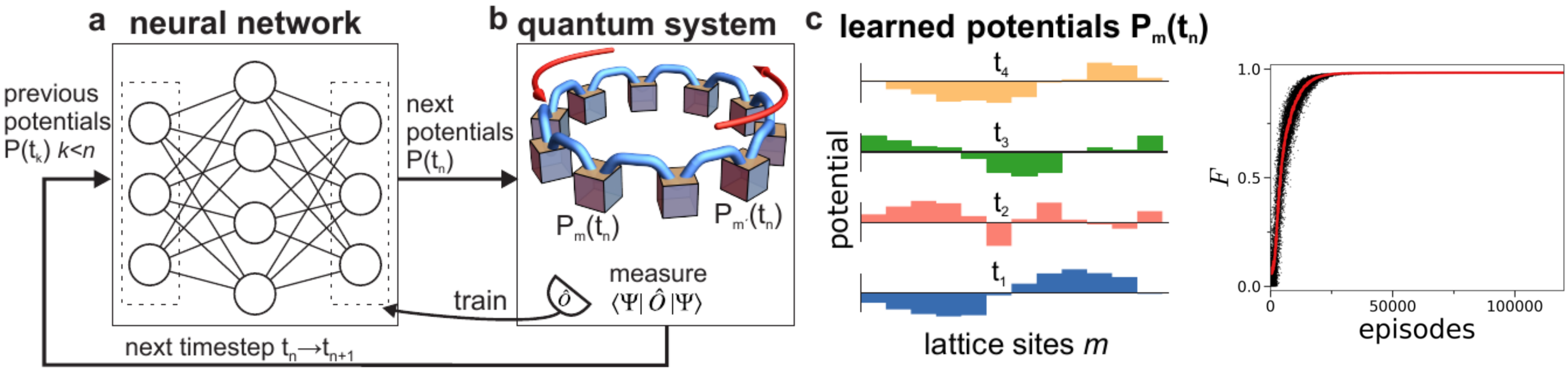
arXiv:2205.01636

04.05.2022

Machine learning for quantum currents



- Drive confinement potential of atomic ring in time to generate currents
- Learn optimal protocol from observables (i.e. TOF momentum)



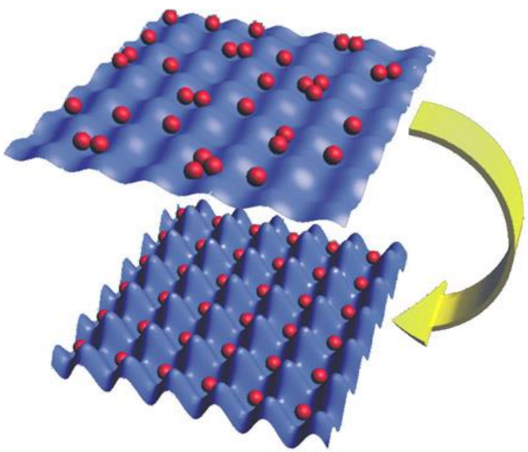
- We find fast protocols to prepare highly entangled atomic currents
- Prepare strange entangled currents of three momenta

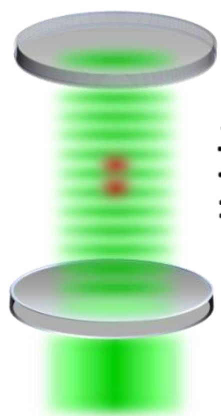
$$|\psi\rangle \propto |k=-1\rangle^{\otimes N_{\mathrm{P}}} + |k=0\rangle^{\otimes N_{\mathrm{P}}} + |k=1\rangle^{\otimes N_{\mathrm{P}}}$$

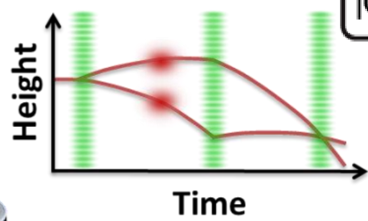
T. Haug, R. Dumke, L.C. Kwek, C. Miniatura, L. Amico, *Physical Review Research*, 3(1) (2021)

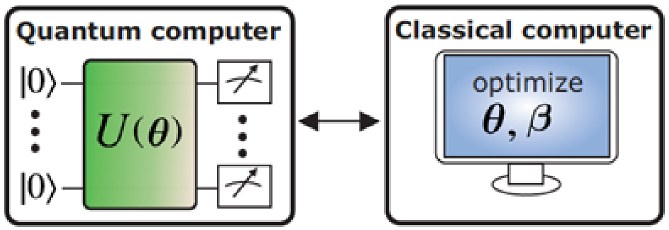
Quantum technologies

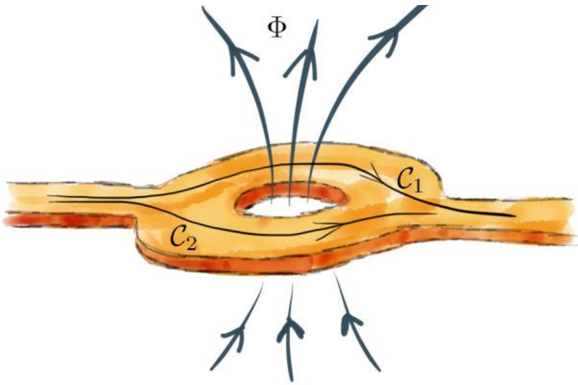
- Rapid progress in cold atoms for quantum simulators, machine learning, quantum computers, sensors, memory, …











- Need to combine devices
  - Can we connect different devices to each other?
  - Can we integrate multiple functionalities into one device?

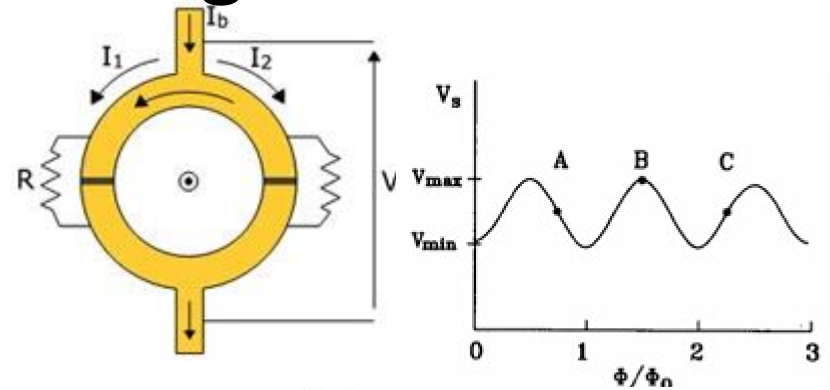
L. Amico, et al. *AVS Quantum Science* 3.3 (2021): 039201
I. Bloch, J. Dalibard, and S. Nascimbene. *Nature Physics* 8.4 (2012)
K. Bharti, A. Cervera-Lierta, T. Kyaw, T. Haug, ... , L.C. Kwek, A. Aspuru-Guzik. *Rev. Mod. Phys.* 94 (2022).

Integrated electric circuits

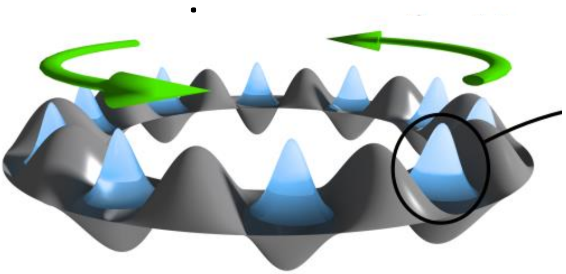
- One circuit combining multiple functionalities
- First IC in 1920s (one tube for a complete radio receiver)
- Smaller, faster and cheaper
- Future of Atomtronic technology?

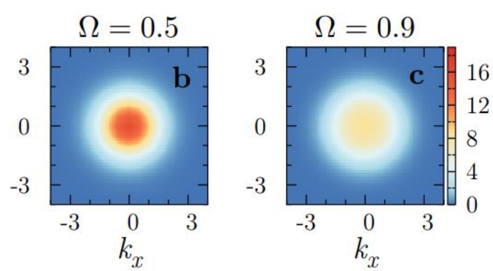
Ryu, C., & Boshier, M. G. (2015) *New Journal of Physics*, *17*(9), 092002.

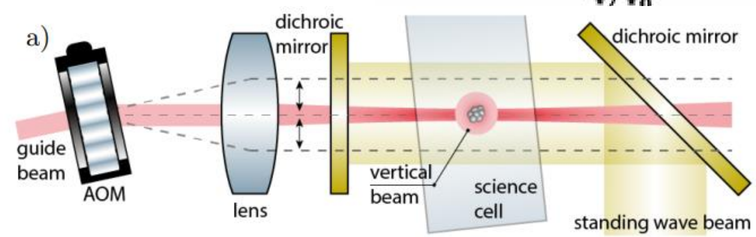
Atomtronic sensing

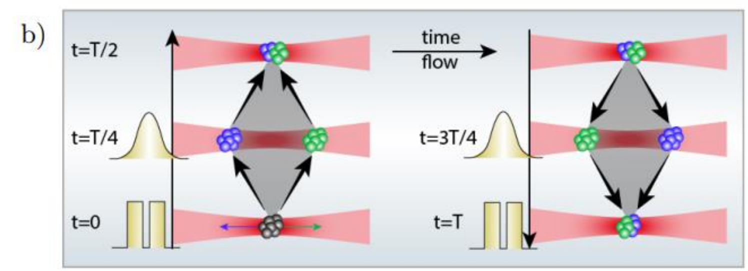


- SQUIDs most accurate sensors by measuring current through superconductor
- Atoms can sense rotation by interferometry of BECs or time-of-flight

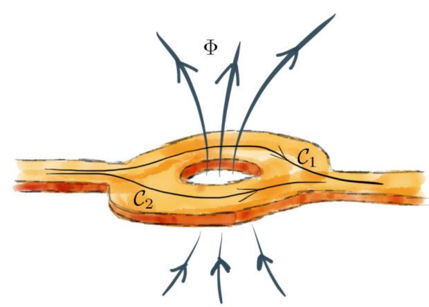








- Can we measure rotation via current through atomic device (like in SQUID)?



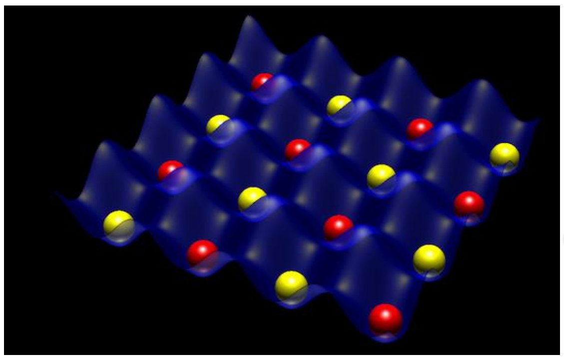
Krzyzanowska, Katarzyna, et al. *arXiv:2201.12461* (2022).

Naldesi, Piero, et al. *SciPost Physics* 12.4 (2022): 138.

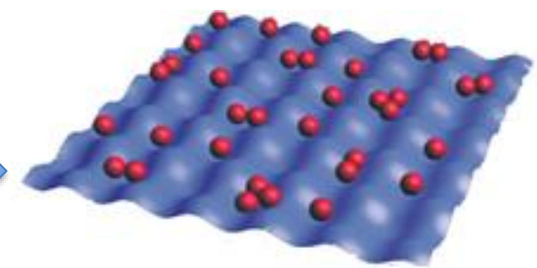
Atomtronic engineering

switch

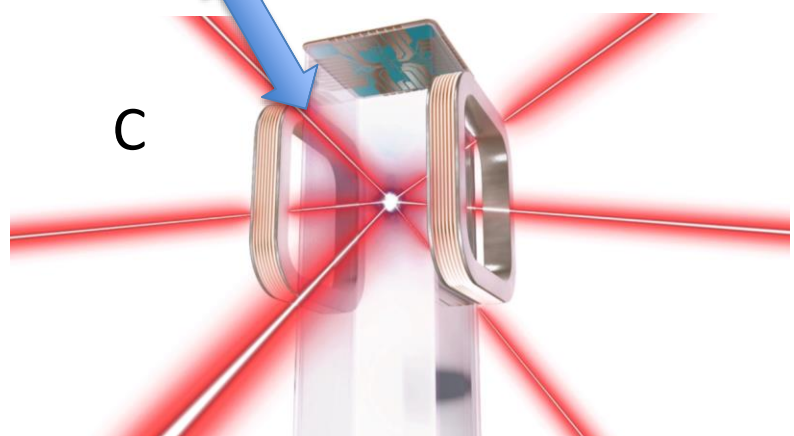
A



B



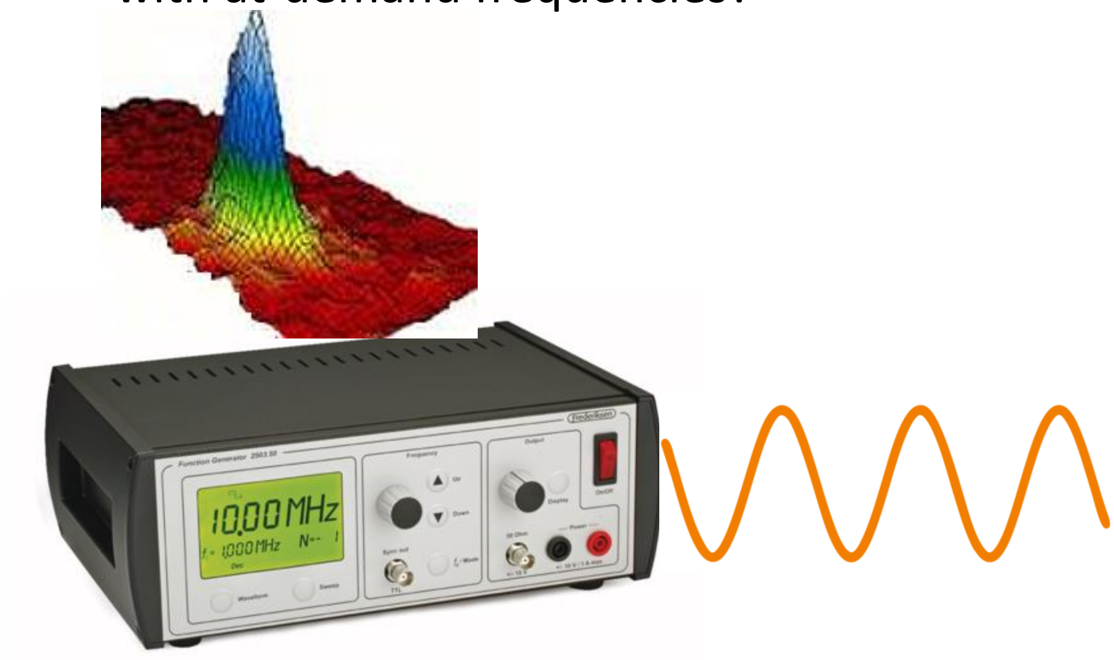
C

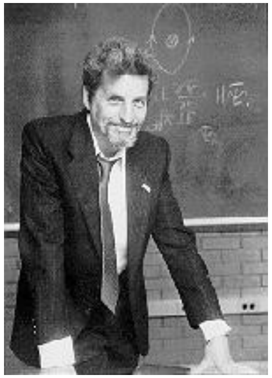


- Can we connect multiple atomic quantum devices together?
- Controllable multi-way switch?

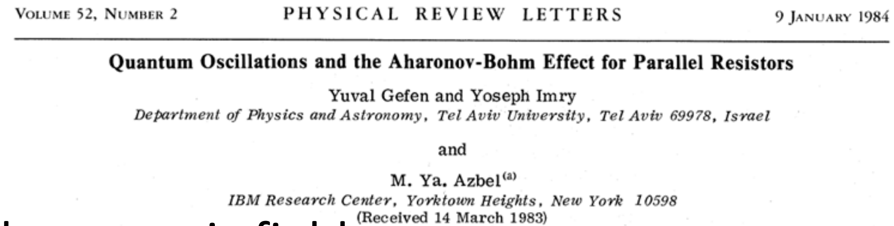
Atomtronic frequency generation

- Alternating electric current crucial for engines, transport, communication,…
- So far cold atom currents mostly constant
- Can we generate alternating atomic current of atoms with at-demand frequencies?






Aharonov-Bohm effect



VOLUME 52, NUMBER 2 PHYSICAL REVIEW LETTERS 9 JANUARY 1984

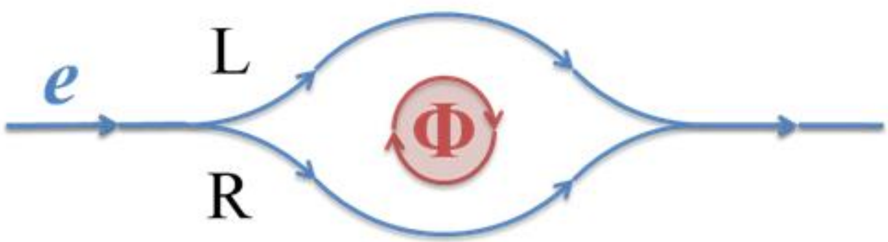
Quantum Oscillations and the Aharonov-Bohm Effect for Parallel Resistors

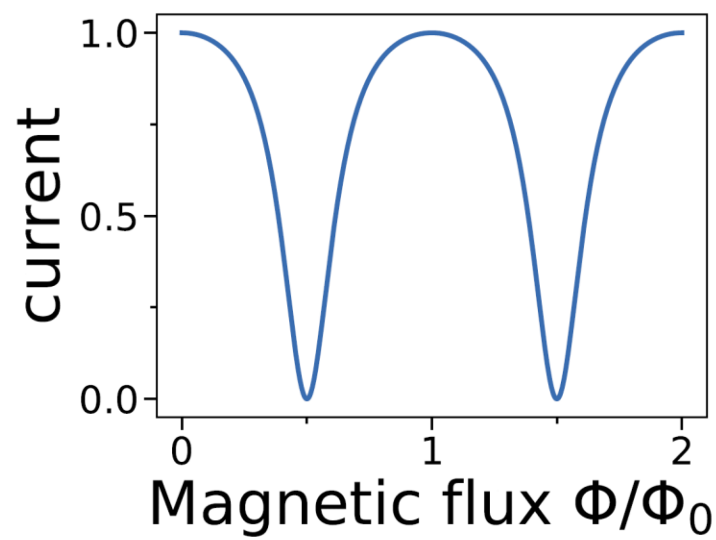
Yuval Gefen and Yoseph Imry
Department of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
and
M. Ya. Azbel[a]
IBM Research Center, Yorktown Heights, New York 10598
(Received 14 March 1983)

- Charged particle enclosing a region with magnetic field

$$\Delta\phi = \frac{e}{\hbar}\oint_C \mathbf{A}(\mathbf{r})\mathrm{d}\mathbf{r} \propto \Phi$$

- Phase shift by magnetic field changes interference pattern/current



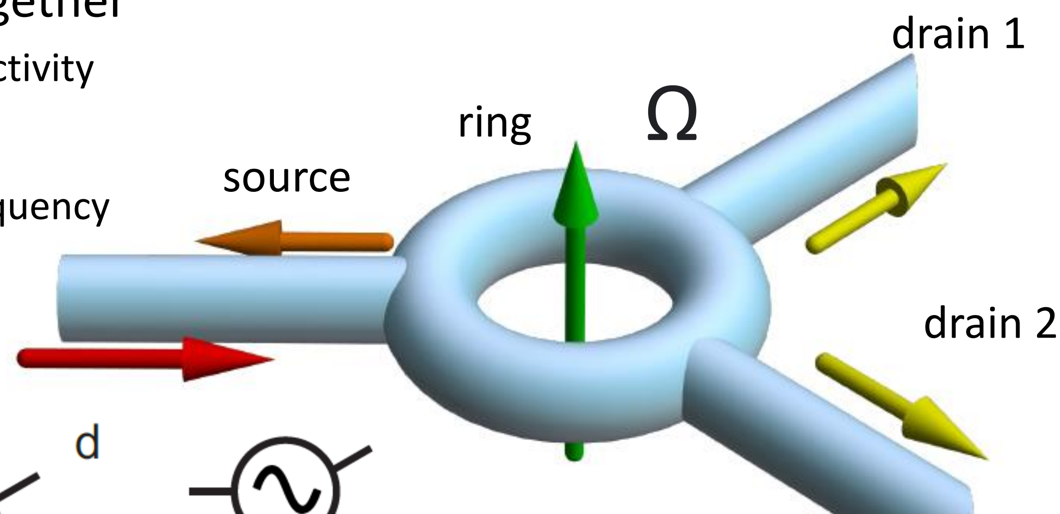


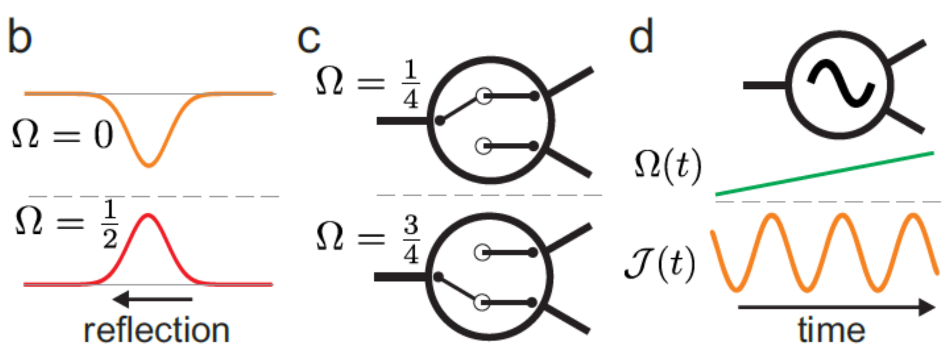
- Periodic modulation of current
  - Period given by flux quantum
- In neutral atoms induce synthethic flux
  by rotation or driving

Multi-terminal Aharonov-Bohm circuit

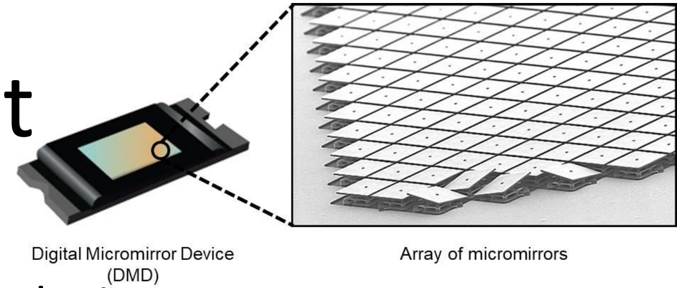
- Three-terminal ring with synthetic flux Ω integrates multiple tasks

1. Flux sensor
   – Read out flux from current through device
2. Connect multiple devices together
   – Flux controls current and connectivity
3. DC to AC converter
   – Acceleration of flux controls frequency

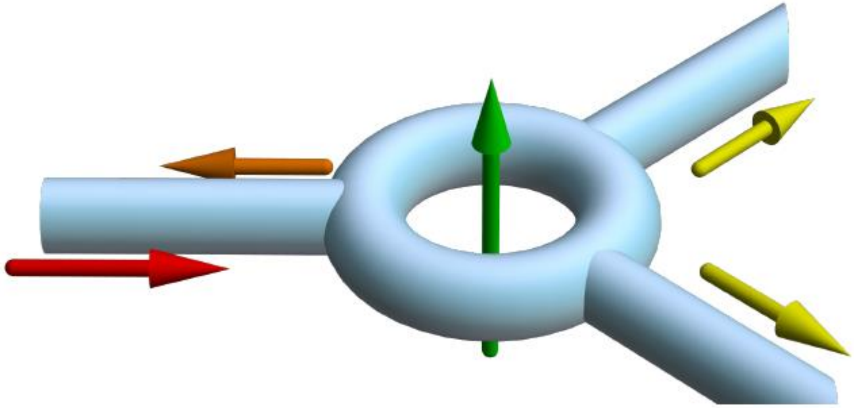


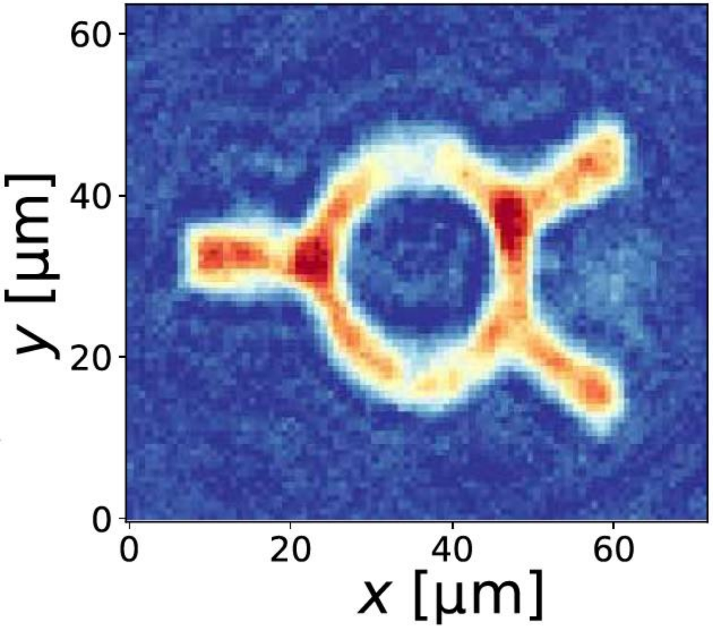


First experiment



- Optical potential of device via digital micromirror device
- Transfer atoms from dipole trap into DMD potential
- BEC of 6×10^4 Rb atoms is condensed into potential
- Absorption image of atomic density
- Demonstration of initial state of circuit





Theory of dynamics

- Source, two drains and ring as nearest-neighbor coupled chain

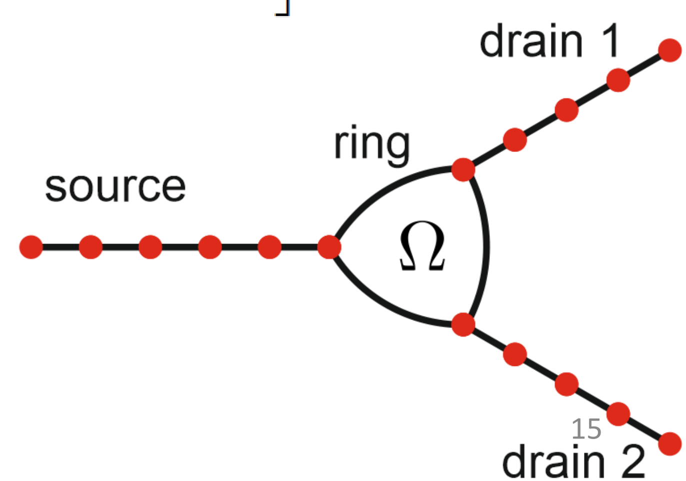
$$H_r = \sum_{j=1}^{L}\left[\frac{U}{2}\hat{n}_j(\hat{n}_j - 1) - J(e^{-i2\pi\Omega(t)/L}\hat{a}^{\dagger}_{j+1}\hat{a}_j + H.C.)\right]$$

$$H_{r\ell} = -K \sum_{\alpha=\{b,c,s\}} \left(\hat{\alpha}^{\dagger}_1 \hat{a}_{x_\alpha} + H.C.\right) \qquad (1)$$

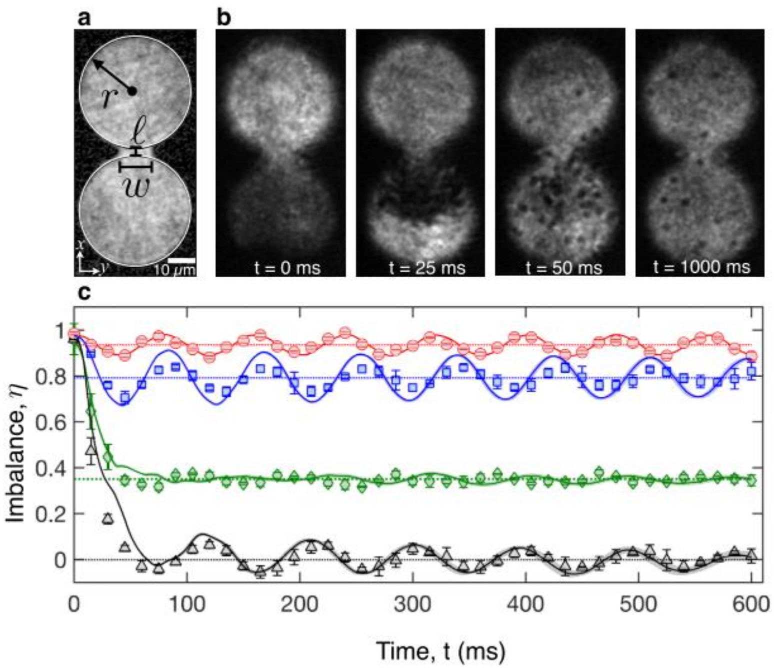
$$H_{\ell} = \sum_{\alpha=\{b,c,s\}} \sum_{j=1}^{L_\alpha}\left[\frac{U_\alpha}{2}\hat{n}^{\alpha}_j(\hat{n}^{\alpha}_j - 1) - J_\alpha(\hat{\alpha}^{\dagger}_{j+1}\hat{\alpha}_j + H.C.)\right]$$

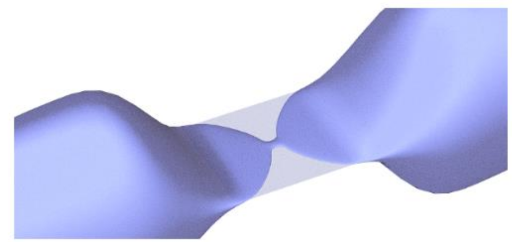
- Flux periodic with flux quantum=1

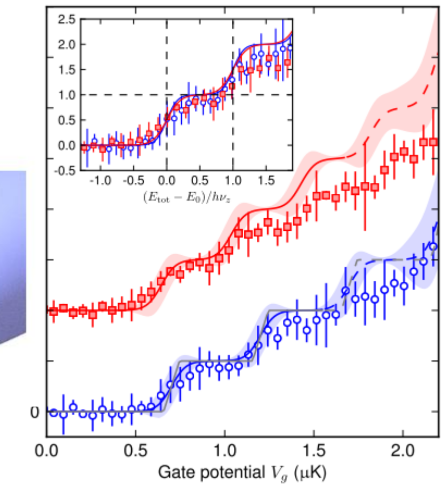
$$\Omega \rightarrow \Omega + k$$



Transport regimes



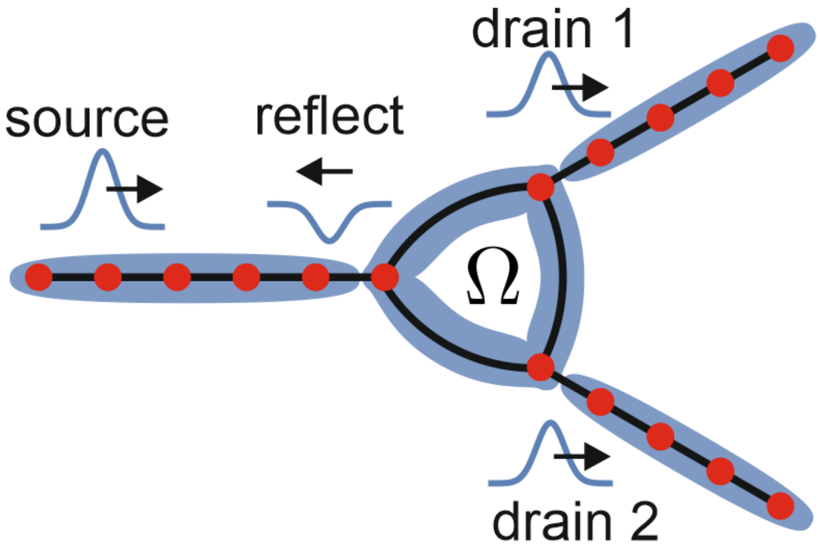




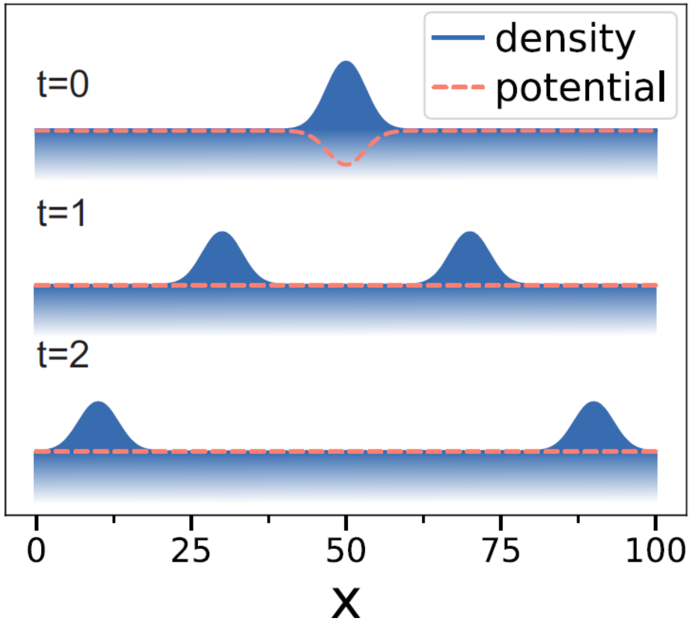
- Two transport regimes
  - Close to ground state: System filled with atoms, induce small perturbation for transport
  - Far from ground state: Only source lead filled, rest of system empty →Current from source via ring to drain

Krinner, Sebastian, Tilman Esslinger, and Jean-Philippe Brantut *Journal of Physics: Condensed Matter* 29.34 (2017): 343003.
Gauthier, Guillaume, et al. "Quantitative acoustic models for superfluid circuits." *Physical review letters* 123.26 (2019): 260402.

Transport close to ground state

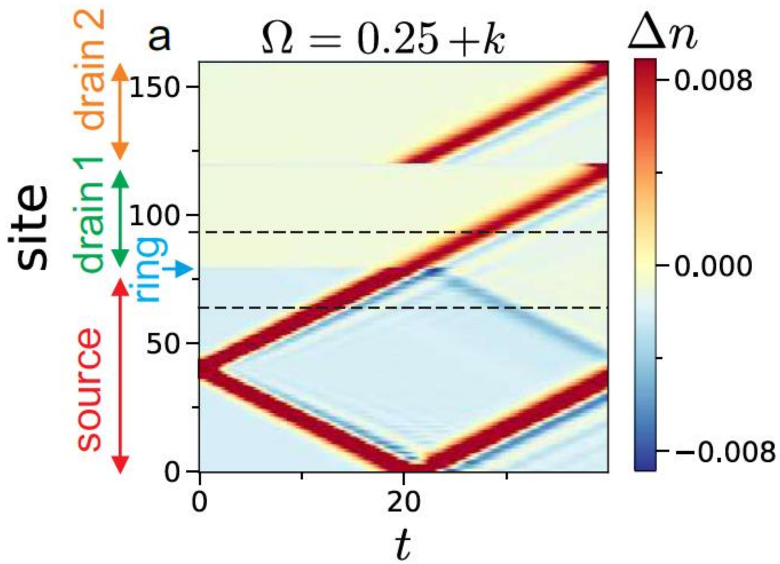


- Fill system with atoms in ground state
- Transport via **density wave**
  1. Small potential depression in source lead
  2. Quench of potential induces density wave

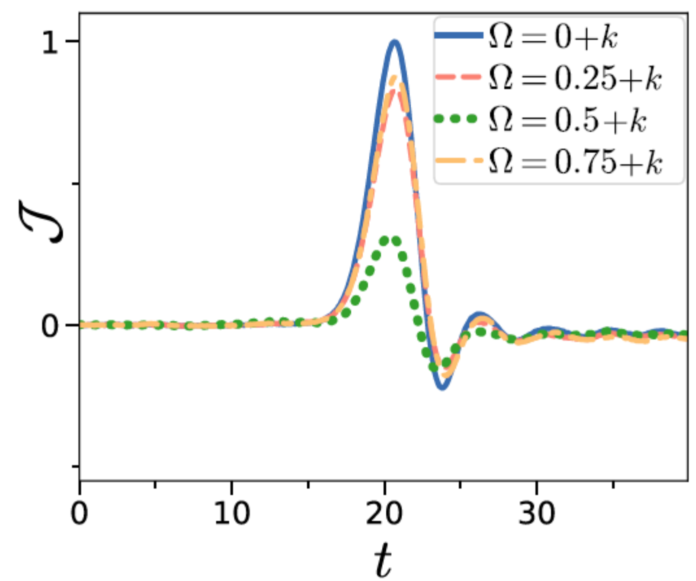


Current close to ground state

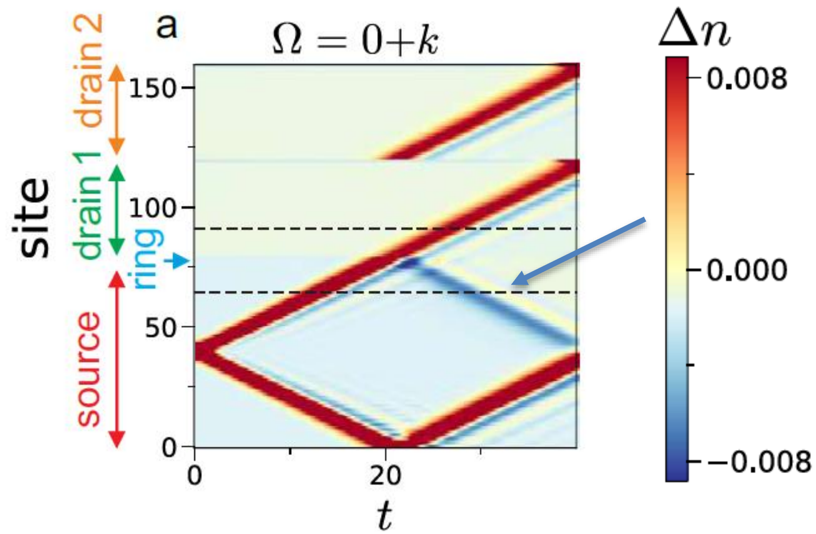
Difference density to background density

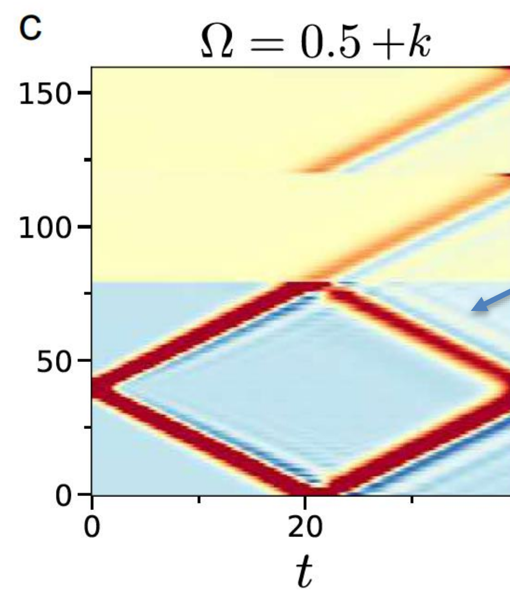


- Current into both drains symmetric
- Flux controls magnitude of current
  - Maximal for Ω=0
  - Minimal for Ω=0.5

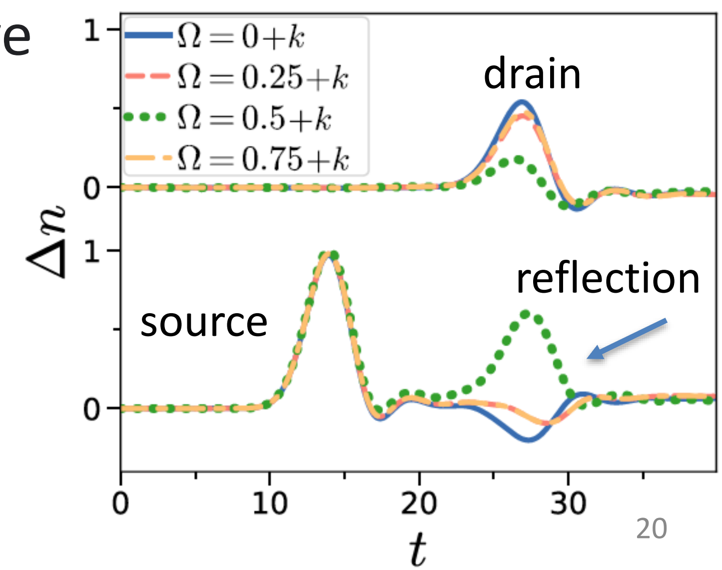


Reflection close to ground state

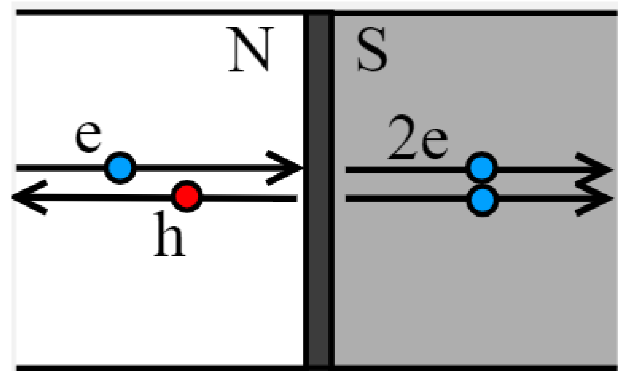




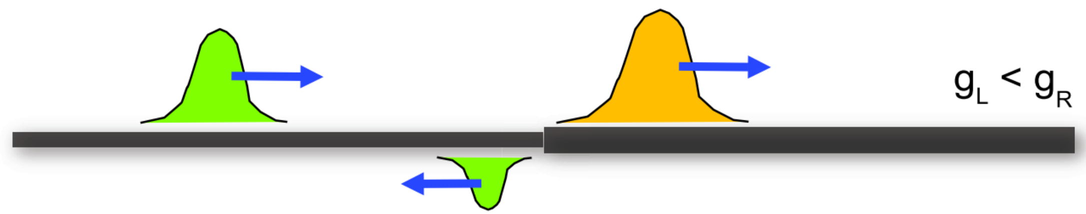
- Transition in reflection of density wave
  - Ω=0 negative Andreev reflection
  - Ω=0.5 positive reflection



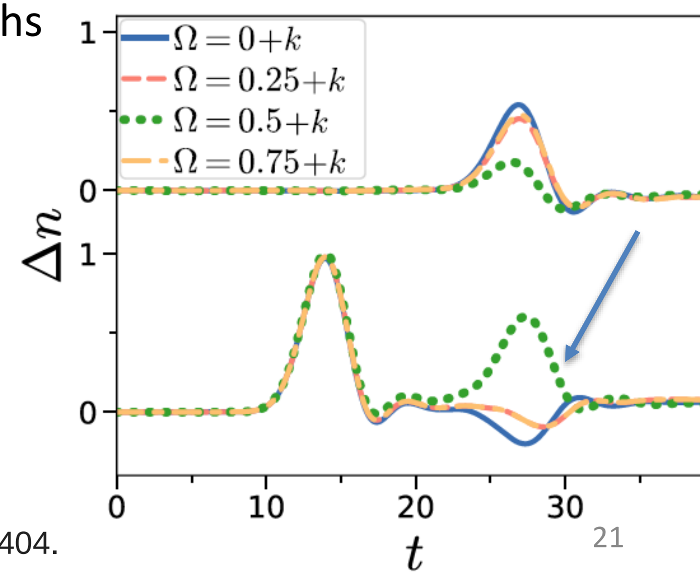
Andreev reflection



- Hole reflection at interface of normal and superconducting material



- Also appear in bosons
  - Y-junctions
  - interface between different interaction strengths

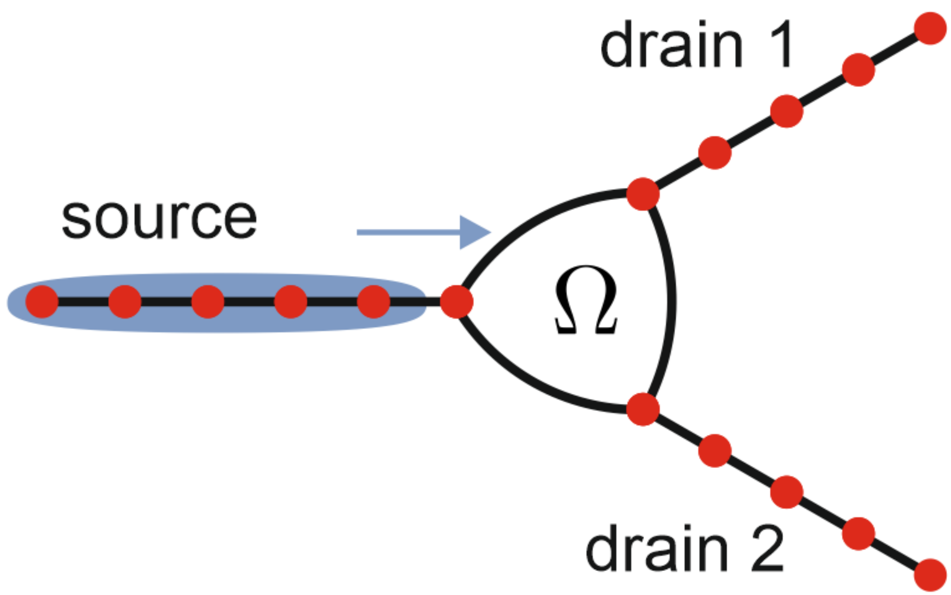


- We demonstrate flux-induced transition from Andreev to positive reflections
- Flux sensor from reflection
  - Negative → Ω=0
  - Positive → Ω=0.5
- In-situ readout, no time-of-flight needed

Daley, A. J., P. Zoller, and B. Trauzettel. *Physical review letters* 100.11 (2008): 110404.
Haug, Tobias, et al. *Quantum Science and Technology* 4.4 (2019): 045001.

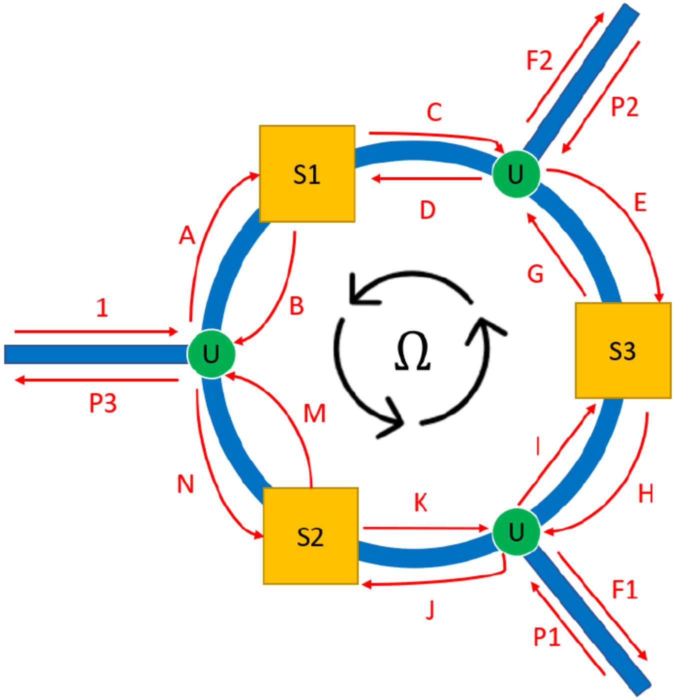
Non-equilibrium dynamics

- Fill source full of atoms
- Ring and drains empty
- Atoms flow from source via ring to drain
- Flux controls dynamics



Landauer theory

- Assume non-interacting particles→Landauer theory
- Described by scattering matrices of incoming particle wave



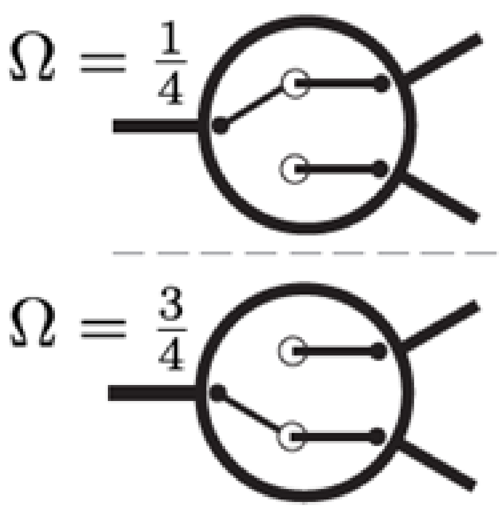
$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} r_1 & t_1 e^{-i2\pi\Omega/3} \\ t_1 e^{i2\pi\Omega/3} & r_1' \end{bmatrix} \begin{bmatrix} A \\ D \end{bmatrix}$$

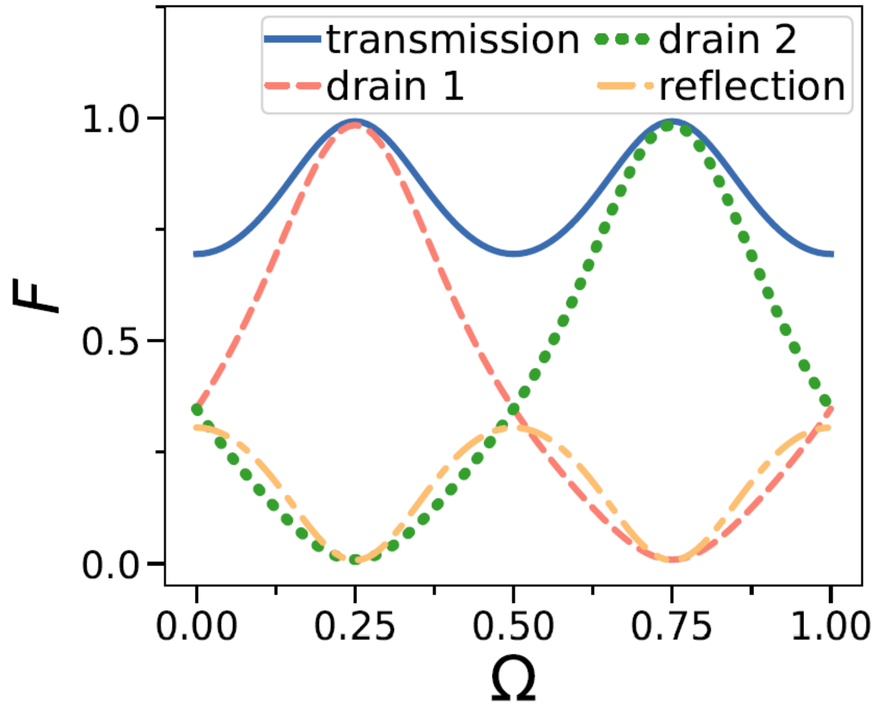
$$T_\alpha = 16 \left| \frac{1-\sqrt{2}+2i(2\sqrt{2}-3)\exp(-i\pi(2\Omega+\alpha))}{62-46\sqrt{2}+2i\cos(\pi(2\Omega+\alpha))} \right|^2$$

Non-interacting device

- Flux controls now magnitude and direction of current
- Can direct current into either drain 1 (Ω=0.25) or drain 2 (Ω=0.75)

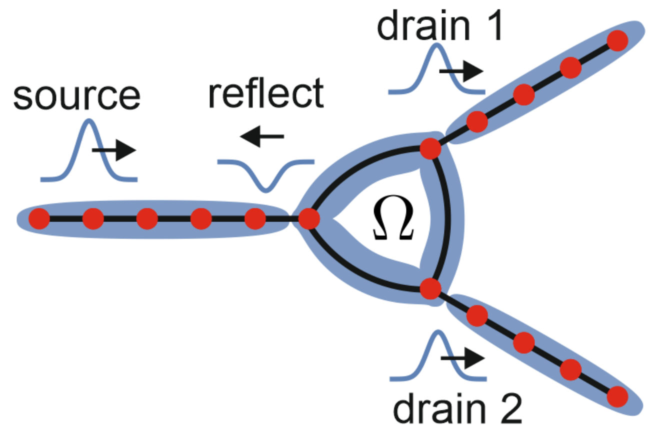
  → Non-reciprocal switch

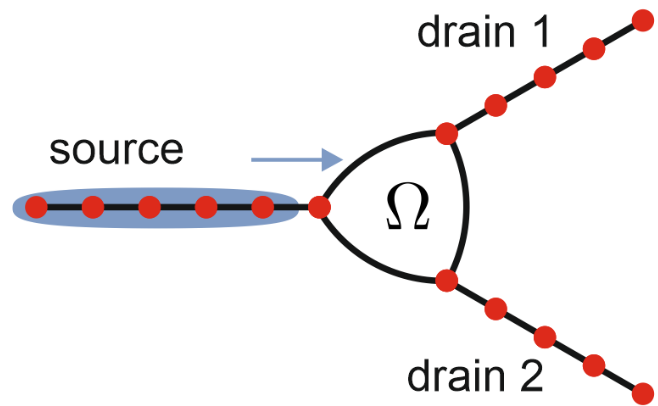


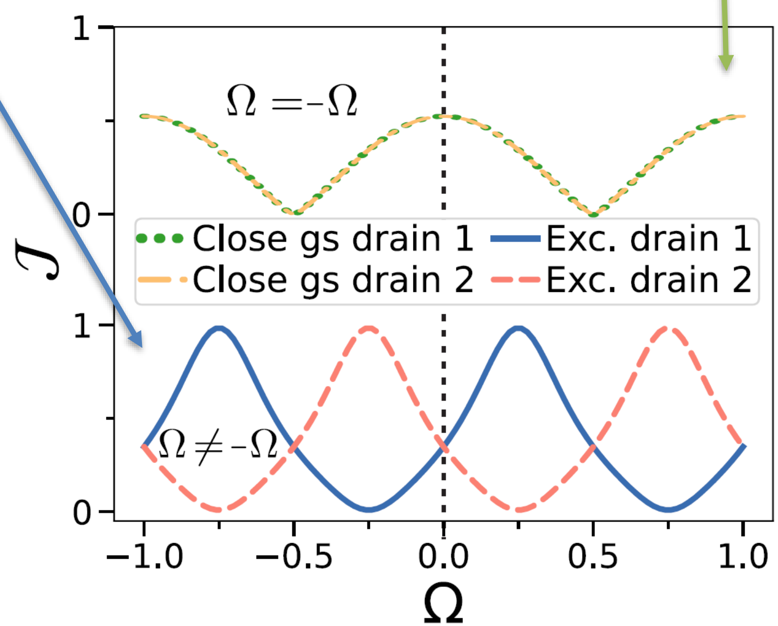


Comparison dynamics ground state vs far from ground state

- Close to ground state (top, qualitative)
  - Reflection symmetry Ω=- Ω
  - Same current both drains
  - Symmetries not present in Hamiltonian
- Strongly excited configuration (bottom)
  - No reflection symmetry Ω≠- Ω
  - current into either drain



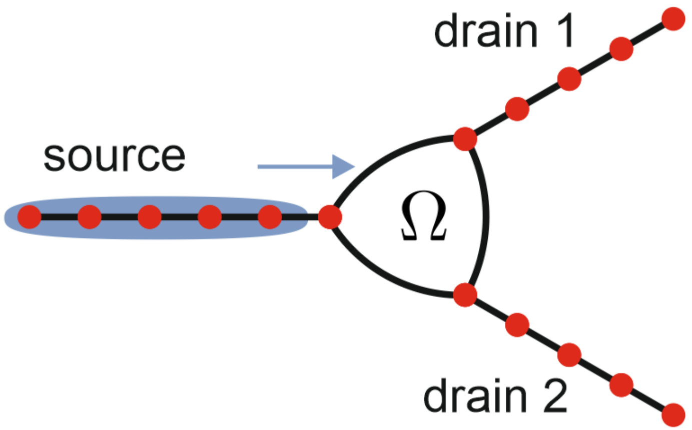




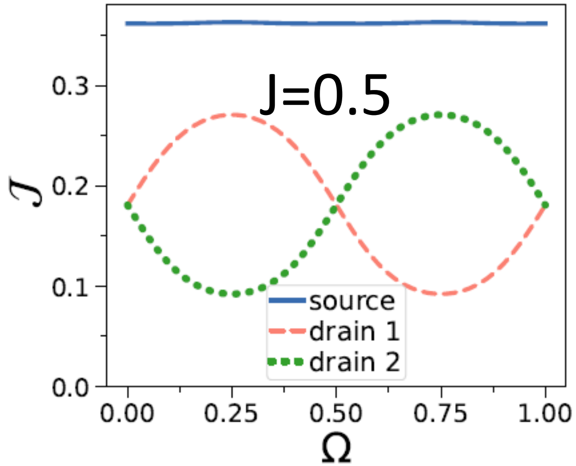
Strongly interacting limit

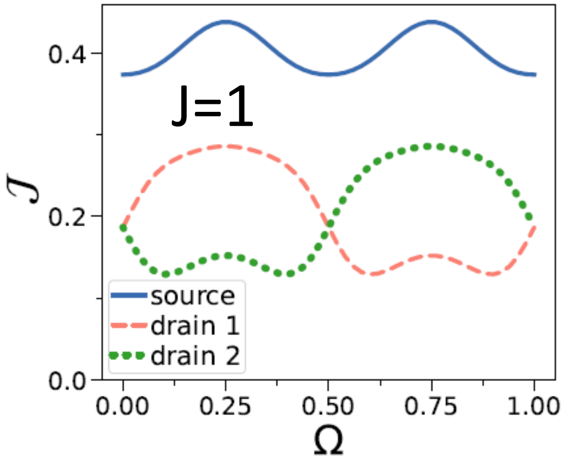
- Assume strong interaction between atoms
  →hard-core bosons
- Describe leads with Master equation

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H,\rho] - \frac{1}{2}\sum_m \{L_m^\dagger L_m, \rho\} + \sum_m L_m \rho L_m^\dagger$$



- Similar qualitative behavior as Landauer
  - Transition in flux-dependence of source current

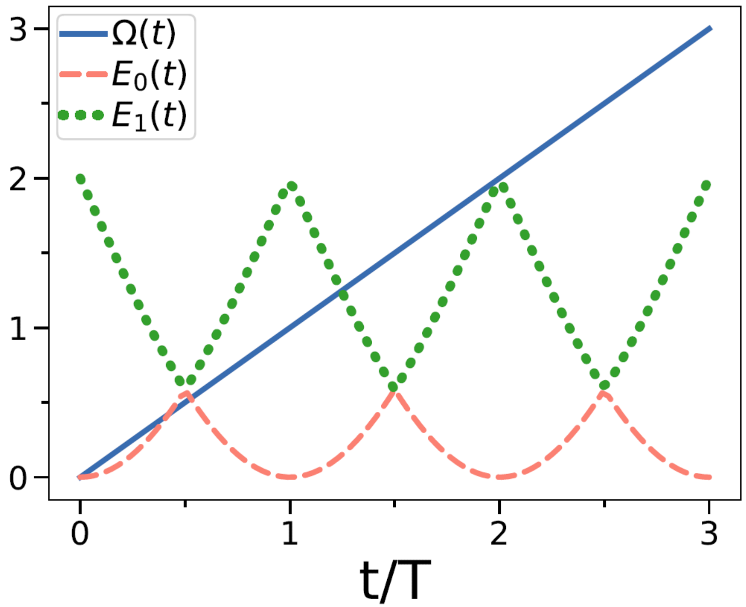




Change flux in time

- So far Ω=const
- Accelerate flux linearly in time
- *Ω(t)=t/T*, *T* period of one flux quantum
  - Create e.g. via accelerated rotation of ring
- Energy of system is periodically modulated with *T* due to flux quantum

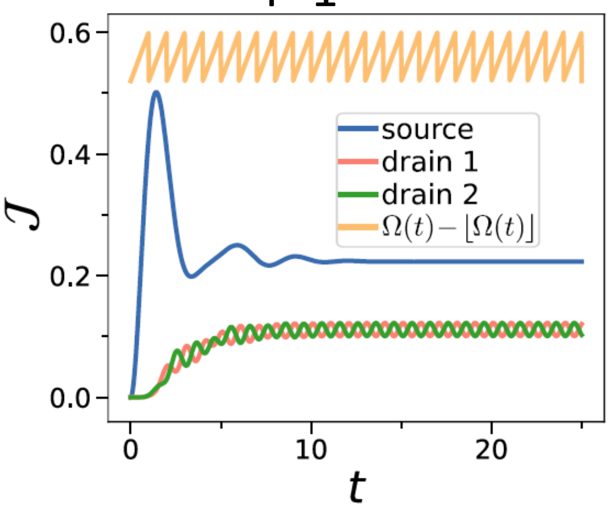
→ Periodic dynamics



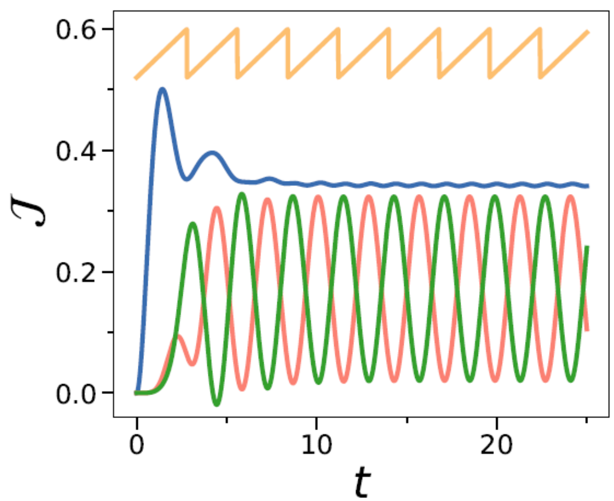
Time-dependent flux

- Accelerated flux Ω(t)=t/T, *T* period of one flux quantum
- After transient, current periodic with T
- Three regimes
  - T <<1/J: Nearly constant current
  - T ≈ 1/J: Large sinusoidal oscillation
  - T>> 1/J: Current follows steady-state current

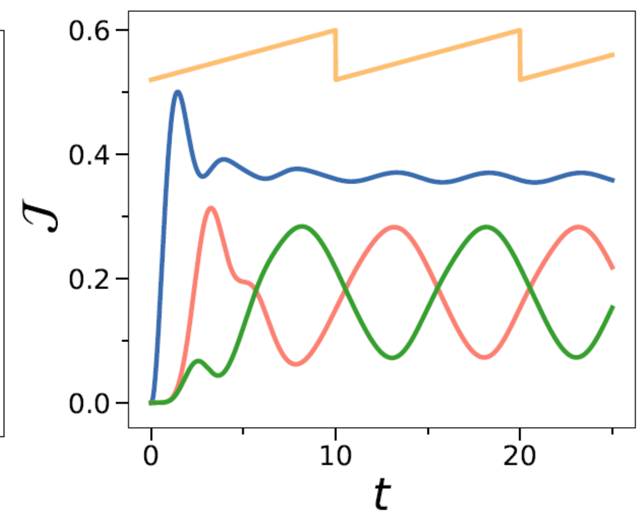
T=1



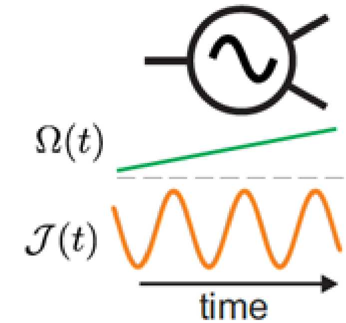
T=2.8



T=10



DC/AC converter



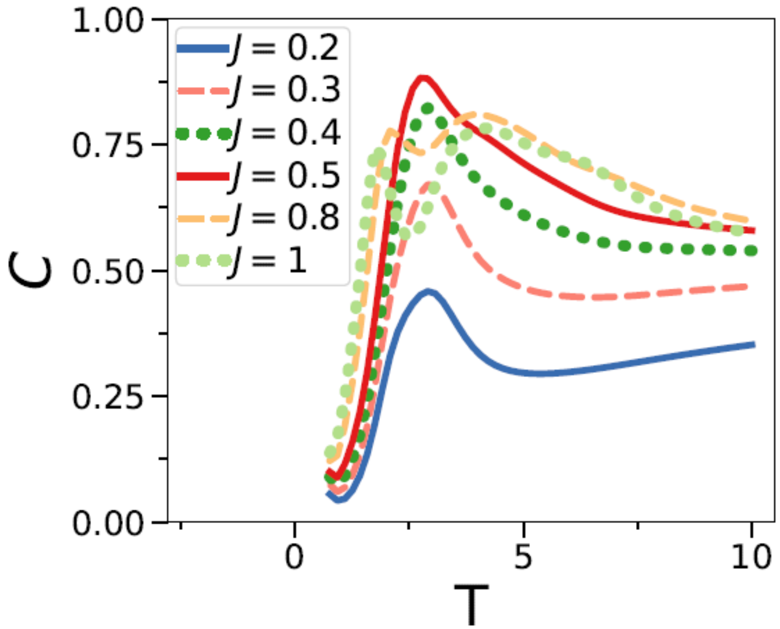
- Constant source current turned into oscillating drain current with frequency 1/T

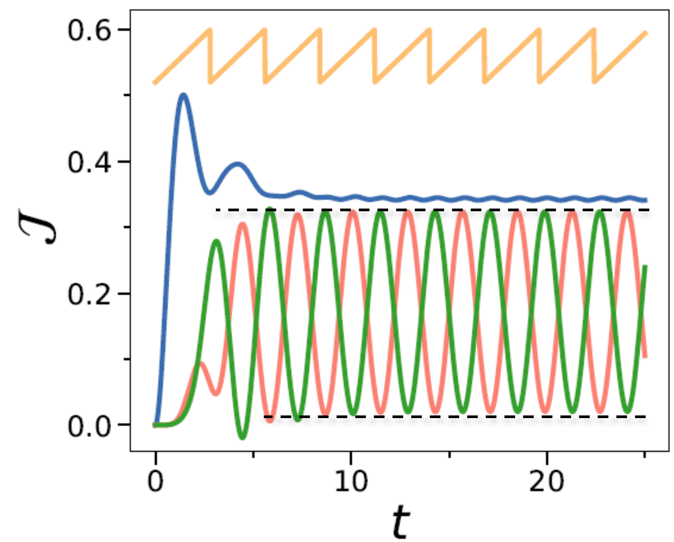
  →DC to AC

- Conversion efficiency

$$C = \Delta\mathcal{J}_{\mathrm{drain}} / \langle \mathcal{J}_{\mathrm{source}} \rangle$$

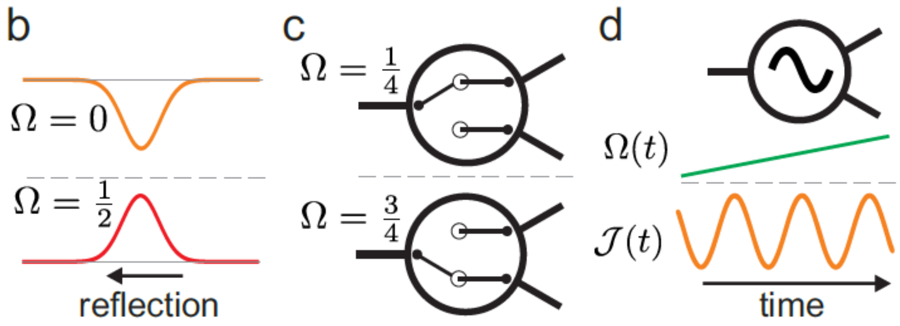
- Maximal for T=2.8, J=0.5, C≈0.88

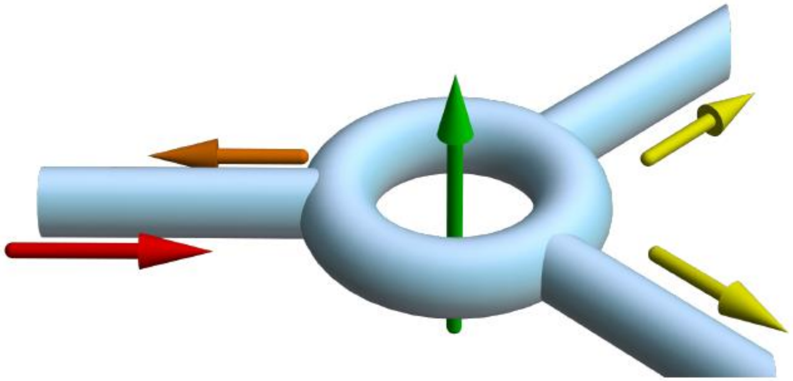




Conclusion

- Multifunctional atomtronic device
  - In-situ flux sensor: Close to ground state transition from negative Andreev to positive reflection
  - Non-reciprocal switch: Steer current into drain via flux far from ground state
  - DC/AC converter: Accelerate flux for tunable frequency generator





- Future steps
  - Origin of difference in dynamics close to ground state and excited?
  - Extension to fermions/solitons/SU(N)

J. Lau, K.S. Gan, R. Dumke, L. Amico, L.C. Kwek, T. Haug, *arXiv:2205.01636* (2022)