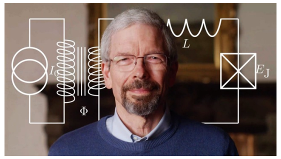
Quantum electron transport controlled by cavity vacuum fields

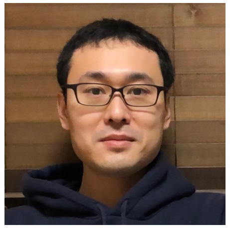
Cristiano Ciuti
Université Paris Cité, CNRS,
Laboratoire Matériaux et Phénomènes Quantiques, France

@Varenna
QFLM2022

Connection to previous lectures and keywords



Steve Girvin: circuits and QED vacuum fluctuations



Tomoki Ozawa: edge states and topology

Nicola Regnault: 2D electron systems, Landau levels, topology

Atac Imamoglu: light-matter interaction in 2D electron gases

References of work presented today

Experiments and theory:

F. Appugliese, J. Enkner, G. L. Paravicini-Bagliani, M. Beck, C. Reichl, W. Wegscheider, G. Scalari, CC, J. Faist,
Breakdown of topological protection by cavity vacuum fields in the integer quantum Hall effect,
Science 375, 1030 (2022)

Theory:

CC, *Cavity-mediated electron hopping in disordered quantum Hall systems*,
PRB 104, 155307 (2021)

G. Arwas and CC, *Quantum electron transport controlled by cavity vacuum fields*,
arXiv:2206.13432

Acknowledgements

ETH zürich

Felice Appugliese

Josephine Enkner

Giacomo Scalari

Jérôme Faist

Université Paris Cité

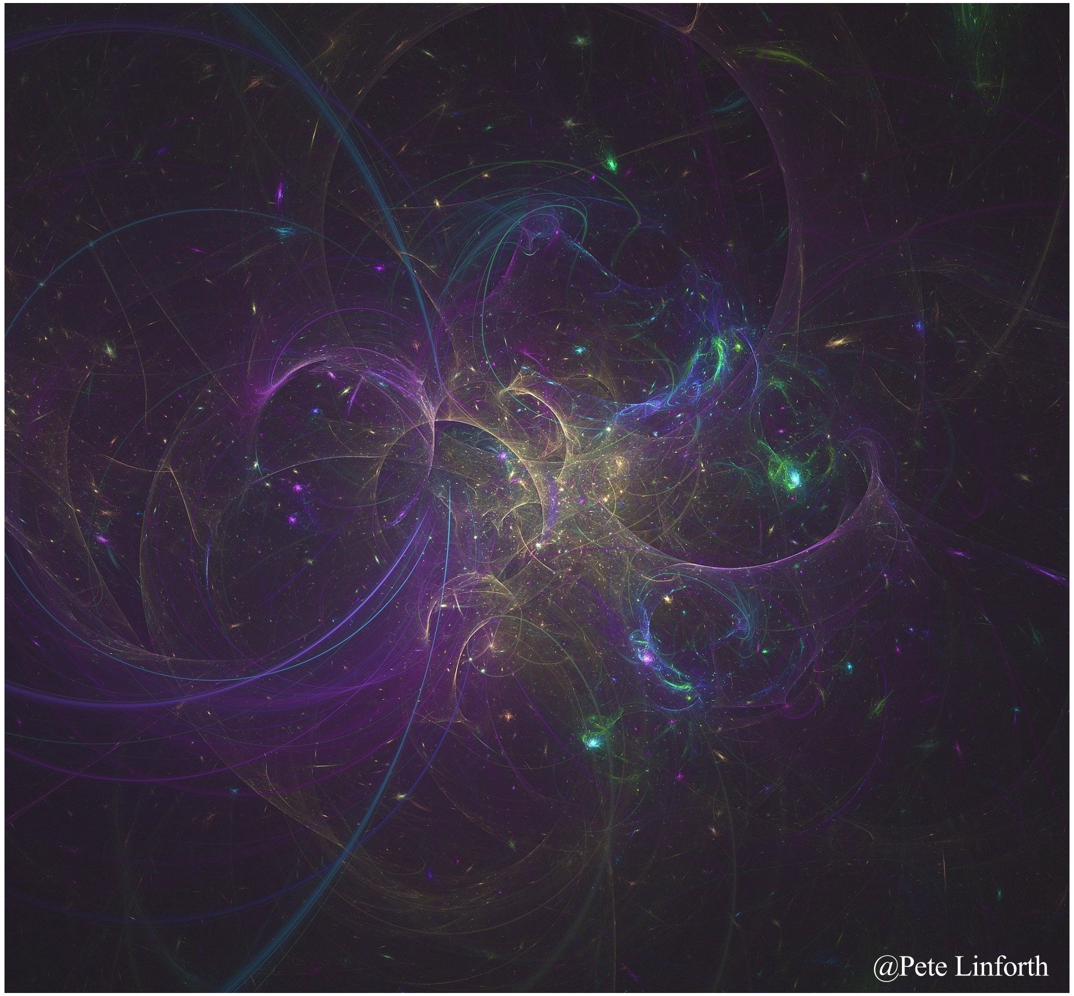
MPQ

Geva Arwas

Introduction

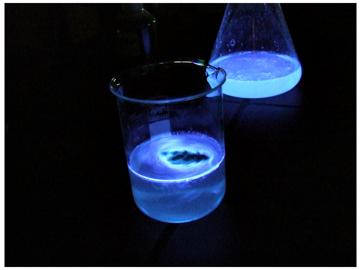
Quantum vacuum

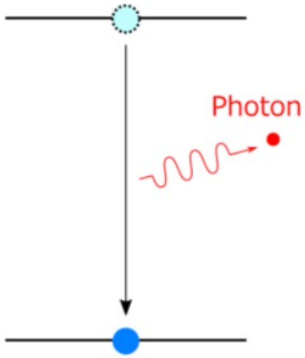
Quantum vacuum is not empty, but filled with fluctuating fields



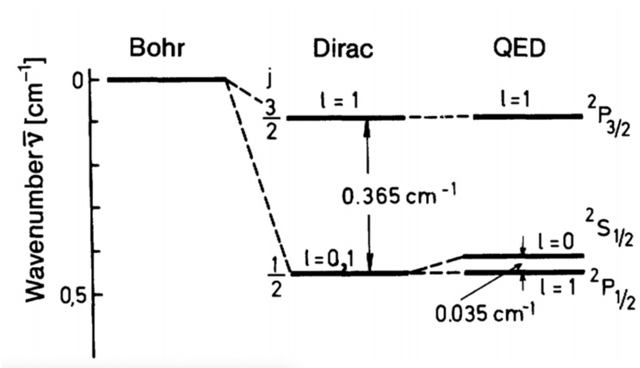
Famous effects due to electromagnetic quantum vacuum

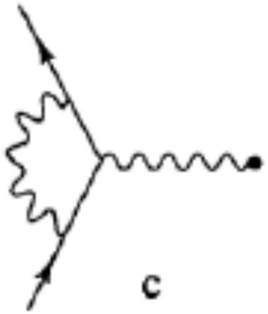
Spontaneous photon emission (luminescence)



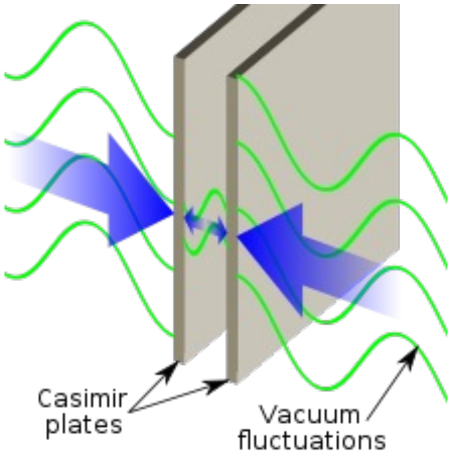


Lamb shift of the hydrogen atom

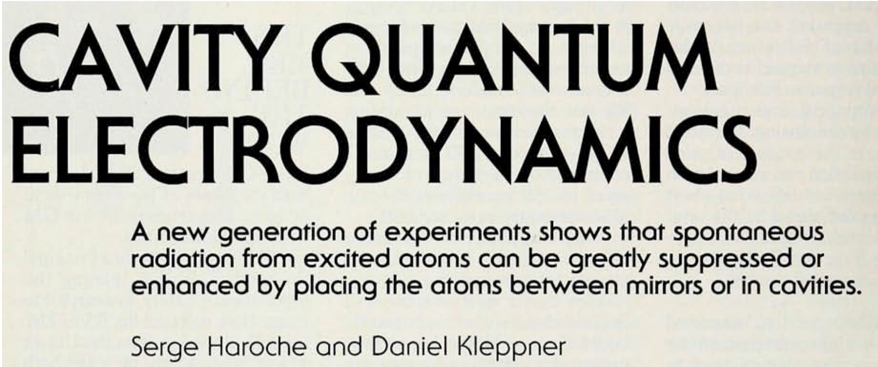




Casimir forces



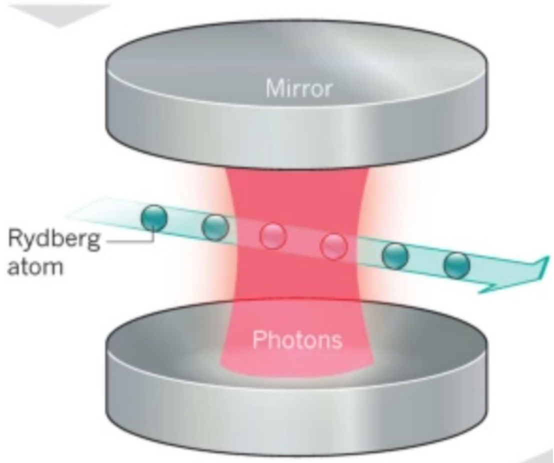
Enhancing vacuum effects by spatial confinement: cavity QED



CAVITY QUANTUM ELECTRODYNAMICS

A new generation of experiments shows that spontaneous radiation from excited atoms can be greatly suppressed or enhanced by placing the atoms between mirrors or in cavities.

Serge Haroche and Daniel Kleppner



$$E_0 \propto \frac{1}{\sqrt{V}}$$

Vacuum electric field fluctuation

Mode volume

Vacuum field
increases with decreasing mode volume

Emerging topic: manipulation of matter by vacuum fields

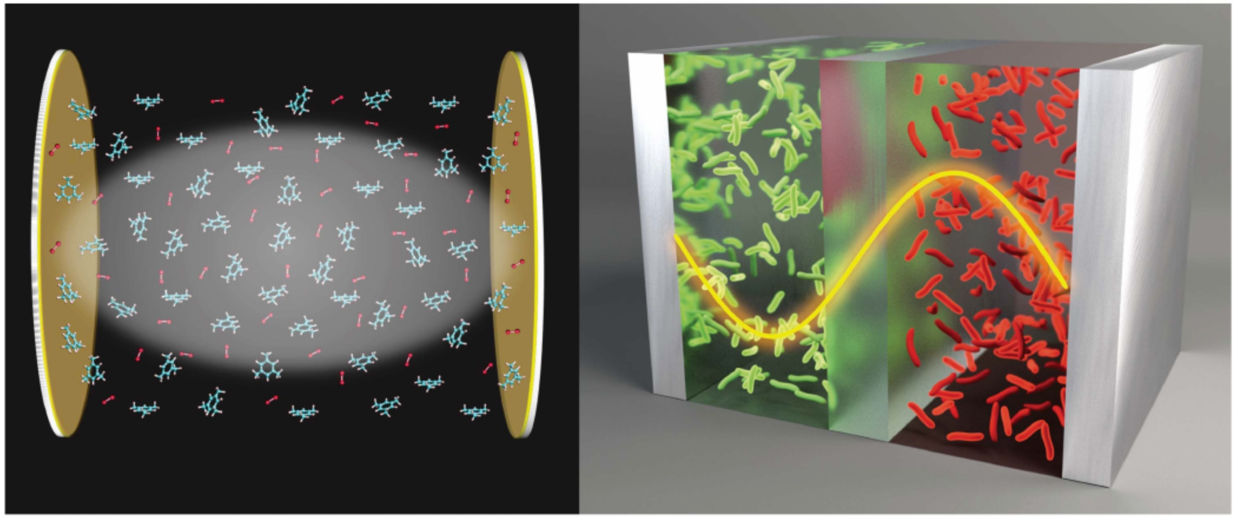
RESEARCH

REVIEW SUMMARY

LIGHT-MATTER COUPLING

Manipulating matter by strong coupling to vacuum fields

Francisco J. Garcia-Vidal*, Cristiano Ciuti*, Thomas W. Ebbesen*



Garcia-Vidal, C. Ciuti, Ebbesen, Science 373, 178 (2021)

Modification of:

- Condensed matter phases
- Transport properties
- Chemical reactions
- ….

Other recent reviews

Applied Physics Reviews REVIEW scitation.org/journal/are

Cavity quantum materials

Cite as: Appl. Phys. Rev. **9**, 011312 (2022); doi: 10.1063/5.0083825
Submitted: 30 December 2021 · Accepted: 31 January 2022 ·
Published Online: 25 February 2022

View Online Export Citation CrossMark

F. Schlawin,[1,2] D. M. Kennes,[1,3] and M. A. Sentef[1,a)]

Perspective

Strongly correlated electron–photon systems

https://doi.org/10.1038/s41586-022-04726-w

Received: 2 December 2020

Accepted: 2 December 2021

Published online: 25 May 2022

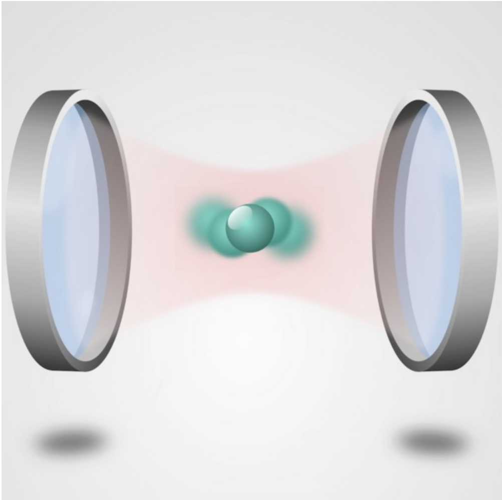
Check for updates

Jacqueline Bloch[1], Andrea Cavalleri[2], Victor Galitski[3]✉, Mohammad Hafezi[4] & Angel Rubio[2,5]

An important goal of modern condensed-matter physics involves the search for states of matter with emergent properties and desirable functionalities. Although the tools for material design remain relatively limited, notable advances have been recently achieved by controlling interactions at heterointerfaces, precise alignment of low-dimensional materials and the use of extreme pressures. Here we highlight a paradigm based on controlling light–matter interactions, which provides a way to manipulate and synthesize strongly correlated quantum matter. We consider the case in which both electron–electron and electron–photon interactions are strong and give rise to a variety of phenomena. Photon-mediated superconductivity, cavity fractional quantum Hall physics and optically driven topological phenomena in low dimensions are among the frontiers discussed in this Perspective, which highlights a field that we term here 'strongly correlated electron–photon science'.

Cavity-control of quantum Hall systems

Cavity Quantum Electrodynamics
CQED



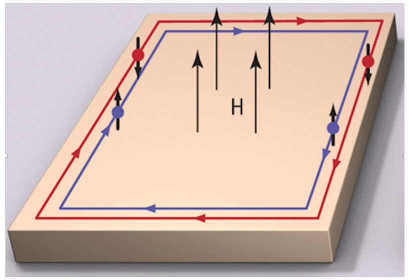
Lamb shift, Casimir,…
Enhanced light matter-interaction
Vacuum Rabi oscillations,…

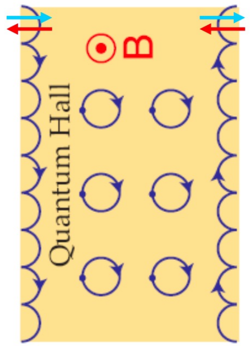
CAVITY QUANTUM ELECTRODYNAMICS

A new generation of experiments shows that spontaneous radiation from excited atoms can be greatly suppressed or enhanced by placing the atoms between mirrors or in cavities.

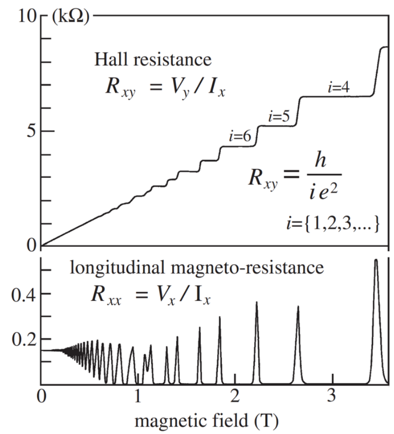
Serge Haroche and Daniel Kleppner

Quantum Hall Effect
(QHE)

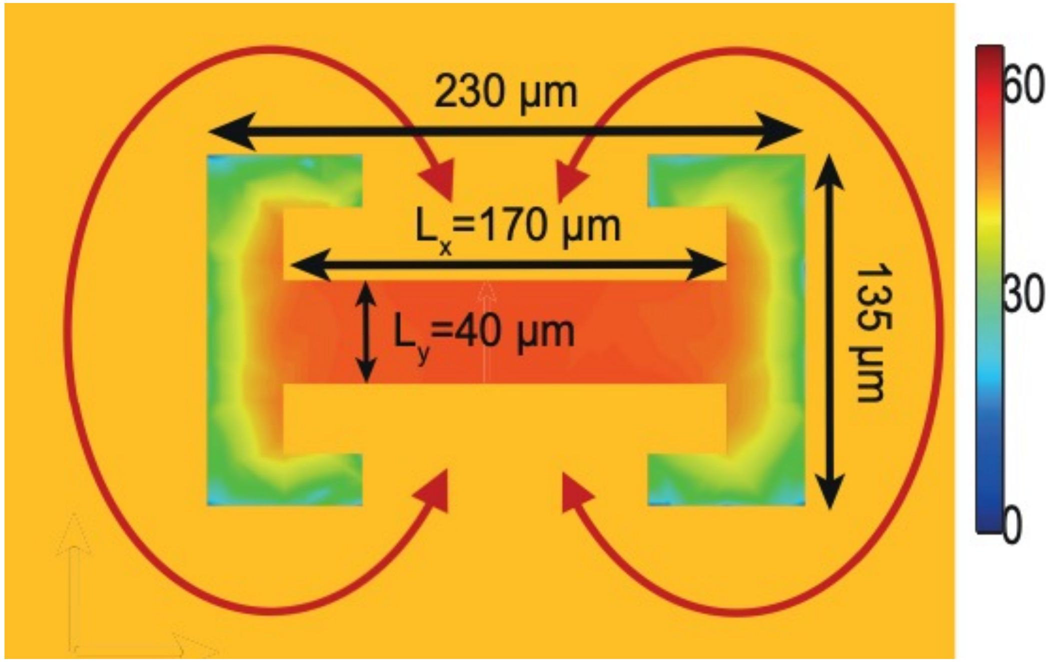




Paradigmatic
Topological Insulator



Giant vacuum fields with split-ring resonators

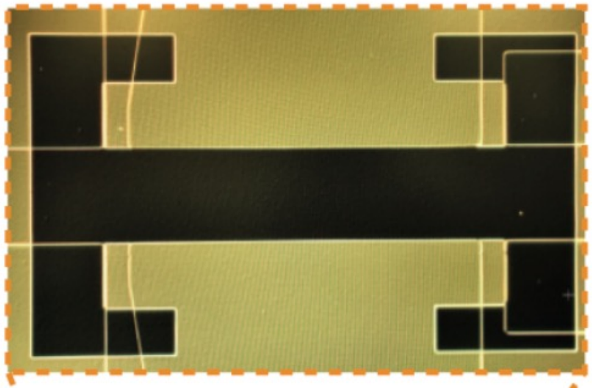


LC-like resonator

Strong vacuum electric fields in the capacitive gap

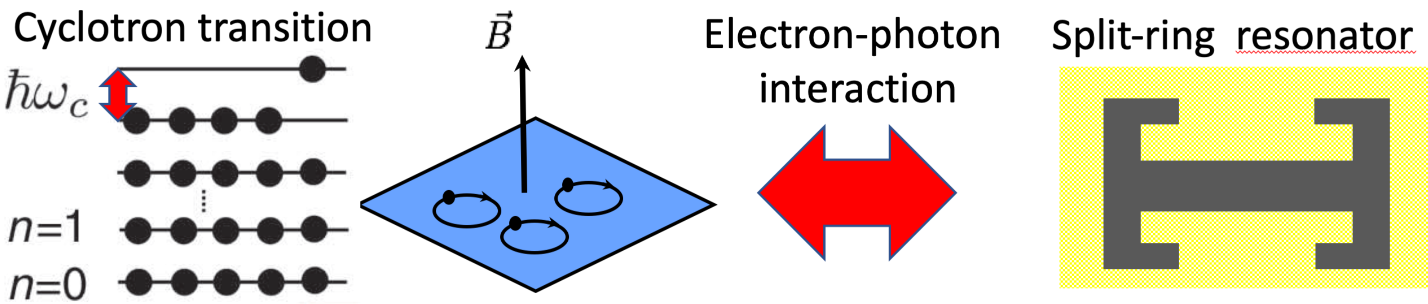
Deeply subwavelength mode confinement

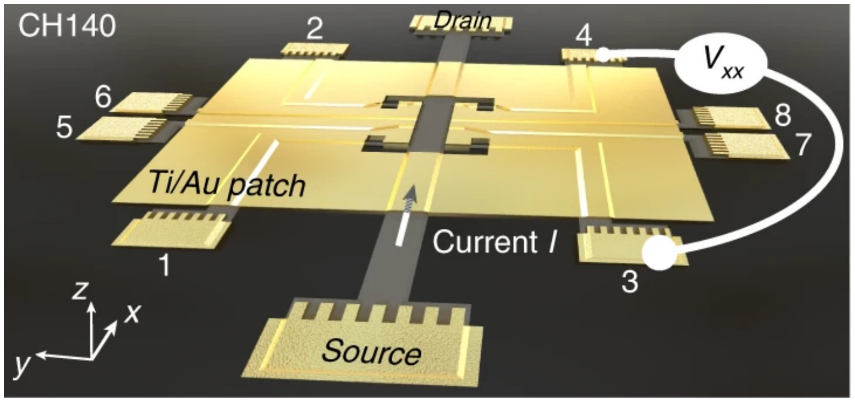
$$10^{-10}(\lambda/n)^3 < V < 10^{-4}(\lambda/n)^3$$



Courtesy of J. Faist's group @ ETH

The new frontier: 2D electron gas in split-ring resonators





Optics: Landau polaritons
Hagenmüller, De Liberato, CC, PRB (2010)
Scalari et al, Science (2012)
…
See next talk by
J. Mornhinweg and references therein

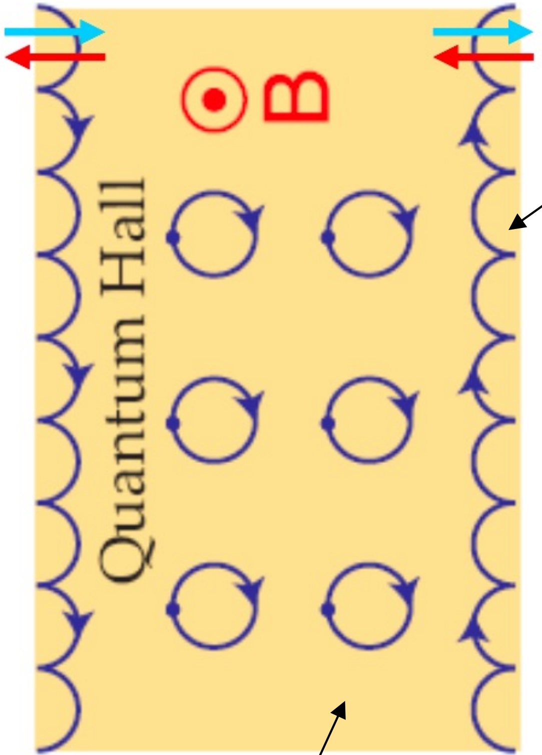
Magneto-transport: Shubnikov-de Haas regime

Paravicini-Bagliani et al., Nature Physics (2019) Bartolo & CC, PRB (2018)

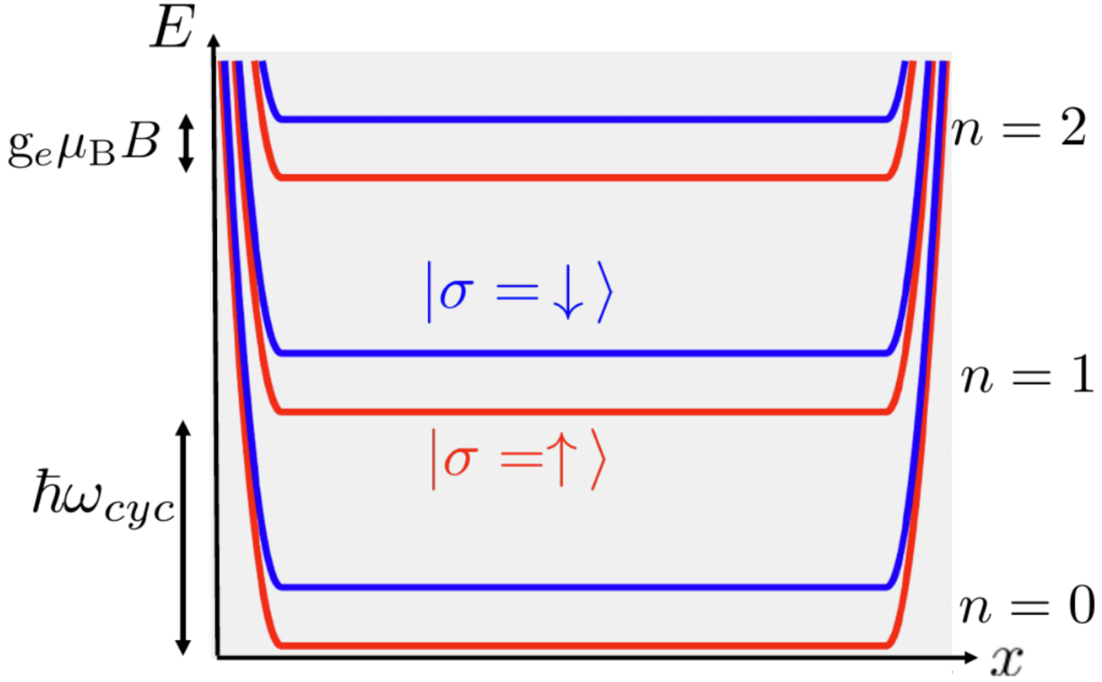
Can the **cavity quantum vacuum** fluctuations **modify quantum Hall physics**?

Quantum Hall transport: edge picture

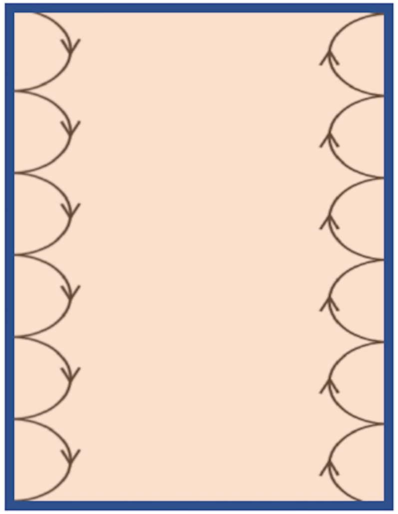
Chiral skipping orbits (edge states)



Insulating bulk states



Integer quantum Hall: edge transport picture

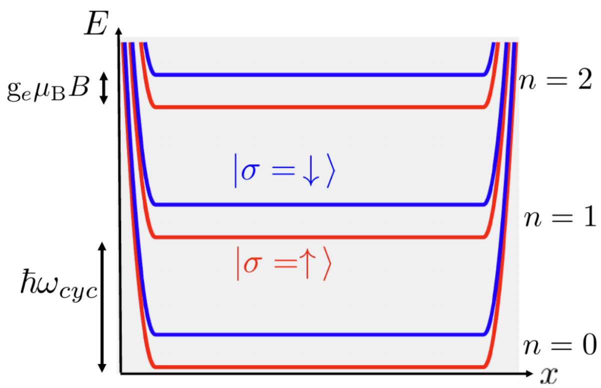


- Localized bulk states do not contribute to transport
- **No back-scattering for chiral 1D edge channels**

Landauer formula

$$G_{\mathrm{H}} = \frac{e^2}{h} \sum_{n,\sigma} T_{n,\sigma}(E_F)$$

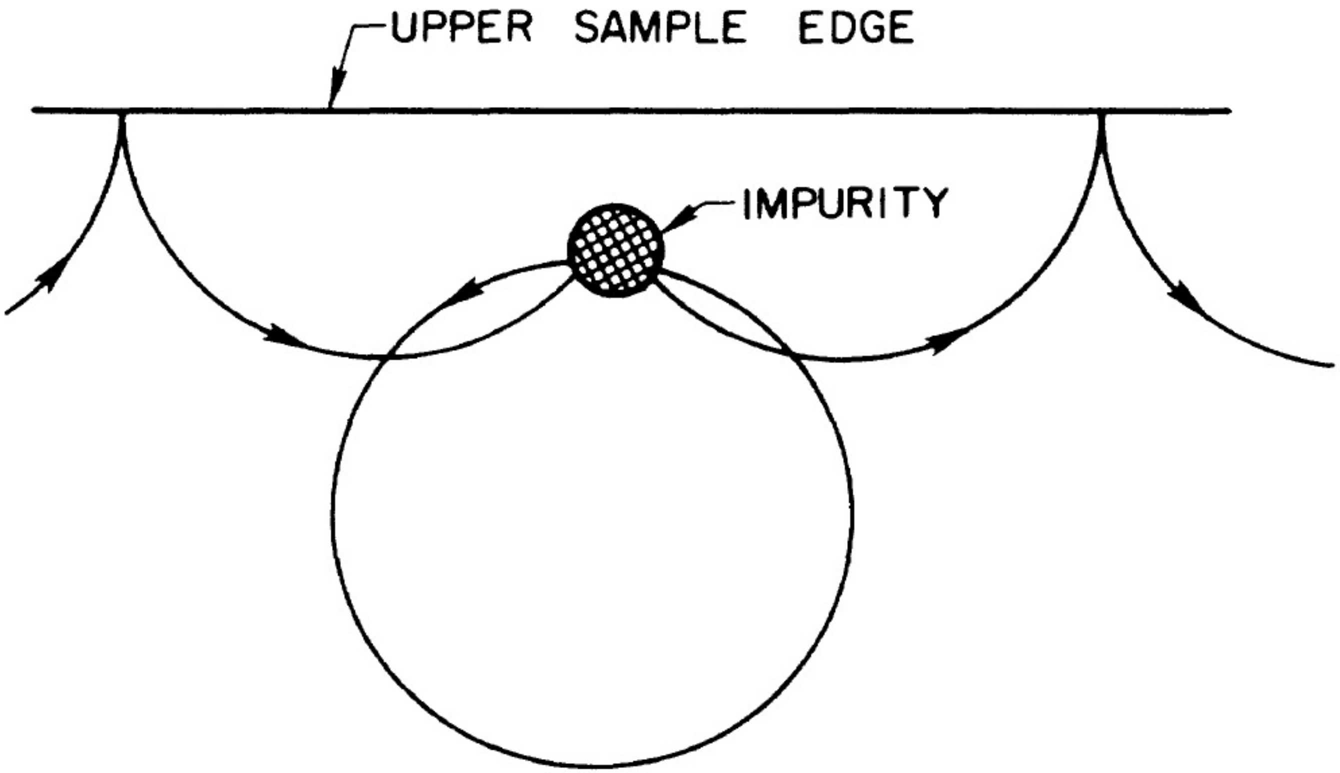
$$T_{n,\sigma} = 1$$



Edge transport is topologically protected

The only way would be for an electron in one edge state to scatter to the other side

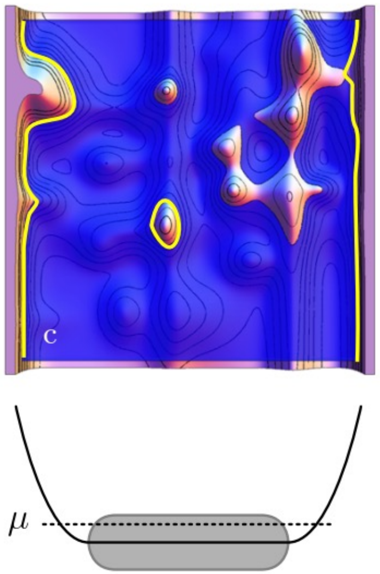
Absence of backscattering for chiral edge states



M. Büttiker, Phys. Rev. B 38, 9375 (1988)

Quantization of conductance is topological property

A mug or a donut have one hole



When edge states have no back-scattering,
number of edge channels is what matters

Resistance metrology: QH is topologically robust

Séminaire Poincaré 2 (2004) 39 – 51 | **Séminaire Poincaré**

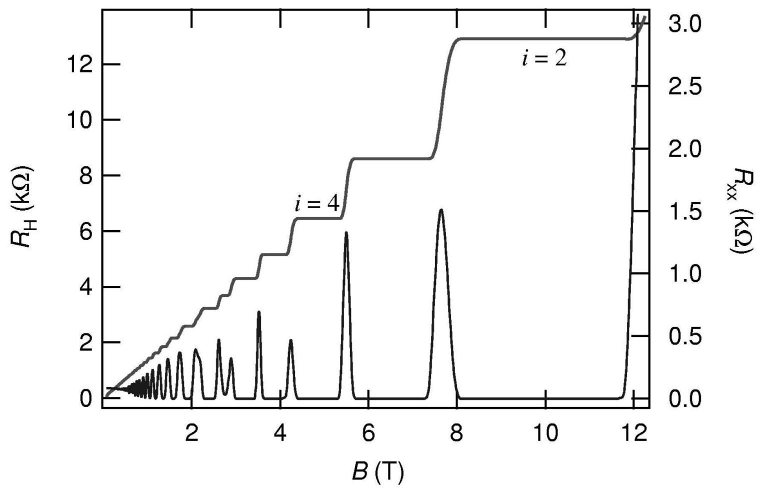
The Quantum Hall Effect as an Electrical Resistance Standard*

B. Jeckelmann and B. Jeanneret
Swiss Federal Office of Metrology and Accreditation
Lindenweg 50
CH-3003 Bern-Wabern
Switzerland

Abstract. The quantum Hall effect (QHE) provides an invariant reference for resistance linked to natural constants. It is used worldwide to maintain and compare the unit of resistance. The reproducibility reached today is almost two orders of magnitude better than the uncertainty of the determination of the ohm in the International System of Units SI. This article is a summary of a recently published review article which focuses mainly on the aspects of the QHE relevant for its metrological application.

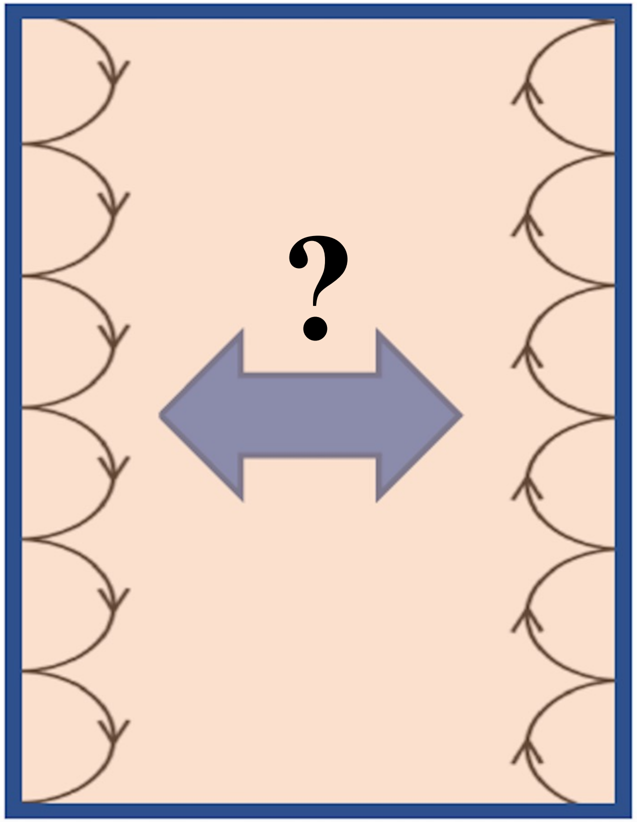
Metrological accuracy….

$$\overline{\frac{i \cdot R_H(i)}{2 \cdot R_H(2)}} = 1 - (1.2 \pm 2.9) \cdot 10^{-10}, \quad i = 1, 3, 4, 6, 8.$$



Giant vacuum fields a threat to the topological protection?

Can **cavity vacuum fluctuations**
induce a **inter-edge coupling?**



All in all, we have…….

1) Cavity vacuum field is all over the 2D electron gas

2) Topological robustness not immune
   to non-local perturbations

Experiments (collaboration with Faist's group at ETH Zürich)

Felice Appugliese

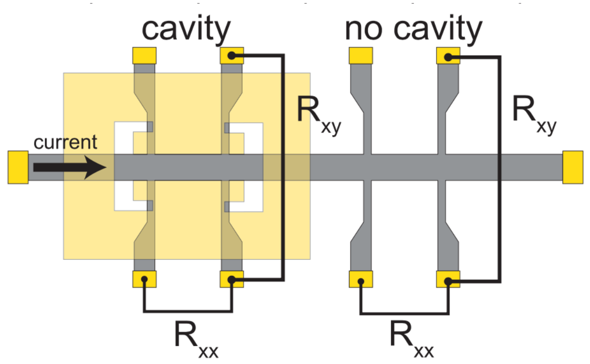
Josephine Enkner

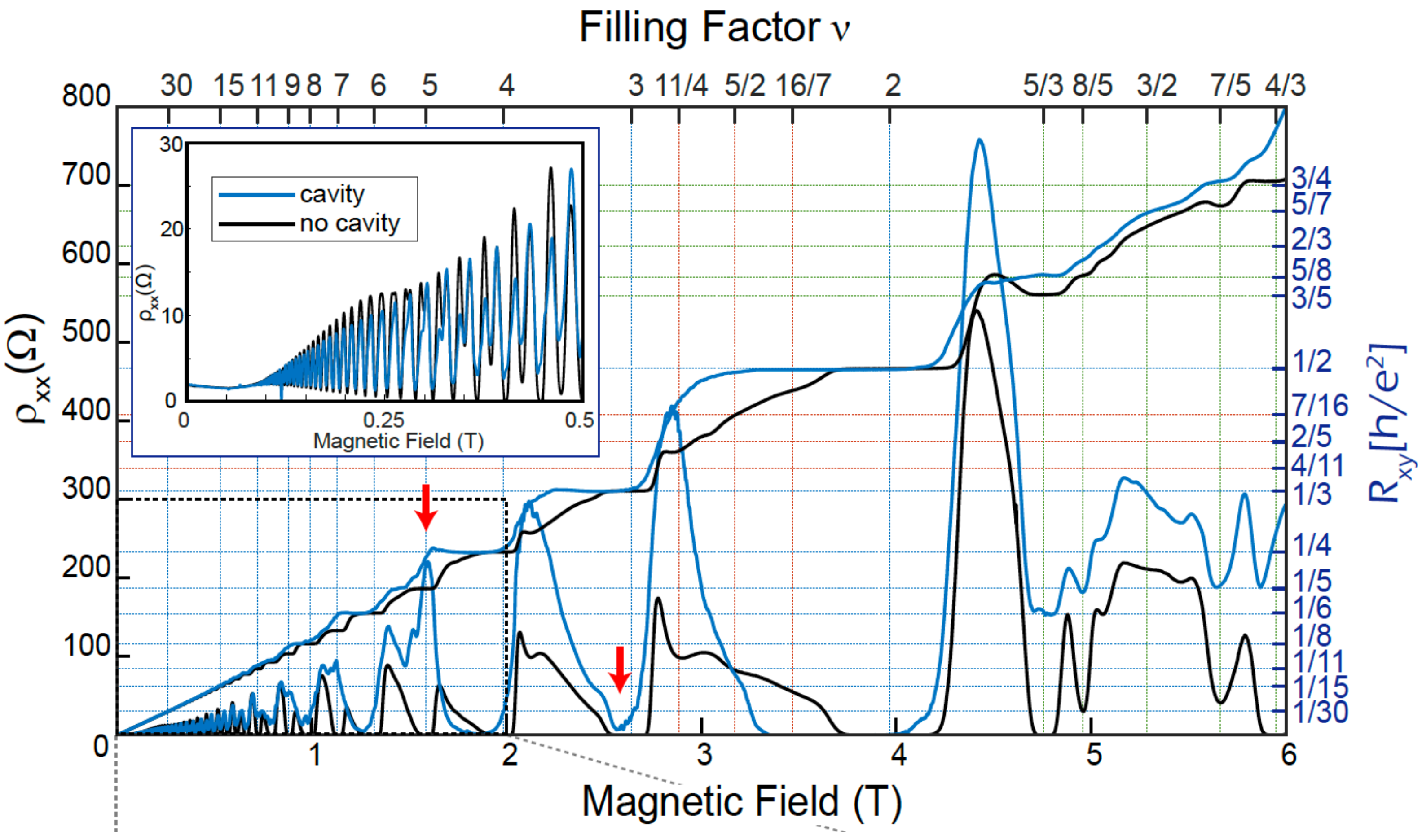
Giacomo Scalari

Jérôme Faist

F. Appugliese, J. Enkner, G. L. Paravicini-Bagliani, M. Beck, Ch. Reichl, W. Wegscheider, G. Scalari, C. Ciuti, J. Faist, Science 375, 1030 (2022)

Breakdown of the topological protection of integer QH effect

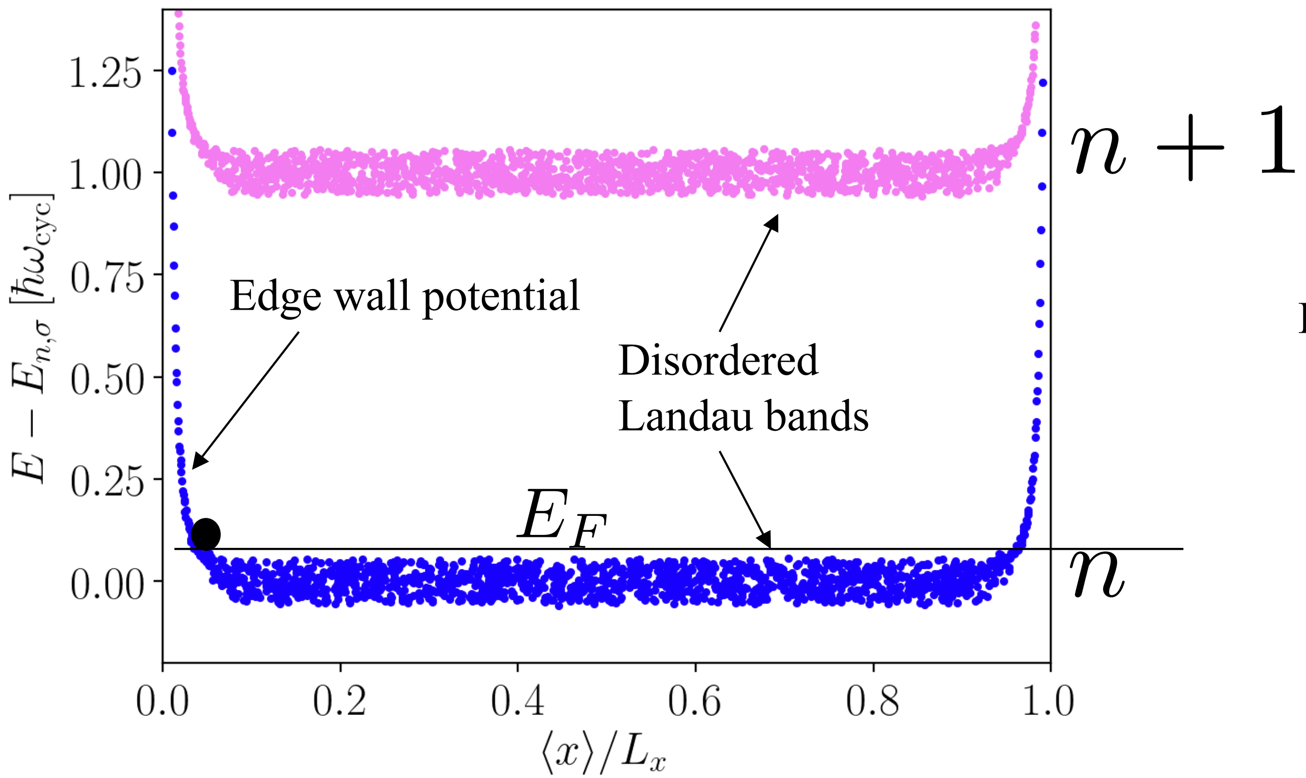




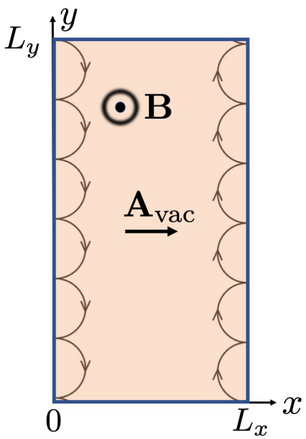
Cavity-mediated electron hopping in disordered electron quantum Hall systems

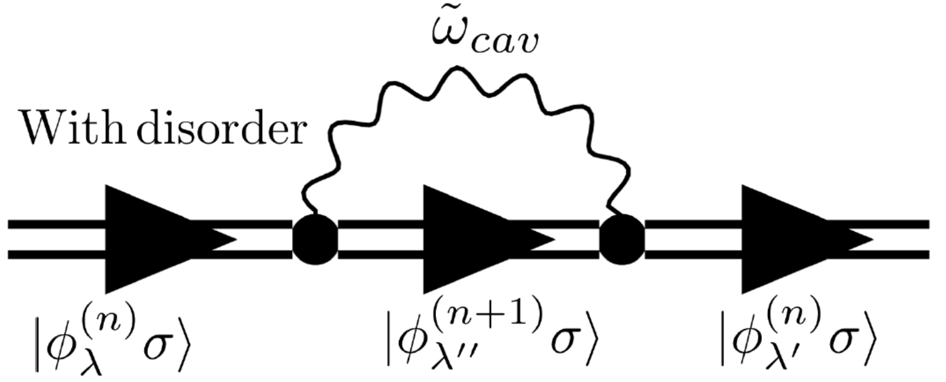
CC, PRB 104, 155307 (2021)

Cavity-mediated electron hopping with disordered Landau levels

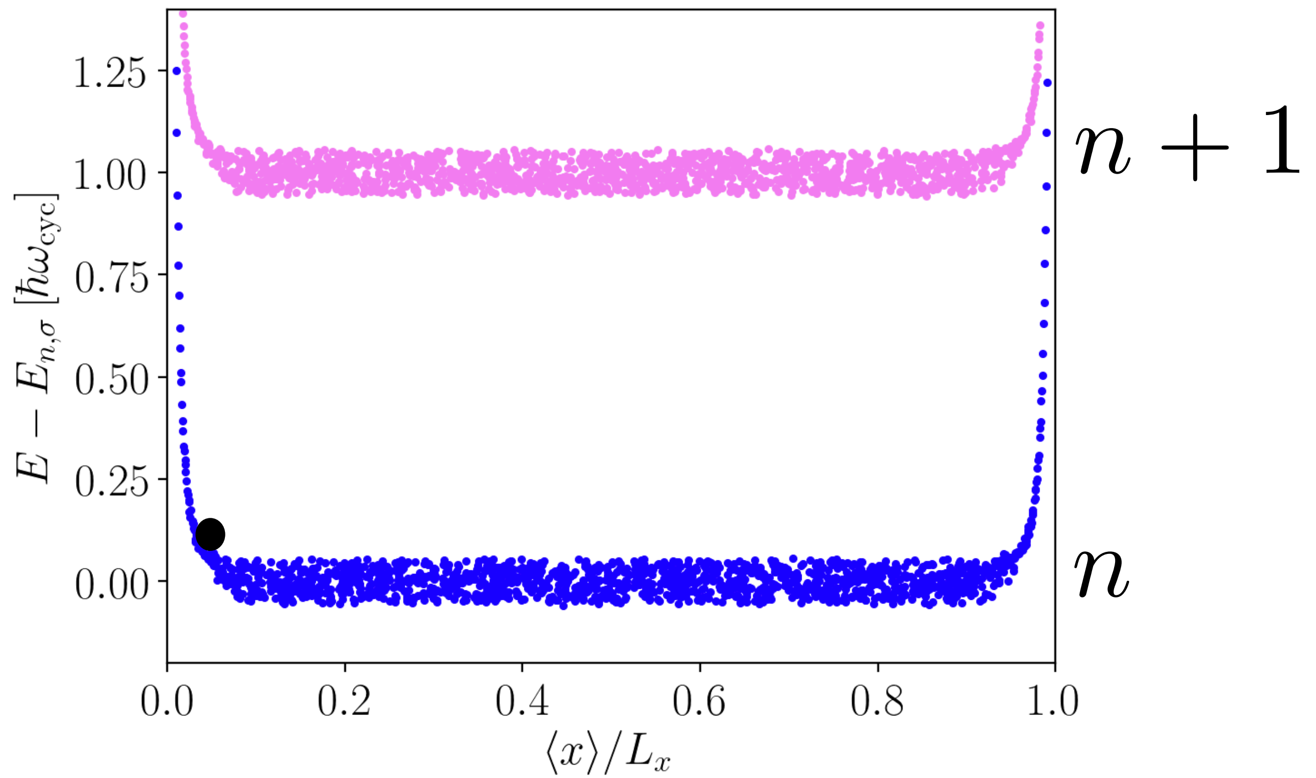


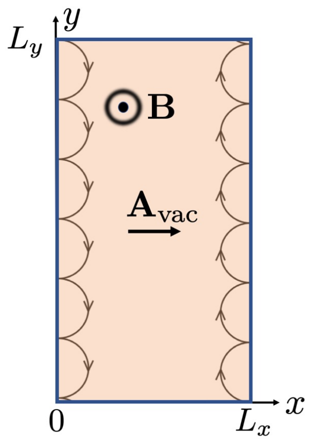
Landau gauge

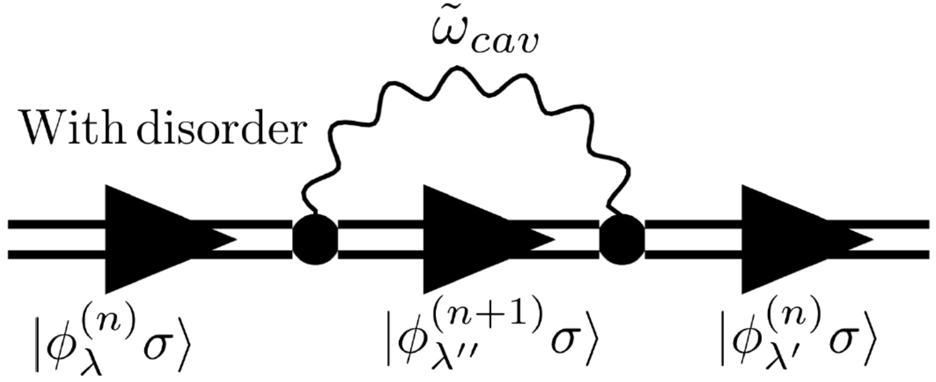




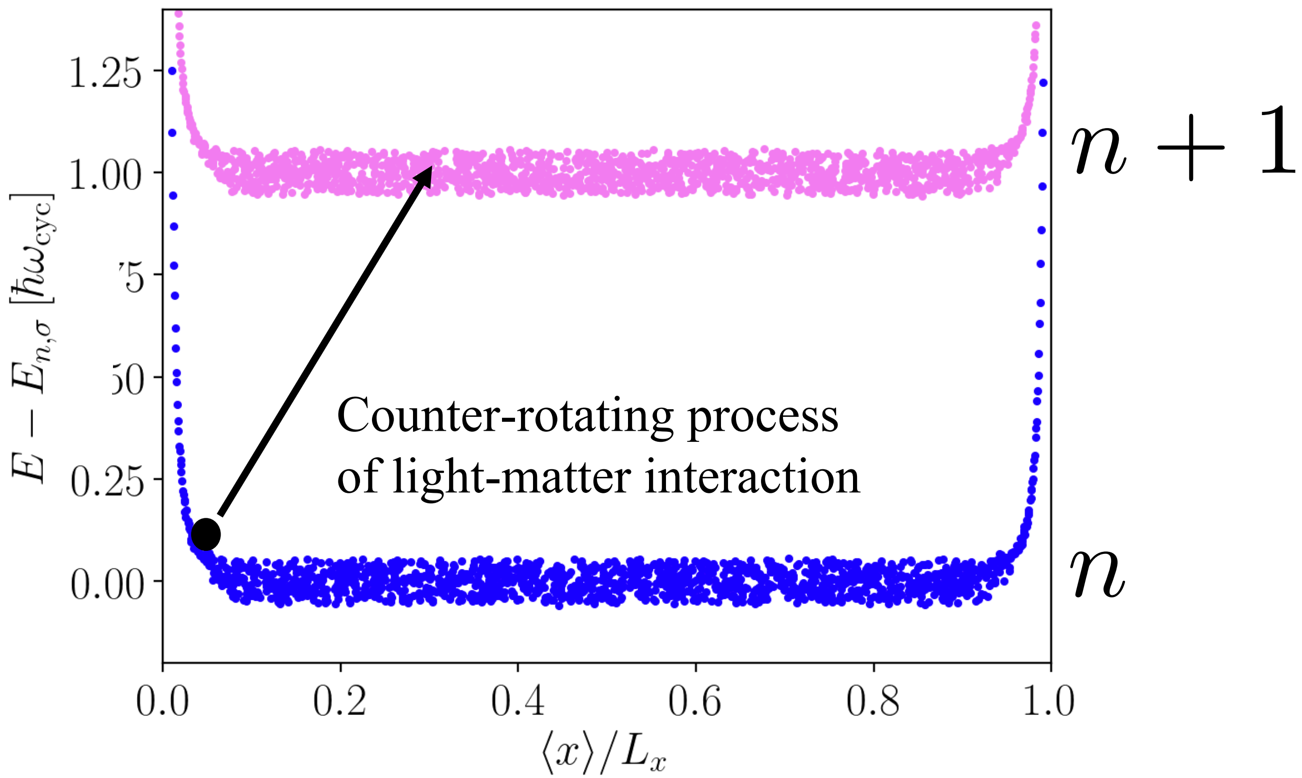
Yes … The physical mechanism

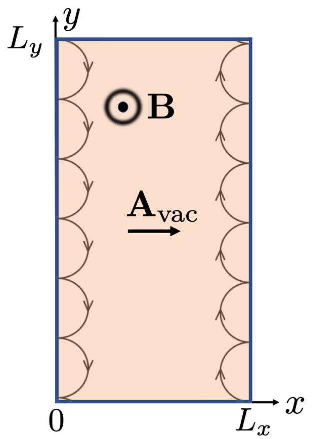


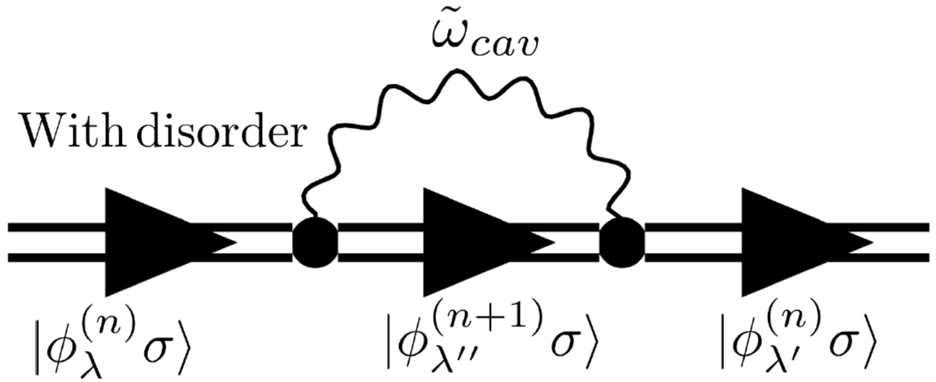




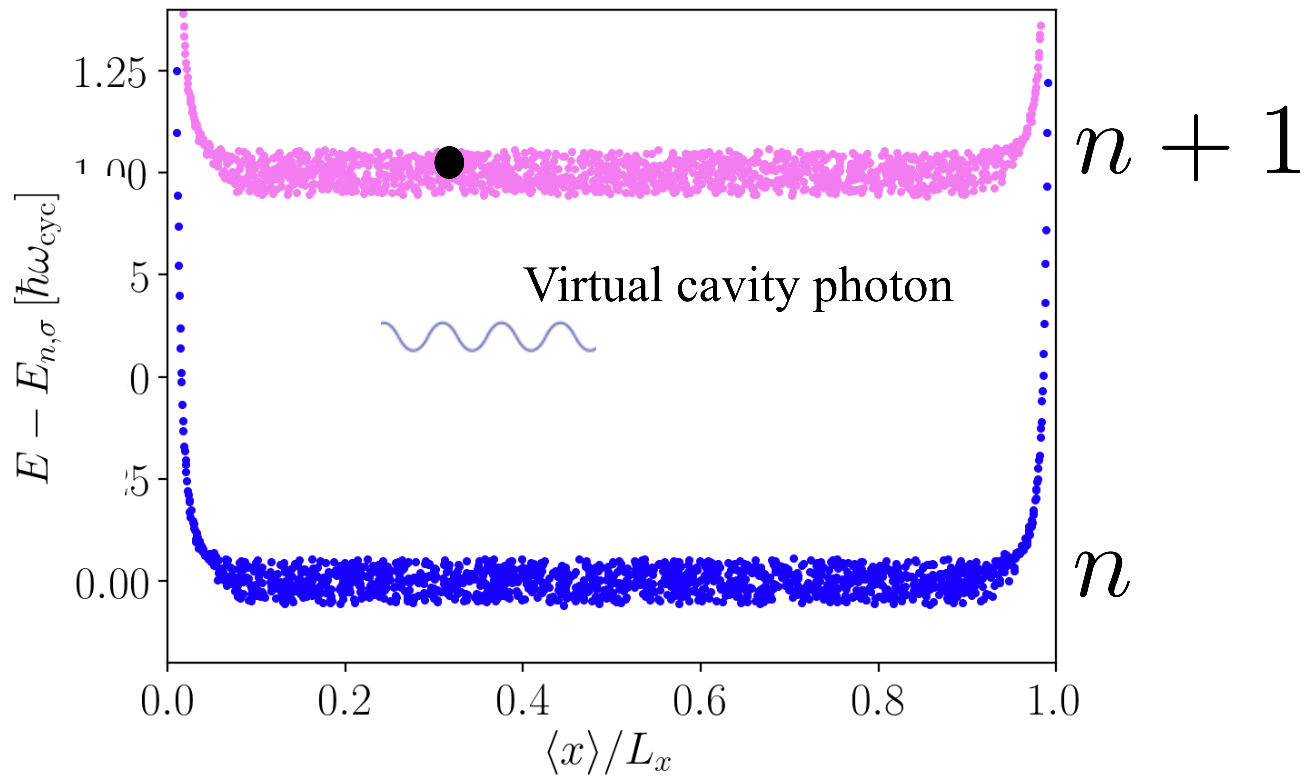
Yes… The physical mechanism

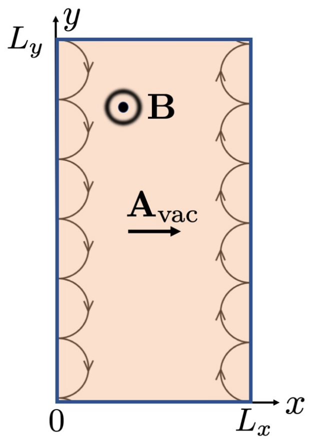


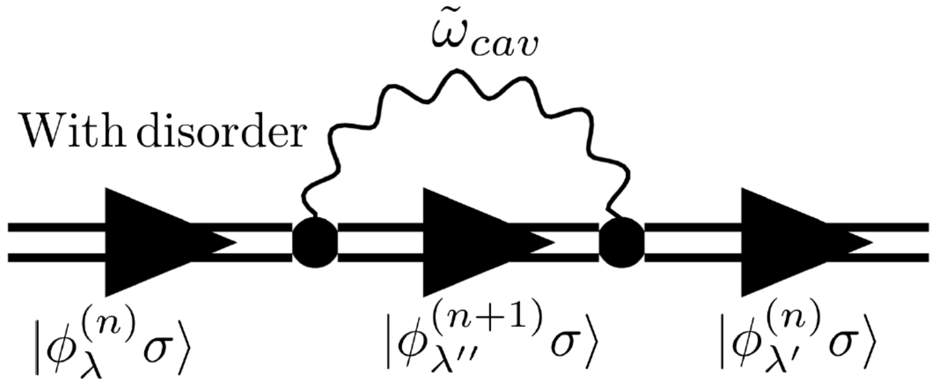




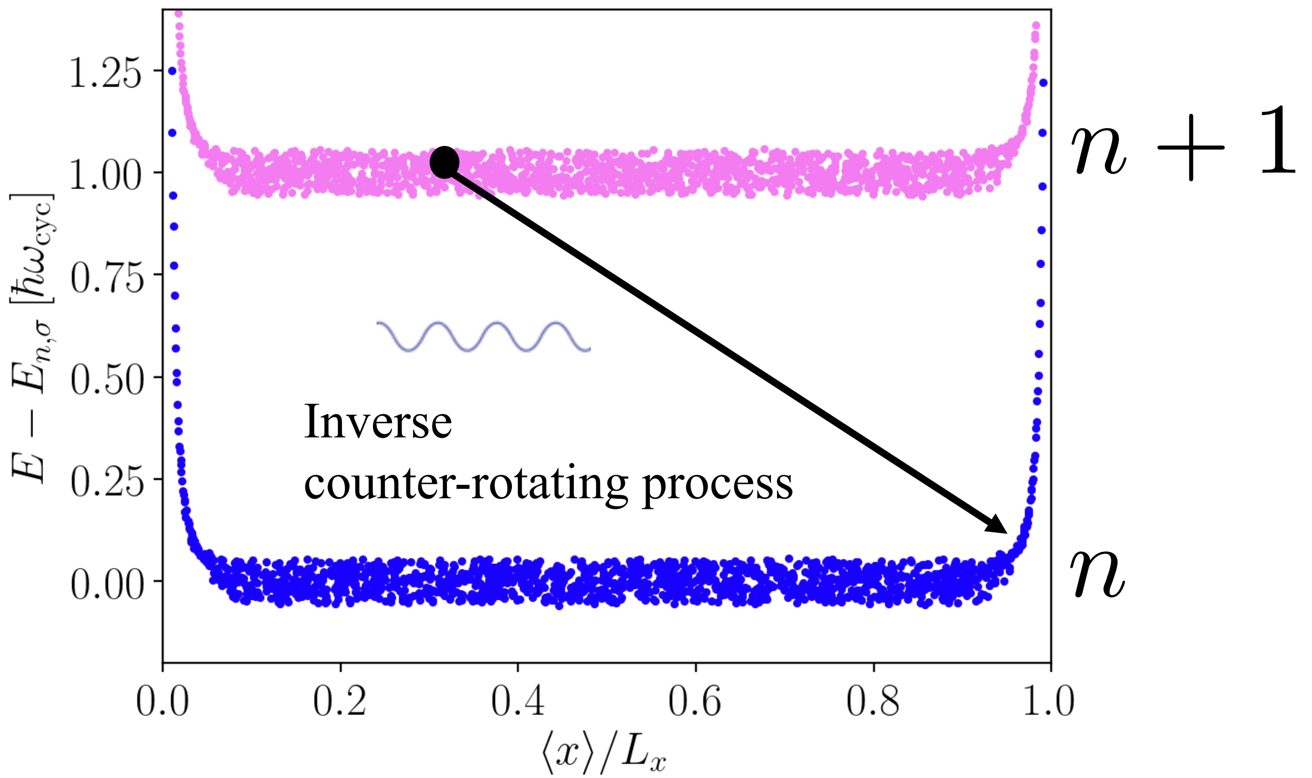
Yes… The physical mechanism

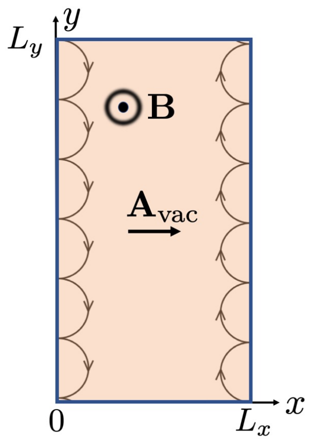


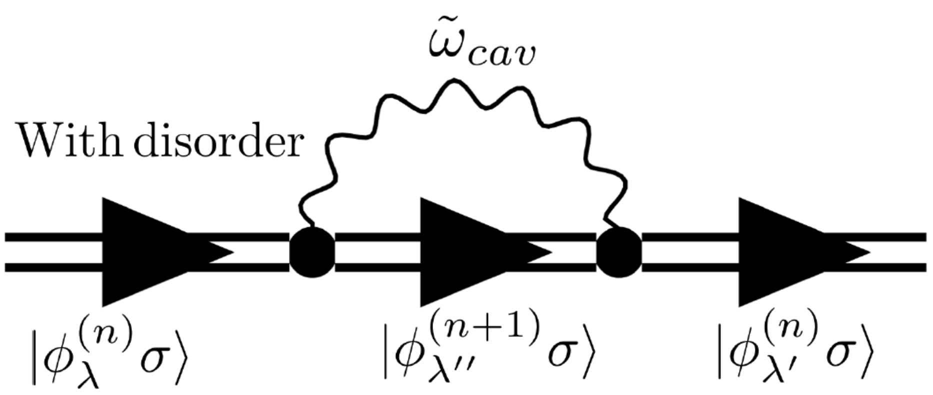




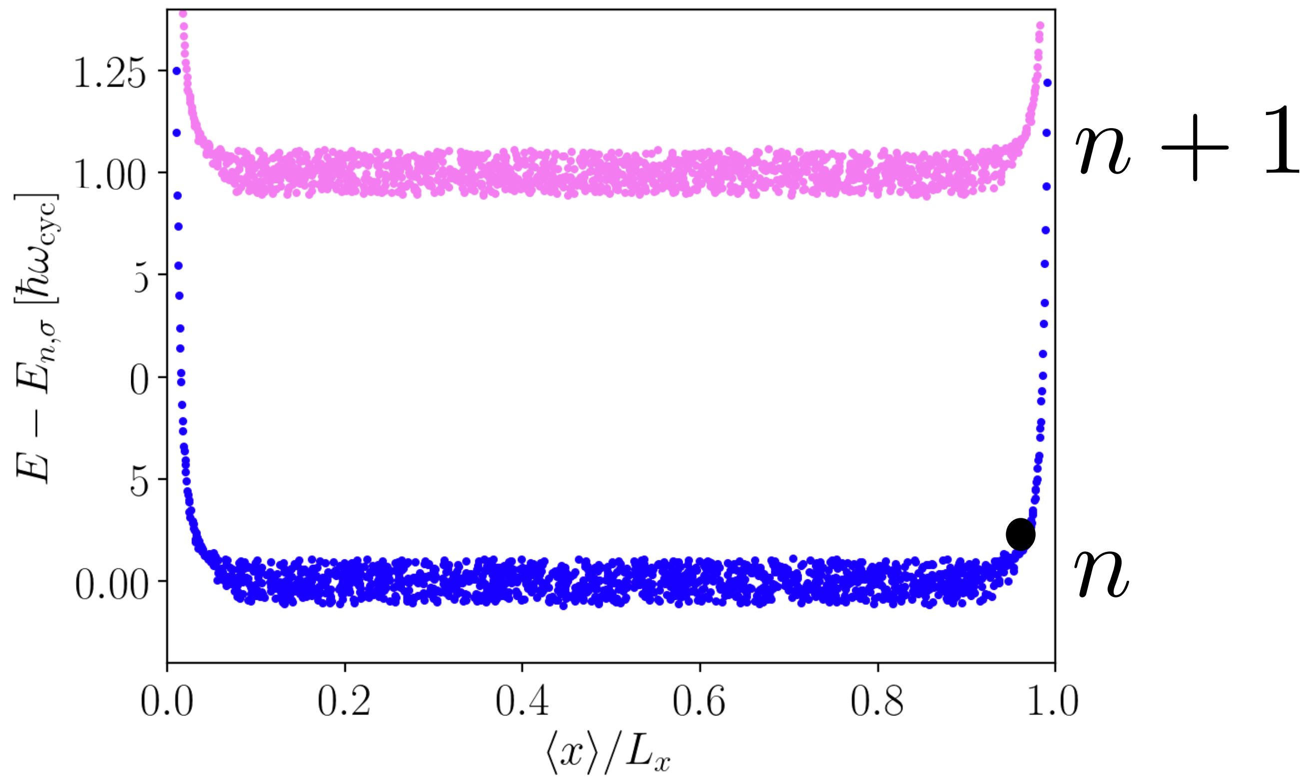
Yes… The physical mechanism

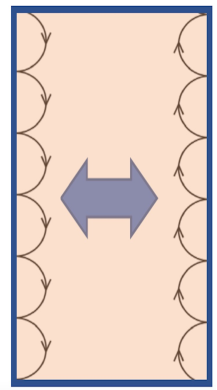


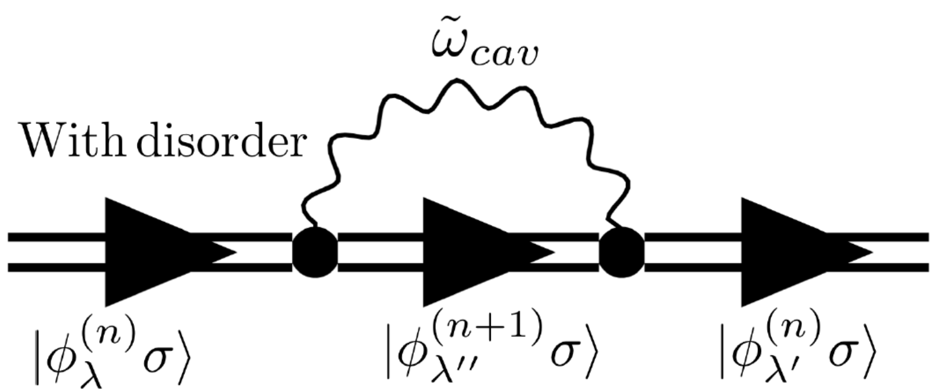




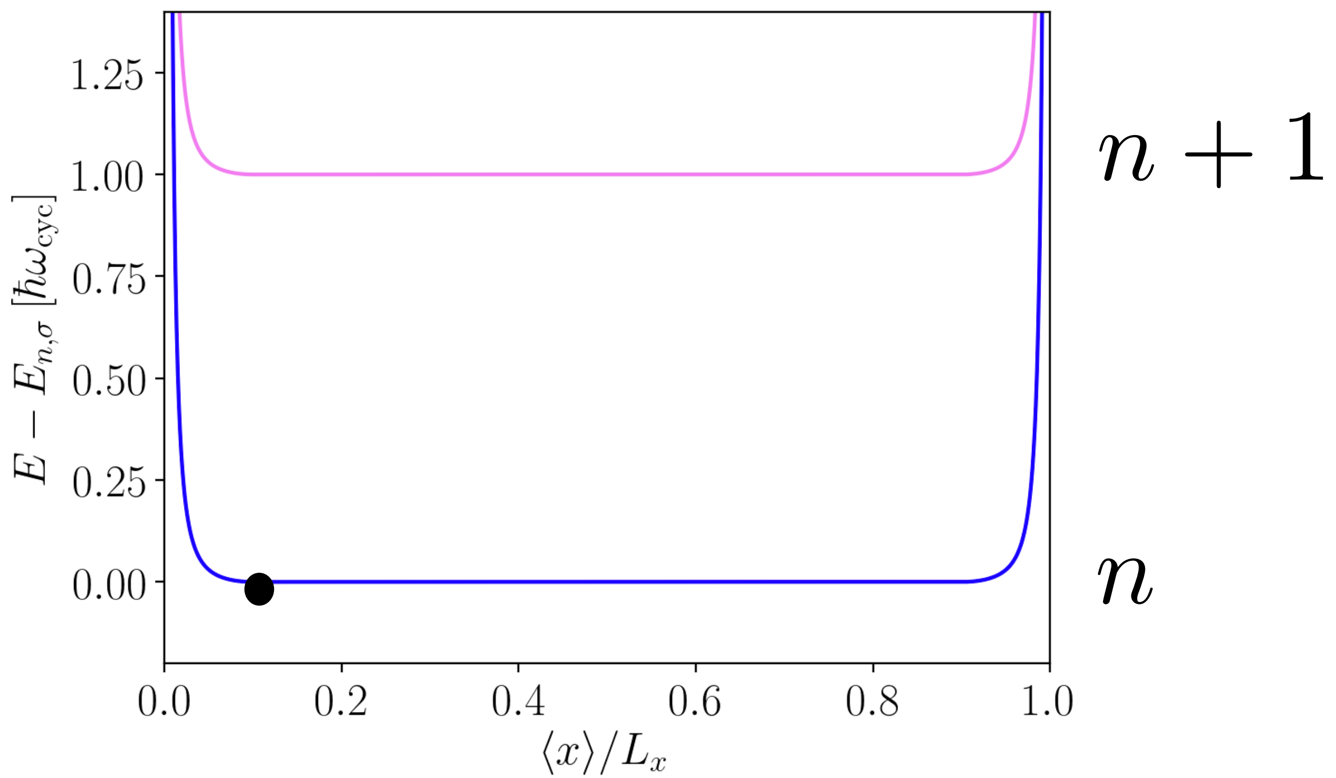
Cavity-mediated hopping via the exchange of a virtual cavity photon

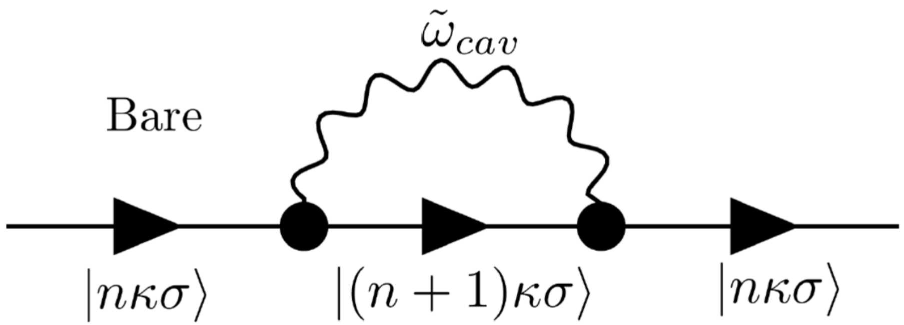




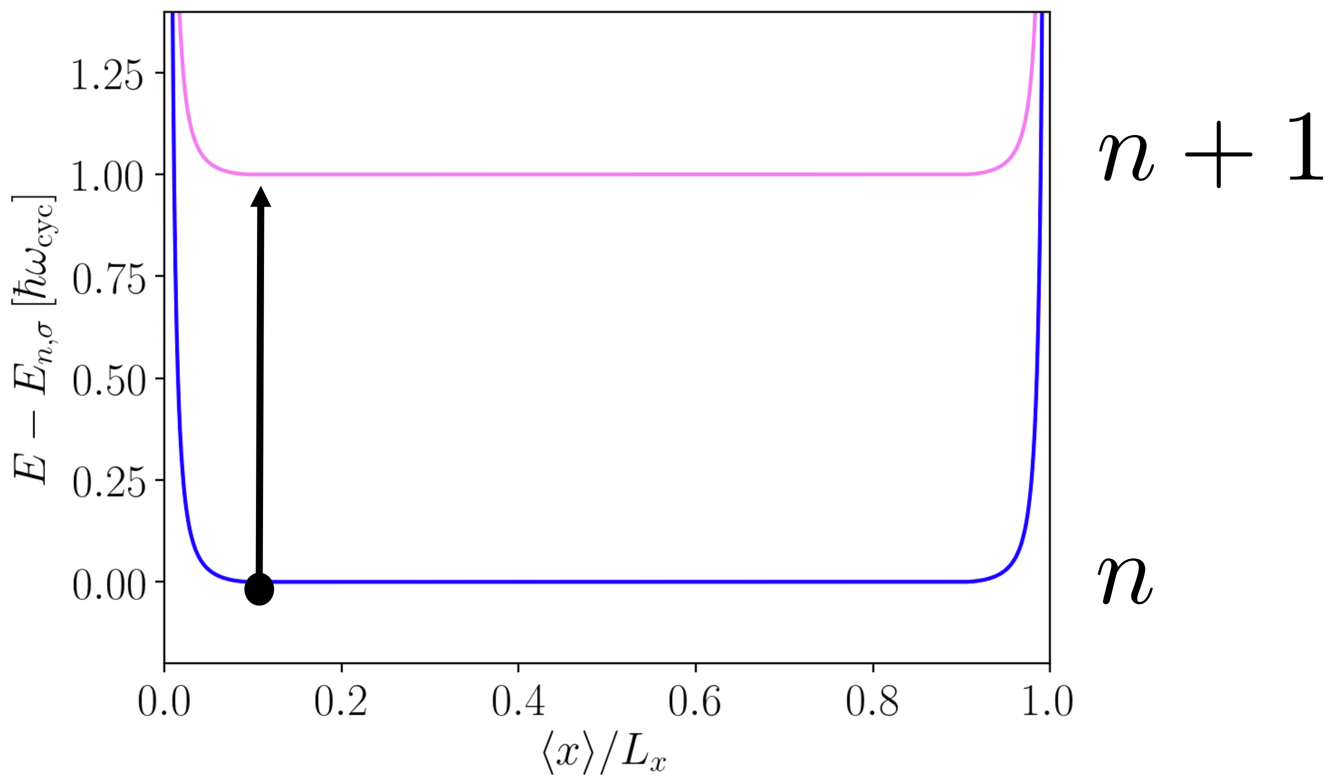


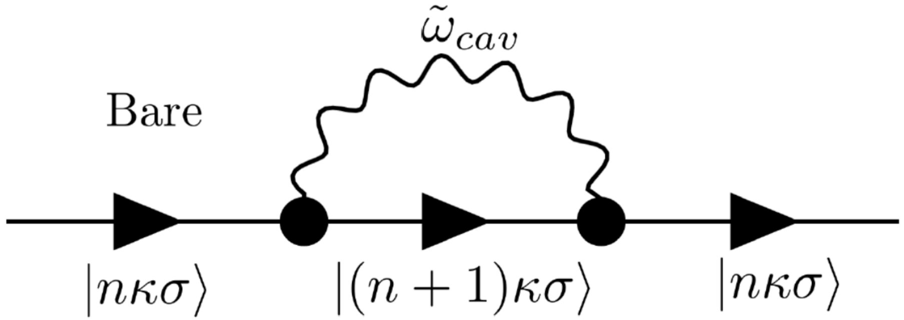
Important: no disorder, no cavity-mediated hopping!



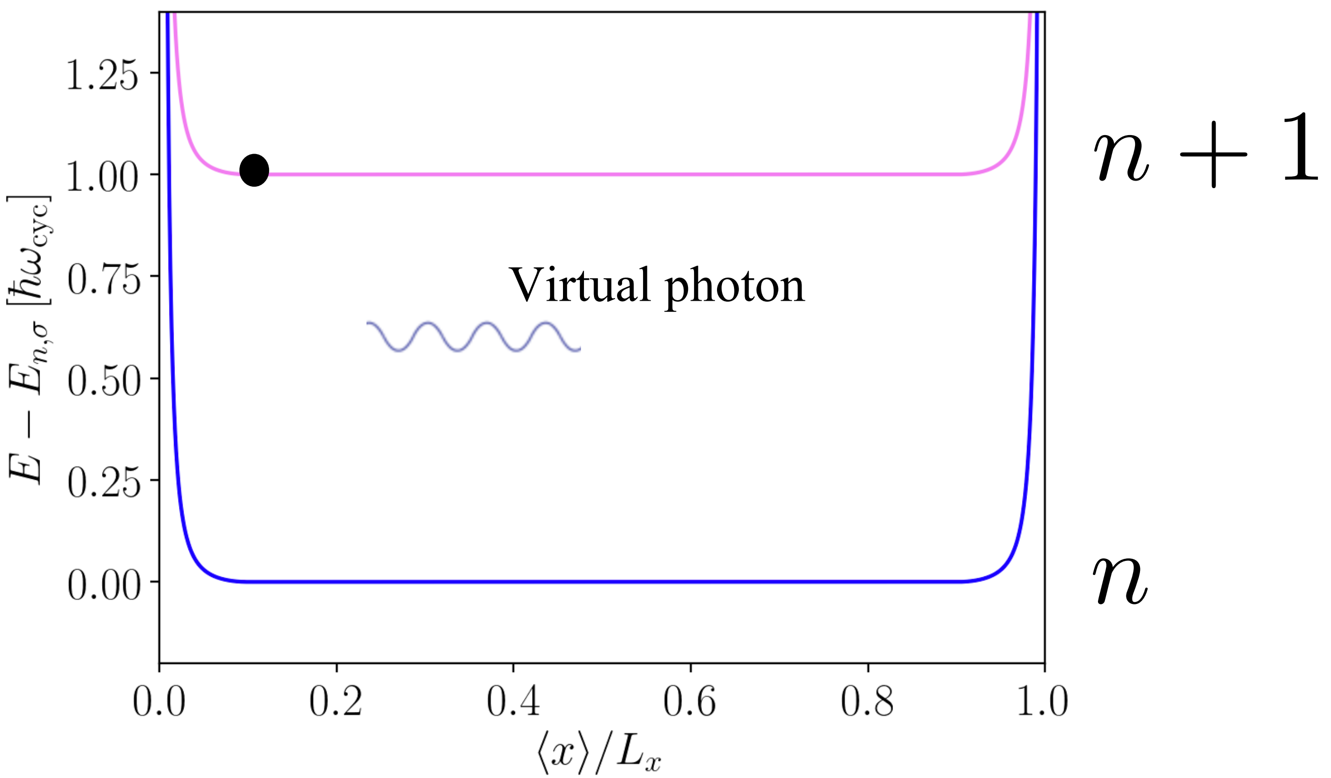


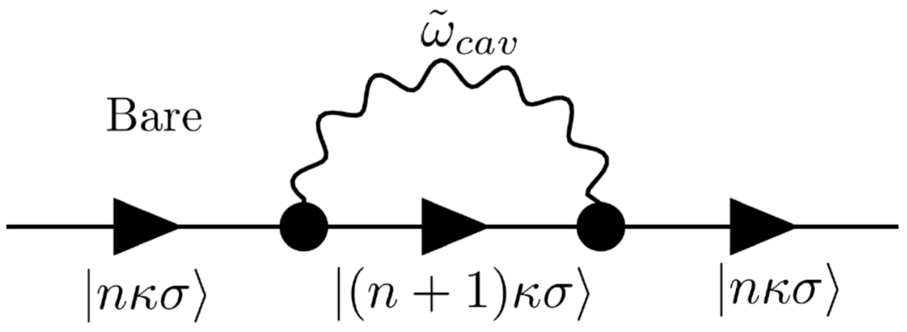
Important: no disorder, no cavity-mediated hopping!



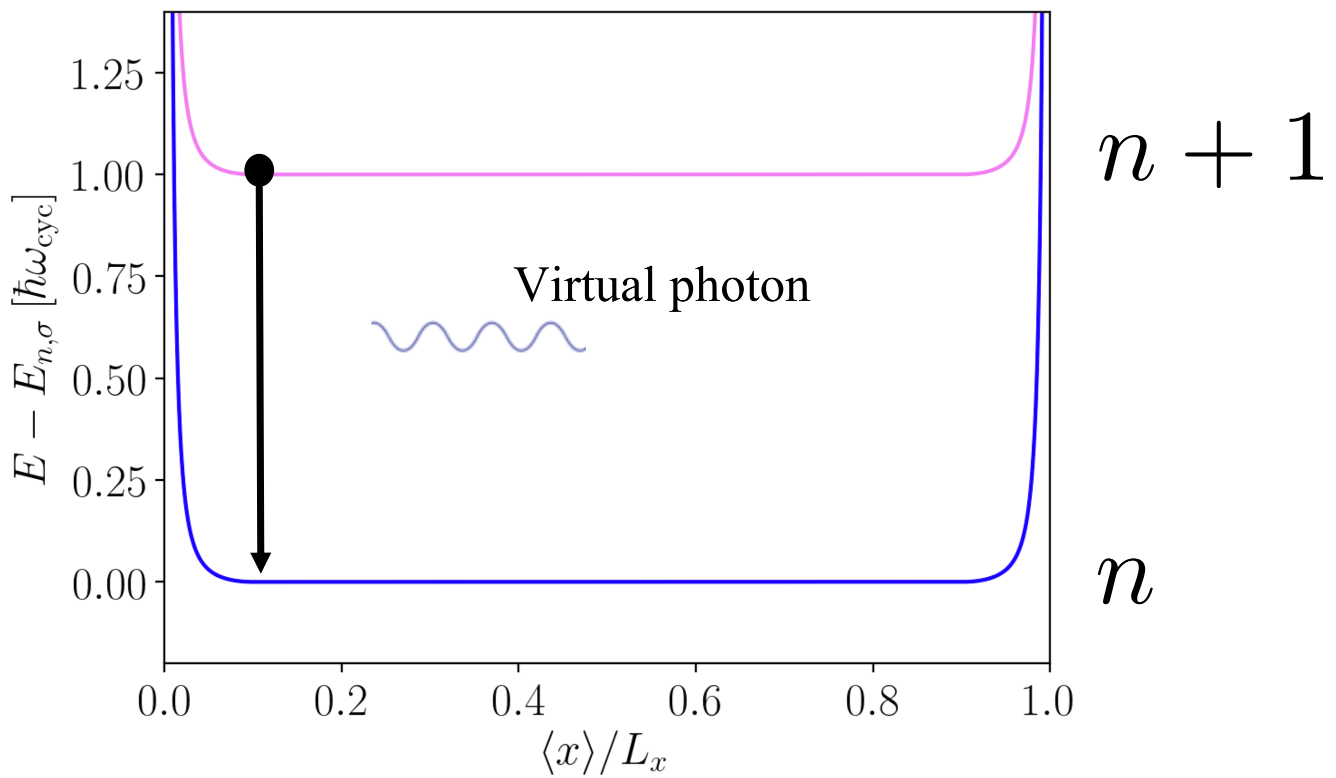


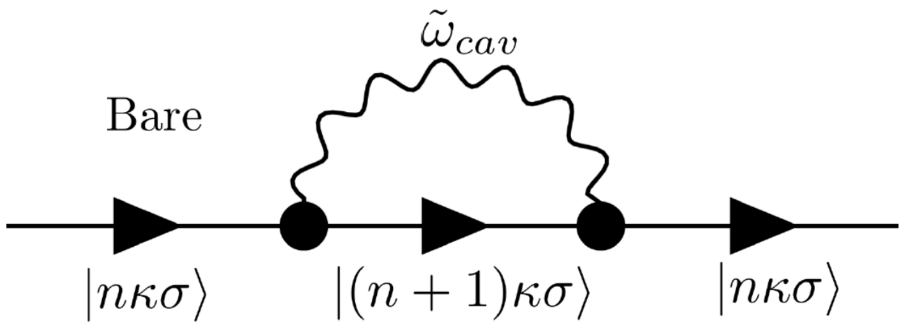
Important: no disorder, no cavity-mediated hopping!



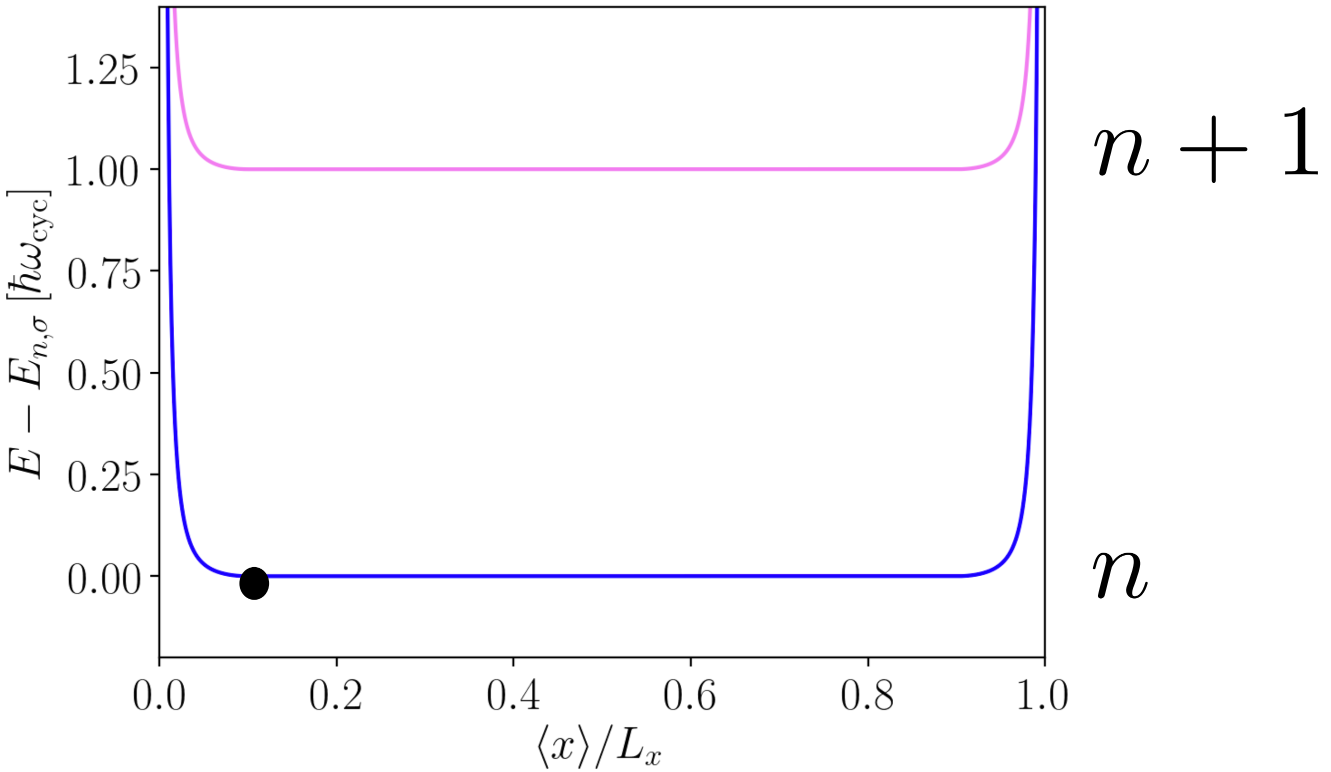


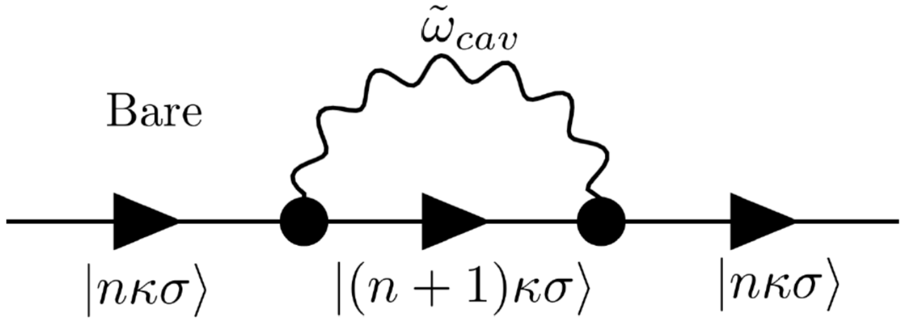
Important: no disorder, no cavity-mediated hopping!



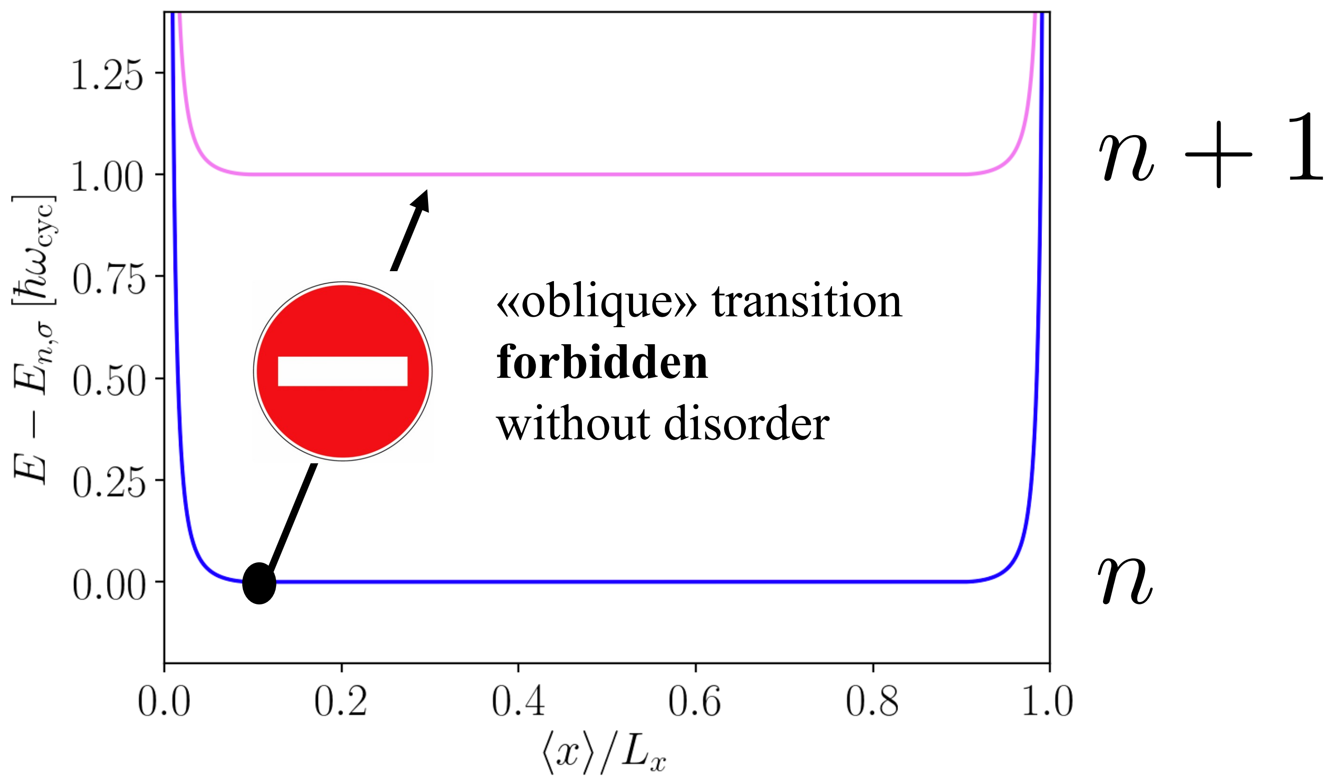


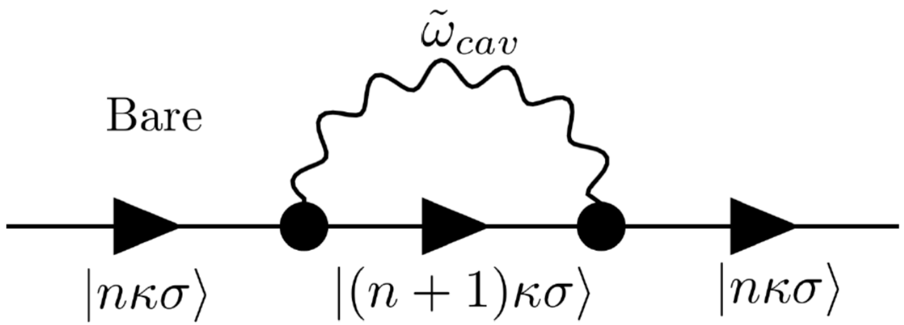
Important: no disorder, no cavity-mediated hopping!





Important: no disorder, no cavity-mediated hopping!





Summarizing the final Hamiltonian

Single-particle Hamiltonian in terms of disordered eigenstates (wall included)

$$\hat{H}_{\rm sp} = \hat{H}_{\rm el} + \hat{H}_{\rm dis} = \sum_{n,\kappa,\sigma} \left(\epsilon_{n,\lambda} + \frac{1}{2}\sigma\, {\rm g}_e \mu_B B \right) \hat{d}^{\dagger}_{n,\lambda,\sigma} \hat{d}_{n,\lambda,\sigma} \, ,$$

Renormalized cavity mode (due to diamagnetic term)

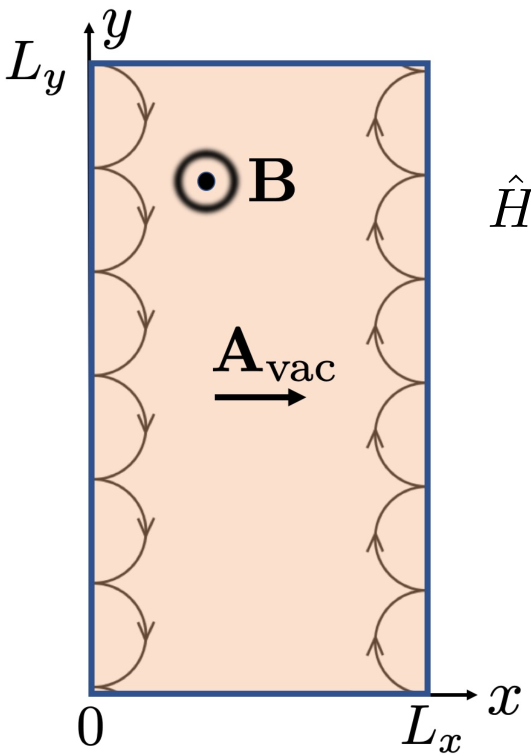
$$\hat{H}_{\rm mode} = \hat{H}_{\rm cav} + \hat{H}_{\rm dia} = \hbar\tilde{\omega}_{\rm cav}\hat{\alpha}^{\dagger}\hat{\alpha}$$

Interaction between disordered eigenstates and renormalized mode

$$\hat{H}_{\rm para} = \sum_{n,\lambda,\lambda'',\sigma} (-{\rm i})\hbar\tilde{g}^{(n,n+1)}_{\lambda,\lambda'} \, (\hat{\alpha} + \hat{\alpha}^{\dagger})\, \hat{d}^{\dagger}_{n+1,\lambda'',\sigma} \hat{d}_{n,\lambda,\sigma} + {\rm h.c.}$$

Renormalized interaction (disorder + diamagnetic term)

Coupling constant modified by disorder and diamagnetism



$$\hat{H}_{\rm para} = \sum_{n,\lambda,\lambda'',\sigma} (-{\rm i})\hbar \tilde{g}^{(n,n+1)}_{\lambda,\lambda'} \left(\hat{\alpha} + \hat{\alpha}^\dagger\right) \hat{d}^\dagger_{n+1,\lambda'',\sigma} \hat{d}_{n,\lambda,\sigma} + {\rm h.c.}$$

Renormalized vacuum Rabi frequency
(disorder and **diamagnetic)**

$$\tilde{g}^{(n,n+1)}_{\lambda,\lambda''} = \tilde{g}\sqrt{n+1} \sum_{\kappa} \langle \phi^{(n+1)}_{\lambda''} | n+1\,\kappa\rangle \langle n\kappa | \phi^{(n)}_{\lambda}\rangle$$

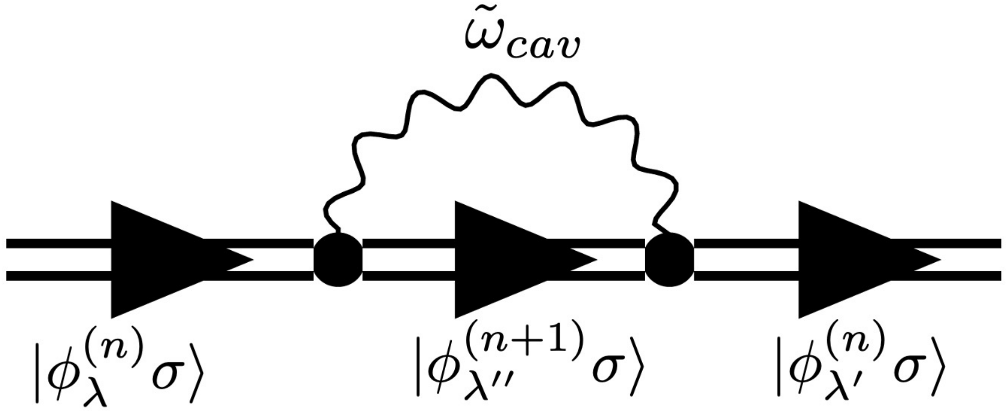
$$\tilde{g} = g\sqrt{\omega_{cav}/\tilde{\omega}_{cav}}$$

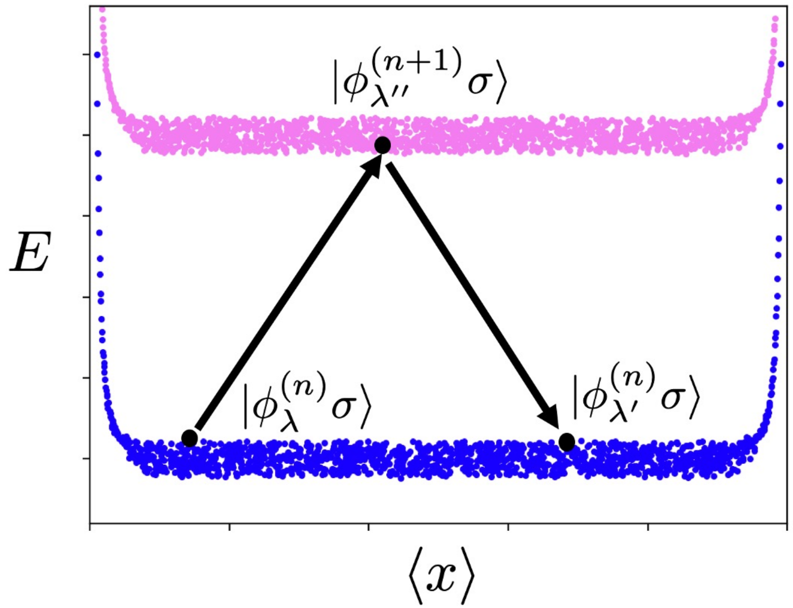
$$\hat{\mathbf{A}} = A_{\rm vac}\,\mathbf{e_x}\left(\hat{a} + \hat{a}^\dagger\right)$$

Vector potential operator

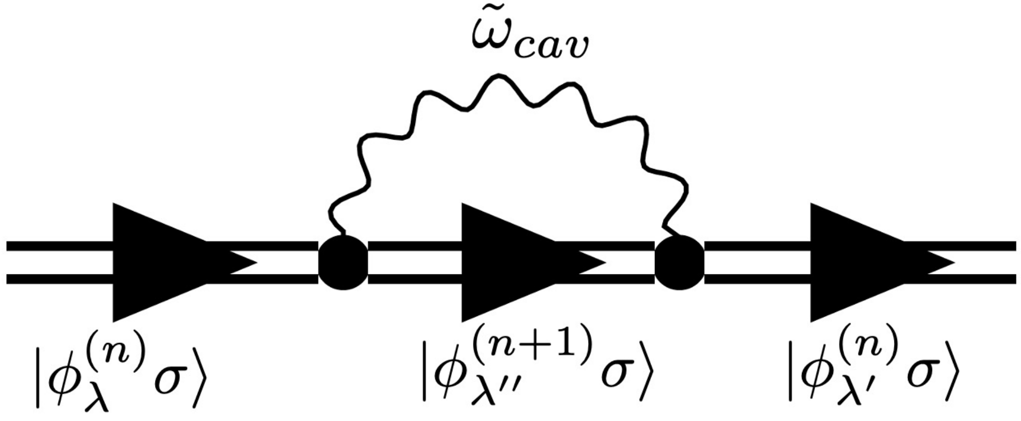
$$g = \frac{eA_{\rm vac}}{\hbar}\sqrt{\frac{\hbar\omega_{cyc}}{2m}}$$

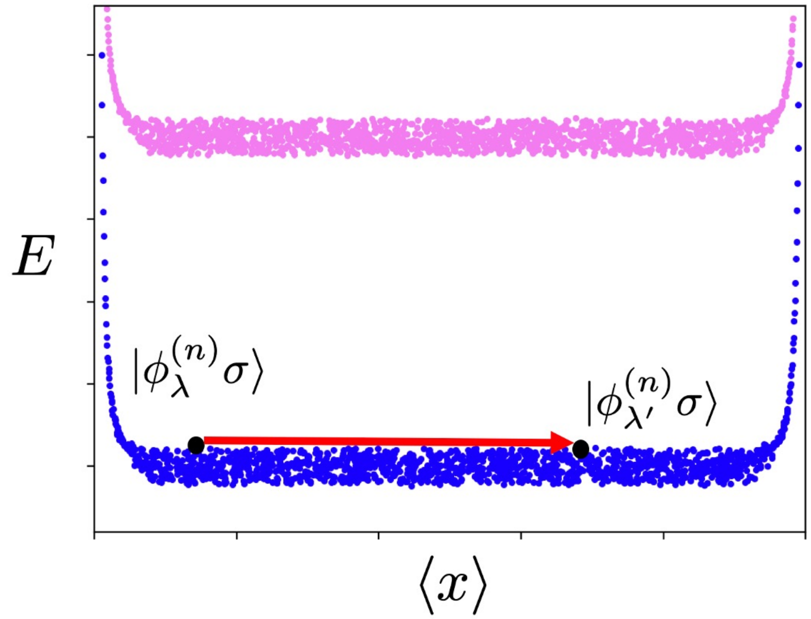
Cavity-mediated hopping between disordered Landau states





Effective hopping coupling

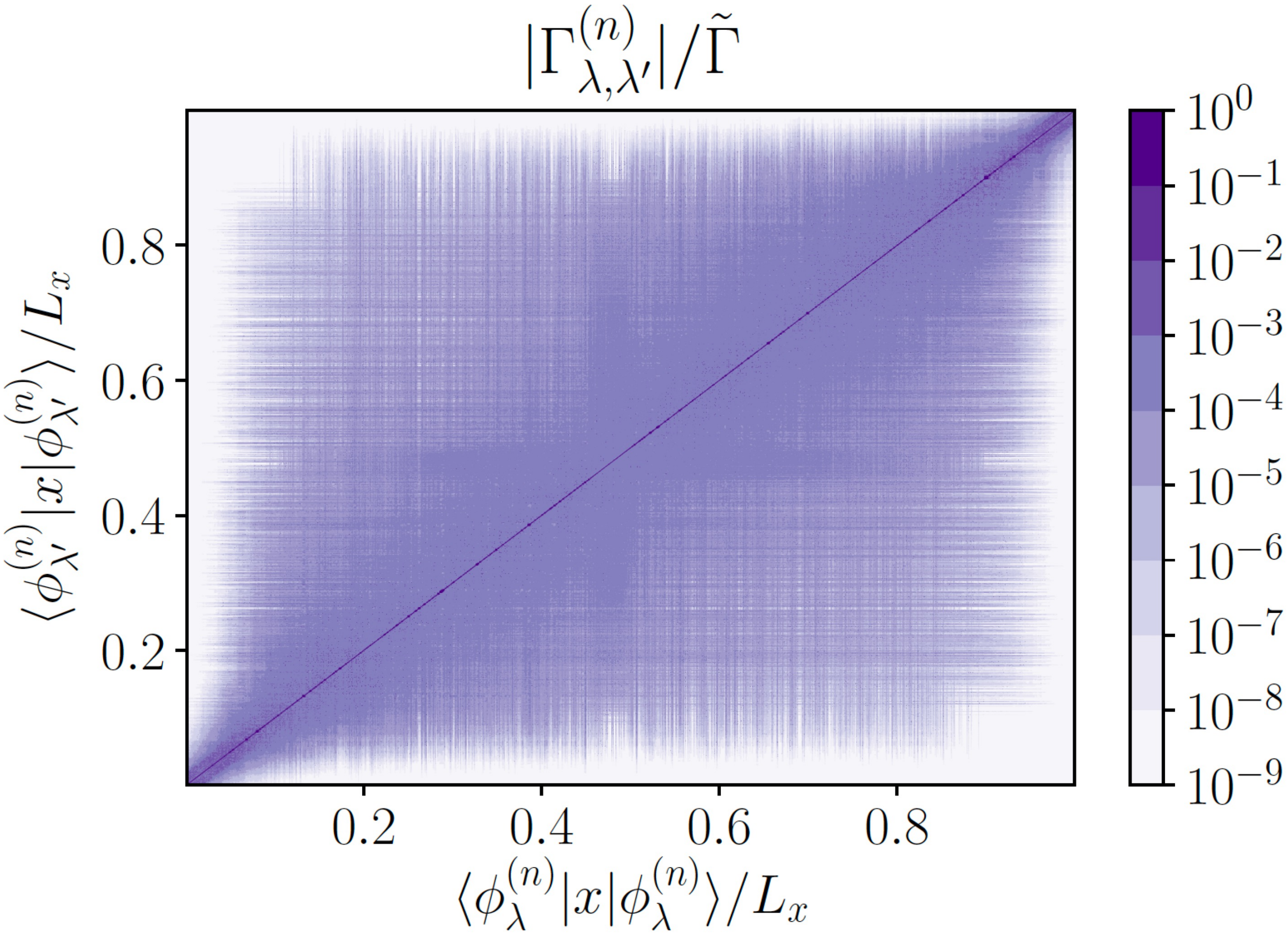




Effective cavity-mediated hopping (lowest order perturbation theory)

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

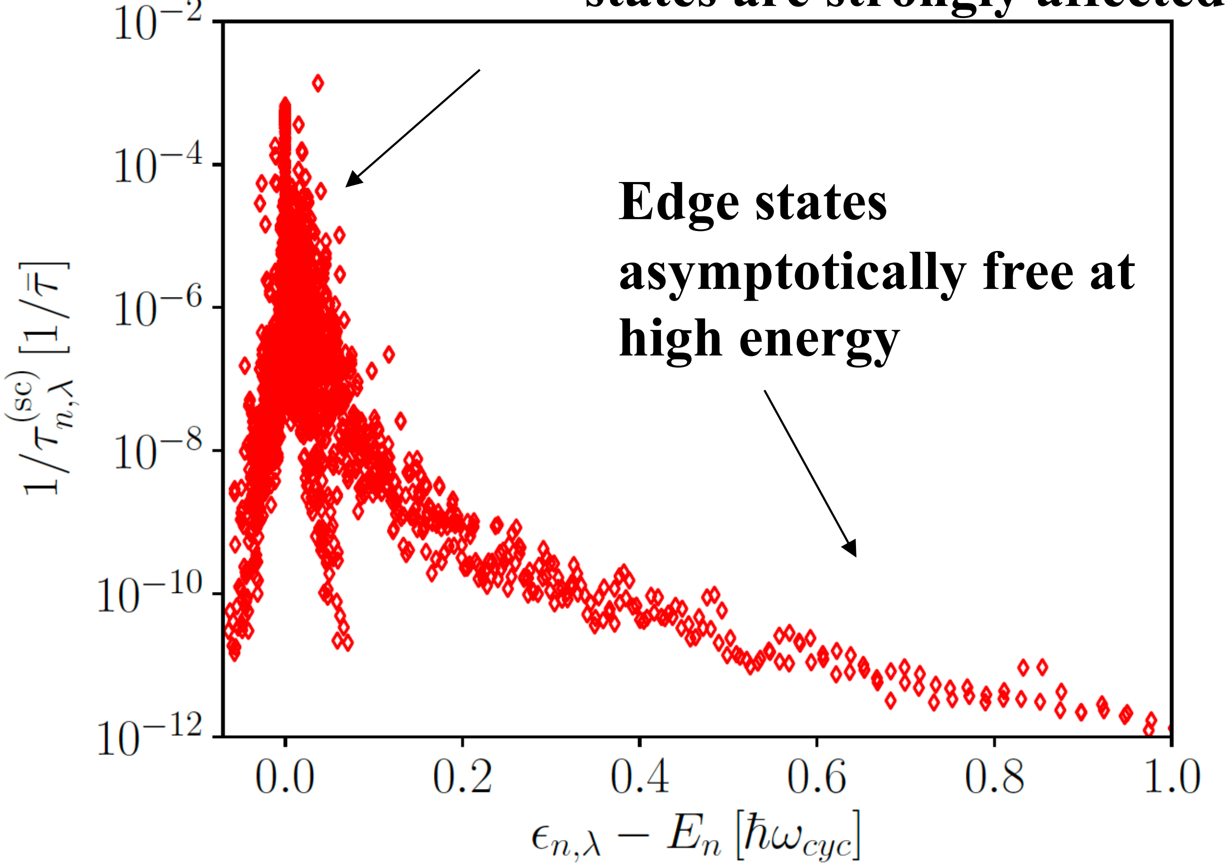
Long-range interaction



Cavity mediate-scattering rate

$$\frac{1}{\tau^{(sc)}_{n,\lambda}} = \frac{2\pi}{\hbar}\sum_{\lambda'\neq\lambda}|\Gamma^{(n)}_{\lambda,\lambda'}|^2\delta(\epsilon_{n,\lambda}-\epsilon_{n,\lambda'})$$

Edge states close to bulk states are strongly affected



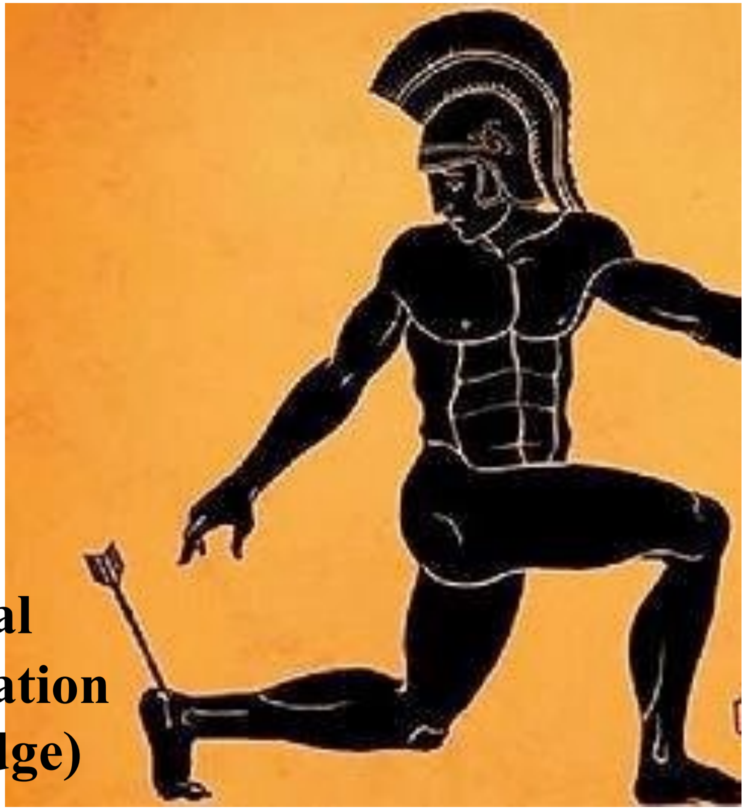
Edge states asymptotically free at high energy

$$\frac{1}{\bar{\tau}} \equiv \frac{2\pi}{\hbar}\tilde{\Gamma}^2\frac{N_{\text{deg}}}{\hbar\omega_{\text{cyc}}}$$

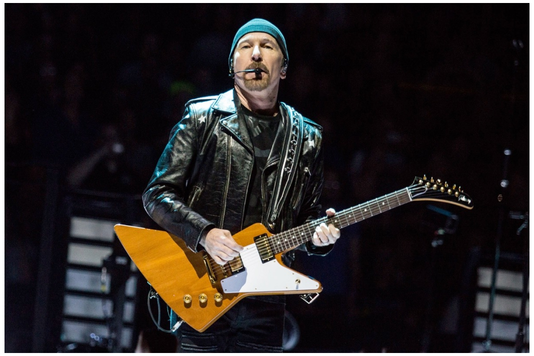
Characteristic rate

Achilles' heel of the integer quantum Hall effect

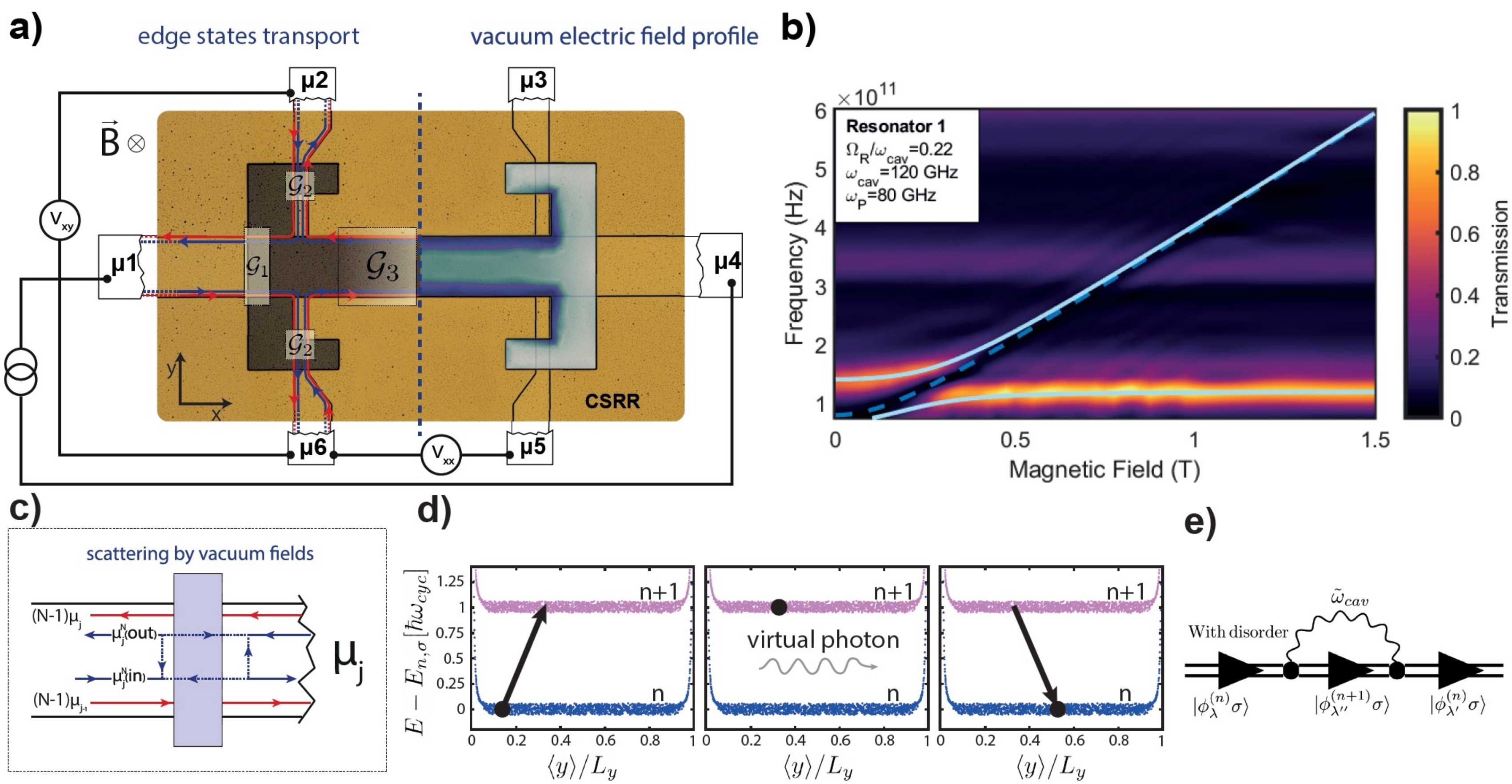
Topological insulator
(integer quantum Hall system)



Non-local perturbation (inter-edge)

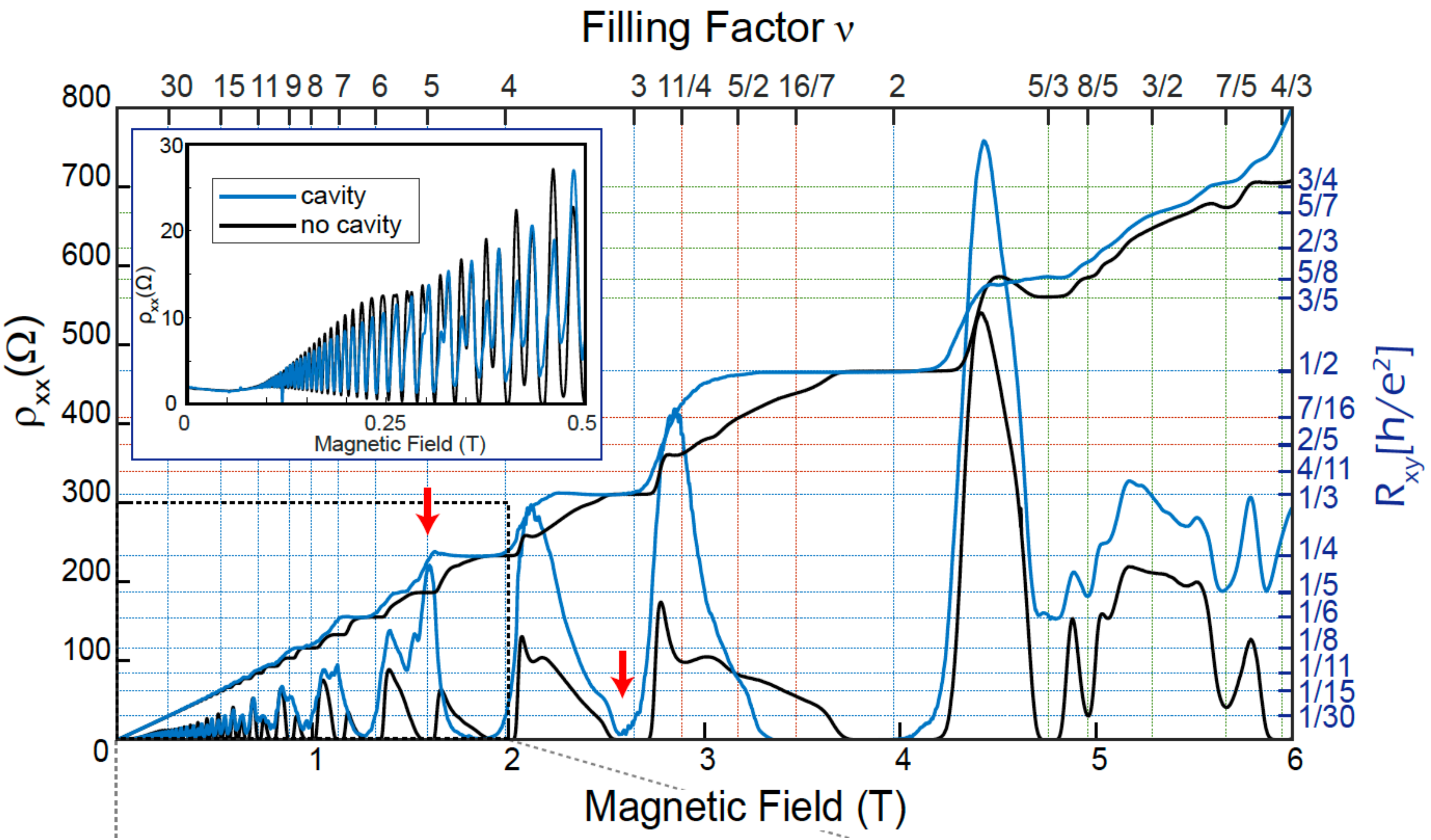


Experiments: J. Faist’s group @ ETH Zürich

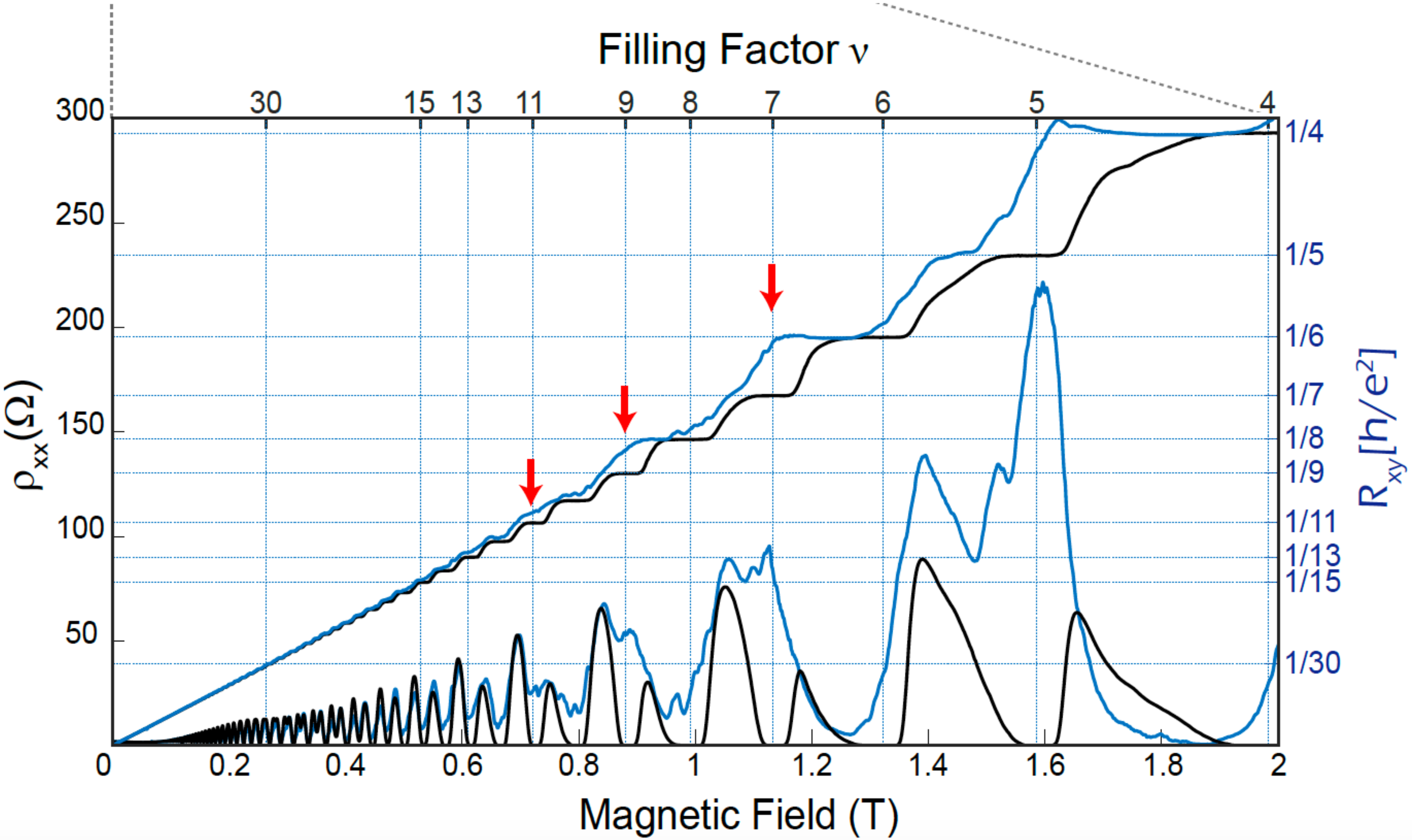


F. Appugliese, J. Enkner, G. L. Paravicini-Bagliani, M. Beck, Ch. Reichl, W. Wegscheider, G. Scalari, C. Ciuti, J. Faist, Science 375, 1030 (2022)

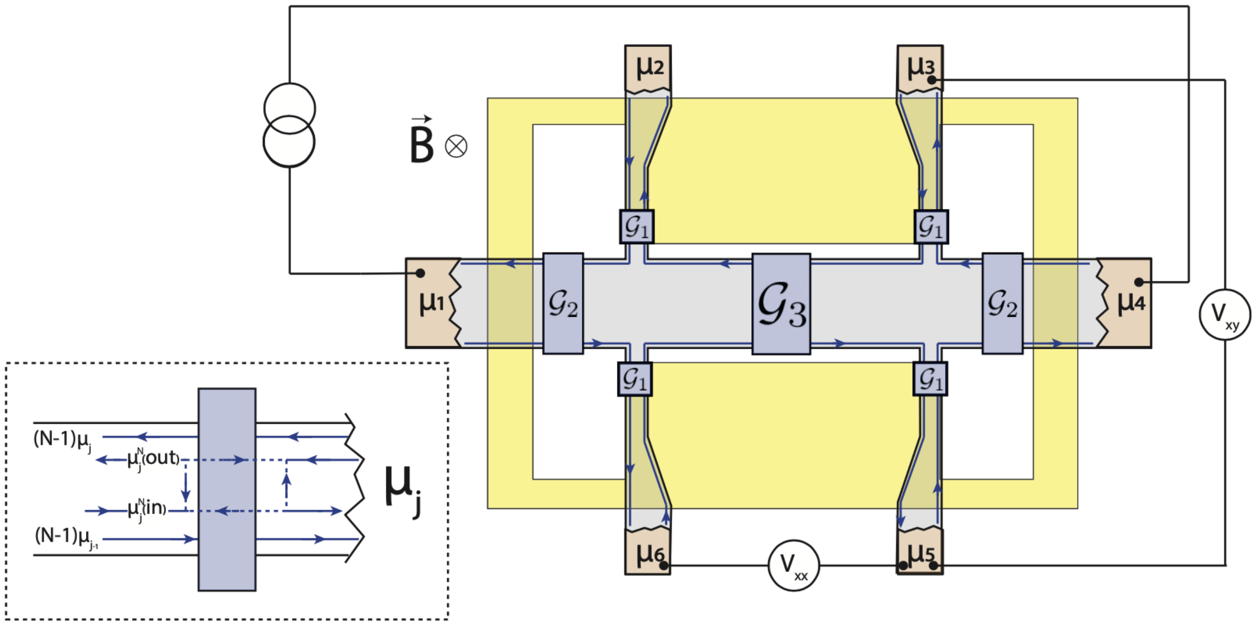
Experiments: J. Faist's group @ ETH Zürich



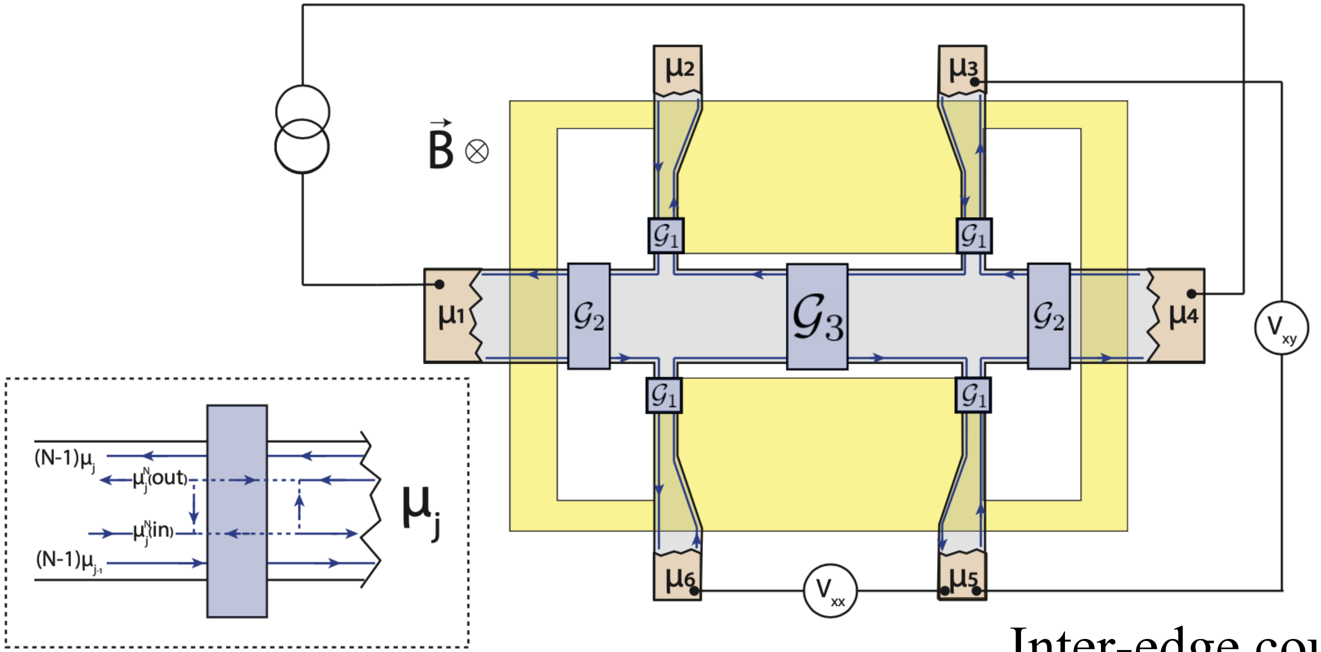
QH Plateaux at odd integer filling are destroyed….



Transport via the Büttiker formalism with inter-edge coupling



Multiprobe network model with inter-edge coupling



Büttiker's equations

$$\mu_j^{\mathrm{out}} = \mu_j t_j + \mu_j^{\mathrm{in}}(1 - t_j)$$

$$I_j = \left(\frac{e}{h}\right)\left[(N-1)(\mu_j - \mu_{j-1}) - \mu_j^{(in)} + \mu_j^{(out)}\right]$$

Inter-edge coupling

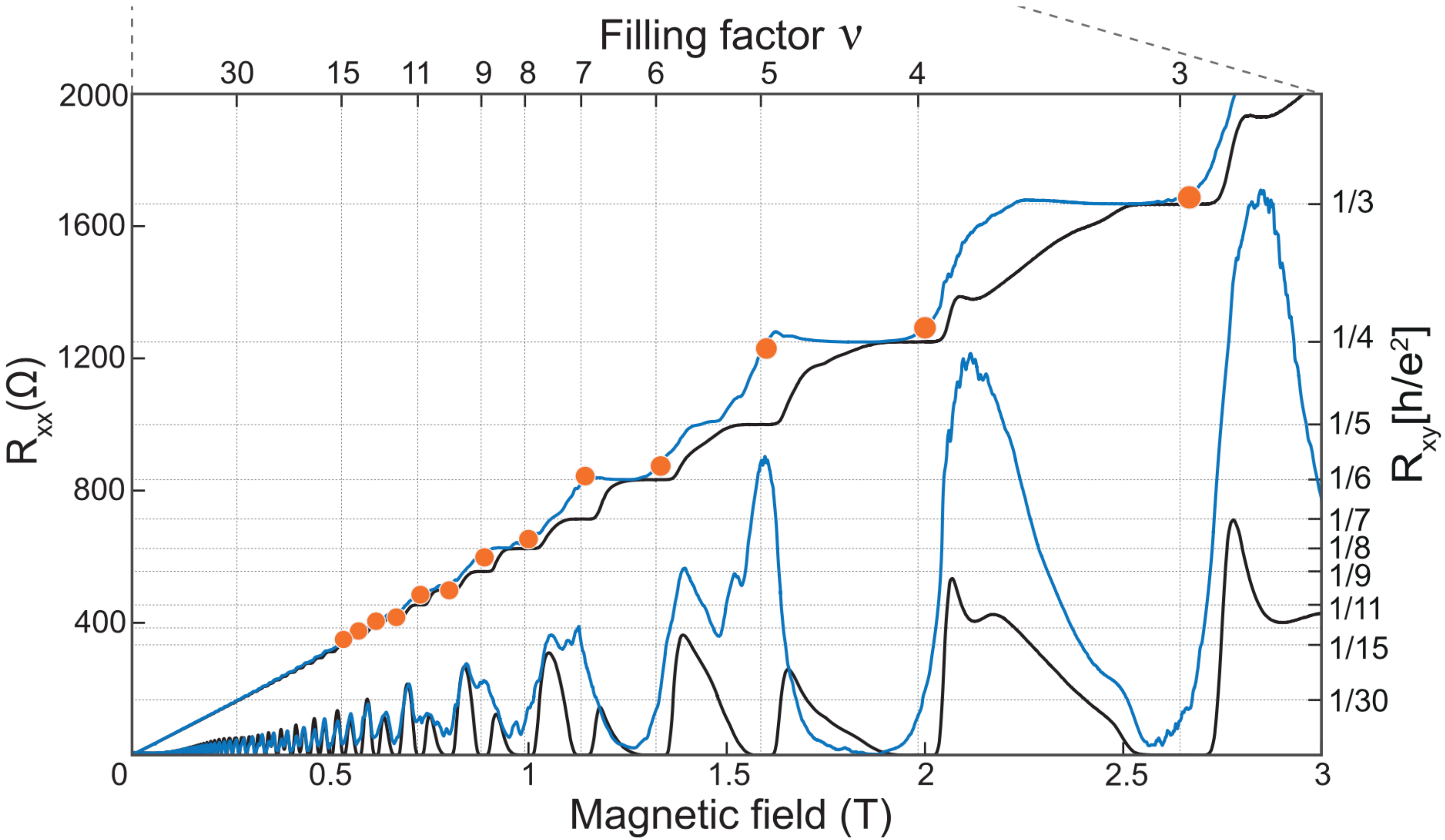
$$t_j = \frac{1}{1 + \rho_{xx}^{\nu}\mathcal{G}_j}$$

'Vacuum resistivity'

P. McEuen et al., PRL 64, 2062 (1990).

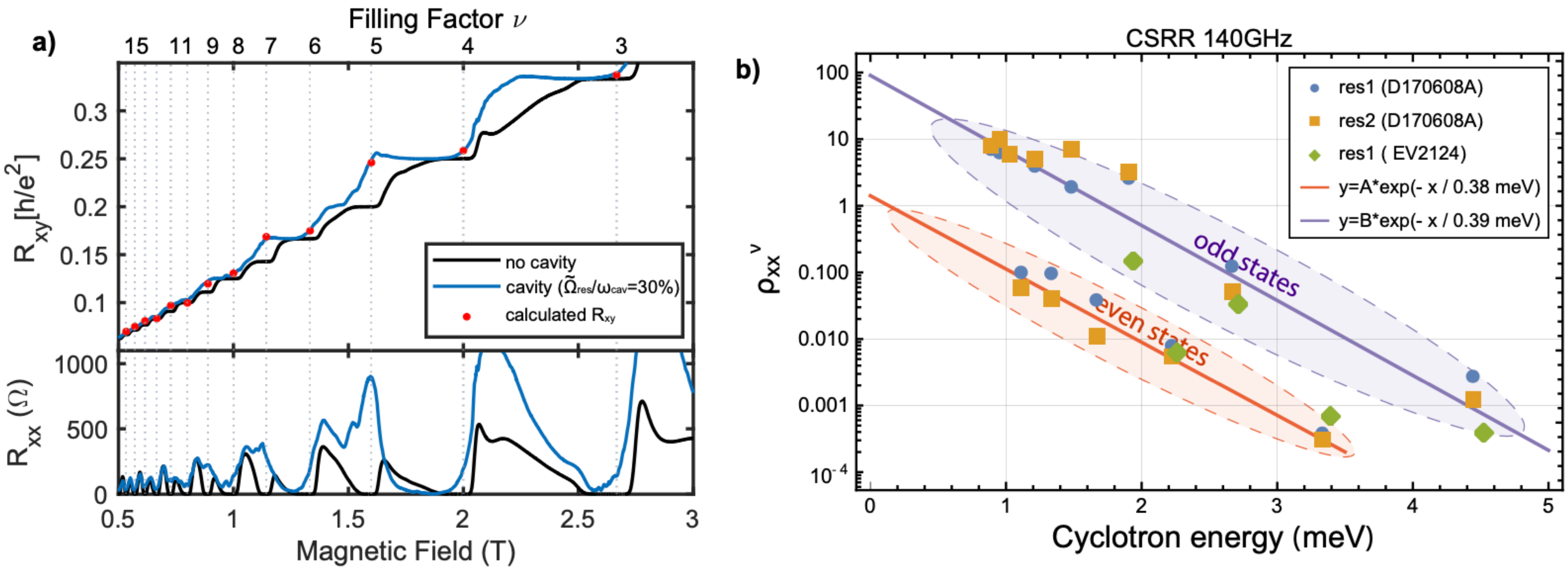
A. Szafer, A. D. Stone, P. McEuen, B. Alphenaar, Granular Nanoelectronics (Springer, 1991), pp. 195–222

Predictions of the model at integer filling factors



1) Inter-edge coupling fitted from longitudinal resistance
2) Transverse Hall resistance predicted without adjustable parameters

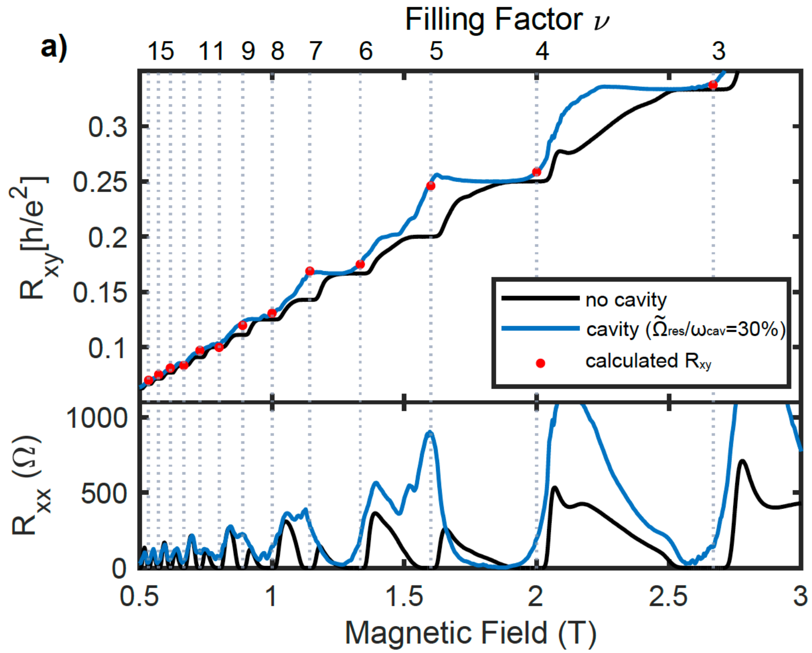
Application of the network model at integer filling factors

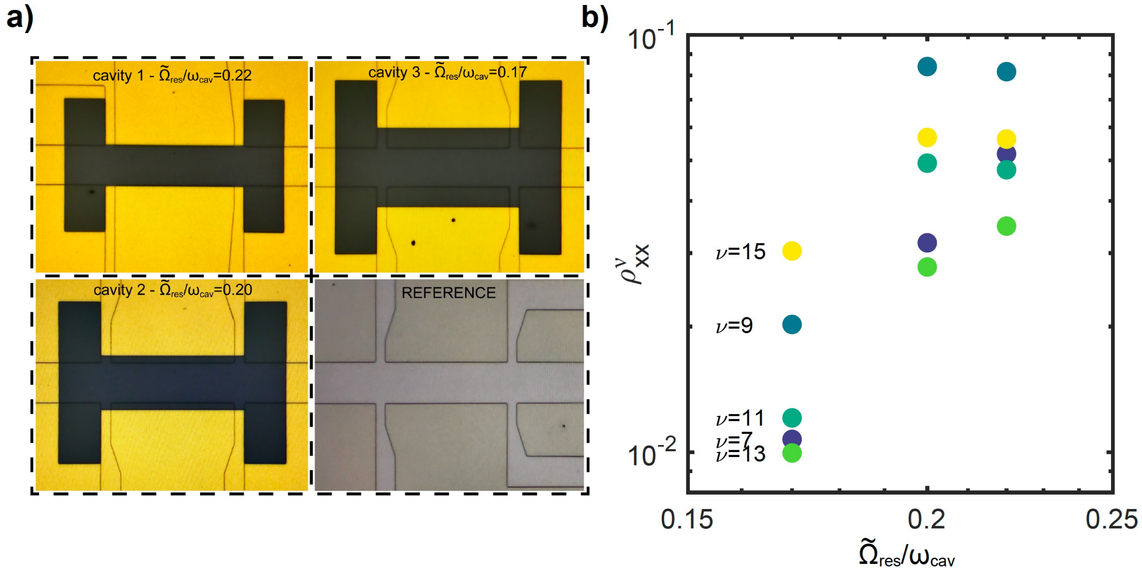


Knowing the longitudinal resistance, we can get the inter-edge coupling

With no adjustable parameters, we can then calculate the Hall resistance and find excellent agreement with experimental values

Effect increase with increasing vacuum Rabi frequency



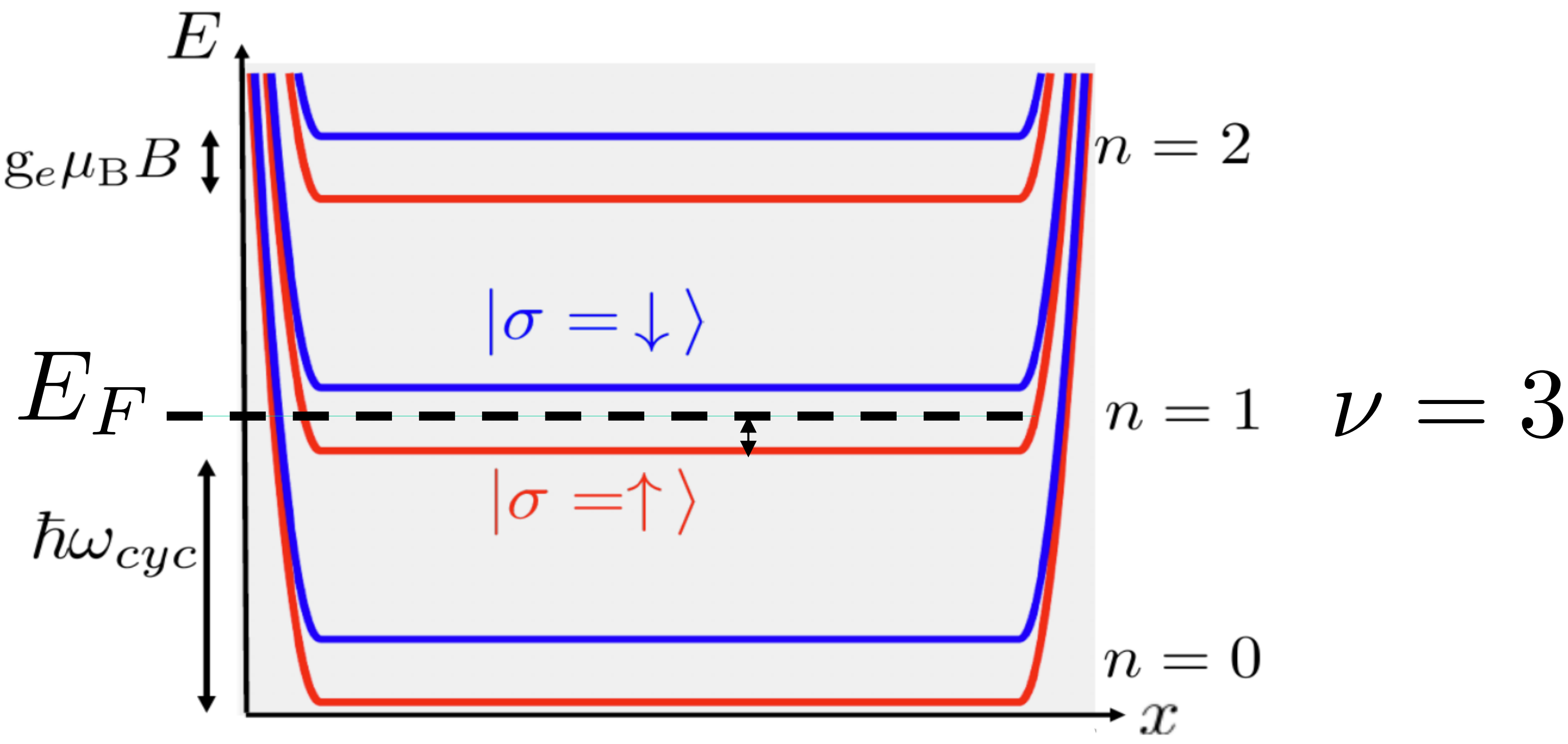


Why odd/even strong asymmetry?

Cavity-mediated hopping is spin-independent but ....

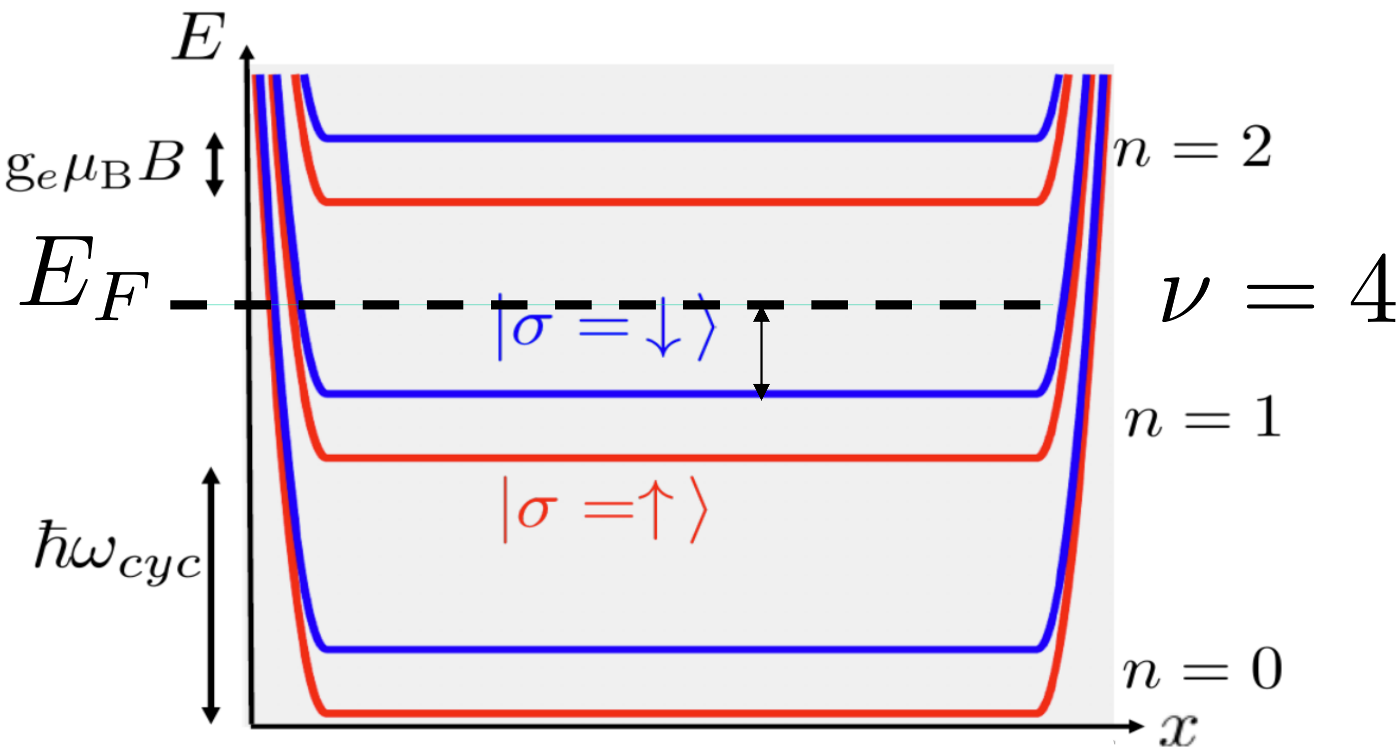
i) Cyclotron splitting much larger than Zeeman splitting

ii) **EDGE states** at **ODD integer filling factors** are **CLOSER TO BULK states**



Why odd/even strong asymmetry?

EDGE states at EVEN integer filling factors
are energetically more distant from bulk states

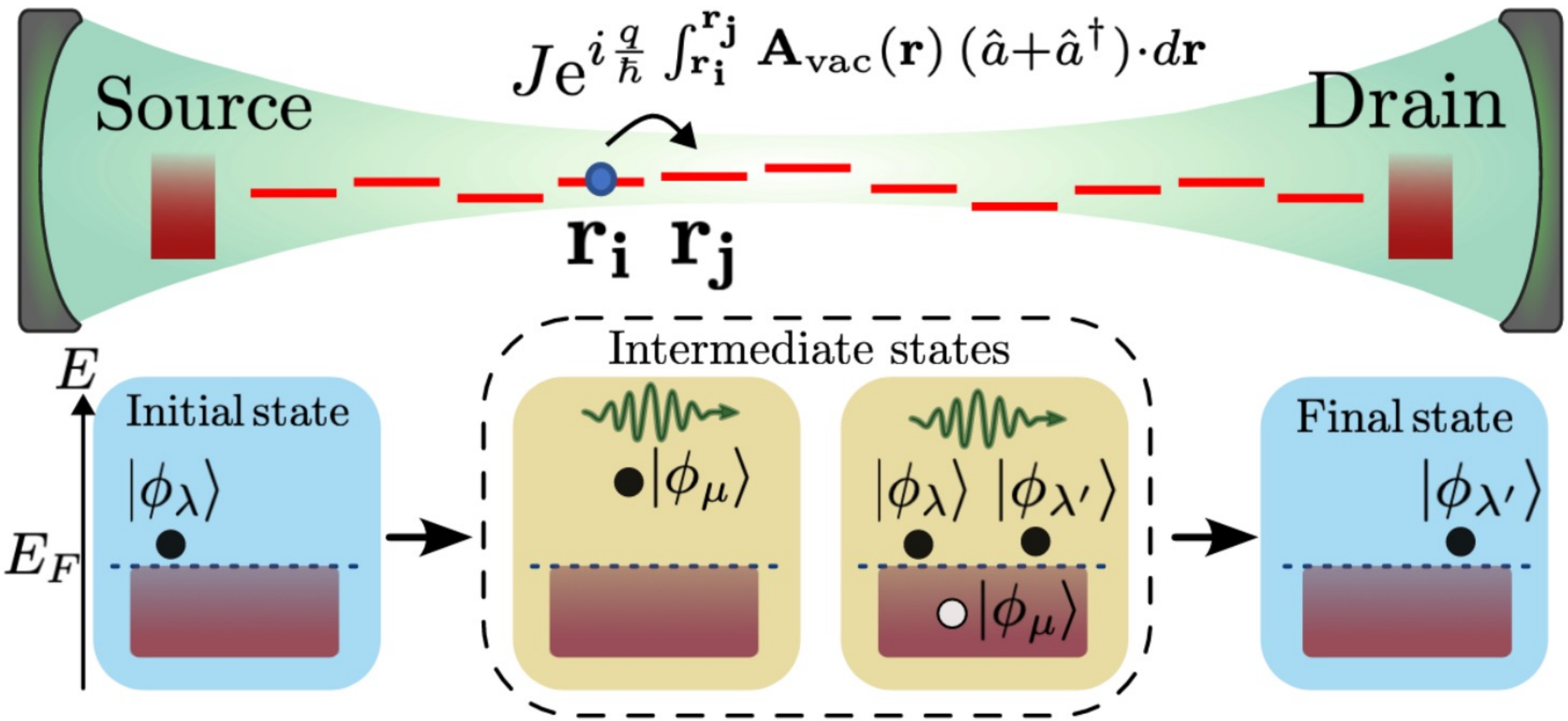


A general theoretical framework for coherent quantum electron transport controlled by cavity vacuum fields

Geva Arwas

G. Arwas and CC, arXiv:2206.13432

A microscopic quantum electron transport theory



Tight-binding model

$$\hat{\mathcal{H}} = \sum_{\mathbf{i}} E_{\mathbf{i}} \hat{d}^{\dagger}_{\mathbf{i}} \hat{d}_{\mathbf{i}} - \sum_{\langle \mathbf{i},\mathbf{j} \rangle} J e^{i \frac{q}{\hbar} \int_{\mathbf{r_i}}^{\mathbf{r_j}} \hat{\mathbf{A}}(\mathbf{r}) \cdot d\mathbf{r}} \hat{d}^{\dagger}_{\mathbf{i}} \hat{d}_{\mathbf{j}} + \hbar \omega_{cav} \hat{a}^{\dagger} \hat{a}$$

$$g_{\mathbf{ij}} = \frac{q}{\hbar} \int_{\mathbf{r_i}}^{\mathbf{r_j}} \mathbf{A}_{\text{vac}}(\mathbf{r}) \cdot d\mathbf{r}$$

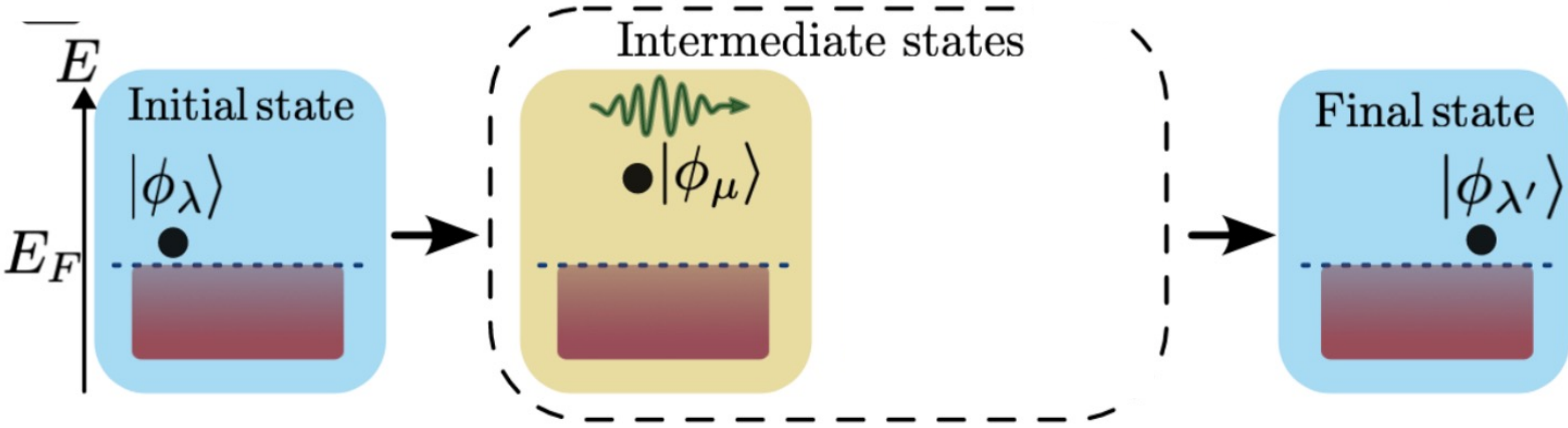
$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_0 + \hbar \omega_{\text{cav}} \hat{a}^{\dagger} \hat{a} + \hat{V}$$

$$\hat{\mathcal{H}}_0 = \sum_{\mathbf{i}} E_{\mathbf{i}} \hat{d}^{\dagger}_{\mathbf{i}} \hat{d}_{\mathbf{i}} - J \sum_{\langle \mathbf{i},\mathbf{j} \rangle} \hat{d}^{\dagger}_{\mathbf{i}} \hat{d}_{\mathbf{j}} = \sum_{\lambda} \epsilon_{\lambda} \hat{c}^{\dagger}_{\lambda} \hat{c}_{\lambda}$$

$$\hat{V} = -J \sum_{\lambda,\lambda'} \sum_{n=1}^{\infty} \frac{\mathrm{i}^n}{n!} \tilde{g}^{(n)}_{\lambda,\lambda'} (\hat{a} + \hat{a}^{\dagger})^n \hat{c}^{\dagger}_{\lambda} \hat{c}_{\lambda'}$$

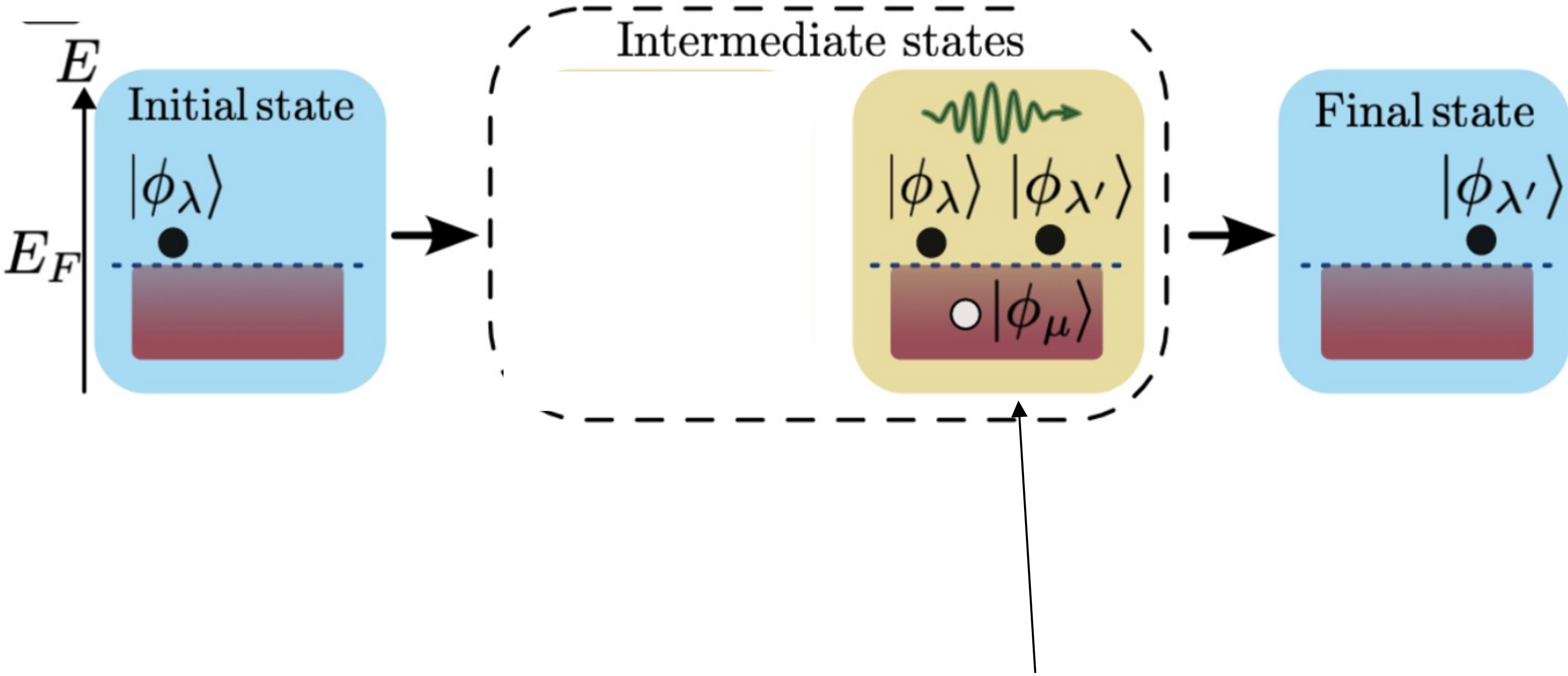
$$\tilde{g}^{(n)}_{\lambda\lambda'} = \sum_{\langle \mathbf{i},\mathbf{j} \rangle} g^n_{\mathbf{ij}} \langle \phi_{\lambda} | \mathbf{i} \rangle \langle \mathbf{j} | \phi_{\lambda'} \rangle$$

Effective interaction mediated by intermediate states



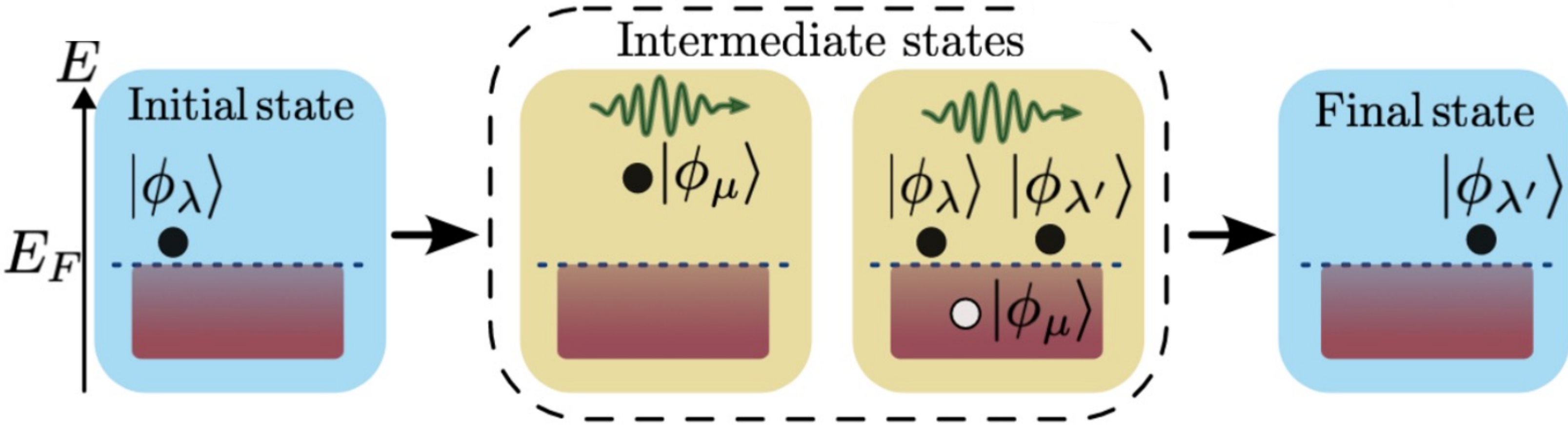
$$\hat{c}_\lambda^\dagger|G\rangle \;\rightarrow\; \hat{c}_\mu^\dagger \hat{a}^\dagger|G\rangle \;\rightarrow\; \hat{c}_{\lambda'}^\dagger|G\rangle$$

Effective interaction mediated by intermediate states



$$\hat{c}^\dagger_\lambda|G\rangle \;\rightarrow\; \hat{c}^\dagger_\lambda \hat{c}^\dagger_{\lambda'} \hat{c}_\mu \hat{a}^\dagger|G\rangle \;\rightarrow\; \hat{c}^\dagger_{\lambda'}|G\rangle$$

Effective interaction mediated by intermediate states



$$\tilde{\Gamma}_{\lambda,\lambda'} \simeq \sum_{\epsilon_\mu \geq E_F} \frac{J^2\, \tilde{g}_{\lambda,\mu}\tilde{g}_{\mu,\lambda'}}{\epsilon_\mu - \epsilon_\lambda + \hbar\omega_{cav}} - \sum_{\epsilon_\mu < E_F} \frac{J^2\, \tilde{g}_{\lambda,\mu}\tilde{g}_{\mu,\lambda'}}{\epsilon_{\lambda'} - \epsilon_\mu + \hbar\omega_{cav}}$$

$$\hat{\mathcal{H}}_{\text{eff}} = \sum_{\lambda} \epsilon_\lambda |\phi_\lambda\rangle\langle\phi_\lambda| + \sum_{\lambda,\lambda'} \frac{\tilde{\Gamma}_{\lambda,\lambda'} + \tilde{\Gamma}^*_{\lambda',\lambda}}{2} |\phi_\lambda\rangle\langle\phi_{\lambda'}|\,.$$

Quantum conductance in terms of transmission coefficients

$$G(E_\mathrm{F}) = \frac{e^2}{h} \sum_{j \in \mathcal{S}\,, j' \in \mathcal{D}} T_{j,j'}(E_\mathrm{F})$$

Transmission matrix between contacts calculated with effective Hamiltonian

See e.g.

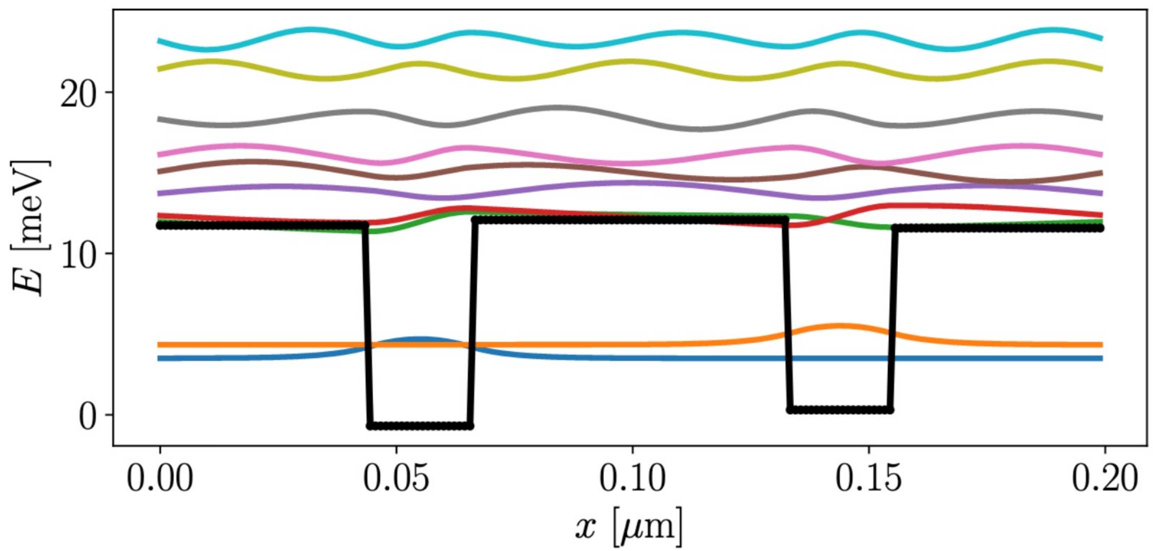
ELECTRONIC TRANSPORT IN MESOSCOPIC SYSTEMS

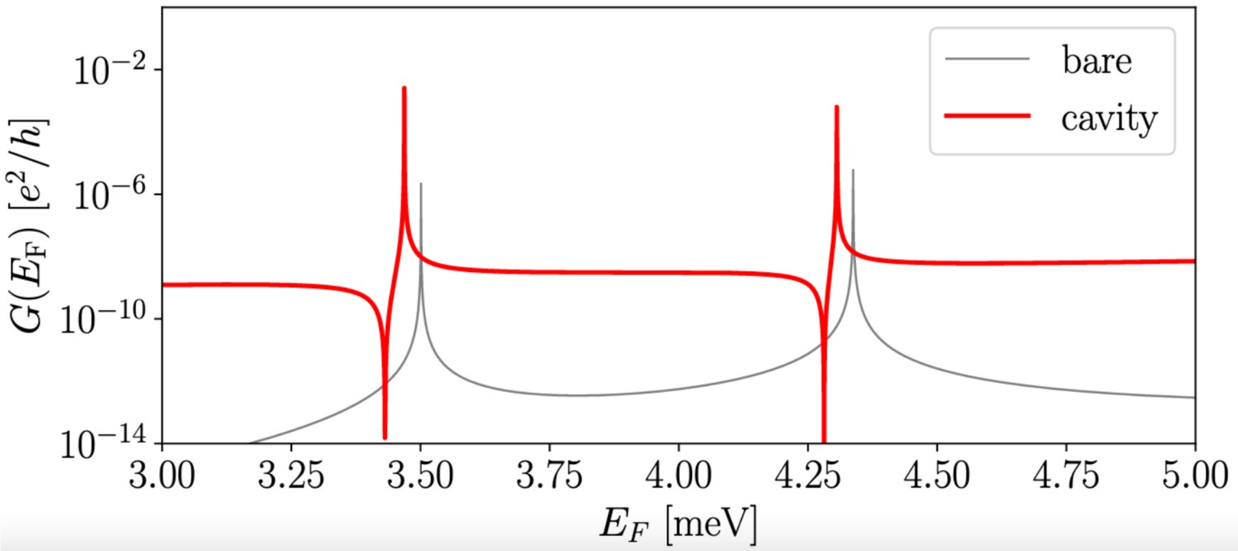
SUPRIYO DATTA

Professor of Electrical Engineering
Purdue University

CAMBRIDGE UNIVERSITY PRESS

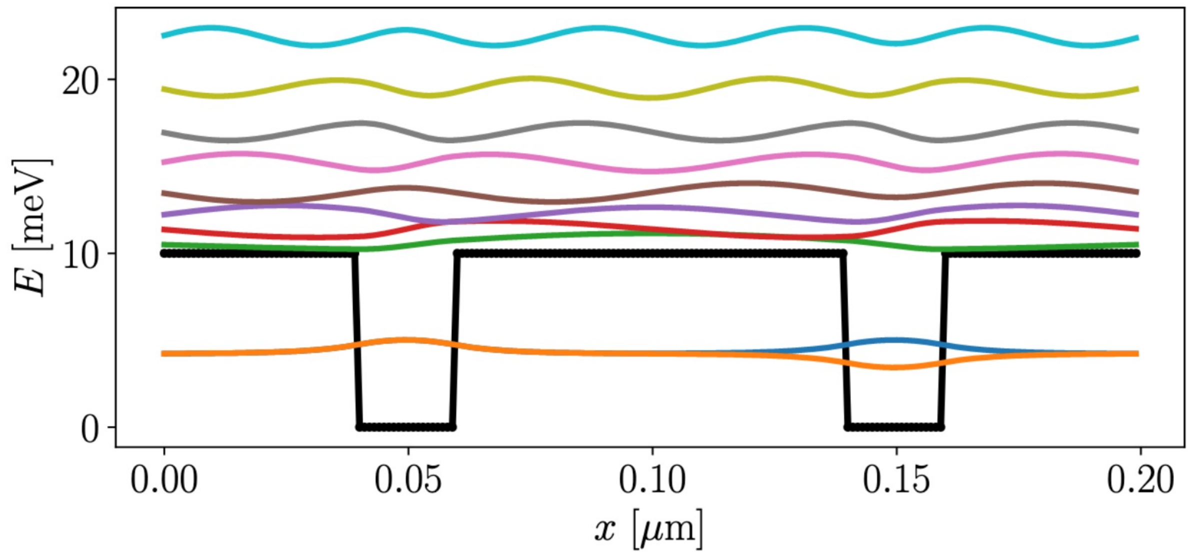
Example of 1D system: asymmetric double quantum well

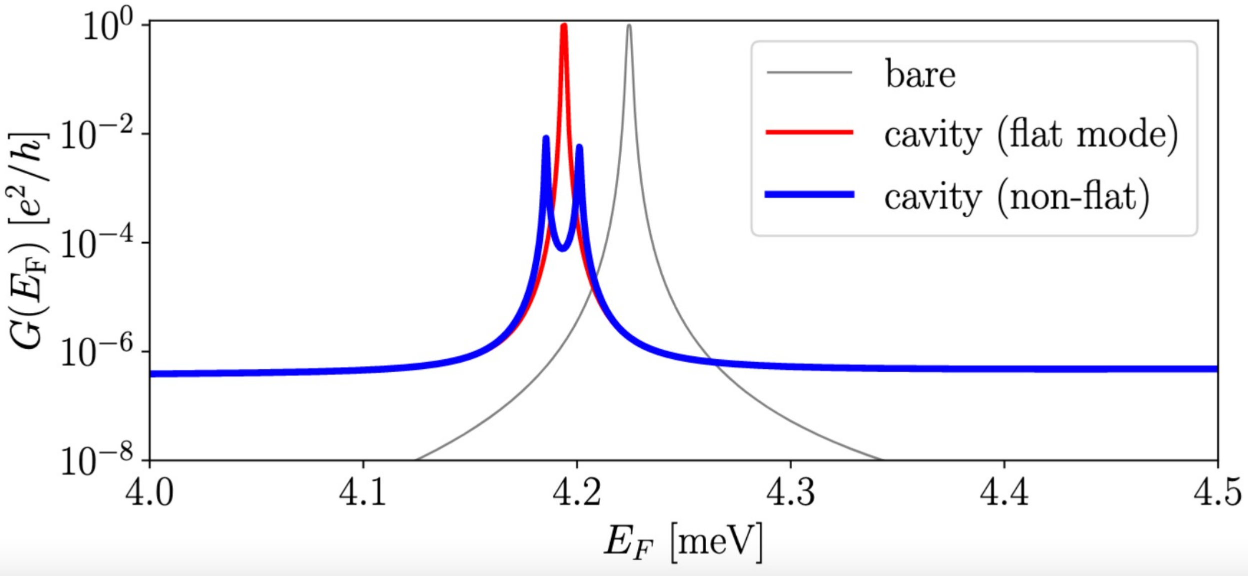




Conductance enhancement

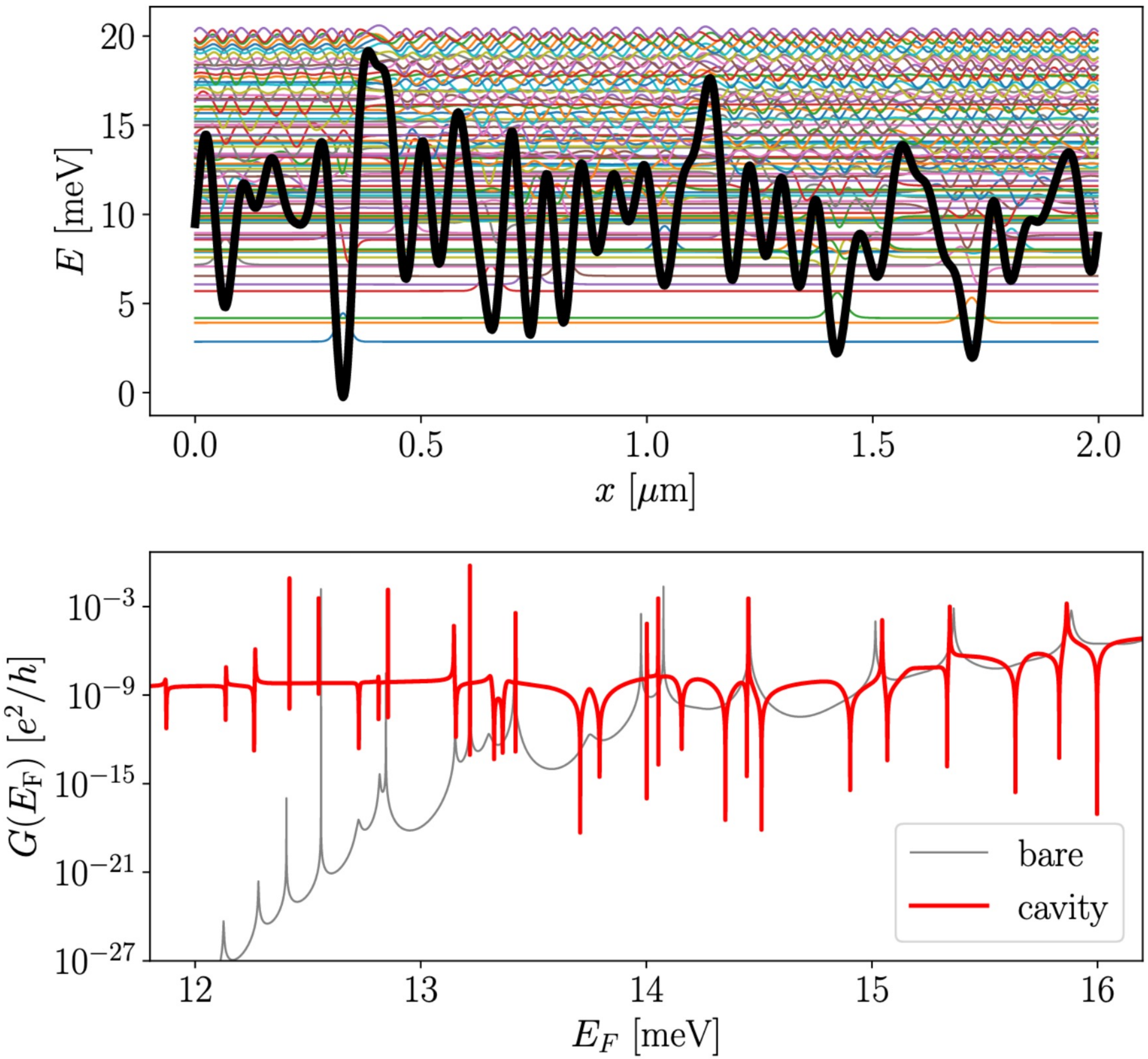
Example of 1D system: symmetric double well



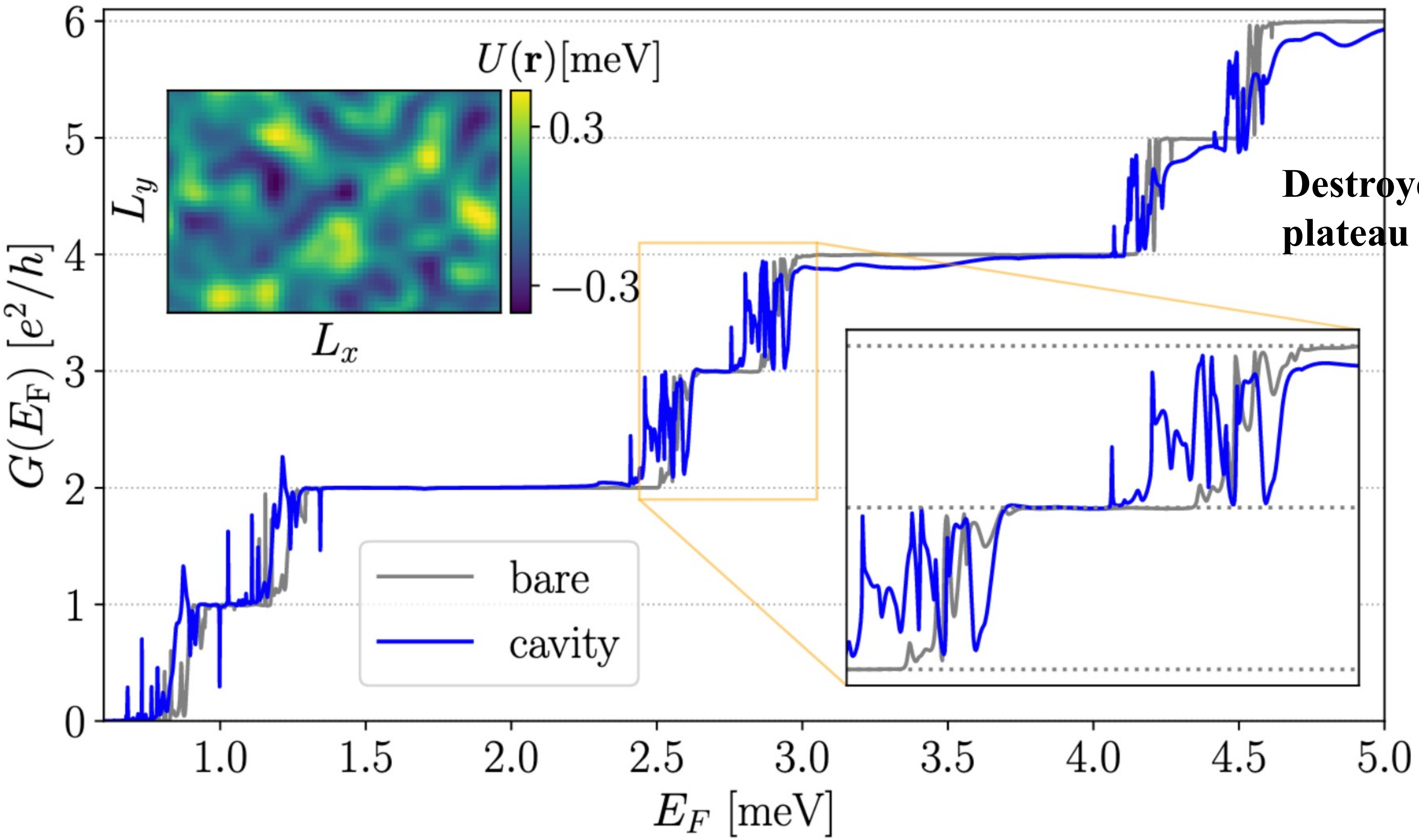


Conductance suppression

Example of 1D system: smooth disordered potential



Example of 2D system: disordered quantum Hall system



Destroyed plateau

Take-home message

Electromagnetic vacuum fluctuations cannot be generally overlooked in mesoscopic systems

Cavity-mediated long-range interactions alter quantum transport

Topological conductors not immune to cavity-mediated interactions

Challenge: we might try this physics as a tool to control