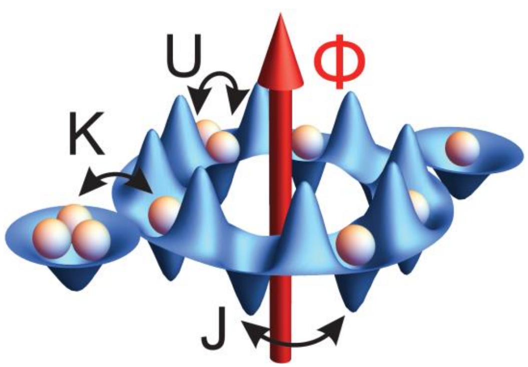
Andreev-reflection and Aharonov-Bohm dynamics in atomtronic circuits

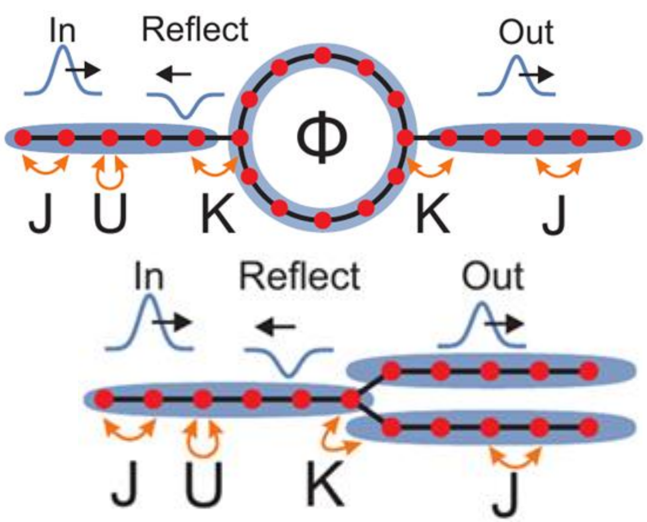
arXiv:1807.03616

arXiv:1706.05180

Tobias Haug, Rainer Dumke, Leong-Chuan Kwek, Luigi Amico

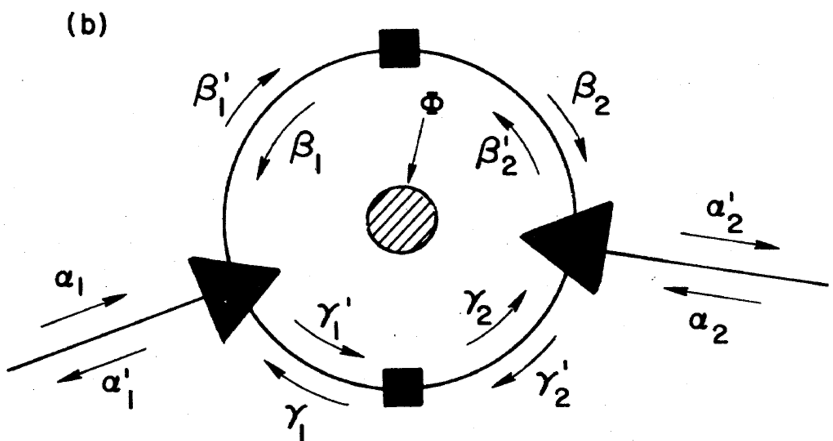
17.05.2019

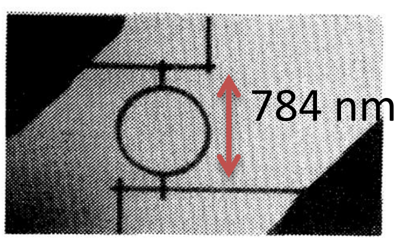


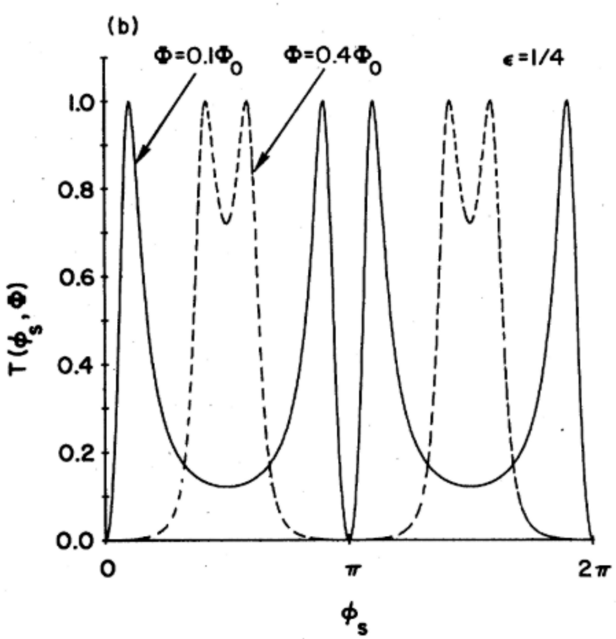


Mesoscopic physics

- Transport in small electronic systems
- Quantum effects influence transport of electrons
- **Bosons** instead of **fermions**???





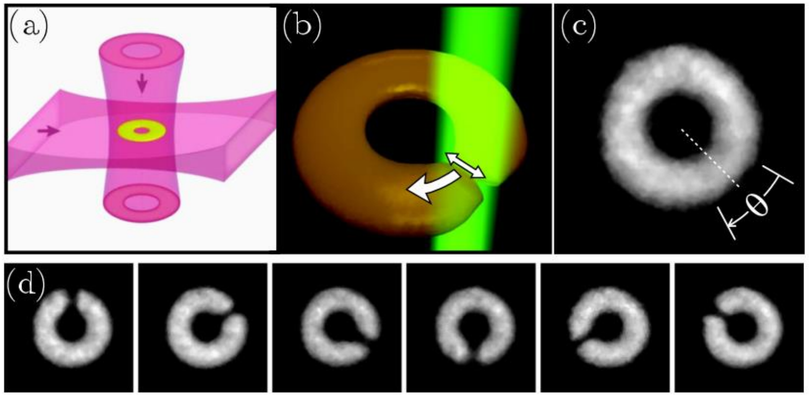


Washburn Web 1986

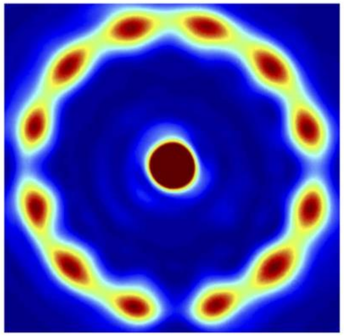
M. Büttiker, Y. Imry, and M. Y. Azbel, Phys. Rev. A 30, 1982 (1984).

Cold atom ring and Y-junction

Create rotation/artificial magnetic field in atomic ring

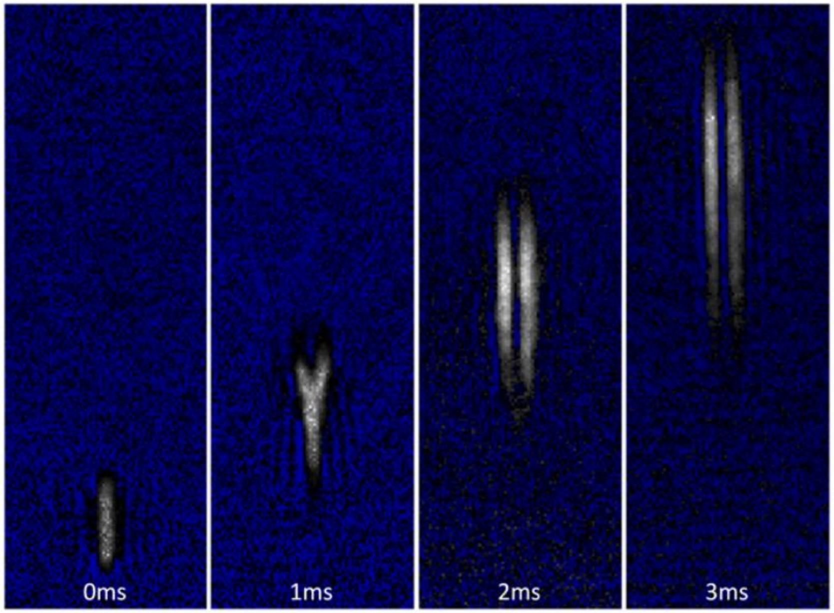


G. Campbell, W. Phillips, C. Clark and co-workers@NIST, (2014–2015)



Amico, Aghamalyan, Aukstol, Crepatz, Kwek, Dumke SREP 2014

Control BEC in a Y-junction



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

Centre for Quantum Technologies

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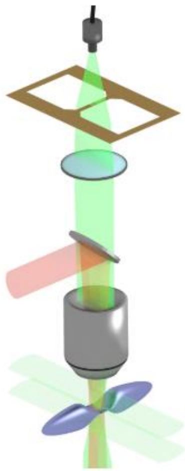
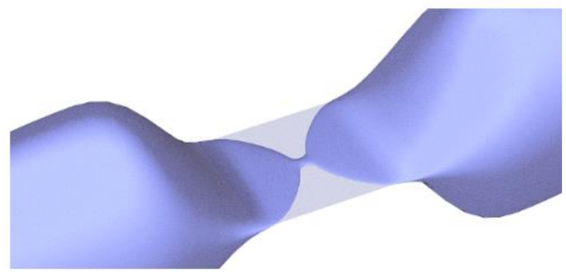
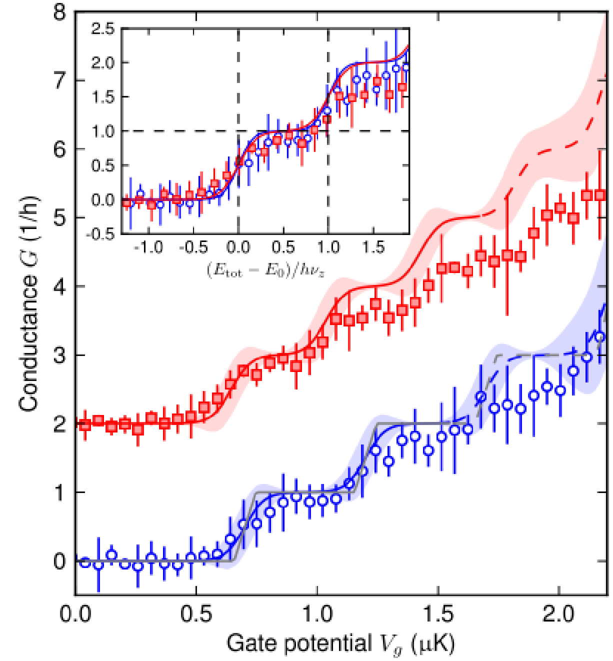
Transport dynamics

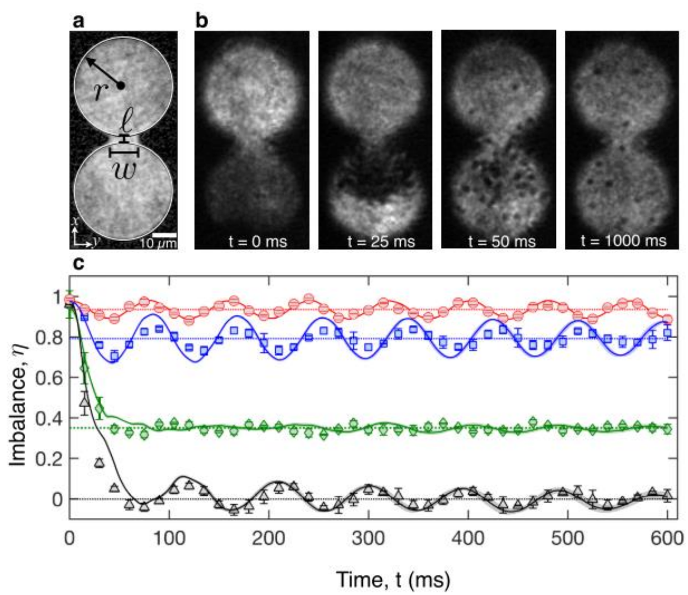
- Fermions





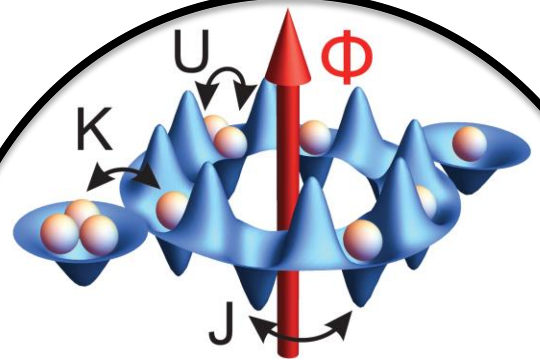


- Bosons



Gauthier, Guillaume, et al. *arXiv:1903.04086* (2019).

Krinner, Sebastian, Tilman Esslinger, and Jean-Philippe Brantut *Journal of Physics: Condensed Matter* 29.34 (2017): 343003.

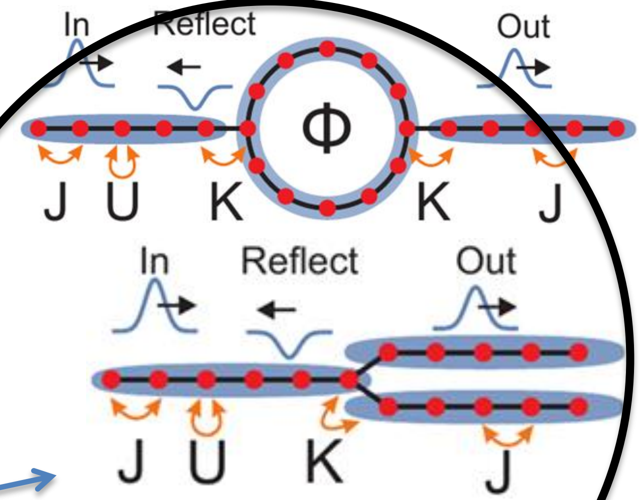


Aharonov-Bohm effect

TH, H. Heimonen, R. Dumke, L.-C. Kwek, L. Amico
arXiv:1706.05180

Fragmented states

N. Victorin, TH, L.-C. Kwek, L. Amico, A. Minguzzi
Phys. Rev. A ***99****, 033616*
arXiv:1810.03331



Transport

TH, R. Dumke, L.-C. Kwek, L. Amico
arXiv:1807.03616

Cold atoms + potential shaping+ control currents

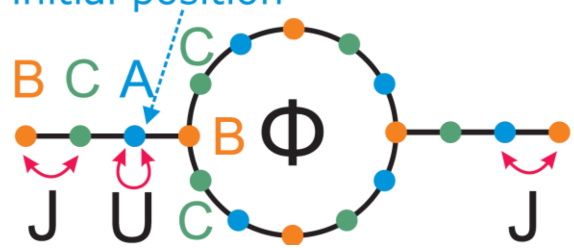
Quantum phases

TH, L. Amico, R. Dumke, L.-C. Kwek
Quantum Sci. Technol. (2018)
arXiv:1612.09109

AQUID read-out

TH, J. Tan, M. Theng, R. Dumke, L.C. Kwek, L. Amico
Phys. Rev. A 97 (2018)
arXiv: 1707.09184

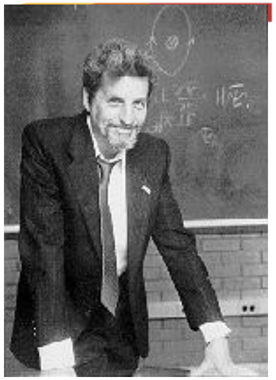
Topological pumping in rings



TH, R. Dumke, L.-C. Kwek, L. Amico
arXiv:1810.08525

Topological pumping with spin dualities

TH, L. Amico, L.-C. Kwek, W.J. Munro, V.M. Bastidas
arXiv:1905.03807

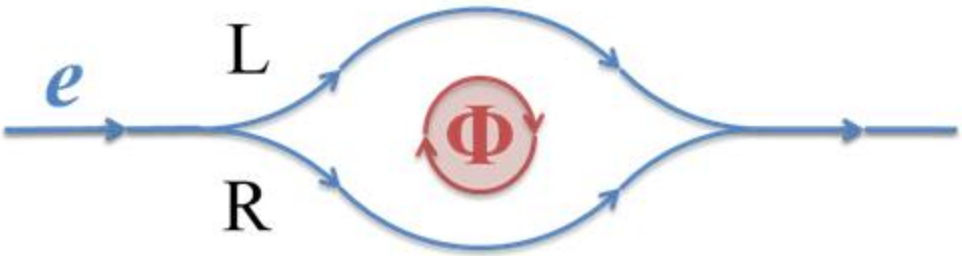



Aharonov-Bohm effect

- Charged particle enclosing a region with magnetic field

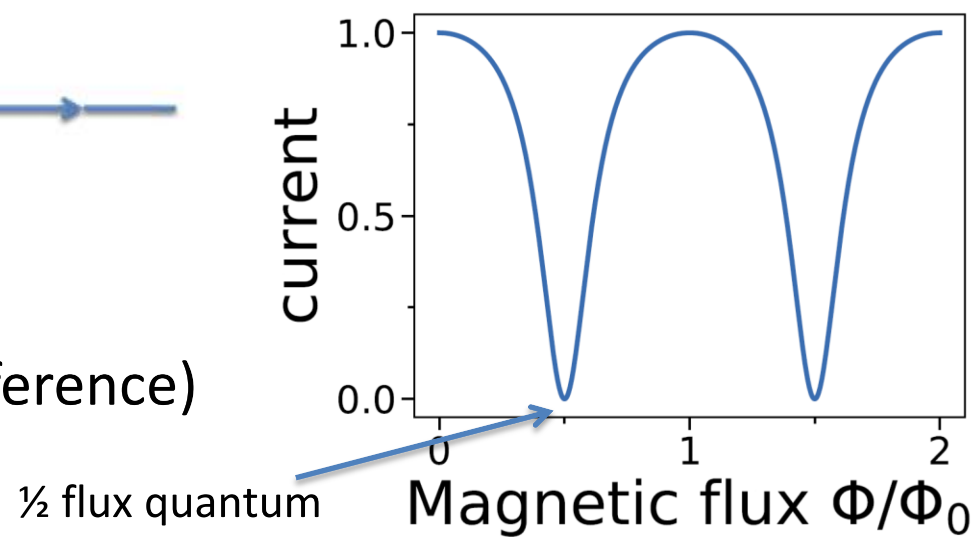
$$\Delta\phi = \frac{e}{\hbar}\oint_C \mathbf{A}(\mathbf{r})\mathrm{d}\mathbf{r} \propto \Phi$$

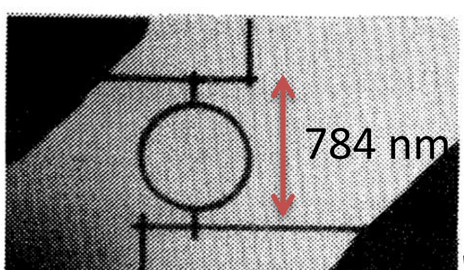
- Phase shift by magnetic field changes interference pattern/current



- Minimal current at

  Φ/Φ_0 =1/2 (destructive interference)





Washburn Web 1986

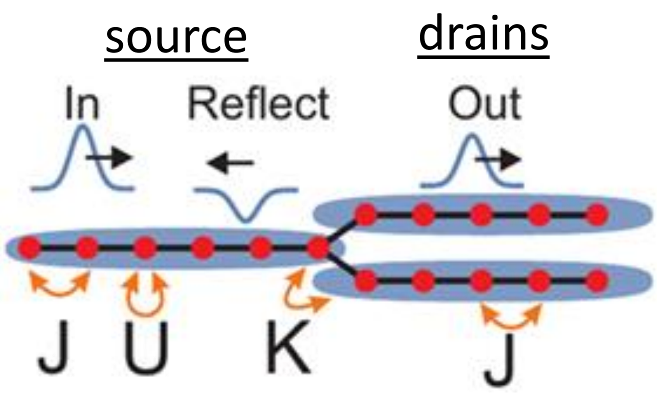
Models

- Bose-Hubbard model (atoms on lattice with tunneling)
- Simulate with DMRG and TEBD

Y junction: three 1D chains coupled with K

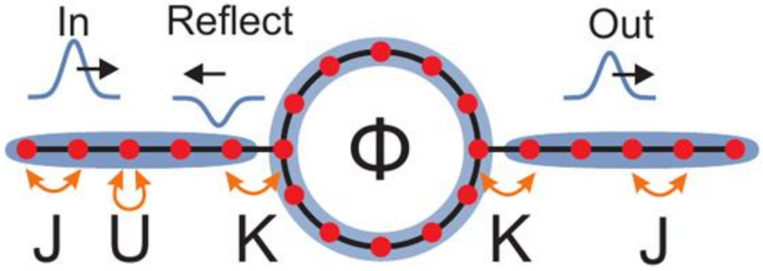
$$\mathcal{H}_{\mathrm{S}} = -\sum_{j=1}^{L_{\mathrm{S}}-1}\left(J\hat{s}_j^\dagger \hat{s}_{j+1} + \mathrm{H.C.}\right) + \sum_{j=1}^{L_{\mathrm{S}}} \frac{U}{2}\hat{n}_j^s(\hat{n}_j^s - 1)$$

$$\mathcal{H}_{\mathrm{I}} = -K\hat{s}_1^\dagger\left(\hat{d}_1 + \hat{f}_1\right) + \mathrm{H.C.}$$ (junction coupling)



Ring with leads and artificial magnetic field Φ

$$\mathcal{H}_{\mathrm{R}} = -\sum_{j=1}^{L_{\mathrm{R}}}\left(Je^{i2\pi\Phi/L}\hat{a}_j^\dagger \hat{a}_{j+1} + \mathrm{H.C.}\right) + \frac{U}{2}\sum_{j=1}^{L_{\mathrm{R}}} \hat{n}_j^a(\hat{n}_j^a - 1)$$

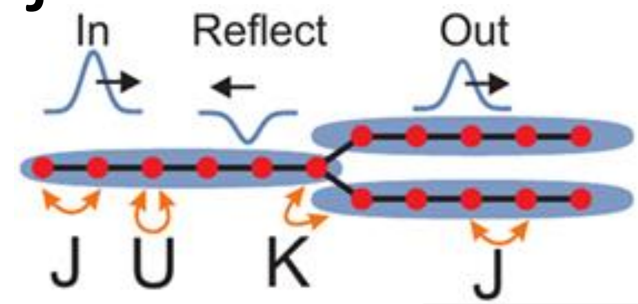


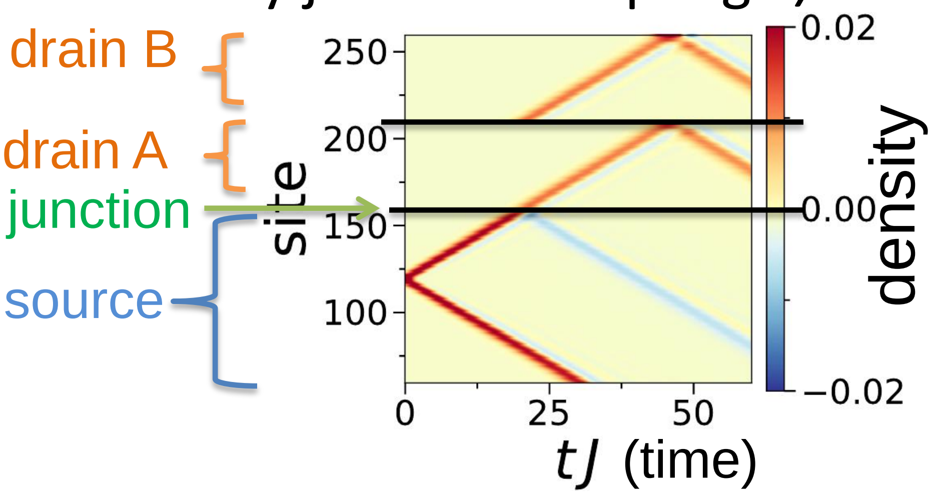
- Add localized potential offset in source lead, calculate ground state, then switch off →density wave

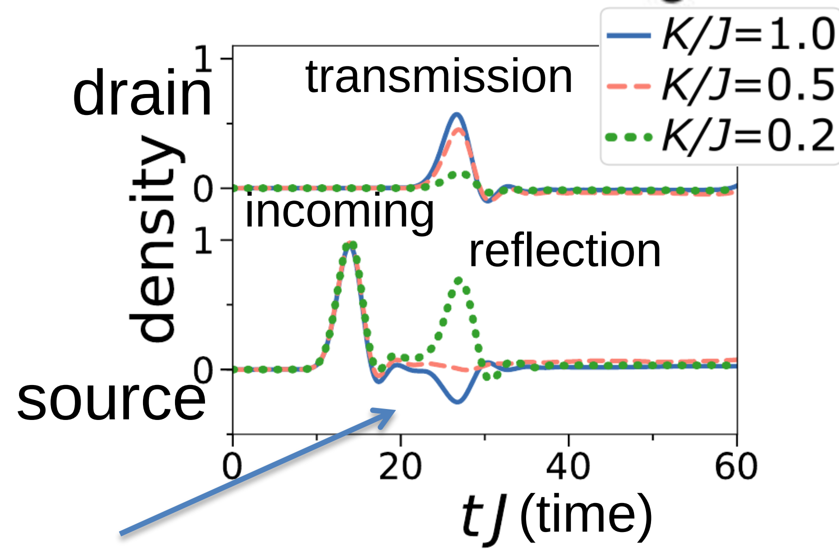
$$\mathcal{H}_{\mathrm{P}} = -\epsilon_{\mathrm{D}}\sum_{j=1}^{L_{\mathrm{S}}} \exp\left(-\frac{(j-j_0)^2}{2\sigma^2}\right)\hat{n}_j$$

Hard-core boson: Y junction

- On-site interaction U→ ∞
- 260 sites, half-filling (superfluid)
- Vary junction coupling *K/J*







Three regimes (J=1)

- *K*≈1: negative reflection (similar to Andreev reflection) (transmission 4/3, reflection -1/3)
- *K≈0.5:* no/positive-negative reflection
- *K≈0.2:* positive reflection

Also at bosonic interfaces: I. Zapata and F. Sols, Phys. Rev. Lett. 102, 180405 (2009)

Many-body symmetry

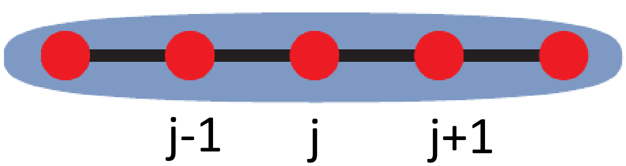
- Two types of particles
- Fermion anti-symmetric
  - Exchange gives minus sign
  - Pauli principle

$$|\Psi(r_a, r_b)\rangle = \pm |\Psi(r_b, r_a)\rangle$$

- Bosons symmetric
  - Exchange gives plus sign
  - Can occupy same space
- Bosons with infinite repulsion: Pauli principle, but still symmetric
- Jordan-Wigner to map fermion to hard-core boson in 1D

$$a_j^\dagger = e^{\left(+i\pi \sum_{k=1}^{j-1} f_k^\dagger f_k\right)} \cdot f_j^\dagger$$

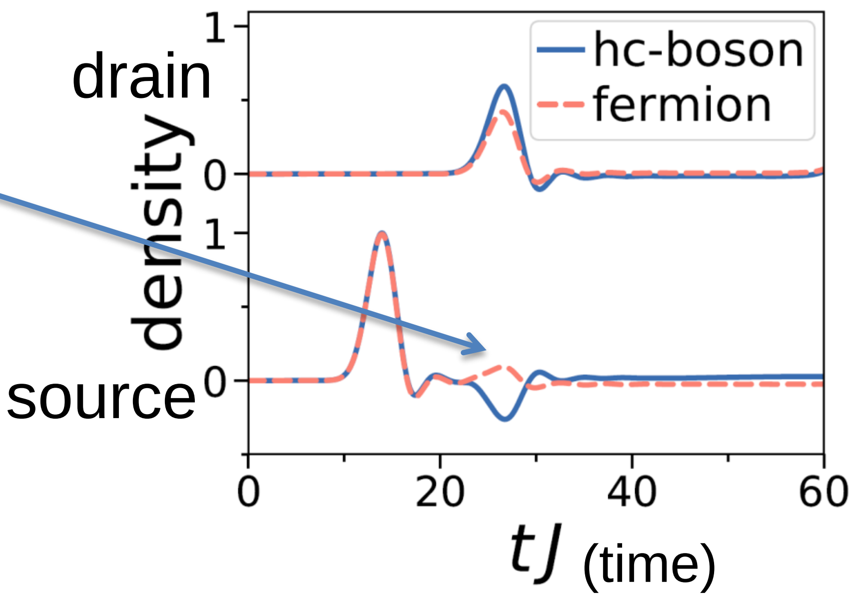
$$a_j = e^{\left(-i\pi \sum_{k=1}^{j-1} f_k^\dagger f_k\right)} \cdot f_j$$

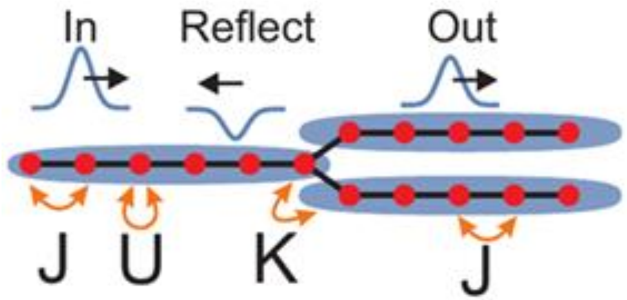


- Mapping not exact beyond 1D →break 1D a little (Y-junction)

Fermion vs hard-core boson

- Non-interacting fermions ***do not have Andreev-reflection peak*** for strongly coupled junction
- Reason: Jordan-Wigner cannot be applied on Y-junction





Gross-Pitaevskii

- Limit of weak interaction and many atoms
- →Gross-Pitaevskii equation (GPE)

$$i\partial_t \Psi(x,t) = \left[\frac{1}{2}(-i\partial_x - A(x,t))^2 + V(x) + g\,|\Psi(x,t)|^2\right]\Psi(x,t)$$

- Linearize equation $\partial_t^2 \delta n = g n_0 \partial_x^2 \delta n$

  (small excitation→ sound waves)

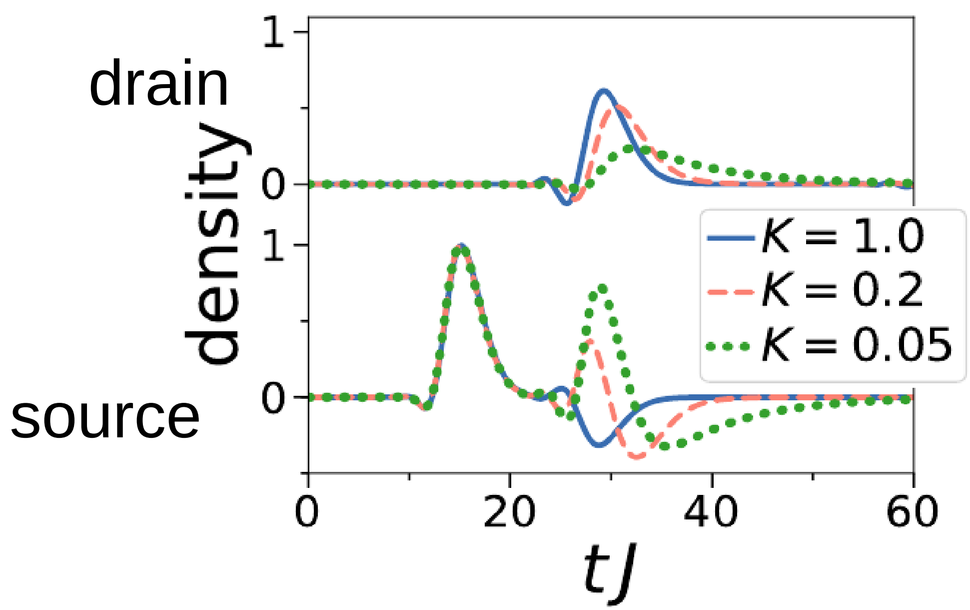
- **Y-junction**: solve at a boundary between three chains, assume
  - current conserved
  - Density/ derivative of phase continuous at boundary

→ **4/3 transmission**, **-1/3 reflection** for strong coupling (GPE).

Numerically found for BHM in strong coupling

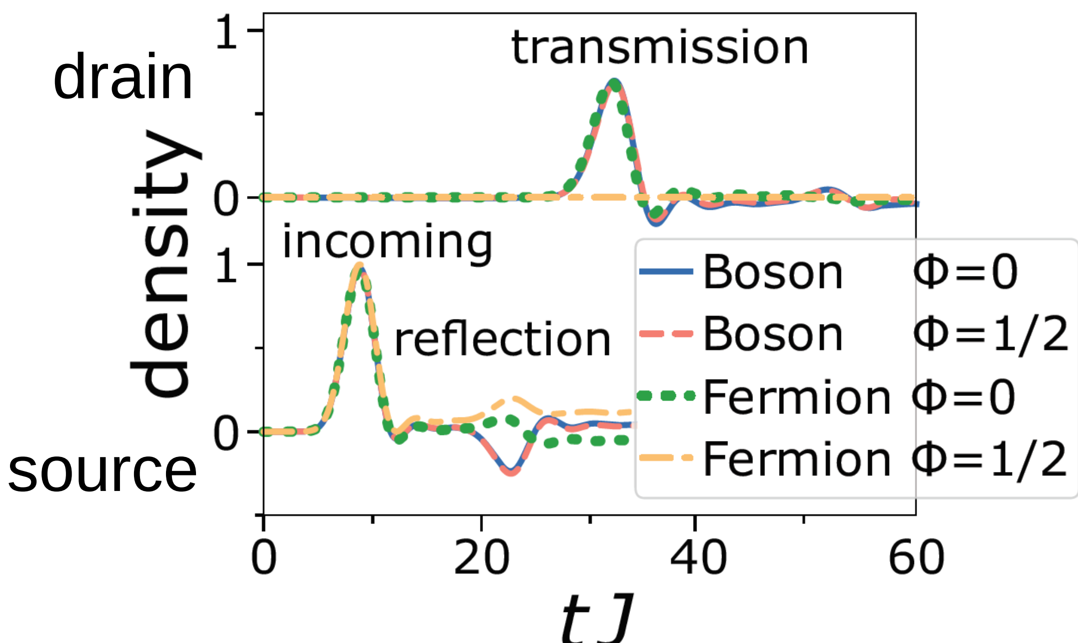
Gross-Pitaevskii Y-junction

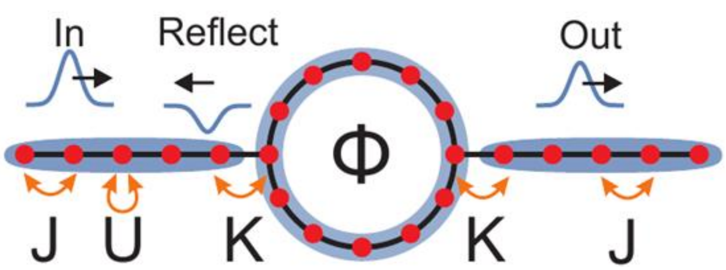
- For **GPE**: Total transmission is always 4/3, reflection -1/3, **independent of coupling *K*** (dynamics just stretched longer in time) →contrast to Bose-Hubbard (coefficient depend on ***K***)
- Even for weakest coupling *K* there is no purely positive reflection (as in BHM) → No weak coupling regime
- Reason: GPE is limit of many particles, weak interaction?



Ring dynamics

- Simulate full closed system ring + long leads (hard-core bosons)
- Initialize small density excitation in source lead
- Spinless fermions: Aharonov-Bohm effect, total reflection Φ=1/2
- **Interacting bosons** *independent of flux* (no Aharonov-Bohm!)
- Bosons have condensate phase, cancels AB flux!





Also for Luttinger Liquid: A. Tokuno, M. Oshikawa, and E. Demler, Phys. Rev. Lett. 100, 140402 (2008).

Gross-Pitaevskii

- Ring with Gross-Pitaesvkii equation (GPE) with flux A

$$i\partial_t \Psi(x,t) = \left[\frac{1}{2}(-i\partial_x - A(x,t))^2 + V(x) + g\,|\Psi(x,t)|^2\right]\Psi(x,t)$$

- Linearize equation on top of condensate

$$\partial_t^2 \delta n = \left[g n_0 - (A - v_0)^2\right]\partial_x^2 \delta n + 2(A - v_0)\partial_t \partial_x \delta n$$

$$c_\pm = \sqrt{g n_0} \pm (A - v_0)$$

- **Ring with gauge field A**: Flux causes a (direction dependent) shift in speed of sound, but no change in interference pattern
- v_0 is phase winding (integer quantized)

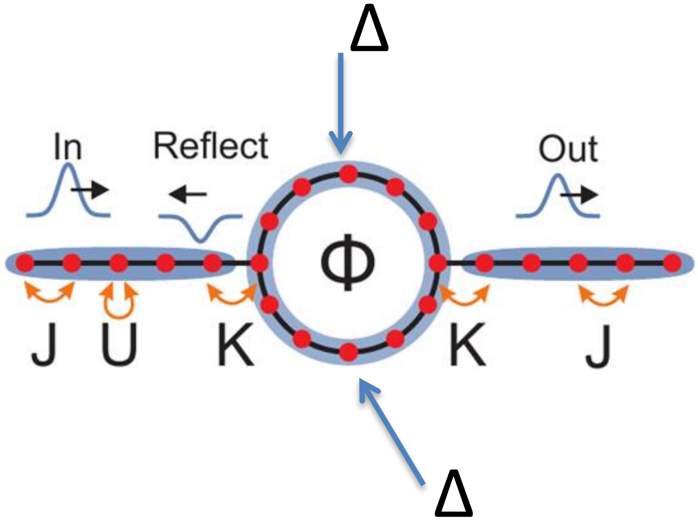
→**No Aharonov-Bohm** effect for excitations on top of a bosonic condensate

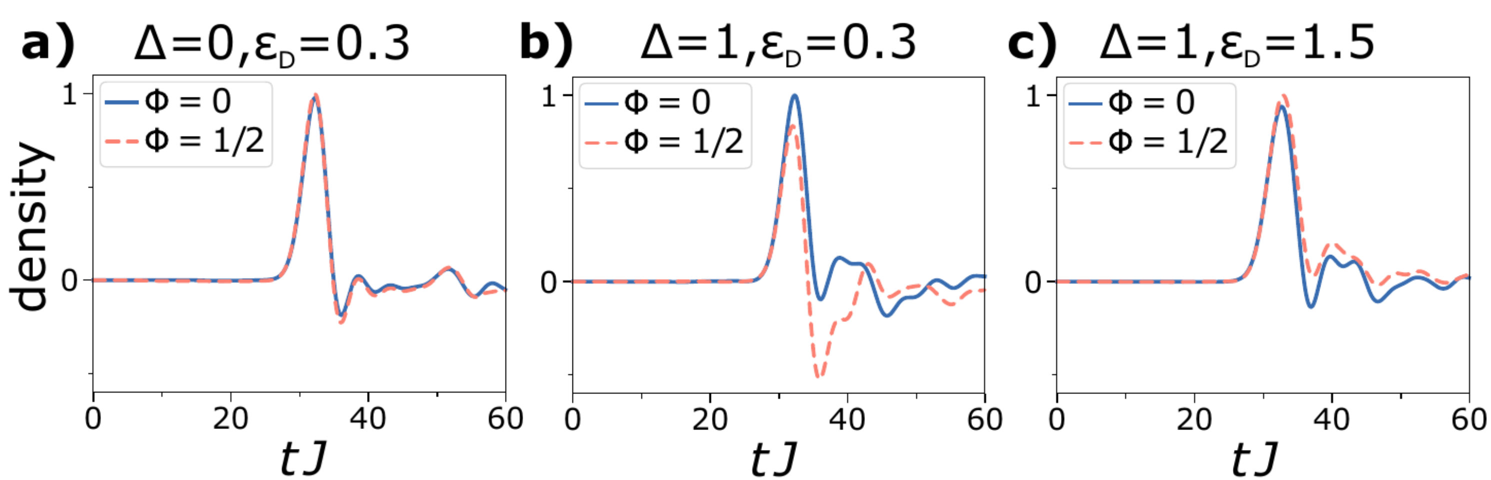
Breaking translational invariance

- Add two potential barriers Δ into the ring (Bose-Hubbard)

→Barrier disturb local phase dynamics

- Restores flux dependence for small amplitude excitations
- Large amplitude excitations AB effect disappears again

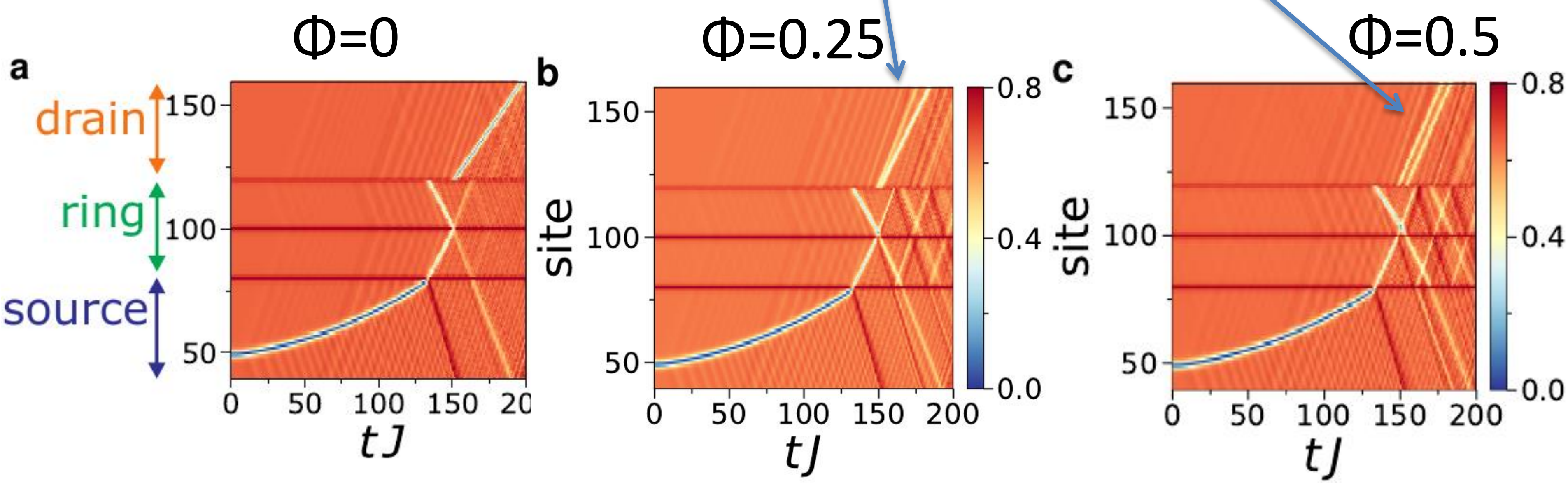




Gray soliton in ring

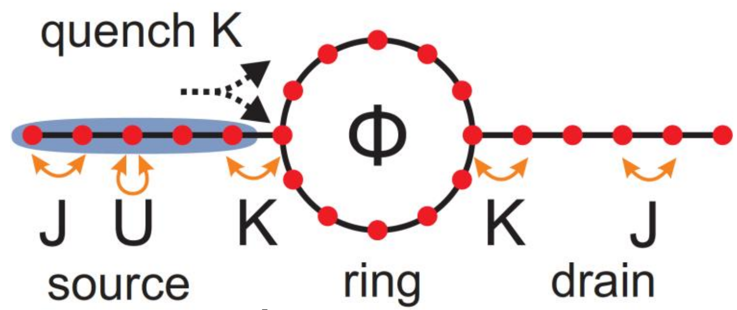
- Gray soliton passing through ring
- Soliton splits into two in transmission with flux

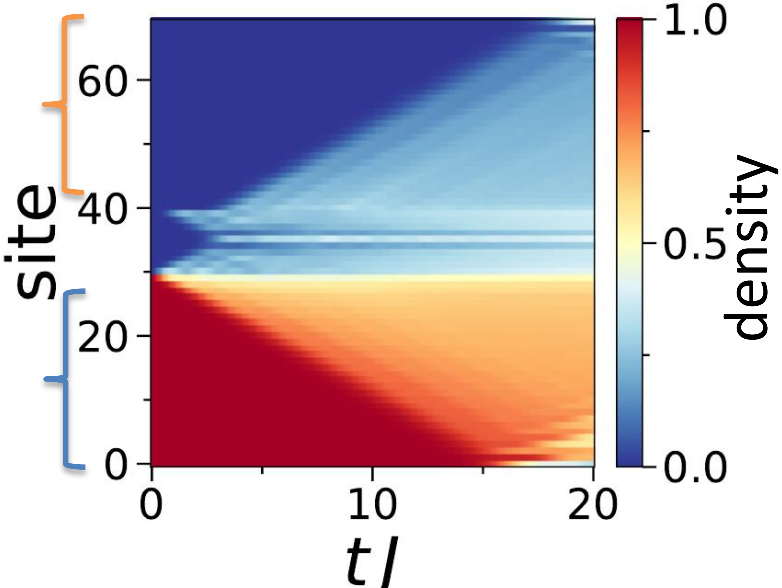
→Use to measure rotation

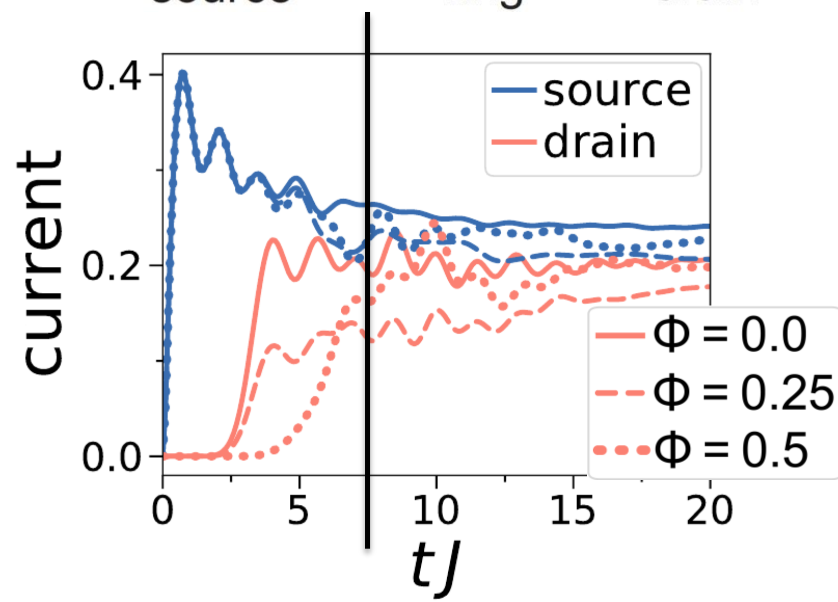


Quench of ring

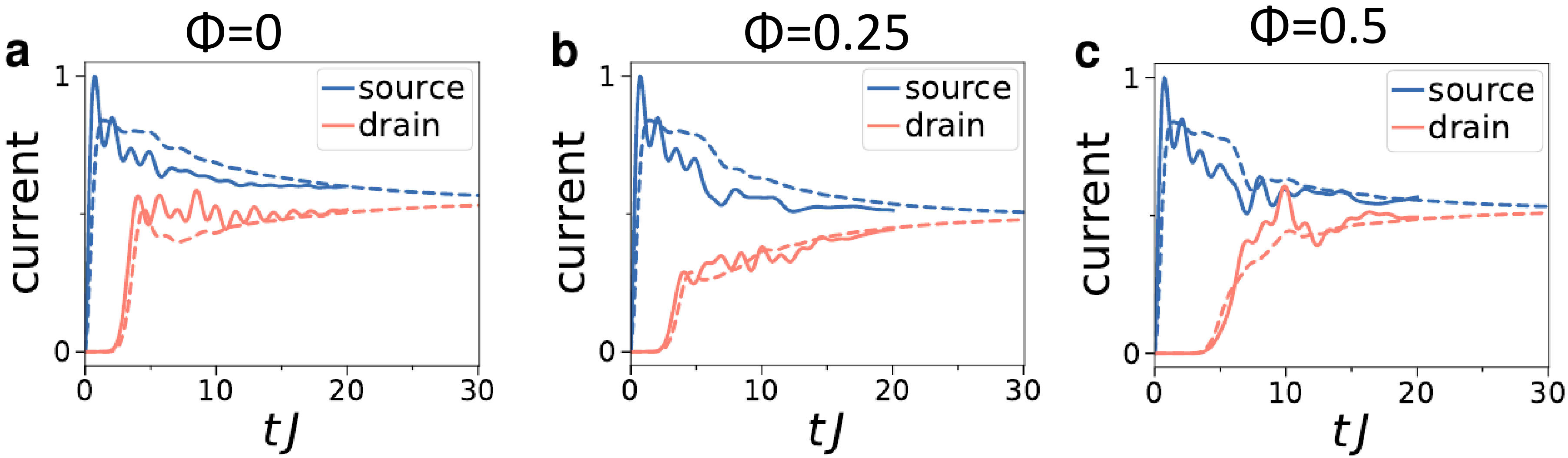
- Simulate full closed system ring + long leads (hard-core bosons)
- Initially fill only source lead with atoms
- Switch on coupling K to ring (K=J)







Towards the steady-state



- <u>Solid</u>: Full simulation of ring+lead with **tDMRG**
- <u>Dashed</u>: Approximate leads as **Markovian baths:** Open system with Lindblad + ring
- For Φ=0.5, current into drain starts later
- For Φ=0.25, current increases slower
- **Dynamics depends on flux**, however **steady-state** nearly **independent** of **flux**

Conclusion

Y-junction:

- Different types of reflection (Andreev-like, positive-negative, positive) controlled by the coupling strength
- GPE shows different behavior than Bose-Hubbard (no weak coupling regime)

Ring:

- Aharonov-Bohm effect **suppressed for bosons**
- Can be restored by breaking translational invariance
- Solitons could measure flux in ring device
- Quench dynamics is **flux dependent**, **steady-state not**

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arXiv:1706.05180