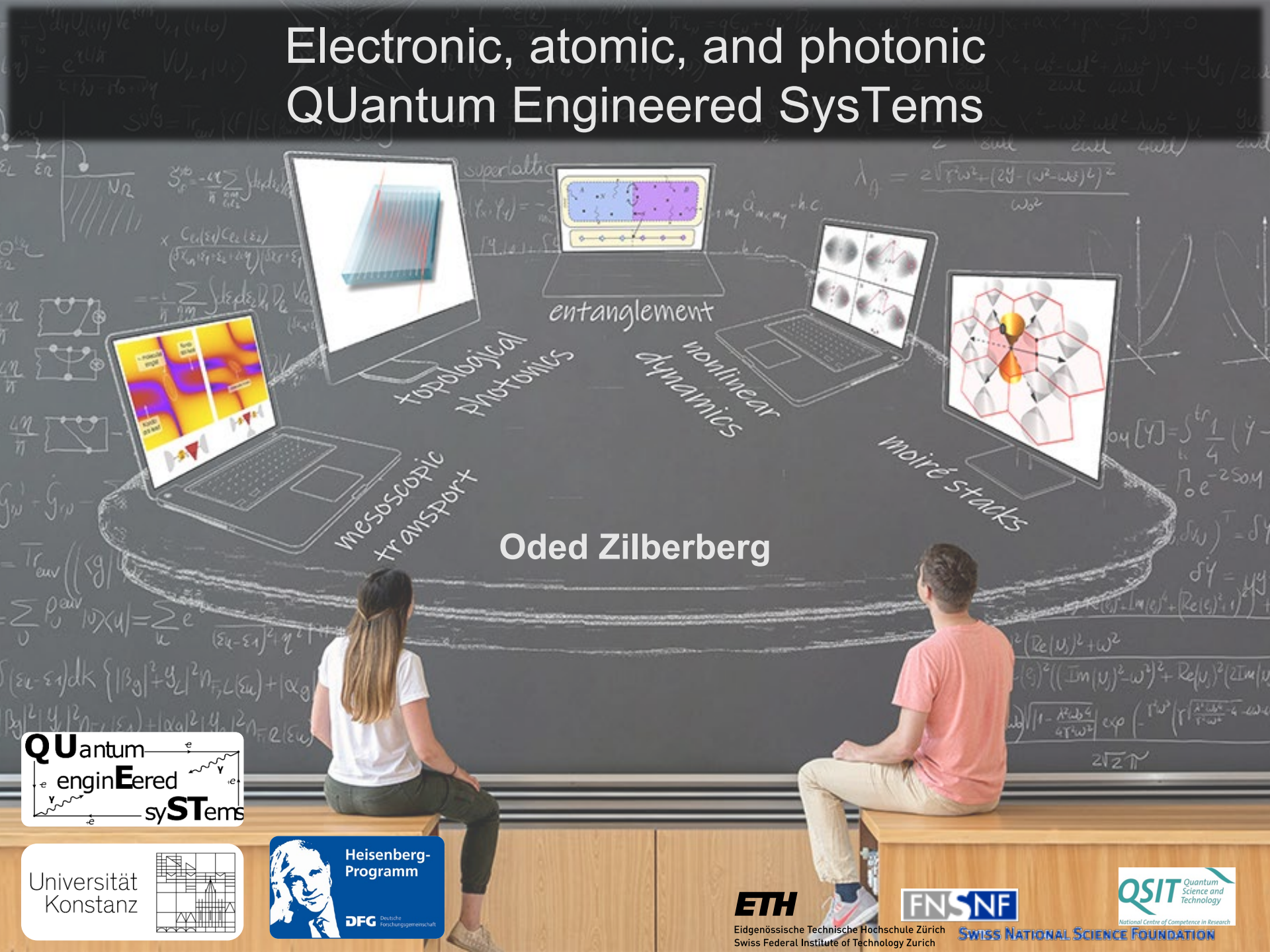
Electronic, atomic, and photonic QUantum Engineered SysTems



QUantum enginEered sySTems

Universität Konstanz

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

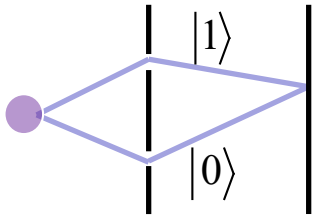
FNSNF
Swiss National Science Foundation

QSIT Quantum Science and Technology
National Centre of Competence in Research

Quantum mechanical journey

Discovery (1920s)
Particle-wave duality

Superposition and coherence



$$|0\rangle + e^{i\varphi}|1\rangle$$

Quantum mechanical journey

Discovery (1920s)
Particle-wave duality

Philosophy (1935-1990)
EPR paradox

Superposition and coherence

$$|0\rangle + e^{i\varphi}|1\rangle$$

Entanglement

$$(|0\rangle + |1\rangle) \otimes (|0\rangle + |1\rangle)$$

$$|00\rangle + |01\rangle + |10\rangle + |11\rangle$$

$$|00\rangle + |\times\rangle + |\times\rangle + |11\rangle$$

Quantum mechanical journey

Discovery (1920s)
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Superposition and coherence

$|0\rangle + e^{i\varphi}|1\rangle$

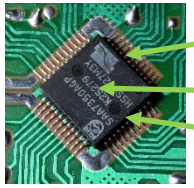
Philosophy (1935-1990)
EPR paradox

Entanglement

$|00\rangle + |11\rangle$

Material engineering (1930s-today)
Applications

Integrated circuits



Conductors

Semiconductors

Insulators

Quantum mechanical journey

Discovery (1920s)
Particle-wave duality

Superposition and coherence

$|0\rangle + e^{i\varphi}|1\rangle$

Philosophy (1935-1990)
EPR paradox

Entanglement

$|00\rangle + |11\rangle$

Material engineering (1930s-today)
Applications

Integrated circuits

Conductors

Semiconductors

Insulators

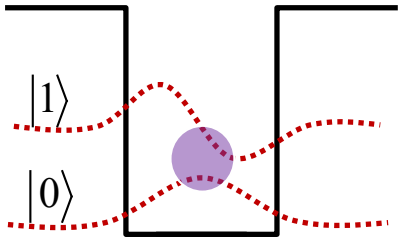
Quantum engineering (1980s-today)
Future technology

Control, manipulate, and harness **quantum resources**

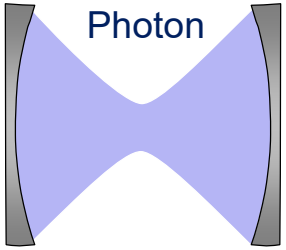
Control, manipulate, and harness

Superposition and coherence

Trap quantum particles

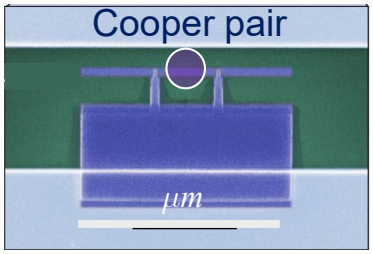


Optical cavities



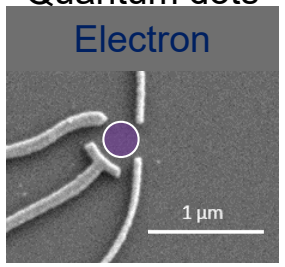
RMP **85,** 1083 (2013)

Superconducting loops



Nature **431,** 162 (2004)

Quantum dots

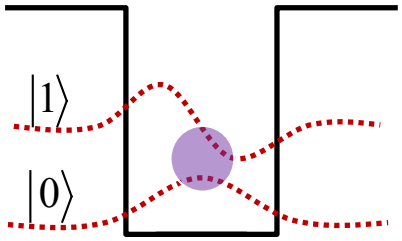


PRL **115**, 166603 (2015)

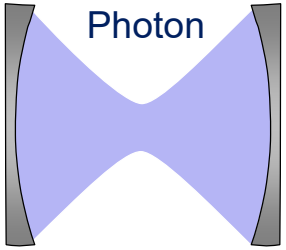
Control, manipulate, and harness

Superposition and coherence

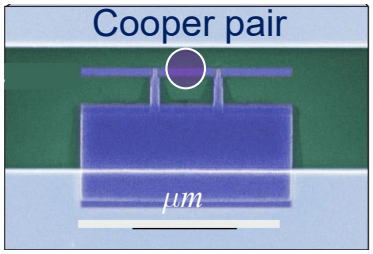
Trap quantum particles



Optical cavities

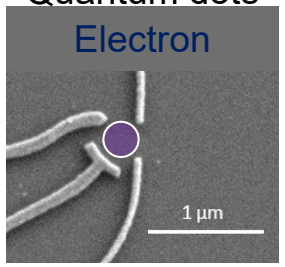


Superconducting loops



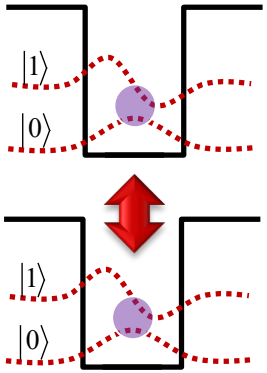
Nature **431,** 162 (2004)

Quantum dots

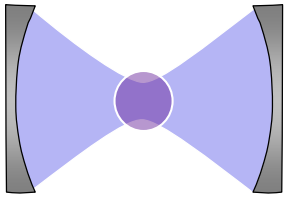


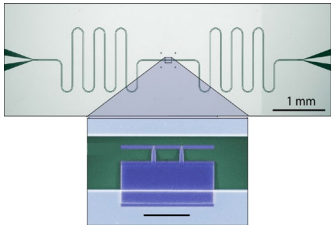
PRL **115**, 166603 (2015)

Entanglement



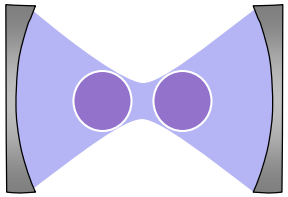
atom-photon

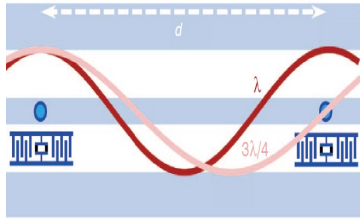




Nature **431,** 162 (2004)

atom-atom

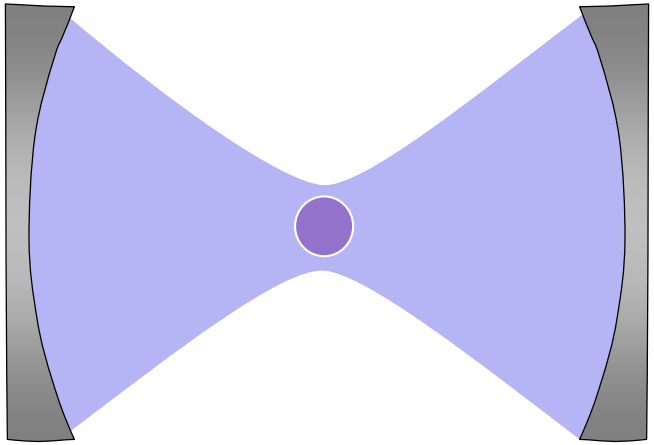




Science **342,** 1494 (2013)

QUEST research

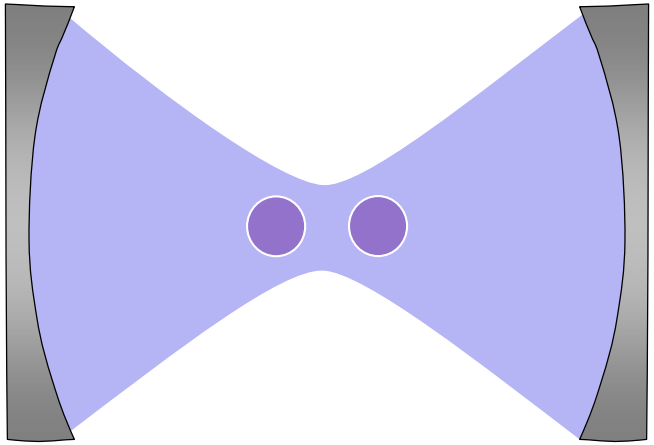
Coherence ⟺ **Open system**



1

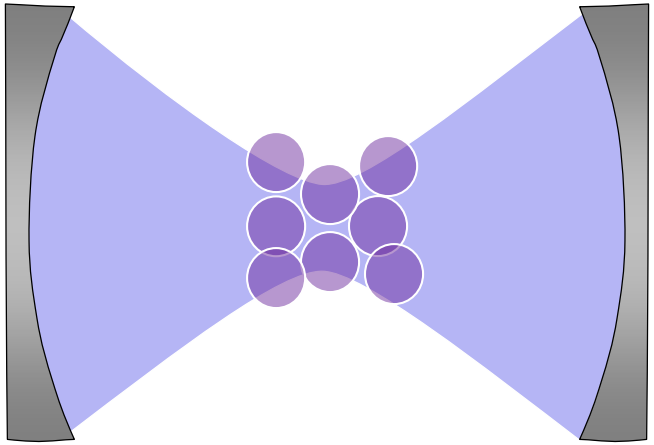
QUEST research

Coherence ⟺ **Open system**



QUEST research

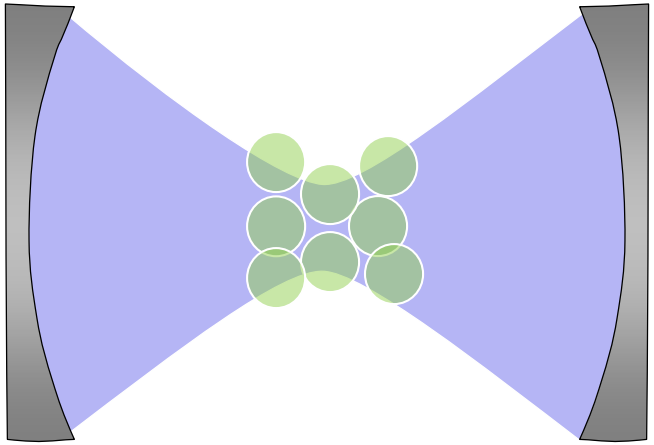
Coherence ⟷ **Open system**



many

QUEST research

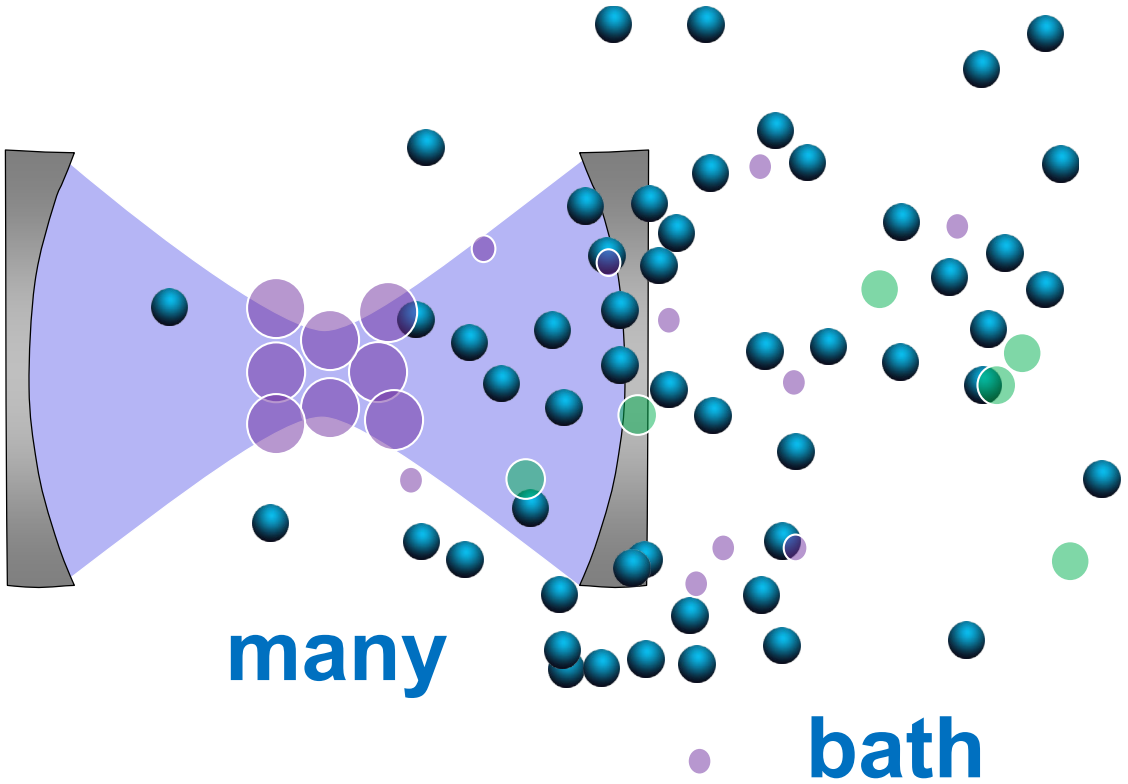
Coherence ⟷ **Open system**



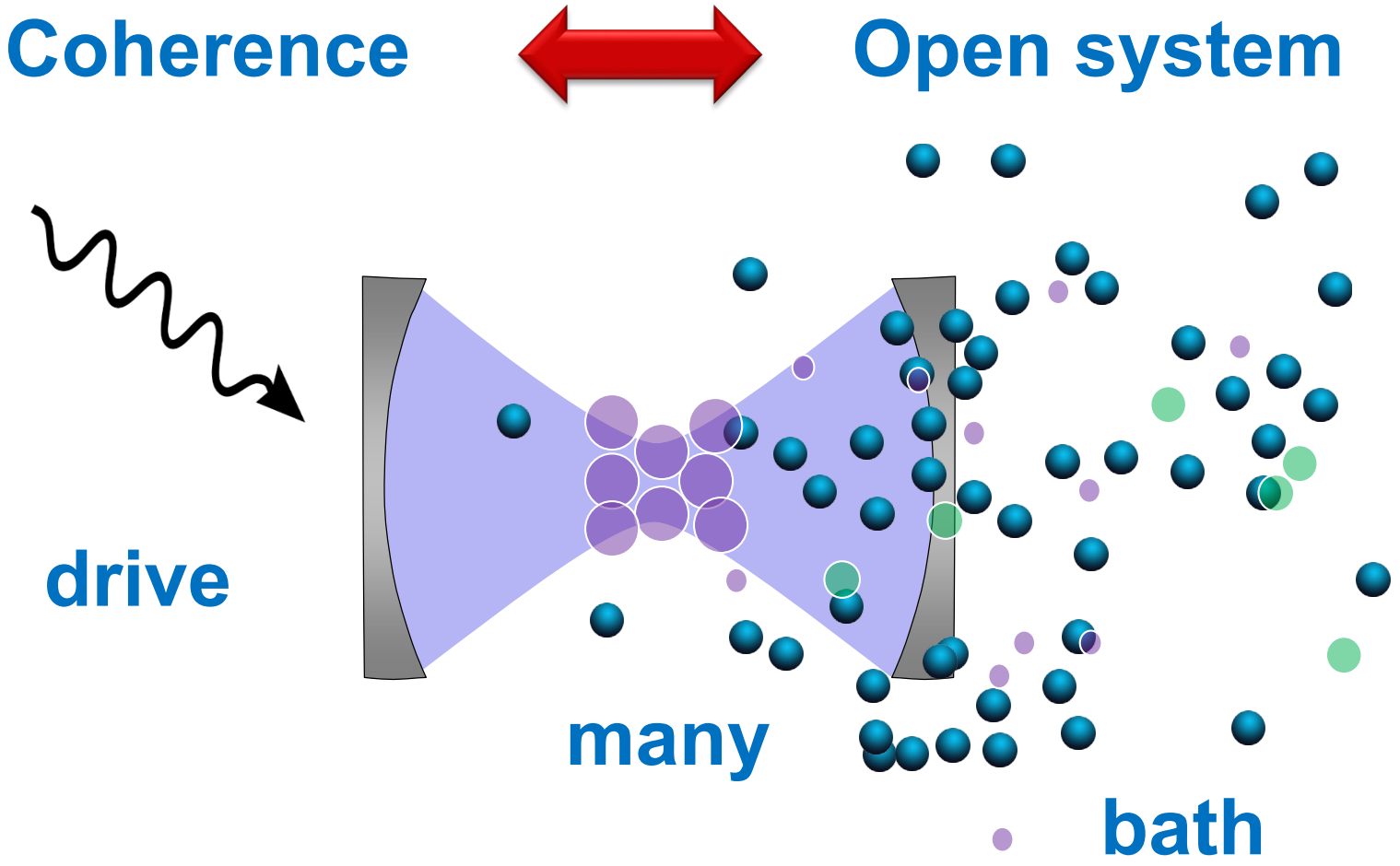
bosons ⟷ **fermions**

QUEST research

Coherence ⟷ **Open system**



QUEST research



Quantum simulation

Cold atoms

~1μm

~1nK

~10^{-10}meV

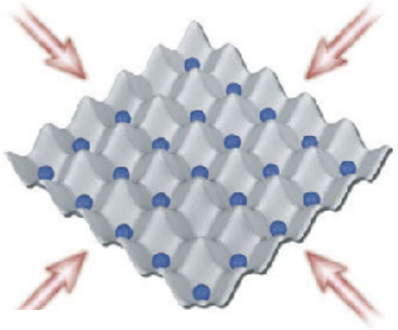


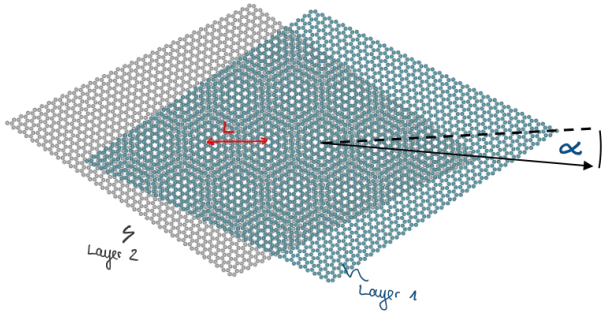
Figure from Bloch, Nature 453, 1016 (2008)

Moiré lattices

~10nm

~1K

~0.1meV

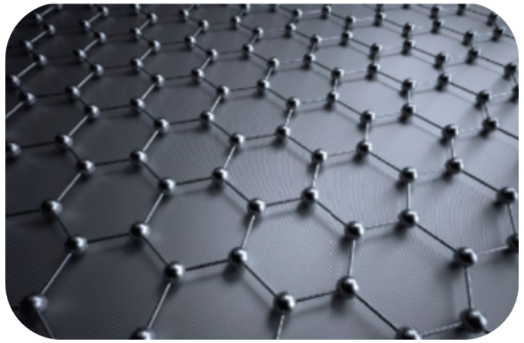


Condensed matter

~few Å

100-1000K

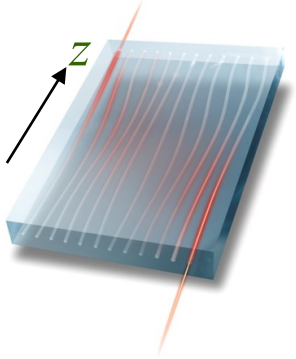
~10-100meV

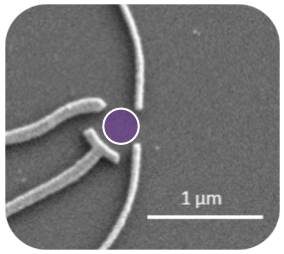


Photons

~1μm

~5/cm





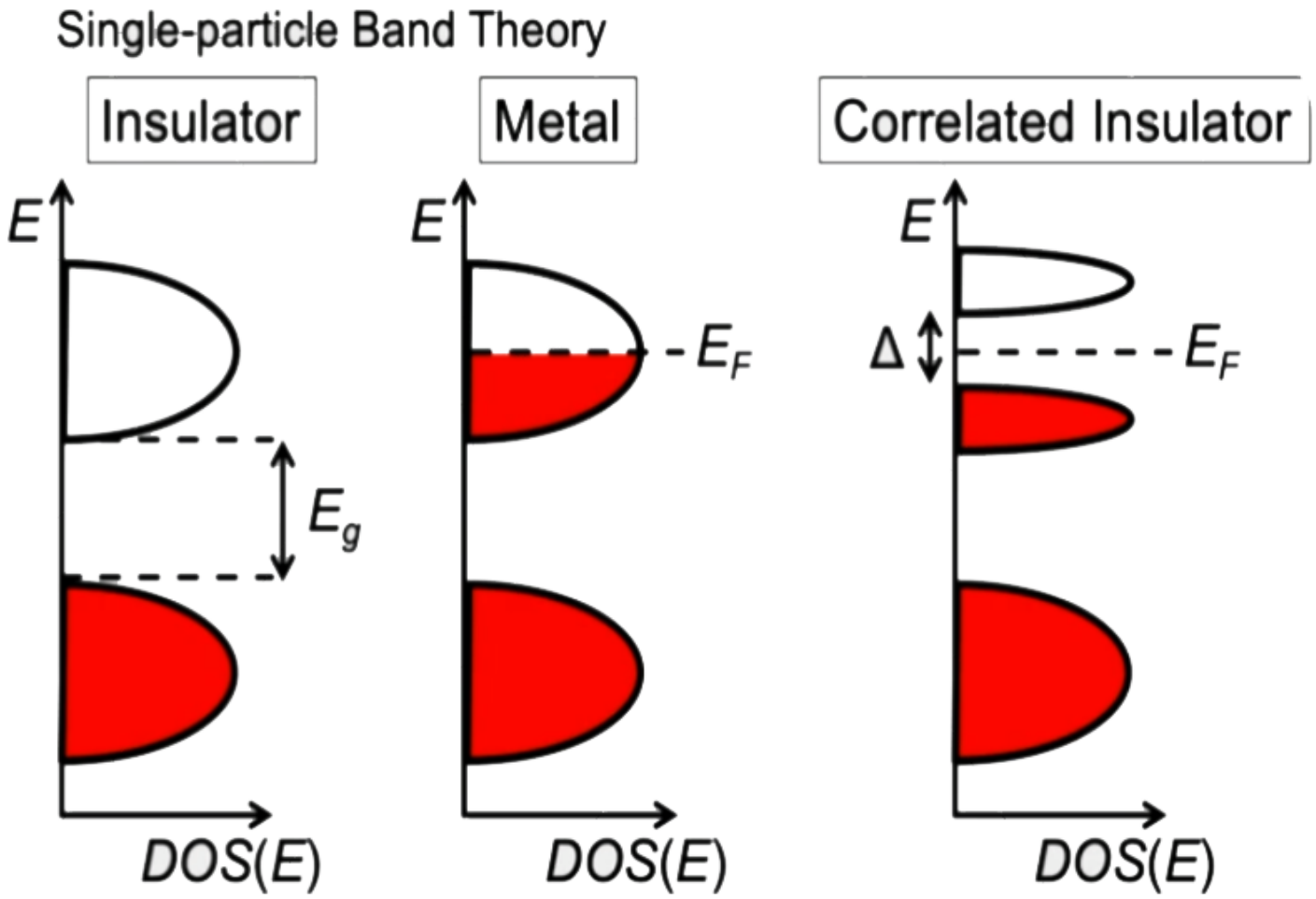
Mesoscopic devices

~10-1000nm

~10mK

~10-100meV

From single to many-body physics

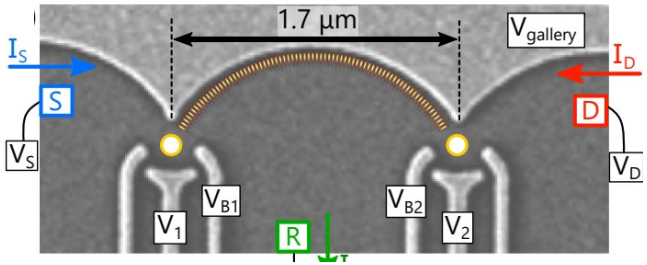


QUEST research

Quantum engineering of

Devices

Mesoscopic transport



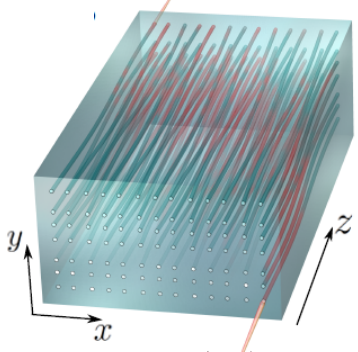
engineered quantum chemistry

⟺

many-body cond. mat.

Material properties

Quantum simulation



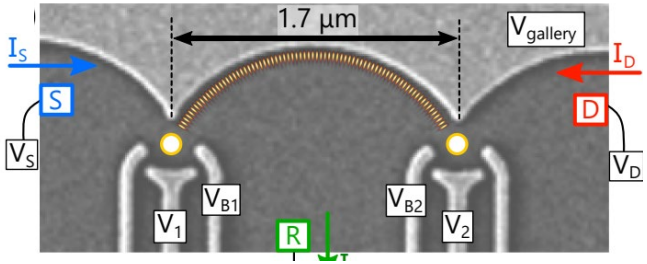
designer models ⟺ real materials

QUEST research

Quantum engineering of

Devices

Mesoscopic transport



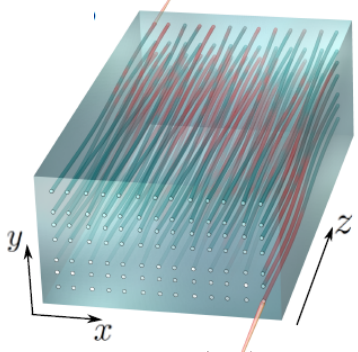
engineered quantum chemistry

many-body cond. mat.

- Electronic interferometers
- Kondo impurities
- Quantum measurement
- Topological semimetals

Material properties

Quantum simulation



designer models  real materials

QUEST research

Quantum engineering of

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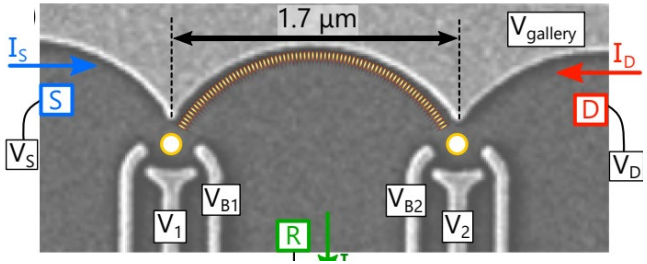
Mesoscopic transport



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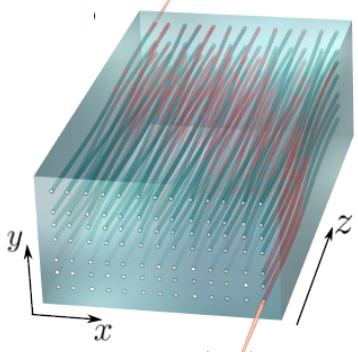
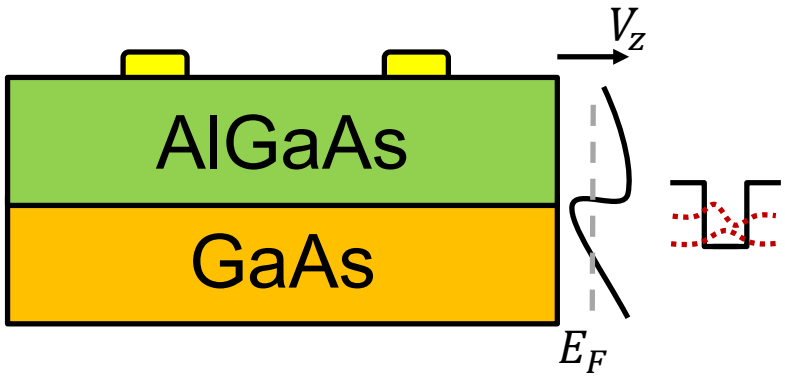


designer models  real materials

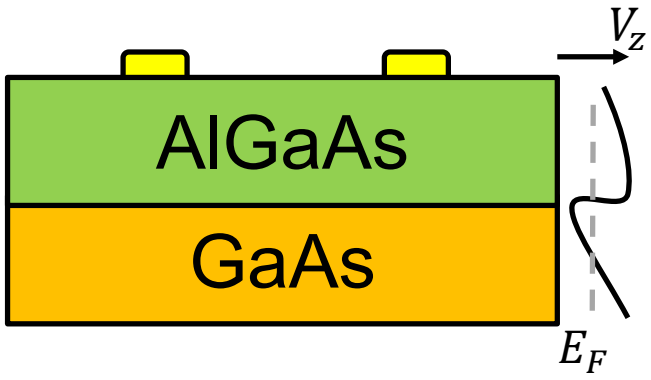
- Topological photonics
- Synthetic dimensions
- Quasicrystals
- Dissipative phase transitions

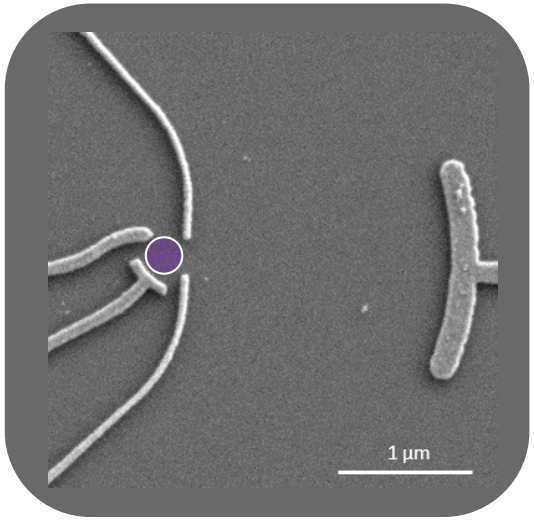
Material progress ⇨ engineer electron landscape

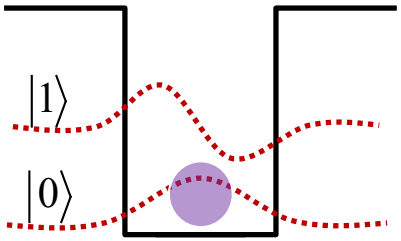


PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Material progress ⇨ engineer electron landscape







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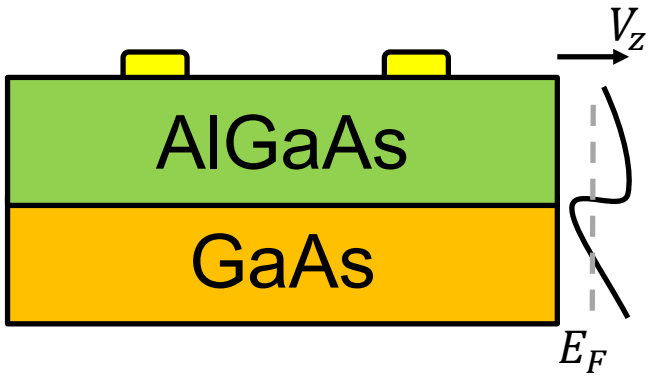
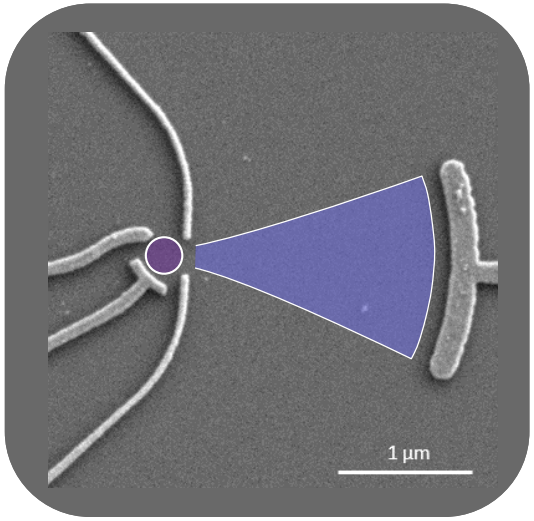
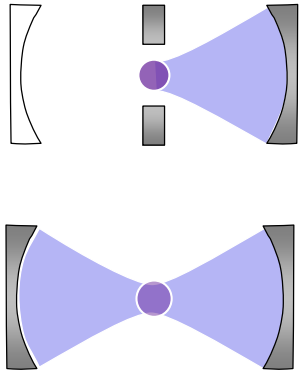
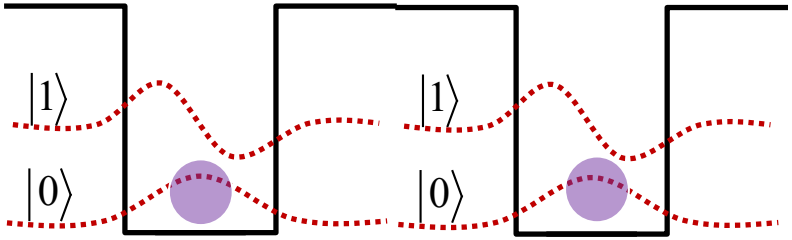


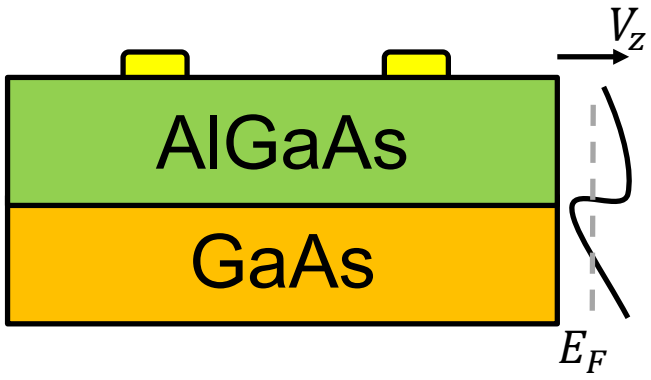


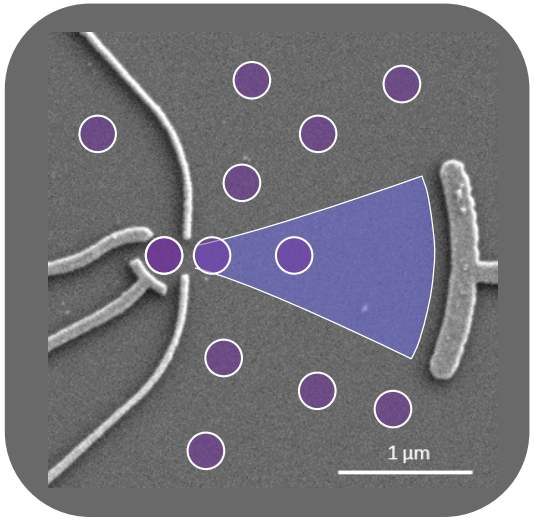


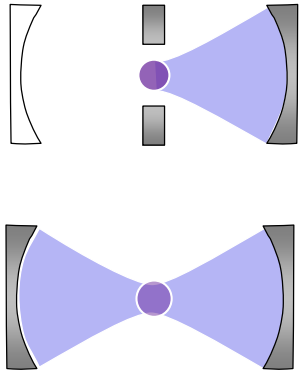


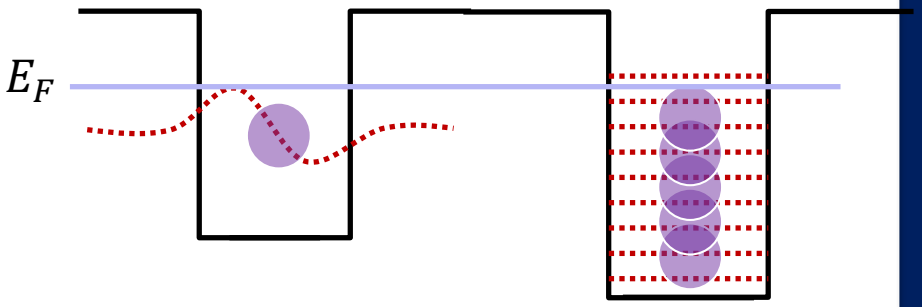
PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Many-body Fermi sea









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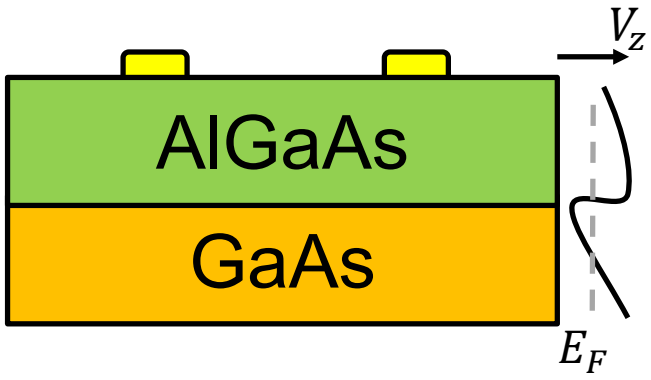
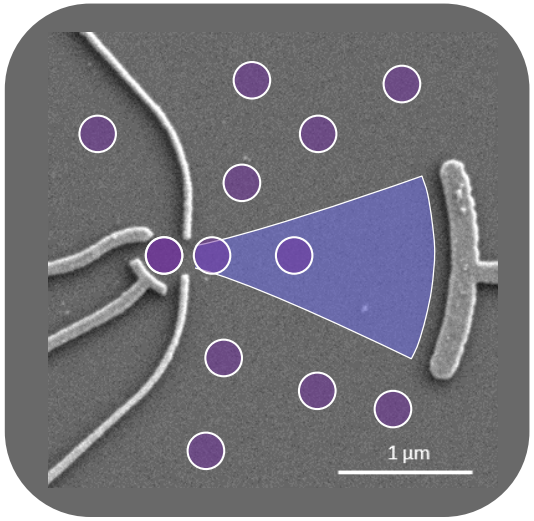
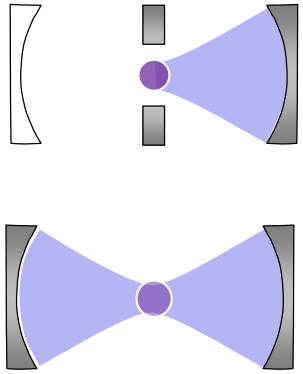
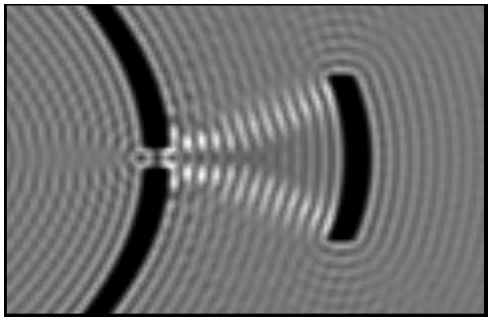


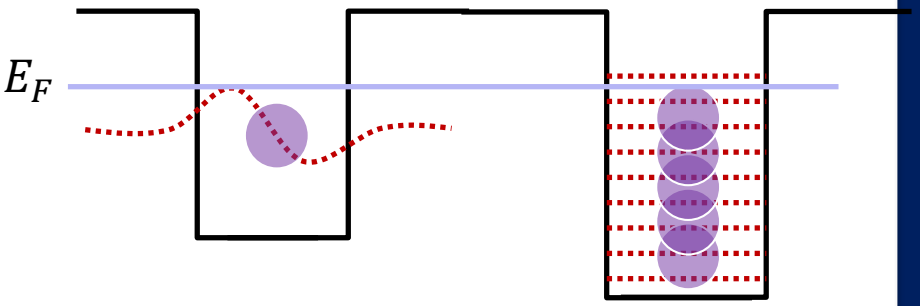




Single-particle waves

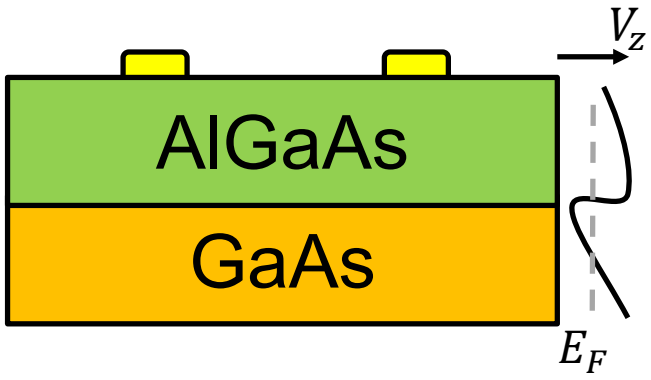


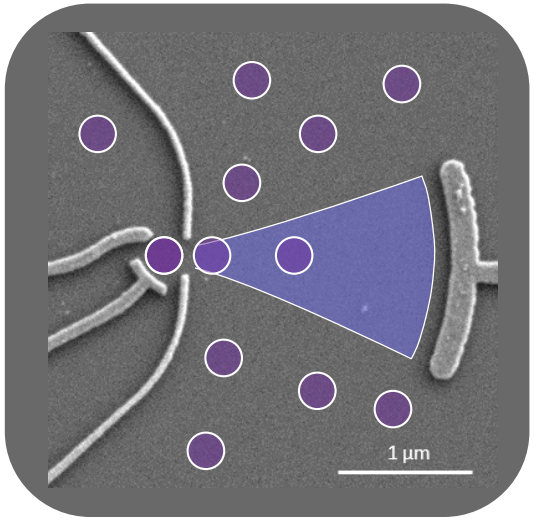
KWANT, NJP **16**, 063065 (2014)

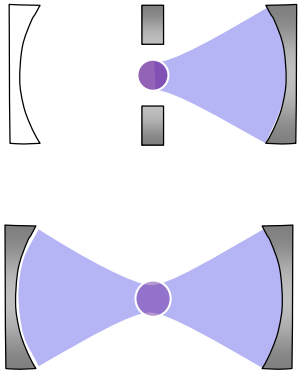


PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

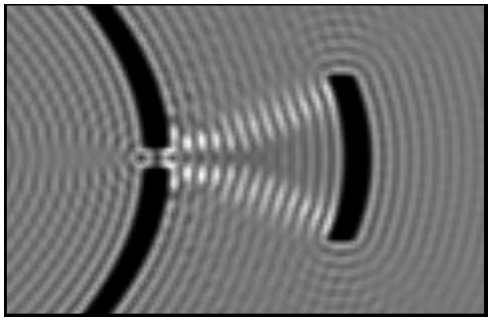
Many-body transport



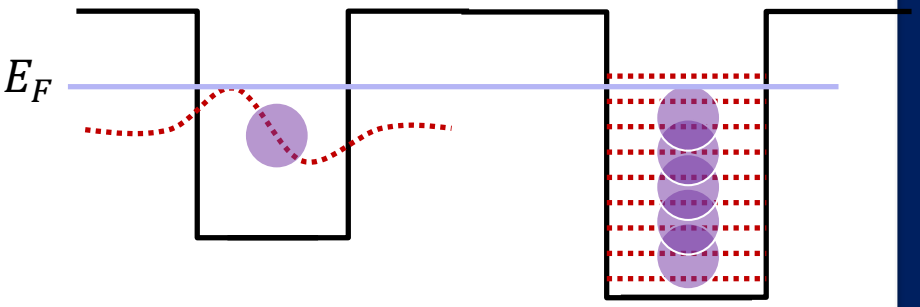




Single-particle waves



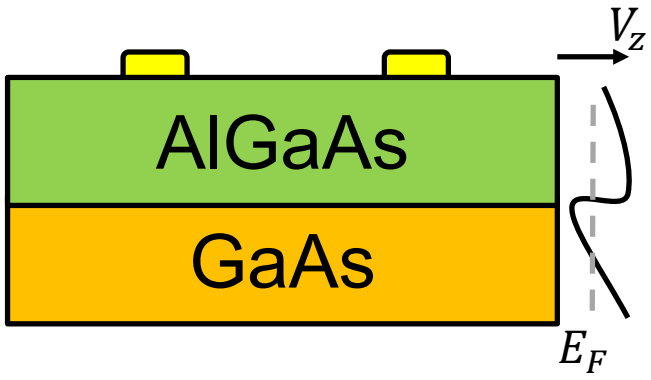
KWANT, NJP **16**, 063065 (2014)

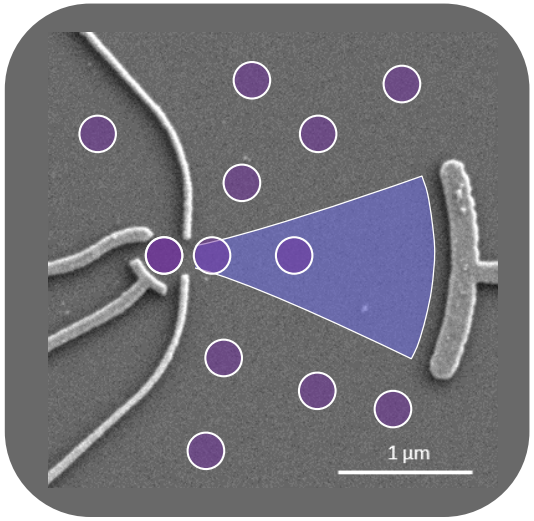


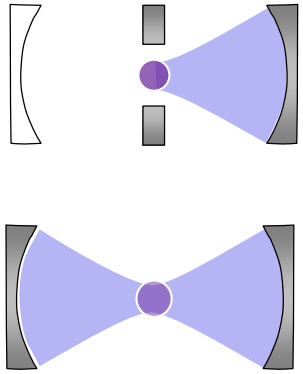
Electrons ⇒ Spin + Interaction

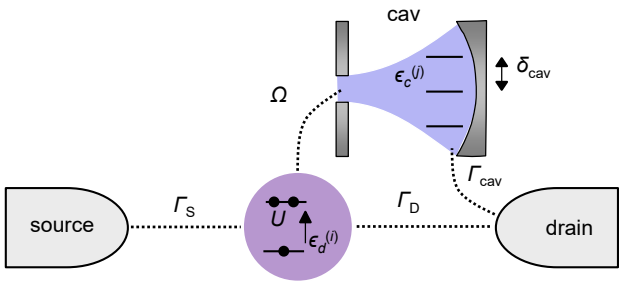
PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

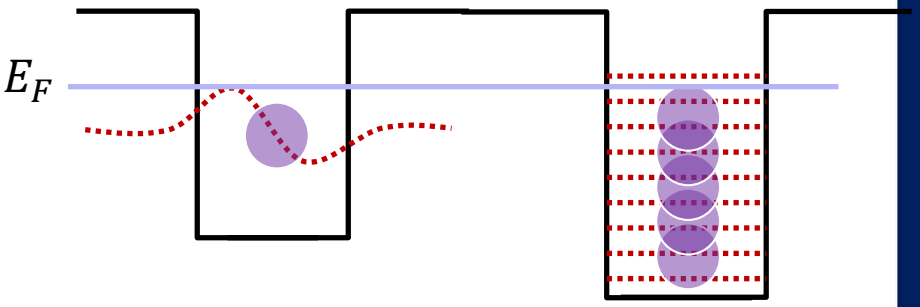
Many-body transport







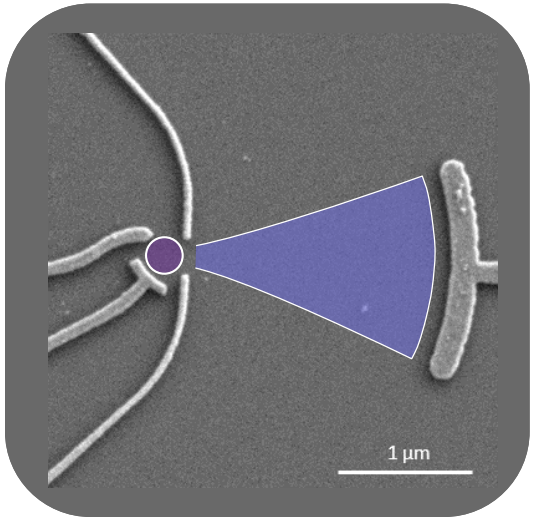


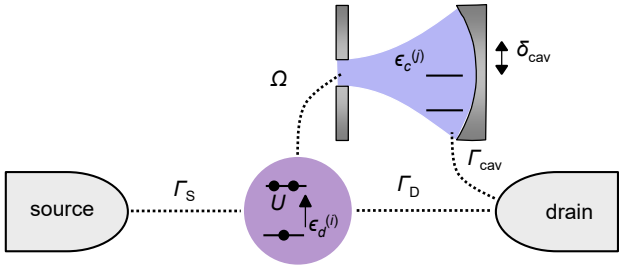


Open Kondo box problem

PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Many-body transport





Open Kondo box problem

$$H = H_{\text{leads}} + H_{\text{dot}} + H_{\text{cav}} + H_{\text{coupl}} + H_{\text{tun}}$$

$$H_{\text{dot}} = \sum_{\sigma} \epsilon_{\text{d}}\, d_{\sigma}^{\dagger} d_{\sigma} + U n_{\uparrow} n_{\downarrow}$$

$$H_{\text{leads}} = \sum_{k,\sigma} \epsilon_{\text{L}k} c_{\text{L}k\sigma}^{\dagger} c_{\text{L}k\sigma} + \sum_{k,\sigma} \epsilon_{\text{R}k} c_{\text{R}k\sigma}^{\dagger} c_{\text{R}k\sigma}$$

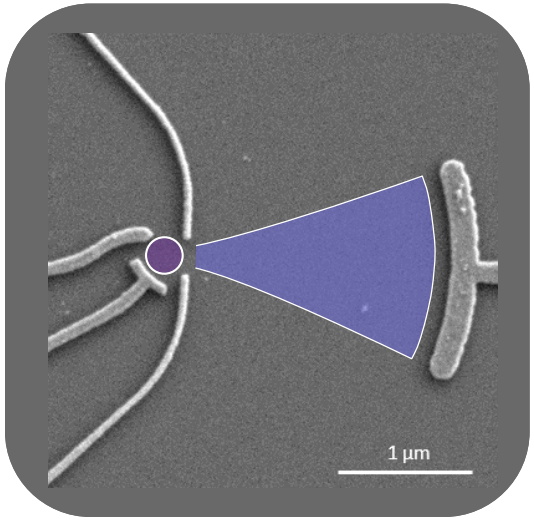
$$H_{\text{cav}} = \sum_{\sigma,j} \epsilon_{\text{c}}^{(j)} f_{j\sigma}^{\dagger} f_{j\sigma}$$

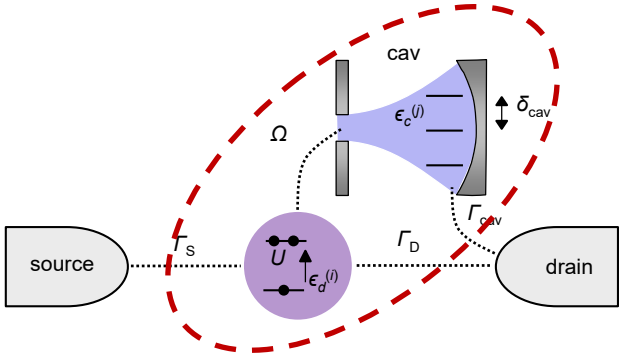
$$H_{\text{coupl}} = \sum_{j,\sigma} \Omega_j f_{j\sigma}^{\dagger} d_{\sigma} + \text{h.c.}$$

$$H_{\text{tun}} = \sum_{k,\sigma} t_{\text{L}} d_{\sigma}^{\dagger} c_{\text{L}k\sigma} + \text{h.c.} + \sum_{k,\sigma} t_{\text{R}} d_{\sigma}^{\dagger} c_{\text{R}k\sigma} + \text{h.c.} + \sum_{j,k,\sigma} t_c f_{j\sigma}^{\dagger} c_{\text{R}k\sigma} + \text{h.c.}$$

PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Many-body transport





Exact diagonalization

$$H = H_{\text{leads}} + H_{\text{dot}} + H_{\text{cav}} + H_{\text{coupl}} + H_{\text{tun}}$$

$$H_{\text{dot}} = \sum_{\sigma} \epsilon_{\text{d}}\, d_{\sigma}^{\dagger} d_{\sigma} + U n_{\uparrow} n_{\downarrow}$$

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$$H_{\text{cav}} = \sum_{\sigma,j} \epsilon_{\text{c}}^{(j)} f_{j\sigma}^{\dagger} f_{j\sigma}$$

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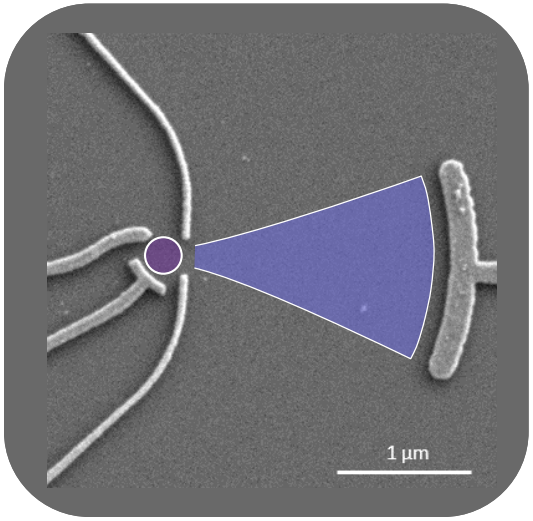
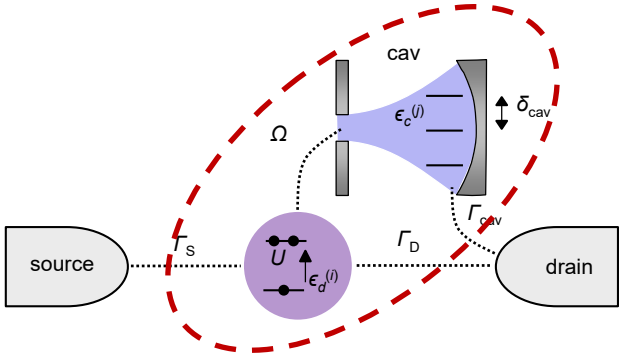
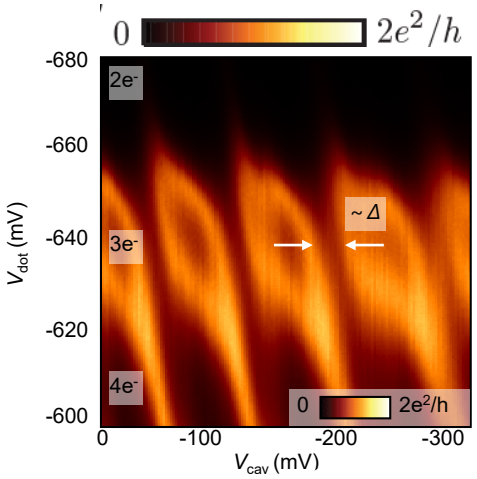
PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

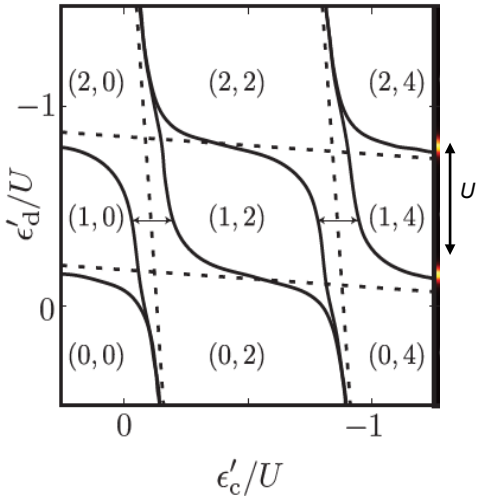
Many-body transport





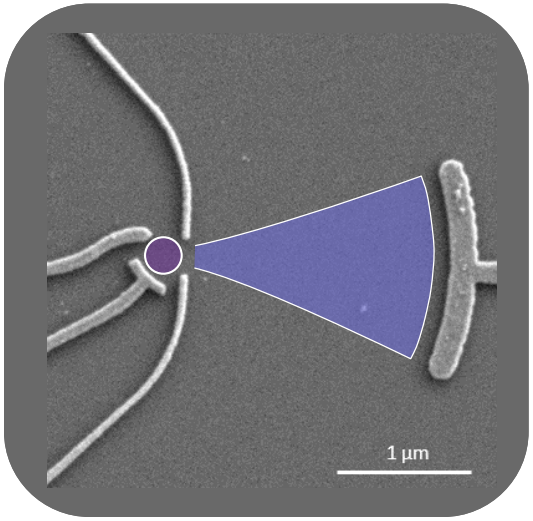
Exact diagonalization

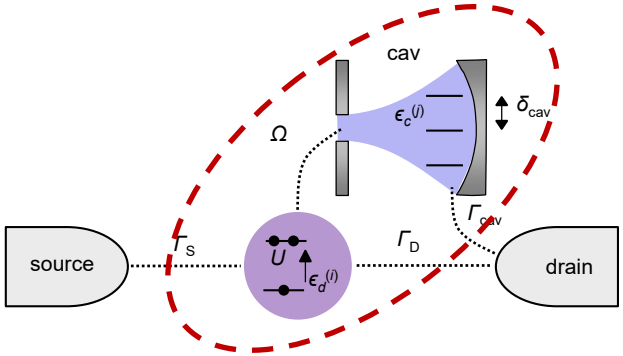




PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Many-body transport

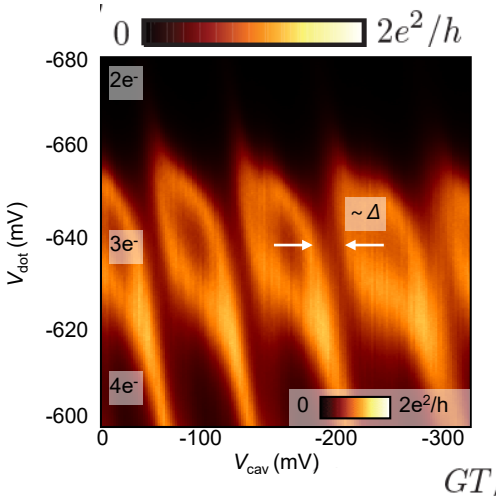


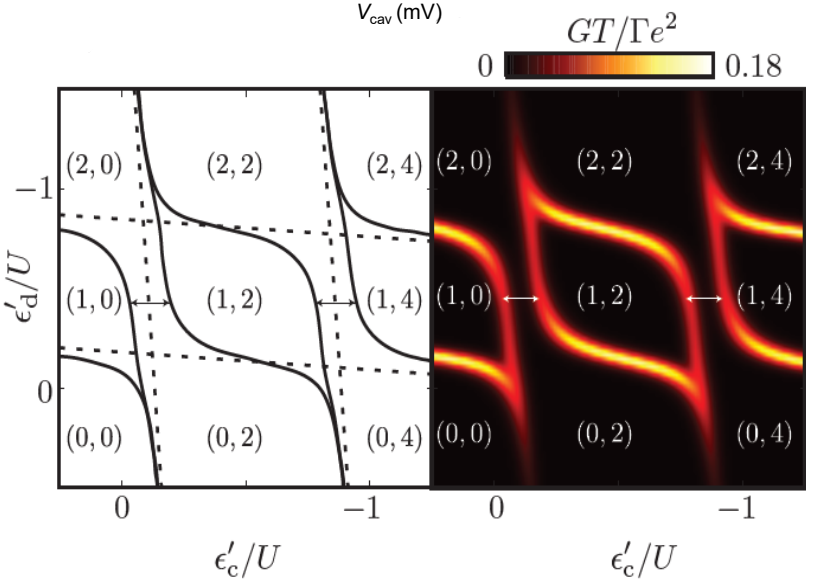


Exact diagonalization

+

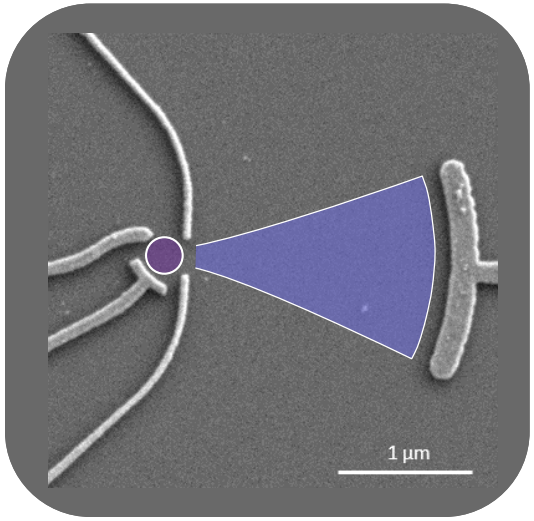
Master equation

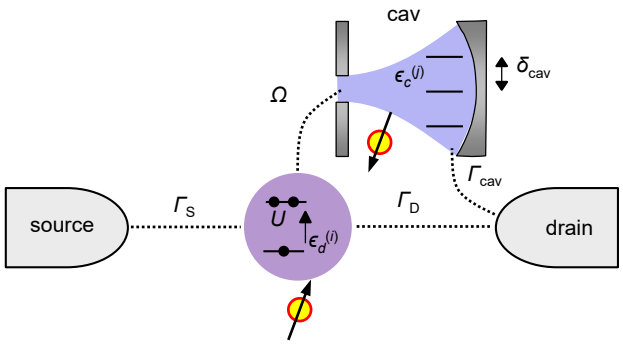




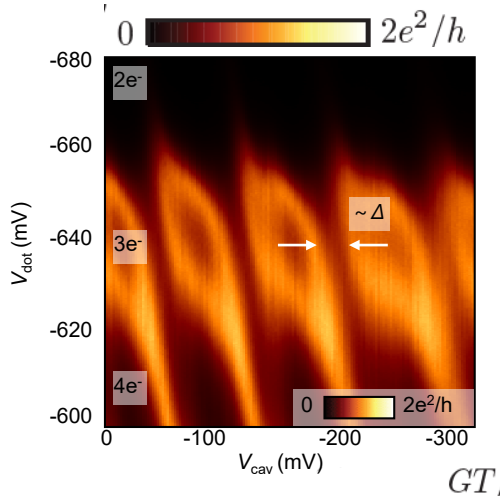
PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

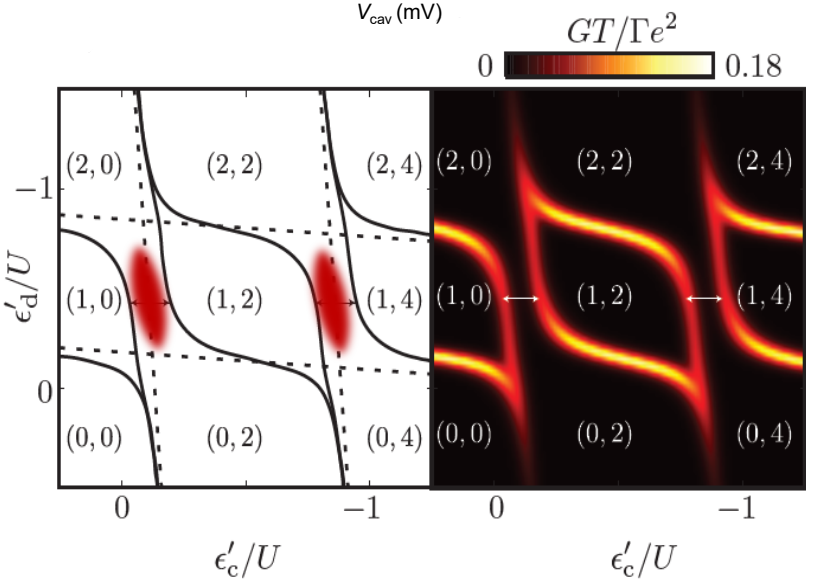
Many-body transport





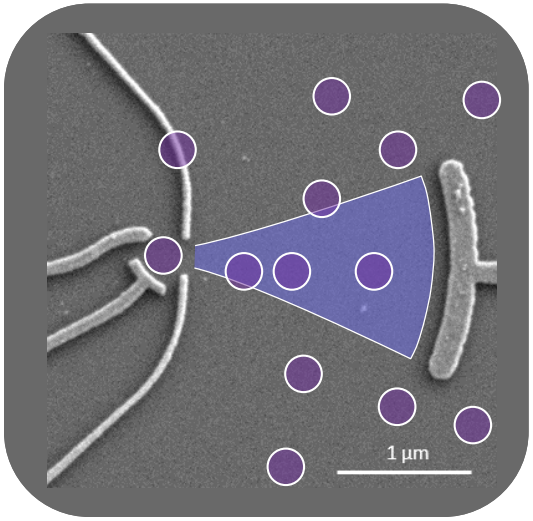
Singlet dot-cavity molecule

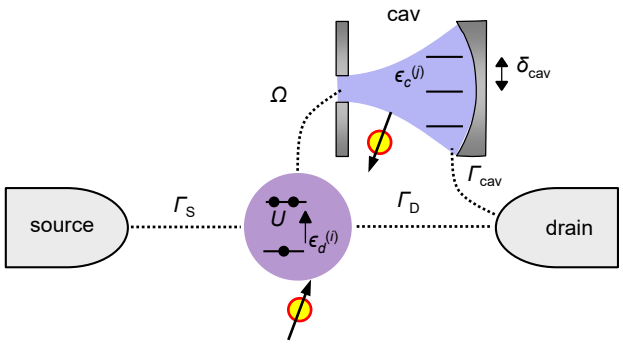




PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Many-body transport





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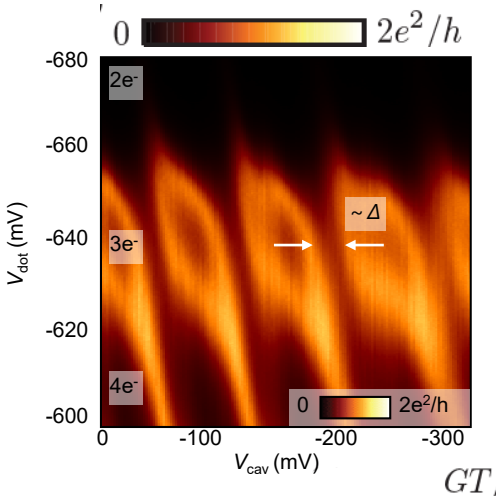
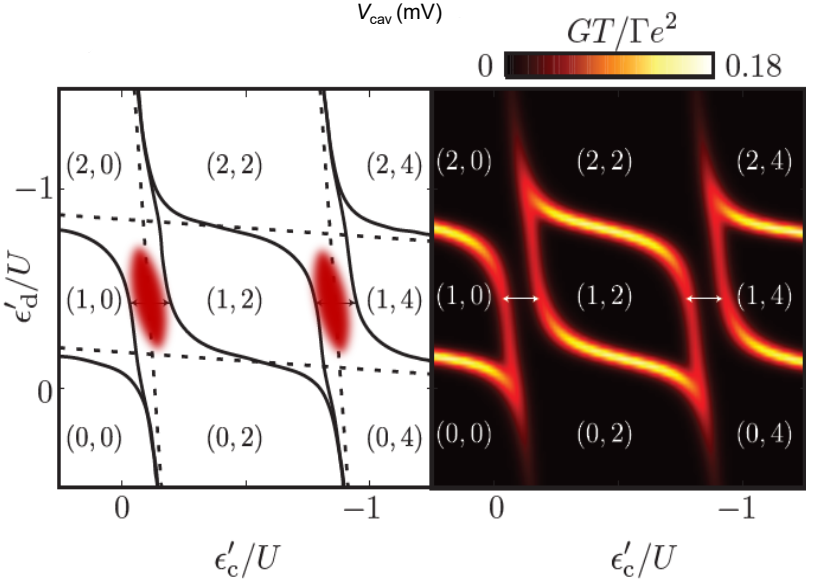
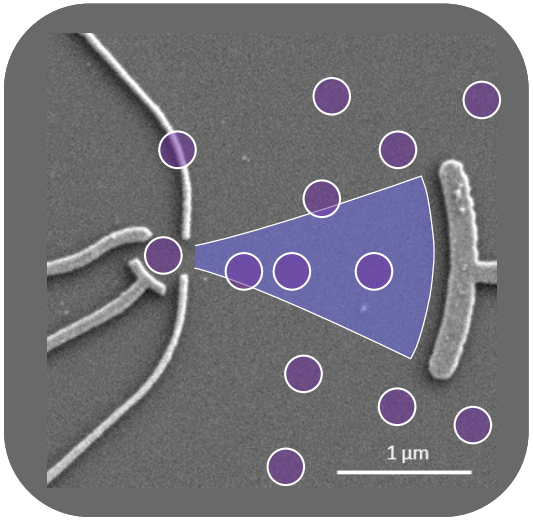
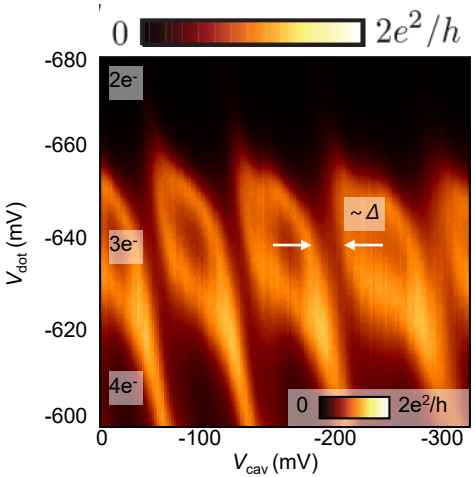


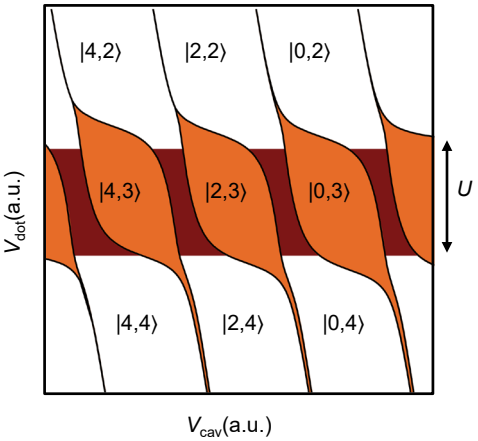


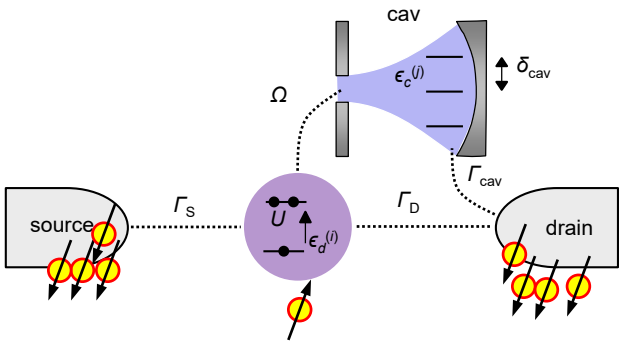
PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

Many-body transport

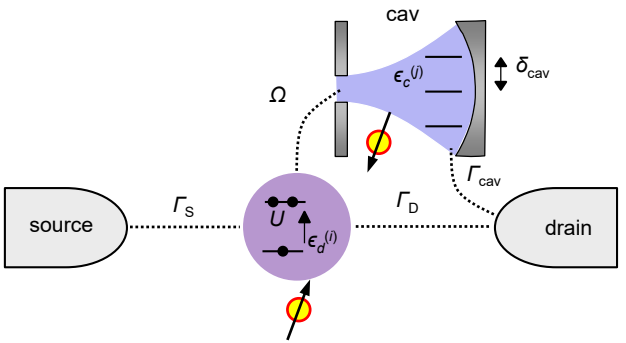








Many-body Kondo singlet



Singlet dot-cavity molecule

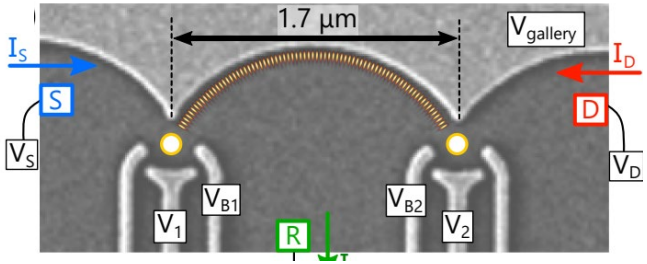
PRL 115, 166603 (2015), Physics 8, 98 (2015), PRB 96, 235431 (2017), PRL 120, 236801 (2018), arXiv:1612.03850

QUEST research

Quantum engineering of

Devices

Mesoscopic transport



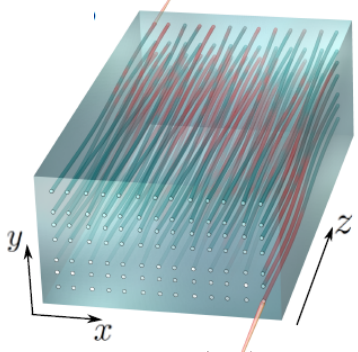
engineered quantum chemistry

many-body cond. mat.

- Electronic interferometers
- Kondo impurities
- Quantum measurement
- Topological semimetals

Material properties

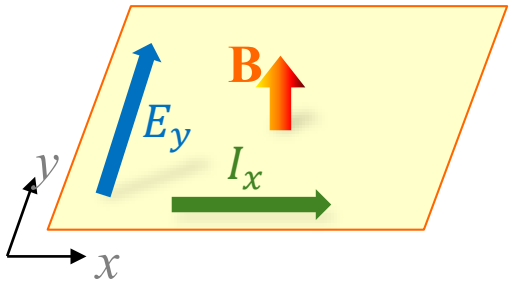
Quantum simulation



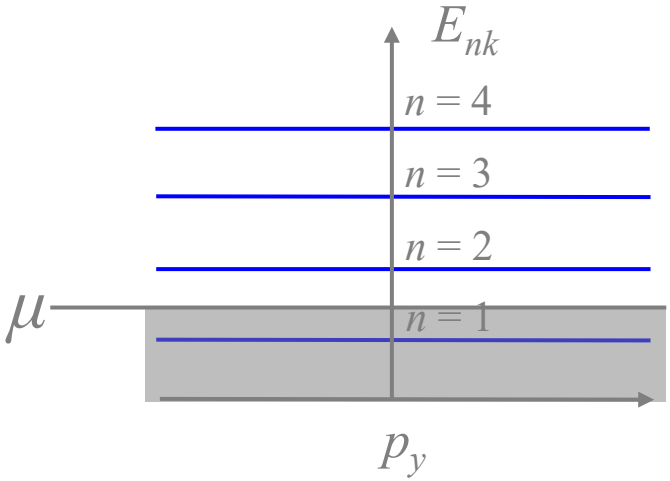
designer models  real materials

- Topological photonics
- Synthetic dimensions
- Quasicrystals
- Dissipative phase transitions

2D quantum Hall effect



K. Von Klitzing, RMP 58, 519 (1986).



quantized transverse linear response

$$\sigma_{xy} \equiv \frac{I_x}{E_y} = \frac{e^2}{h}\sum_i^{\mu} C_i$$

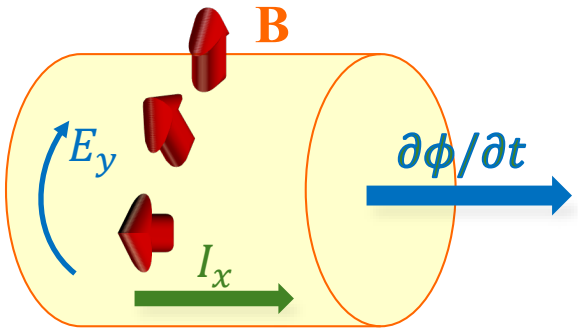
1st Chern number

$$C_n = \frac{1}{2\pi}\iint_{BZ} \Omega_n(\boldsymbol{k})dk^2$$

Berry curvature $\Omega_n(\boldsymbol{k}) = i\left(\left\langle \partial_{k_y} u_n(\boldsymbol{k}) \middle| \partial_{k_x} u_n(\boldsymbol{k}) \right\rangle - \left\langle \partial_{k_x} u_n(\boldsymbol{k}) \middle| \partial_{k_y} u_n(\boldsymbol{k}) \right\rangle\right)$

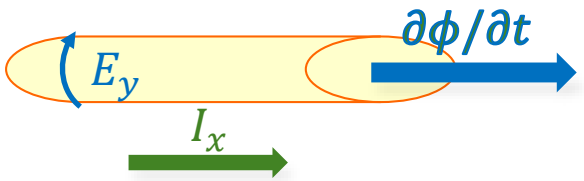
Topological pumps

$$\sigma_{xy} \equiv \frac{I_x}{E_y} = \frac{e^2}{h} \sum_i^{\mu} C_i$$



Topological pumps

$$\sigma_{xy} \equiv \frac{I_x}{E_y} = \frac{e^2}{h} \sum_i^{\mu} C_i$$



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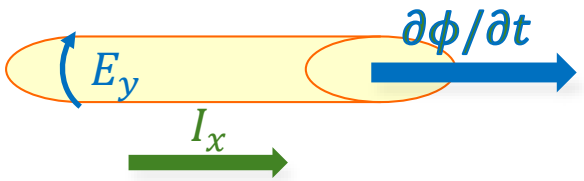
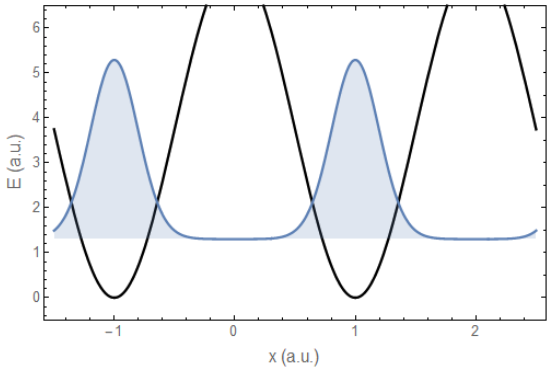


Dimensional reduction

Laughlin, PRB 23, 5632 (1981)
Thouless PRB 27, 6083 (1983)



Topological pumps

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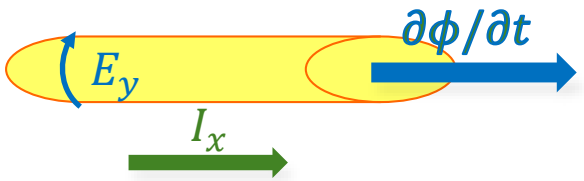

Dimensional reduction

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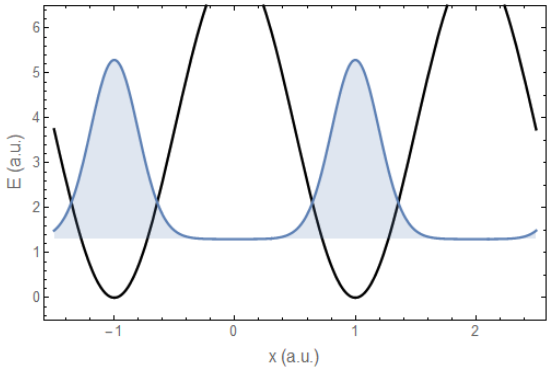
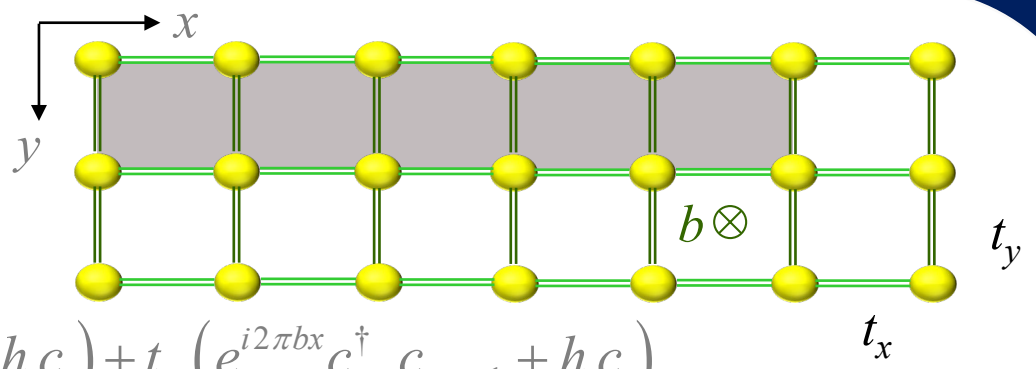


$$\langle x \rangle = \iint \langle v_n(k_x,t) \rangle dk_x dt = C_n d_1$$

$$C_n = \frac{1}{2\pi}\iint \Omega_n(k_x,\phi) dk_x d\phi$$

Hofstadter model



- Hamiltonian:

$$\mathcal{H} = \sum_{x,y} t_x \left(c^{\dagger}_{\mathrm{x,y}} c_{x+1,\mathrm{y}} + h.c. \right) + t_y \left(e^{i2\pi bx} c^{\dagger}_{\mathrm{x,y}} c_{\mathrm{x,y}+1} + h.c. \right)$$

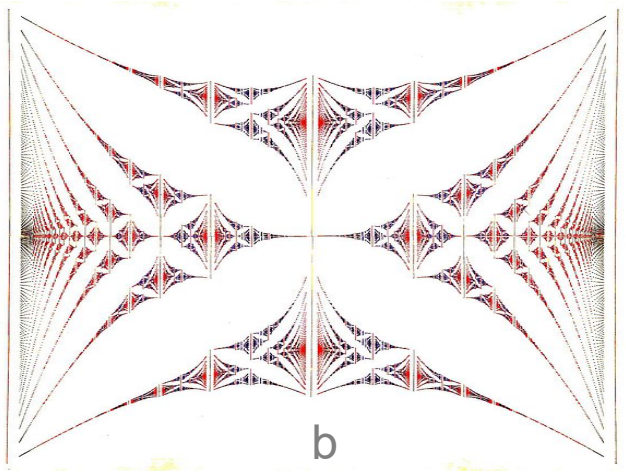
$$= \sum_{\mathrm{x},k_y} t \left(c^{\dagger}_{\mathrm{x},k_y} c_{x+1,k_y} + h.c. \right) + 2t_y \cos(2\pi bx + k_y) c^{\dagger}_{\mathrm{x},k_y} c_{\mathrm{x},k_y}$$

- Spectrum:

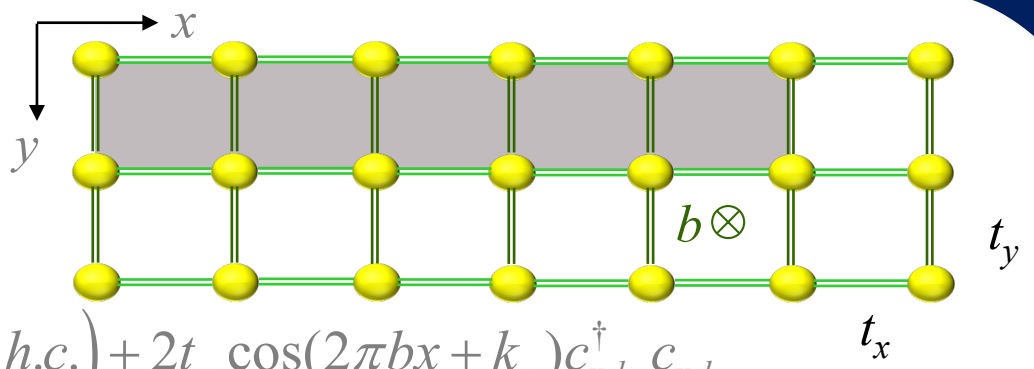
Harper, PPSL A **68**, 874 (1955)
Azbel, JETP **19**, 634 (1964)
Hofstadter, PRB **14**, 2239 (1976)

$$b = p/q$$

$$c_{\mathrm{x,y}} = \sum_{k_y} e^{ik_y y} c_{\mathrm{x}}$$



Hofstadter model



- Hamiltonian:

$$\mathcal{H}=\sum_{x,k_y} t_x\left(c^{\dagger}_{x,k_y}c_{x+1,k_y}+h.c.\right)+2t_y\cos(2\pi bx+k_y)c^{\dagger}_{x,k_y}c_{x,k_y}$$

- Quantized Hall conductance:

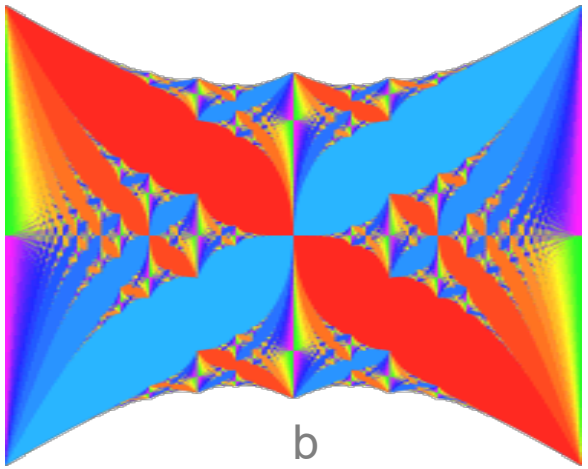
  TKNN, PRL **49**, 405 (1982)

$$\sigma_{xy}=\nu\frac{e^2}{h}$$

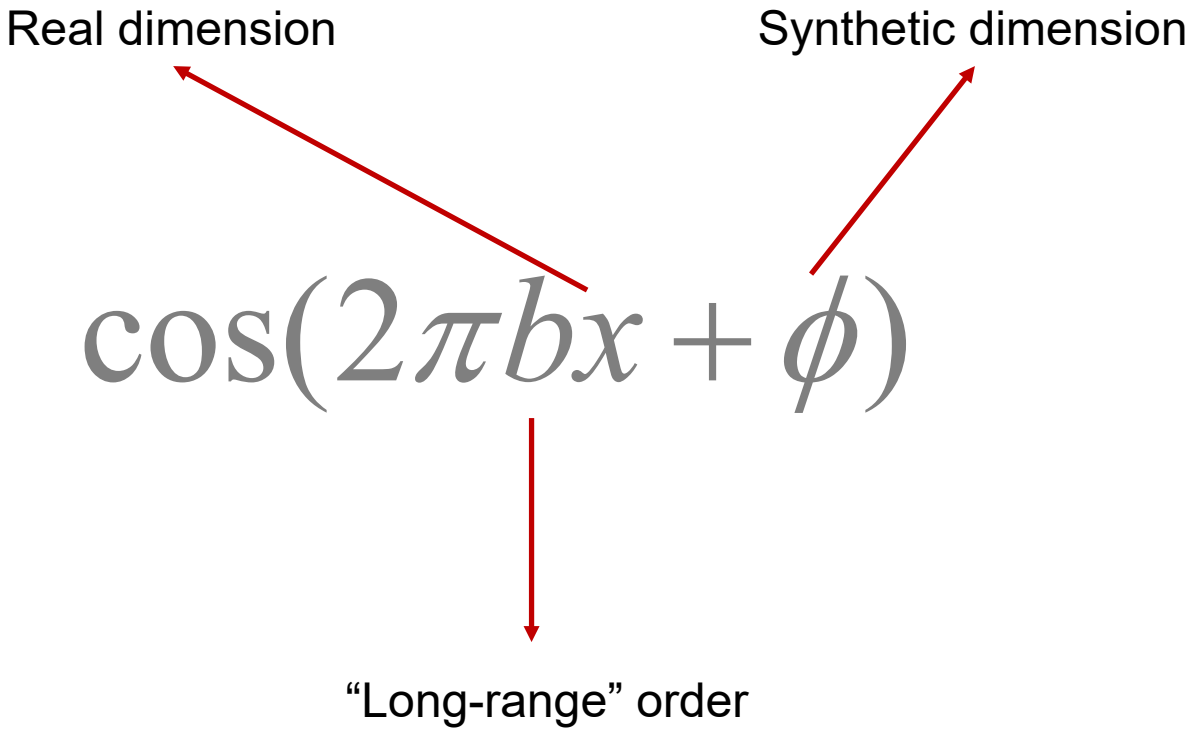
- Chern numbers:

$$\nu=\int_0^{2\pi}\mathrm{d}p_x\int_0^{2\pi}\mathrm{d}p_y\,\Omega(p_x,p_y)$$

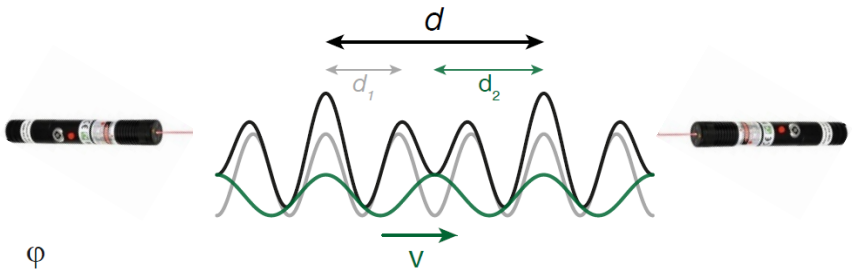
D. Osadchy and J. E. Avron, J. Math. Phys. **42**, 5665 (2001)

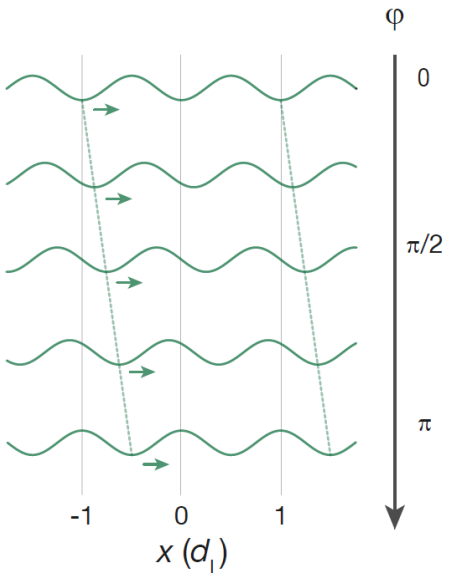


Dimensional reduction, pumps, and quasicrystals



Atomic topological pumps

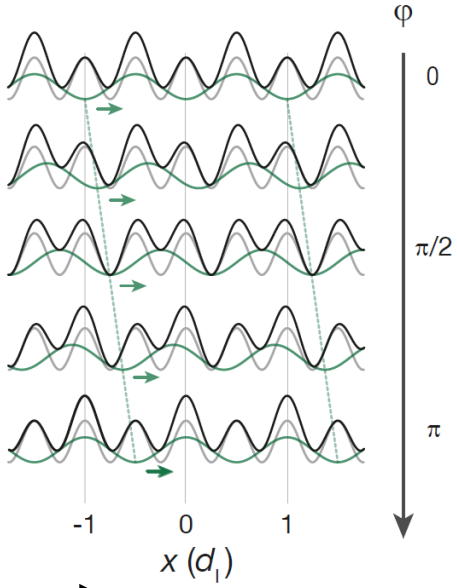


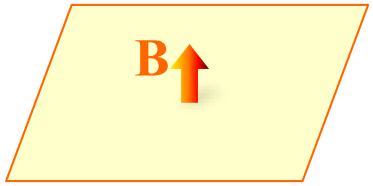


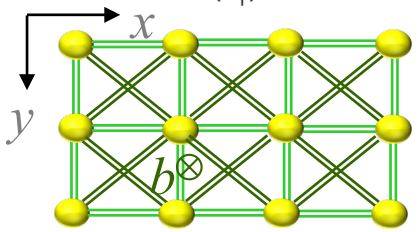
$$V_s \sin^2(\pi x/d_s + \pi/2) + V_l \sin^2(\pi x/d_l - \varphi/2)$$

$$d_l \approx d_s$$

Cool atoms into a Mott insulator state
Homogeneous delocalization over first Brillouin zone

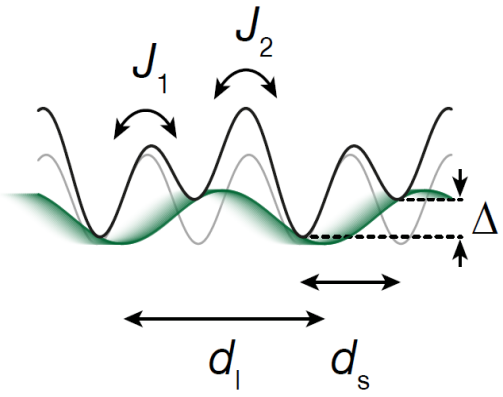


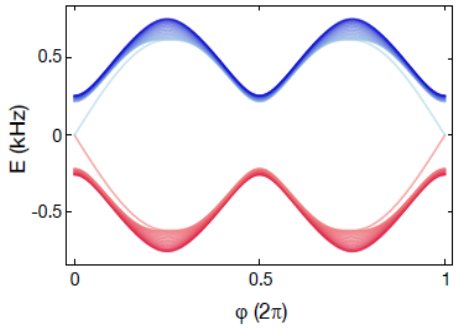




Nat. Phys. **12**, 350 (2016)

Atomic topological pumps



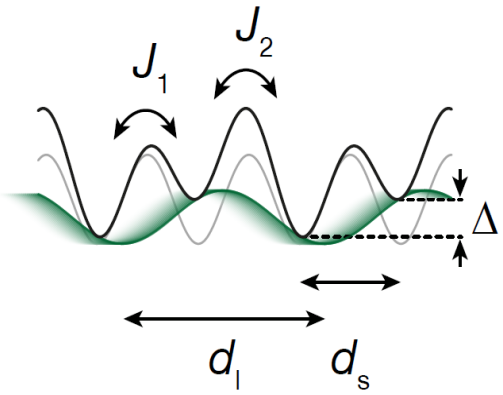


Rice-Mele Model [PRL 49, 1455 (1982)]

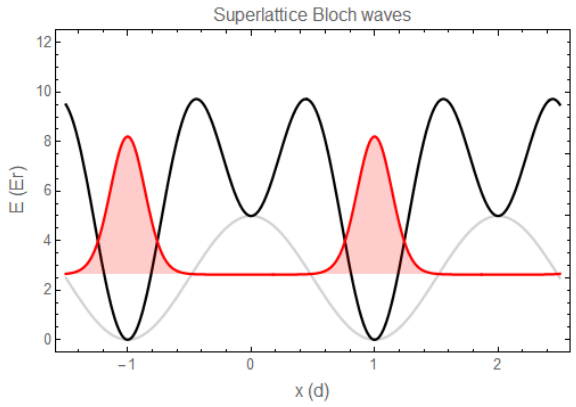
$$\hat{H}(\varphi) = -\sum_m \left(J_1(\varphi)\, \hat{b}_m^\dagger \hat{a}_m + J_2(\varphi)\, \hat{a}_{m+1}^\dagger \hat{b}_m + \text{h.c.} \right) + \frac{\Delta(\varphi)}{2} \sum_m \left(\hat{a}_m^\dagger \hat{a}_m - \hat{b}_m^\dagger \hat{b}_m \right)$$

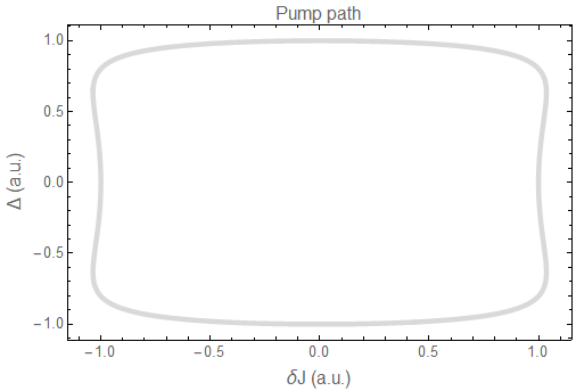
Nat. Phys. **12**, 350 (2016)

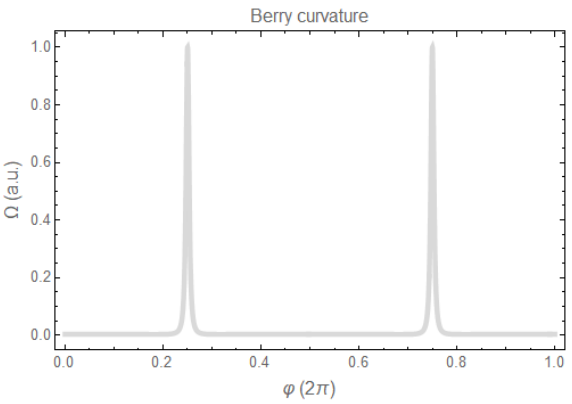
Atomic topological pumps



$$\hat{H}(\varphi) = -\sum_m \left(J_1(\varphi)\, \hat{b}_m^\dagger \hat{a}_m + J_2(\varphi)\, \hat{a}_{m+1}^\dagger \hat{b}_m + \text{h.c.} \right) + \frac{\Delta(\varphi)}{2} \sum_m \left(\hat{a}_m^\dagger \hat{a}_m - \hat{b}_m^\dagger \hat{b}_m \right)$$



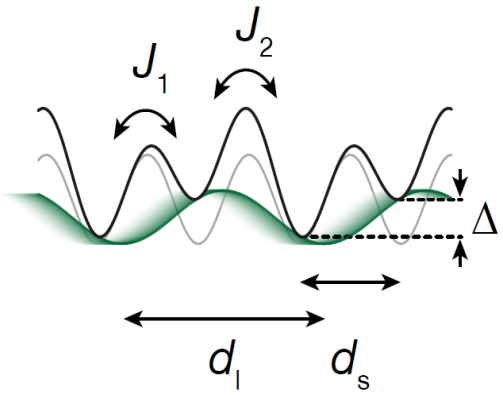




$$\langle x \rangle = \iint \langle v_n(k_x, t) \rangle \, dk_x dt = C_n d_1$$

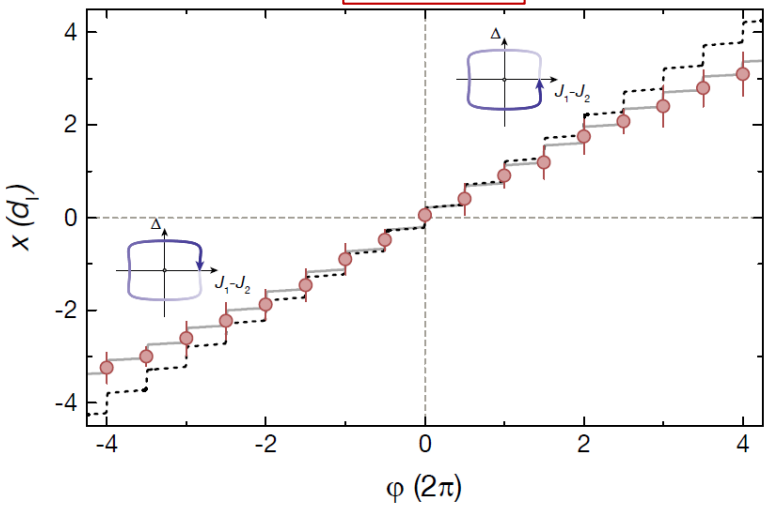
Nat. Phys. **12**, 350 (2016)

Atomic topological pumps



$$\hat{H}(\varphi) = -\sum_m \left(J_1(\varphi)\, \hat{b}_m^\dagger \hat{a}_m + J_2(\varphi)\, \hat{a}_{m+1}^\dagger \hat{b}_m + \text{h.c.} \right) + \frac{\Delta(\varphi)}{2} \sum_m \left(\hat{a}_m^\dagger \hat{a}_m - \hat{b}_m^\dagger \hat{b}_m \right)$$

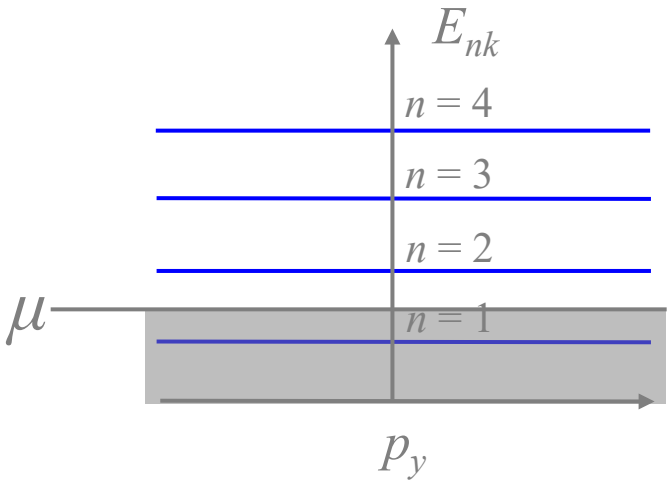
$C_1 = +1$



Nat. Phys. **12**, 350 (2016)

4D quantum Hall effect

S^4



$$I_\alpha = \chi \frac{e^2}{h} \varepsilon_{\alpha\beta\gamma\delta} \frac{B_{\beta\gamma}}{\Phi_0} E_\delta ;$$

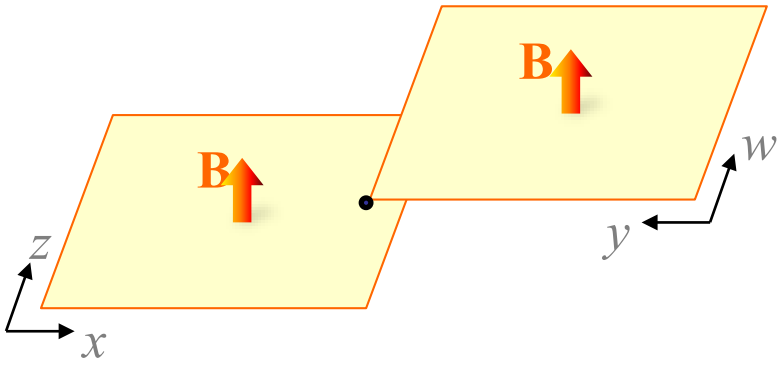
$$\chi = \frac{1}{(2\pi)^2} \iint \iint_{BZ} \mathrm{d}k_x \mathrm{d}k_y \mathrm{d}k_z \mathrm{d}k_w \Omega \wedge \Omega$$

First derivations:

J. E. Avron *et al.*, Comm. Math. Phys. 124, 595 (1989).
J. Fröhlich and B. Perdini, in Mathematical Physics 2000 (Imperial College Press, London, United Kingdom)..
S.-C. Zhang and J. Hu, Science Vol. 294, 823 (2001):
X.-L. Qi and S.-C. Zhang, Rev. Mod. Phys. 83, 1057 (2011).

4D quantum Hall effect

K. Kraus, Z. Ringel, and OZ, PRL **111**, 226401 (2013)



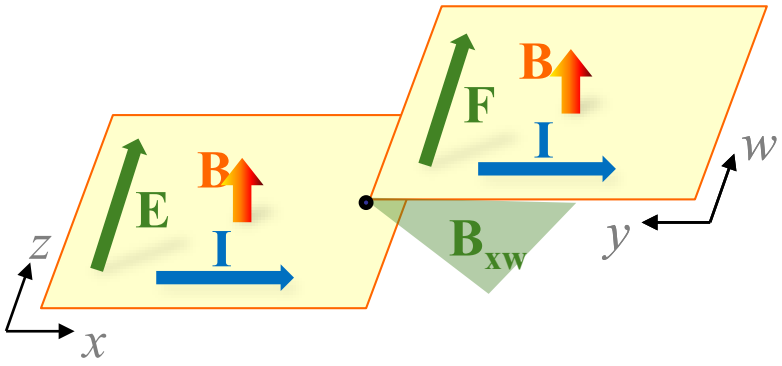
$$I_\alpha = \chi \frac{e^2}{h} \varepsilon_{\alpha\beta\gamma\delta} \frac{B_{\beta\gamma}}{\Phi_0} E_\delta ;$$

$$\chi = \frac{1}{(2\pi)^2} \iint\!\!\iint_{BZ} \mathrm{d}k_x \mathrm{d}k_y \mathrm{d}k_z \mathrm{d}k_w \Omega_{xz} \Omega_{yw}$$

See also PRL **115**, 195303 (2015), PRA **93**, 043827 (2016), PRB **93** 245113 (2016)

4D quantum Hall effect

K. Kraus, Z. Ringel, and **OZ**, PRL **111**, 226401 (2013)



$$I_y = \chi \frac{e^2}{h} \varepsilon_{x\beta\gamma\delta} \frac{B_{\beta\gamma}}{\Phi_0} E_\delta ;$$

Lorentz-type response

$$I_v = I_w = 0$$

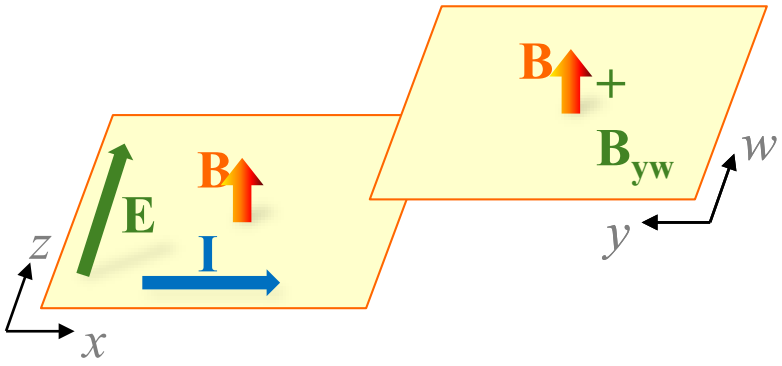
$$I_x = \frac{e^2}{h} n_{yw} \nu_{xz} E_z ;$$

$$I_y = \chi \frac{e^2}{h} \frac{B_{xw}}{\Phi_0} E_z$$

See also PRL **115**, 195303 (2015), PRA **93**, 043827 (2016), PRB **93** 245113 (2016)

4D quantum Hall effect

K. Kraus, Z. Ringel, and **OZ**, PRL **111**, 226401 (2013)



$$I_y = \chi \frac{e^2}{h} \varepsilon_{x\beta\gamma\delta} \frac{B_{\beta\gamma}}{\Phi_0} E_\delta ;$$

Lorentz-type response

$$I_v = I_w = 0$$

$$I_x = \frac{e^2}{h} n_{yw} \nu_{xz} E_z ;$$

$$I_y = \chi \frac{e^2}{h} \frac{B_{xw}}{\Phi_0} E_z$$

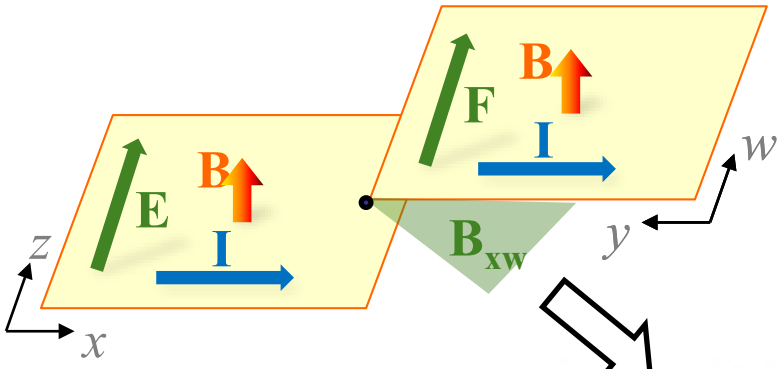
Density-type response

$$I_v = I_y = I_w = 0$$

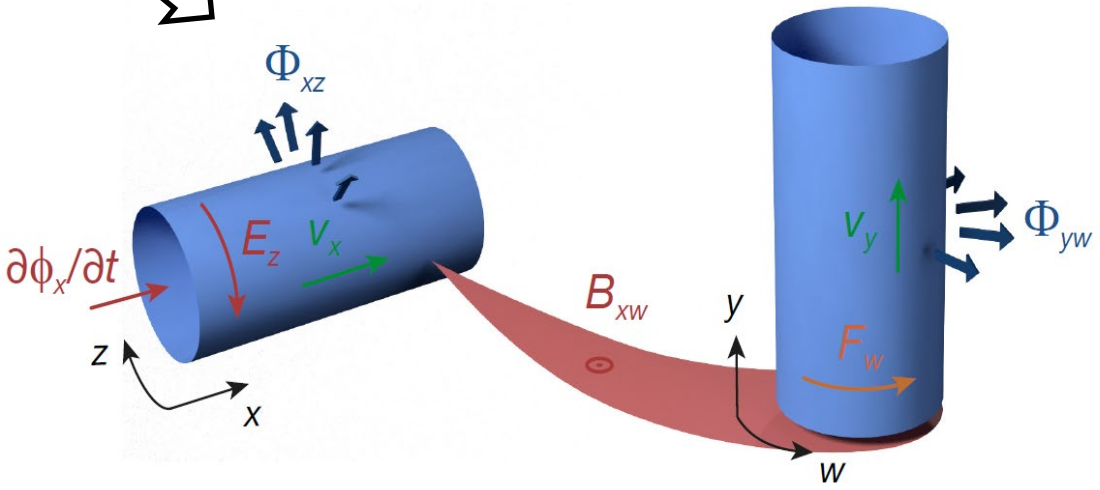
$$I_x = \chi \frac{e^2}{h} \frac{B_{yw}}{\Phi_0} E_v + \frac{e^2}{h} \nu_{xv} n_{yw} E_v ;$$

See also PRL **115**, 195303 (2015), PRA **93**, 043827 (2016), PRB **93** 245113 (2016)

2D topological charge pump

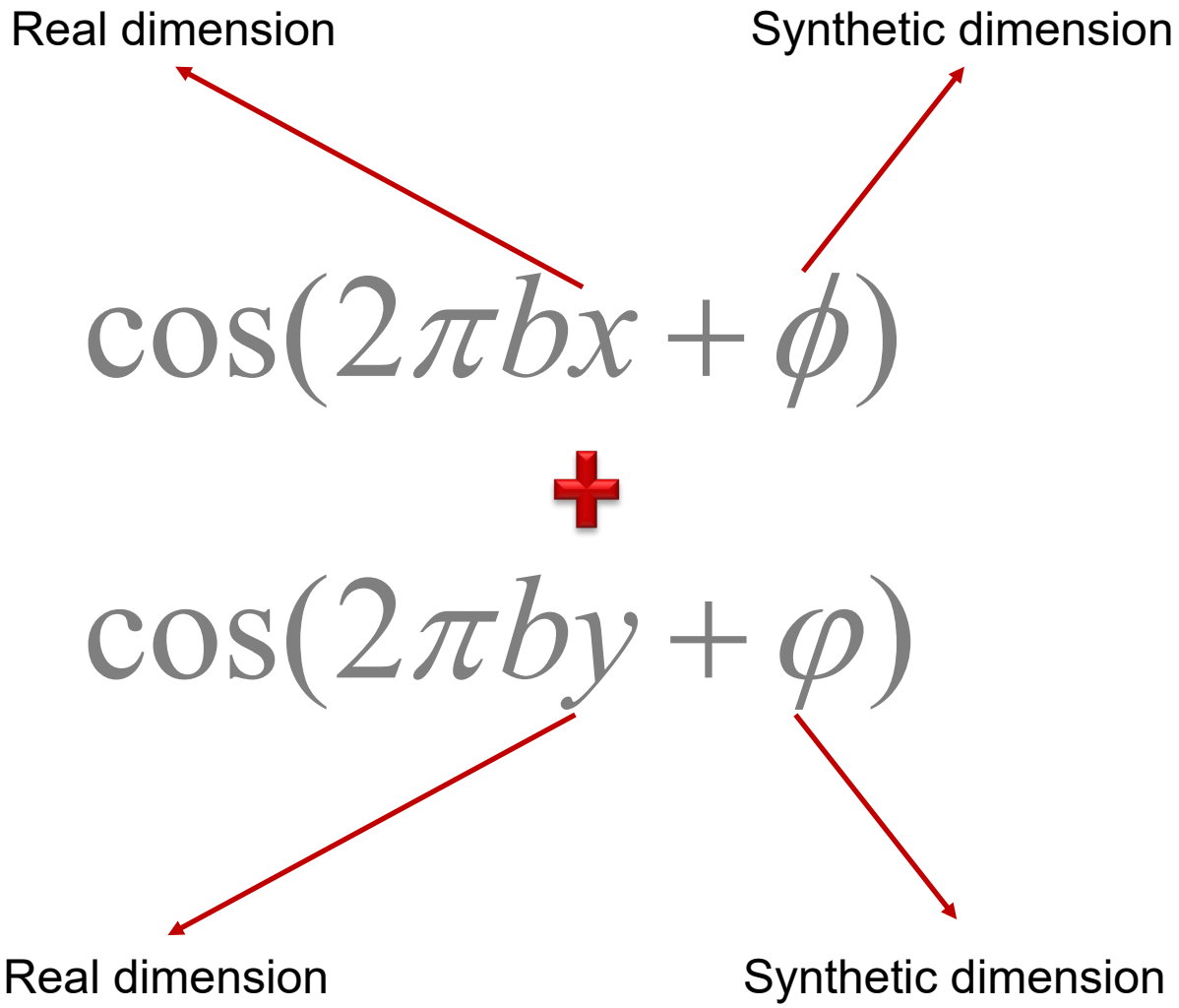


$$I_y = \chi \frac{e^2}{h} \frac{B_{xw}}{\Phi_0} E_z;$$



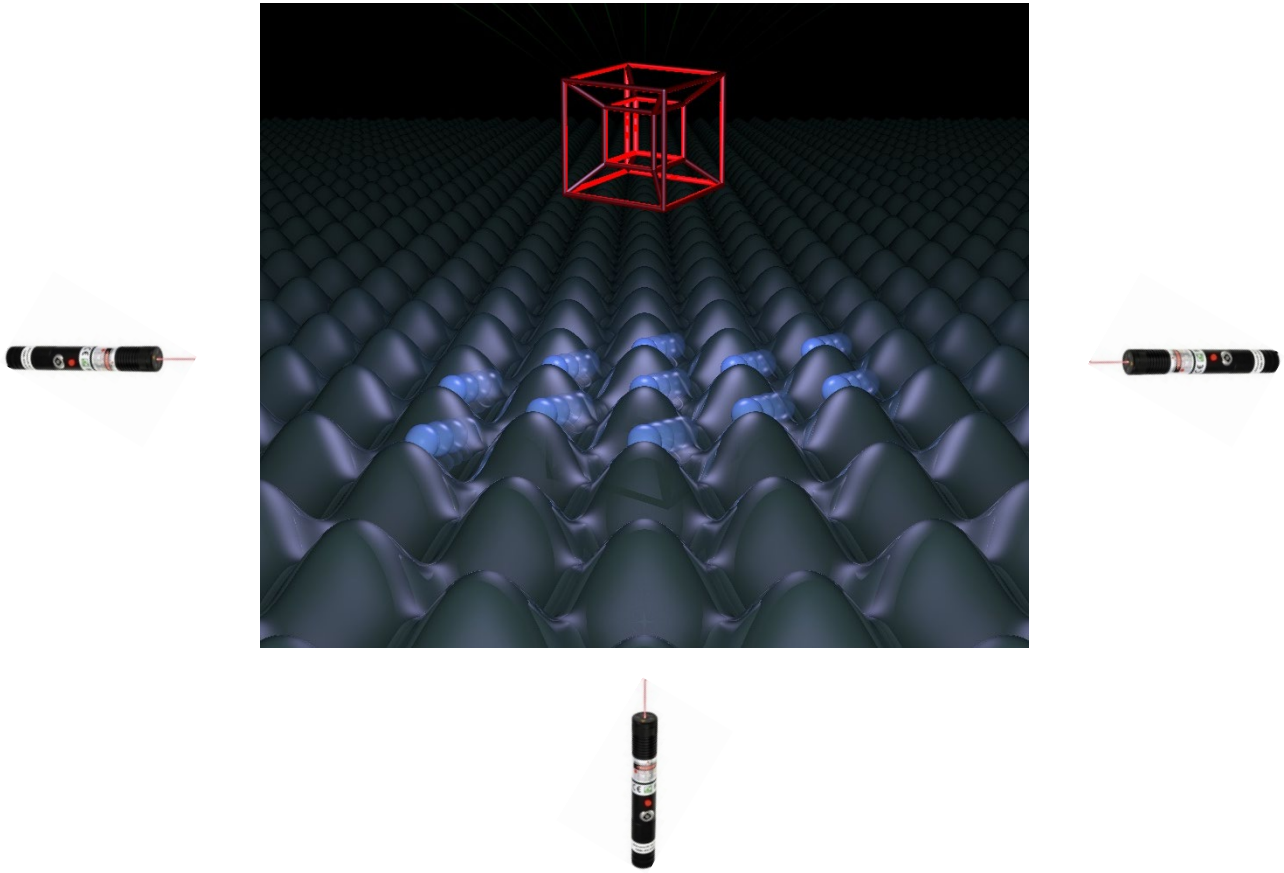
PRL **111**, 226401 (2013), Nature **553**, 55 (2018) & Nature **553**, 59 (2018)

Dimensional reduction, pumps, and quasicrystals



2D topological charge pump

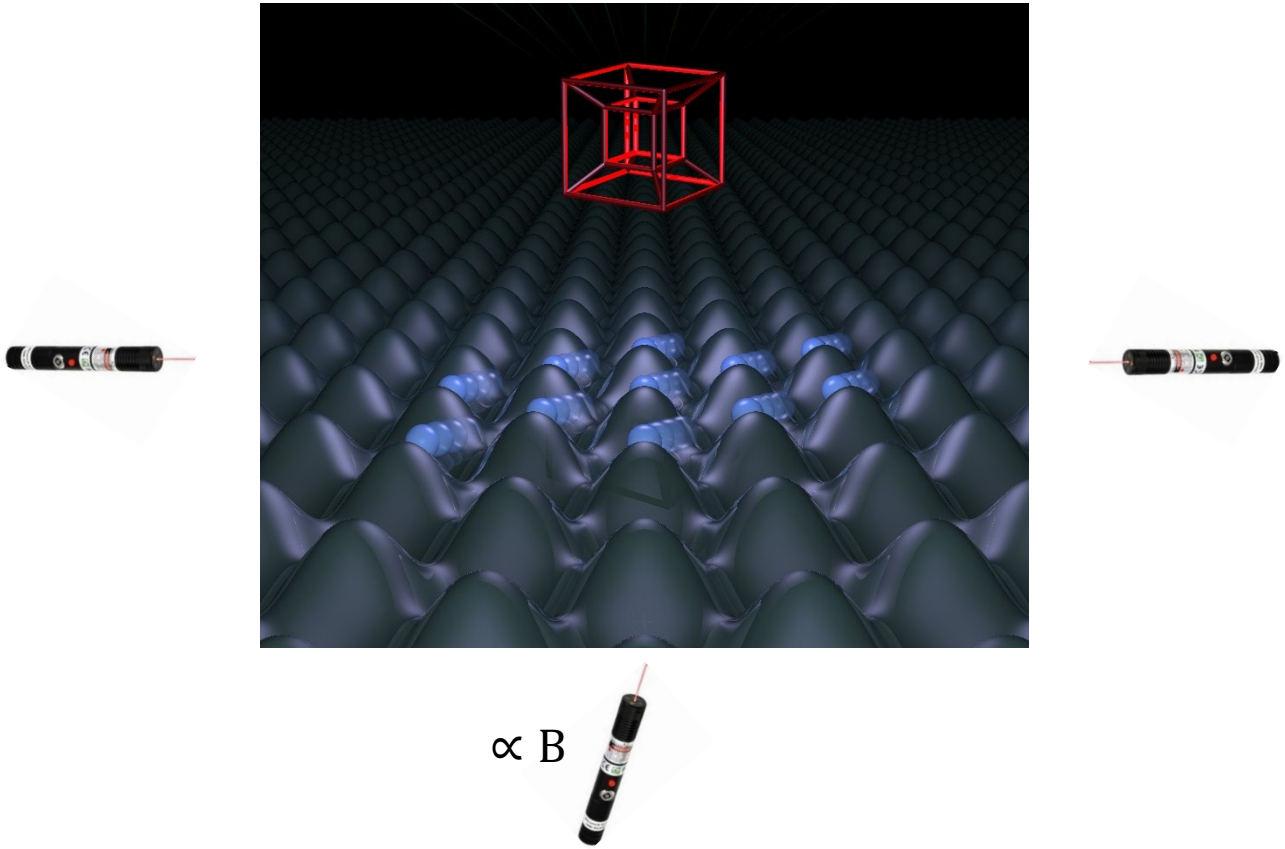
- An optical superlattice



Nature **553**, 55 (2018)

2D topological charge pump

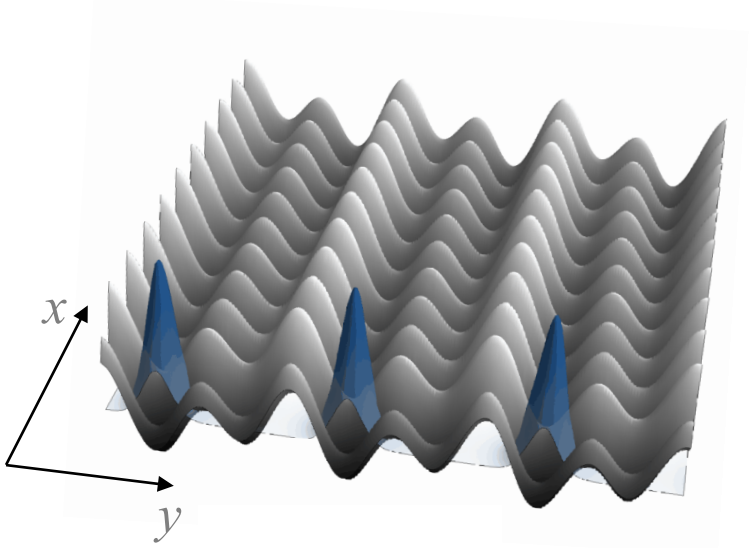
- An optical superlattice



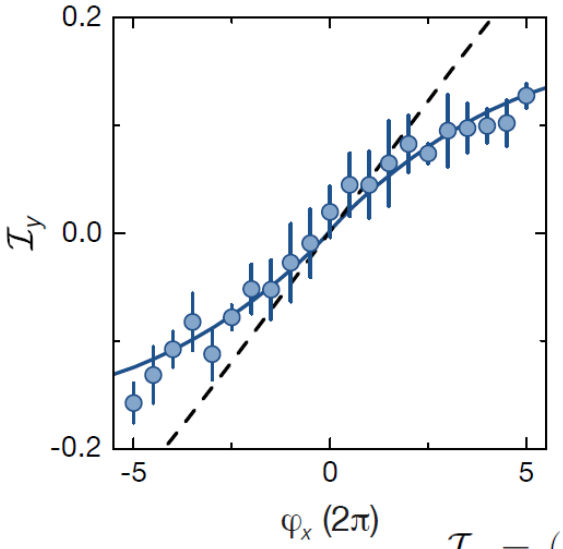
Nature **553**, 55 (2018)

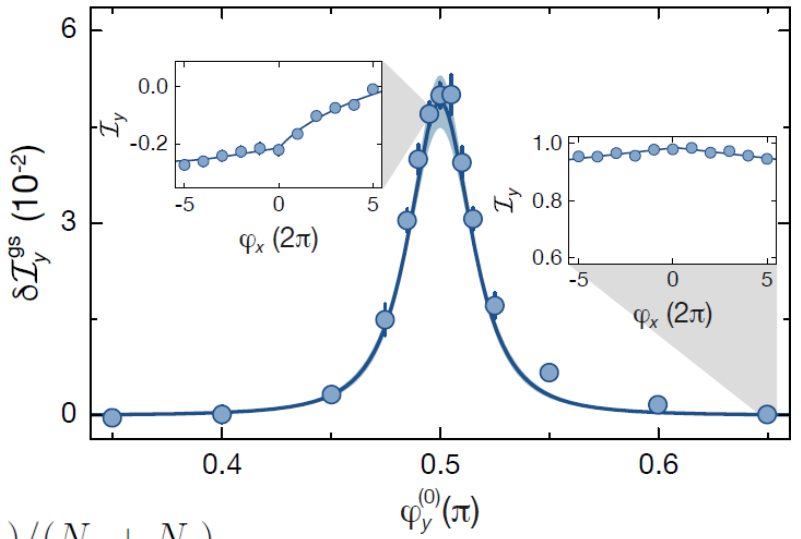
2D topological charge pump

$$I_y = \chi \frac{e^2}{h} \frac{B_{xw}}{\Phi_0} E_z;$$



$$\chi = 1.07(8)$$





$$\mathcal{I}_y = (N_o - N_e)/(N_o + N_e)$$

Nature **553**, 55 (2018)

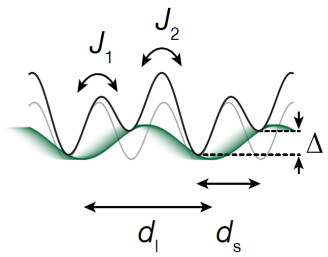
Boundary effects in photonics

Topological pumps

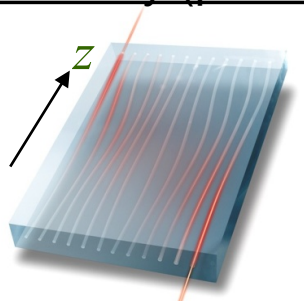
Bulk (cold atoms)

Boundary (photons)

1+1D

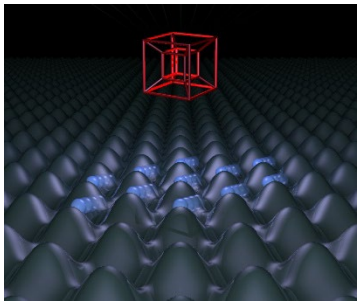


Nat. Phys. 12, 350 (2016)

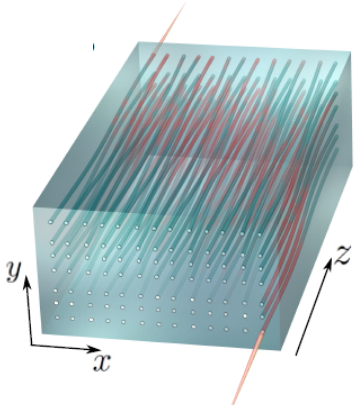


Phys. Rev. Lett. 109, 106402 (2012)

2+2D



Nature 553, 55 (2018)



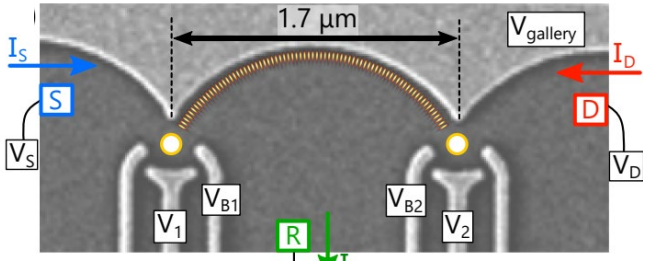
Nature 553, 59 (2018)

QUEST research

Quantum engineering of

Devices

Mesoscopic transport



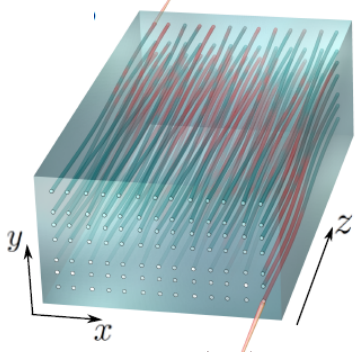
engineered quantum chemistry

many-body cond. mat.

- Electronic interferometers
- Kondo impurities
- Quantum measurement
- Topological semimetals

Material properties

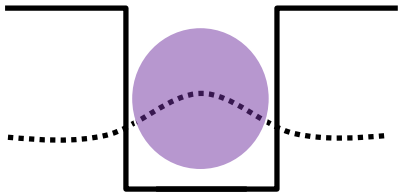
Quantum simulation



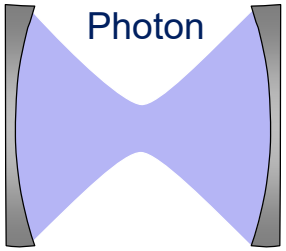
designer models  real materials

- Topological photonics
- Synthetic dimensions
- Quasicrystals
- Dissipative phase transitions

Particle in a box

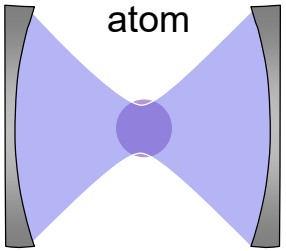


Optical resonators



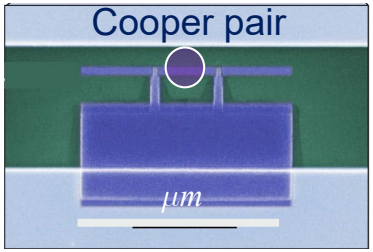
RMP **85,** 1083 (2013)

Optical cavities



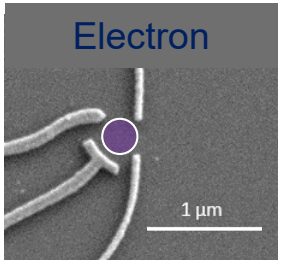
RMP **85,** 1083 (2013)

Superconducting loops



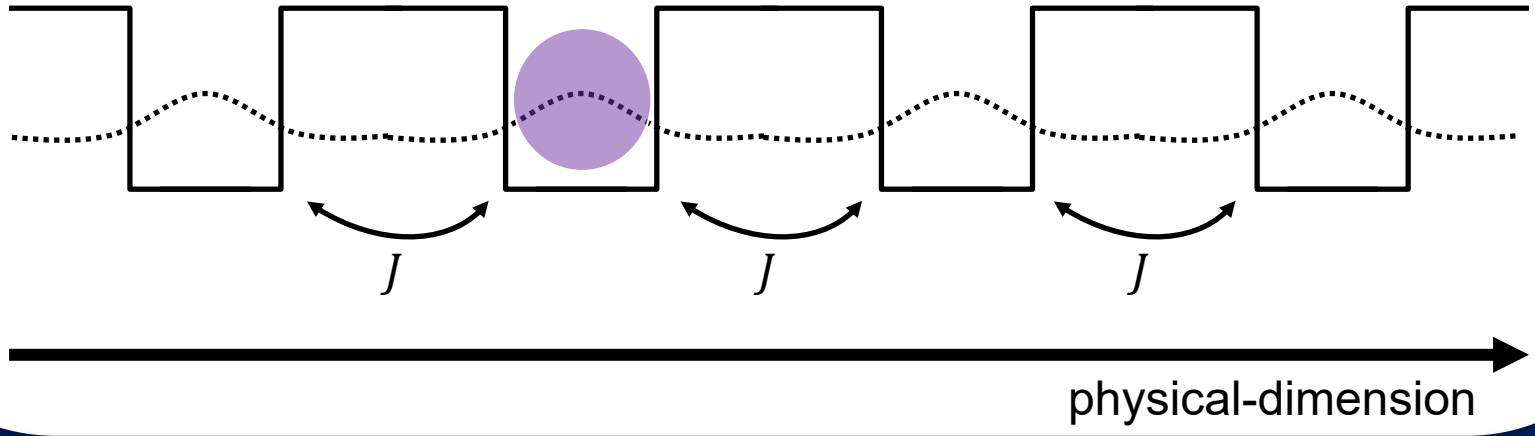
Nature **431,** 162 (2004)

Quantum dots

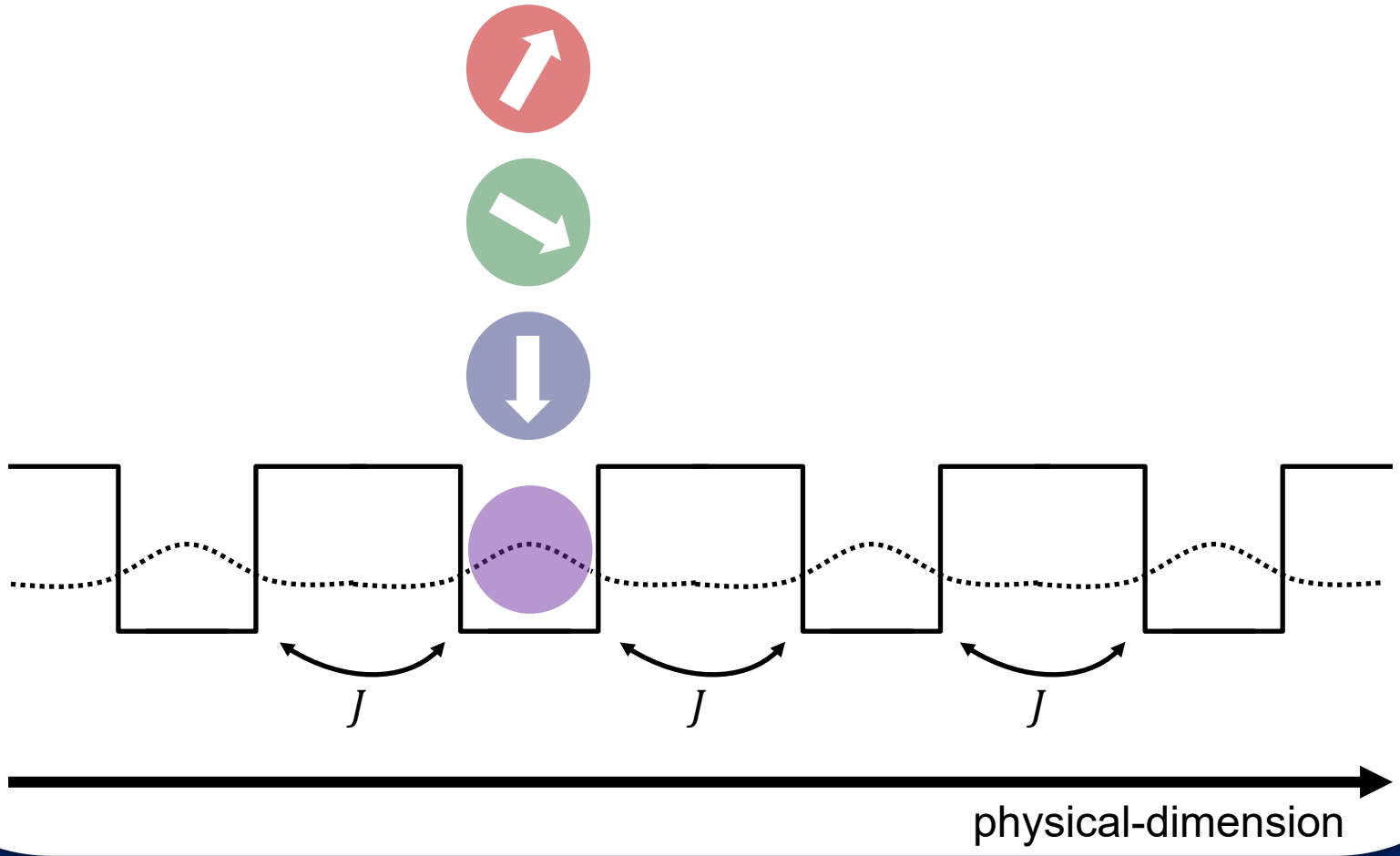


PRL **115**, 166603 (2015)

Quantum simulation

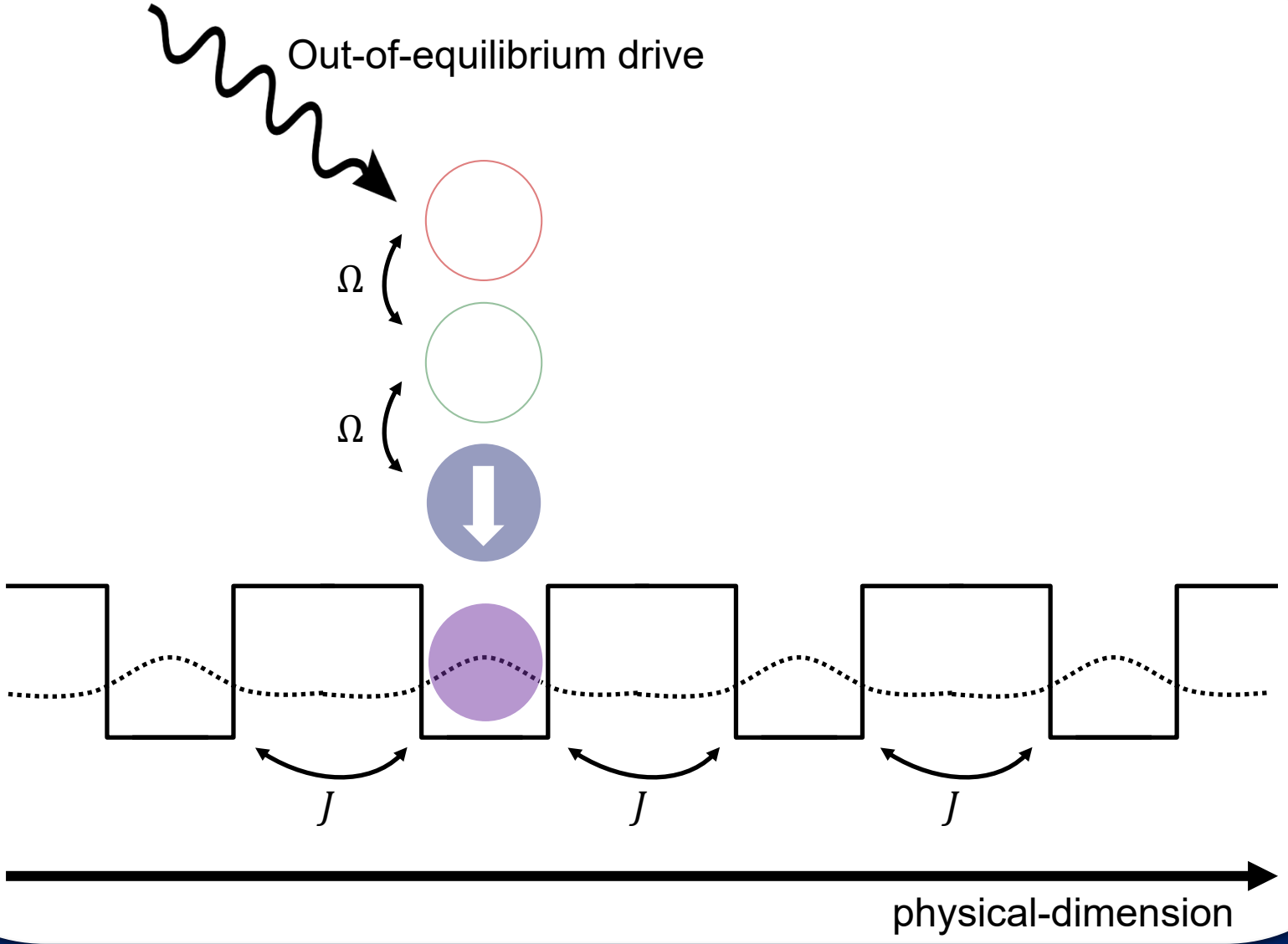


Synthetic dimensions



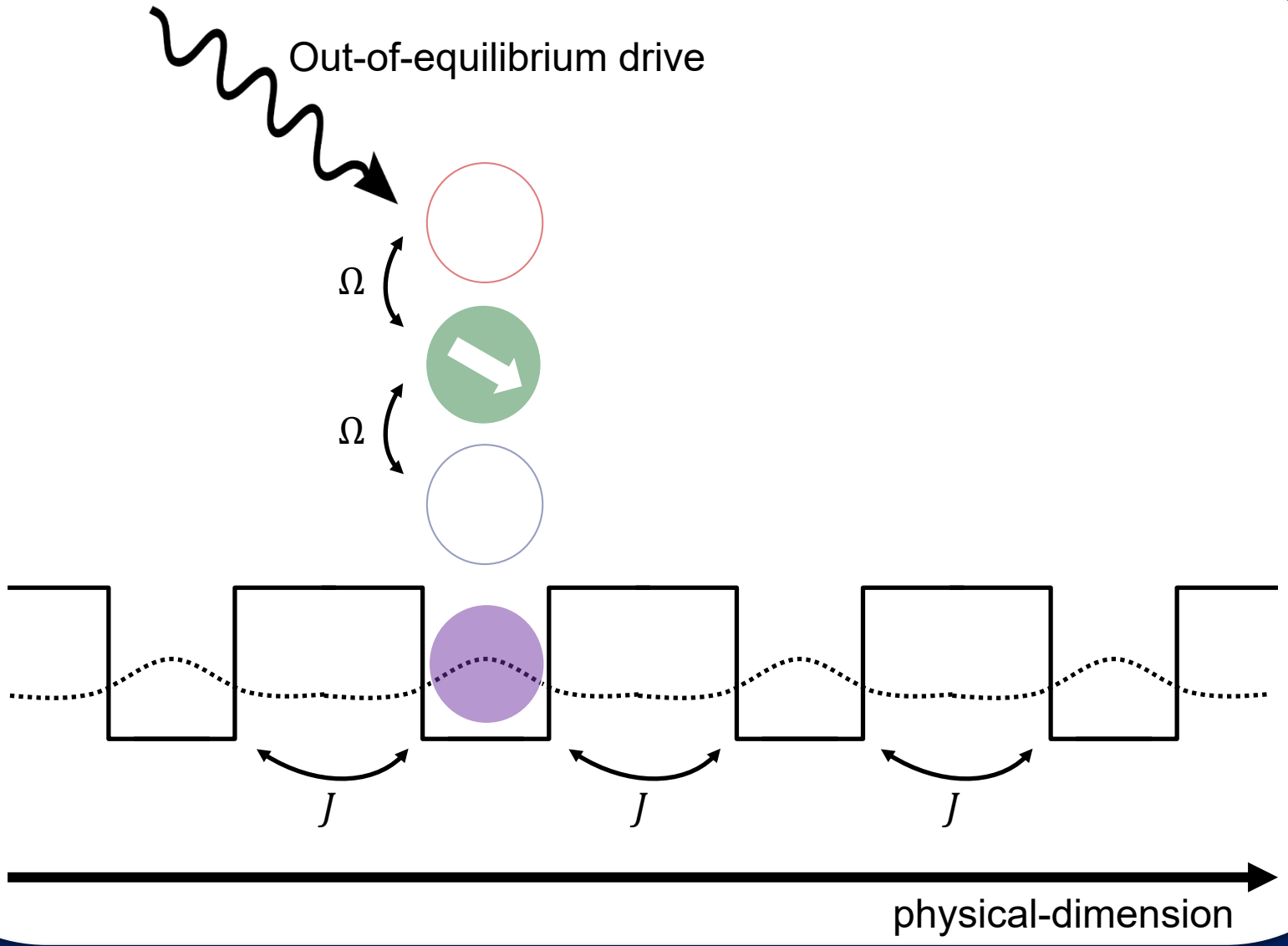
F. Nori et al., RMP 86, 153 (2014); Celi et al., PRL 112, 043001 (2014)

Synthetic dimensions



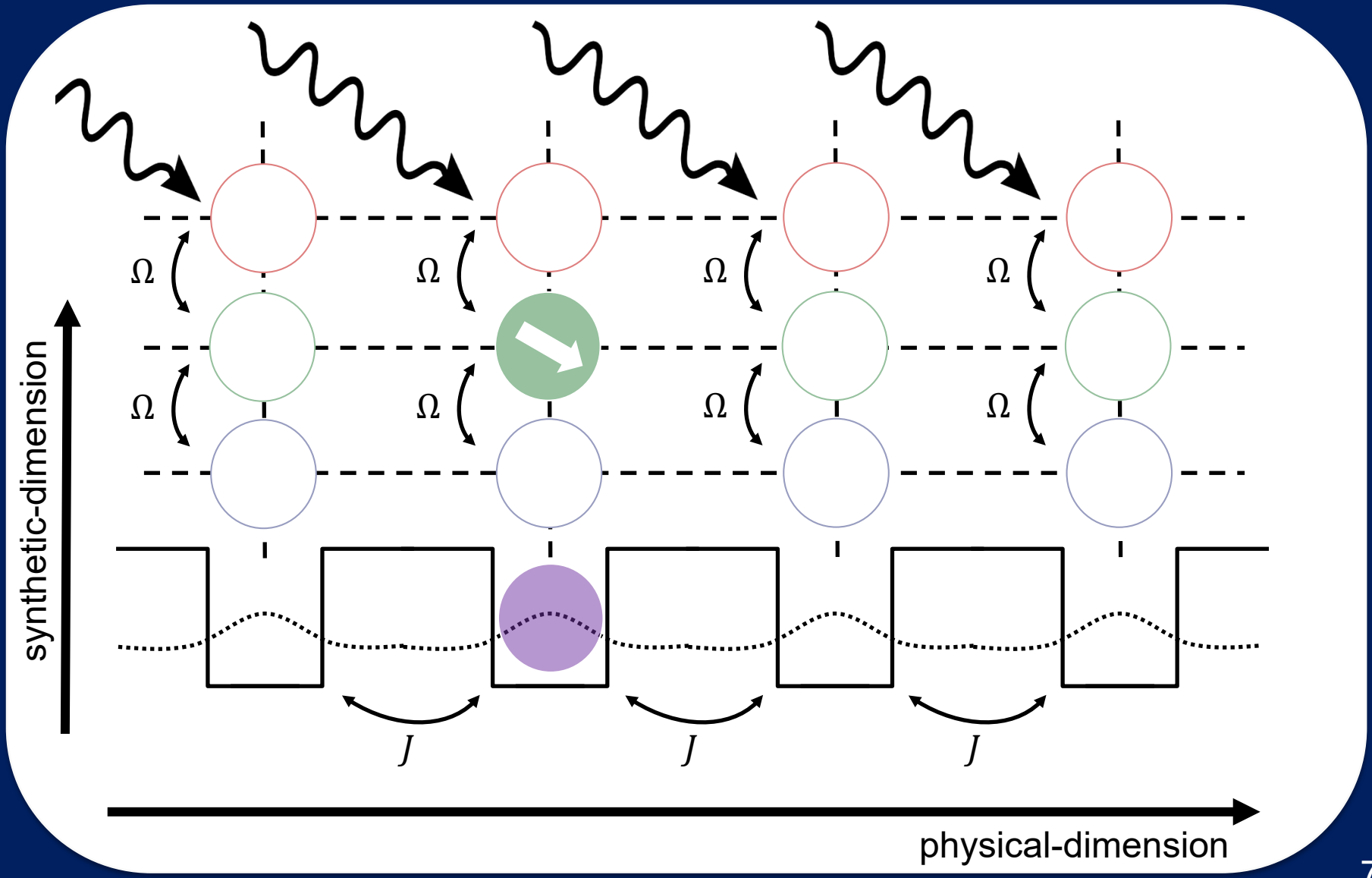
F. Nori et al., RMP 86, 153 (2014); Celi et al., PRL 112, 043001 (2014)

Synthetic dimensions



F. Nori et al., RMP 86, 153 (2014); Celi et al., PRL 112, 043001 (2014)

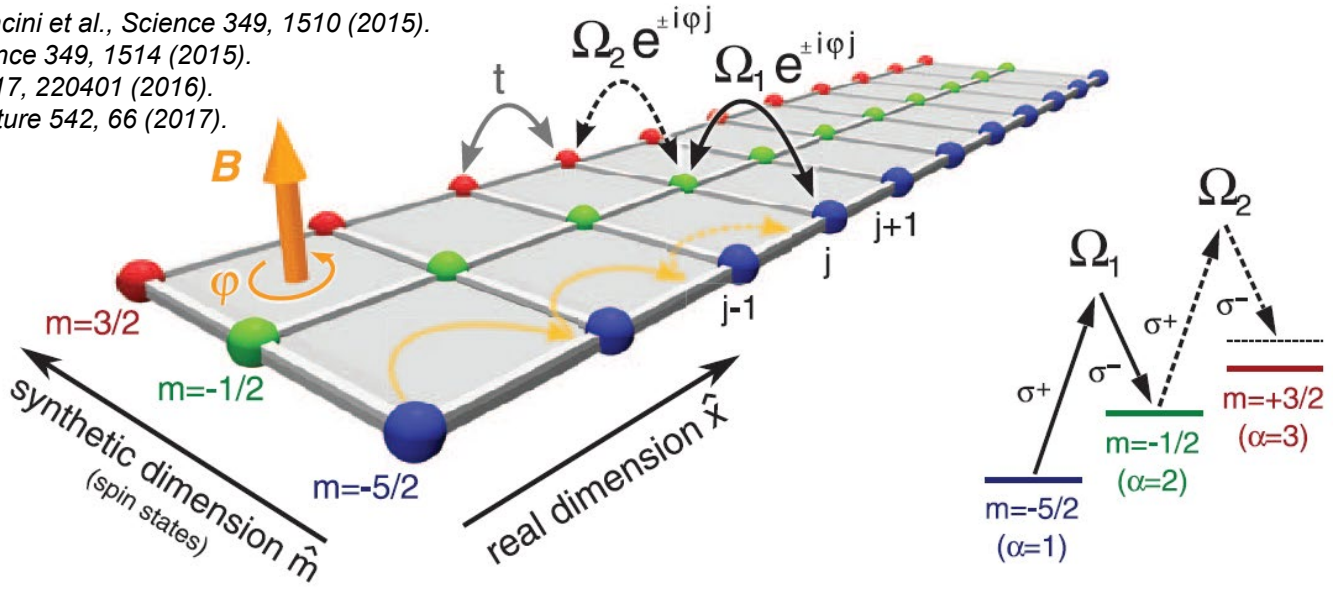
1 Synthetic + 1 physical dimensions



F. Nori et al., RMP 86, 153 (2014); Celi et al., PRL 112, 043001 (2014)

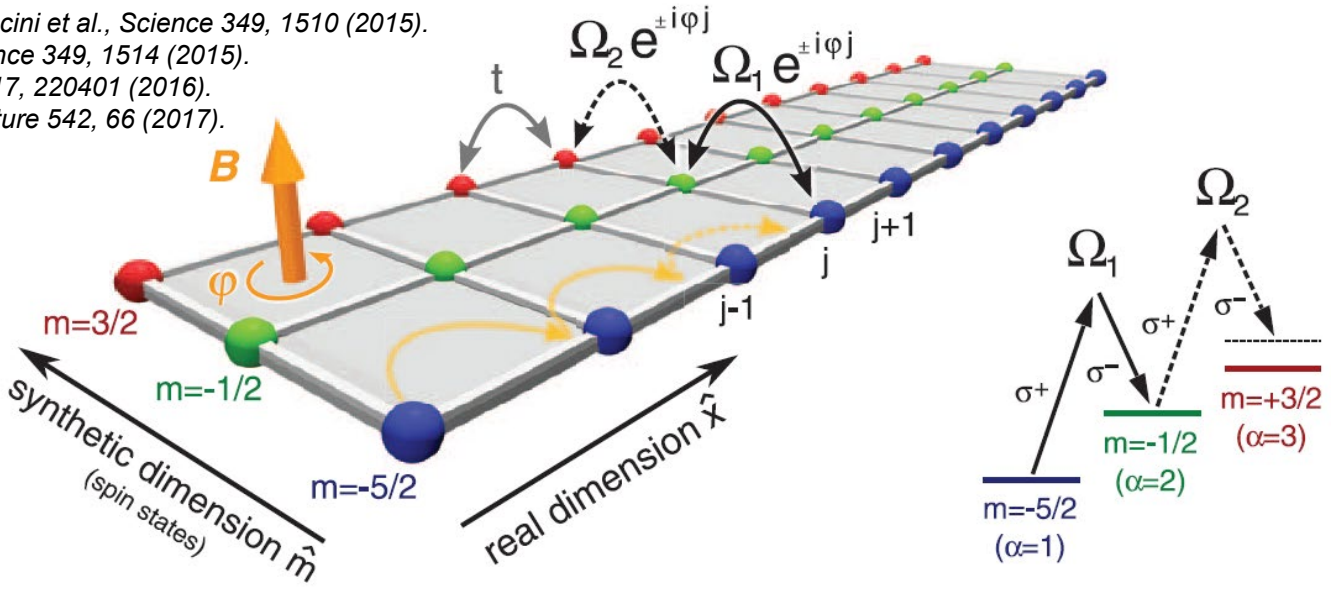
Recent experimental realizations

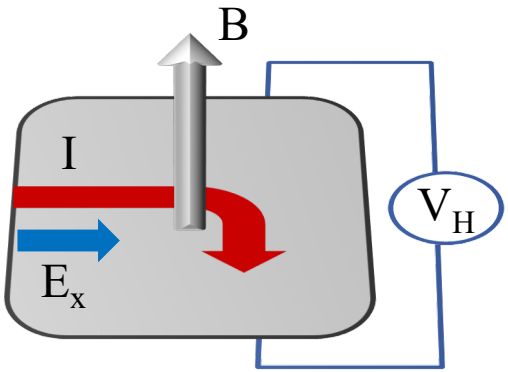
Image source: M. Mancini et al., Science 349, 1510 (2015).
B. K. Stuhl et al., Science 349, 1514 (2015).
L. F. Livi et al., PRL 117, 220401 (2016).
S. Kolkowitz et al., Nature 542, 66 (2017).



(1+1)D quantum Hall effect

Image source: M. Mancini et al., Science 349, 1510 (2015).
B. K. Stuhl et al., Science 349, 1514 (2015).
L. F. Livi et al., PRL 117, 220401 (2016).
S. Kolkowitz et al., Nature 542, 66 (2017).





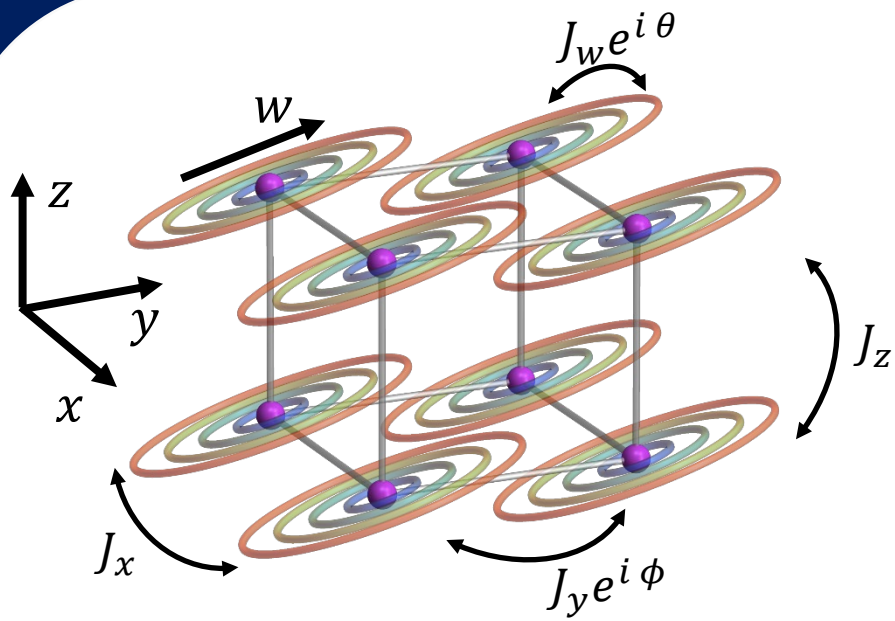
K. Von Klitzing, RMP 58, 519 (1986).

quantized transverse linear response

$$I_y = C_1 \frac{e^2}{h} E_x$$

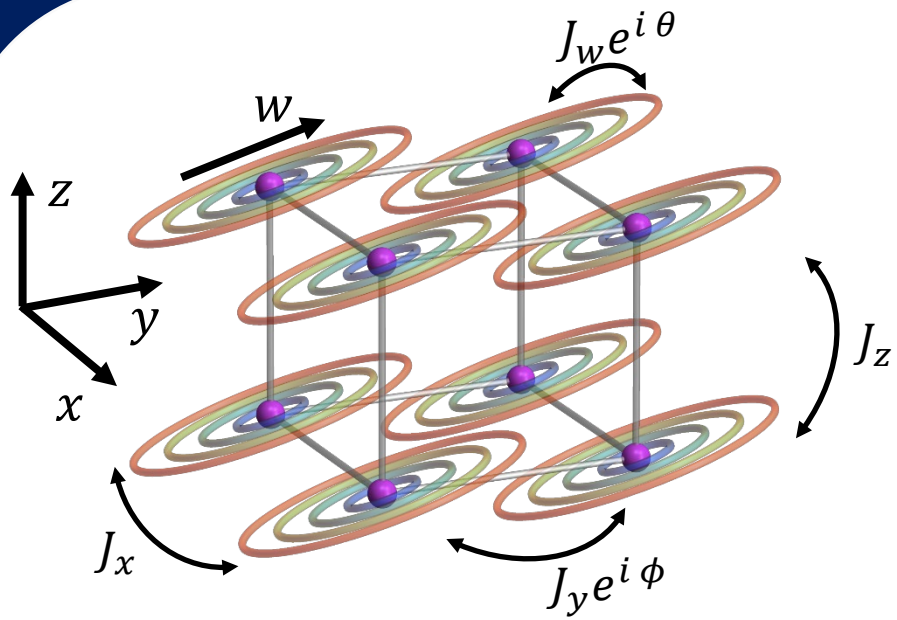
1st Chern number

1 Synthetic + 3 physical dimensions



Phys. Rev. Lett. 115, 195303 (2015)

4D quantum Hall effect



Phys. Rev. Lett. 115, 195303 (2015)

S^4

J. Fröhlich and B. Pedrini, Mathematical Physics (2000)
S.-C. Zhang and J. Hu, Science 294, 823 (2001)

quantized transverse non-linear response

$$I_\alpha = C_2 \frac{e^2}{h} \varepsilon_{\alpha\beta\gamma\delta} B_{\beta\gamma} E_\delta$$

2nd Chern number

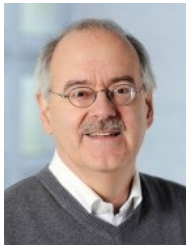
Collaborators

Open Kondo box


W. Wegscheider


K. Ensslin


M. S. Ferguson


G. Blatter

Atomic topological pump


Monika Aidelsburger (LMU)


Michael Lohse


Christian Schweizer


Immanuel Bloch (LMU)

Ioannis Petrides (Harvard)


Jan Kosata


Jose L. Lado (Aalto)

4D Topology


Hannah Price (Birmingham)


Tomoki Ozawa (Tohoku)


Nathan Goldman (ULB)


Iacopo Carusotto (Trento)

The quest continues