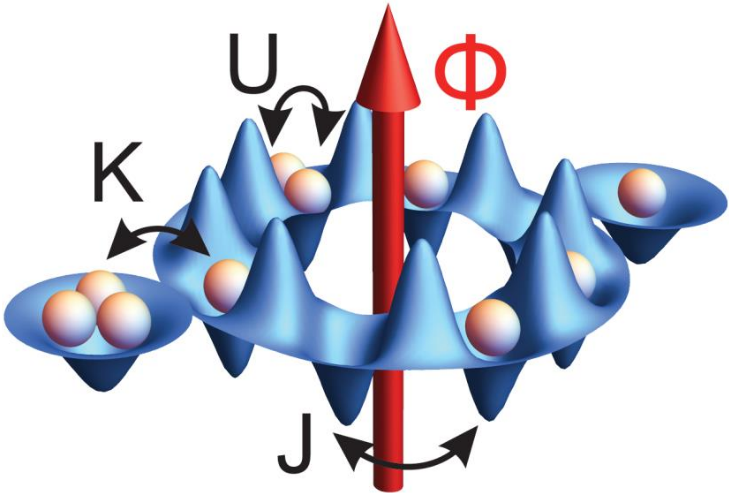
The Aharonov-Bohm effect in mesoscopic Bose-Einstein condensates

arXiv:1706.05180

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

12.09.2017



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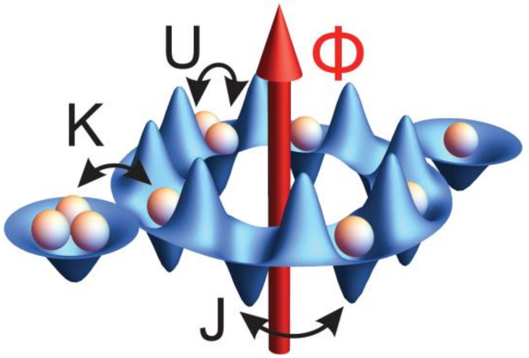
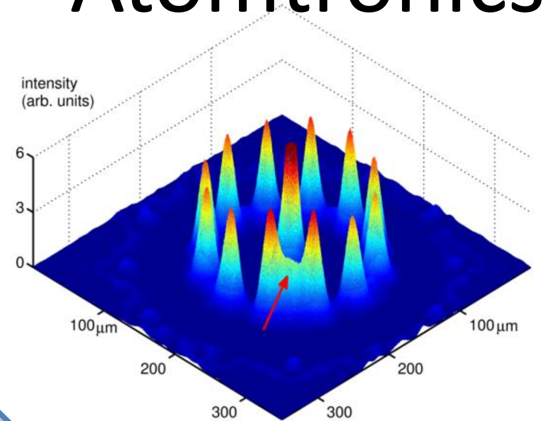
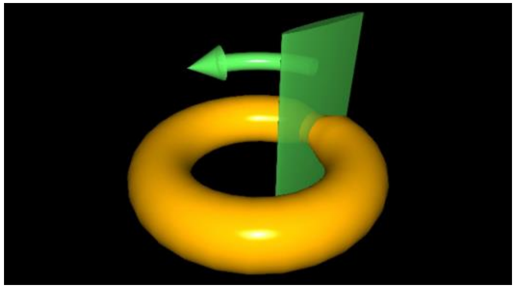
Atomtronics







Aharonov-Bohm effect

T. Haug, H. Heimonen, R. Dumke, L.-C. Kwek, L. Amico *arXiv:1706.05180*

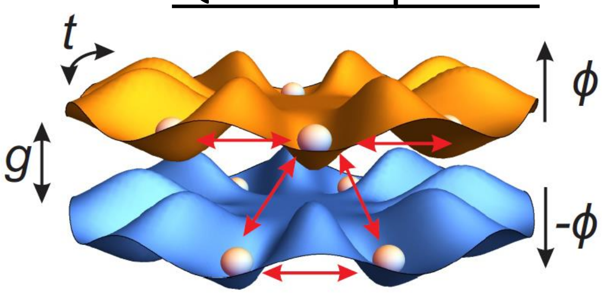
Time-dependent potential?

Cold atoms + potential shaping (DMD)+

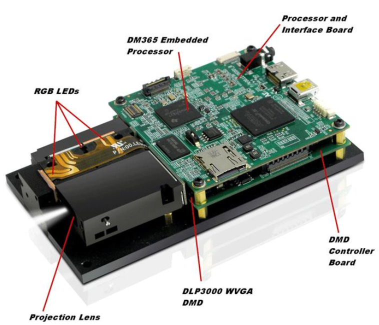
control currents

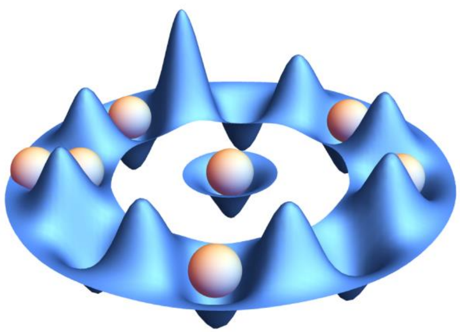
AQUID read-out

Quantum phases



T. Haug, L. Amico, R. Dumke, L.-C. Kwek *arXiv:1612.09109*





T. Haug, J. Tan, M. Theng, R. Dumke, L.C. Kwek, L. Amico *arXiv:1707.09184*

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L. Amico, D. Aghamalyan, F. Auksztol, H. Crepaz, R. Dumke, L.C. Kwek *Scientific reports 4* (2014)

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 controls current in device

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Quantum Oscillations and the Aharonov-Bohm Effect for Parallel Resistors

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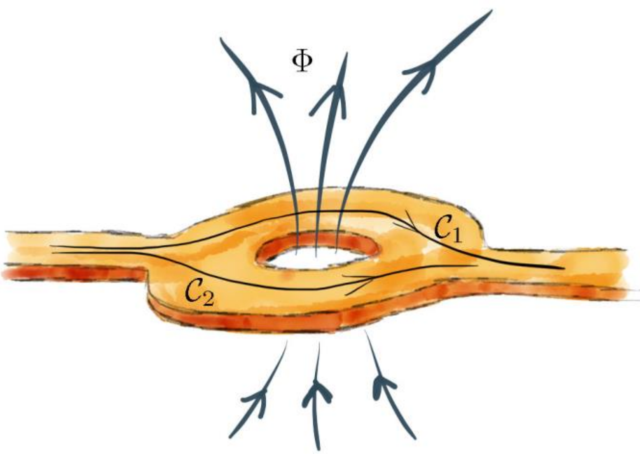

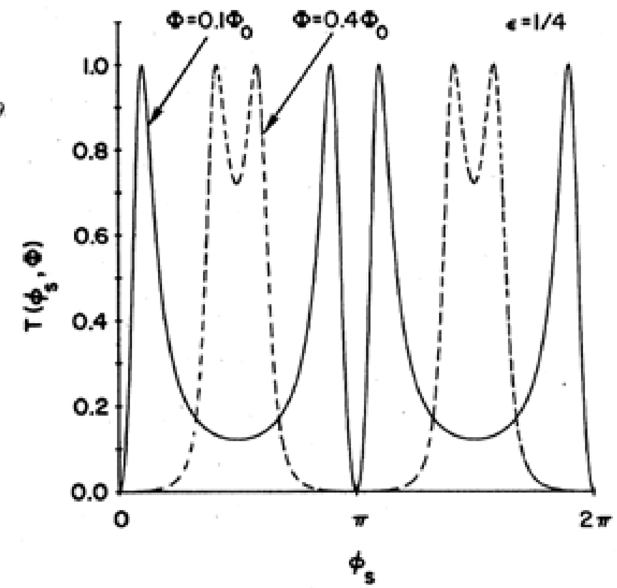

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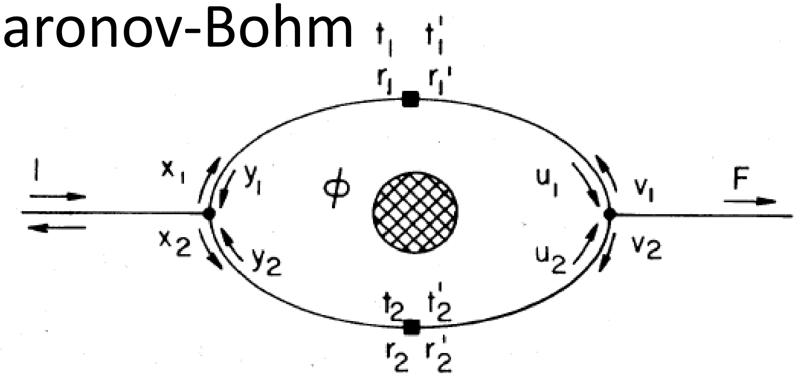
Ultracold atom AB-effect

- Study with solid state devices restricted
- Effect of particle interaction on Aharonov-Bohm effect?
- Particle statistics?
- Time dynamics?
- New possible applications?



- Atomtronics for
  - Controlled potential landscape
  - Access to current/density distribution

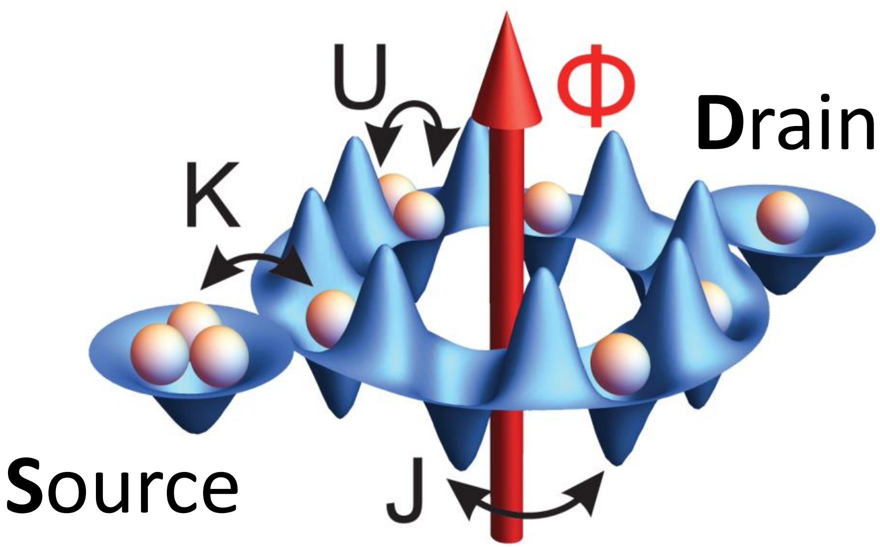
Model

- Bose-Hubbard ring with *L* sites coupled to leads

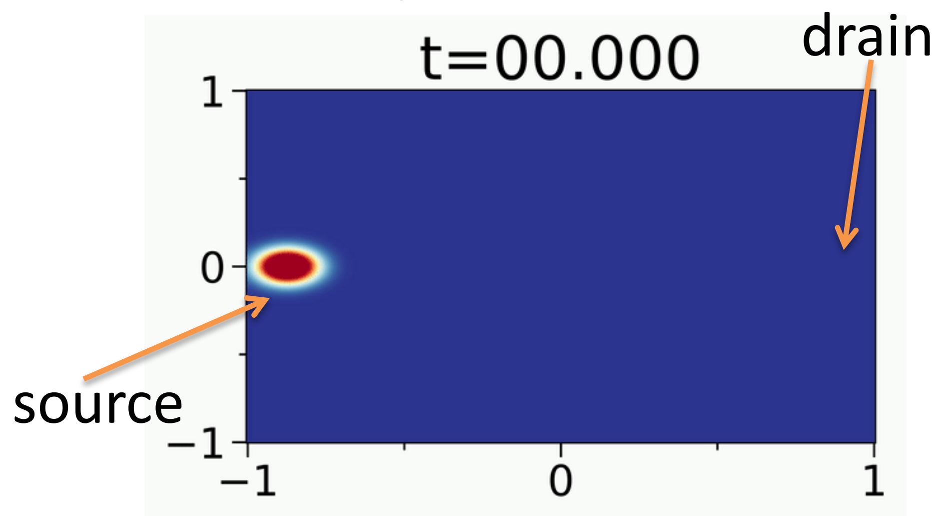
$$\mathcal{H} = \mathcal{H}_{\mathrm{R}} + \mathcal{H}_{\mathrm{L}}$$

$$\mathcal{H}_{\mathrm{R}} = -\sum_{j=0}^{L-1}\left(Je^{i2\pi\Phi/L}\hat{a}_j^{\dagger}\hat{a}_{j+1} + \mathrm{H.C.}\right) + \frac{U}{2}\sum_{j=0}^{L-1}\hat{n}_j(\hat{n}_j - 1)$$

$$\mathcal{H}_{\mathrm{L}} = -K(\hat{a}_S^{\dagger}\hat{a}_0 + \hat{a}_D^{\dagger}\hat{a}_{L/2} + \mathrm{H.C.})$$

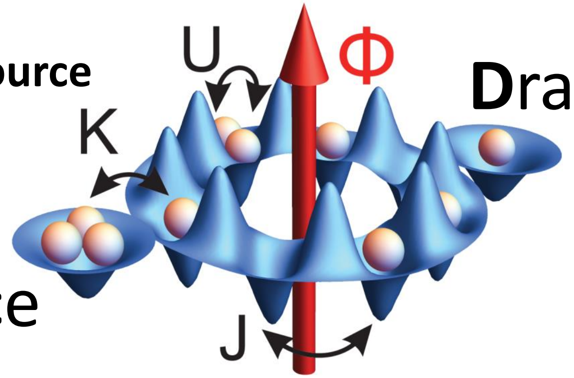


Initially, all atoms are in source



Drain time evolution

Initially, all atoms are in source
→Drain dynamics



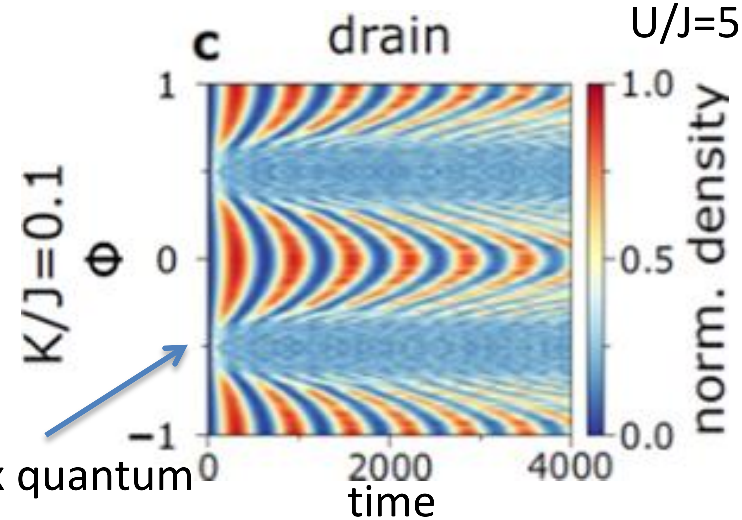
Weak-coupling K/J=0.1: Regular source-drain oscillations

- Flux modifies periodicity
- Small ring population → minor effect of atom-atom interaction

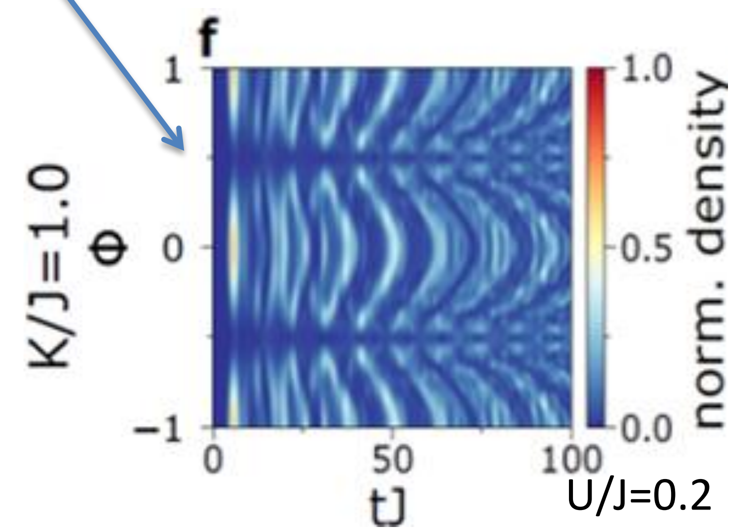
Strong-coupling K/J=1.0: Unregular, small oscillations

- Ring highly populated→ Atom-atom interaction has strong effect, washes out patterns

U/J=5



½ flux quantum



U/J=0.2

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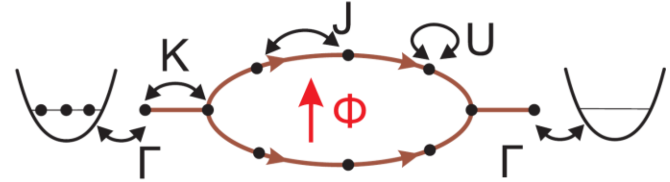
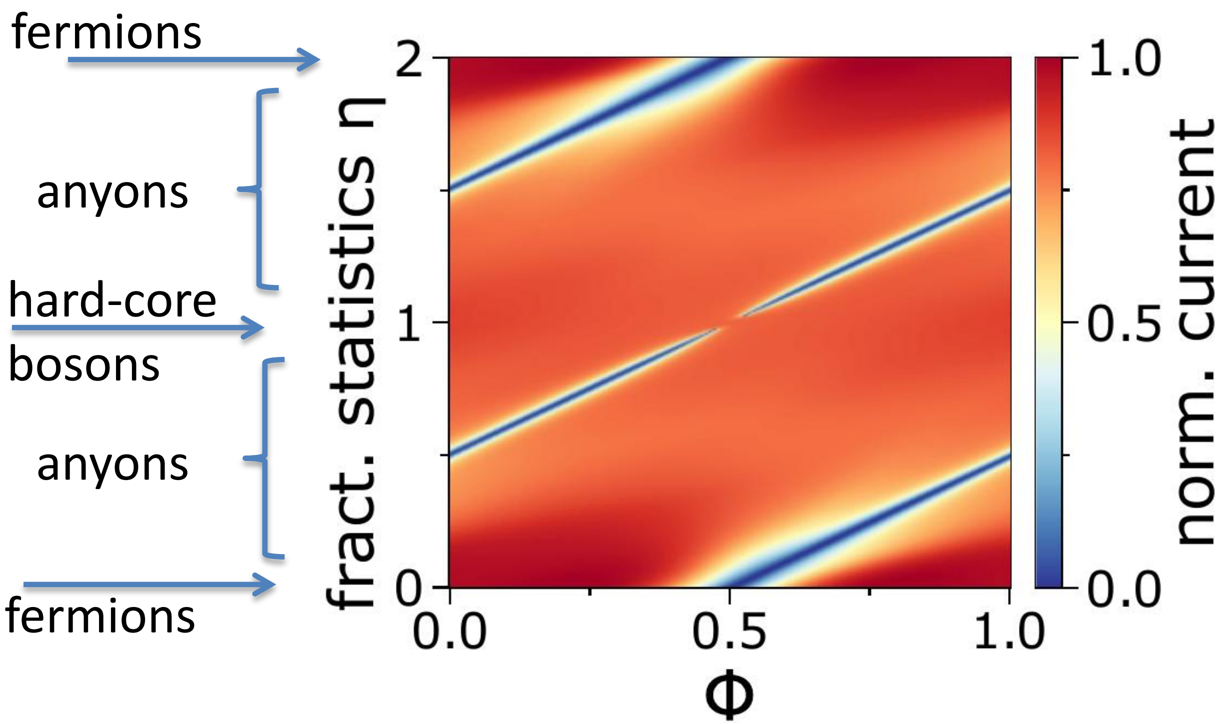
Steady-state current



$$\hat{a}_n^\dagger \hat{a}_m^\dagger + e^{i\pi\eta} \hat{a}_m^\dagger \hat{a}_n^\dagger = 0$$

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H,\rho] - \frac{1}{2}\sum_m \left\{\hat{L}_m^\dagger \hat{L}_m, \rho\right\} + \sum_m \hat{L}_m \rho \hat{L}_m^\dagger$$

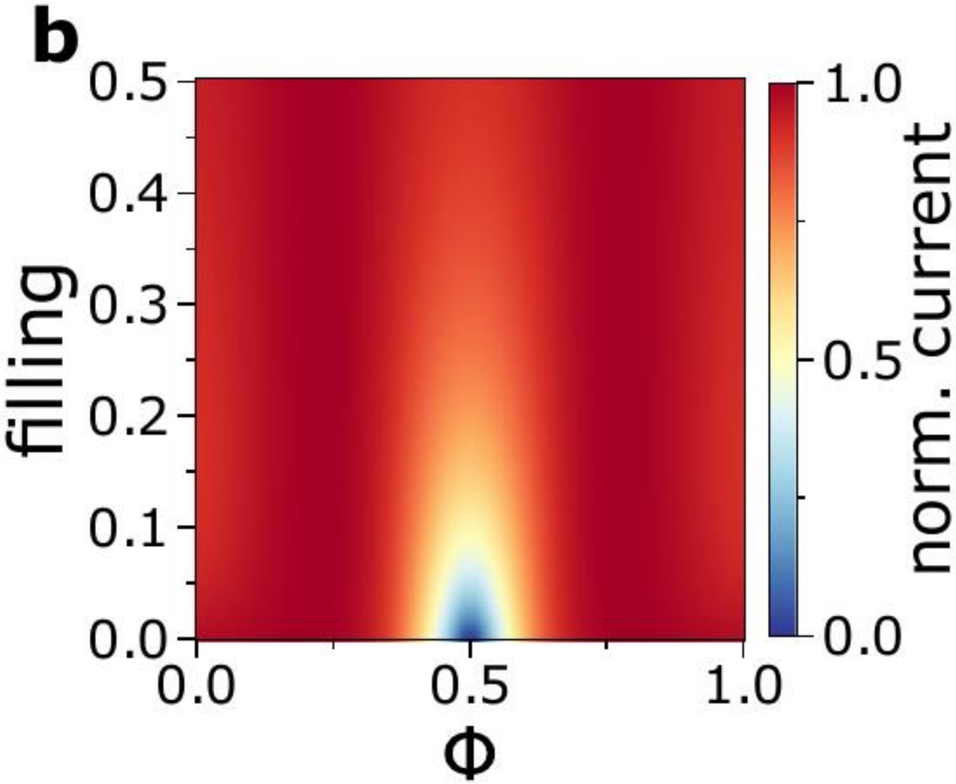
- Attach bath to leads→ induce current
- Strong on-site interaction→ only one particle per site
- Generalize particle commutation rules η → fractional statistics



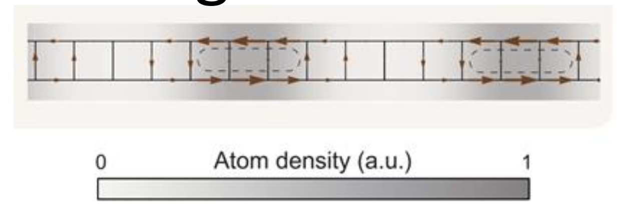
- Current **nearly constant** for strongly interacting Bosons: No Aharonov-Bohm effect

Interaction

Increase boson filling factor →Aharonov-Bohm effect vanishes



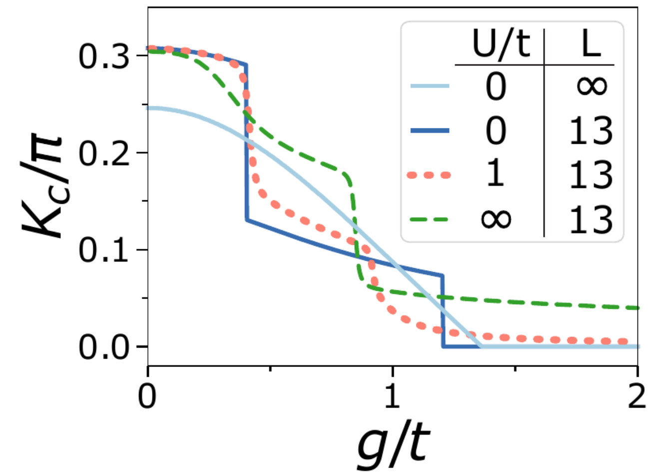
Mesoscopic Vortex-Meissner currents in ring ladders

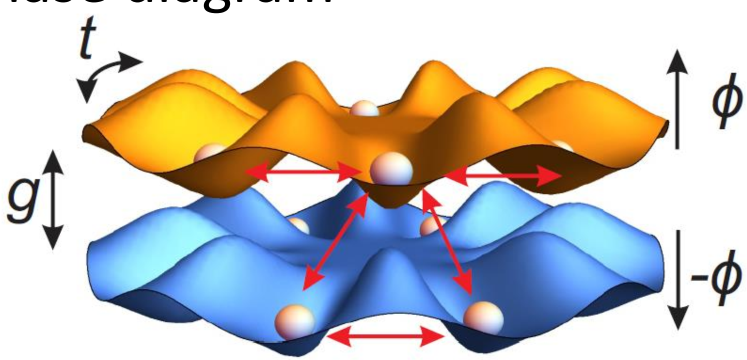


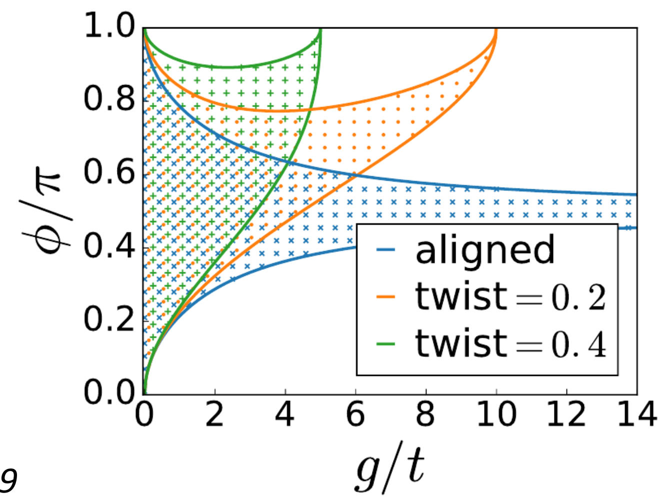
- Ladder with artificial gauge field realizes a Meissner-Vortex phase transition **[1]**

  →mesoscopic ring ladder **[2]**

- Mesoscopic size and ring geometry modify order parameter→ shift in value & step structure
- Potential shaping generates re-entrance in phase diagram







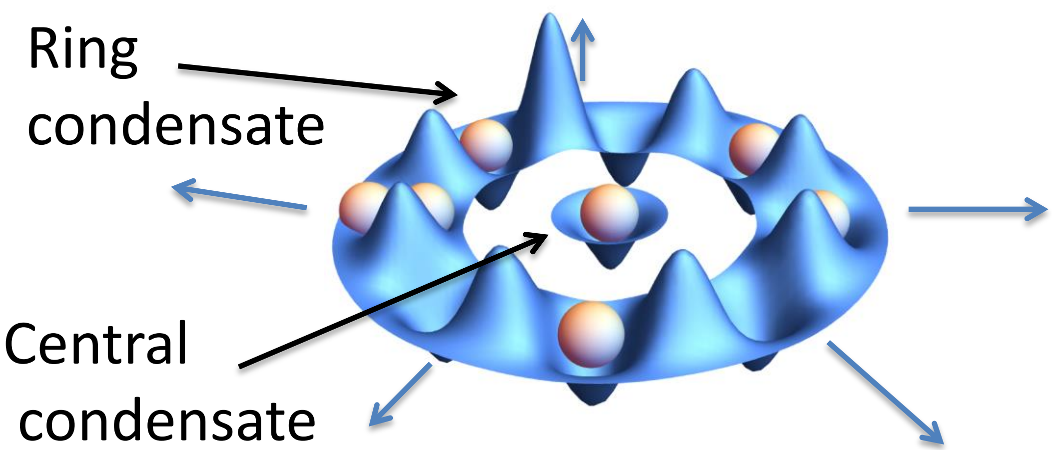
[1] M. Atala, et. al. *Nature Physics 10, 588 (2014)*

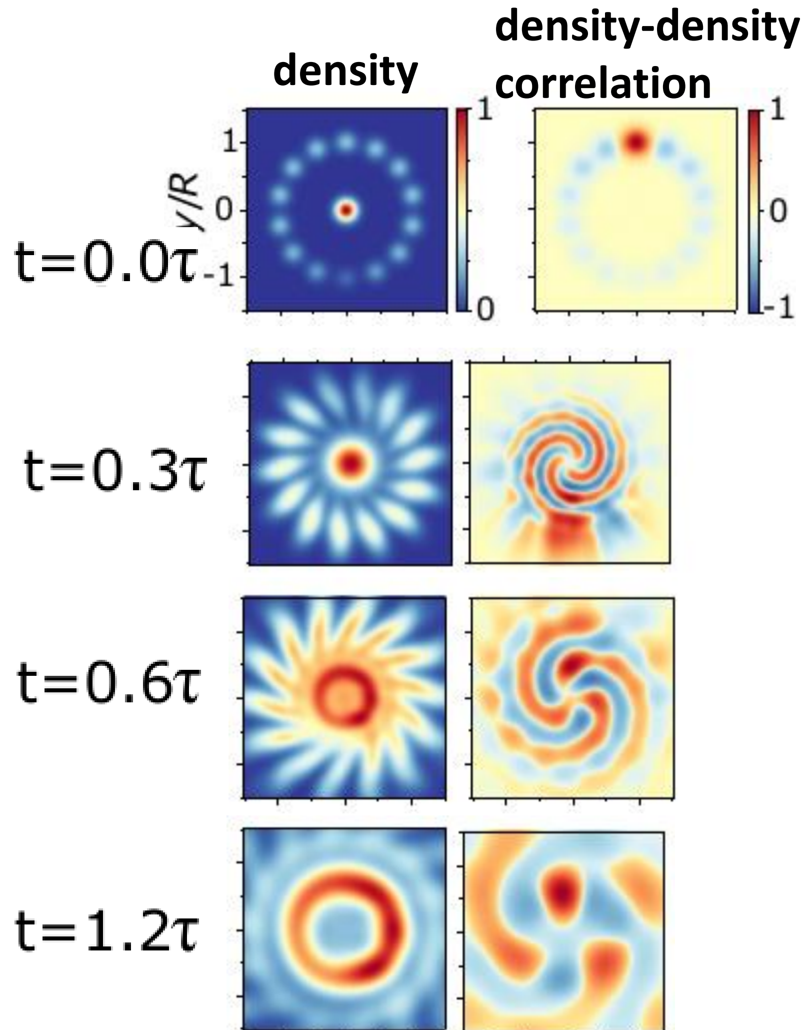
[2] Tobias Haug, Luigi Amico, Rainer Dumke, Leong-Chuan Kwek, *arXiv:1612.09109*

Read-out of the atomtronic quantum interference device

T. Haug, ***J. Tan, M. Theng***, R. Dumke, L.C. Kwek, L. Amico

- Rotating ring condensate co-expanding with central condensate (phase reference) **[1]**
- Density-density correlations reveals winding **[2]**
- Can extract information about superposition state/qubit quality





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[2] T. Haug, *J. Tan, M. Theng*, R. Dumke, L.C. Kwek, L. Amico, arXiv:1707.09184

Conclusion

- Atomtronics to shape potentials & control currents
- Investigate **quantum phases**
- Basis for quantum bit (**AQUID**), controlled read-out

- Cold atoms for Aharonov-Bohm devices
- Time evolution and interaction changes non-trivial with weak/strong lead-ring coupling
- Aharonov-Bohm effect washed out for interacting bosons
- Simulate physics (e.g. Kondo-effect)