ETH zürich

Modifying the integer quantum Hall effect with cavity vacuum fields

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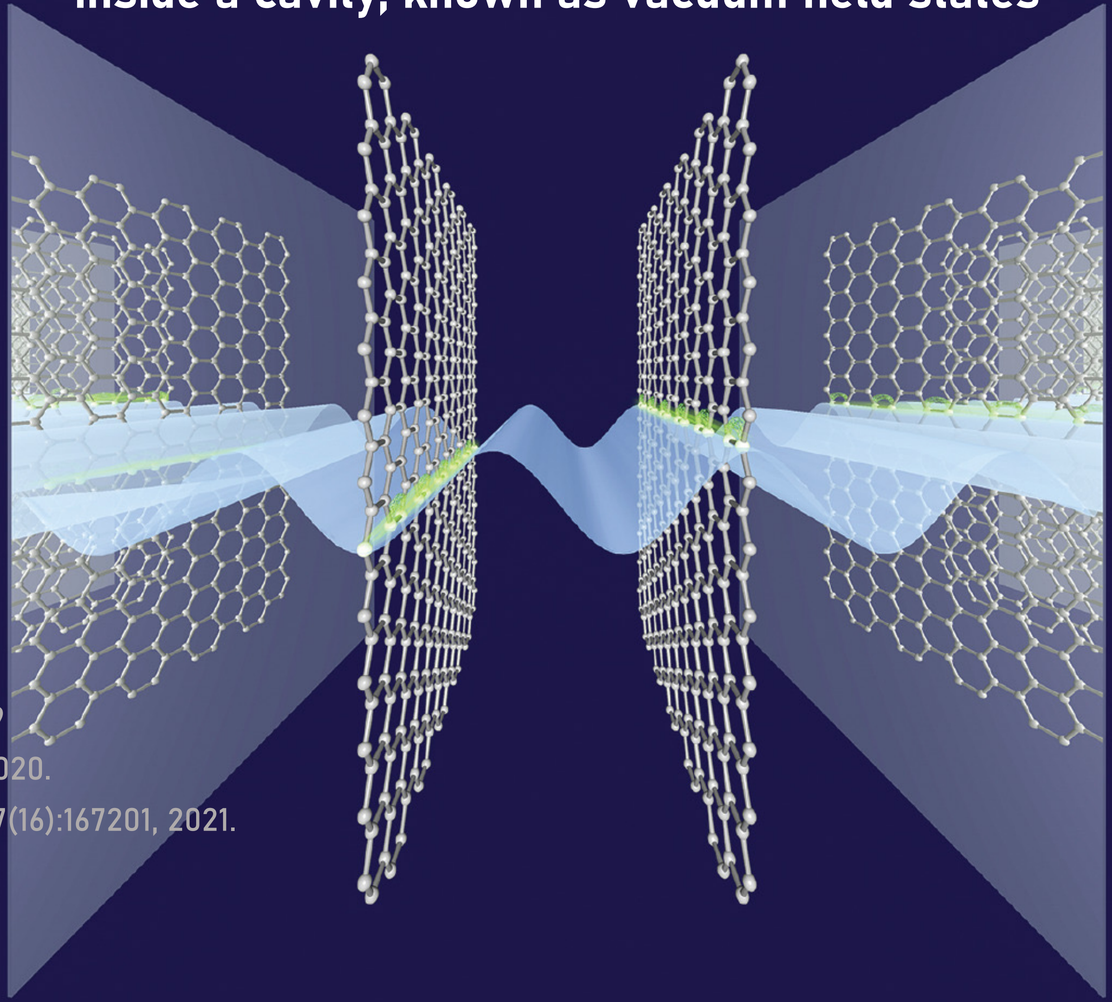
Cavitronics

devices with certain properties that can be controlled by the light waves inside a cavity, known as vacuum field states



properties
- Superconductivity
- Ferroelectricity
- Ferromagnetism

- Control of many-body interactions in 2D materials
- Control the low-energy scales of the moiré bands in twisted bilayer graphene

M. Sentef, et al. *Science advances* 4.11 (2018): eaau6969

Y. Ashida, et al. *Physical Review X*, 10(4):041027, 2020.

J. Román-Roche, et al. *Physical review letters*, 127(16):167201, 2021.

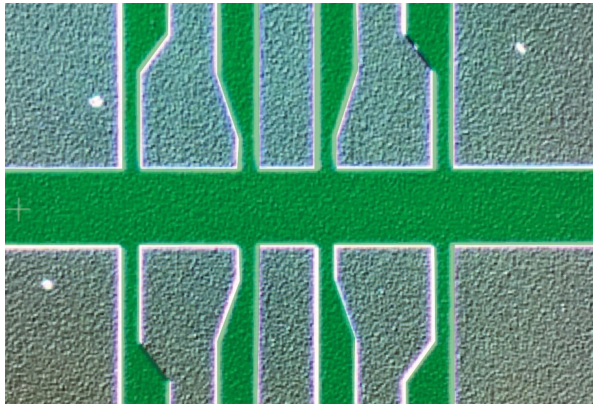
L. Balents, et al. *Nat. Physics* 16.7 (2020): 725-733.

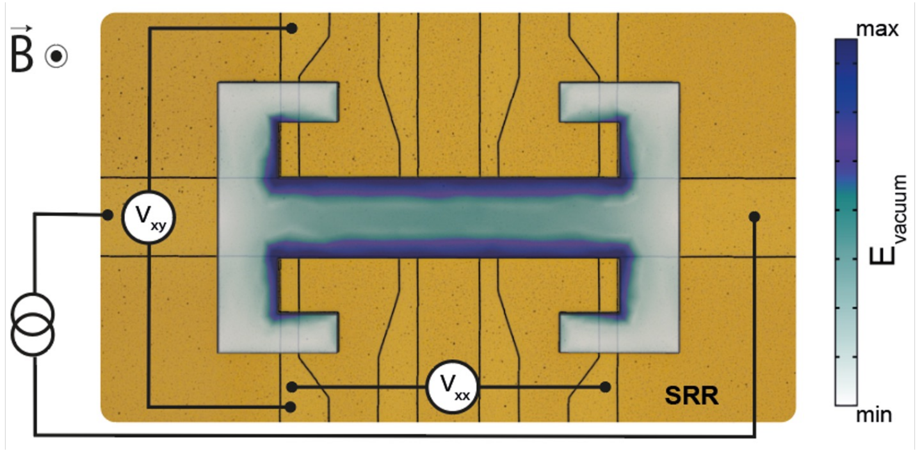
D.M. Kennes, et al. *Nat. Physics* 17.2 (2021): 155-163.

A. Rubio. *Science* 375.6584 (2022): 976-977.

A special case of Cavitronics

A robust topological protected state arising in the integer quantum hall effect can be broken by cavity vacuum fields

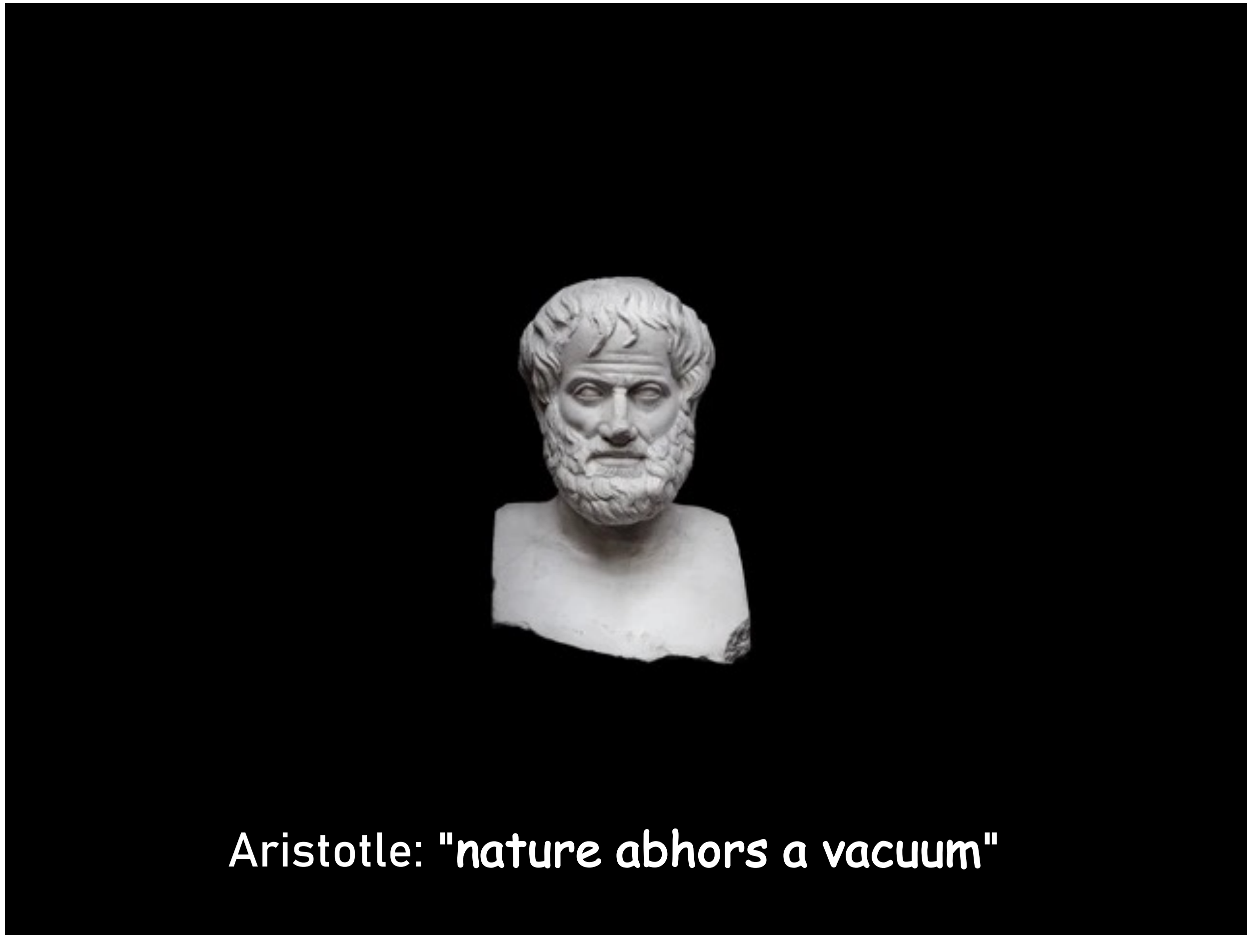




Perspective of controlling materials by engineering cavity vacuum fields

- design of quantum materials and phenomena
- create new exotic states of matter

What is Vacuum?



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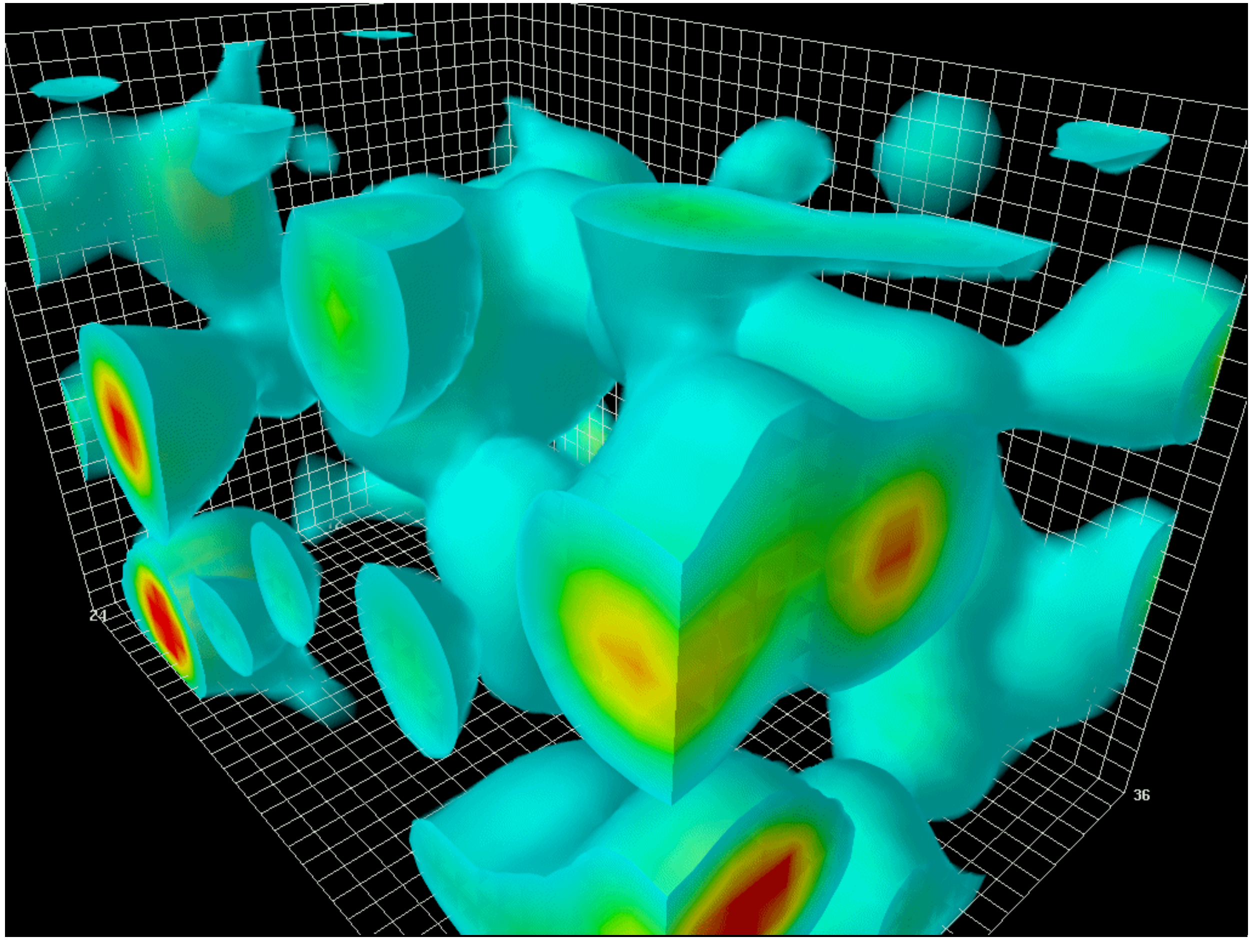
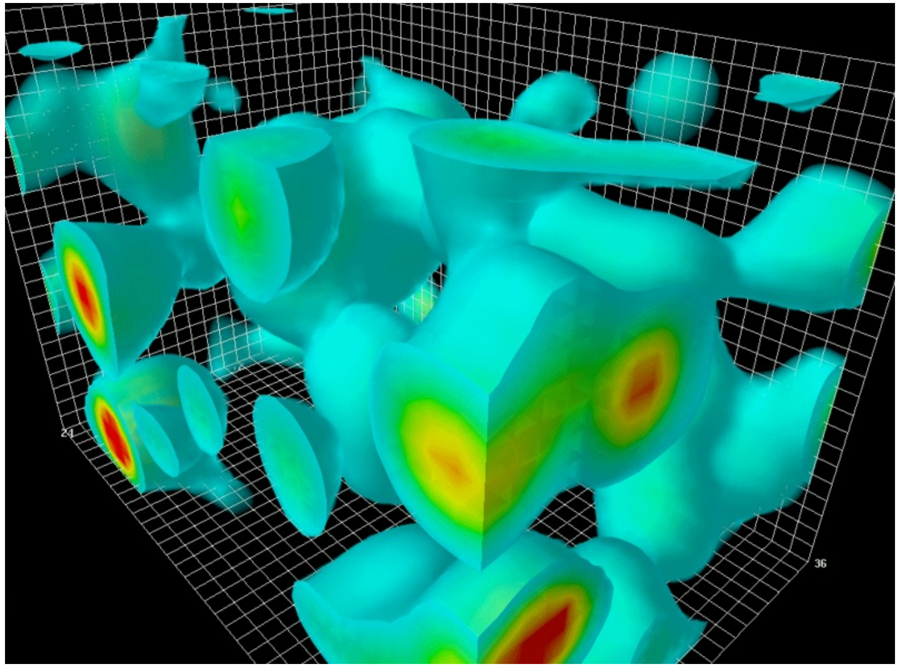


Quantum mechanics changes our interpretation of vacuum: **Vacuum is not Void**

What is Vacuum?

Quantum mechanics changes our interpretation of vacuum: **Vacuum is not Void**

One formulation of Heisenberg's uncertainty states: $\Delta E \Delta t \geq \frac{\hbar}{2}$



Intuitively, we can think the possibility of random fluctuation of energy on a very short time scale

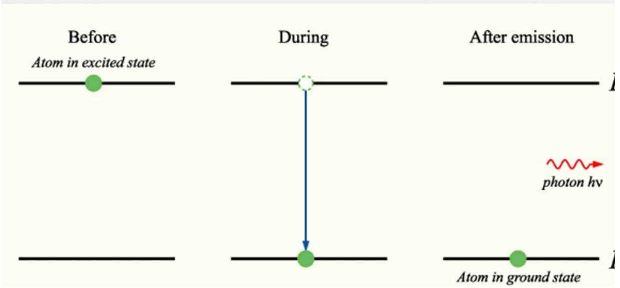
-> Electric and magnetic fields have zero average values, but non-zero variance

-> They cannot be detected directly, because of energy conservation

Why do we care?

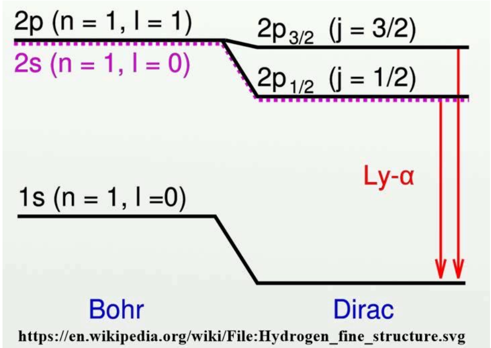
Vacuum fields effects are visible in many systems

Spontaneous emission



The Quantum Theory of the Emission and Absorption of Radiation.
By P. A. M. Dirac, St. John's College, Cambridge, and Institute for Theoretical Physics, Copenhagen.
(Communicated by N. Bohr, For. Mem. R.S.—Received February 2, 1927.)

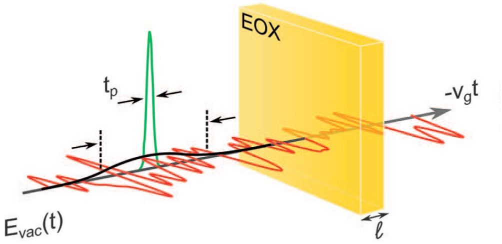
Lamb shift



PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

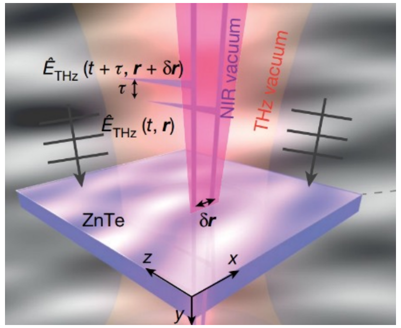
Fine Structure of the Hydrogen Atom by a Microwave Method* **
Willis E. Lamb, Jr. and Robert C. Retherford
Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York
(Received June 18, 1947)

Direct vacuum field detection



Riek, C. et al. Science, 350, 6259 (2015)

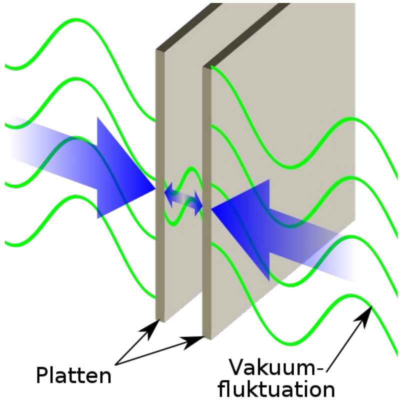
Correlation measurements



Benea-Chelmus, C. et al. Nature, 568, 202 (2019)

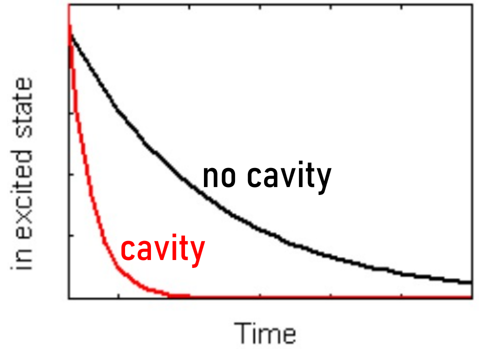
Cavity engineered

Casimir effect



Cavity QED

Weak Light matter coupling

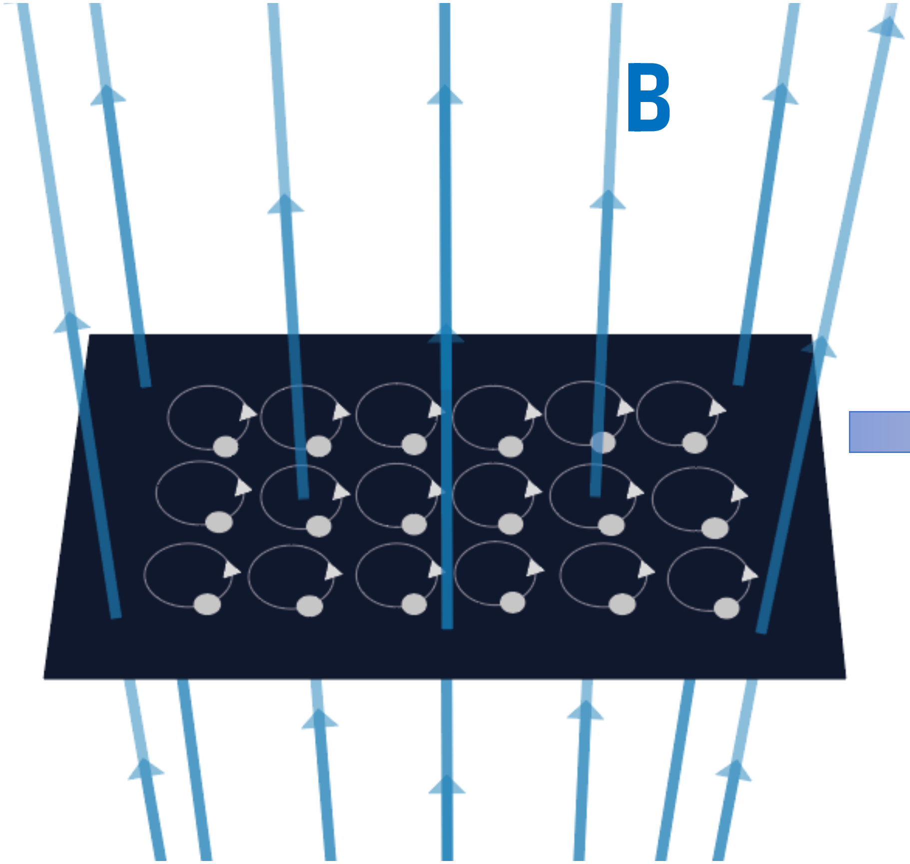


Edward M. Purcell (1912–1997) Nobel Prize 1952

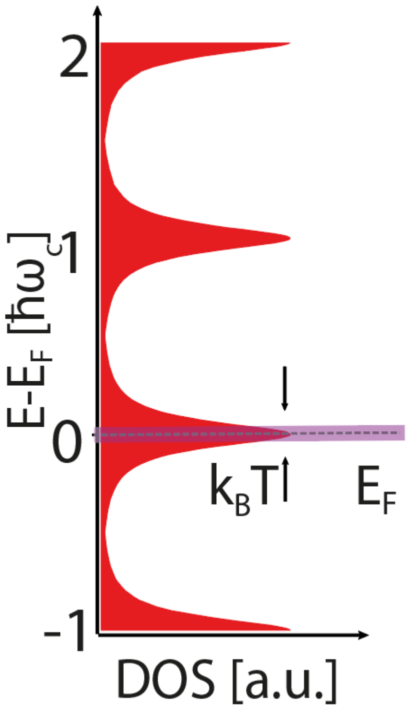
$$\Omega = d * E_{vac}$$

2.1. Matter part – 2deg etched Hallbar

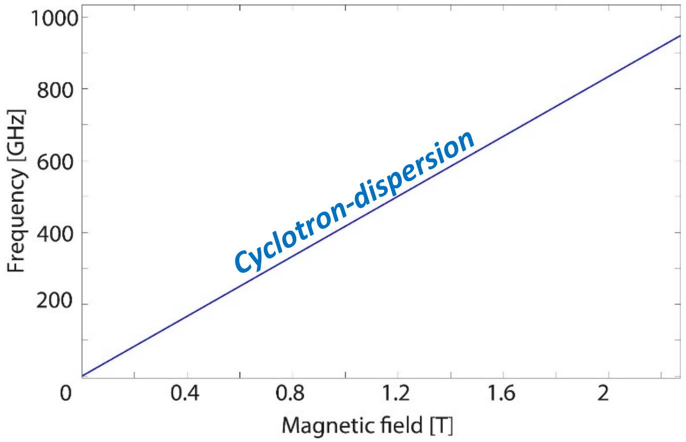
Quantum hall effect and topologically protected states



Classically, charged particles on a plane under a perpendicular magnetic field form circular orbits.

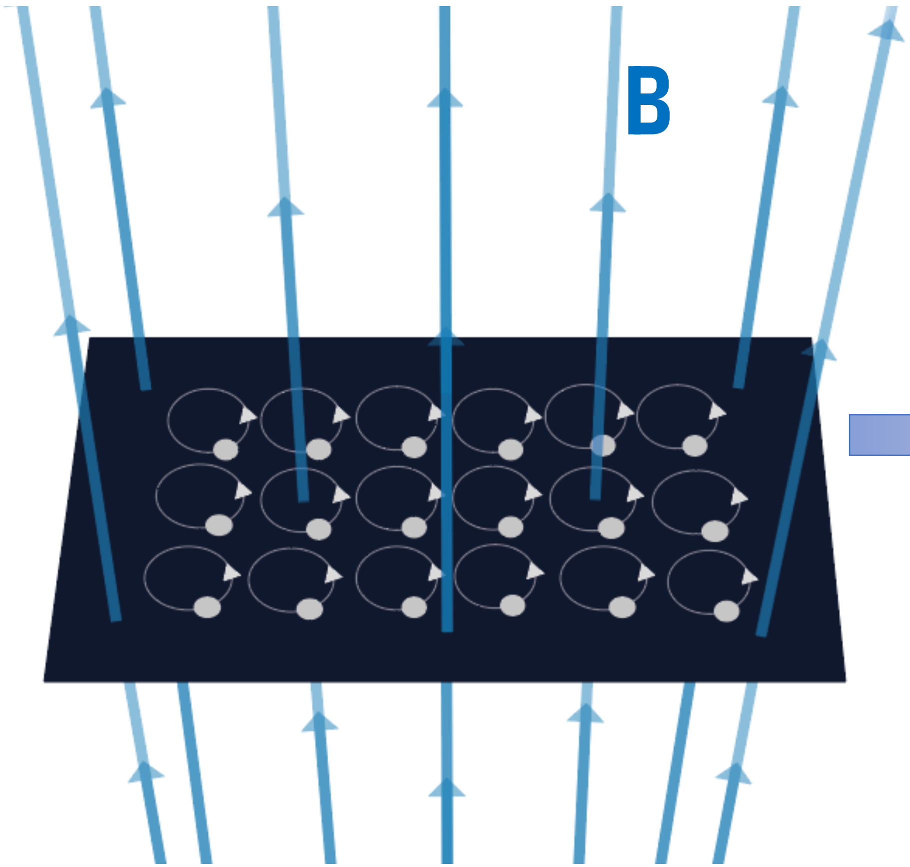


Quantum mechanically, this system behaves as an **harmonic oscillator**. The levels are known as Landau levels



Energy splitting of the levels depends linearly on B

Quantum hall effect and topologically protected states



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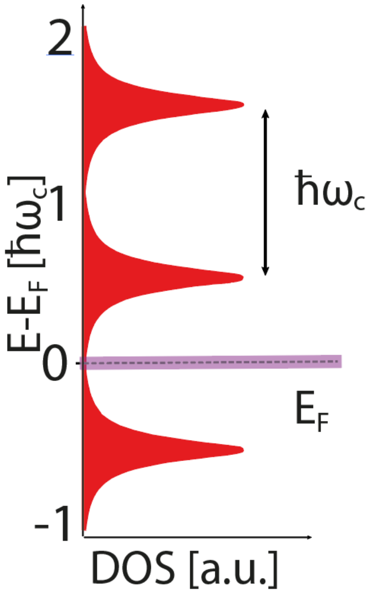
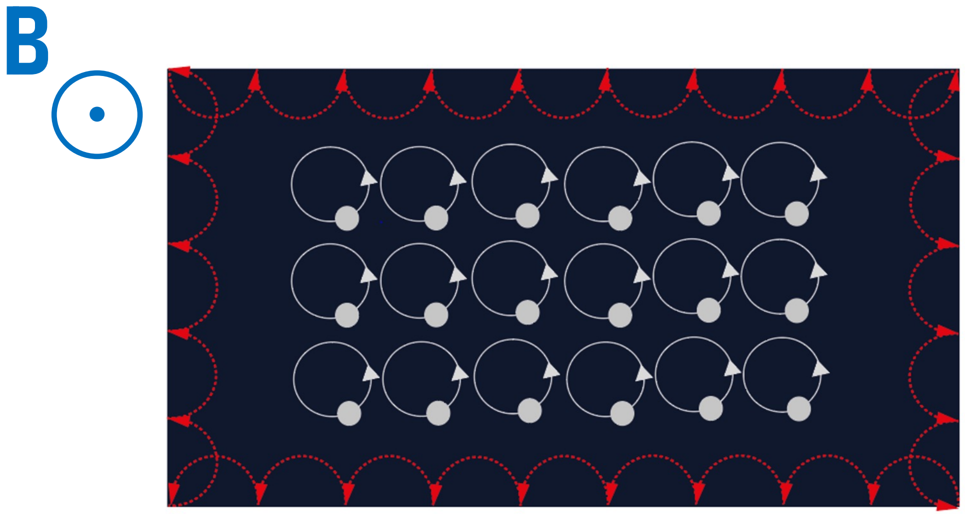


BULK

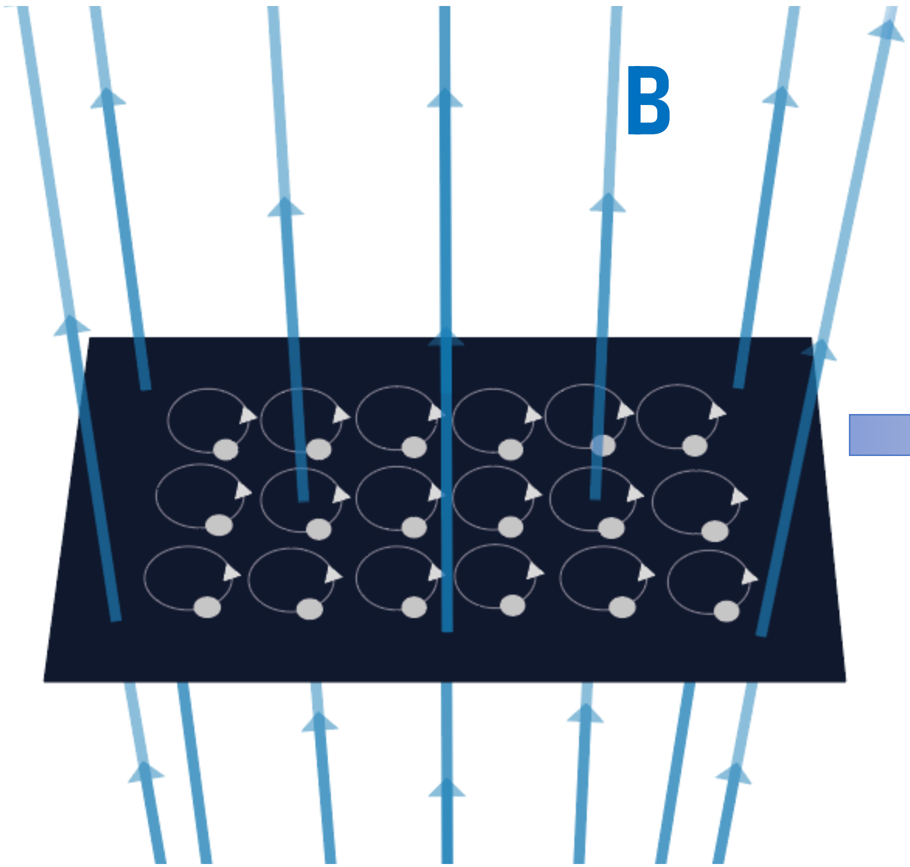
Electrons are stuck in their orbits. No current transport ⇨ Insolator



EDGE

Electrons are scattered on the edge - **skipping orbits**

Quantum hall effect and topologically protected states



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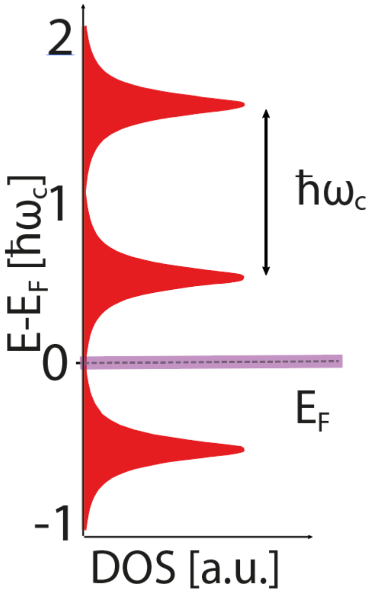
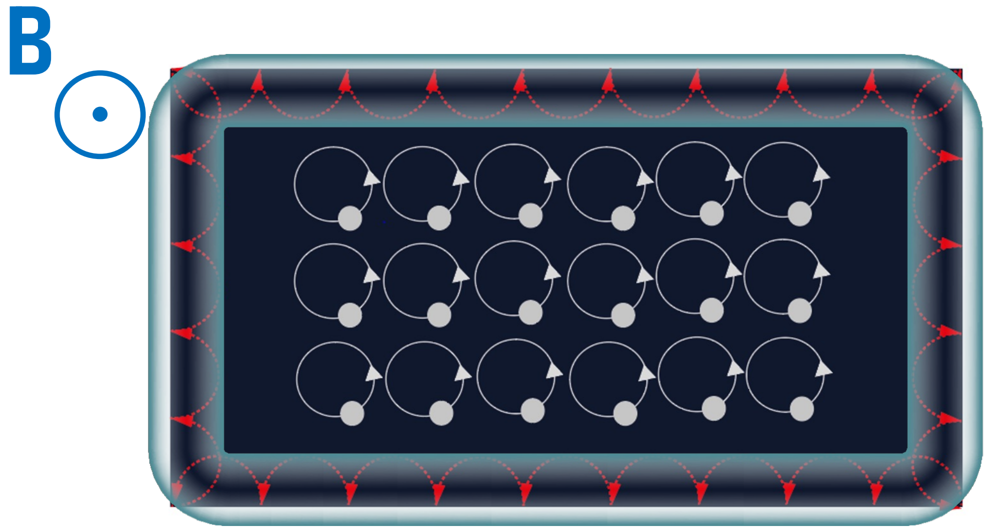


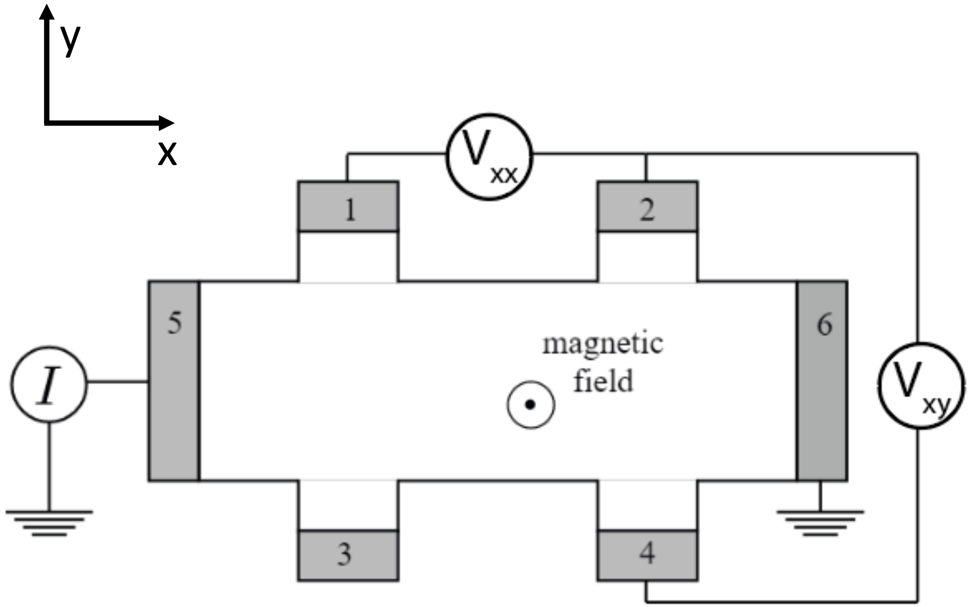
Topological insulator with

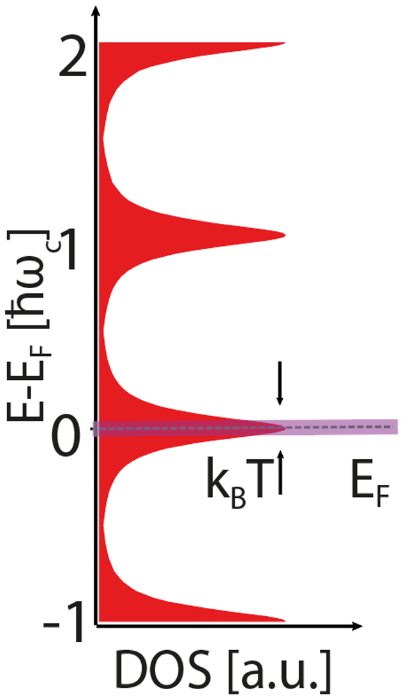
topologically protected edge states

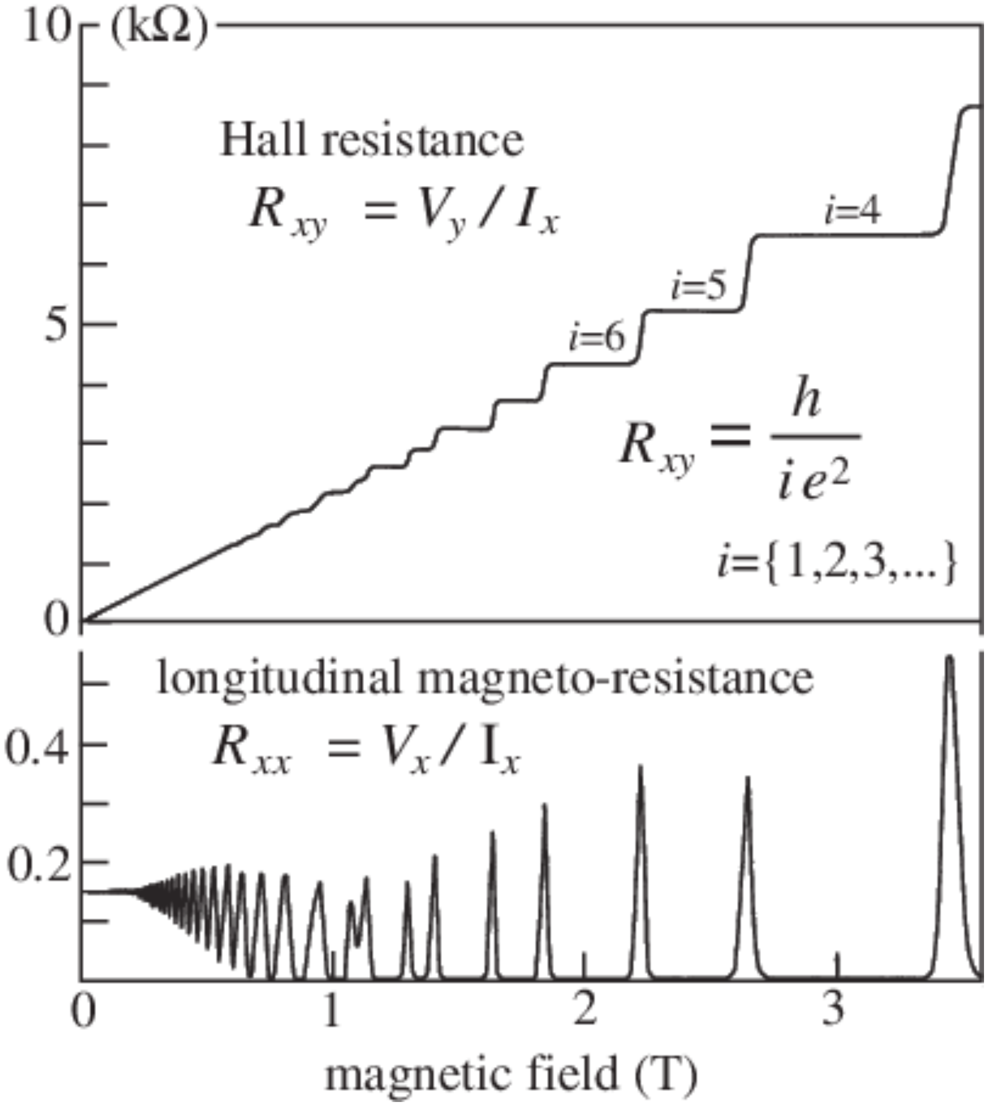


Dissipiationless electron transport on the edge channel

Quantum hall effect and topologically protected states





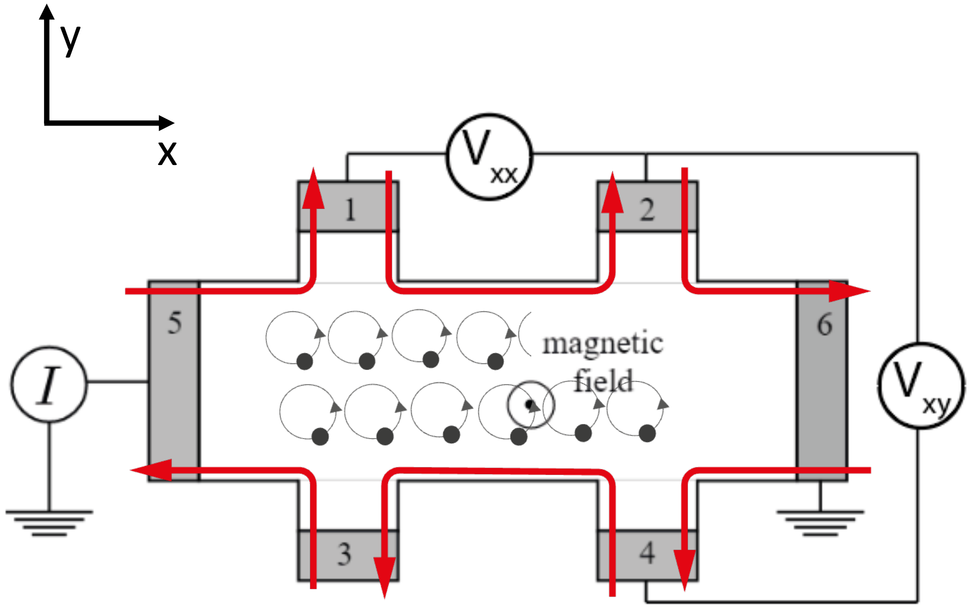


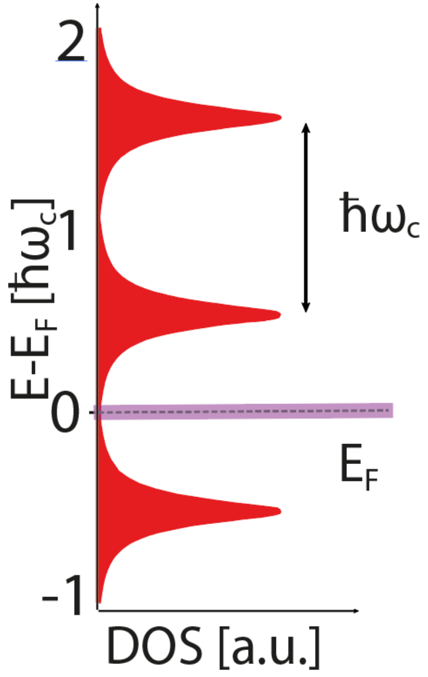
Current is passed between contacts 5 and 6 (source and drain)

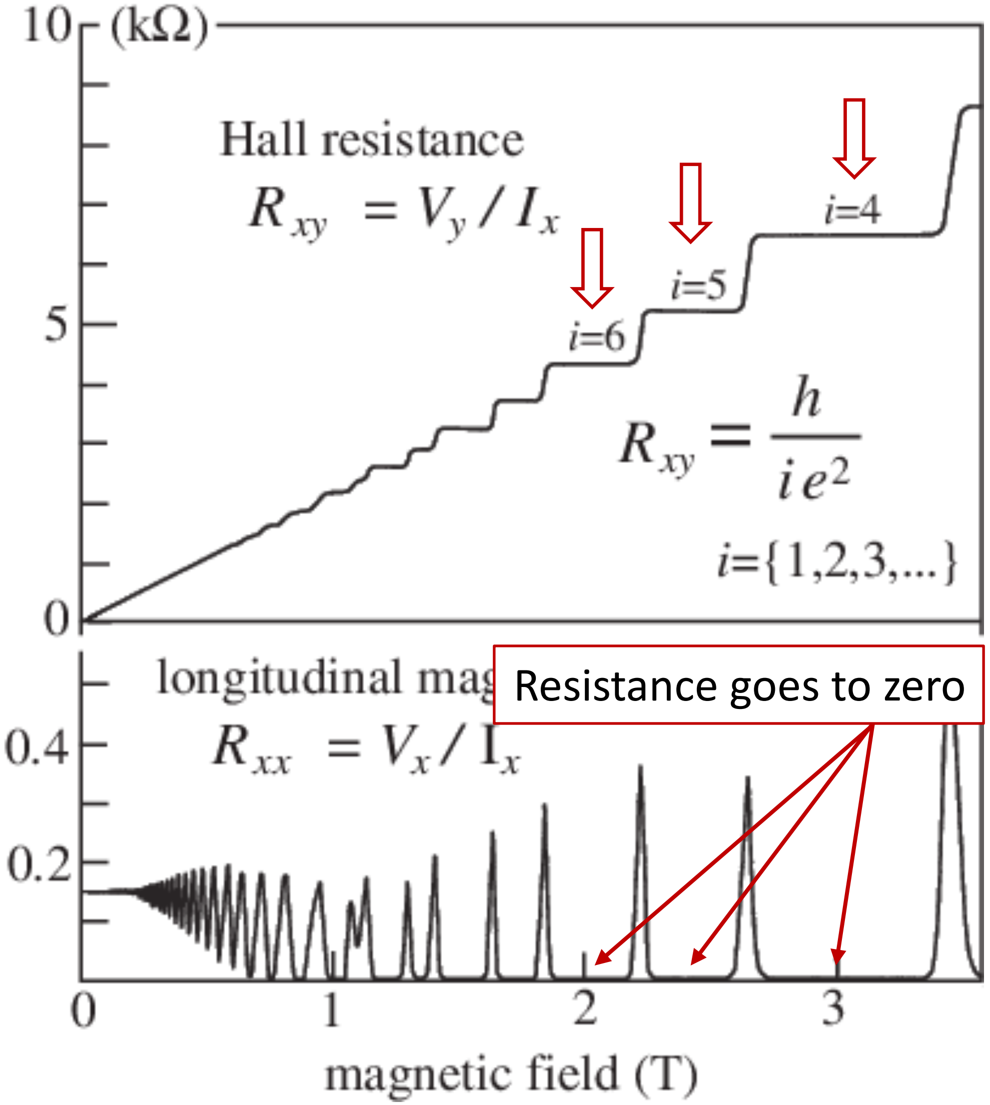
Between 2 and 4 we measure RH or Rxy, which is the Hall or transverse resistance

Between 1 and 2 we measure RL or Rxx, which is the longitudinal resistance

Quantum hall effect and topologically protected states







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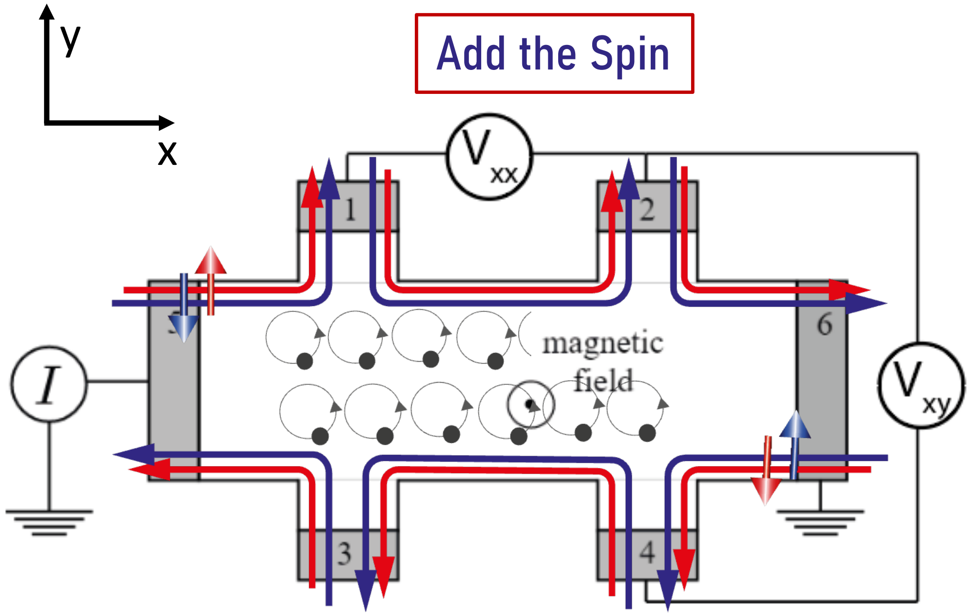
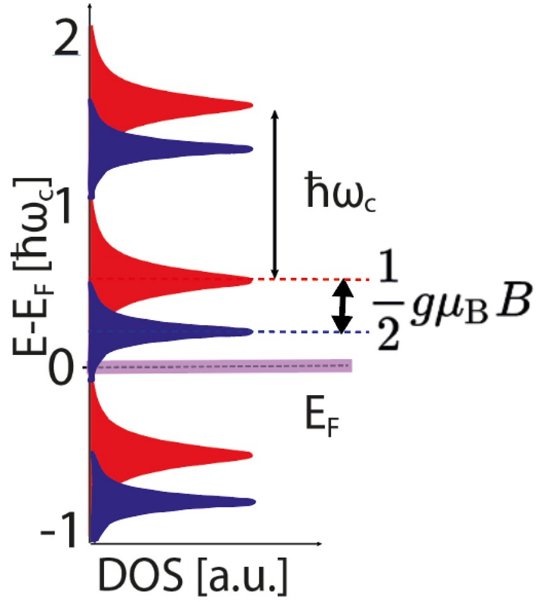
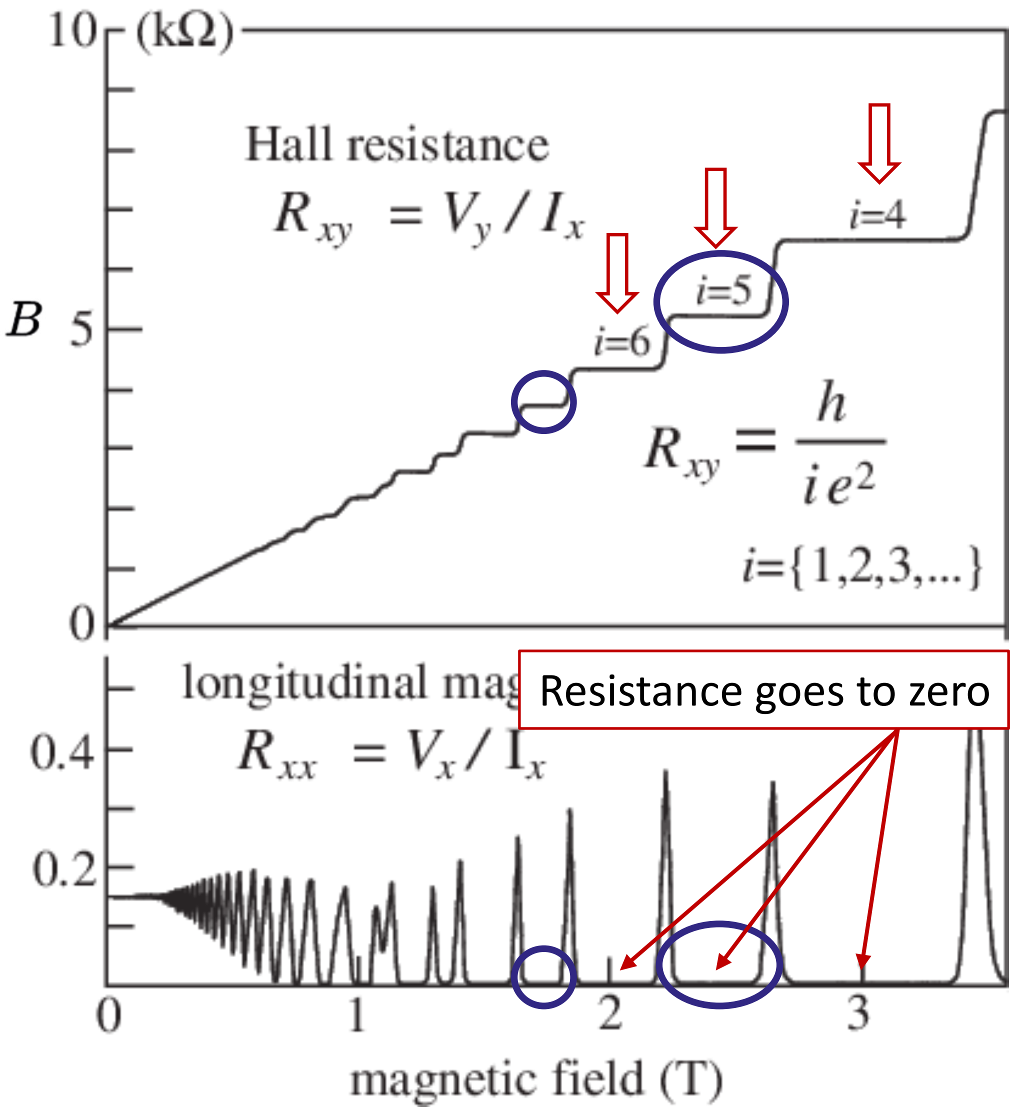
Quantum hall effect and topologically protected states

Add the Spin







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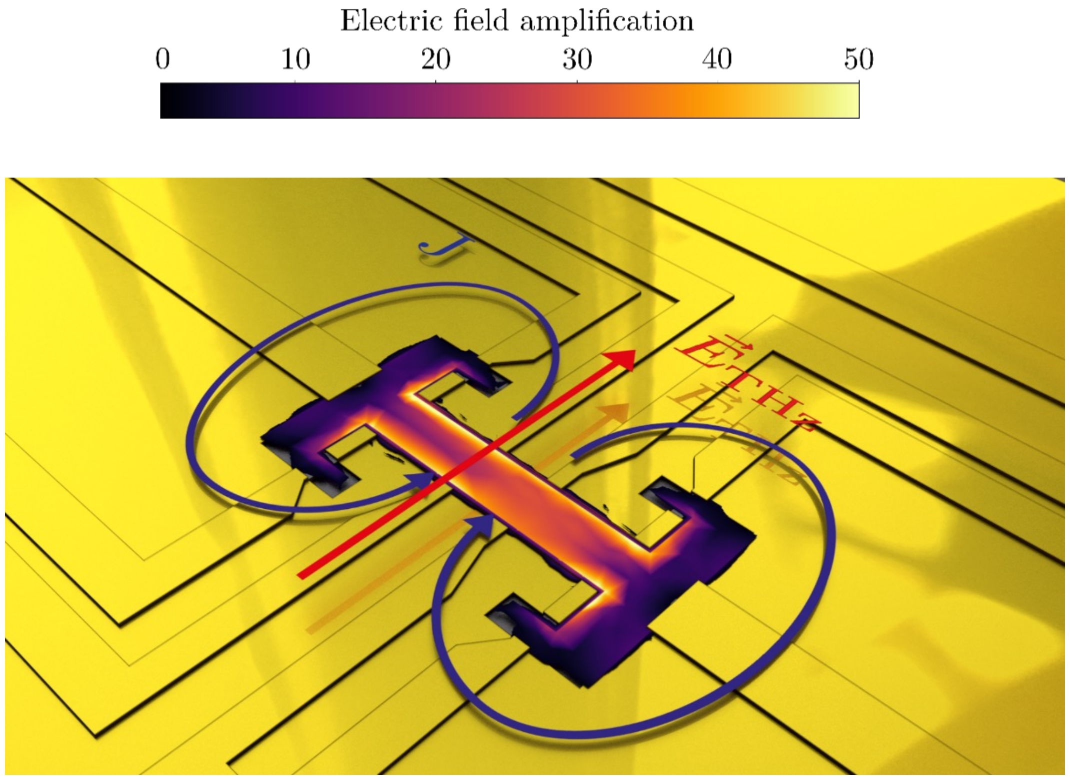
2.2. Light part - Engineering vacuum fields in Thz resonators

Thz resonators



Split-ring resonator (SRR)

- Equivalent to LC circuit

$$\hbar\Omega_R = q\sqrt{N}d_{ij}\boldsymbol{\mathcal{E}_v}$$

$$\mathcal{E}_v = \sqrt{\frac{\hbar\omega}{2\epsilon_r\epsilon_0 V}}$$

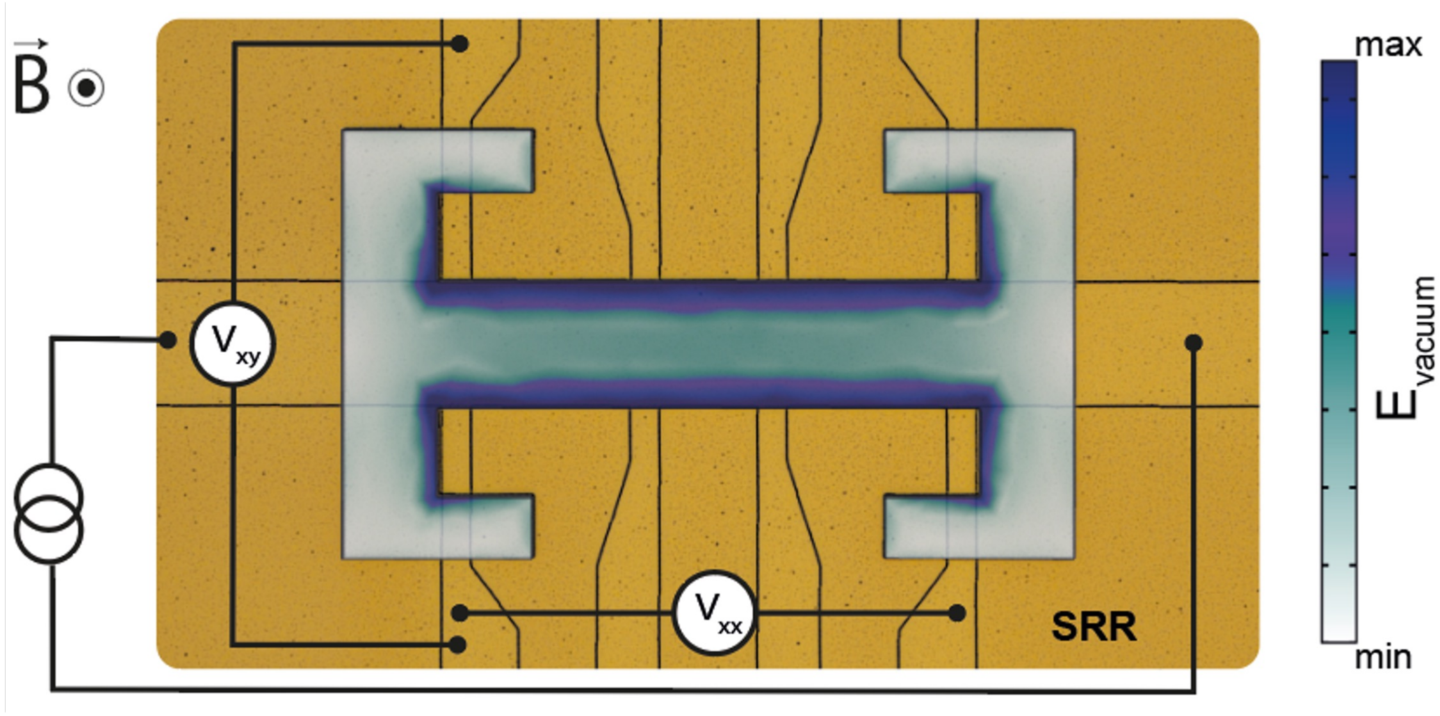
- Subwavelength Cavity $V_{cav} \sim 10^{-4}\,(\lambda/_{2n})^3$
- Strong Vacuum field $E_{vac} \sim 5$ V/m

G. Scalari et al., Science, **335,** 1323 (2012)
G.L. Paravicini-Bagliani et al., Nat. Phys. 15, 186-190 (2019)

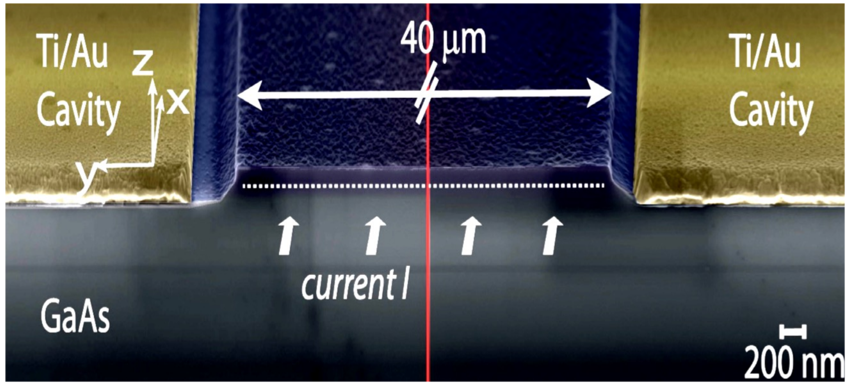
Experimental platform – cavity embedded hall bars

Hall bar geometry allows to measure longitudinal and transverse resistivity

- Hall bar entirely placed in the gap of the srr



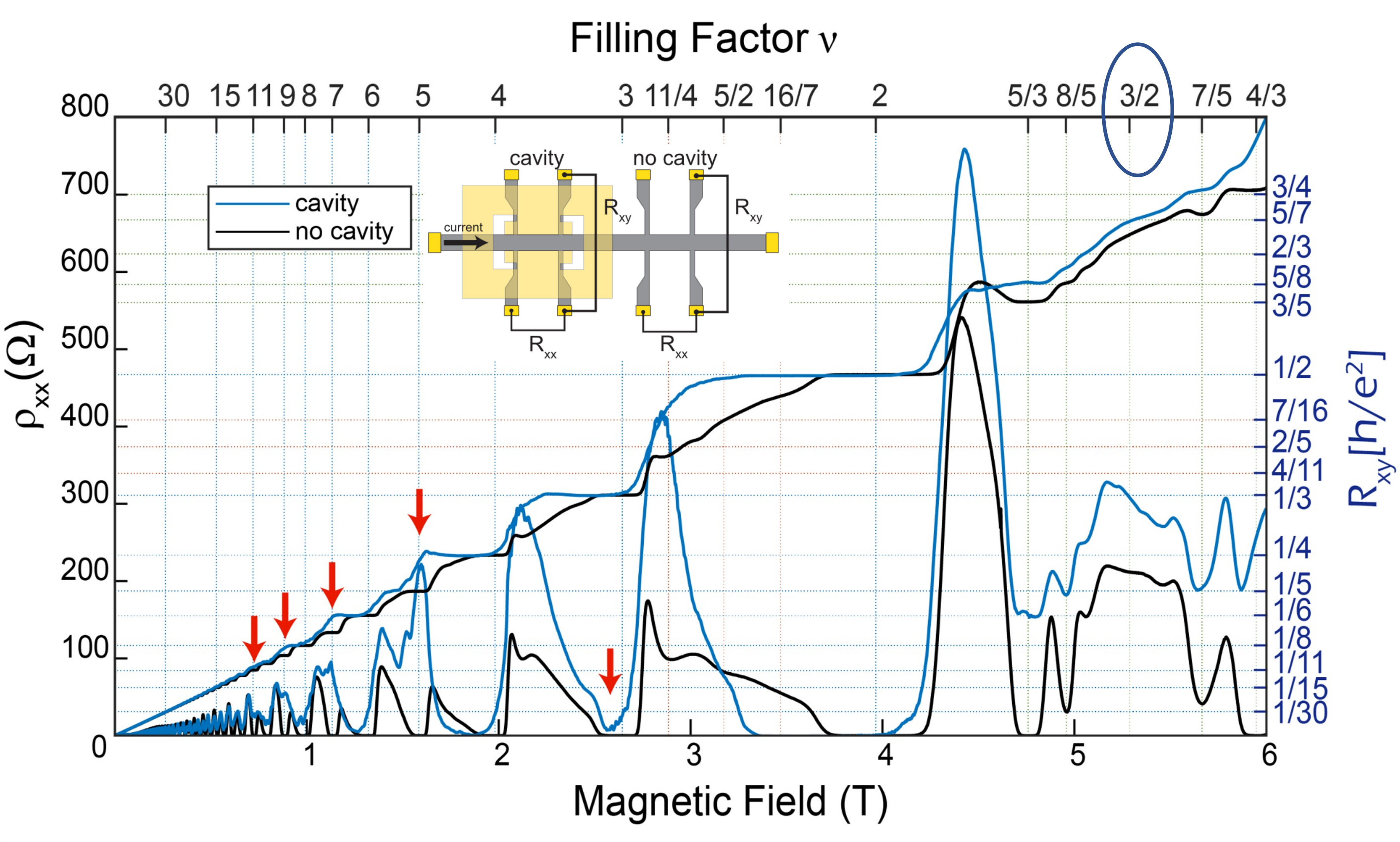
cavity embedded hall bars



F. Appugliese, J.Enkner et al, (2022). *Science*, *375*(6584), 1030-1034.

3. Experimental results

Experimental results

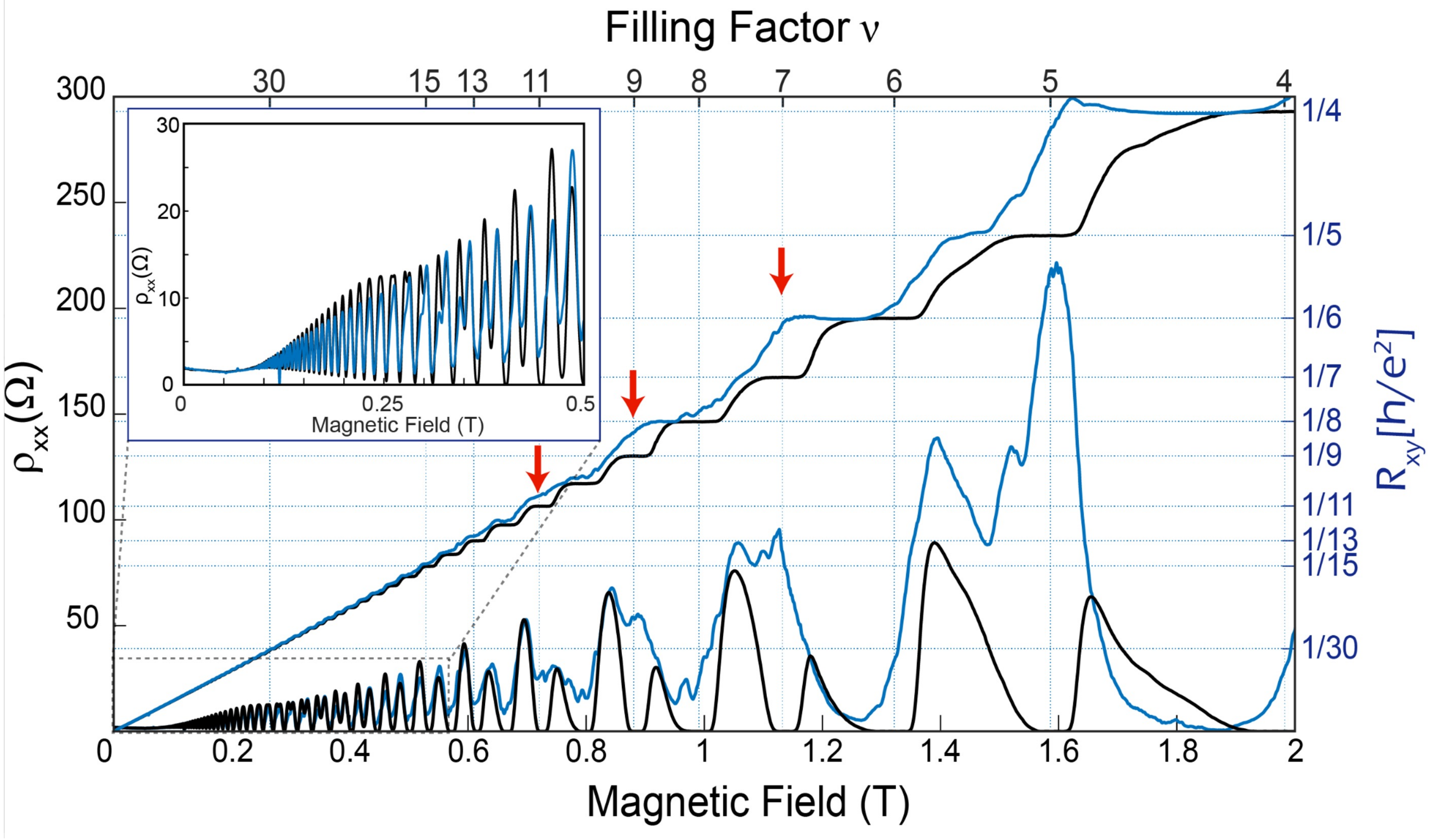


The sample with cavity shows differences with respect to the one without:

- Reference trace is well quantized
- Cavity sample shows collapse of most odd integer steps
- Fractional states around **3/2** are still present

F. Appugliese, J.Enkner et al, (2022). *Science*, *375*(6584), 1030-1034.

Experimental results

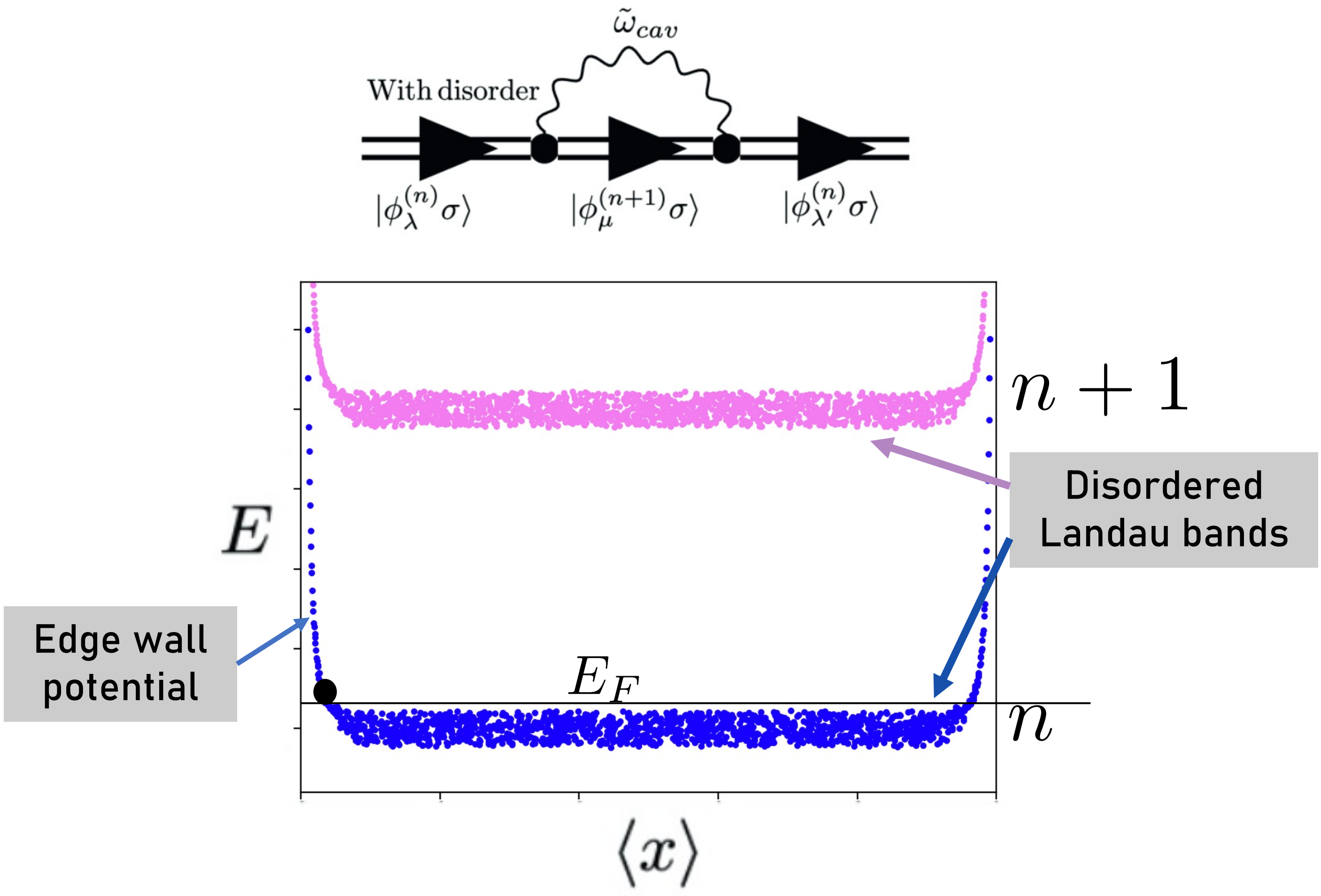


DC mobility and electronic density are the same for both samples

F. Appugliese, J.Enkner et al, (2022). *Science*, *375*(6584), 1030-1034.

3. Interpretation – Cavity mediated electron hopping

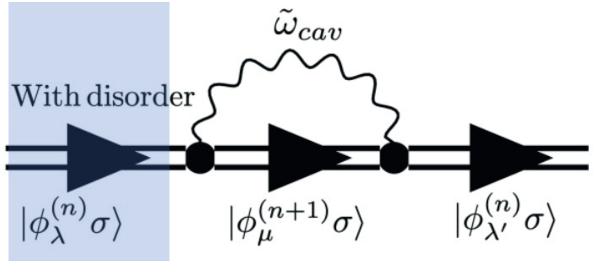
Cavity mediated electron hopping

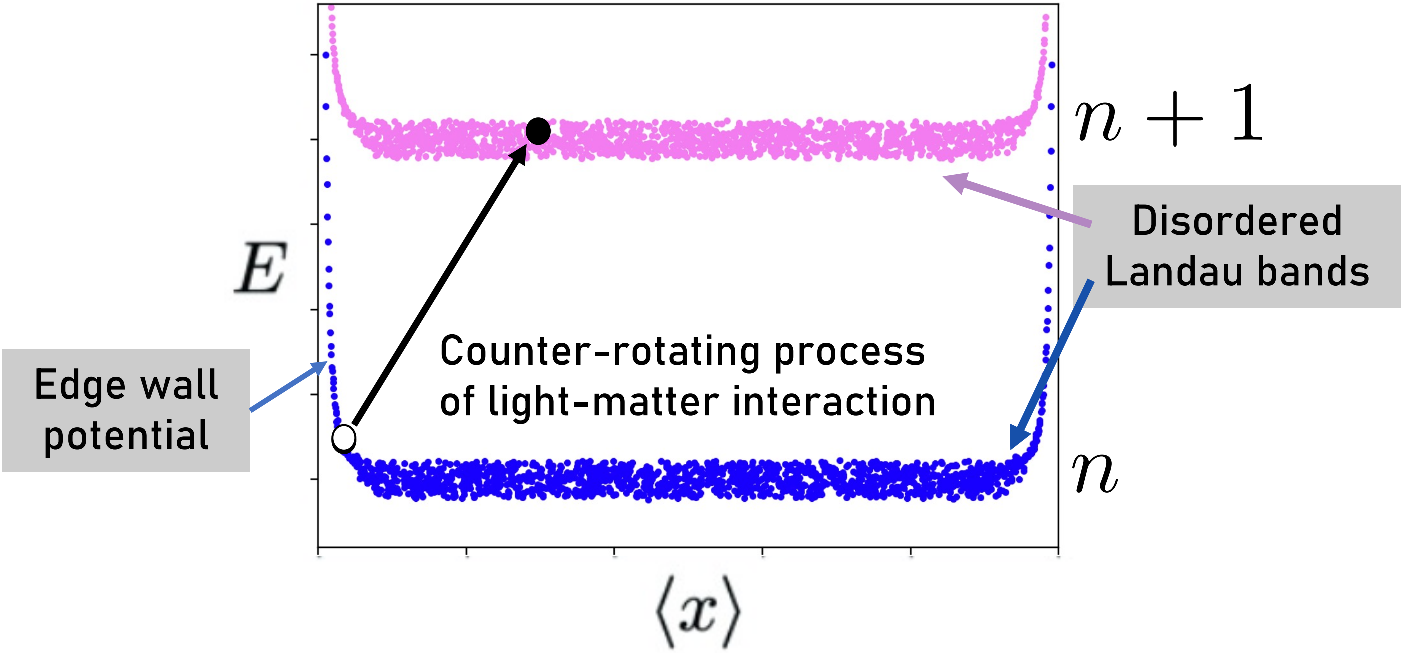


Electrons can scatter between disordered states via an itermediate process containing a virtual particle

C. Ciuti, *Physical Review B* 104.15 (2021): 155307.

Cavity mediated electron hopping





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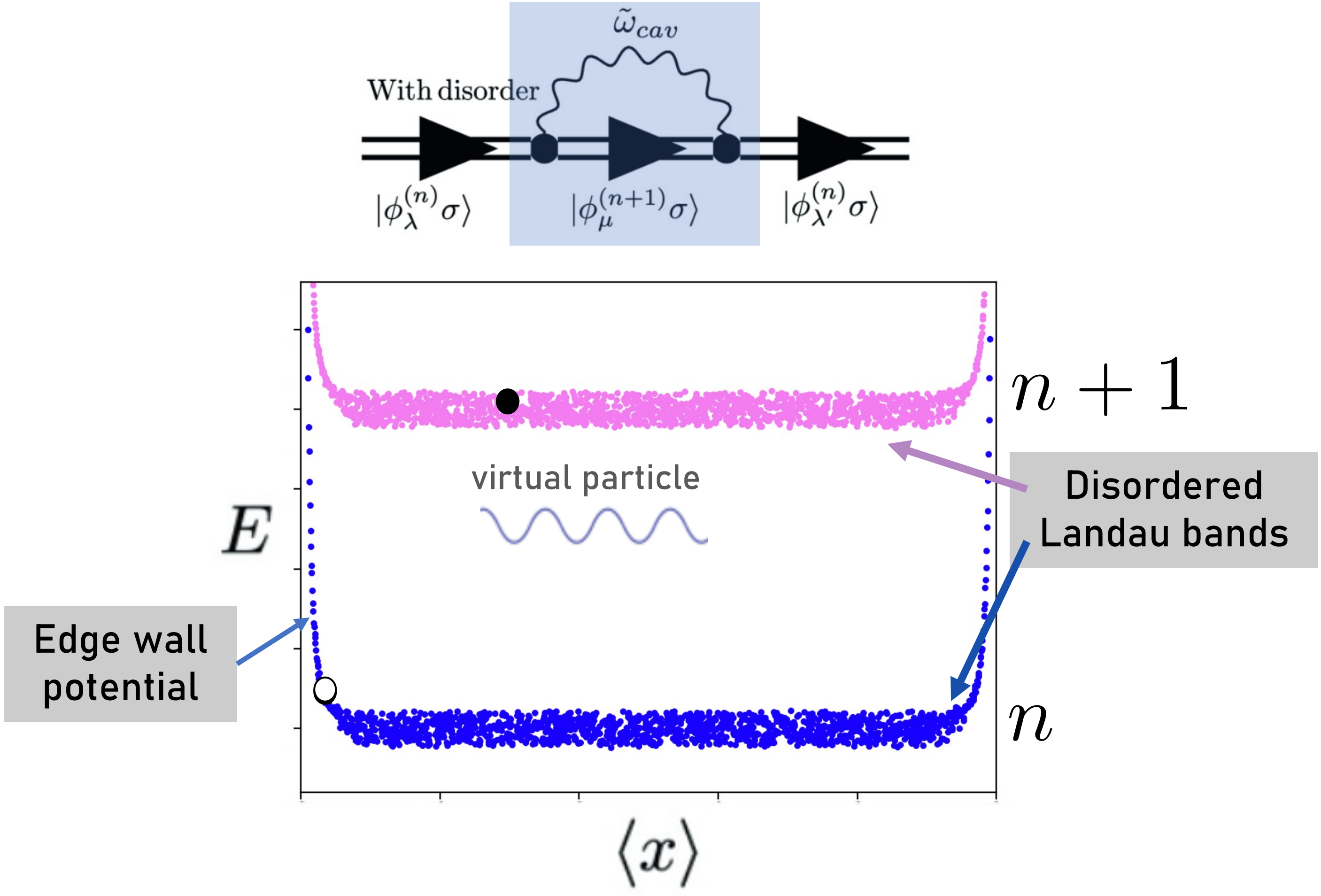

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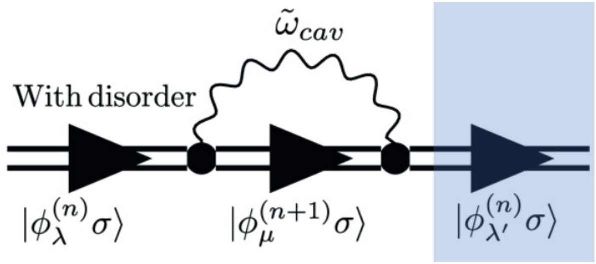

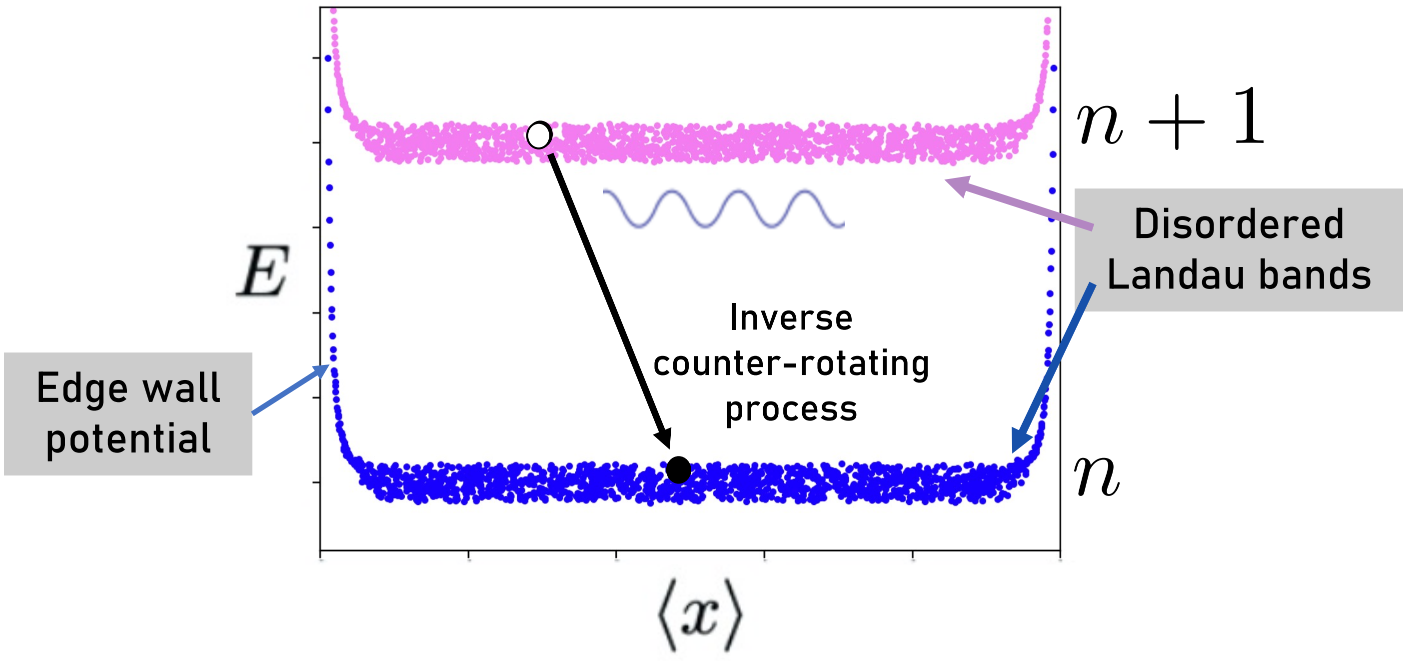

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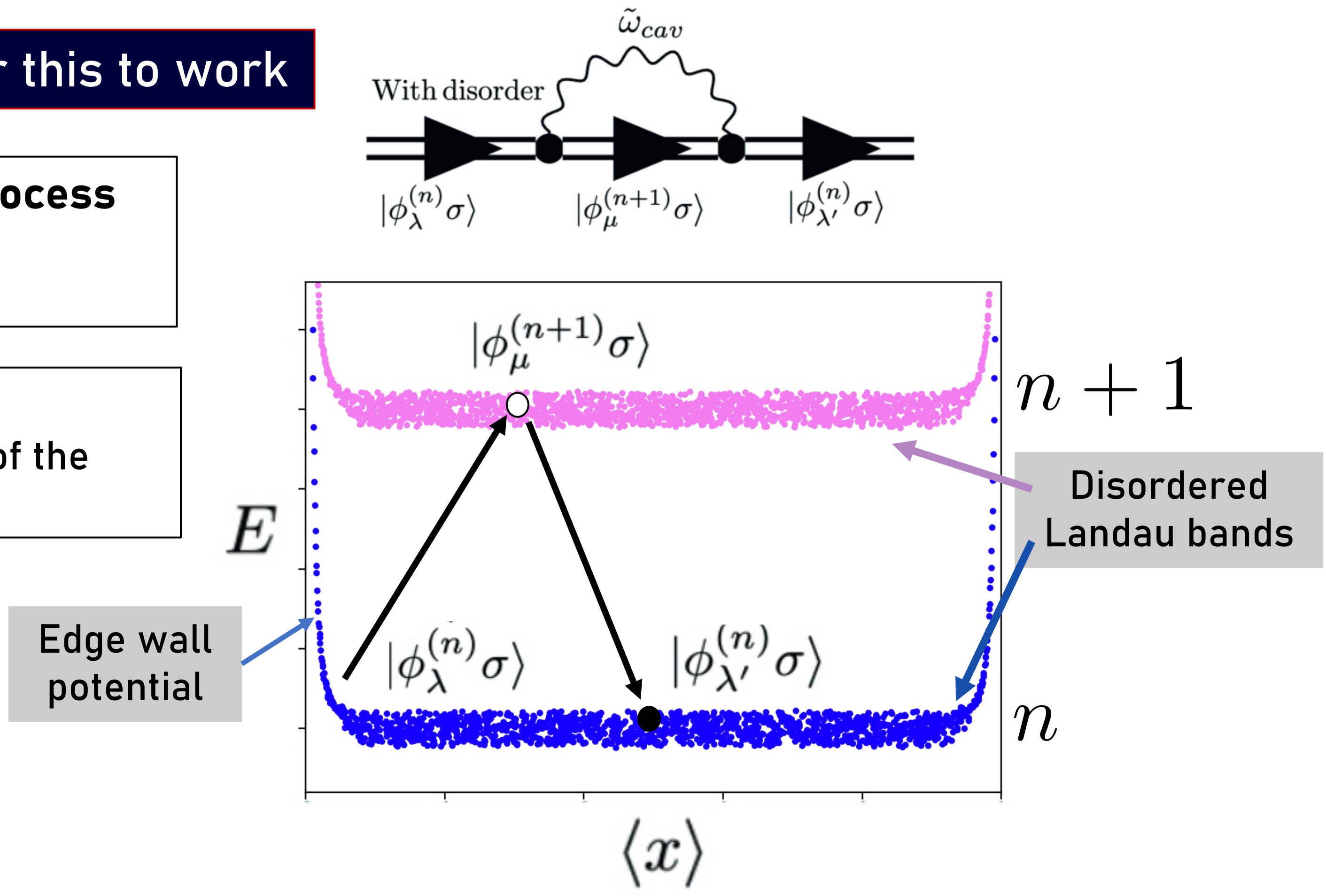
Cavity mediated electron hopping

We need two things for this to work

1. Counter-rotating process
the system has to be ultrastrongly coupled

2. Disorder
breaks the degeneracy of the Landau levels



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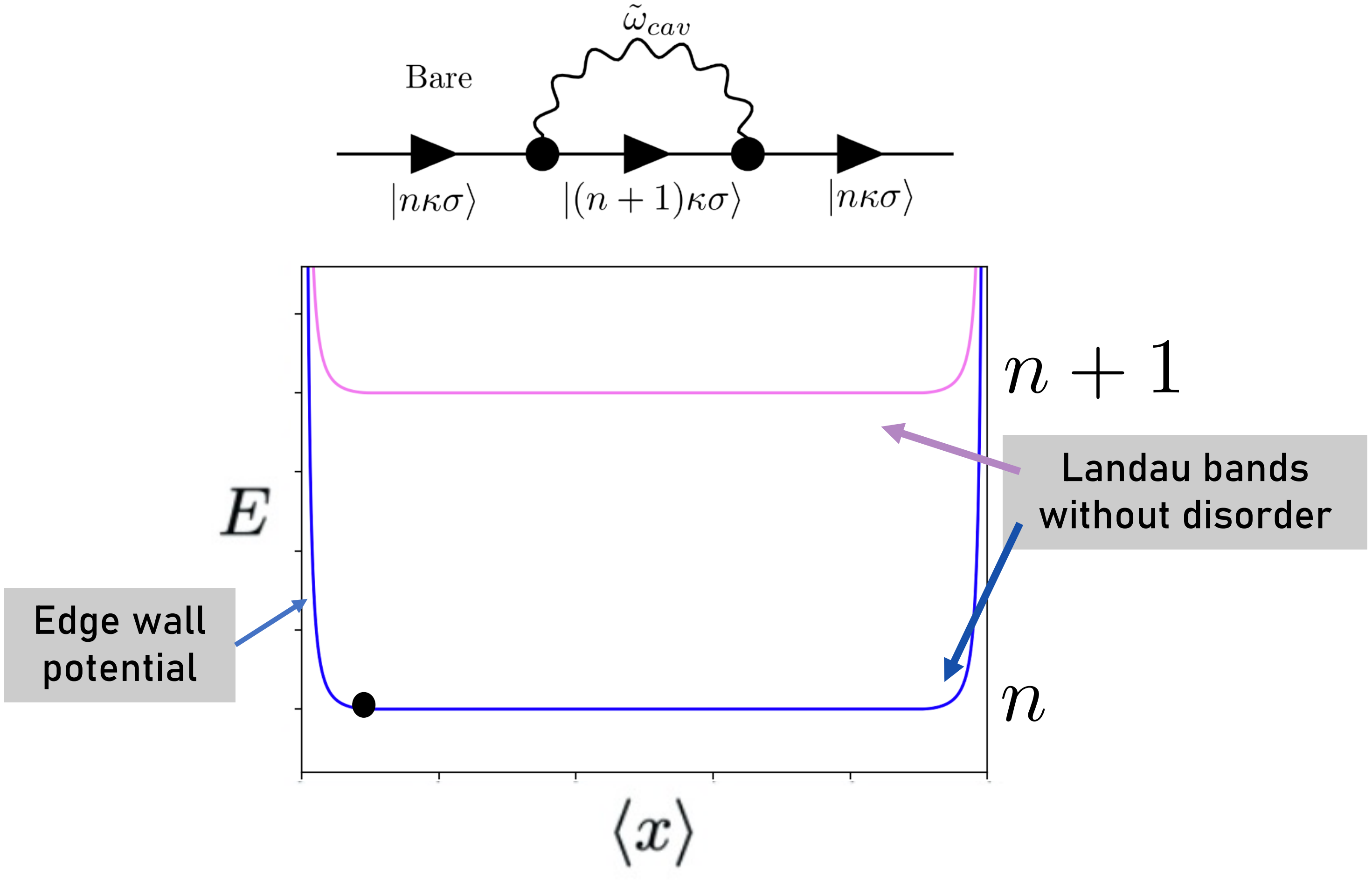

Perfect conductor without disorder

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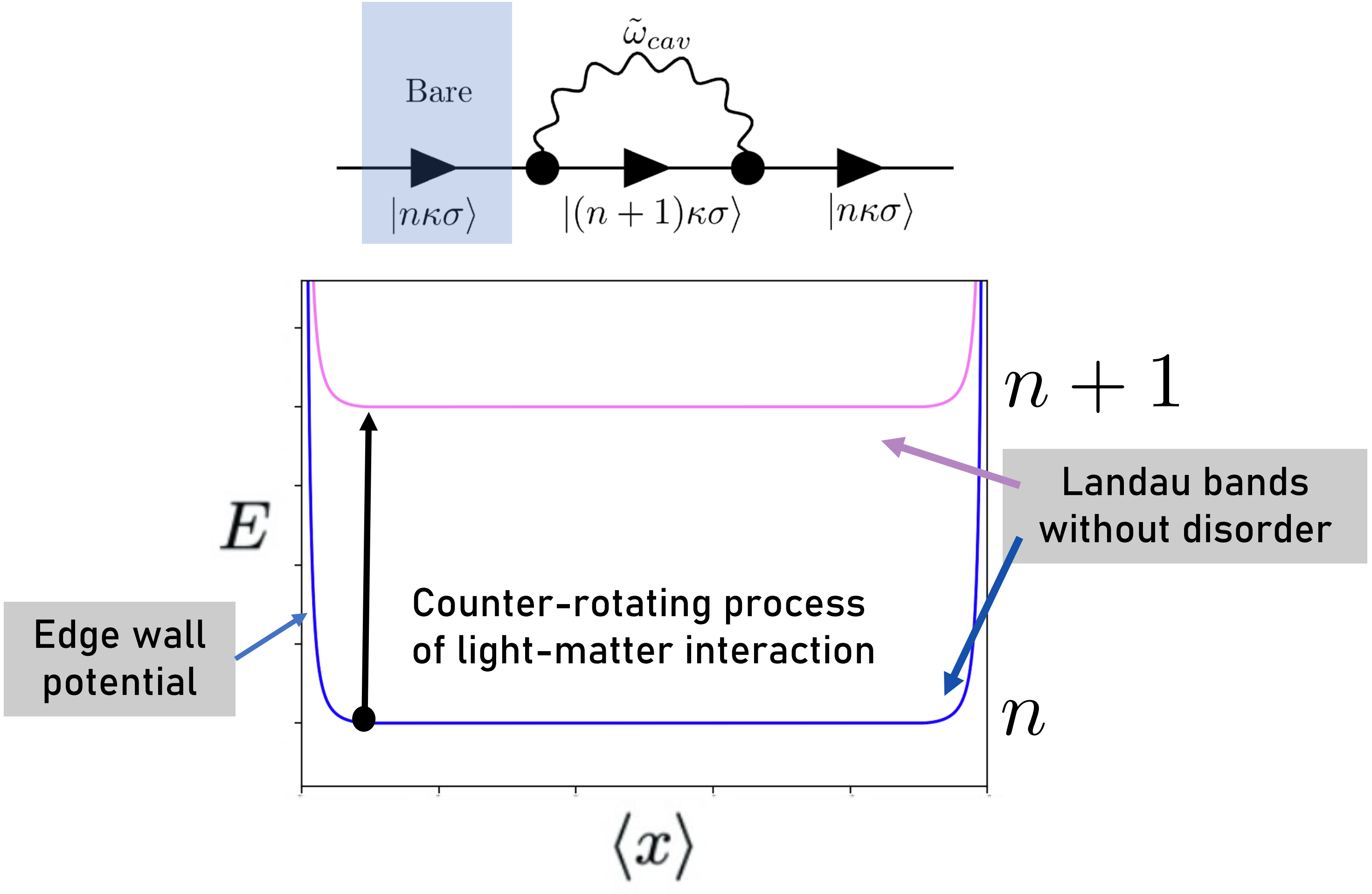

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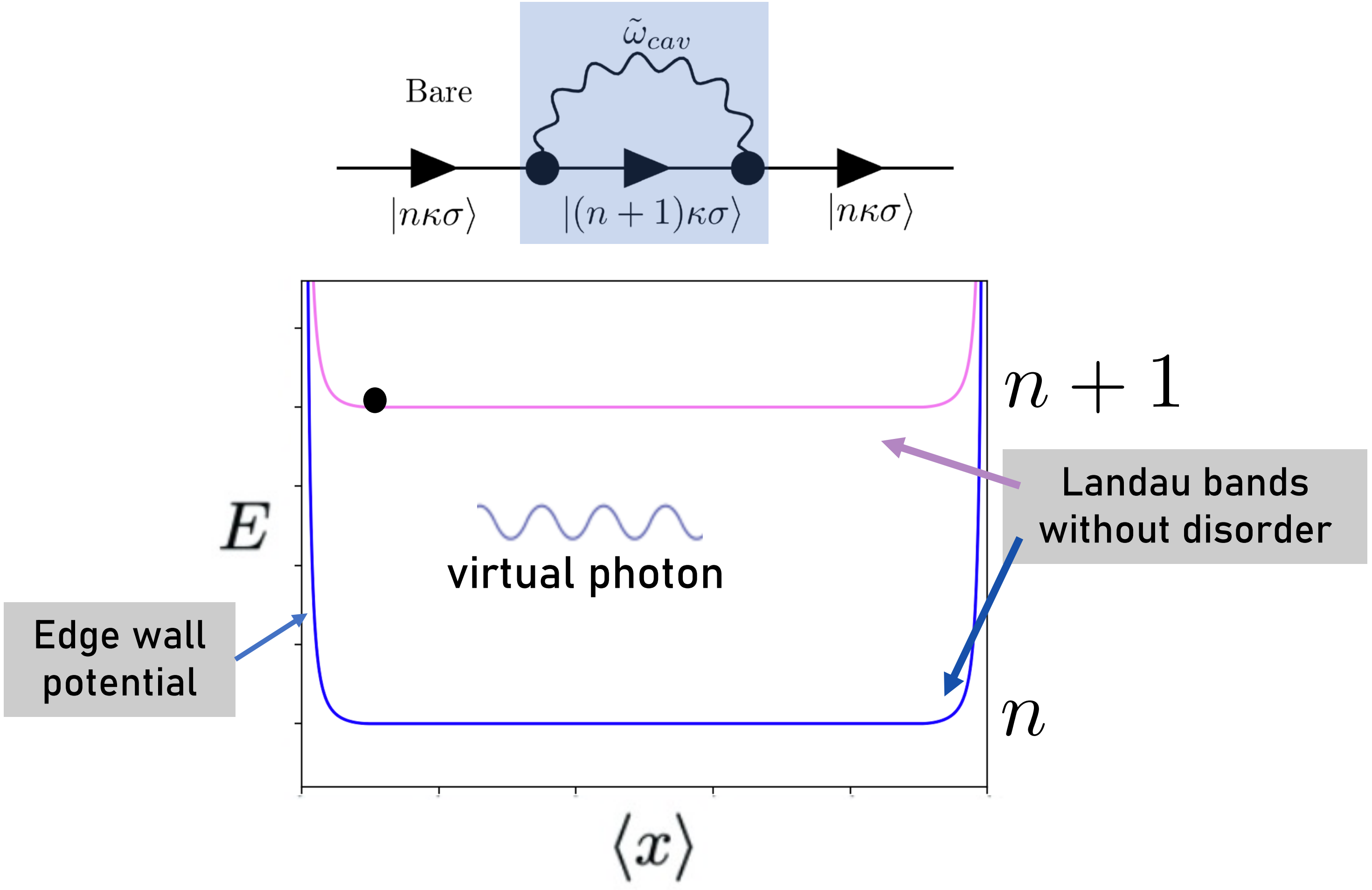

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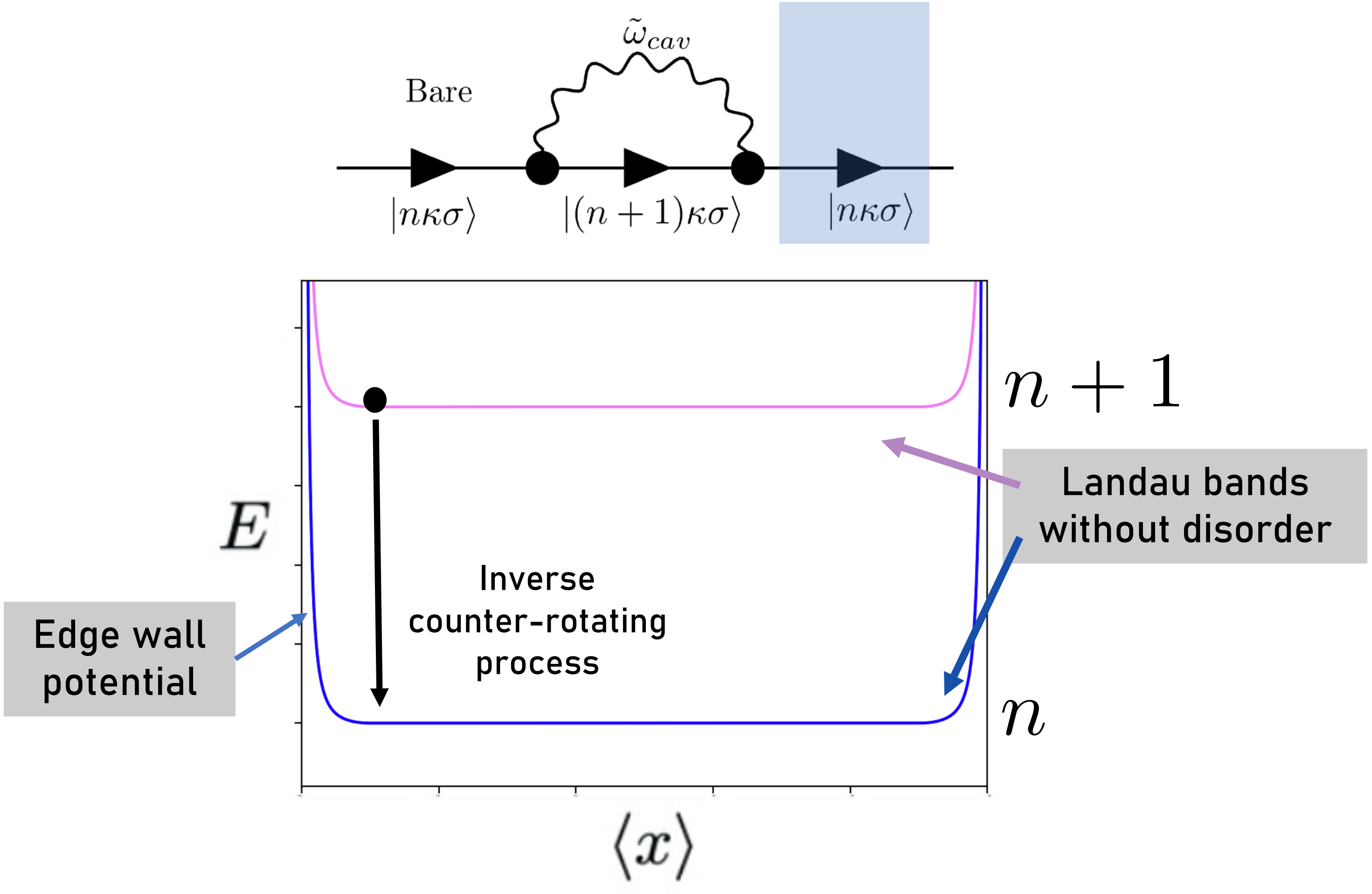

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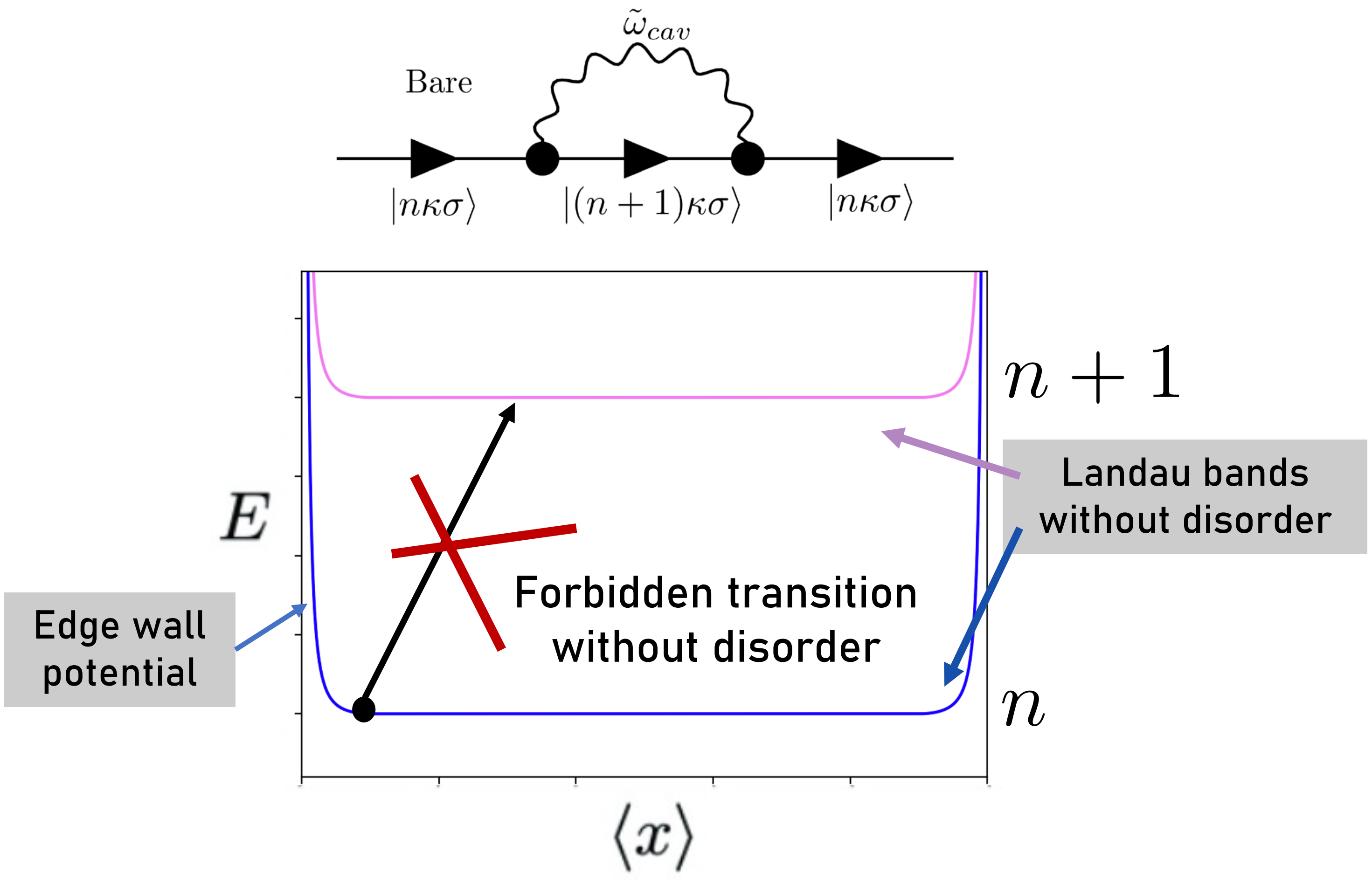

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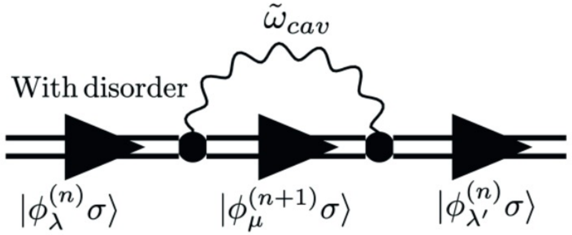

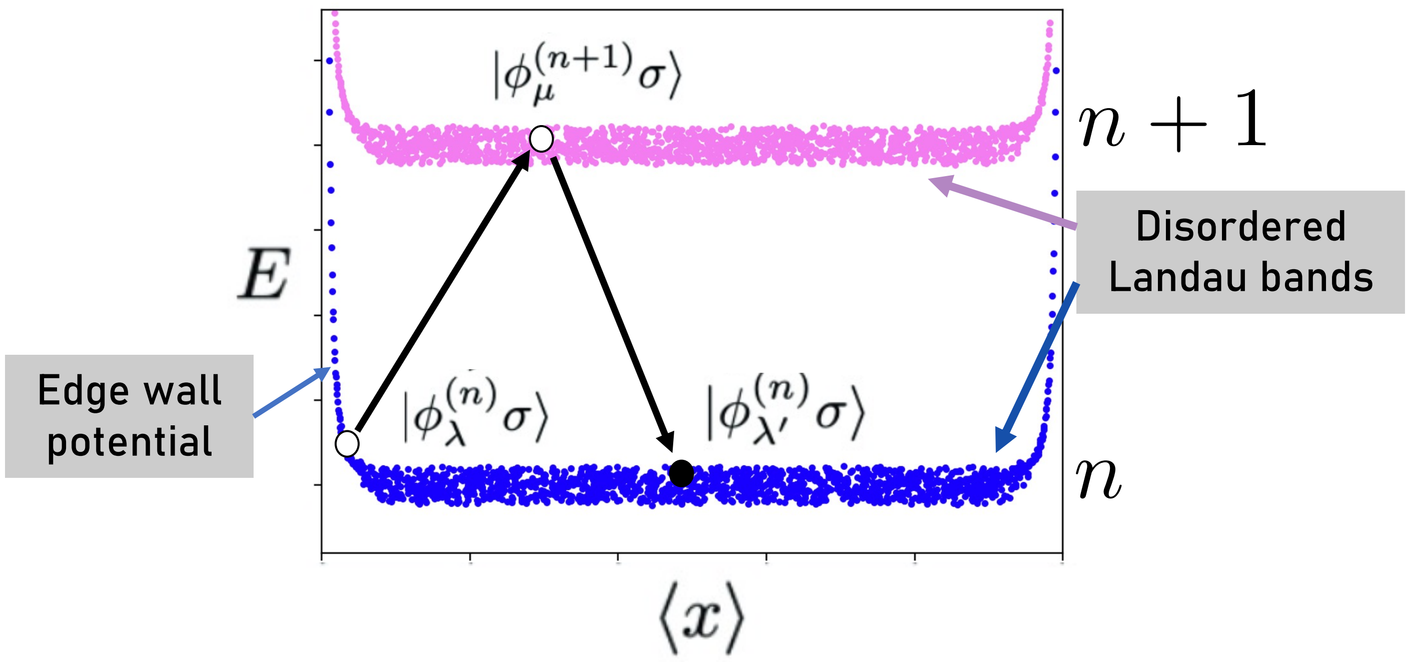

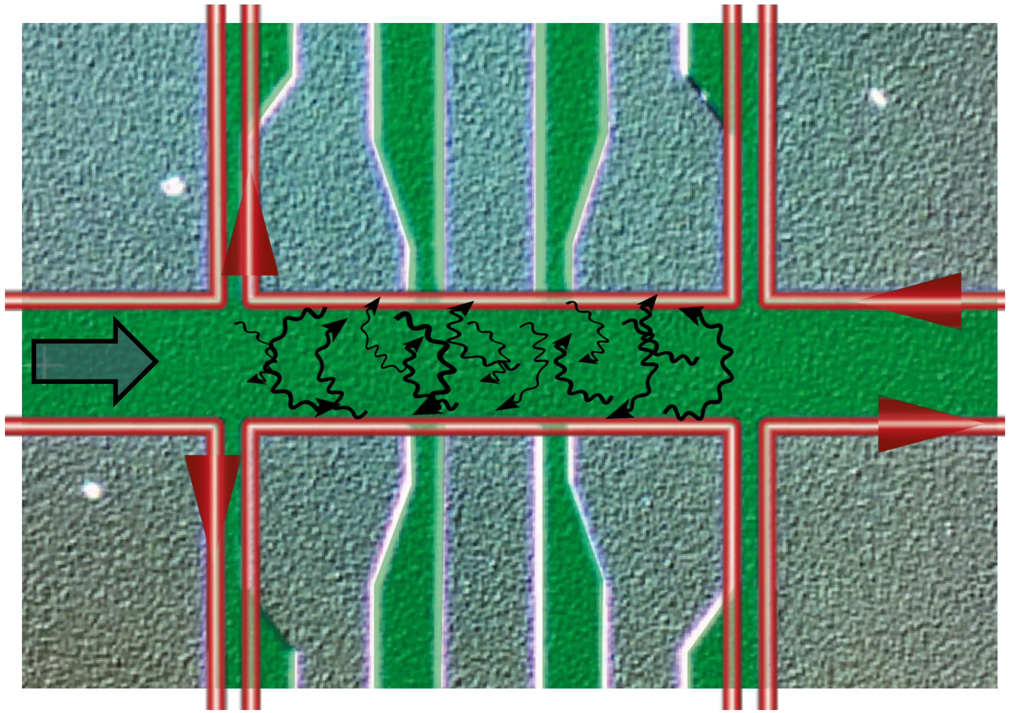

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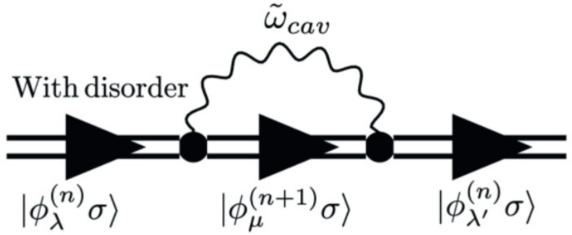

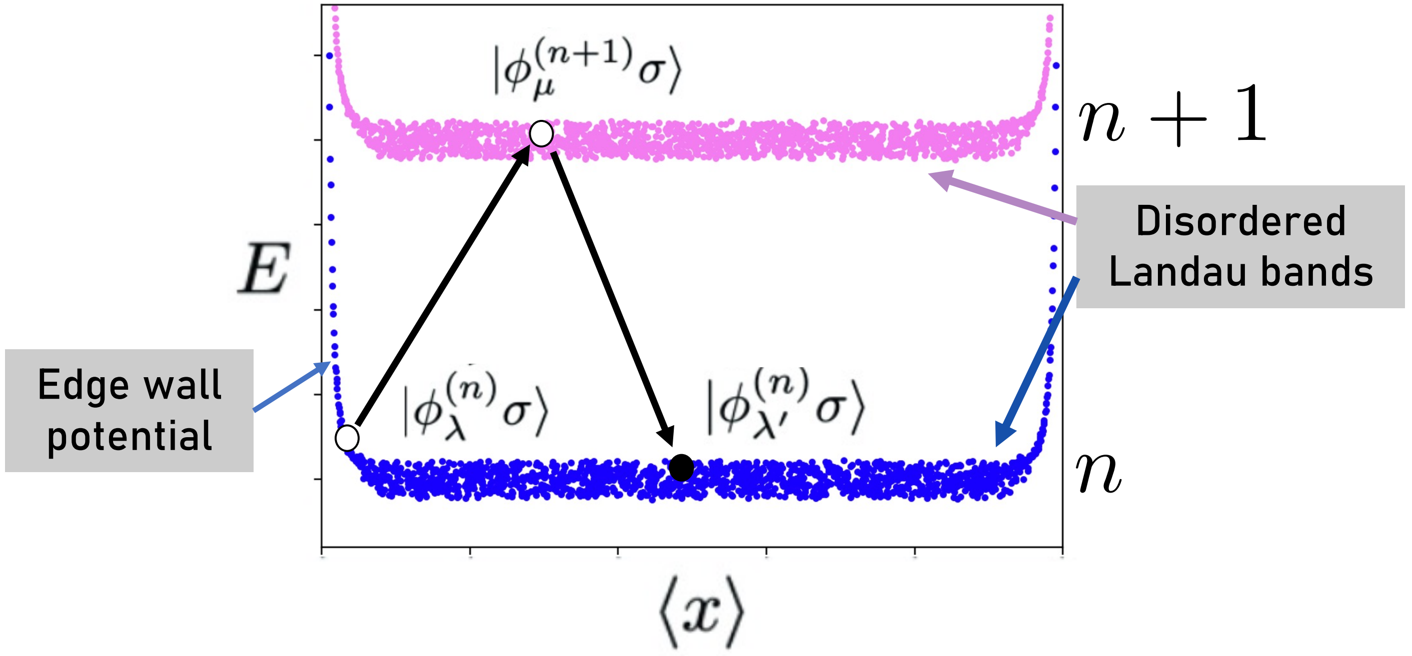

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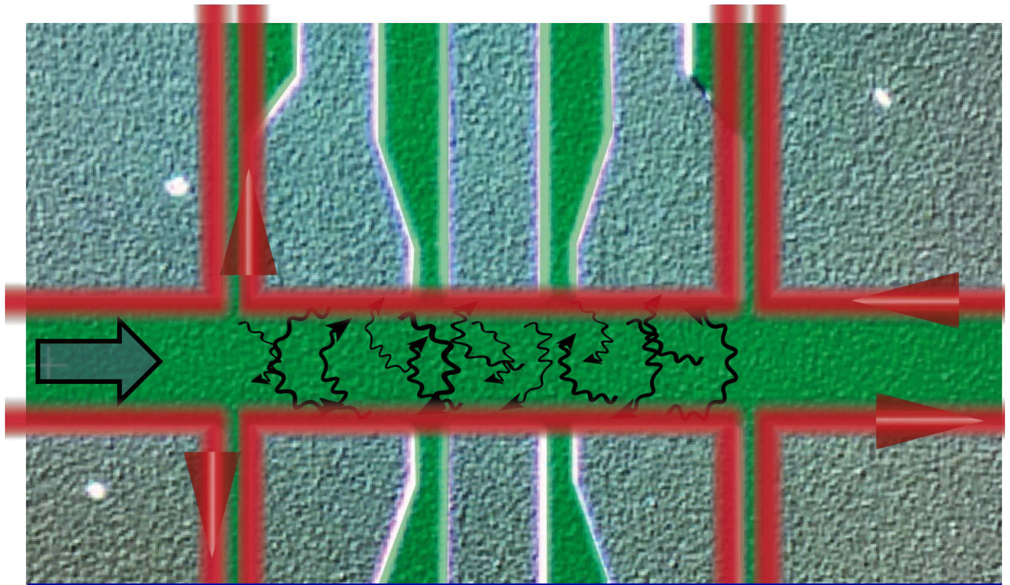
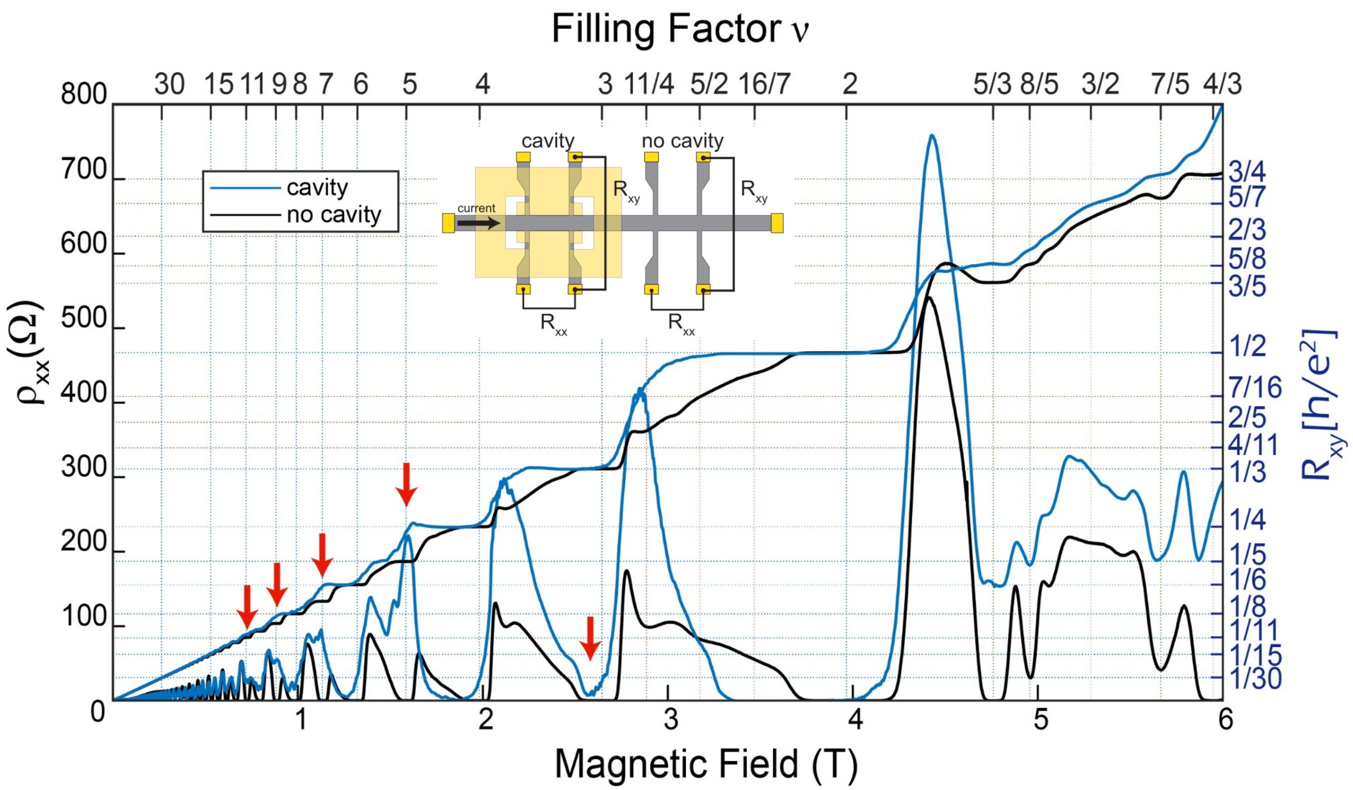
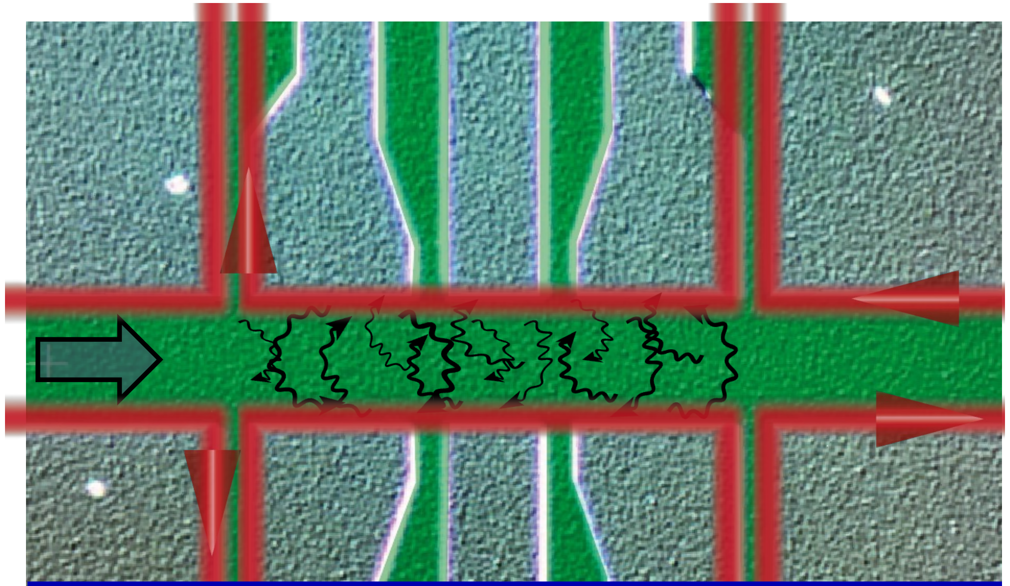


As electrons can scatter from the edge into the bulk and vise versa the topologal protection of the edge channels is broken

Cavity mediated electron hopping



Zero resistance states are lifted in especially visible in the odd plateaux



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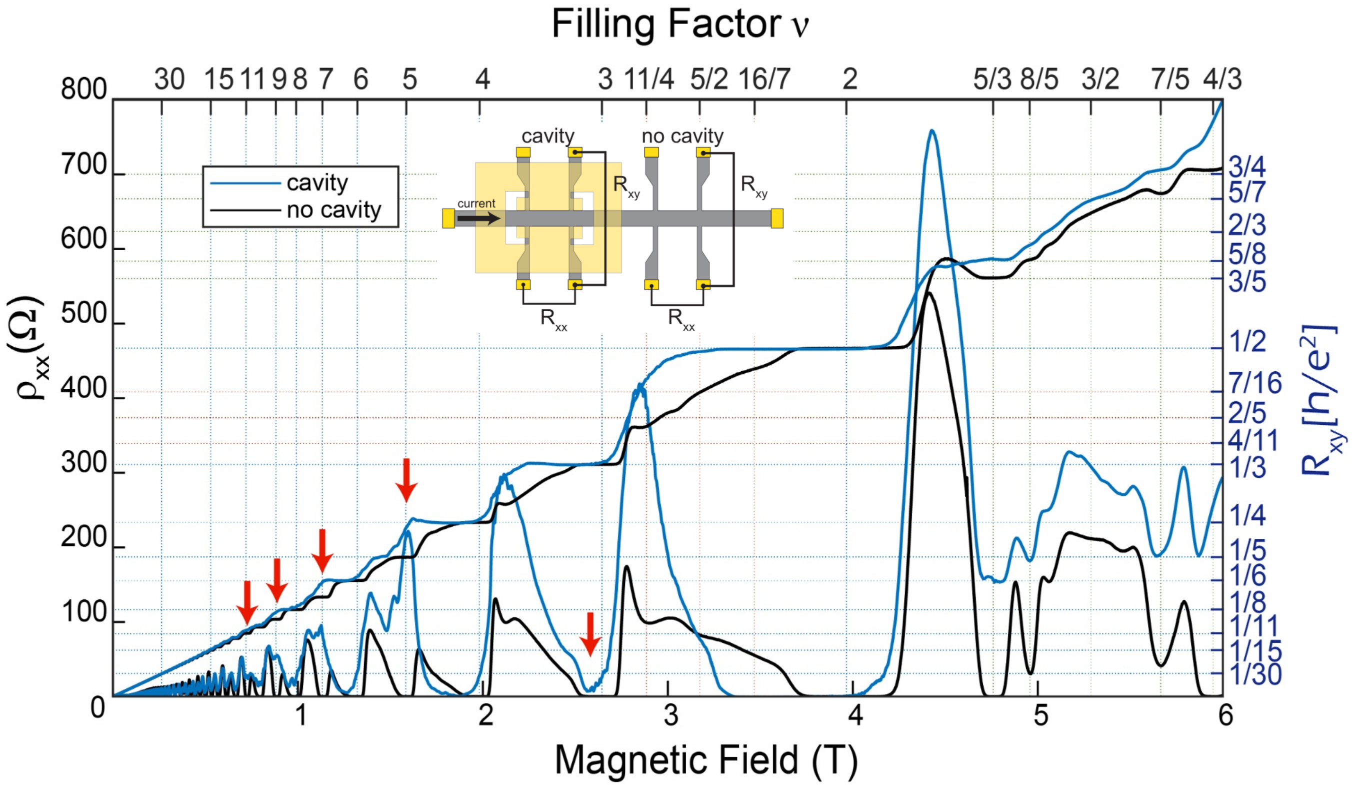
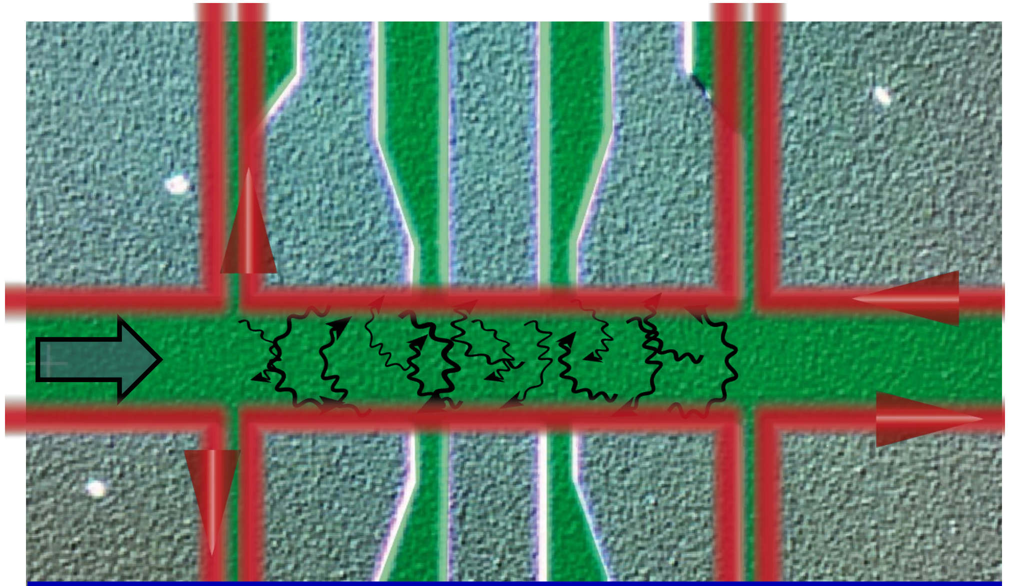
Cavity mediated electron hopping

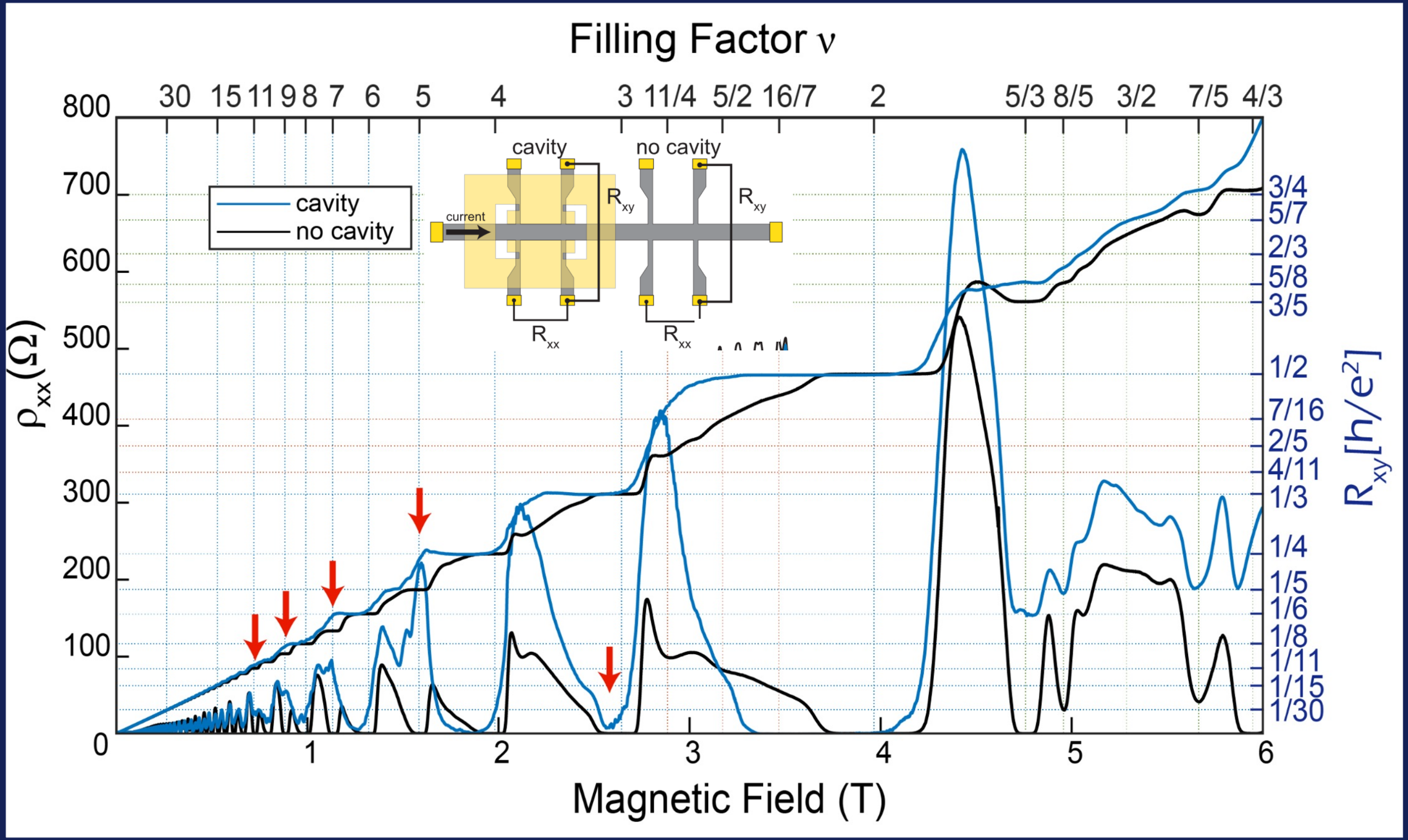


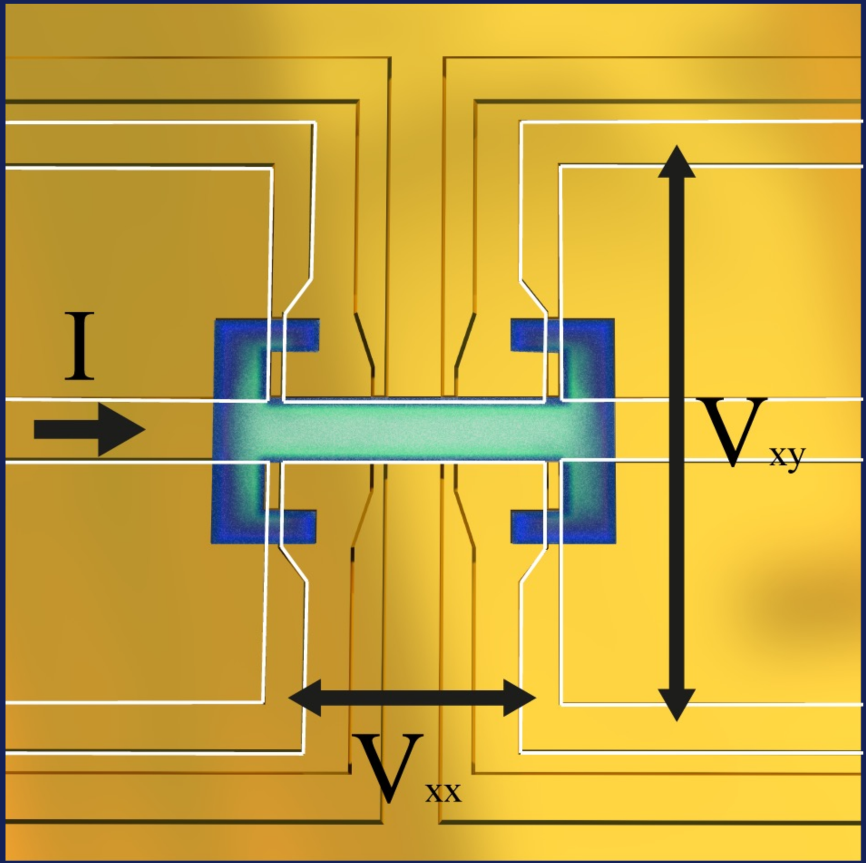


As electrons can scatter from the edge into the bulk and vise versa the topolog al protection of the edge channels is broken

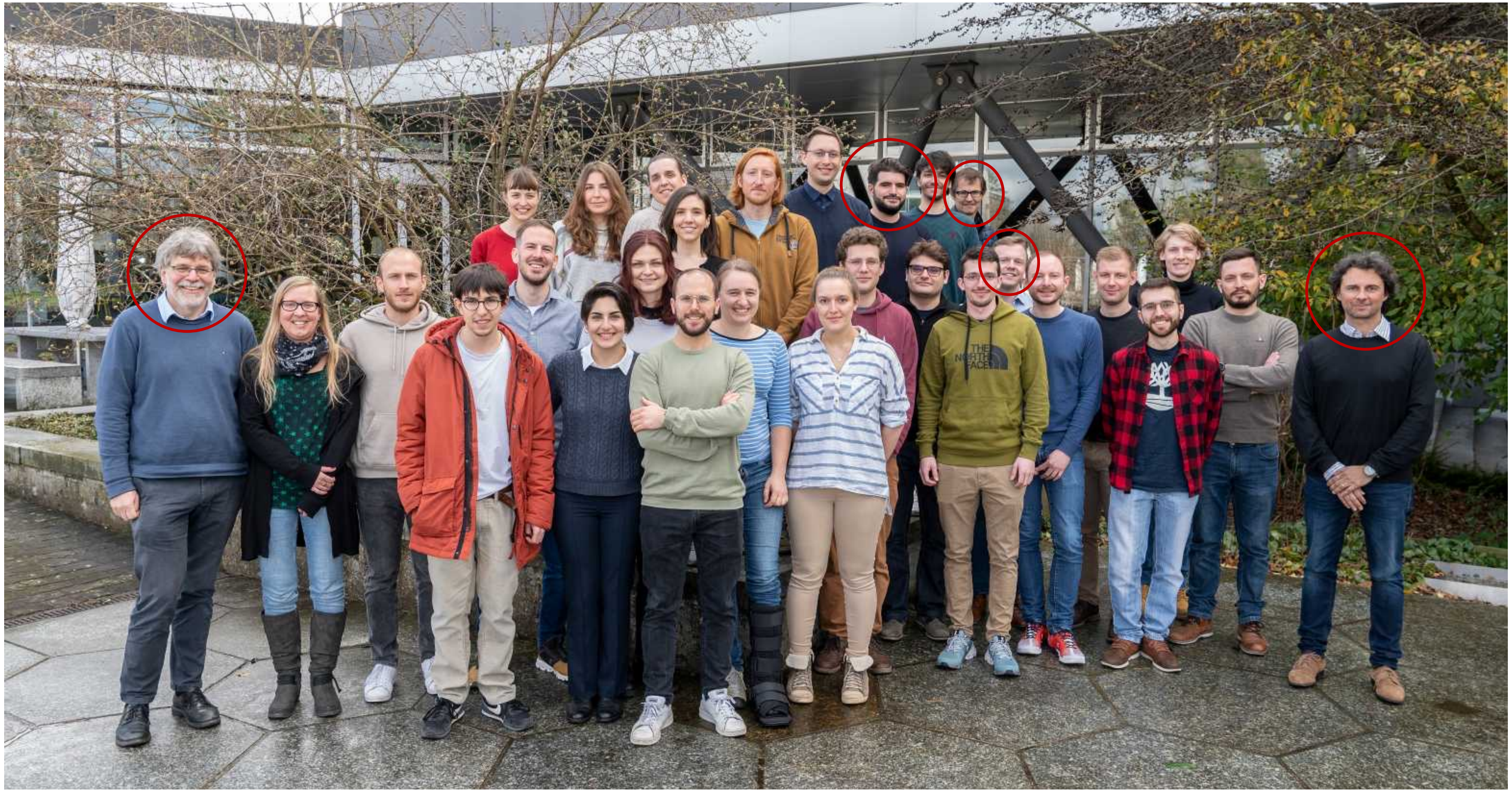
For the virtual process that promotes the electron to the n+1 Landau band, there is a corresponding energy penalty related to the energygap, which the electron crosses and the position of the Fermi energy.
As a rule of thumb, spin-splitted states should indeed show a larger effect since the Zeemannsplitting is smaller than the Landau Gap.

Demonstration of cavitronics





Thank you for your attention!



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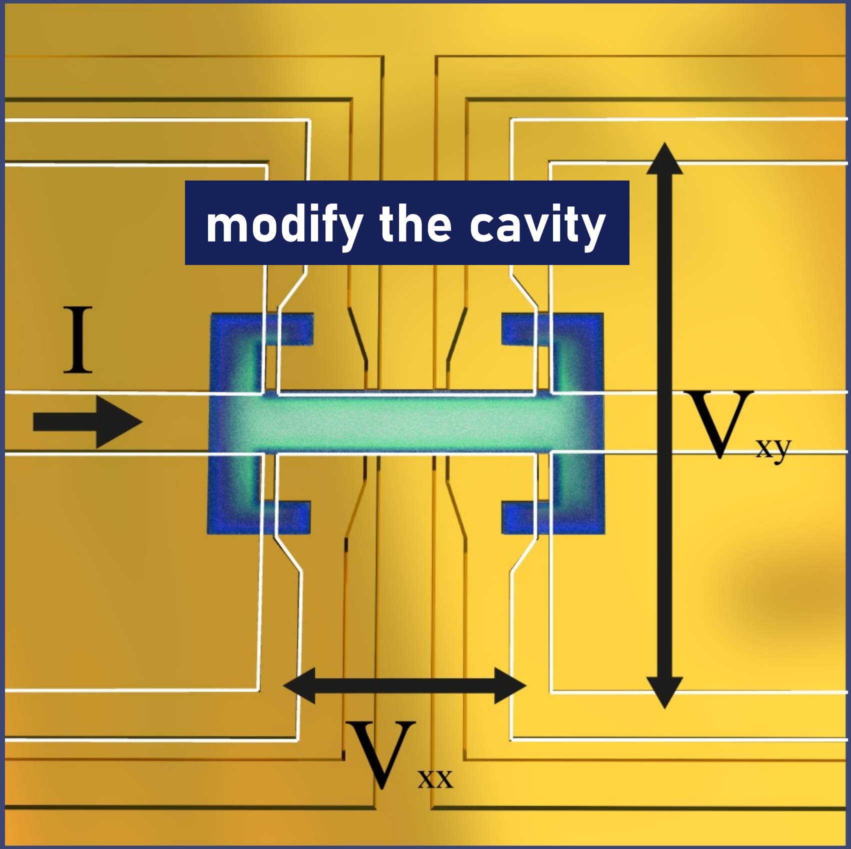
C. Reichl, W. Wegscheider groups (ETHZ)
C. Ciuti (Université Paris Diderot, France)

addons

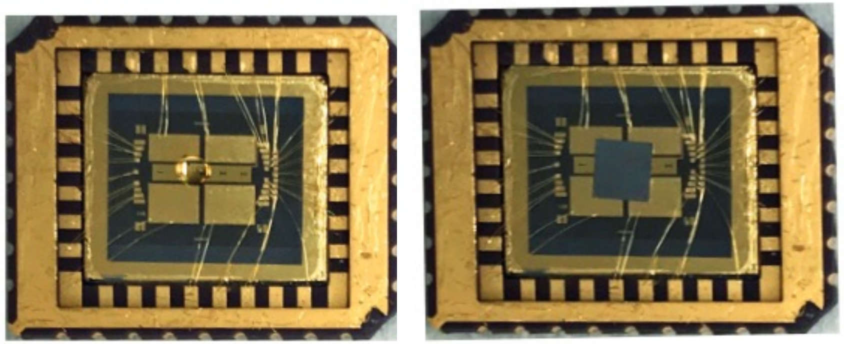
Experimental results

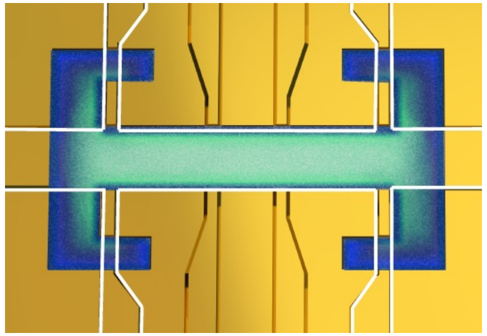
How do we make sure this effect can be attributed to the vacuum field fluctuations inside the cavity?



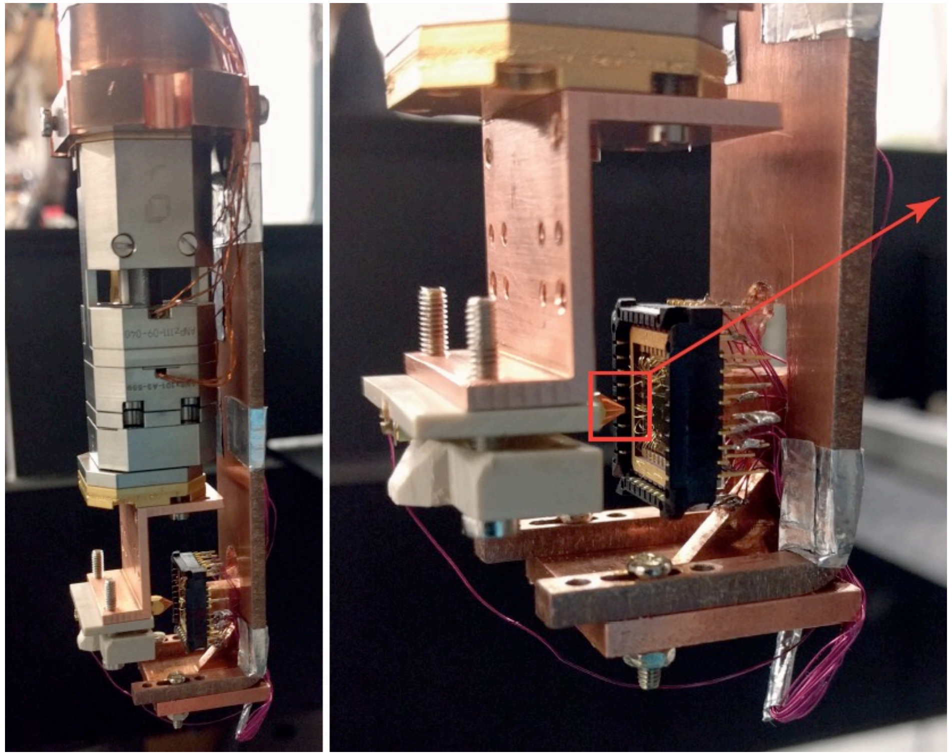
Tip experiment

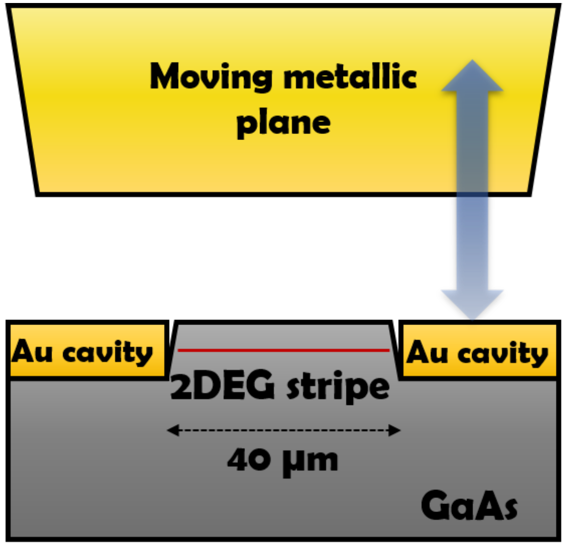
The metallic tip dynamically modifys the vacuum field distribution inside the cavity



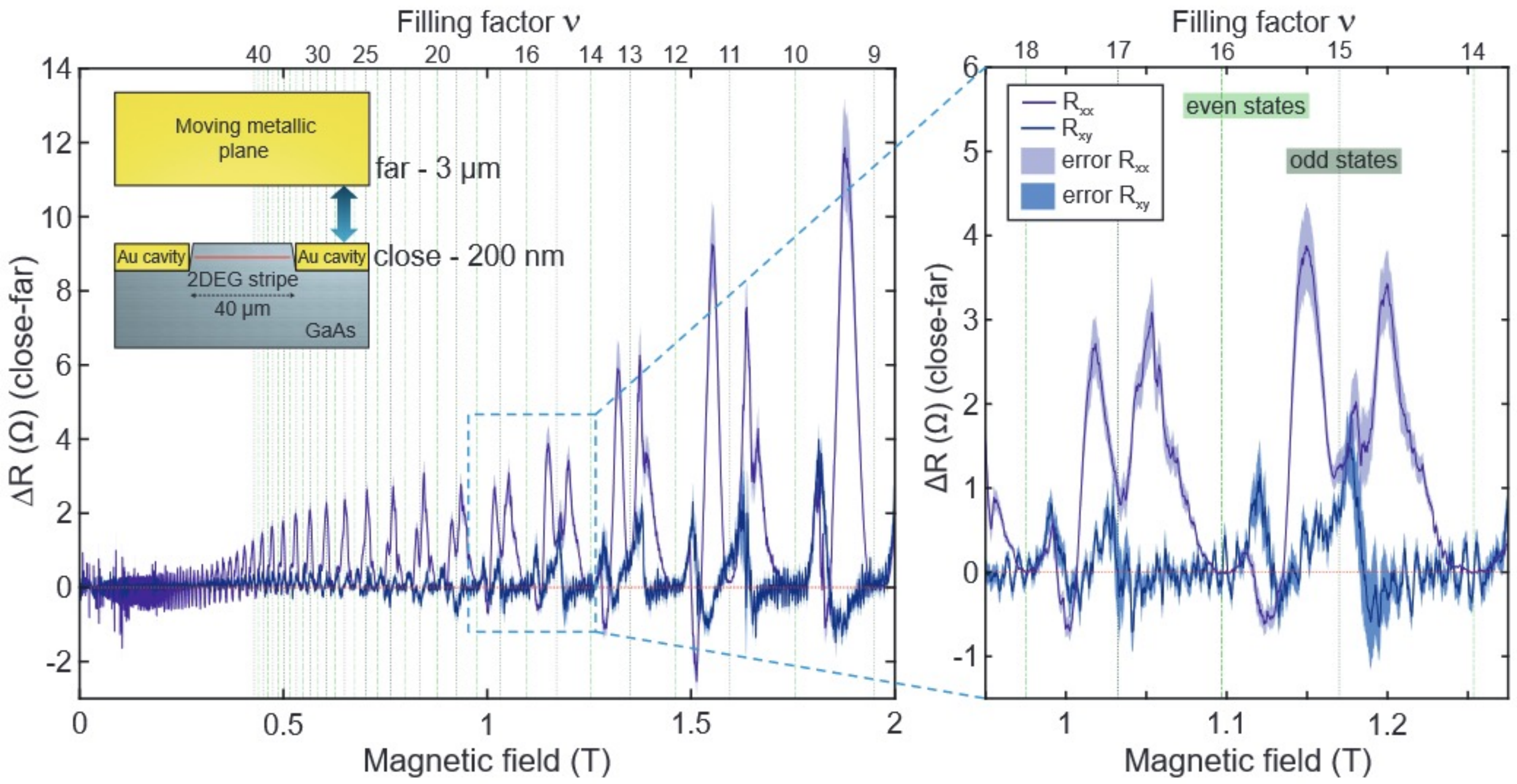


the average field in the capacitive gap decreases



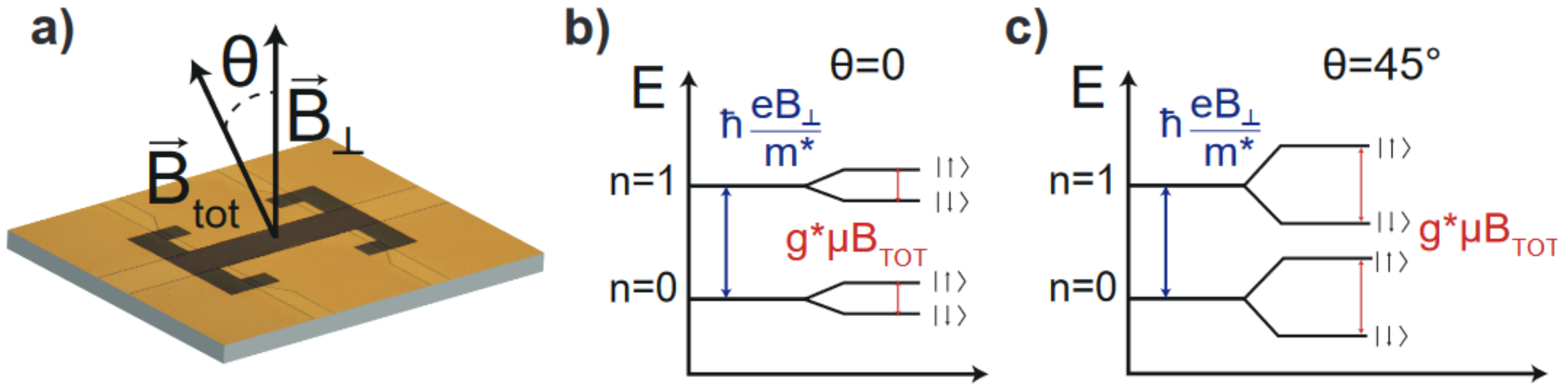


Modulating the cavity changes the magnitude of the effect



How does the effect depend on the energy levels?

Modulating the Zeemannsplitting as a function of tilting angle



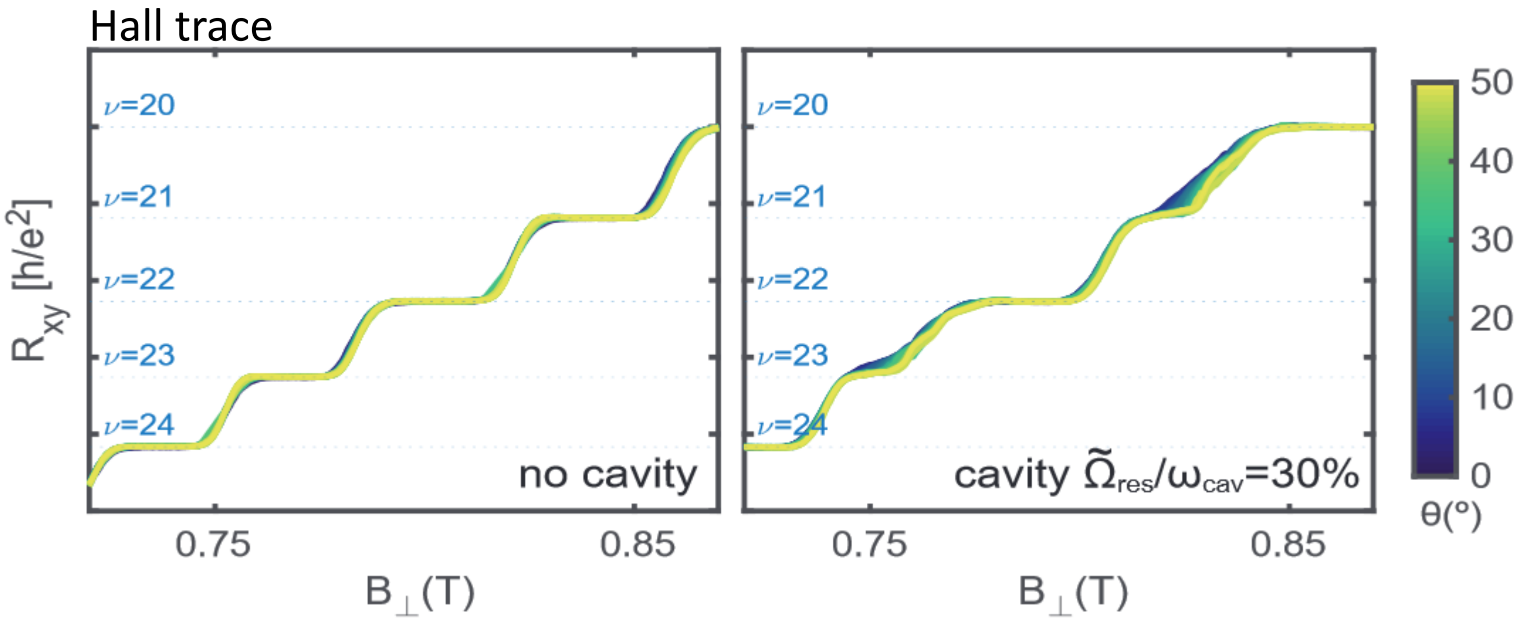
increasing the ratio
Zeemannsplitting / Landausplitting

Increasing the Zeemannsplitting would result in smaller effect as one decreases the processes of cavity mediated electron hopping

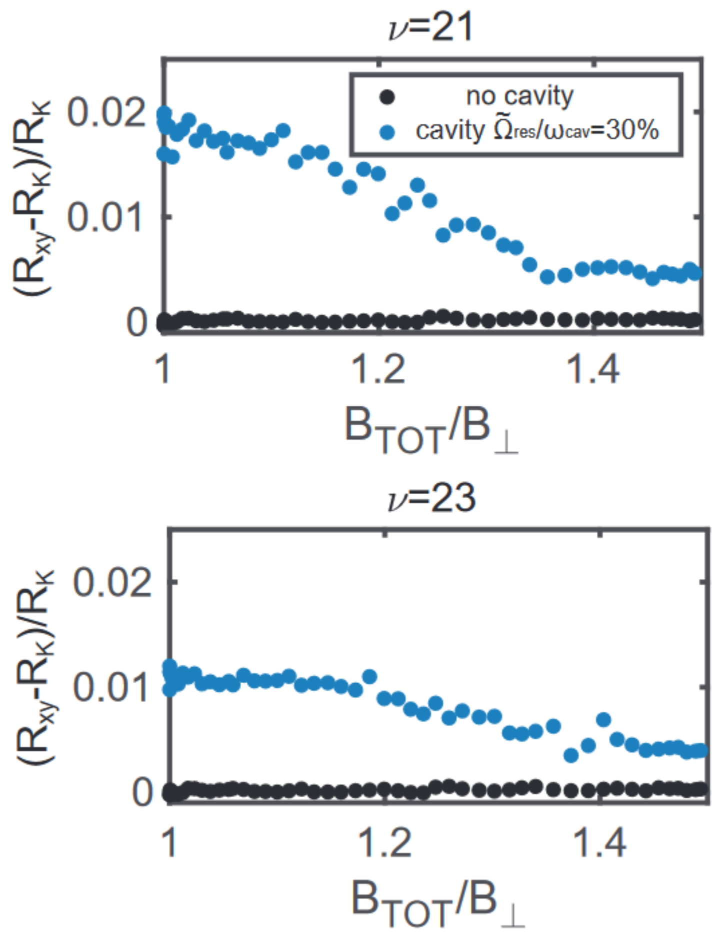
F. Appugliese, J.Enkner et al, (2022). *Science*, *375*(6584), 1030-1034.

How does the effect depend on the energy levels?

Variation of Rxy in the cavity embedded Hall bar as a function of angle



Deviation from quantization



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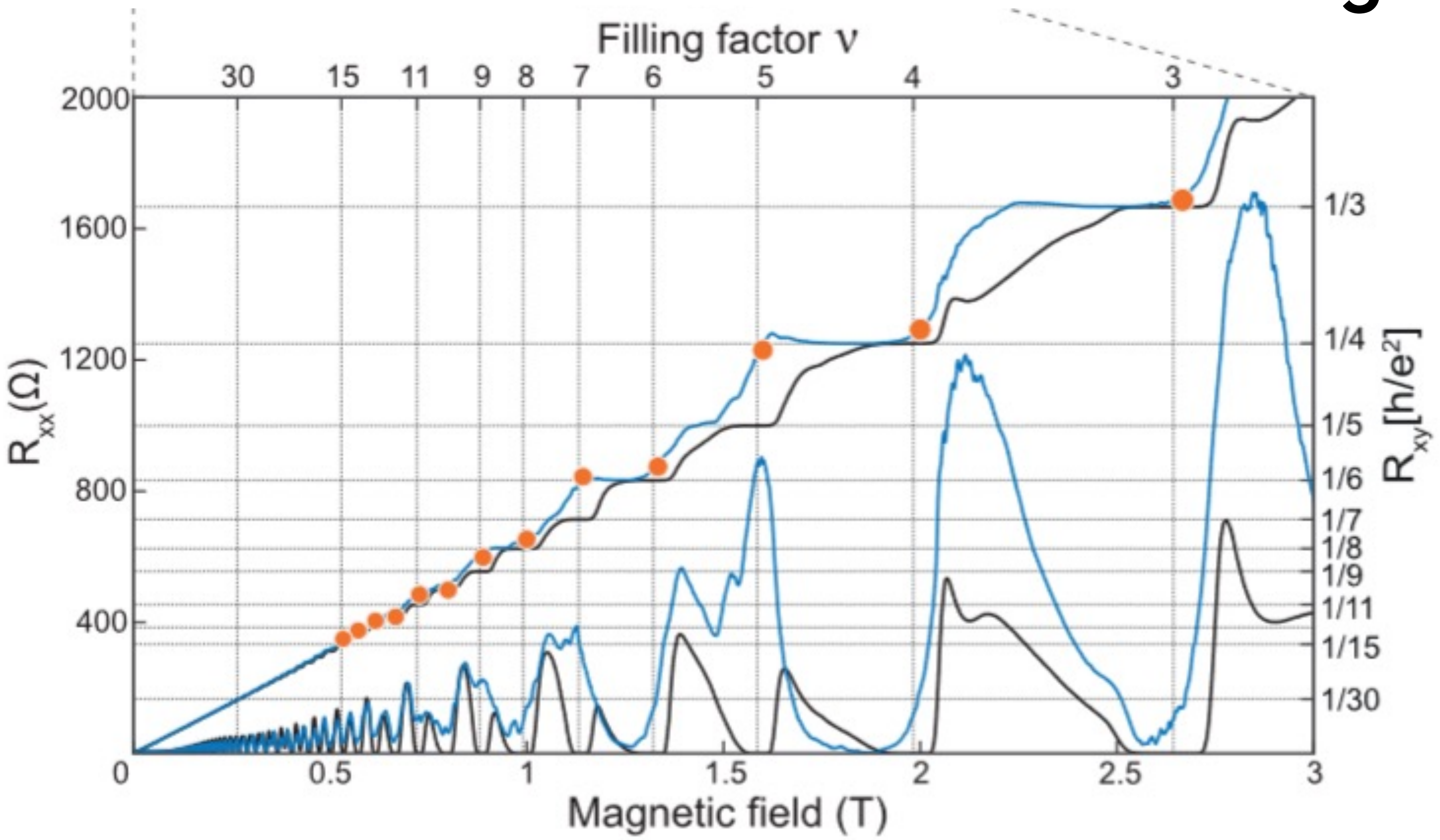
Network model for quantum hall effect- vacuum field scattering



This model can predict the values of the transverse resistance with very high accuracy

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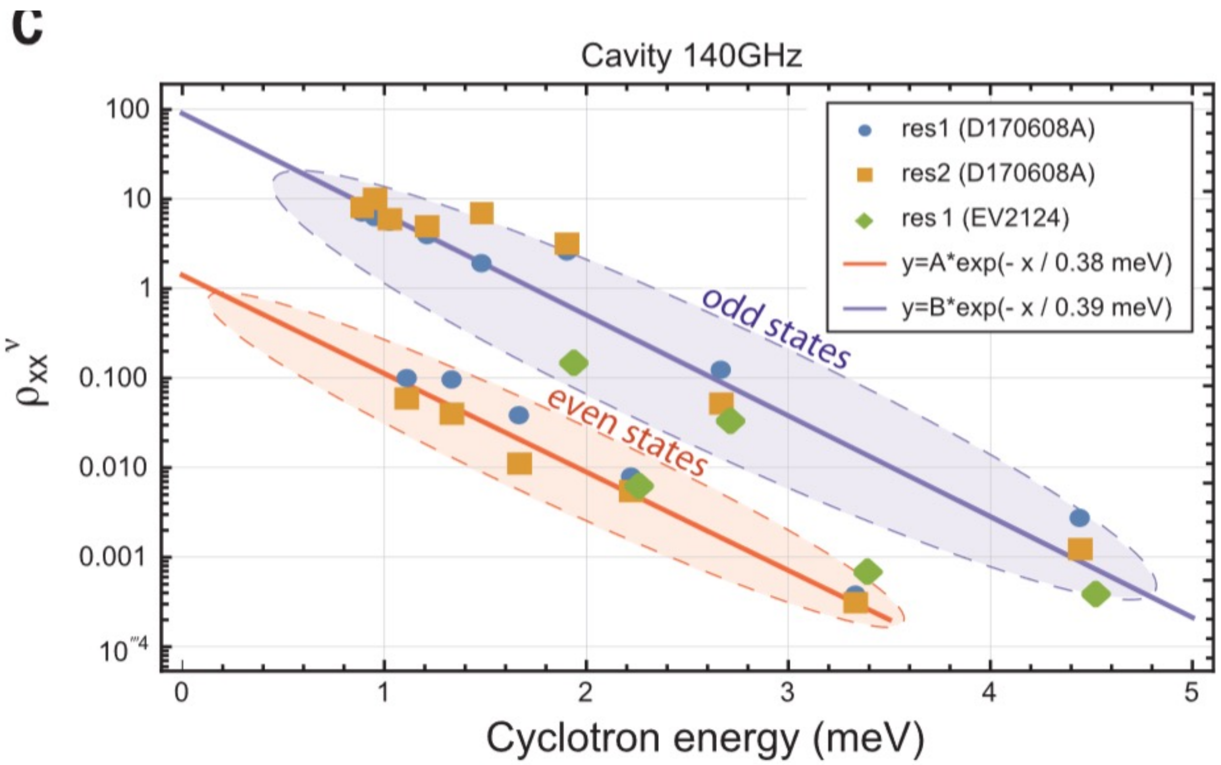
Interpretation of rhoxx



Since ρ^{ν}_{xx} is a resistivity, it is related to the scattering rate of the edge states

$$\tilde{\Gamma}^{(n)}_{\lambda,\lambda'} \simeq \sum_{\mu} \frac{\hbar^2\, \tilde{g}^{(n,n+1)}_{\lambda,\mu}\, \tilde{g}^{(n,n+1)\star}_{\lambda',\mu}}{\epsilon_{n,\lambda} - \epsilon_{n+1,\mu} - \hbar\tilde{\omega}_{\mathrm{cav}}}$$

It follows an exponential dependence on the cycltron energy and it has the same slope for odd and even states.

The energy scale of the exponential decay is around 0.4 meV

The Rabi frequency of the coupled system is also 0.4 meV

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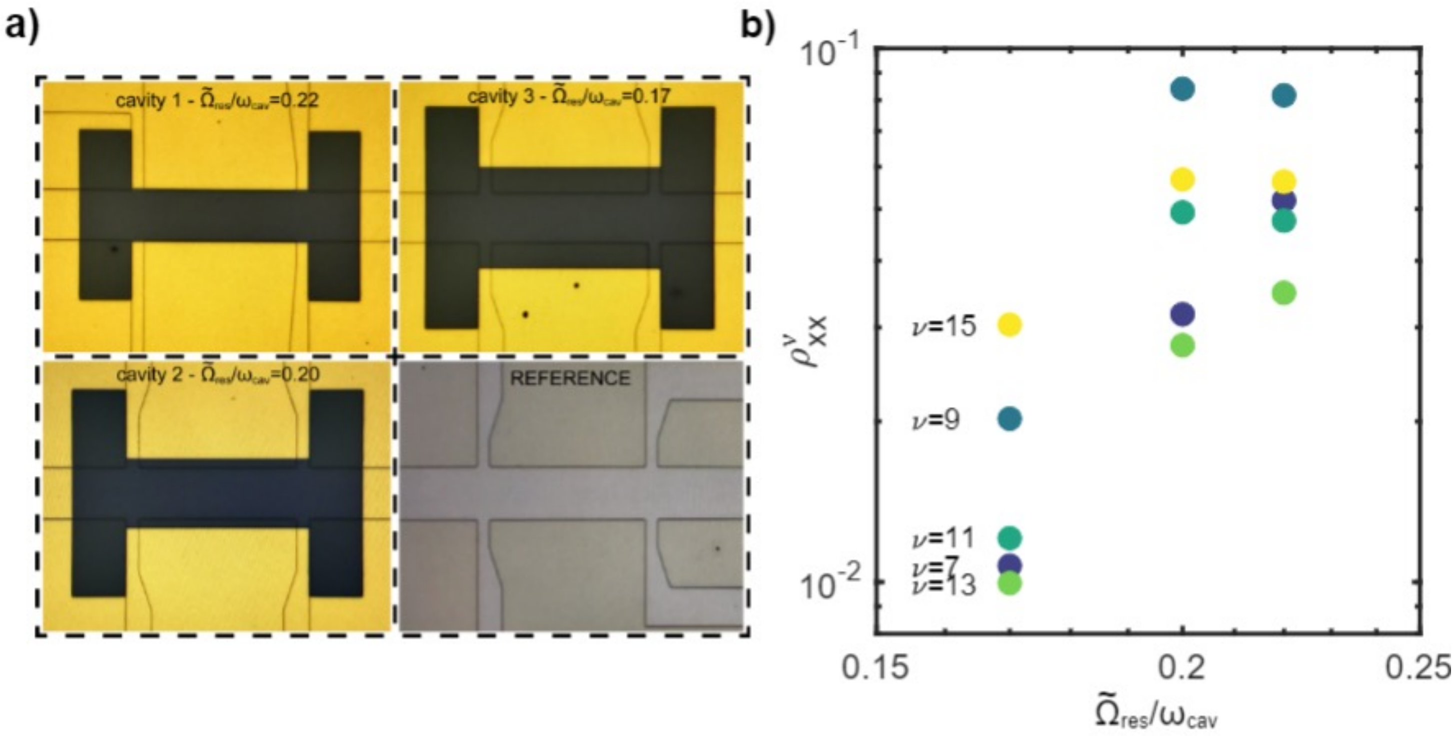
Different confirmations

We verified the dependence of the scattering rate from the different parameters with different experiments

$$\Gamma^{(n)}_{\lambda,\lambda'} = \sum_{\lambda''} \frac{\tilde{g}^{(n,n+1)}_{\lambda,\lambda''} \tilde{g}^{(n,n+1)*}_{\lambda',\lambda''}}{\epsilon_{n,\lambda} - \epsilon_{n+1,\lambda''} - \hbar\tilde{\omega}_{\text{cav}}}$$

We designed different resonators with different coupling strenghts and showed that ρ^{ν}_{xx} increases monotonically with the coupling strenght



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