Atomtronics: Towards Sensors and Devices with Ultracold Atoms and Optical Lattices

L.C. Kwek

New Advances in Quantum Information Science And Quantum Technology
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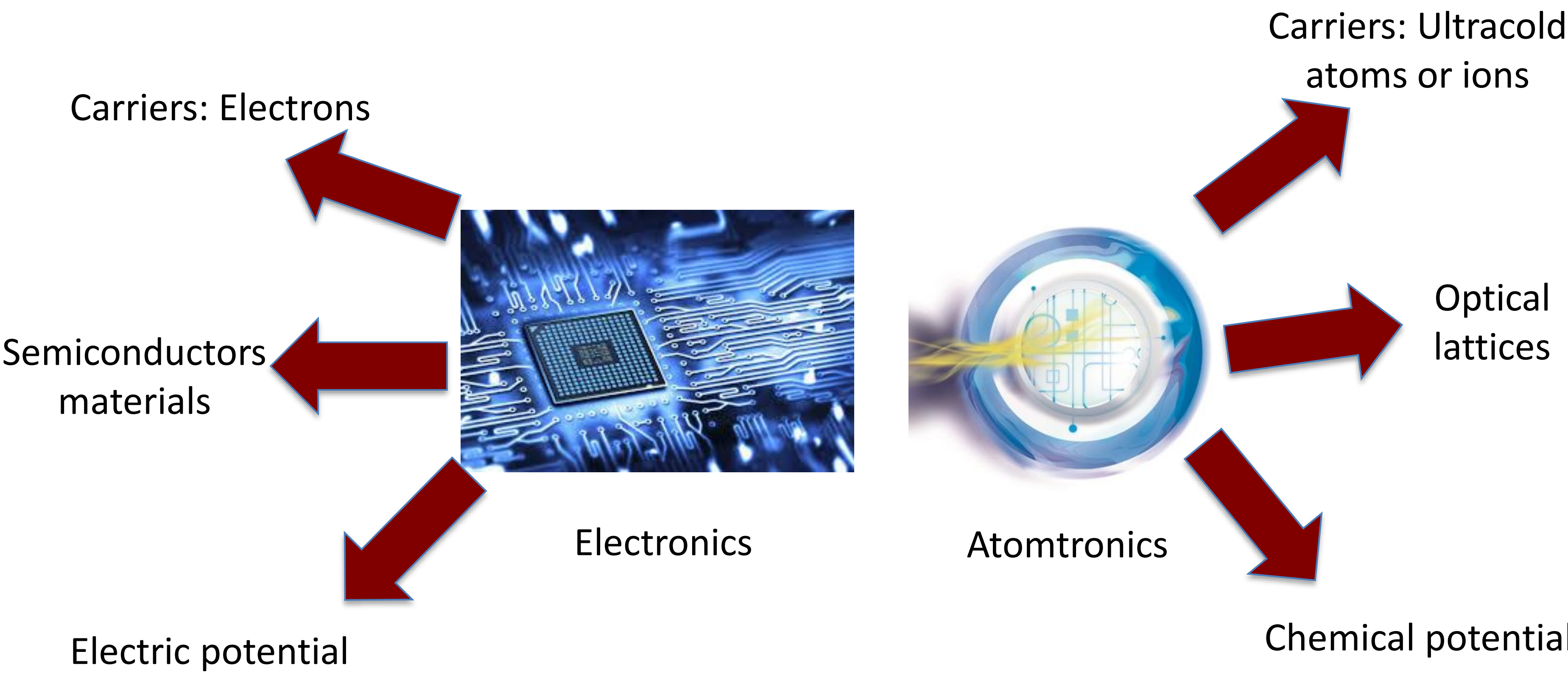
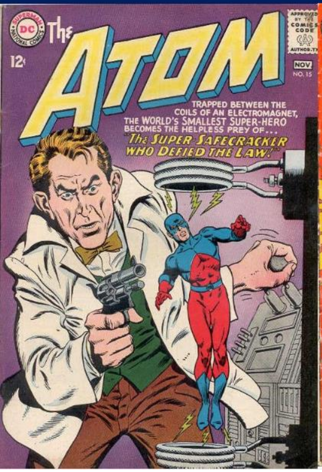
Comparison between atomtronics (iontronics) and electronics

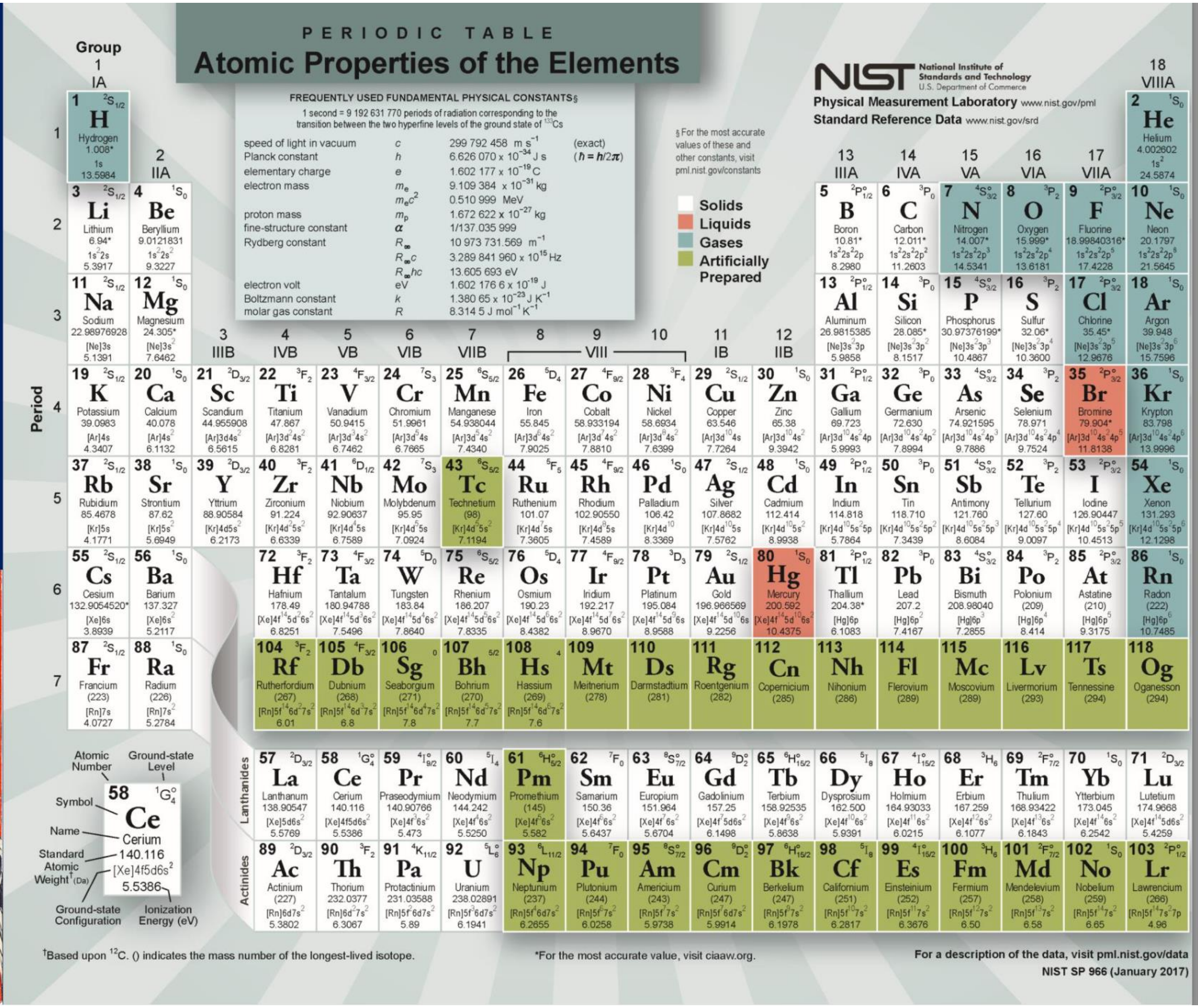


Atoms

- Identical
- Stable
- Quantum
- Diverse

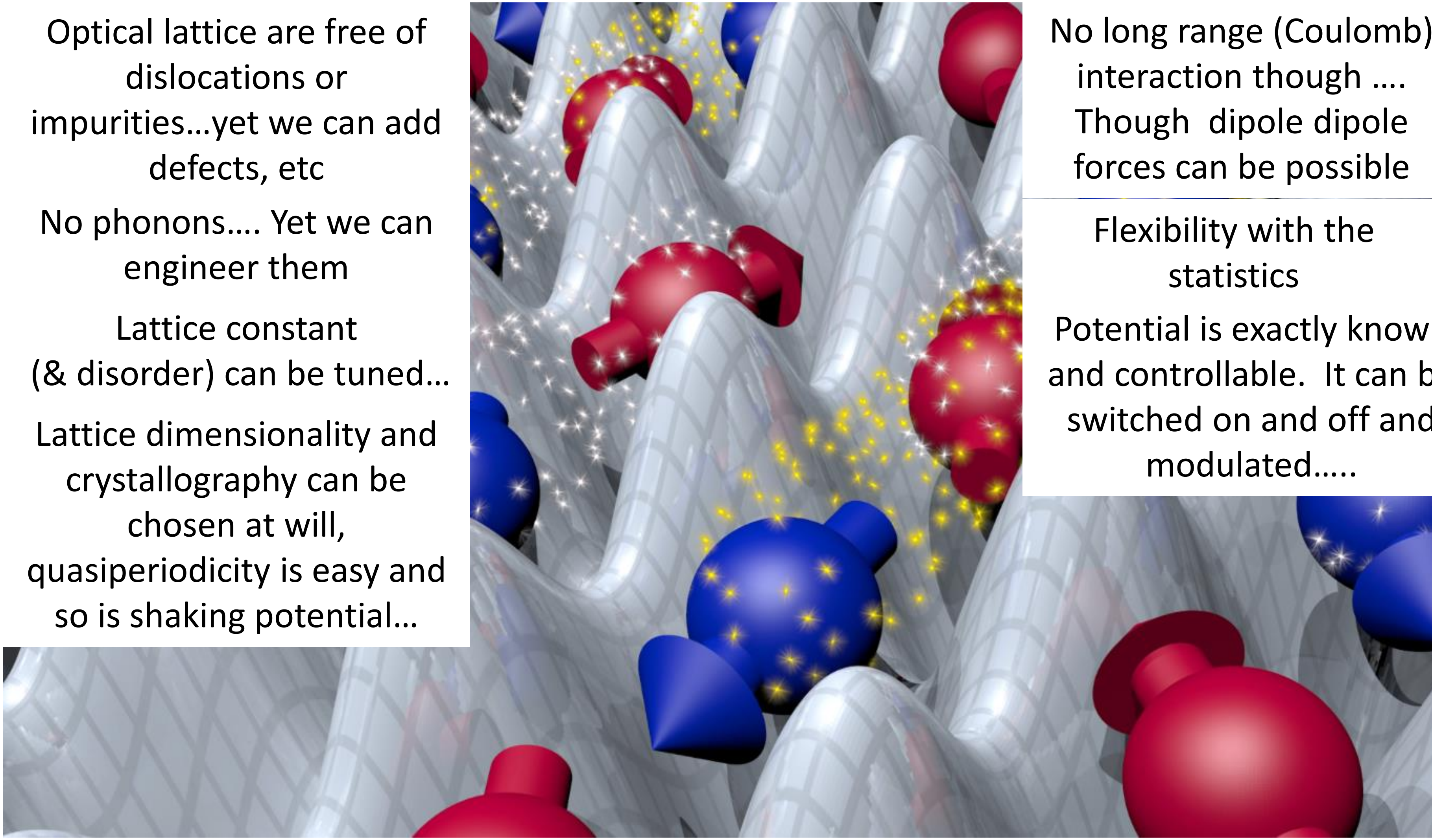


Images: DC Comics



Source: Charles Clark

Atoms in an optical lattice



Optical lattice are free of dislocations or impurities…yet we can add defects, etc

No phonons…. Yet we can engineer them

Lattice constant (& disorder) can be tuned…

Lattice dimensionality and crystallography can be chosen at will, quasiperiodicity is easy and so is shaking potential…

No long range (Coulomb) interaction though …. Though dipole dipole forces can be possible

Flexibility with the statistics

Potential is exactly known and controllable. It can be switched on and off and modulated…..

Atomtronics applications

New Journal of Physics Focus on Atomtronics-enabled Quantum Technologies

http://j.mp/At0mtr0nics

Precision measurement – quantum-enhanced clocks, matter-wave interferometry

Sensing: magnetometry, gravity/gradiometry, rotation, acceleration

Novel scanning probe microscopy

Novel superconductivity and superfluidity

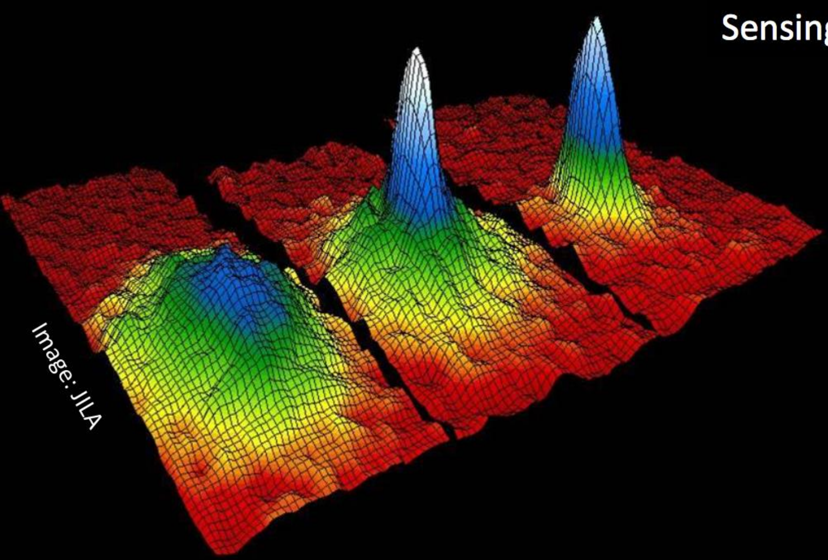
Experimental quantum logic

Novel magnetism and synthetic magnetic fields

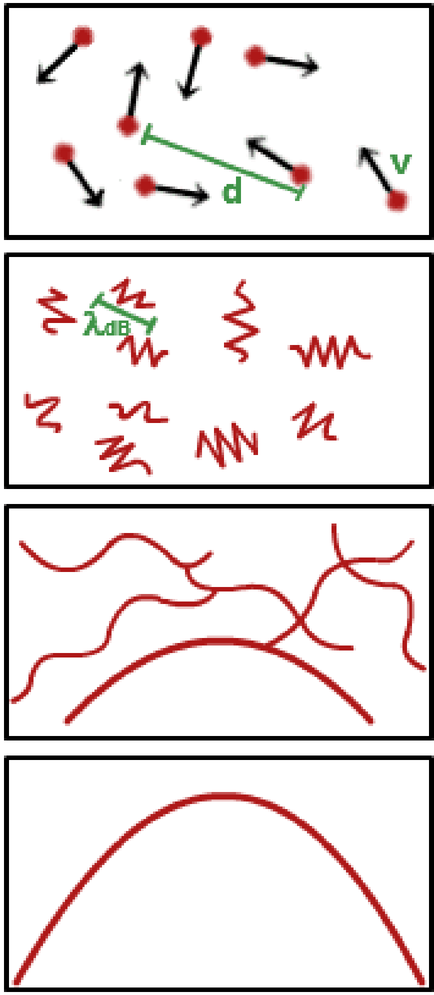
Simulating complex quantum systems

Macroscopic transport devices

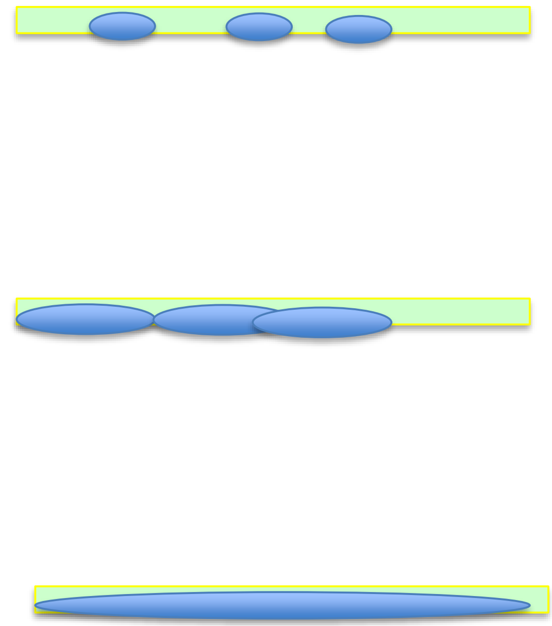
Topological effects and exotic particles…



Source: Charles Clark



$T = T_{Crit}$:
Bose - Einstein Condensation
$\lambda_{dB} \text{ - } d$
"Matter wave overlap"



BEC

Atomtronic Circuits of Diodes and Transistors

R. A. Pepino, J. Cooper, D. Z. Anderson, and M. J. Holland

JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, Colorado 80309, USA

(Received 22 May 2007; revised manuscript received 3 September 2009; published 28 September 2009)

We illustrate that open quantum systems compose
optical lattices can exhibit behavior analogous to semi
demonstrated for bosonic atoms, and the experime
established. The analysis follows from a derivation of
of open quantum systems.

DOI: 10.1103/PhysRevLett.103.140405

diagram. The atom analog of a bipolar junction trans
building blocks for more advanced atomtronic devic
mental logic gates.

[1] B. T. Seaman, M. Kramer, D. Z. Anderson, and M. J. Holland, Phys. Rev. A 75, 023615 (2007).
[2] A. Ruschhaupt and J. G. Muga, Phys. Rev. A 70, 061604 (R) (2004).
[3] A. Ruschhaupt, J. G. Muga, and M. G. Raizen, J. Phys. B 39, 3833 (2006).
[4] J. A. Stickney, D. Z. Anderson, and A. A. Zozulya, Phys. Rev. A 75, 013608 (2007).
[5] A. Micheli, A. J. Daley, D. Jaksch, and P. Zoller, Phys. Rev. Lett. 93, 140408 (2004).

$$\hat{H}_{\text{sys}} = -\sum_{\langle i,j\rangle} J_{ij}\hat{a}_i^\dagger \hat{a}_j + \sum_i \left(\epsilon_i \hat{N}_i + \frac{U}{2}\hat{N}_i(\hat{N}_i - 1)\right), \quad (2)$$

where site i has energy ϵ_i, interaction energy U, and annihilation and number operators $\hat{a}_i$ and $\hat{N}_i = \hat{a}_i^\dagger \hat{a}_i$, respectively, and J_{ij} is the hopping energy between adjacent sites i and j. To achieve a steady-state current, atomtronic circuits require two or more reservoirs held at different chemical potentials. The free Hamiltonian for the reservoirs is

$$\hat{H}_{\text{res}} = \sum_{\nu,l} \hbar\omega_{\nu l} \hat{R}_{\nu l}^\dagger \hat{R}_{\nu l}, \quad (3)$$

where ν identifies the mode of reservoir l with energy $\hbar\omega_{\nu l}$ and annihilation operator $\hat{R}_{\nu l}$. It is assumed that each reservoir is so large that its thermodynamic properties are parametrized by a constant chemical potential μ_l and temperature T_l. Each reservoir is connected to a single system site s_l so that the interaction between the system and reservoir can be written as

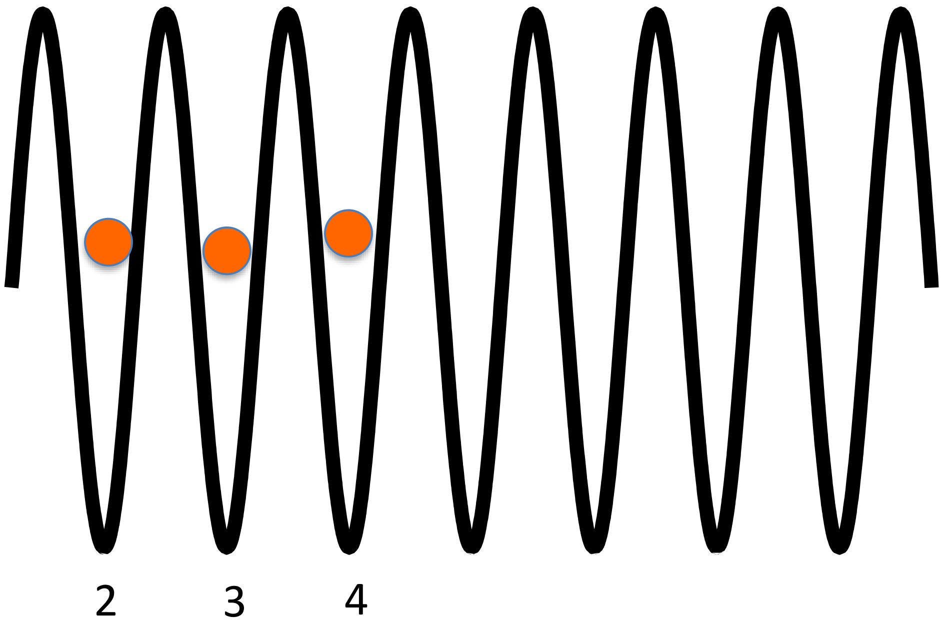
$$\hat{H}_V = \sum_{\nu,l} g_{\nu l} \hat{R}_{\nu l}^\dagger \hat{a}_{s_l} + \text{H.c.}, \quad (4)$$

Bose-Hubbard Model

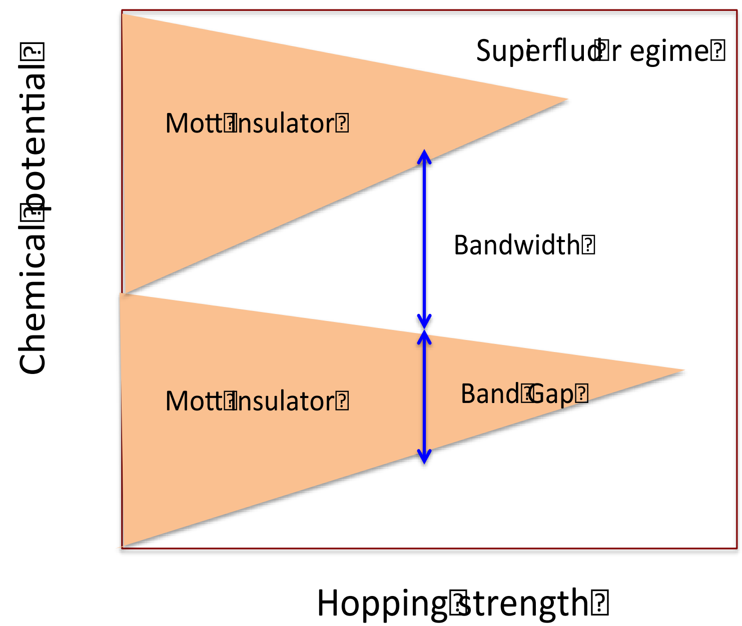
$$\hat{H} = \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) - J\sum_{\langle ij \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i (\epsilon_i - \mu)\hat{n}_i,$$

Ref: Seaman et al, PRA, 75, 023615 (2007)

Coulomb interaction



$$\hat{a}_3^\dagger \hat{a}_2$$



PHYSICAL REVIEW A **75**, 023615 (2007)

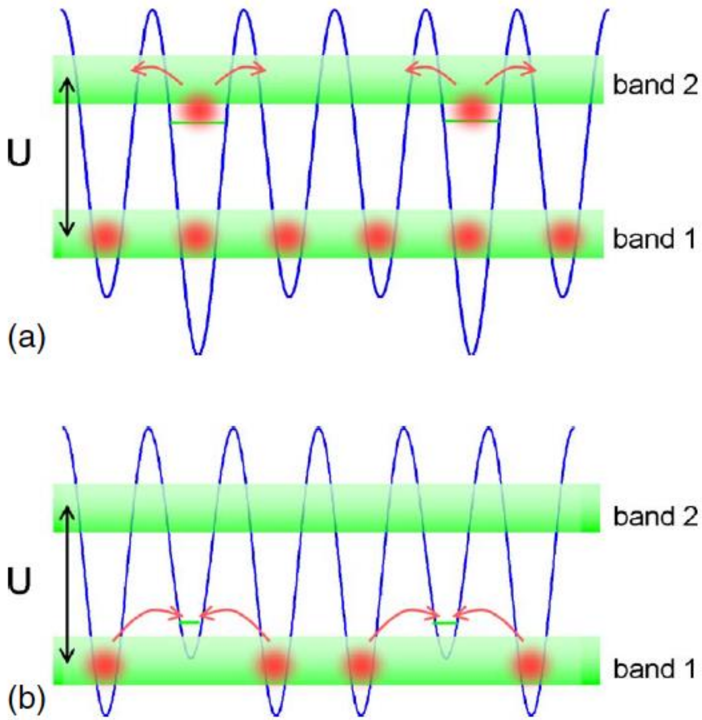
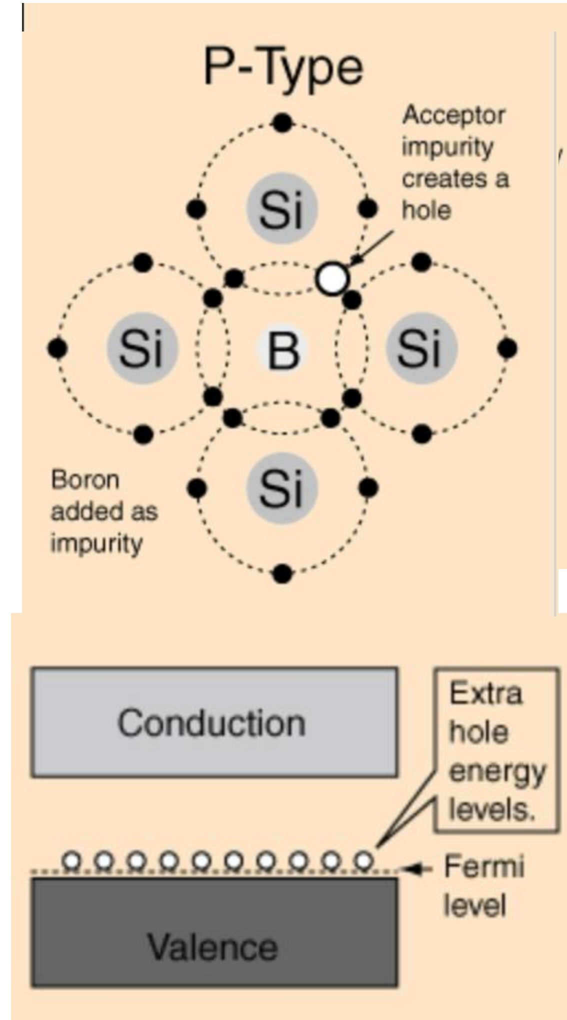
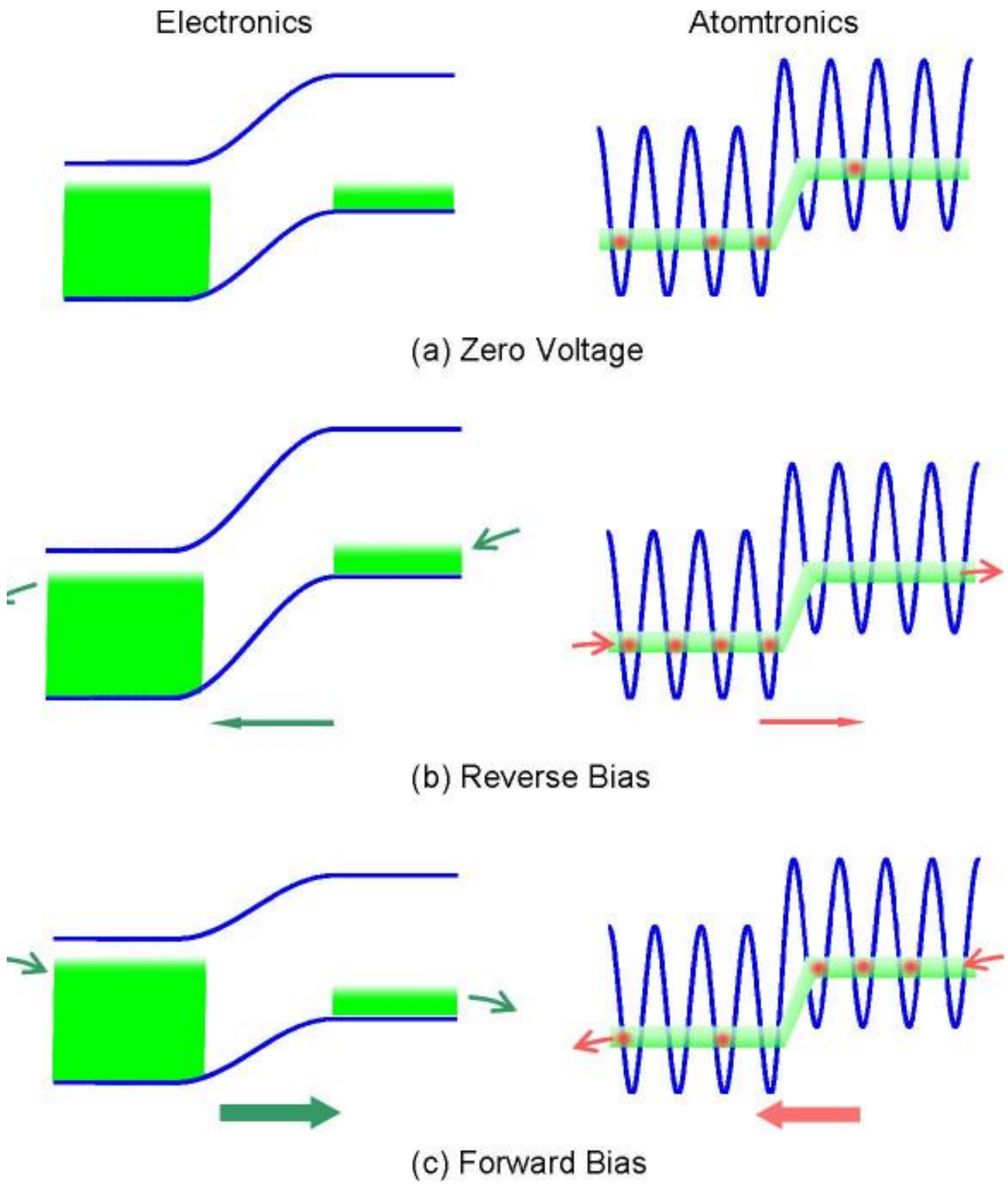


FIG. 4. (Color online) (a) Schematics of an *N*-doped lattice. The donor sites feature a level right below the first empty many-body band. An atom which occupies this level can easily be excited and move throughout the lattice. (b) Schematics of a *P*-doped lattice. Acceptor sites have a level right above the highest full band. Atoms can easily be excited into this level and allow for a hole to move throughout the lattice.



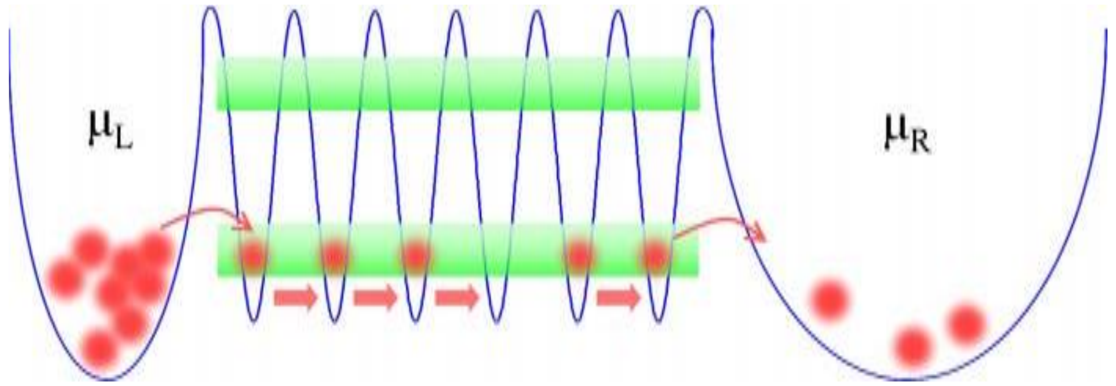
N-Doped lattice

P-Doped lattice



B. T. Seaman, M. Kramer, D. Z. Anderson, and M. J. Holland, Phys. Rev. A 75, 023615 (2007).

Battery



New J. Phys. **19** (2017) 013036 https://doi.org/10.1088/1367-2630/aa56d8

New Journal of Physics

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PAPER

Experimental demonstration of an atomtronic battery

Seth C Caliga[1], Cameron J E Straatsma[2] and Dana Z Anderson[1,3]

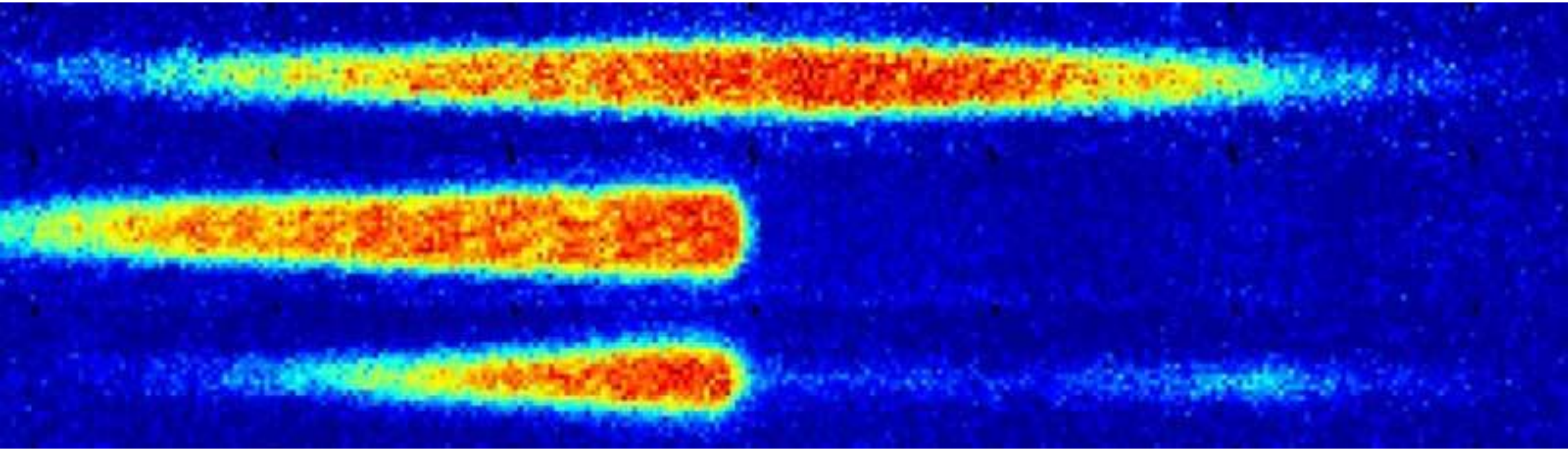
[1] JILA and Department of Physics, University of Colorado and National Institute of Standards and Technology, Boulder, CO 80309-0440, United States

[2] JILA and Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309-0440, United States

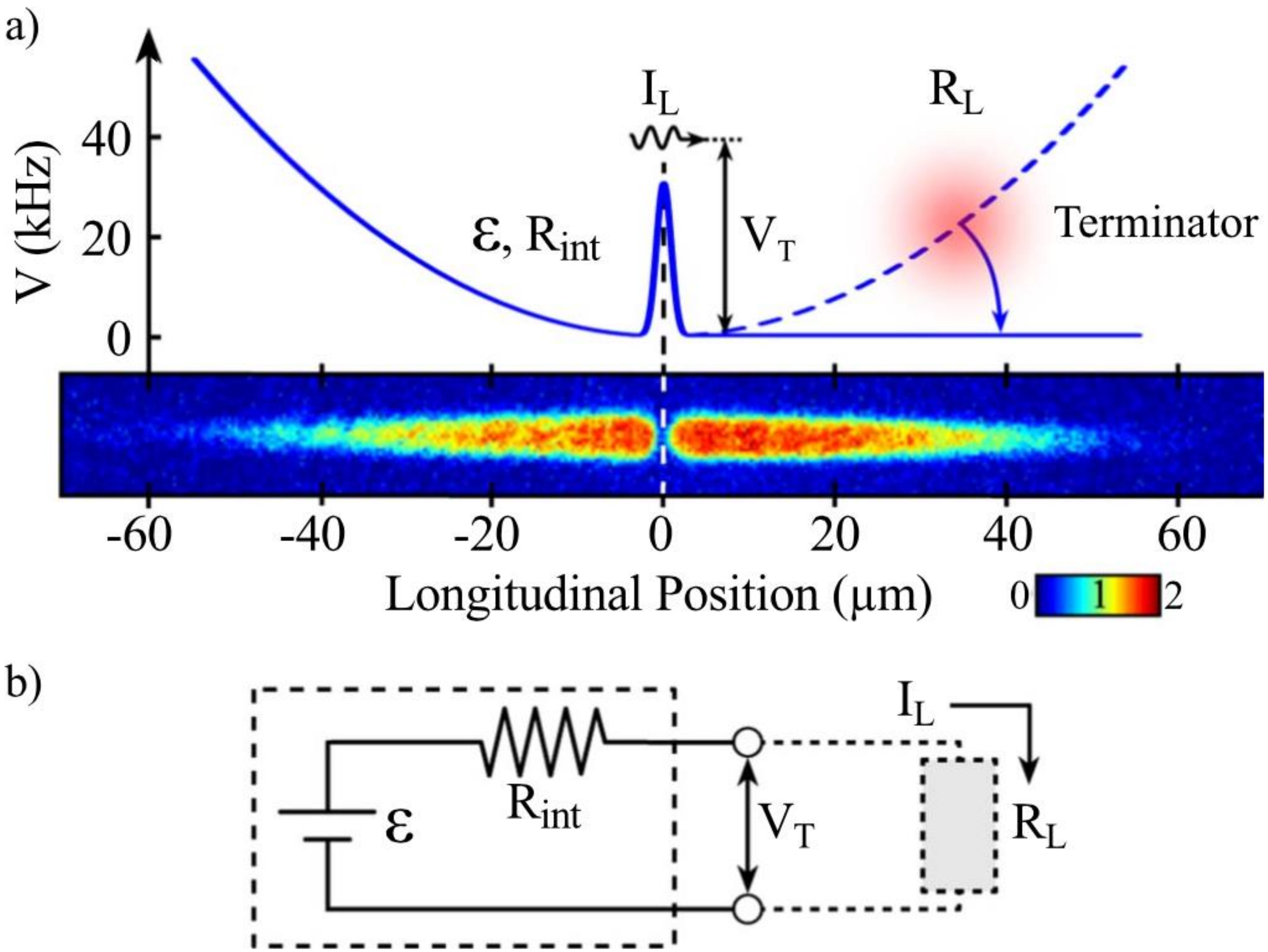
[3] Author to whom any correspondence should be addressed.

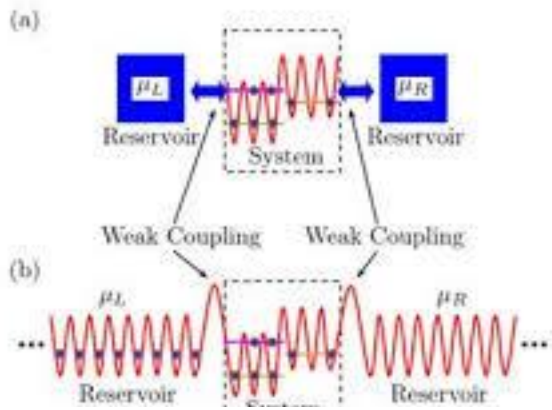
E-mail: dana@jila.colorado.edu

Keywords: atomtronics, battery, finite-temperature, Bose–Einstein condensate



The top image shows the Bose-Einstein condensate (BEC) in a cigar-shaped trap. The middle image shows the BEC after the atoms are swept to the left by an optical potential. The bottom image shows a current of atoms flowing from the left half of the trap into the right. (Courtesy: Seth Caliga *et al.*/*New Journal of Physics*).


a)
V (kHz)
40
20
0
I_L
R_L
ε, R_{int}
V_T
Terminator
-60
-40
-20
0
20
40
60
Longitudinal Position (μm)
0
1
2
b)
I_L
ε
R_{int}
V_T
R_L



LETTER

doi:10.1038/nature12958

Hysteresis in a quantized superfluid 'atomtronic' circuit

Stephen Eckel[1], Jeffrey G. Lee[1], Fred Jendrzejewski[1], Noel Murray[2], Charles W. Clark[1], Christopher J. Lobb[1], William D. Phillips[1], Mark Edwards[2] & Gretchen K. Campbell[1]

Atomtronics[1,2] is an emerging interdisciplinary field that seeks to develop new functional methods by creating devices and circuits where ultracold atoms, often superfluids, have a role analogous to that of electrons in electronics. Hysteresis is widely used in electronic circuits—it is routinely observed in superconducting circuits[3] and is essential in radio-frequency superconducting quantum inter-

superfluid in the frame that rotates with the trap depends on the relative velocity between the superfluid and the trap[5,24], and the energy is proportional to $(n - \Omega/\Omega_0)^2$.

Any ring-shaped superfluid necessarily exhibits both hysteresis and a critical rotation rate, $\Omega_c^{\pm}$ (or, equivalently, a critical velocity), because all these effects fundamentally arise from the energy barrier that cre-

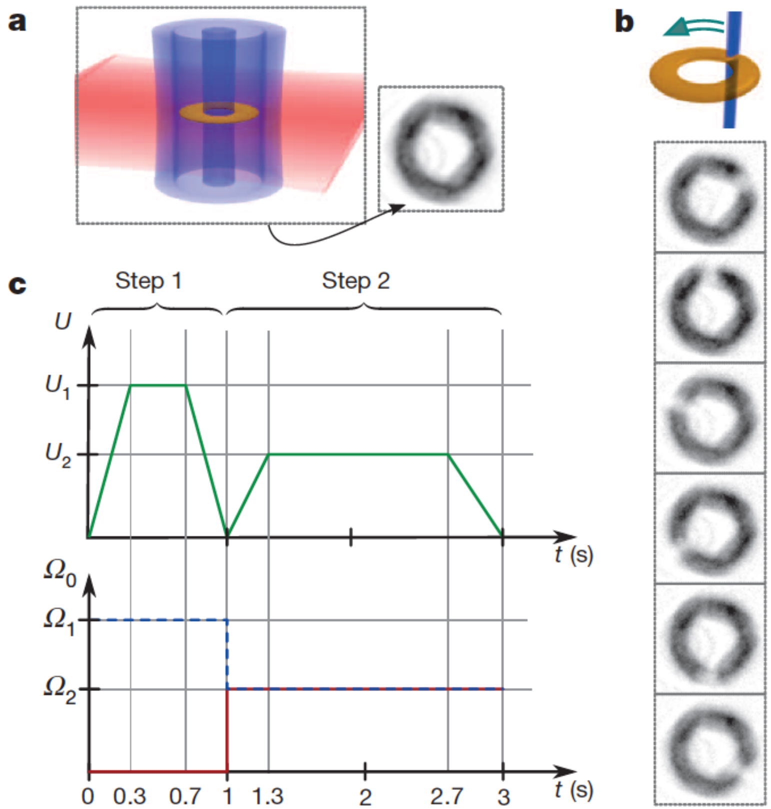
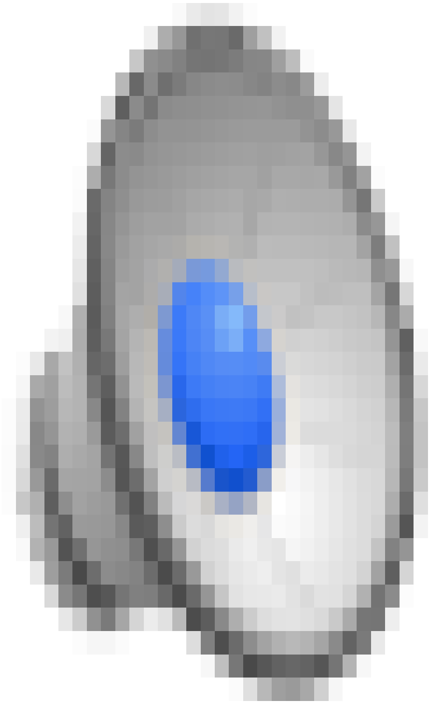


Figure 2 | Experimental set-up and procedure. **a**, Schematic and *in situ* images of our trap, which is formed by crossing a ring-shaped dipole trap for radial confinement and a sheet trap for vertical confinement. **b**, Schematic and *in situ* images of a ring rotated by a repulsive weak link. **c**, Two-step experimental sequence: the height, U, of the repulsive potential and the angular rotation rate, Ω, as a function of time. Step 1 sets the initial using Ω_1 (either 0 or 1.1 Hz) and U_1 ($\sim 1.1\mu_0$); step 2 probes Ω_2 and U_2 (see text).

Gross–Pitaevskii Equation

$$i\hbar\frac{\partial\psi}{\partial t}=(1-i\Lambda)\left[-\frac{\hbar^2}{2m}\nabla^2+V(x,y,z,t)+gN|\psi|^2-\mu\right]\psi$$

doi:10.1038/nature12958



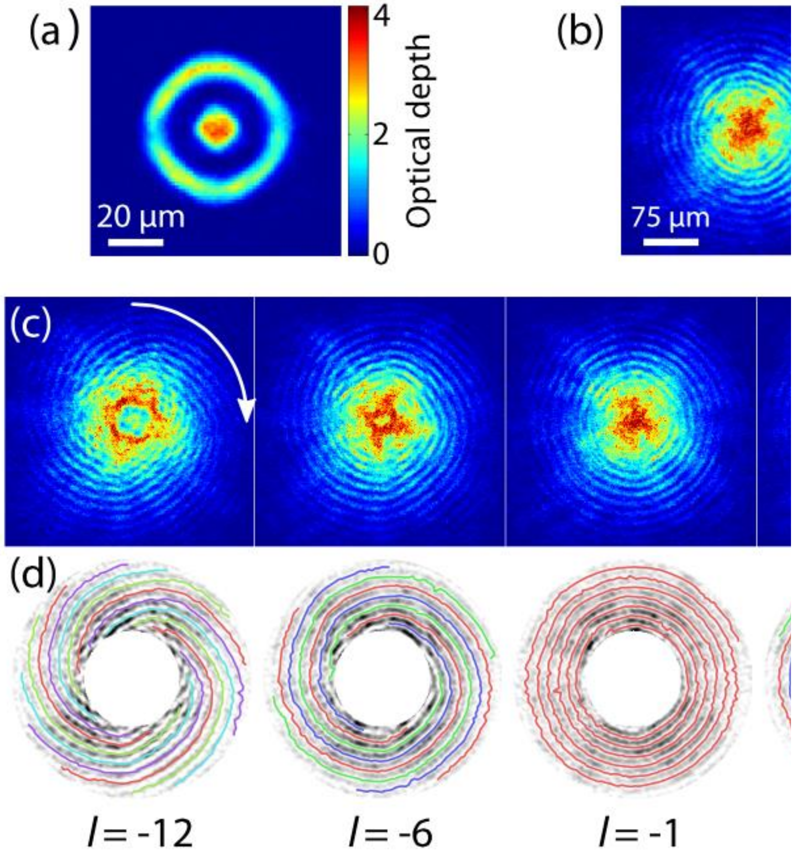


FIG. 1. (a) *In situ* image of the rin
dimensions shown. (b) Example interfer
(left) when there is no current in the ring
azimuthal interference fringes to guide t
ferograms for various winding numb
indicates the direction of flow. (d) Tra
fringes to guide the eye and count the nu
extracted winding number is shown bel

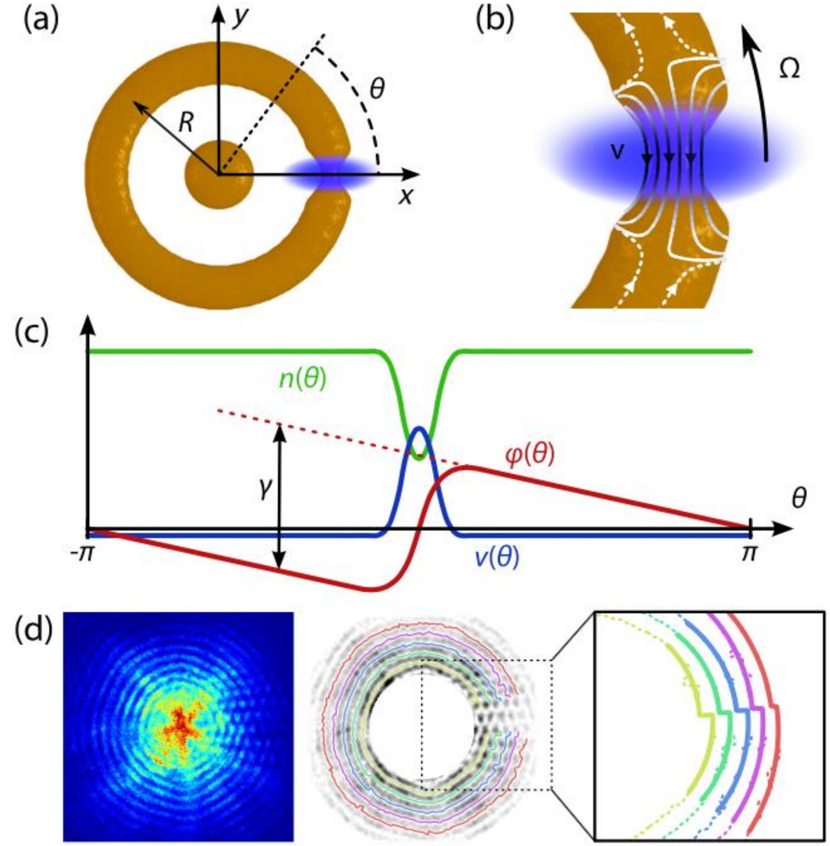


FIG. 2. (a) Schematic of the atoms in the trap with a weak link applied. The coordinate system used throughout is shown; $\theta = 0$ corresponds to the $\hat{x}$ axis. (b) A close-up of the weak-link region. When the weak link is rotated at Ω, atoms flow through the weak link (solid) and around the ring (dashed) as shown by the stream lines. Larger velocities along the stream lines correspond to darker lines. (c) The resulting density $n(\theta)$, velocity $v(\theta)$, and phase $\phi(\theta)$ as a function of angle, with the phase drop γ across the weak link shown. (d) Method of extracting the phase from an interferogram (left). First, we trace the interference fringes around the ring (center), and then we fit the discontinuity across the region where the barrier was (right).

LETTER

https://doi.org/10.1038/s41586-019-1273-5

Hypersonic Bose–Einstein conden accelerator rings

Saurabh Pandey[1,2], Hector Mas[1,3], Giannis Drougakis[1,2], Premjith Thekkeppatt[1], Vasi
Konstantinos Poulios[1,4] & Wolf von Klitzing[1]*

Some of the most sensitive and precise measurements—for example, of inertia[1], gravity[2] and rotation[3]—are based on matter-wave interferometry with free-falling atomic clouds. To achieve very high sensitivities, the interrogation time has to be very long, and consequently the experimental apparatus needs to be very tall (in some cases reaching ten or even one hundred metres) or the experiments must be performed in microgravity in space[4–7]. Cancelling gravitational acceleration (for example, in atomtronic circuits[8,9] and matter-wave guides[10]) is expected to result in compact devices with extended interrogation times and therefore increased sensitivity. Here we demonstrate smooth and controllable matter-wave guides by transporting Bose–Einstein condensates (BECs) over macroscopic distances. We use a neutral-atom accelerator ring to bring BECs to very high speeds (16 times their sound velocity) and transport them in a magnetic matter-wave guide for 15 centimetres while fully preserving their internal coherence. The resulting high angular momentum of more than 40,000*ħ* per atom (where *ħ* is the reduced Planck constant) gives access to the higher Landau levels of quantum Hall states, and the hypersonic velocities achieved, combined with our ability to control potentials with picokelvin precision, will facilitate the study of superfluidity and give rise to tunnelling and a large range of transport regimes of ultracold atoms[11–13]. Coherent matter-wave guides are expected to enable interaction times of several seconds in highly compact devices and lead to portable guided-atom interferometers for applications such as inertial navigation and gravity mapping.

presence of any cor
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transversely excitec
ometer and severel
be guided coherent
Here we report t
guiding of BECs ove
internal coherence
hypersonic speeds
appreciable additio
the static case. The p
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imperfections of th

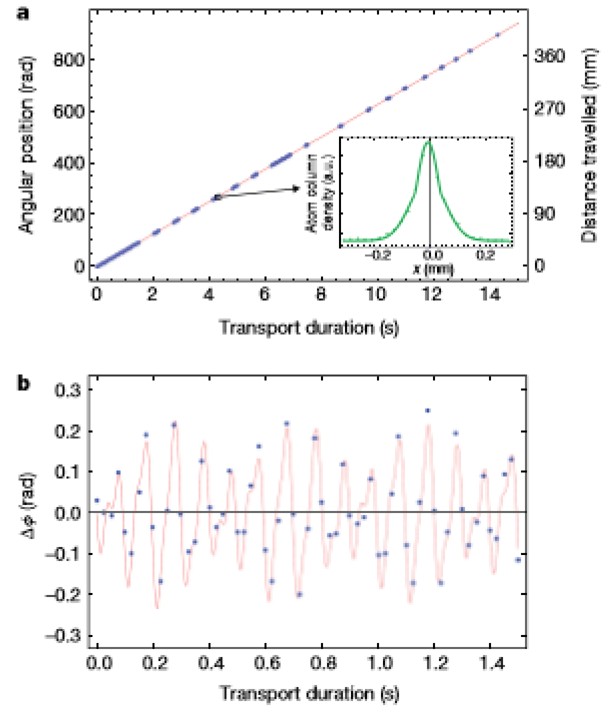
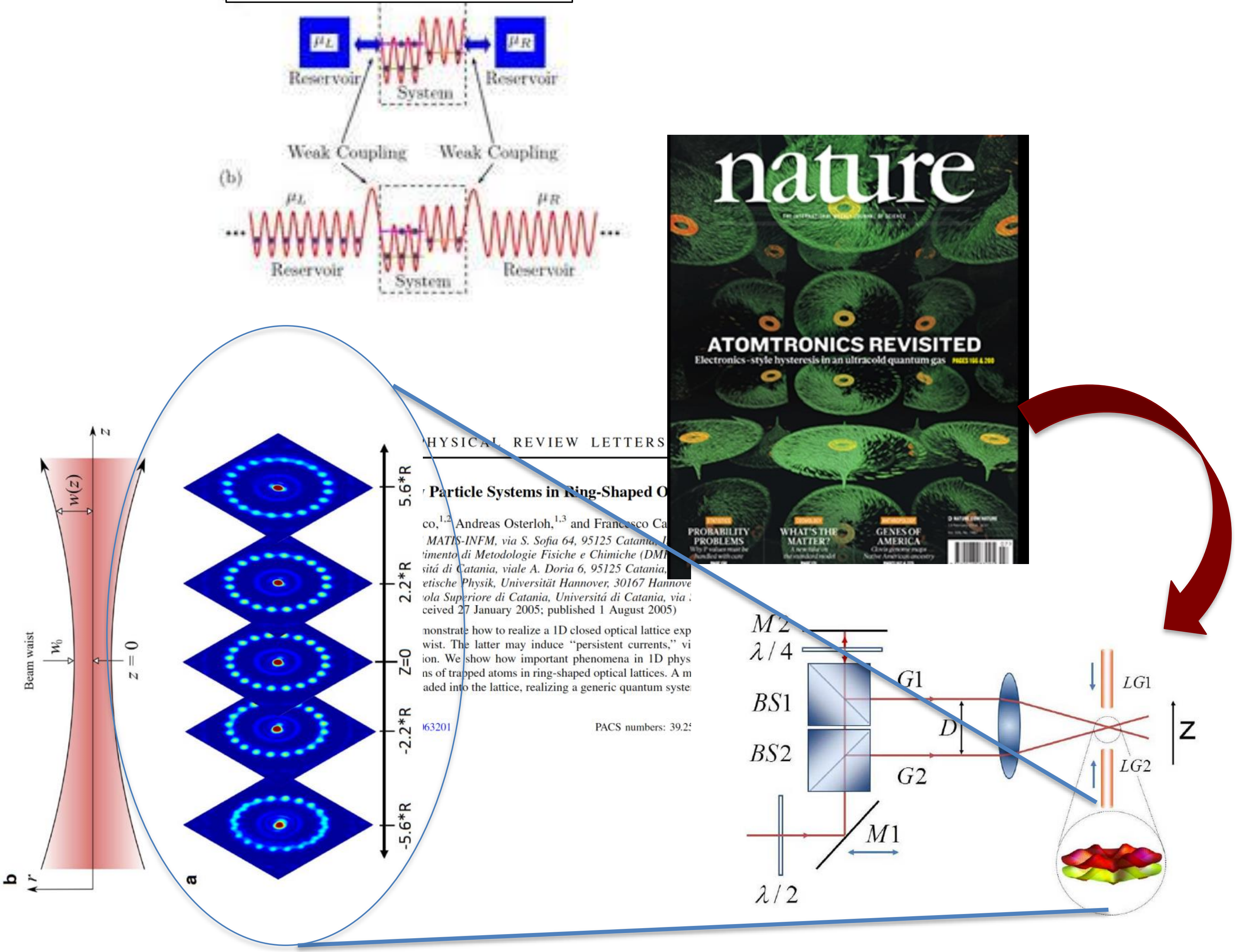
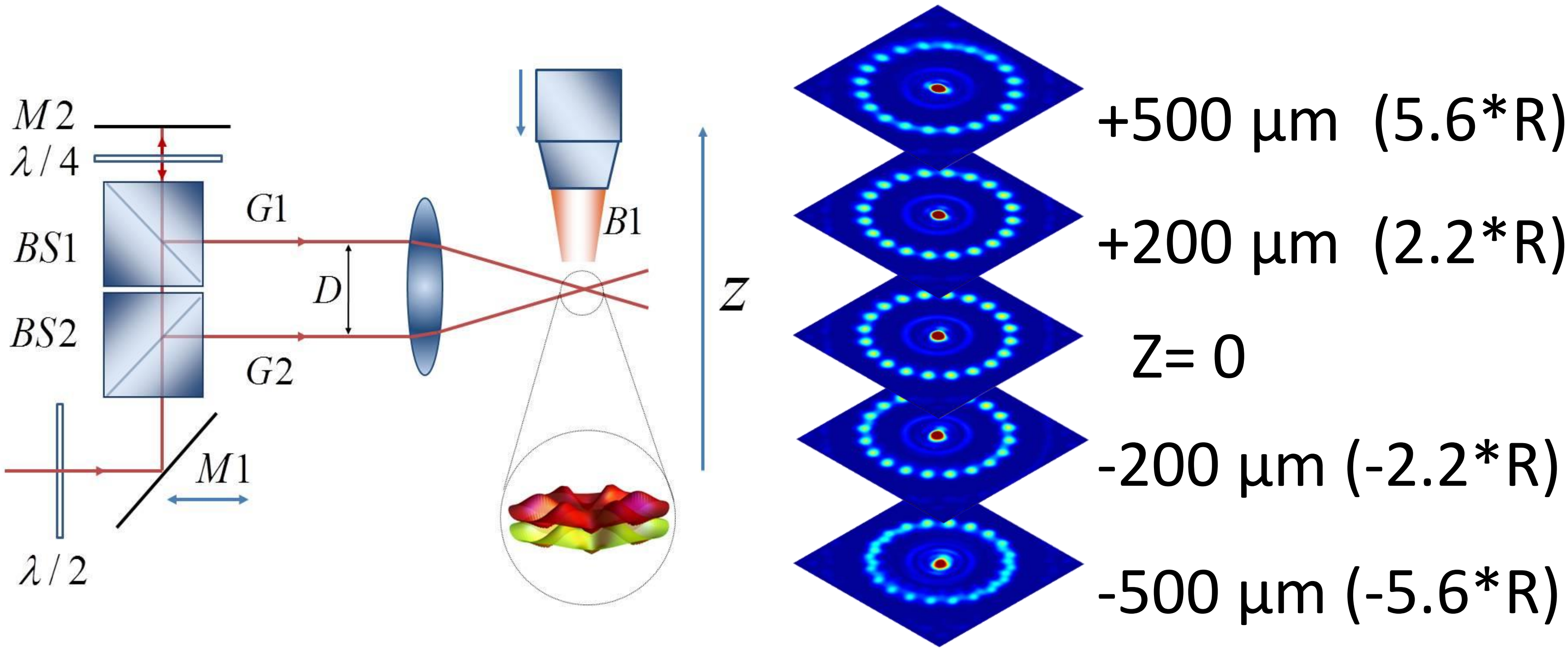


Fig. 3 | Long-distance transport in the accelerator ring. a, Angular position of the condensate and thermal cloud during 14.3 s of transport in the matter-wave guide (blue dots). The red line depicts the programmed trajectory of $2\pi \times 10$ rad s^{-1}. The inset shows the bi-modal distribution of the BEC after 4.1 s of transport and a time-of-flight expansion of 24 ms, with the black arrow pointing to the relevant data point. a.u., arbitrary units. **b**, Angular position of the condensate relative to the programmed trajectory at $2\pi \times 10$ rad s^{-1}. The red curve represents the fitted model of the azimuthal micro-motion of the BEC. The oscillations are partially due to a small azimuthal modulation of the trapping potential and partially due to a small centre-of-mass oscillation of the cloud relative to the moving trap.

Atomtronics in a Line

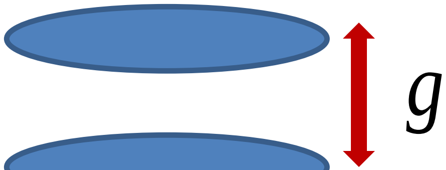


Experimental realization of interacting rings and AQUIDs

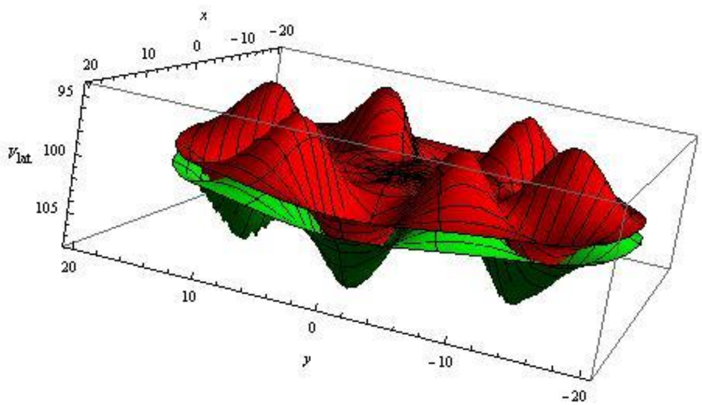


Effect of the axial translation $\Delta R/R$ = 0.0097z

Coupled rings without impurity



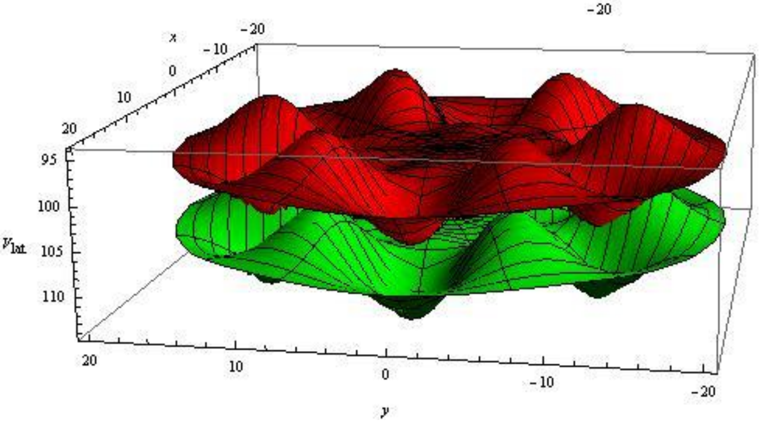
$$H = H_a + H_b + H_{\mathrm{int}}$$



$$H_a = -t\sum_{i=1}^{N}\left(e^{i\Phi_a/N} a_i^{+} a_{i+1} + h.c\right) + \frac{U}{2}\sum_{i=1}^{N}\hat{n}_i^a(\hat{n}_i^a - 1) - \mu_a\sum_{i=1}^{N}\hat{n}_i^a$$

$$H_b = -t\sum_{i=1}^{N}\left(e^{i\Phi_b/N} b_i^{+} b_{i+1} + h.c\right) + \frac{U}{2}\sum_{i=1}^{N}\hat{n}_i^b(\hat{n}_i^b - 1) - \mu_b\sum_{i=1}^{N}\hat{n}_i^b$$

$$H_{\mathrm{int}} = -g\sum_{i=1}^{N}(a_i^{+} b_i + b_i^{+} a_i) \qquad \hat{n}_i^a = a_i^{+} a_i \qquad n_i^b = b_i^{+} b_i$$



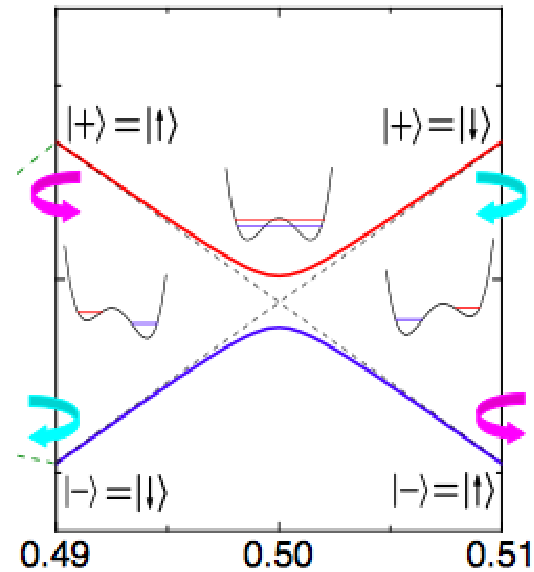
Single qubit gates

Hamiltonian in the two level basis takes form:

$$H \simeq \varepsilon\sigma_z + \alpha\sigma_x$$

$$\sigma_z = |1\rangle\langle 1| - |0\rangle\langle 0| \qquad \alpha = \frac{\Phi - \pi}{\delta}\langle\theta\rangle_{01}$$

$$\sigma_x = |1\rangle\langle 0| - |0\rangle\langle 1| \qquad \delta = \frac{J'(N-1)}{J} > 1$$



WKB estimate for the energy gap is given by:

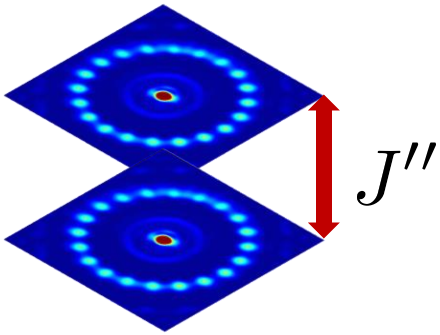
$$\varepsilon \simeq \frac{2\sqrt{UJ'}}{\pi}\sqrt{\left(1-\frac{1}{\delta}\right)}e^{-6\sqrt{J'/U}(1-1/\delta)^{3/2}}$$

Phase gate $\quad U_z(\beta) = exp(i\varepsilon\tau\sigma_z) = \begin{pmatrix} e^{i\varepsilon\tau} & 0 \\ 0 & e^{-i\varepsilon\tau} \end{pmatrix}$

NOT gate $\quad U_x(\beta) = exp(i\alpha\tau\sigma_x) = \begin{pmatrix} \cos\alpha & i\sin\alpha \\ i\sin\alpha & \cos\alpha \end{pmatrix}$

Two-qubit gates

In the lim J''< J' and $\Phi_a = \Phi_b = \Phi$ the Hamiltonian of coupled rings takes form:



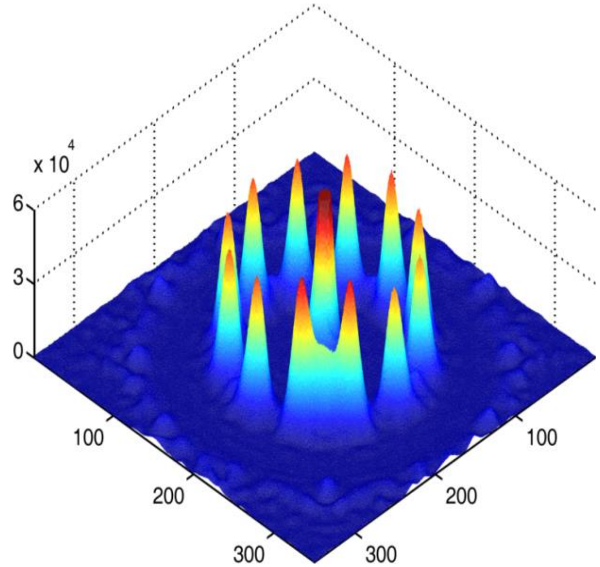
$$H = J'\left[\sum_{\alpha=a,b} H_\alpha + \frac{J''}{J'}\frac{(\theta_a - \theta_b)^2}{2}\right]$$

$$H = H_a + H_b + \frac{J''}{J'}\sigma_x^1\sigma_x^2\langle\theta\rangle_{01}^2$$

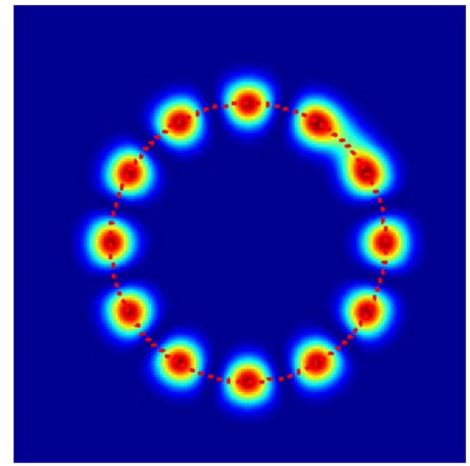
$$H_\alpha = \epsilon\sigma_z^\alpha + (\frac{\Phi - \pi}{\delta} + \frac{J''\pi}{J'})\langle\theta\rangle_{01}\sigma_x^\alpha$$

By choosing ε=0 and Φ= π-(δ J'')/ J'

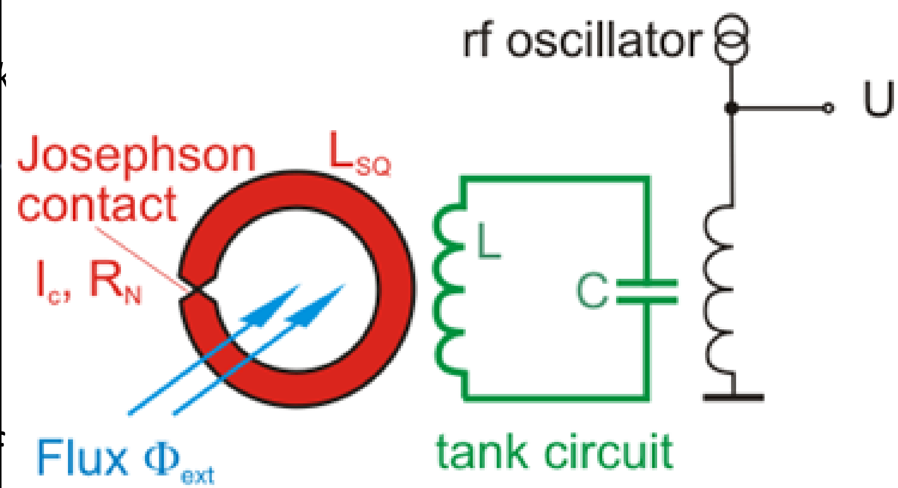
$$U(\tau) = exp[-i\frac{J''}{J'}\sigma_x^1\sigma_x^2\tau]$$



x 10^4
6
3
0
100
200
300
100
200
300



Atomic Squid



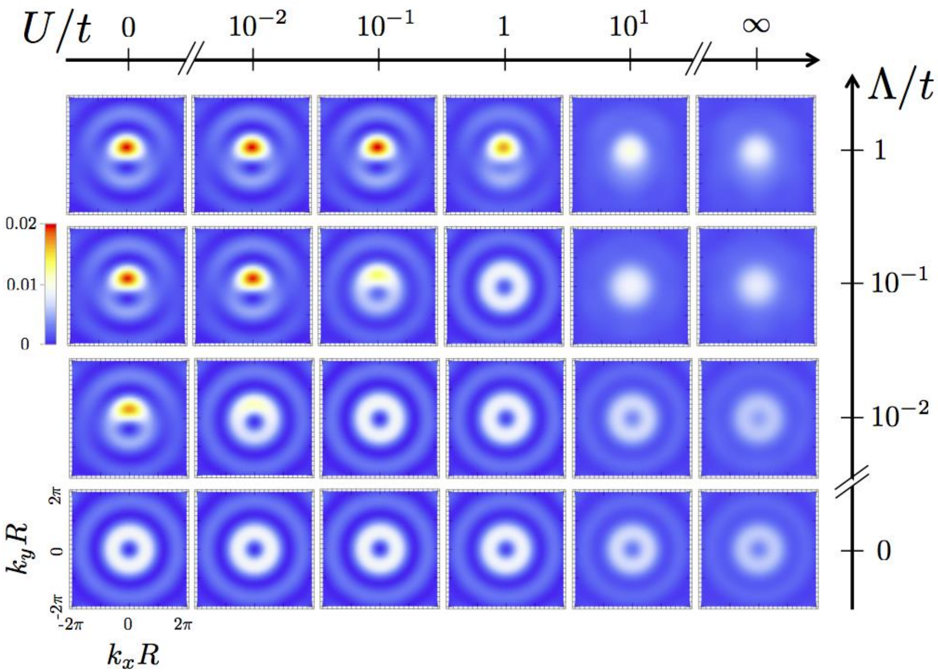
rf oscillator
U
Josephson contact
L_SQ
I_c, R_N
L
C
Flux Φ_ext
tank circuit

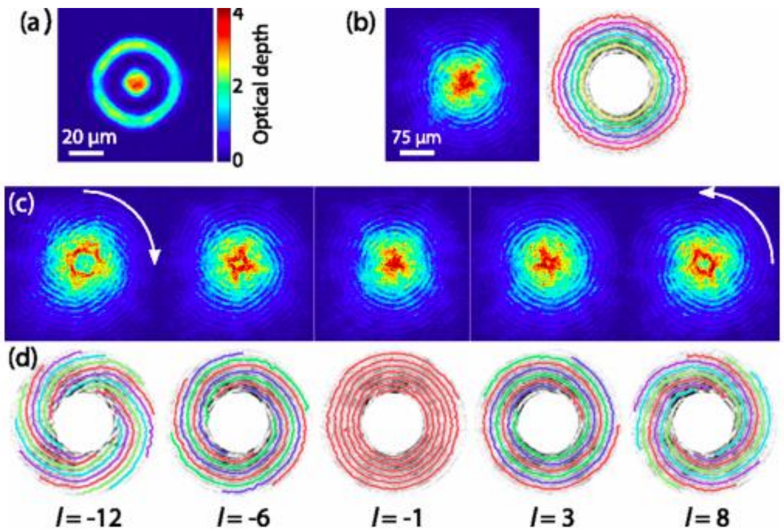
$a_k^+ a_k$

J - 2

$\vec{x}$

AQUID state readout





It is possible to see signatures of the superposition states by studying TOF

The chirality of the spiral like interferogram determines direction of the current

Aghamalyan *et al New J. Phys.* 17, 045023 (2015)

Eckel, et al. Physical Review *X,* 4, 031052, (2014)

PHYSICAL REVIEW A **97**, 013633 (2018)

Readout of the atomtronic quantum interference device

Tobias Haug,[1] Joel Tan,[1] Mark Theng,[1] Rainer Dumke,[1,2] Leong-Chuan Kwek,[1,3,4,5] and Luigi Amico[1,3,6,7,8]

[1]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore*

[2]*Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore*

[3]*MajuLab, Centre National de la Recherche Scientifique, UNS-NUS-NTU International Joint Research Unit, UMI 3654 Singapore, Singapore*

[4]*Institute of Advanced Studies, Nanyang Technological University, 60 Nanyang View, Singapore 639673, Singapore*

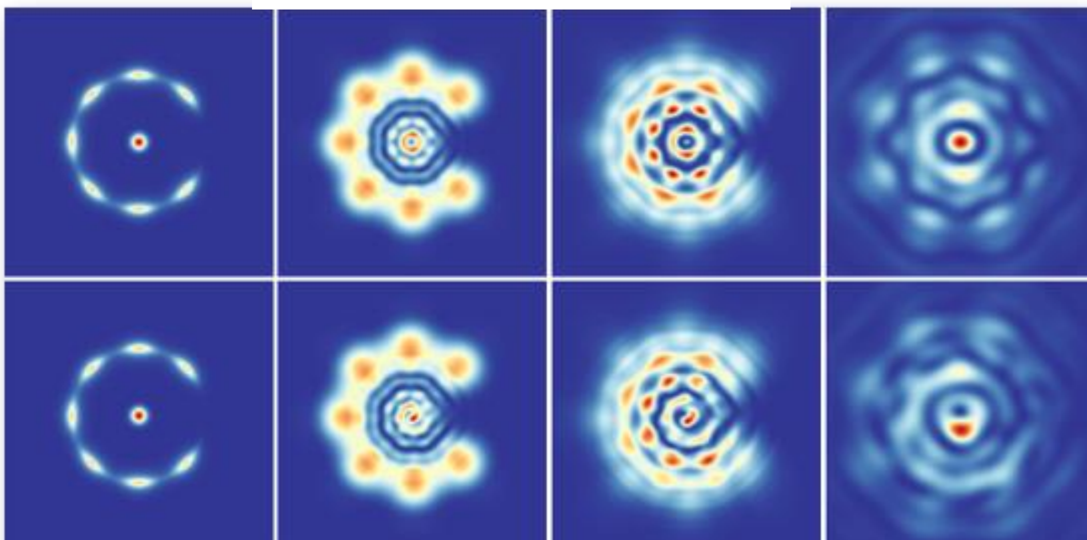
[5]*National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore*

[6]*Dipartimento di Fisica e Astronomia, Via Santa Sofia 64, 95127 Catania, Italy*

[7]*Consiglio Nazionale delle Ricerche, MATIS-IMM and Istituto Nazionale di Fisica Nucleare, Sezione di Catania,*

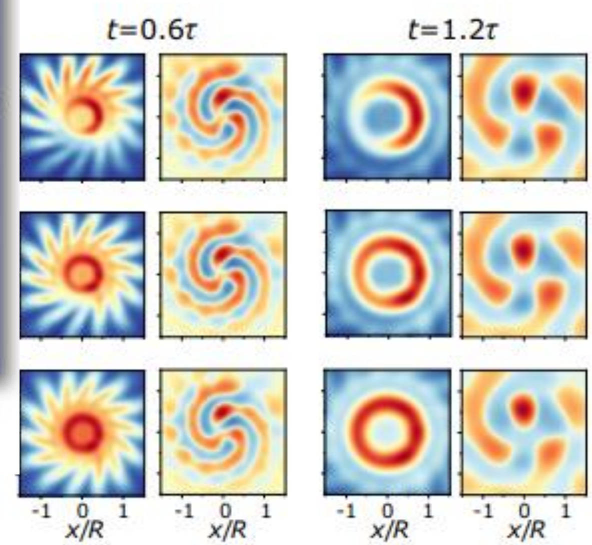
[8]*LANEF* … *e, France*

From the Straits Times…..



Computer simulations by CQT researchers suggest a way to measure the quality of atomic quantum interference devices (AQUIDs). The work is published in *Physical Review A* 97, 013633 (2018).

PHYSICAL REVIEW A **97**, 013633 (2018)



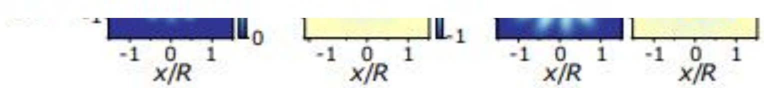
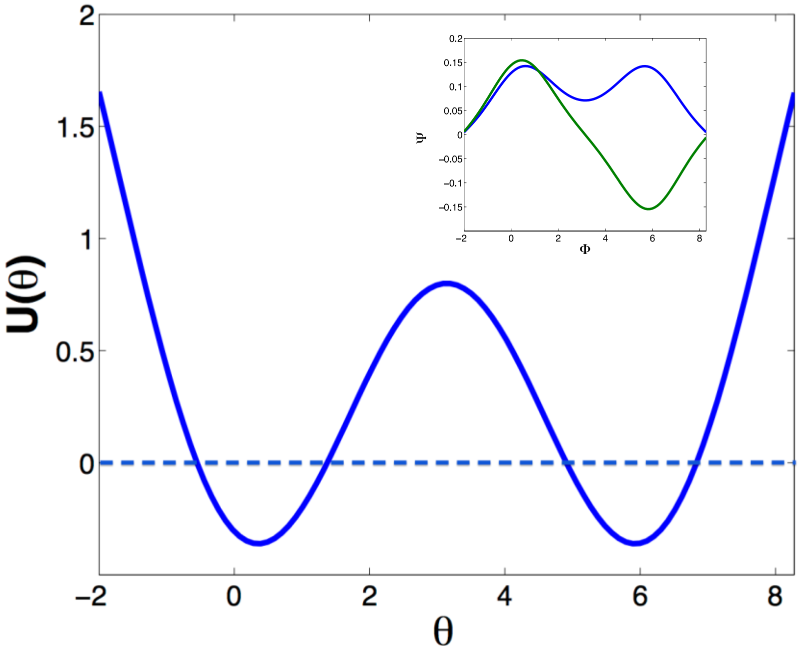
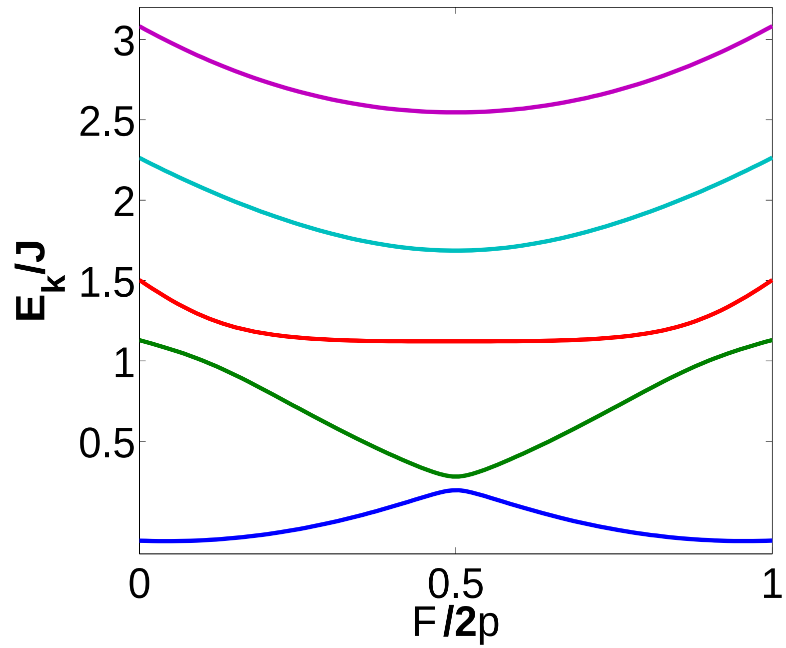


FIG. 1. Density distribution (a) $\langle \hat{n}(\mathbf{r}) \rangle$ and root of density-density covariance (b) $\sigma(\mathbf{r},\mathbf{r}' = \{0, R/2\})$ of expanding atoms at times $t = 0, 0.3\tau, 0.6\tau, 1.2\tau$, with $\tau = mR\sigma_r/\hbar$. Calculated using Bose-Hubbard model, no interaction during expansion. Data in color and

AQUID system based on the clockwise and anti-clockwise currents





Double well for AQUID.
Parameters: J'(N-1)/J = 16, Φ = π.

Energy spectrum.
Same parameters with U=2. Due to avoided crossing near Φ=π, $I_0=-I_1$.

$$|\Psi\rangle_G = \frac{1}{\sqrt{2}}\left(|\circlearrowleft\rangle + |\circlearrowright\rangle\right) \quad |\Psi\rangle_E = \frac{1}{\sqrt{2}}\left(|\circlearrowleft\rangle - |\circlearrowright\rangle\right)$$

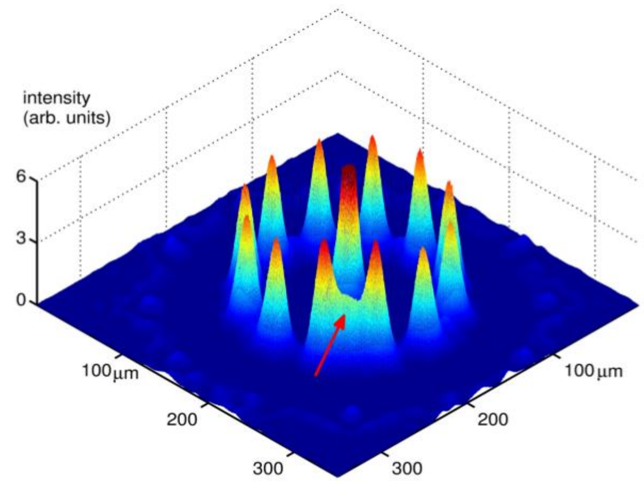
The current in the k-th energy state is given by: $I_k \propto \frac{dE_k(\Phi)}{d\Phi}$

Our model

Interacting bosons on a ***1D lattice***

Localized potential on one lattice site

Magnetic flux piercing the ring



tight-binding

$$H = \sum_{j=1}^{M} \left[-t\left(e^{-i\Omega/M} b_j^\dagger b_{j+1} + \mathrm{H.c.}\right) + \boxed{\frac{U}{2} n_j(n_j - 1)} + \boxed{\Lambda_j n_j} \right]$$

artificial magnetic flux

on-site interactions

local potential

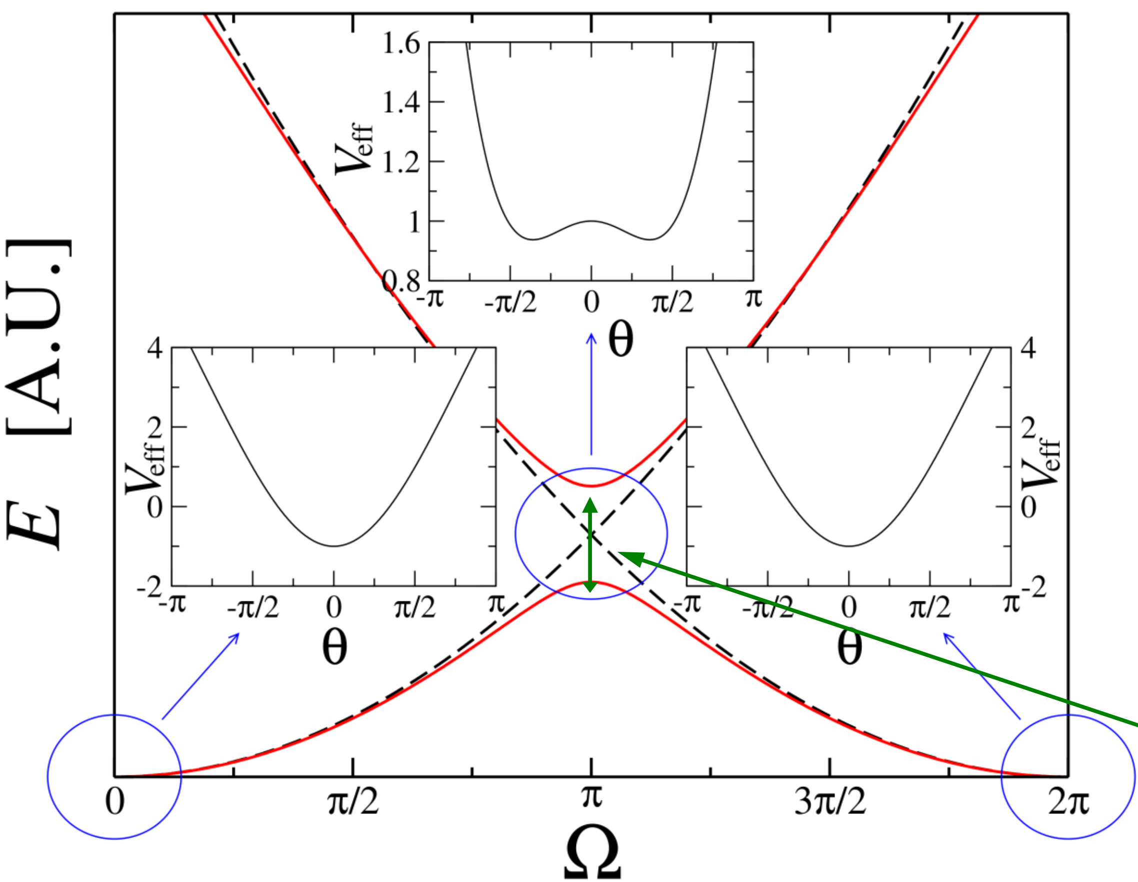
An effective ***Bose-Hubbard model***

→ hopping renormalized by the magnetic flux

$$t/U \rightarrow (t/U)\cos(\Omega/M)$$

Niemeyer, Freericks, Monien (1999)

Effective two-level system



WITHOUT barrier:
rotational invariance
→ set of parabolas with defined angular momentum

WITH barrier:
symmetry breaking
→ avoided crossing

gap separating first two bands

@ large fillings: *quantum phase model*
@ normal fillings, n≈ 1: **Bose-Hubbard**

Bose-Hubbard model: **low-lying spectrum**

Check the dependence of $\boxed{\Delta E_1 = E_1 - E_0}$ & $\boxed{\Delta E_2 = E_2 - E_0}$ on

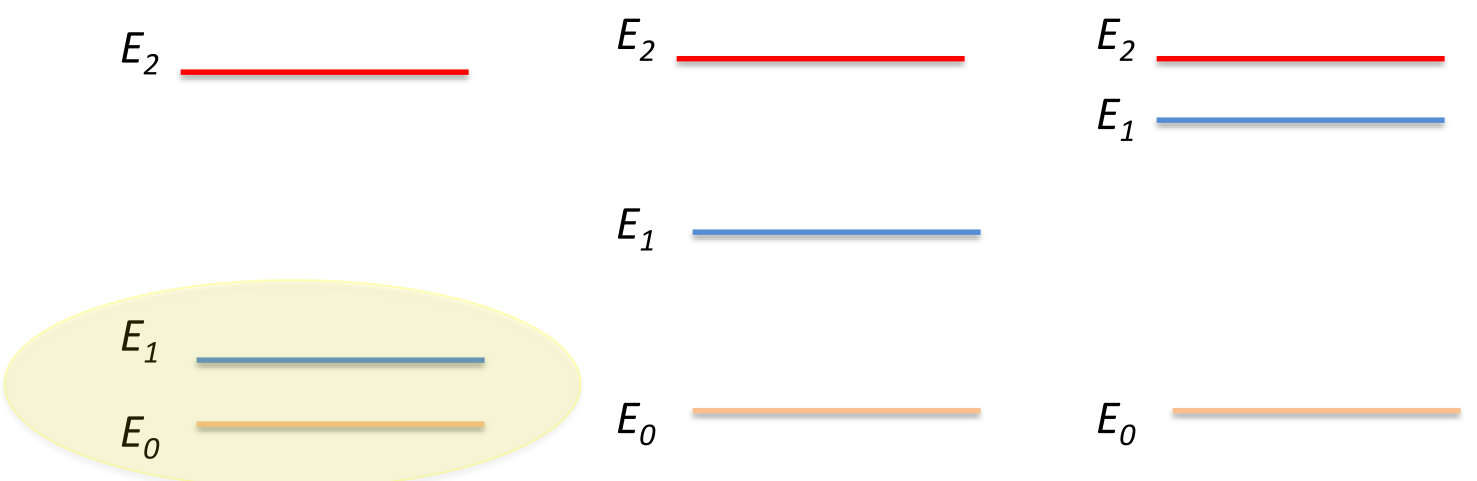
→ interactions U

→ barrier strength L

→ system size M

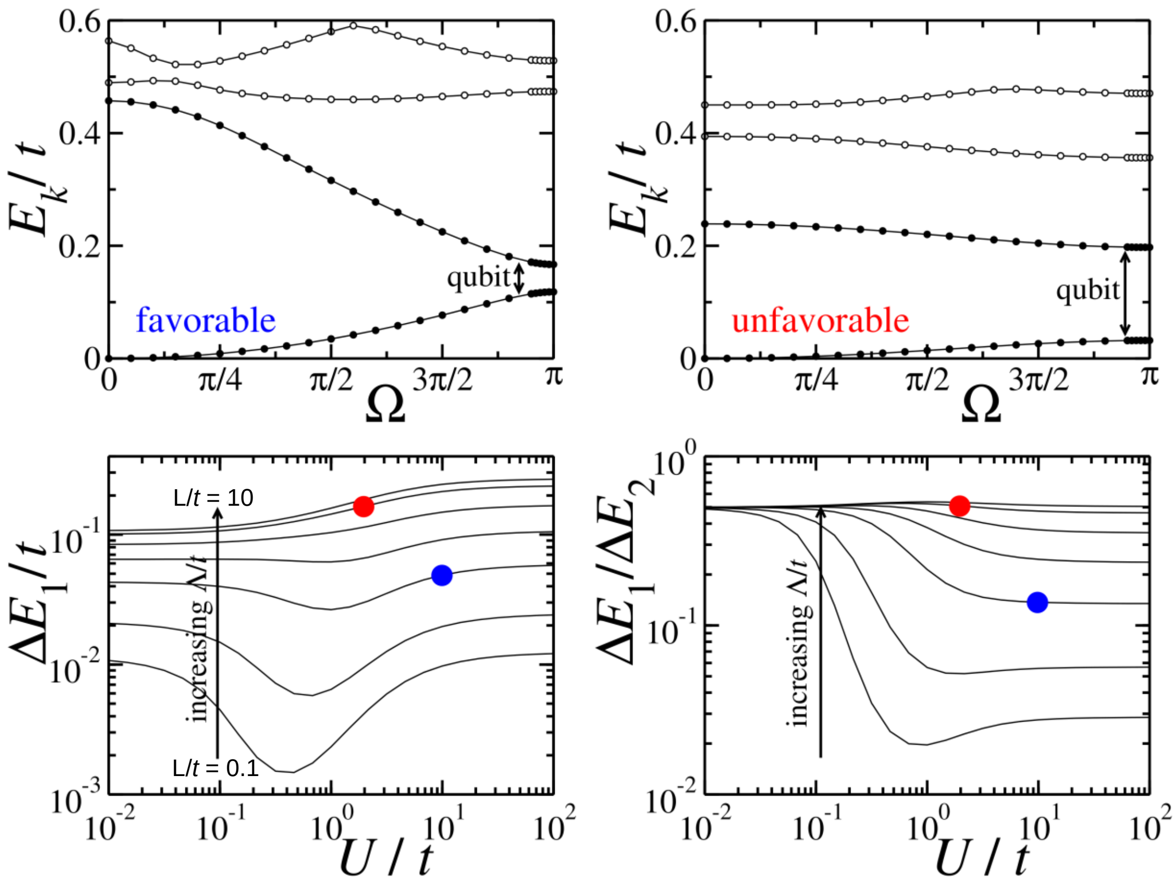
→ filling factor N / M

$\boxed{\Delta E_1 / \Delta E_2}$ our quality factor for the qubit



$\Delta E_1 / \Delta E_2 < 1/2$ $\Delta E_1 / \Delta E_2 \sim 1/2$ $\Delta E_1 / \Delta E_2 > 1/2$

Interactions & barrier strength



✓ U / t = 10, L / t = 0.5

→ large interactions

→ moderate barrier

✗ U / t = 2, L / t = 5

→ weaker interactions

→ larger barrier

ED

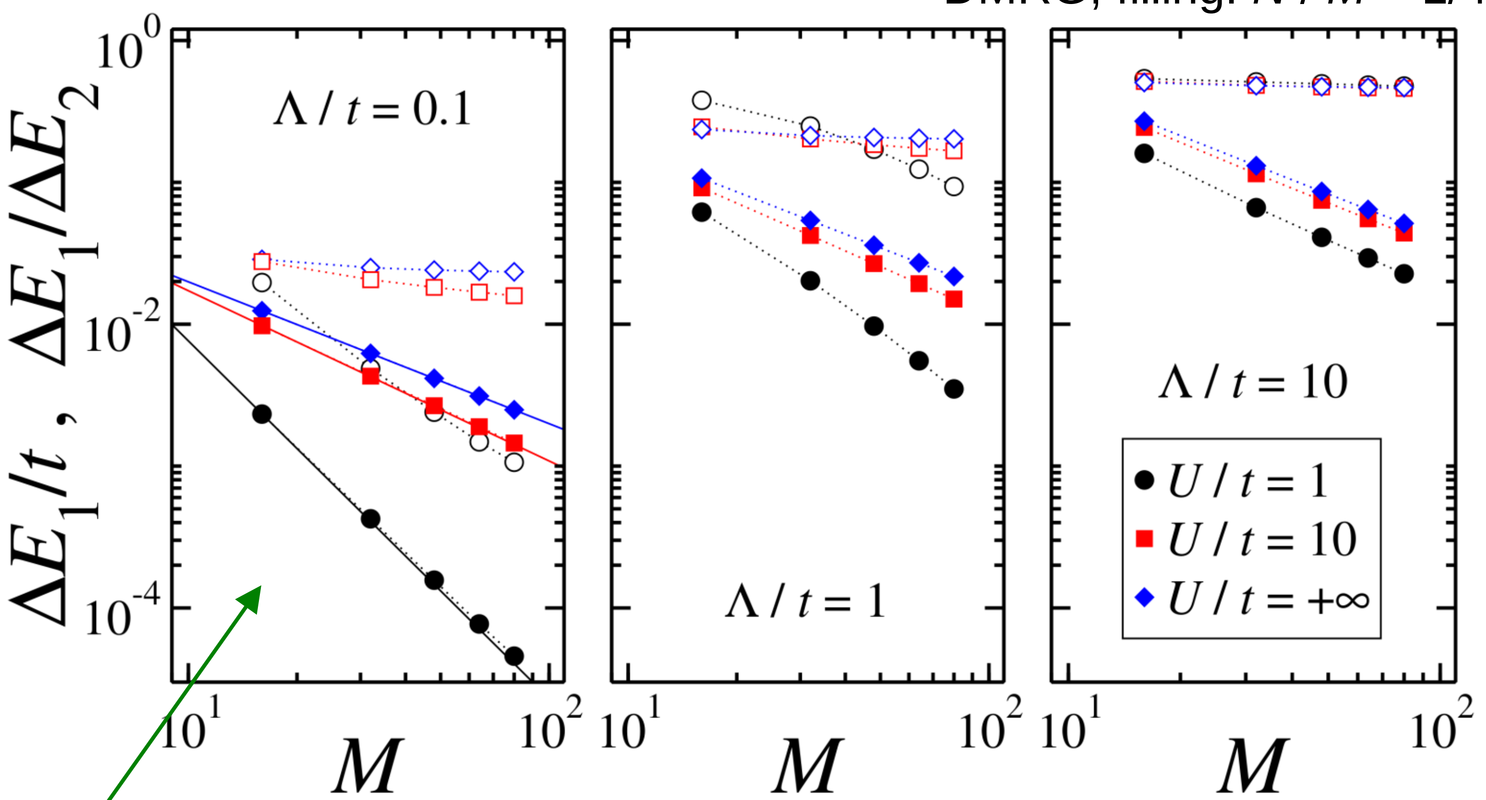
N = 4 bosons

M = 16 sites

Moral: Weak interaction does not isolate the qubit !

System size

DMRG, filling: N / M = 1/4



small barrier

intermediate barrier

large barrier

best regime:

small barrier ***mesoscopic*** *size*

From one weak link to three!

New Journal of Physics
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PAPER

An atomtronic flux qubit: a ring latt
interrupted by three weak links

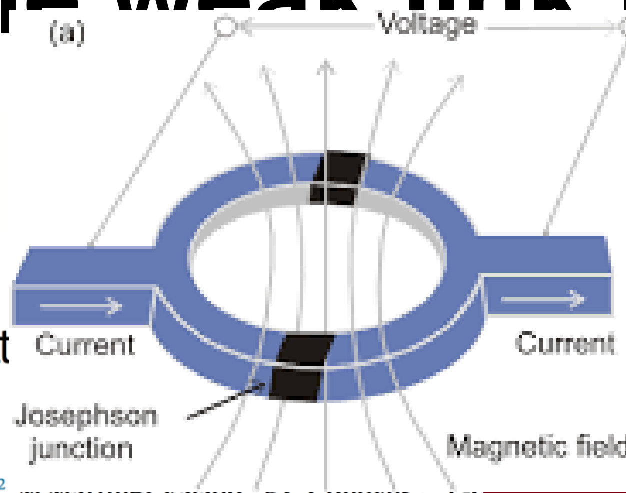
D Aghamalyan[1,2], N T Nguyen[2], F Auksztol[2], K S Gan[2], M Martinez Valado, P C Condylis, L-C
R Dumke[2] and L Amico[2,4,5]

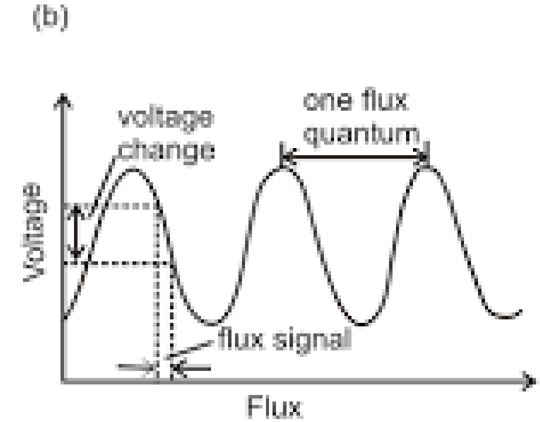
[1] Institut de Physique de Rennes, UMR 6251 du CNRS and Université de Rennes 1, F-35042 Rennes Cedex, France
[2] Centre for Quantum Technologies, National University of Singapore, 117543, Singapore
[3] National Institute of Education and Institute of Advanced Studies, Nanyang Technological University, 1 Nanyang Walk,
Singapore
[4] CNR-MATIS-IMM & Dipartimento di Fisica e
[5] Laboratori Nazionali del Sud, INFN, via S. Sofi
[6] Author to whom any correspondence should b

E-mail: cqtpcc@nus.edu.sg

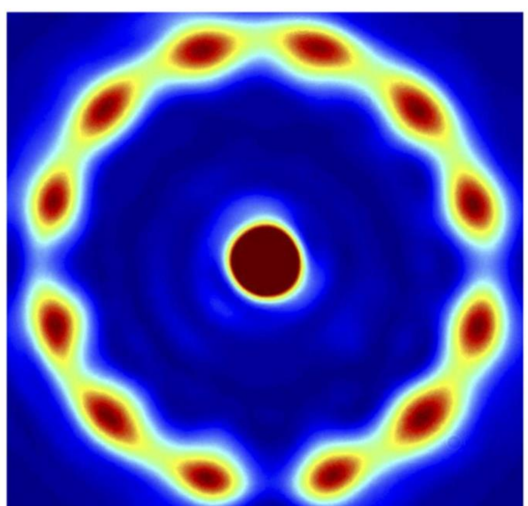
Keywords: atomtronics quantum interference de

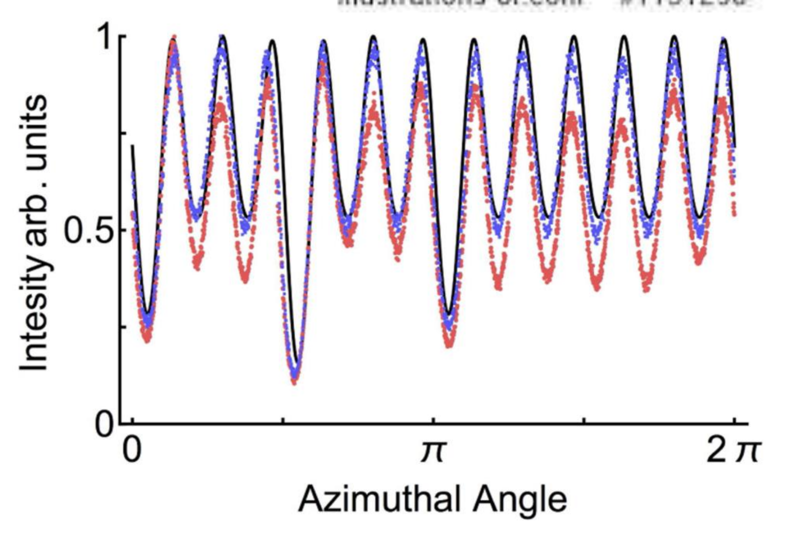
Abstract
We study a physical system consistin
potential interrupted by three weak l
piercing the ring lattice. By employi

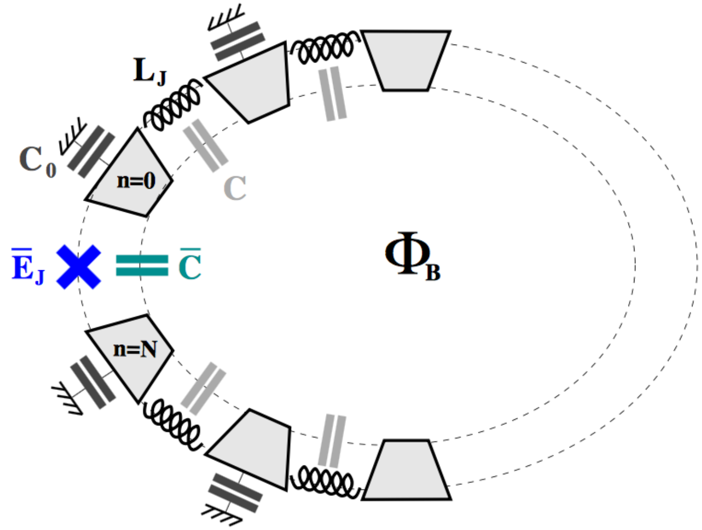




A more verstaile SQUID!!!
DC squid!







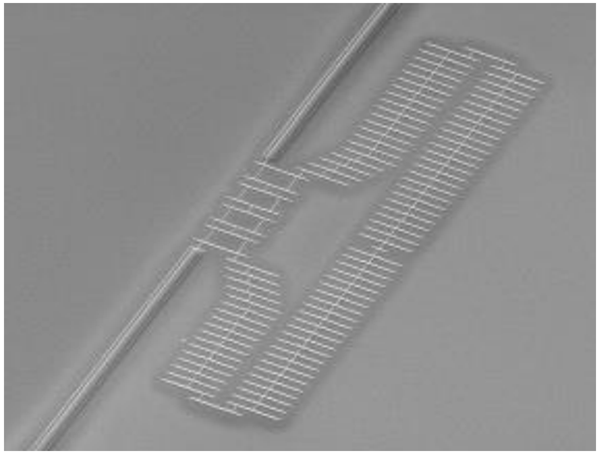
Arxiv: 1403.4565

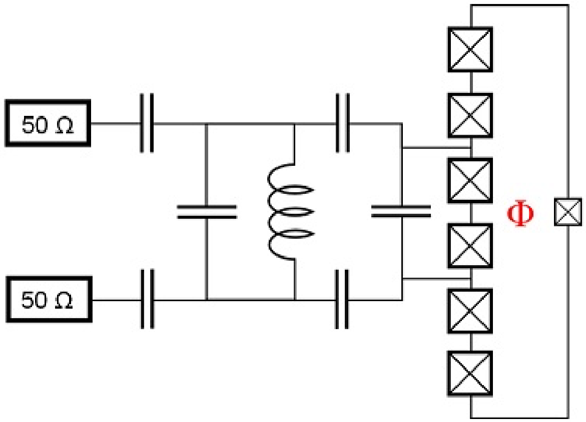
Fluxonium: Single Cooper-Pair Circuit Free of Charge Offsets

Vladimir E. Manucharyan, Jens Koch, Leonid I. Glazman, Michel H. Devoret*

The promise of single Cooper-pair quantum circuits based on tunnel junctions for metrology and quantum information applications is severely limited by the influence of offset charges: random, slowly drifting microscopic charges inherent in many solid-state systems. By shunting a small junction with the Josephson kinetic inductance of a series array of large-capacitance tunnel junctions, thereby ensuring that all superconducting islands are connected to the circuit by at least one large junction, we have realized a new superconducting artificial atom that is totally insensitive to offset charges. Yet its energy levels manifest the anharmonic structure associated with single Cooper-pair effects, a useful component for solid-state quantum computation.

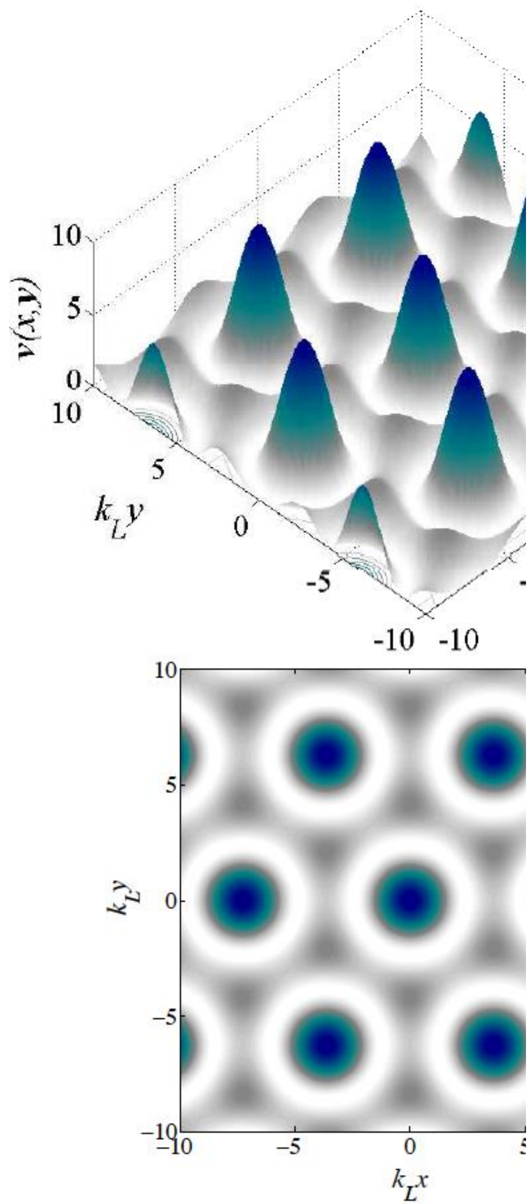
Science, 326, 113 (2009)





Source: http://qulab.eng.yale.edu/devices.html


dreamstime



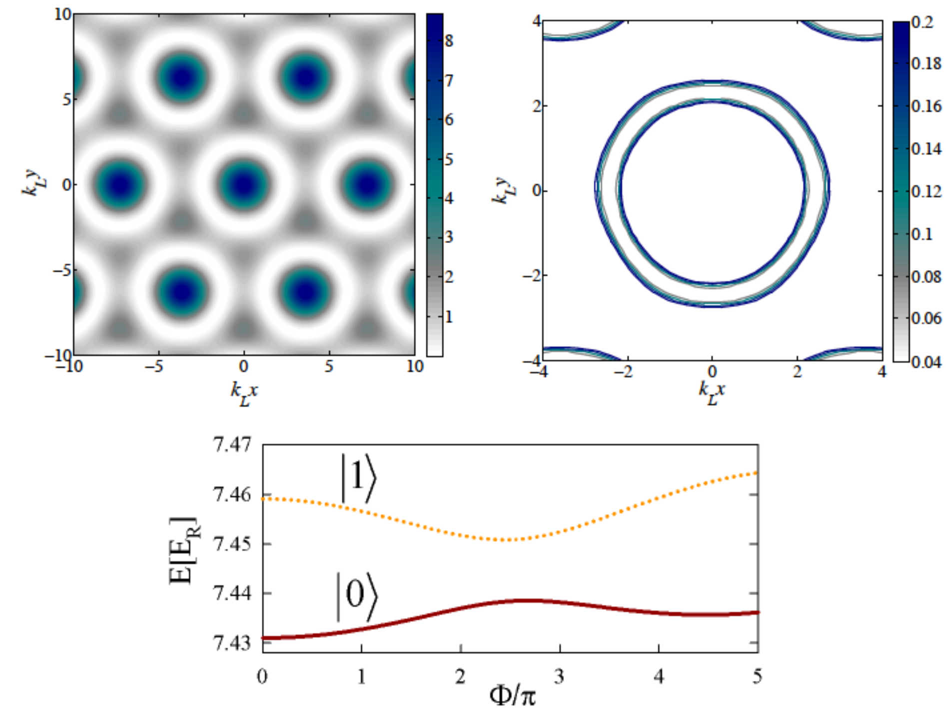


FIG. 4. (Color online) Top-left: lattice potential (1) for $U_0 = 50$, $\gamma = 0.98$ and $\phi = \pi/25$. Top-right: contour plot of the (distorted) ring-shaped potential well hosting the atoms. The qubit is encoded in the two lowest levels $|0\rangle$ and $|1\rangle$ of the potential well which are well separated from higher energy levels. Bottom: qubit level dynamics against flux Φ. Superposition of the qubits states can be achieved by changing Φ through the avoided crossing observed at flux $\Phi_0 \approx 2.525\pi$.

Mesoscopic physics

VOLUME 52, NUMBER 2 PHYSICAL REVIEW LETTERS 9 JANUARY 1984

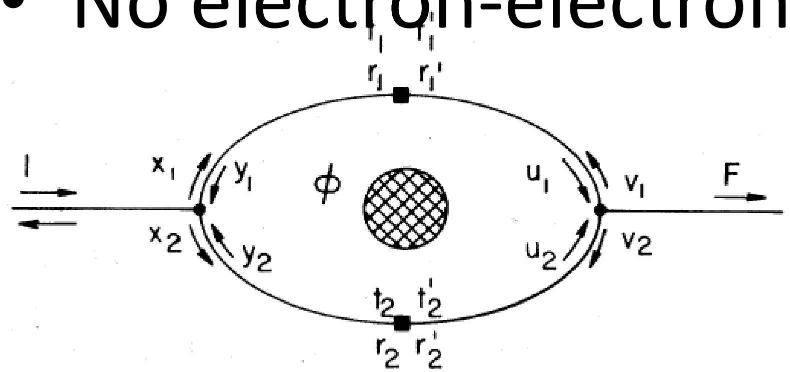
Quantum Oscillations and the Aharonov-Bohm Effect for Parallel Resistors

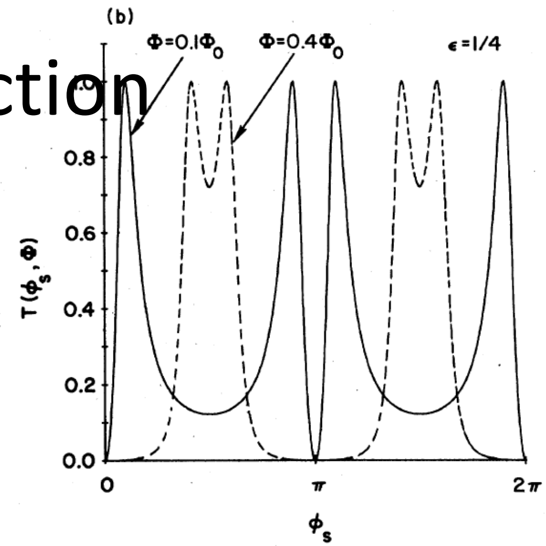
Yuval Gefen and Yoseph Imry
Department of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

and

M. Ya. Azbel[a]
IBM Research Center, Yorktown Heights, New York 10598
(Received 14 March 1983)

- No electron-electron interaction

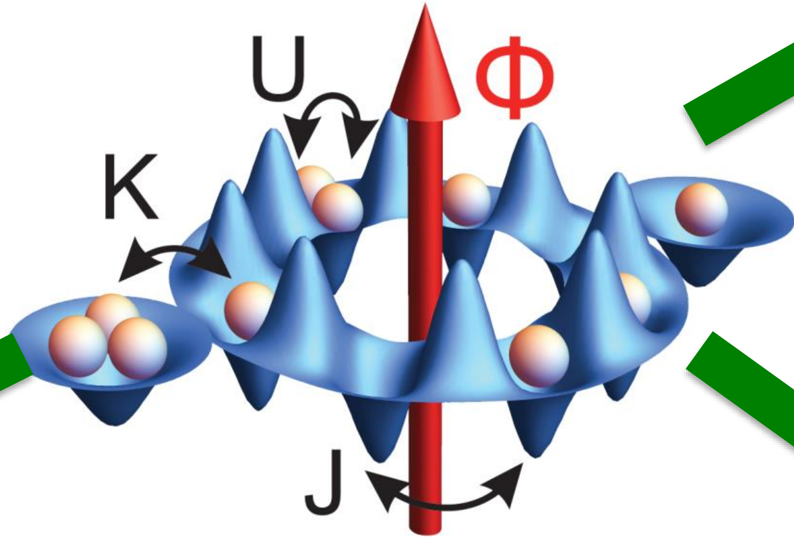




[1] Y. Gefen, Y. Imry, and M. Y. Azbel, Phys. Rev. Lett. 52, 129 (1984).
[2] M. Büttiker, Y. Imry, and M. Y. Azbel, Phys. Rev. A 30, 1982 (1984).

Aharonov-Bohm for interference effects and controls transmission in mesoscopic systems

Study how interaction affects Aharonov-Bohm effect



Possible applications!

Time dynamics?

Model

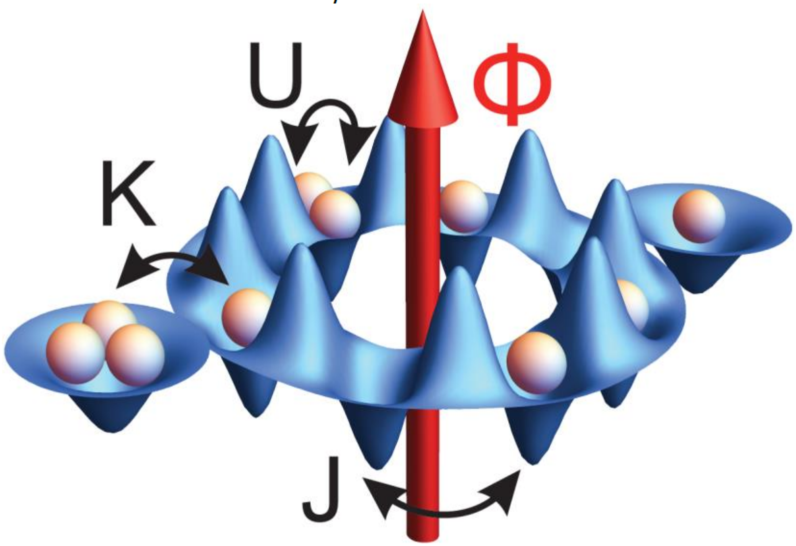
Ri $\mathcal{H} = \mathcal{H}_{\mathrm{R}} + \mathcal{H}_{\mathrm{L}}$ ed to leads

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

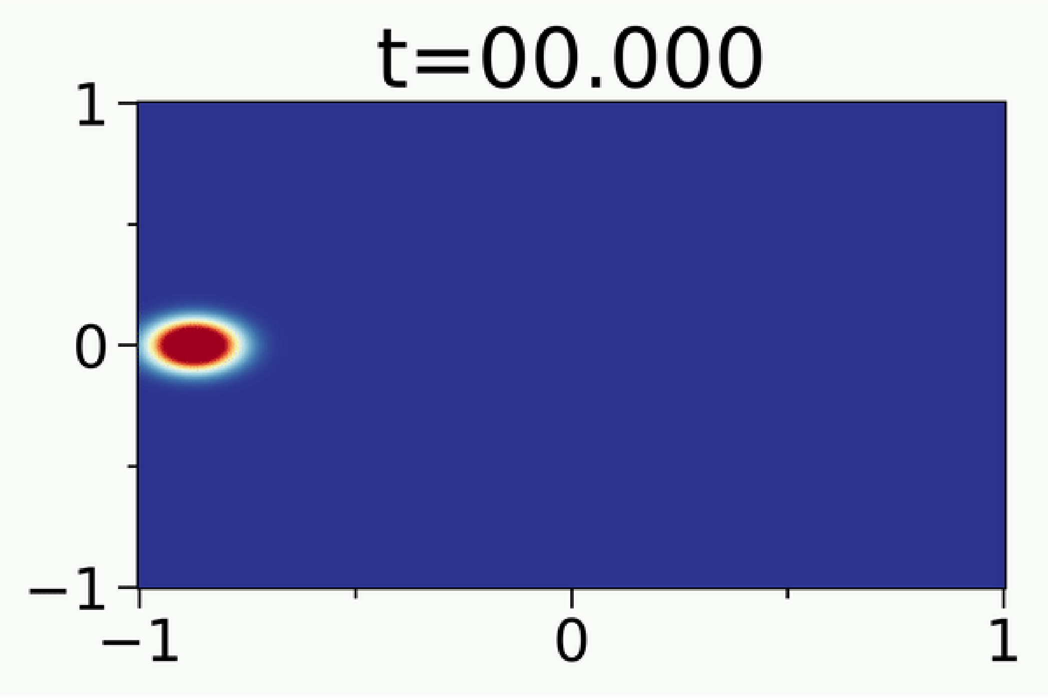
$$\mathcal{H}_{\mathrm{L}} = -K(\hat{a}_S^{\dagger}\hat{a}_0 + \hat{a}_D^{\dagger}\hat{a}_{L/2} + \mathrm{H.C.})$$

Drain

Source

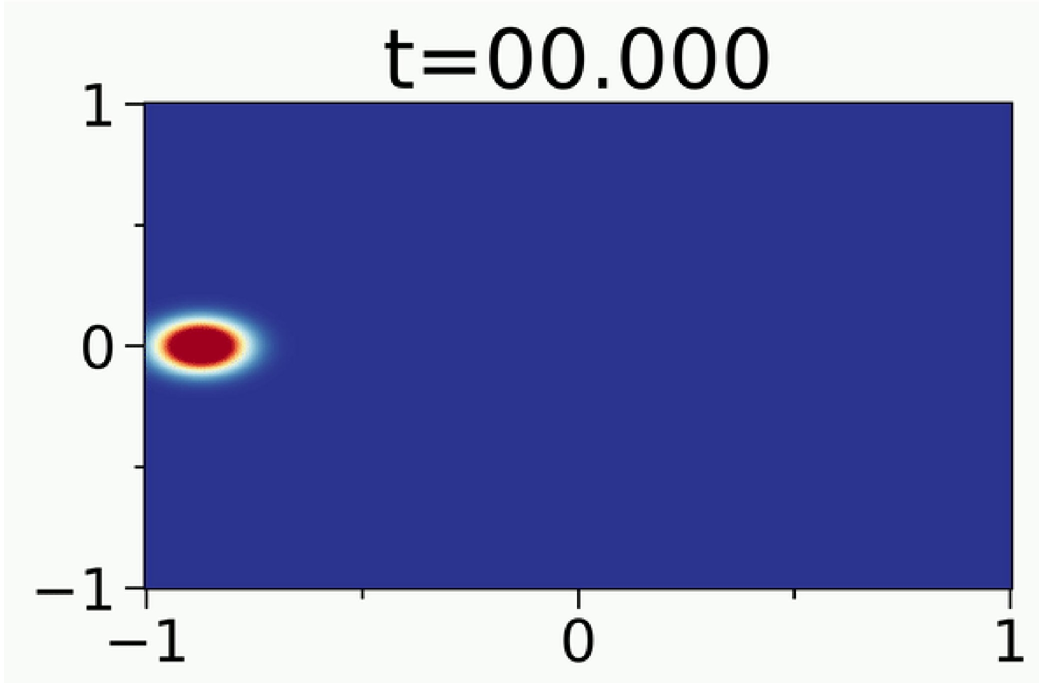


$\Phi=0.0$

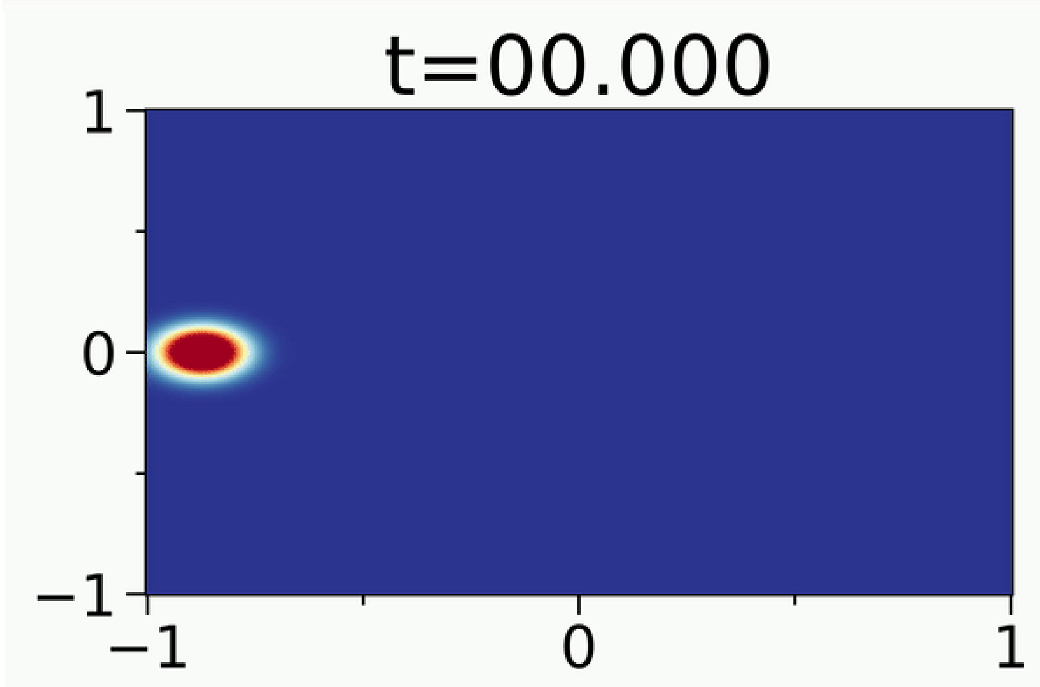


U/J=0.2,L=14,N=4

Φ=0.0



Φ=0.5

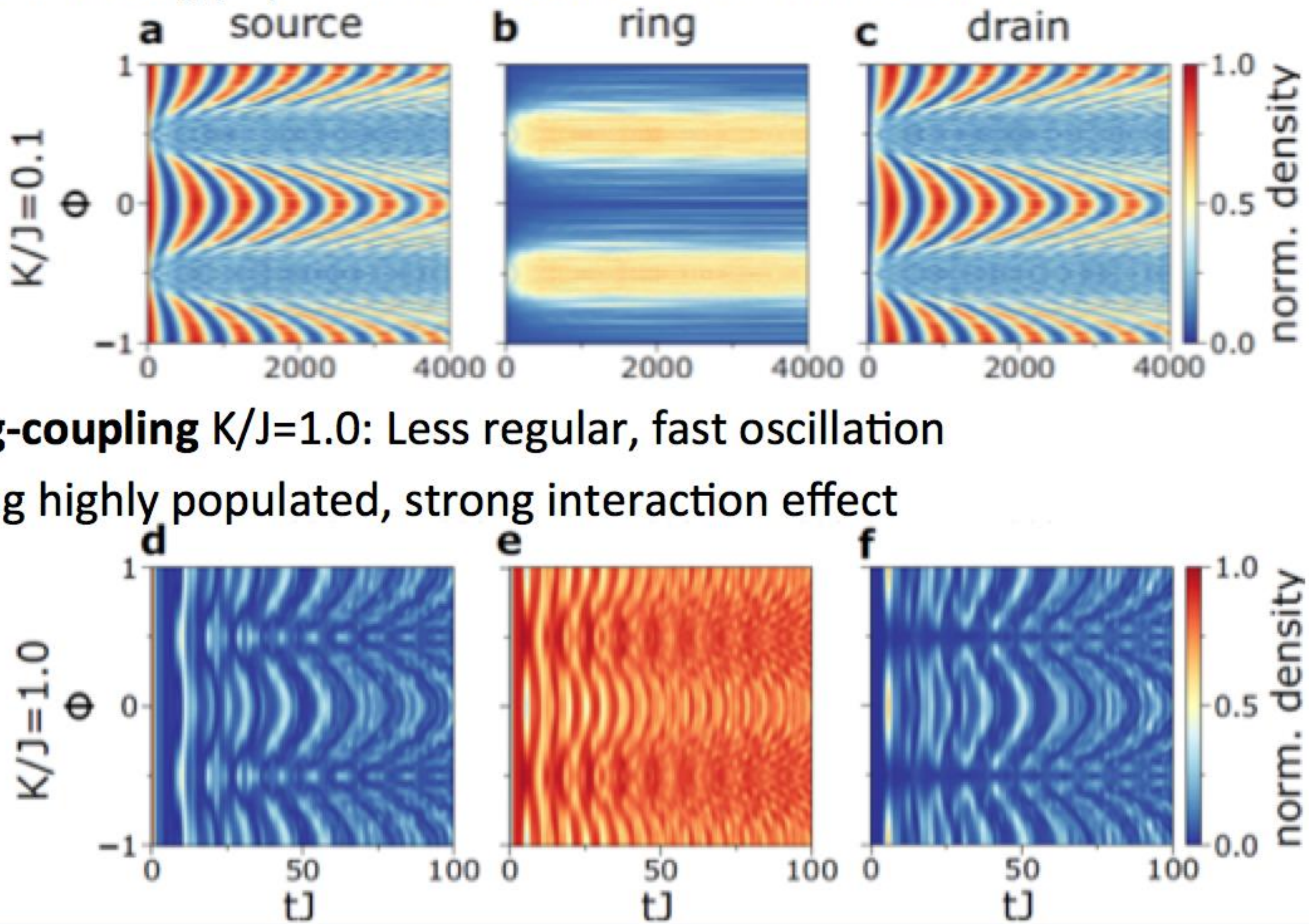


U/J=0.2,L=14,N=4

Time Evolution

Weak-coupling K/J=0.1: Regular, slow source-drain oscillation

- Small ring population → small effect of interaction



Strong-coupling K/J=1.0: Less regular, fast oscillation

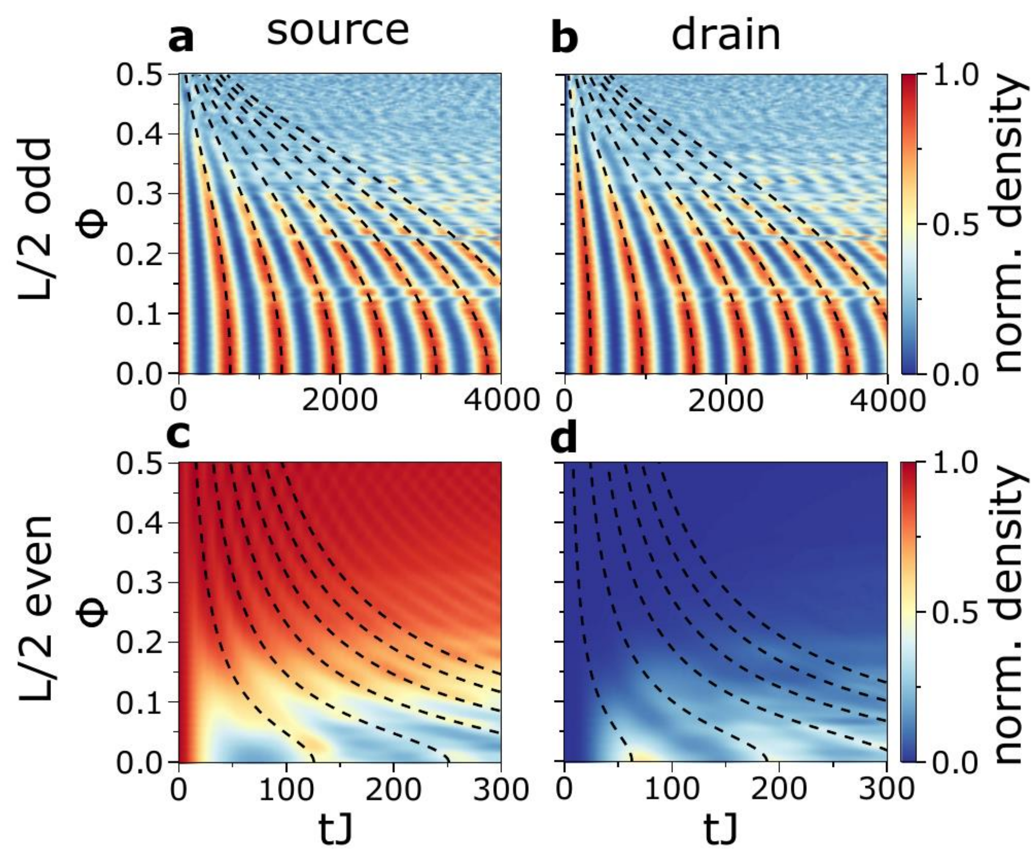
- Ring highly populated, strong interaction effect

U/J=5

U/J=0.2

Parity effect

- Dynamics depend on number of ring sites **L**
- Best visible in weak coupling (K/J=0.1)
- Parity L/2

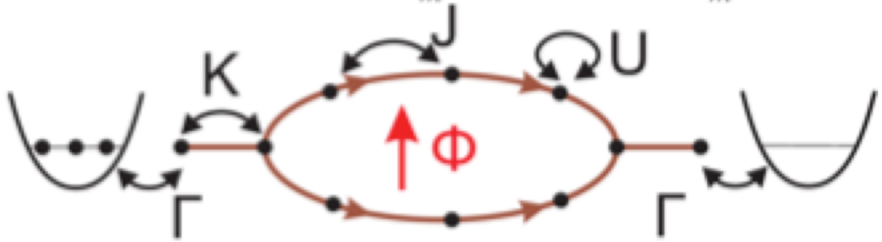


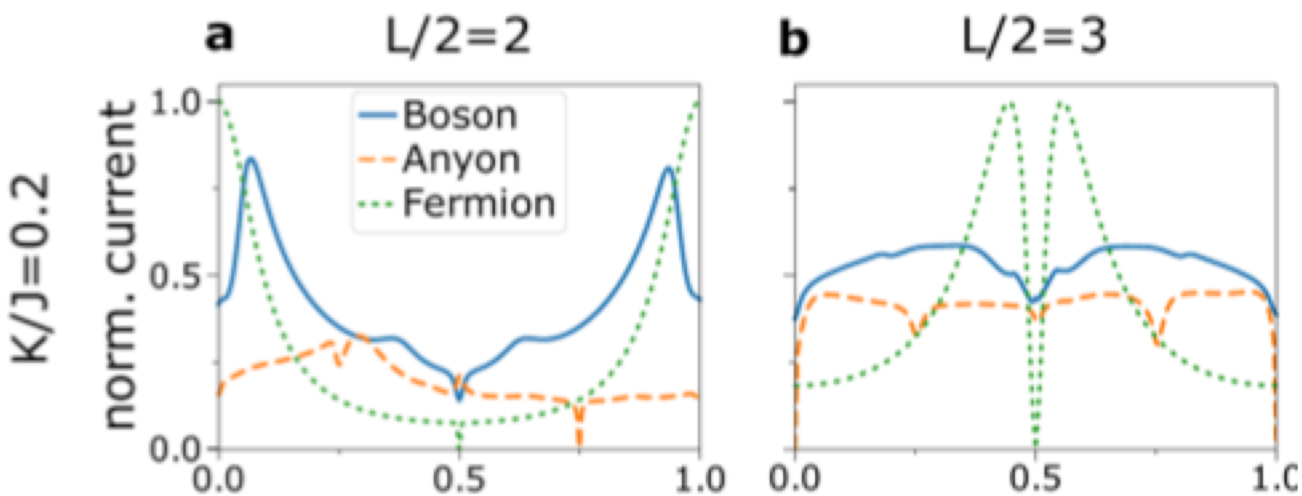
U/J=3, U/J=1

Weak coupling

- What happens in non-empty ring?
- Open system: Leads driven by particle reservoir → Steady-state current
- Fermion/anyon/boson with infinite repulsion U→∞

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





- Bosonic current never zero

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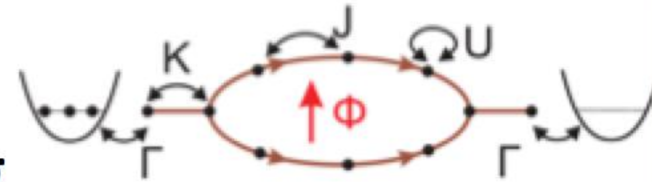
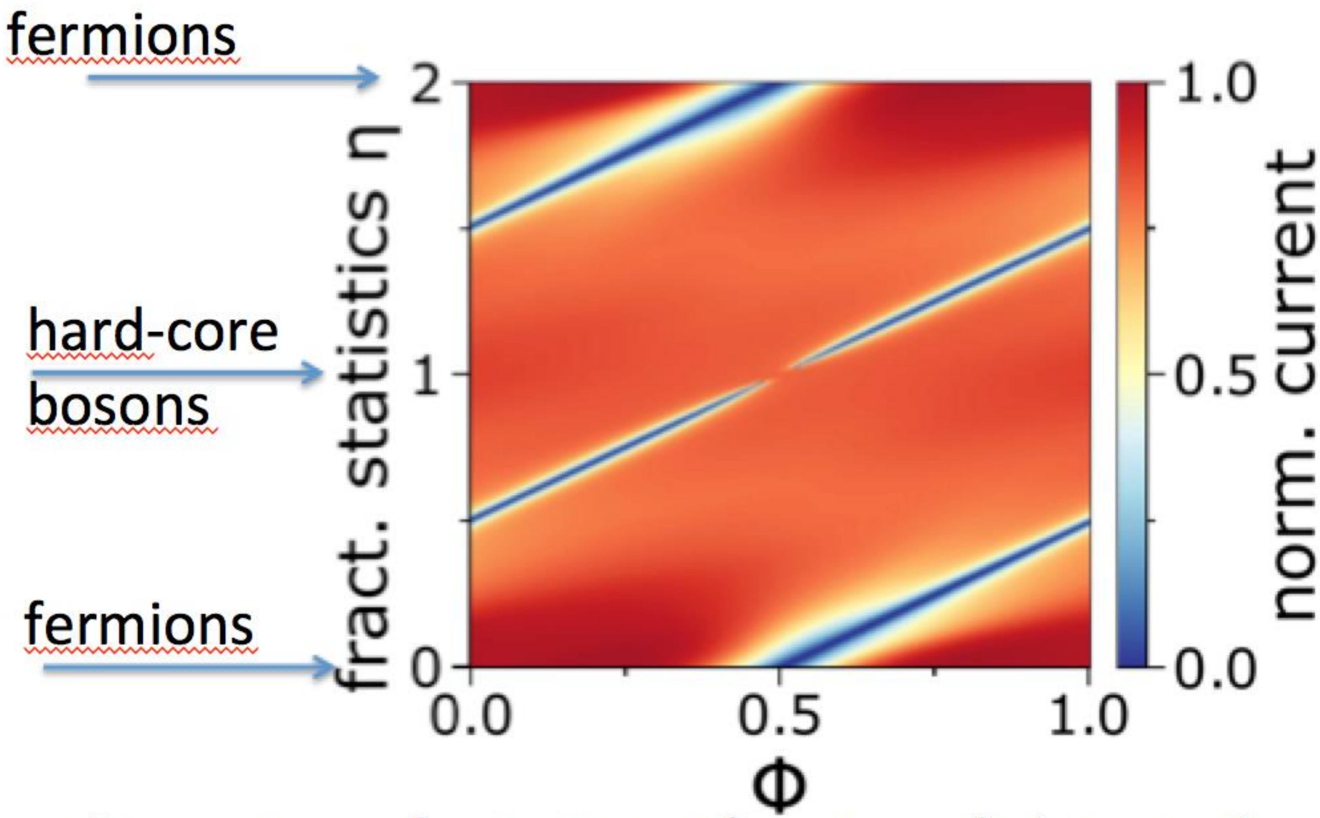
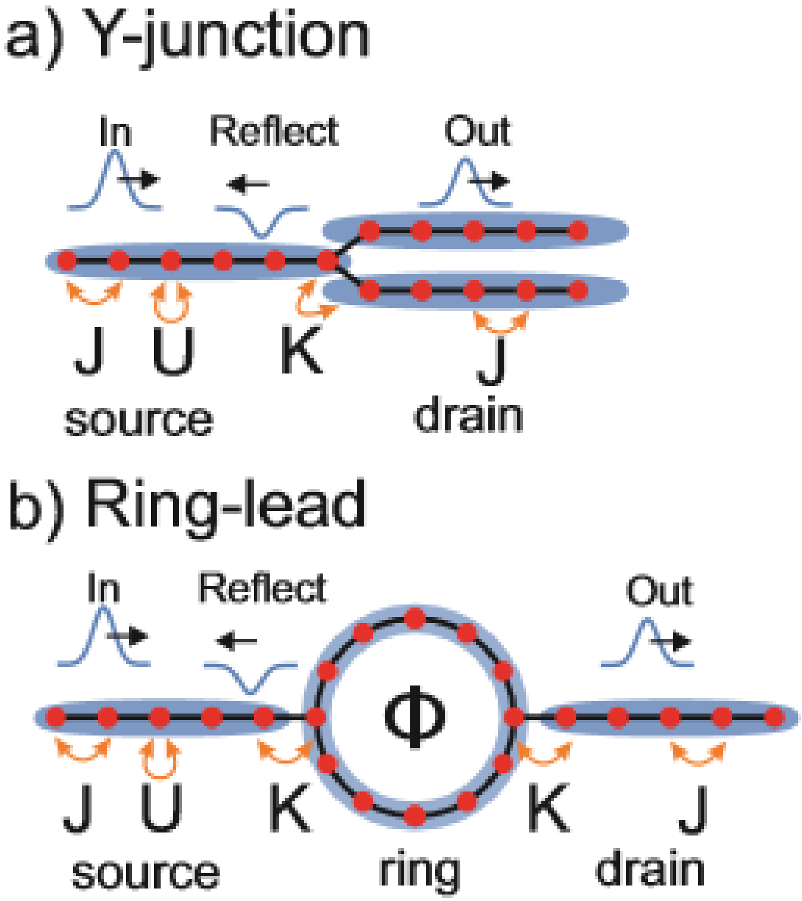


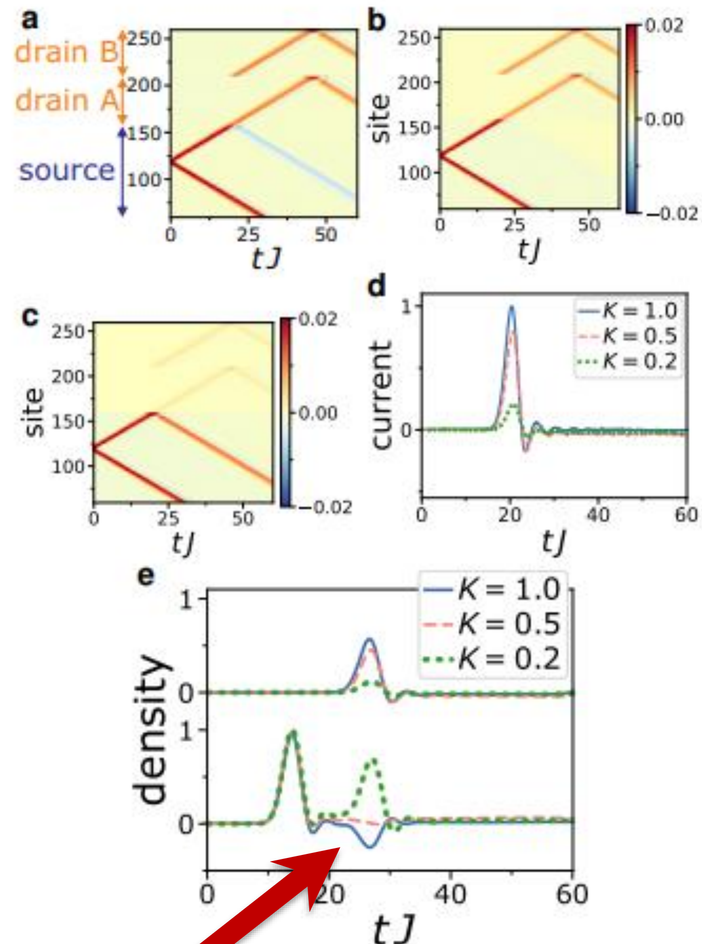
Strong coupling

- Generalize particle commutation rules η $\hat{a}_n^\dagger \hat{a}_m^\dagger + e^{i\pi\eta} \hat{a}_m^\dagger \hat{a}_n^\dagger = 0$



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





Negative reflection: Andreev-like

Add…shaking potential

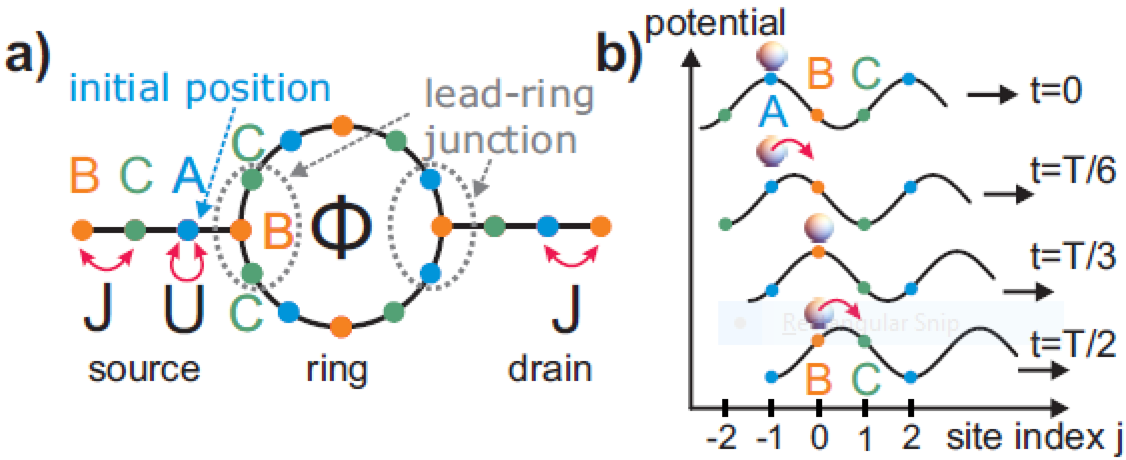
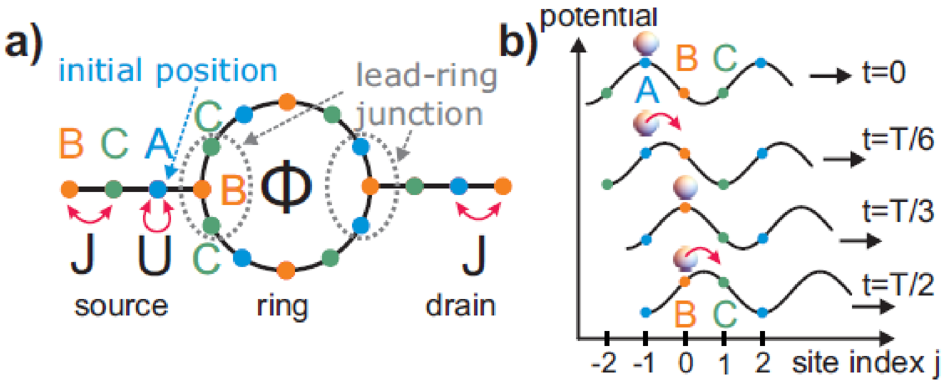
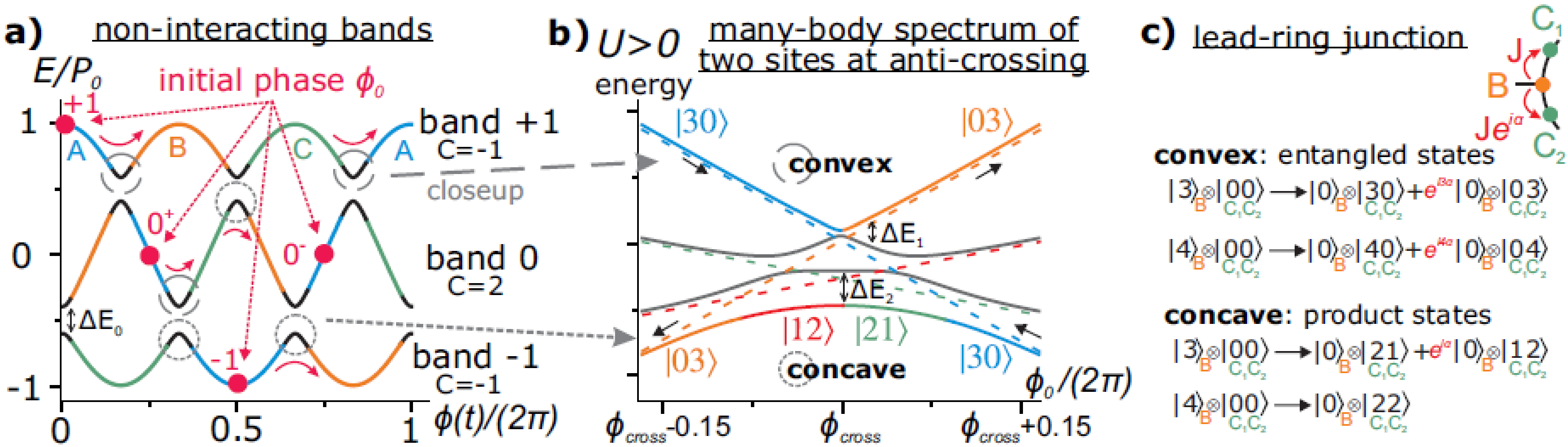


FIG. 1. **a)** Sketch of the ring-lead system. The dots indicate lattice sites j with local potential $V_j(t) = \cos(2\pi/3\, j - \Omega t)$ with a period of three lattice sites (A: $j = 0$, B: $j = 1$, C: $j = 2$). Particles tunnel between different sites along the black lines with strength J. U denotes the on-site interaction and Φ the flux of the ring. **b)** Topological pumping of particles on lattice sites by adiabatic modulation of the periodic potential $V_j(t)$ with Chern number $C = -1$. The cosine potential (black line) is varied adiabatically in time t with a frequency $\Omega = 2\pi/T$, where T is the time of one driving period. Particles are initialized at A. At time $t = 0$ no tunneling occurs due to a large potential difference to neighboring sites. At time $t = 1/6T$, potential of A and B is degenerate, and particles are adiabatically transfered to B. After one period T the particles have moved by 3 sites.



$$
\begin{aligned}
H &= H_R + H_S + H_D + H_L + H_P \\
H_R &= -\sum_{j=1}^{L_R} (J e^{i2\pi\Phi} \hat{a}_j^\dagger \hat{a}_{j+1} + HC) + U/2 \sum_{j=1}^{L_R} \hat{n}_j^a (\hat{n}_j^a - 1) \\
H_S &= -\sum_{j=1}^{L_R} (J \hat{s}_j^\dagger \hat{s}_{j+1} + HC) + U/2 \sum_{j=1}^{L_R} \hat{n}_j^s (\hat{n}_j^s - 1) \\
H_D &= -\sum_{j=1}^{L_R} (J \hat{d}_j^\dagger \hat{d}_{j+1} + HC) + U/2 \sum_{j=1}^{L_R} \hat{n}_j^d (\hat{n}_j^d - 1) \\
H_L &= -J(\hat{a}_0^\dagger \hat{s}_0 + \hat{a}_{L_r/2}^\dagger \hat{d}_0 + HC) \\
H_P(t) &= P_0 \sum_j \cos\left(\frac{2\pi j}{3} - \phi_0 - \Omega t\right) \hat{n}_j
\end{aligned}
$$

Topological Pumping



$$\Delta E_1 \propto \frac{J^N}{U^{N-1}} \text{ for } U >> J$$

$$\Delta E_2 = 2\sqrt{N}J$$

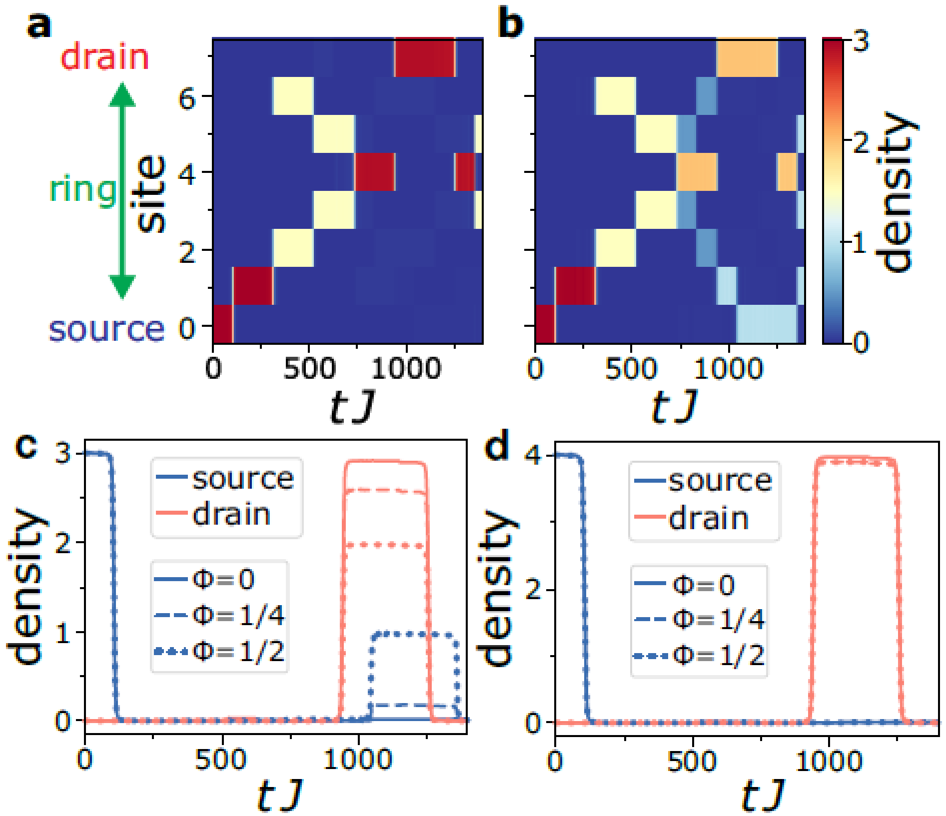
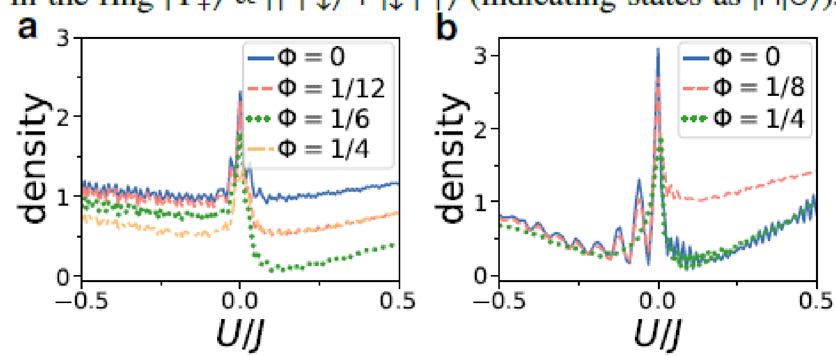


FIG. 3. Time evolution of topological pumping in the ring-lead system with $L_R = 6$, $U/J = 1$, $\Omega = 0.01J$, $P_0 = 40J$ in band -1. **a,b**) Density against time and sites for $N = 3$, **a**) flux $\Phi = 0$ and **b**) $\Phi = 1/2$. Site 0: source, site 1-6: ring, site 7: drain **c-d**) density in source and drain for particle numbers **c**) $N = 3$, **d**) $N = 4$.

Two species pumping.....

$$\mathcal{H}_{\text{int}} = \sum_j U \hat{n}_j^{\uparrow} \hat{n}_j^{\downarrow}$$

Driving this setup for the lower band -1 generates Bell states in the ring $|\Psi_+\rangle \propto |\uparrow\,|\,\downarrow\rangle + |\downarrow\,|\,\uparrow\rangle$ (indicating states as $|\cap|\cup\rangle$).



Density pumped through the ring into the drain for central band with Chern number $C = 2$. Here, band 0^+ with initial condition $\phi_0 = \pi/2$ was chosen. (For dynamics of band 0^-, invert interaction $U \to -U$) **a**) Dependence on interaction U for different values of flux Φ for $N = 3$ particles and **b**) for $N = 4$ particles. Drain density taken at $tJ = 630$ with $L_R = 8$, $\Omega = -0.01J$ and $P_0 = 60J$.

Quantum Science and Technology

PAPER

Mesoscopic Vortex–Meissner currents in ring ladders

Tobias Haug[1,9], **Luigi Amico**[1,2,3,4,5], **Rainer Dumke**[1,6] **and Leong-Chuan Kwek**[1,5,7,8]

[1] Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543, Singapore
[2] Dipartimento di Fisica e Astronomia, Via S. Sofia 64, I-95127 Catania, Italy
[3] CNR-MATIS-IMM & INFN-Sezione di Catania, Via S. Sofia 64, I-95127 Catania, Italy
[4] LANEF *'Chaire d'excellence'*, Université Grenoble-Alpes & CNRS, F-38000 Grenoble, France
[5] MajuLab, CNRS-UNS-NUS-NTU International Joint Research Unit, UMI 3654, Singapore
[6] Division of Physics and Applied Physics, Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore
[7] Institute of Advanced Studies, Nanyang Technological University, 60 Nanyang View, Singapore 639673, Singapore
[8] National Institute of Ed
[9] Author to whom corres

E-mail: tobias.haug@u.nu

Keywords: ultracold atom

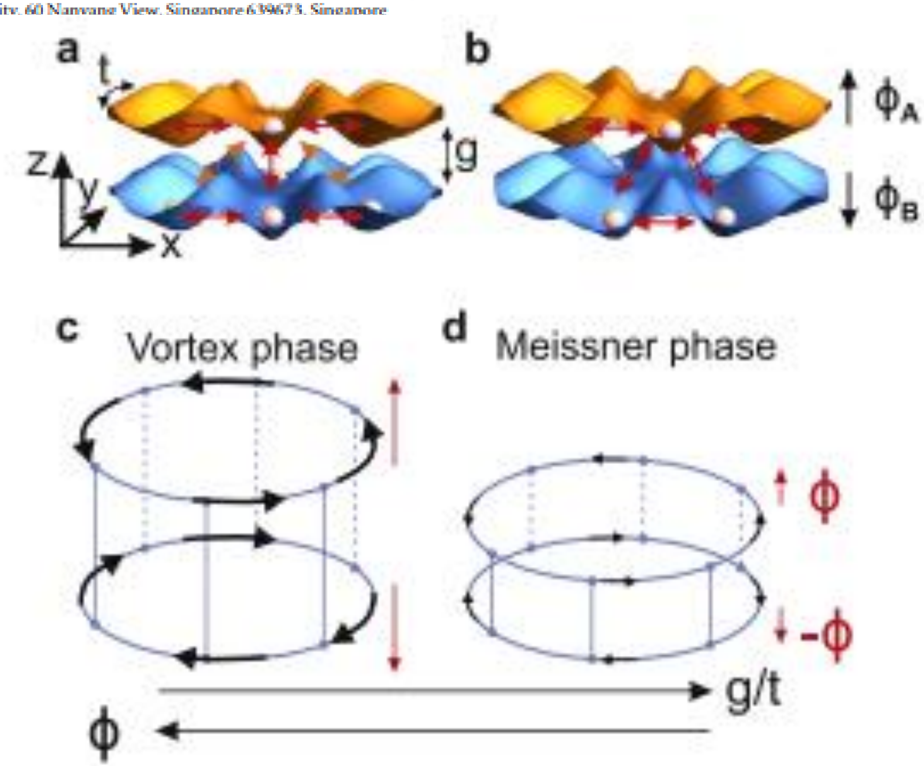
Abstract

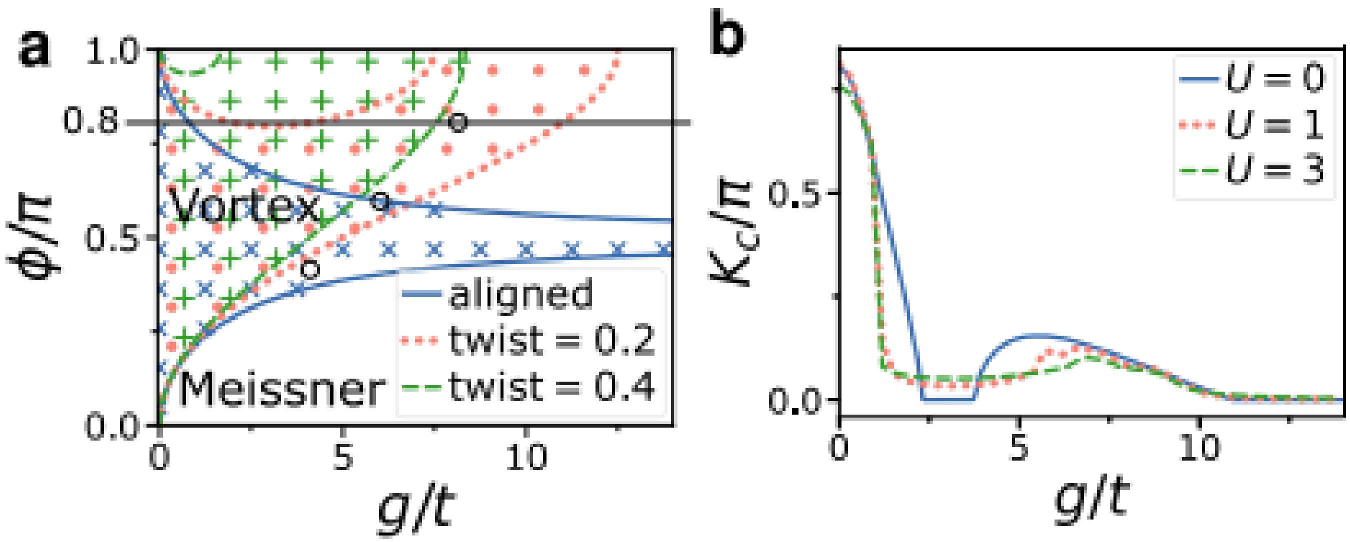
Recent experiment
atoms systems. Ato
system into accoun
between them. We
configuration revea
feasible diagnostic

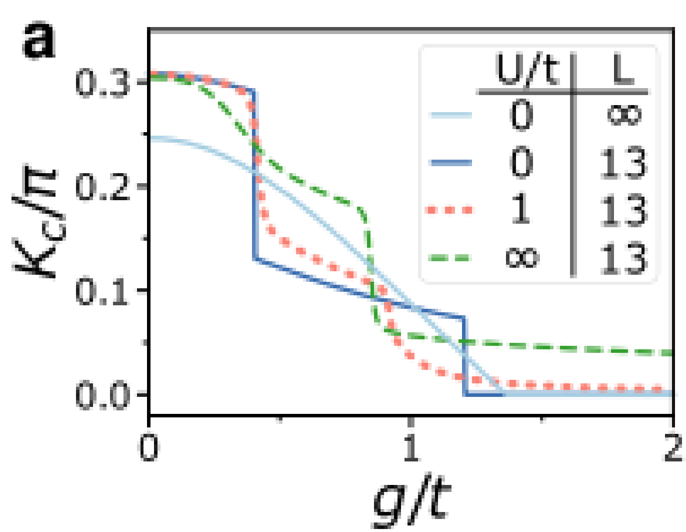
$$\mathcal{H}_A = \sum_{m=1}^{L} (-te^{i\phi_A}\hat{a}_m^{\dagger}\hat{a}_{m+1} + \text{h.c.}) + \frac{U}{2}\hat{n}_m^a(\hat{n}_m^a - 1),$$

$$\mathcal{H}_B = \sum_{m=1}^{L} (-te^{i\phi_B}\hat{b}_m^{\dagger}\hat{b}_{m+1} + \text{h.c.}) + \frac{U}{2}\hat{n}_m^b(\hat{n}_m^b - 1),$$

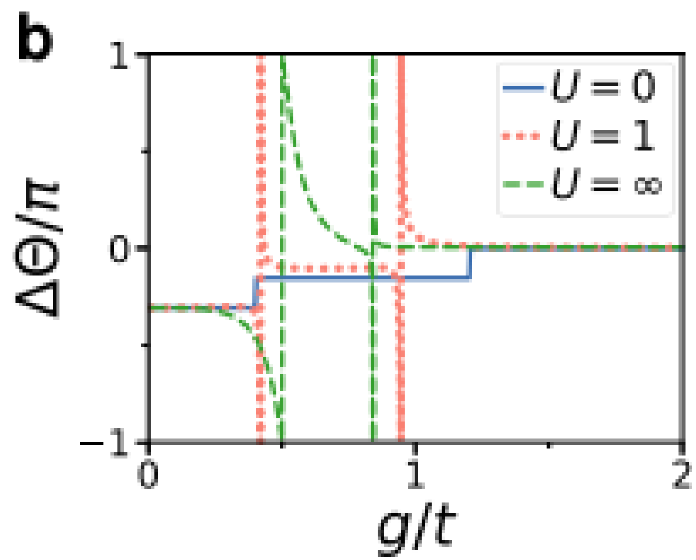
$$\mathcal{H}_I = \sum_{m=1}^{L} -g\Big[(1-w)\hat{a}_m^{\dagger}\hat{b}_m + \frac{w}{2}(1+\gamma)\hat{a}_m^{\dagger}\hat{b}_{m+1} + \frac{w}{2}(1-\gamma)\hat{a}_m^{\dagger}\hat{b}_{m-1}\Big] + \text{h.c.}$$





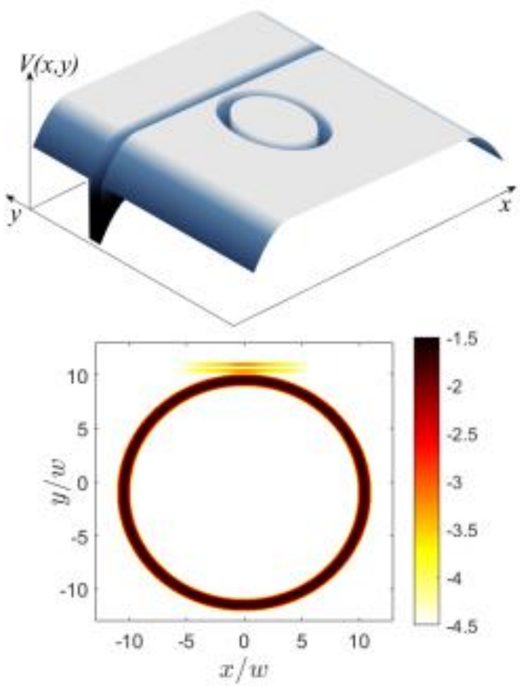


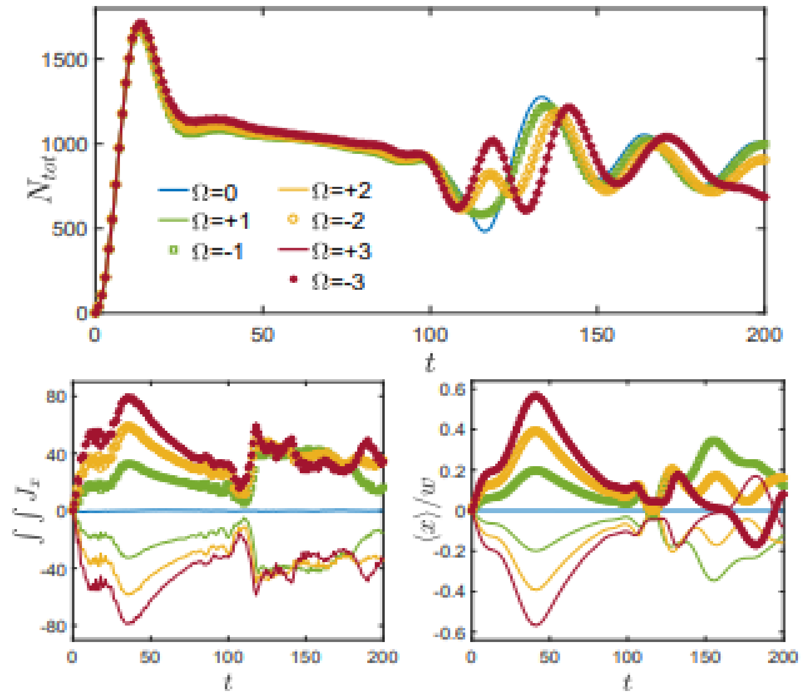
Chiral momentum Kc plotted against inter-ring coupling g/t for different values of interaction U/t



Phase jump of two point correlations

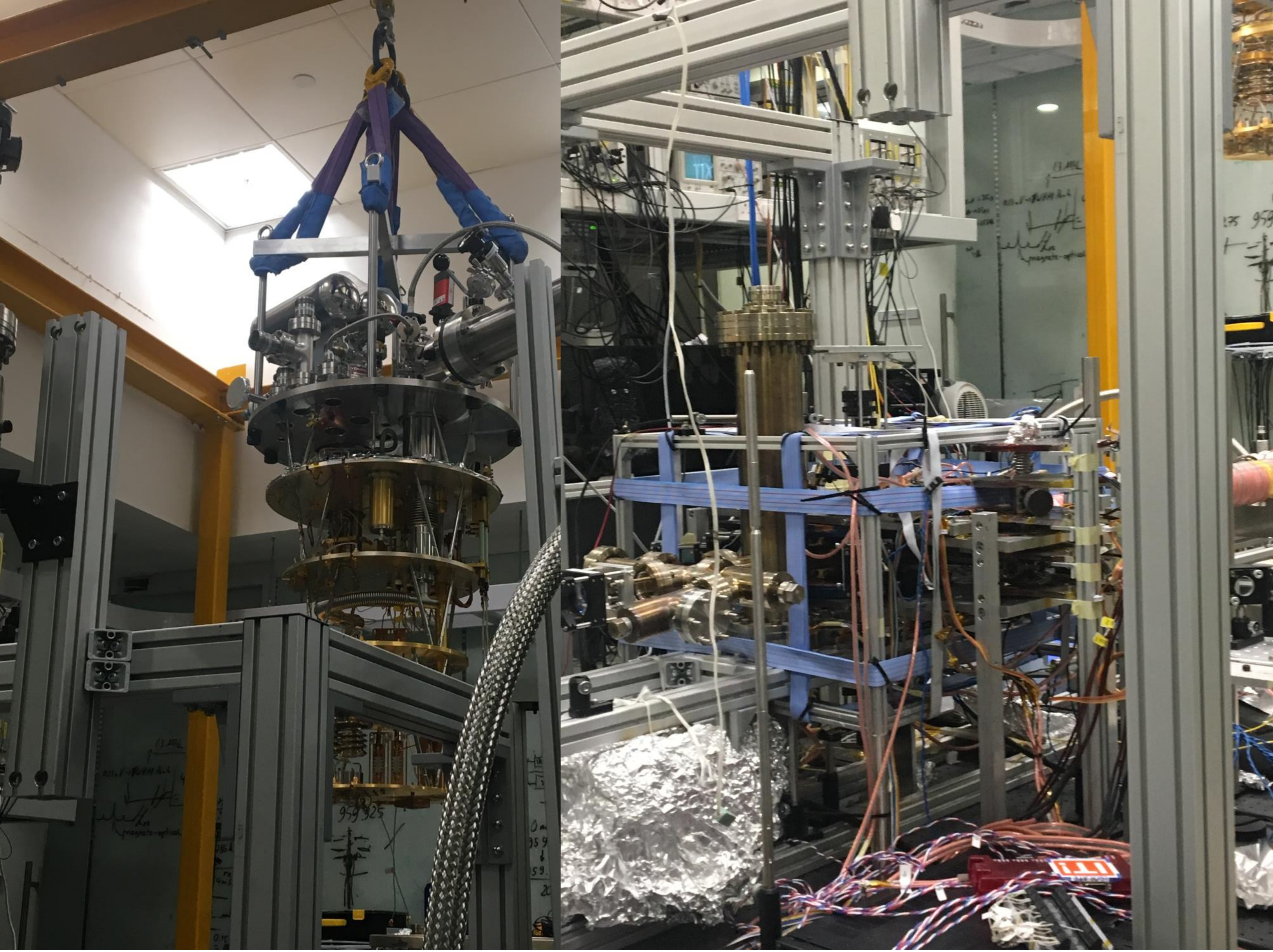
Analogs from quantum optics……





Dynamics of the total number of atoms $N_{\rm tot}$ (top), the net particle flux in x direction $\int dx \int dy J_x$ (bottom-left) and the x component of the center of mass of atomic cloud $\langle x \rangle$ (bottom-right) inside the waveguide, for non-rotating, $\Omega = 0$, and rotating cases with $\Omega = \pm 1, \pm 2, \pm 3$. The ring potential and the waveguide have same width w and depth $U_0 = 20$. Atom-atom interaction strength is $u = 2 \times 10^{-4}$ and ABC potential strength is $V_0 = 20$.

arXiv:1808.04129



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Focus on Atomtronics-enabled Quantum Technologies

Luigi Amico, *Università di Catania & Centre for Quantum Technologies, National University of Singapore*
Gerhard Birkl, *Technische Universität Darmstadt*
Malcolm Boshier, *Los Alamos National Laboratories*
Leong-Chuan Kwek, *Centre for Quantum Technologies, National University of Singapore*

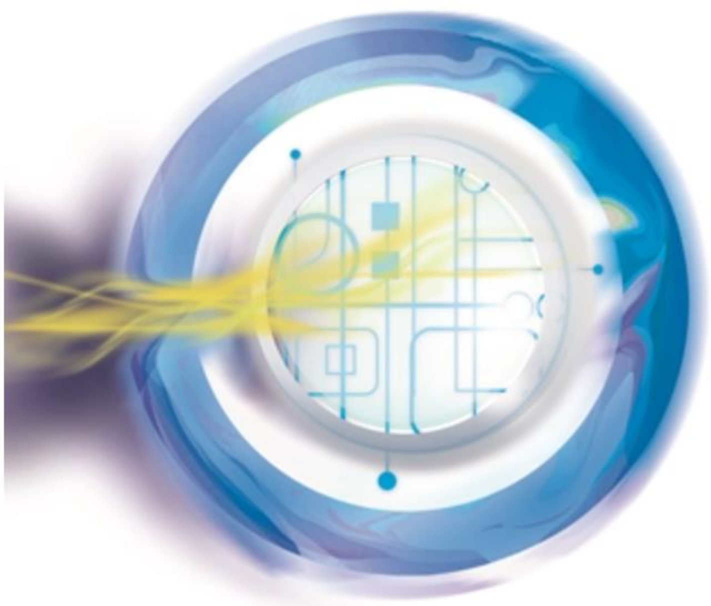


Image credit: Timothy Yeo / CQT, National University of Singapore

Scope

Imagine circuitry with atomic carriers instead of electrons and holes. The most evident features that result from such a design would be a reduced decoherence rate due to charge neutrality of the atomic currents, an ability to realize quantum devices with fermionic or bosonic carriers, and a tunable carrier–carrier interaction from weak-to-strong, from short-to-long range, from attractive-to-repulsive in type

The rapid progress in quantum technology is spurring this dream to reality: Atomtronics is an emerging field in physics that promises to realize those atomic circuit architectures exploiting ultra-cold atoms manipulated in versatile micro-optical circuits generated by laser fields of different shapes and intensities or micro-magnetic circuits known as atom chips.

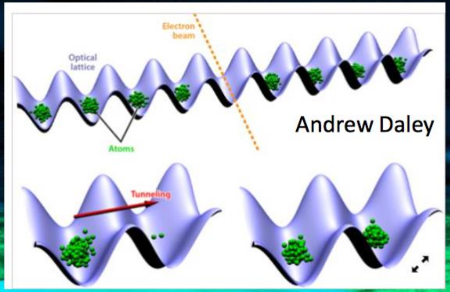
With the added value of a dissipation-less flowing atomic current, Atomtronics would enhance the flexibility and the scope of cold-atom quantum technology. Within the spirit of the solid-state I-V characteristics, a variety of physical phenomena in many-body physics could be studied with high accuracy & controllability as is typical of quantum optics technology. With the current know-how in the field, circuits with a lithographic precision can be realized. In principle, all aspects of mesoscopic physics and devices can also be explored. It is not just classical electronics which is targeted, but also atom-based spintronics and quantum electronic structures like Josephson junction-based circuits (SQUID devices, etc.), quantum point contacts and impurity problems. Core devices for

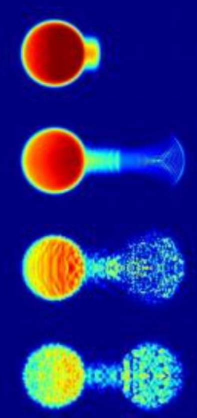
Recent atomtronic devices

Portable BEC chamber (2014)

Atom SQUID (2014)

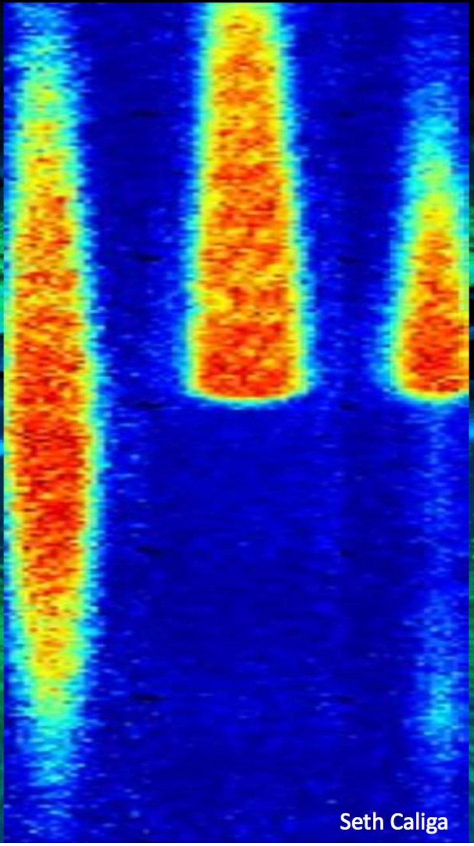
Diode (2015)





Tank Circuit (2016)

Battery (2017)

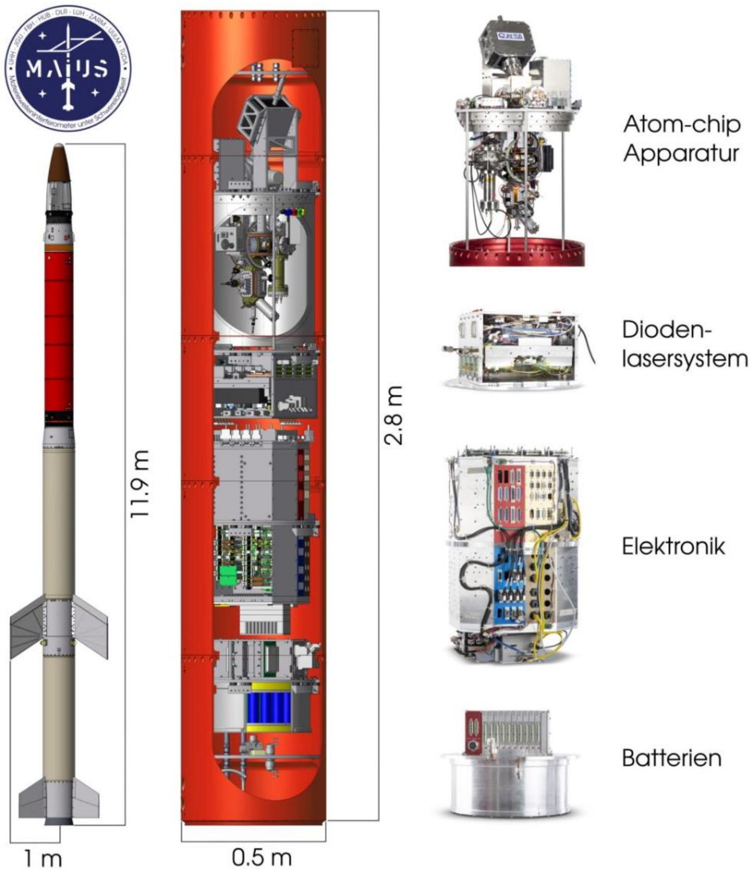


Source: Charles Clark

Atomtronics today

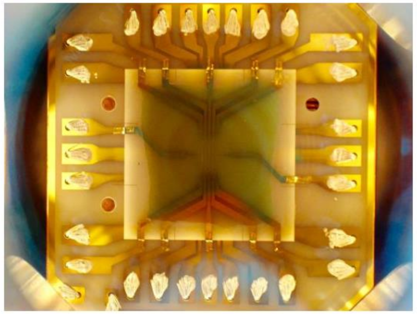
Source: Charles Clark

First Bose-Einstein condensate in space



MAIUS 1 Sounding Rocket Mission

- MAIUS: Matter-Wave Interferometry in Microgravity
- Launched 23 January 2017 in northern Sweden
- Produced Bose-Einstein condensate on board
- Performed 100 experiments in matter-wave interferometry

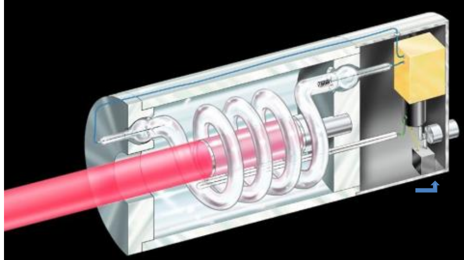


Images: DLR

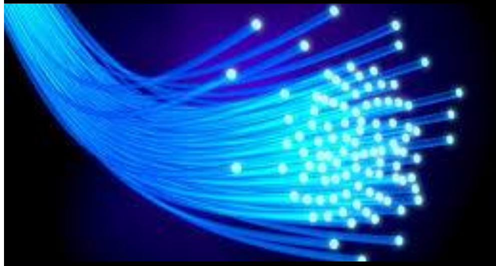
Source: Charles Clark

Unpredictability of blue sky research

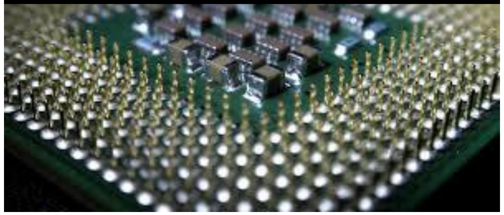
Laser (1960s)



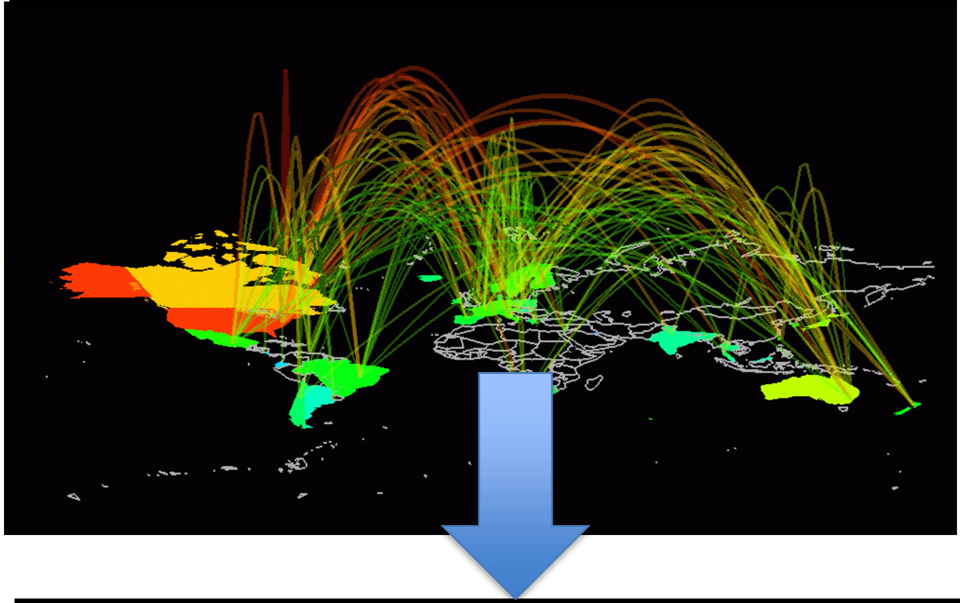
Optical fibers
(1970s)



Integrated circuits
(1950s-90s)



Global commuication network



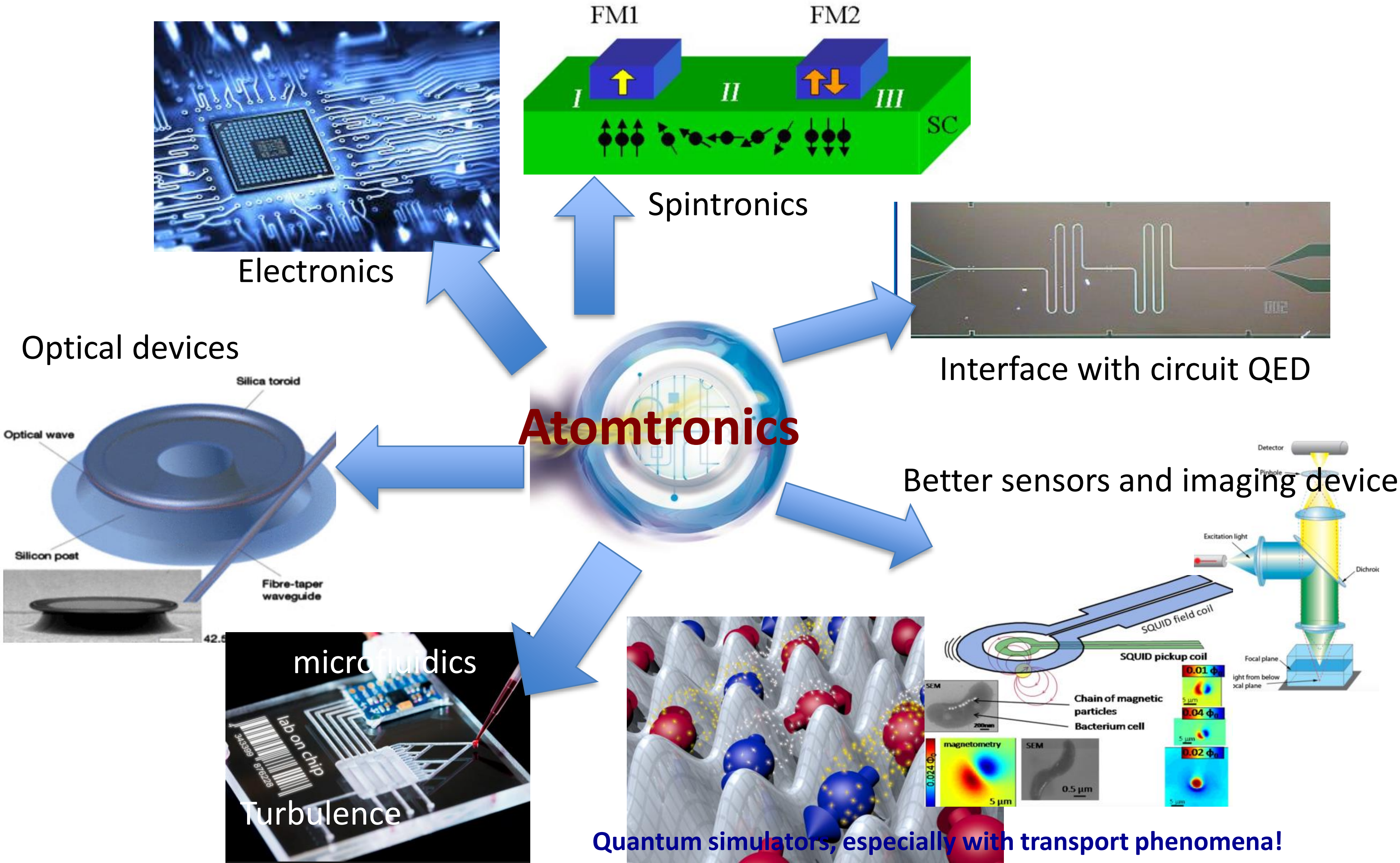
Towards a global quantum network???

Adapted from Serge Haroche slide

What probably is the Grand Scheme?

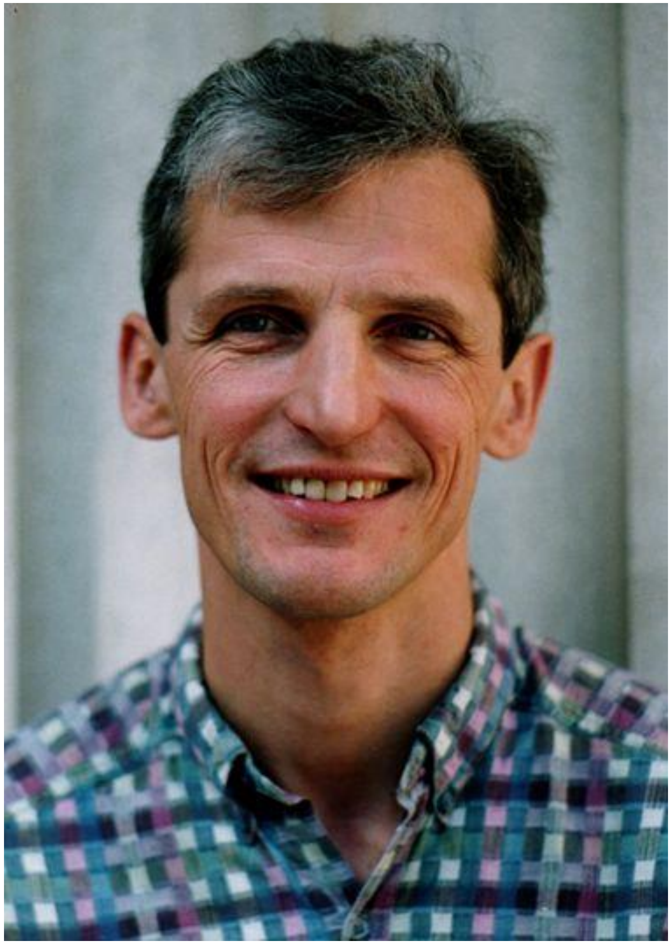
Replacing electronics with atomtronics?

What probably is the Grand Scheme?



Wolfgang Ketterle

“People in the entertainment industry didn't discover lasers for DVDs and BluRays. That was the work of scientists. Dentists didn't discover X-rays for improved medical imaging. That was the work of scientists.”



http://www.businessinsider.com/why-quantum-technology-matters-2013-7?IR=T&

”….not only should scientists be allowed to investigate technologies that might not have an obvious application, they should be encouraged to do so. Improved clocks are an important part of driverless cars. Improved sensors make it easier to find cancer. When you build a bridge to an uninhabited island, people move there, build houses, and start an economy. We're building these bridges."

Misha Lukin

It is hard to make predictions, especially about the future... (Attributed to Niels Bohr)
... but one thing is sure: without basic research, novel technologies cannot be invented...
...and the past teaches us that wonderful applications always emerge serendipitously from blue sky research.

Serge Haroche

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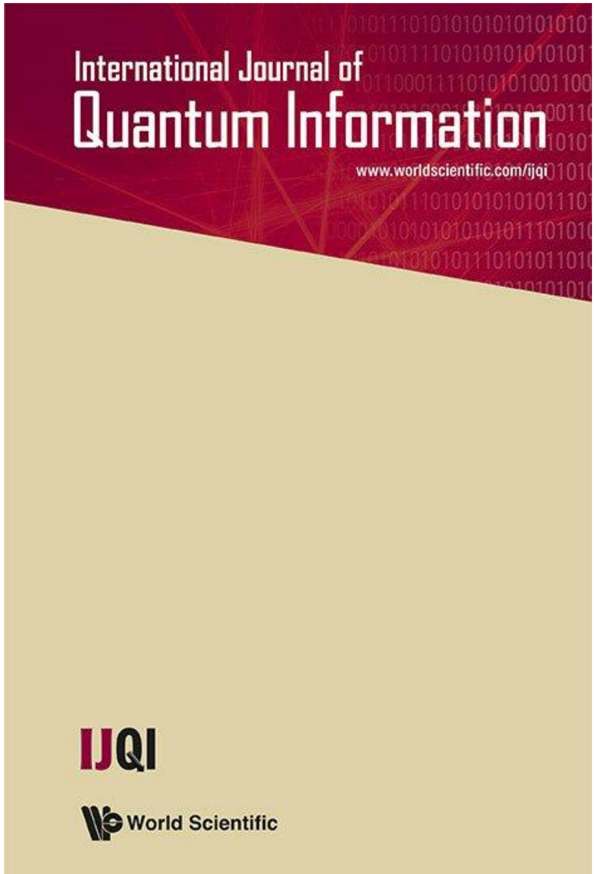

Aims & Scope

The International Journal of Quantum Information (IJQI) provides a forum for the interdisciplinary field of Quantum Information Science. In particular, we welcome contributions in these areas of experimental and theoretical research:

- Quantum Cryptography
- Quantum Computation
- Quantum Communication
- Fundamentals of Quantum Mechanics

Authors are welcome to submit quality research and review papers as well as short correspondences in both theoretical and experimental areas. Submitted articles will be refereed prior to acceptance for publication in the Journal.

Thank you