Quantum Connections in Sweden-16
Summer School

Less is more:

The power of vacuum quantum fluctuations

Qing-Dong Jiang

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TSUNG-DAO LEE INSTITUTE

Quantum Connections in Sweden-16
Summer School

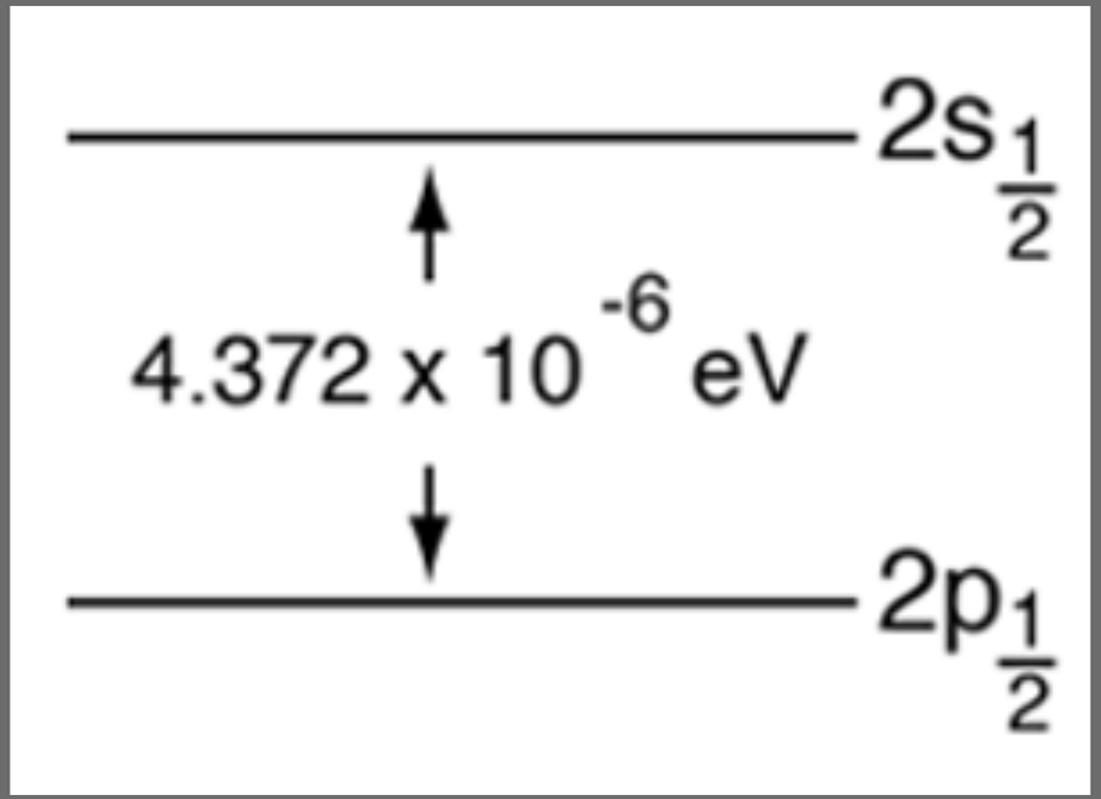
Lecture 1: Renormalization and Casimir Physics

Lecture 2: Casimir Torque, Friction and Spectra

Lecture 3: Quantum atmosphere

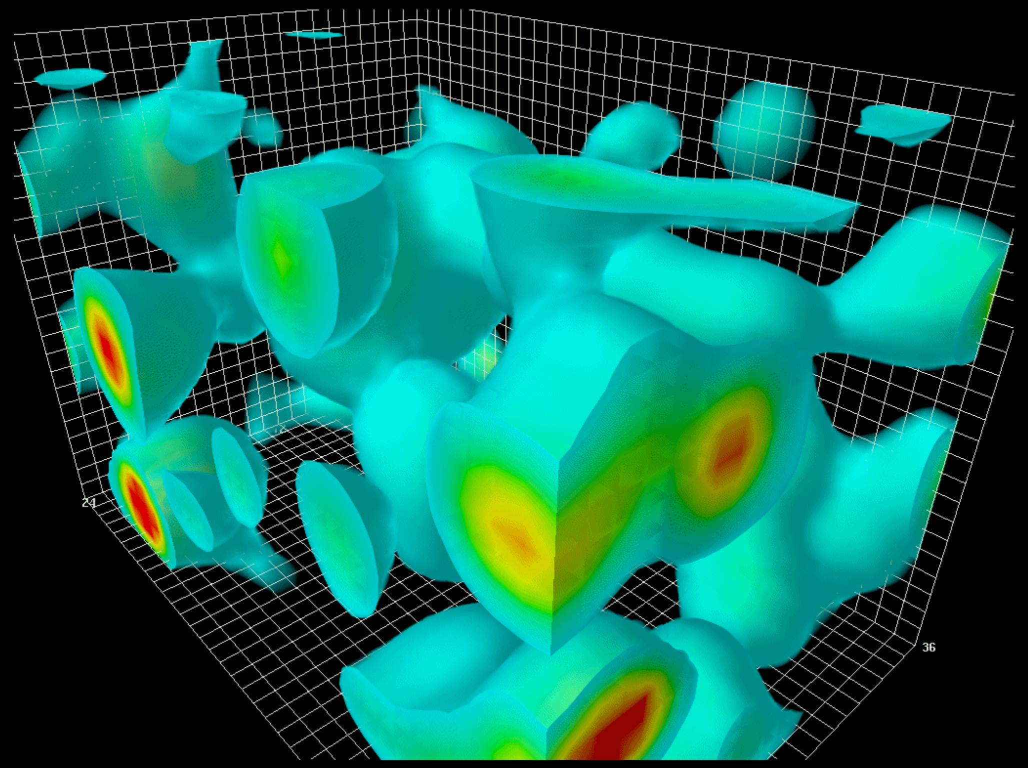
Lecture 4: Cavity Quantum Materials

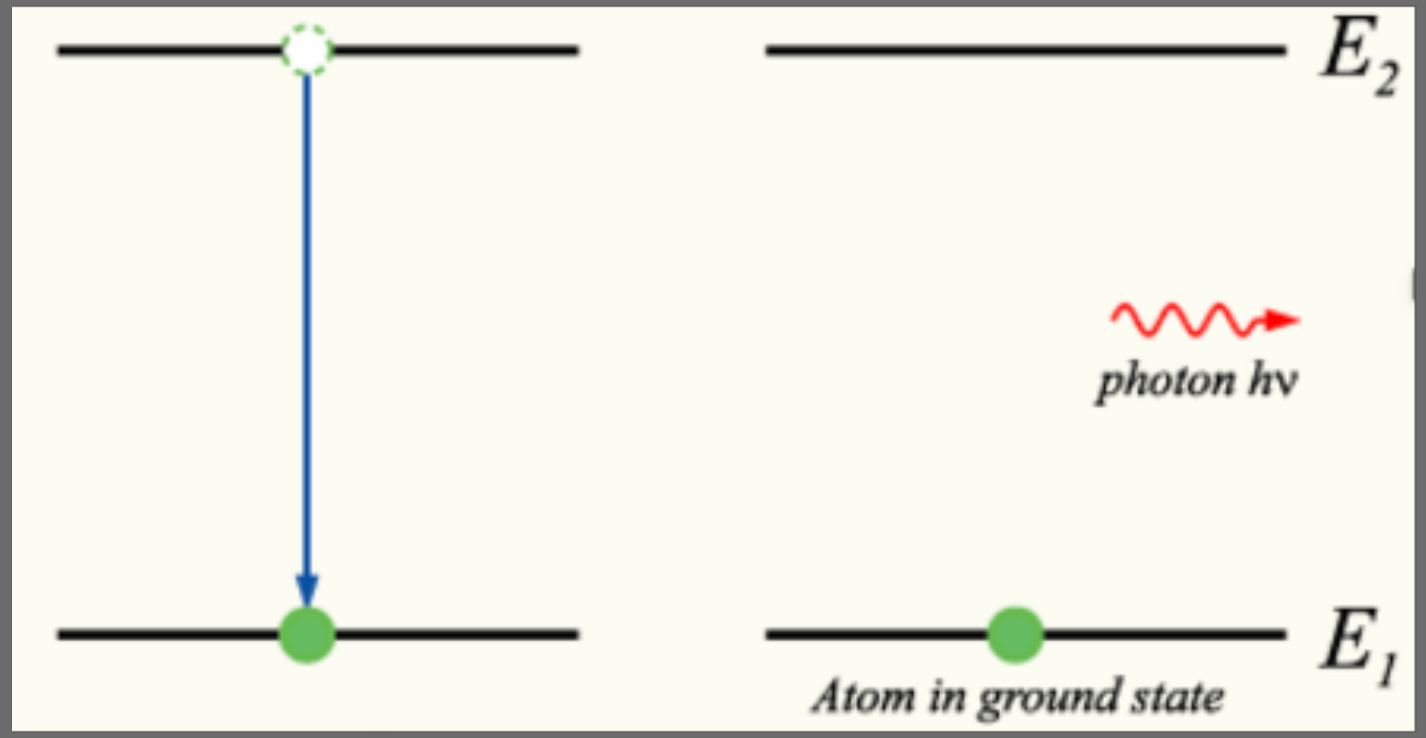
Visible Vacuum Quantum Fluctuations



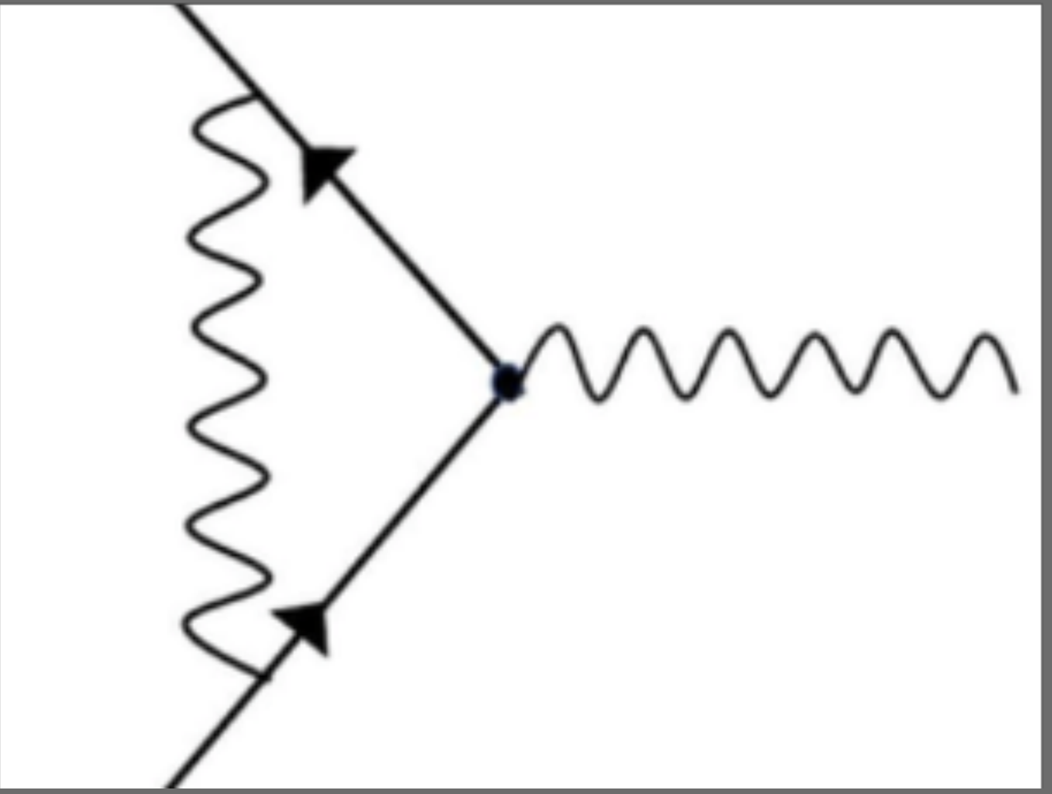
(1955)

Lamb shift



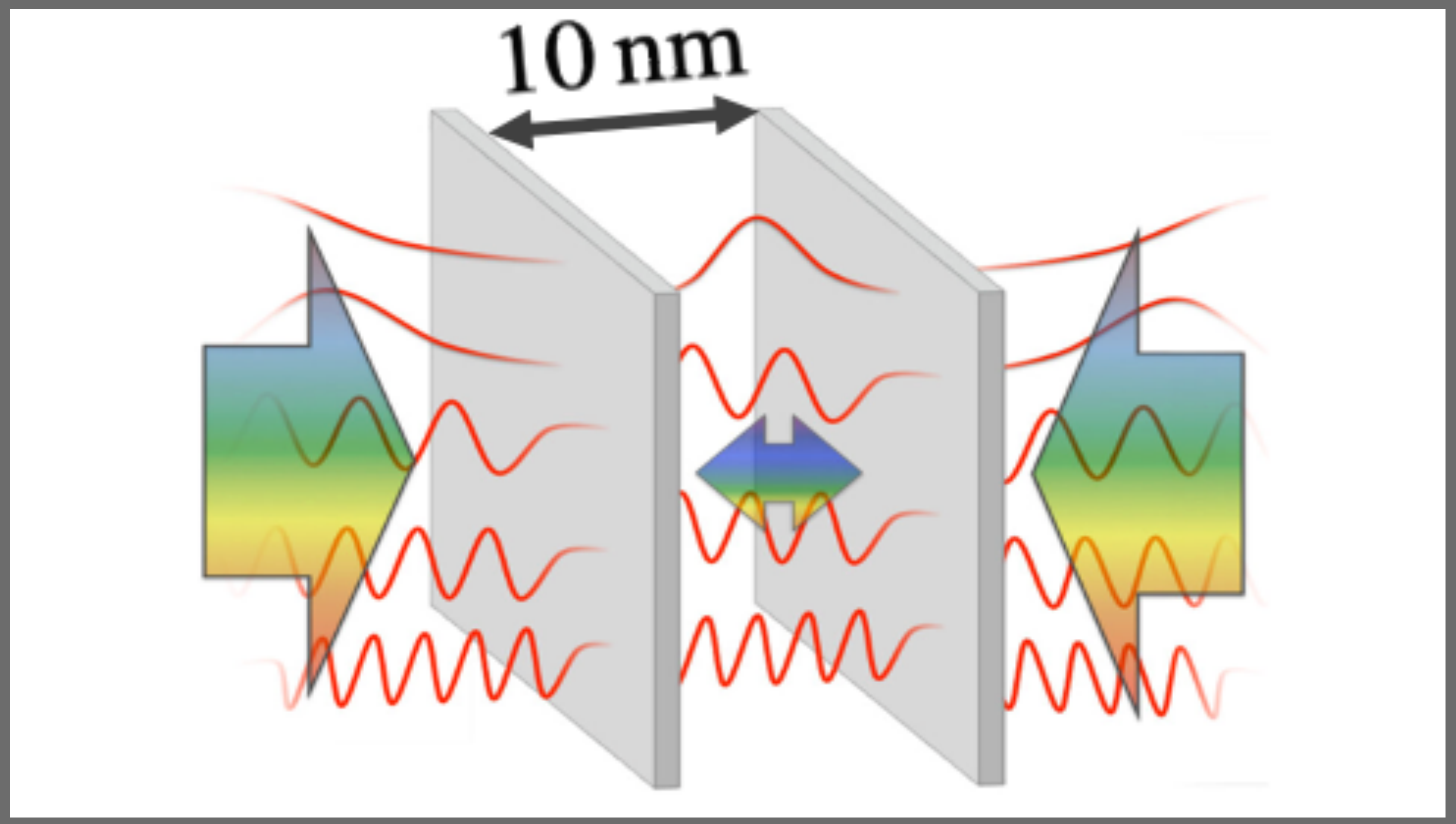


Spontaneous emission



(1955, 1965)

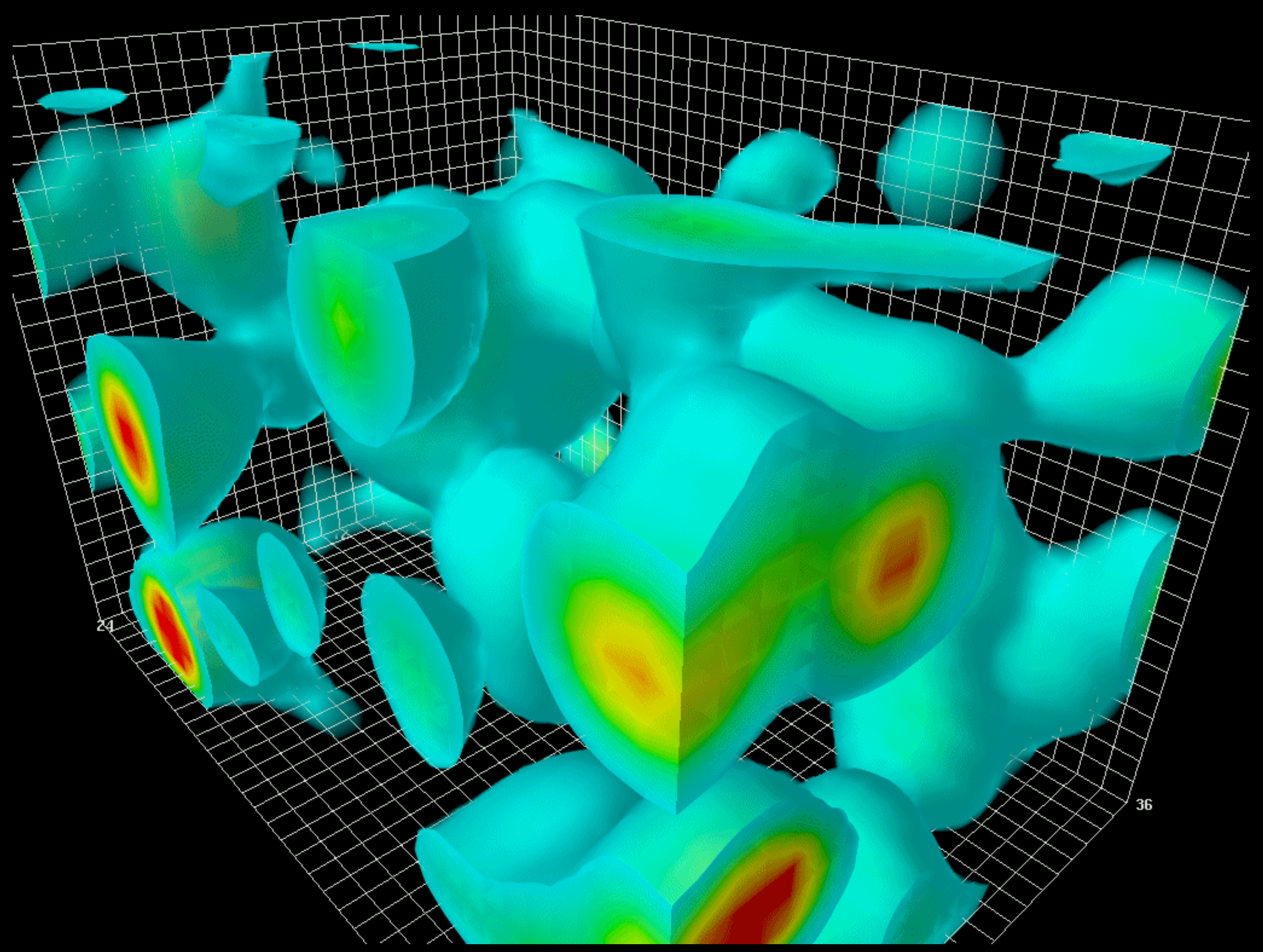
Anomalous magnetic moment



Casimir effect

How quantum fluctuations can Shape Matter*

* npj Nanophotonics 2, 46 (2025)



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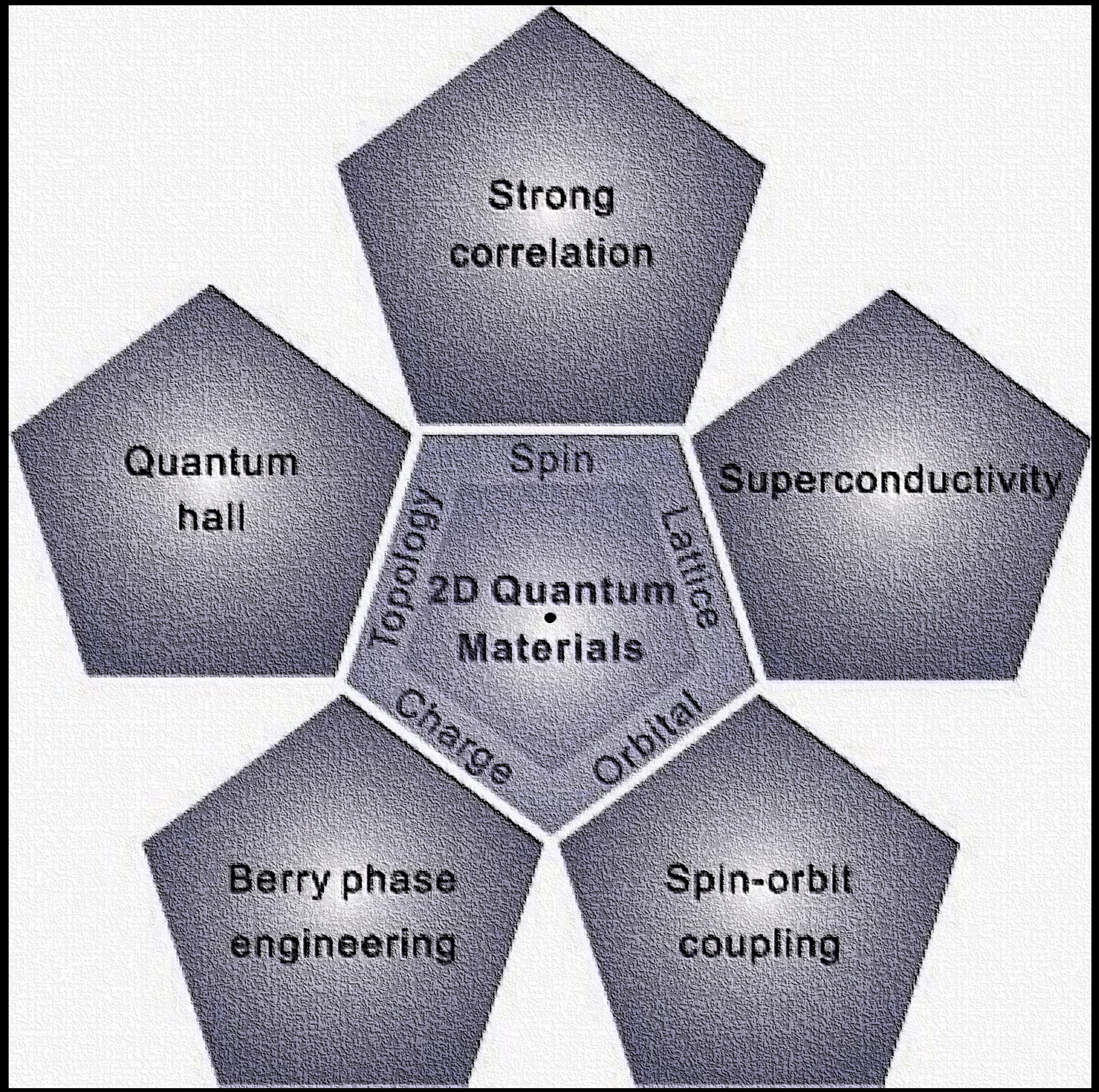

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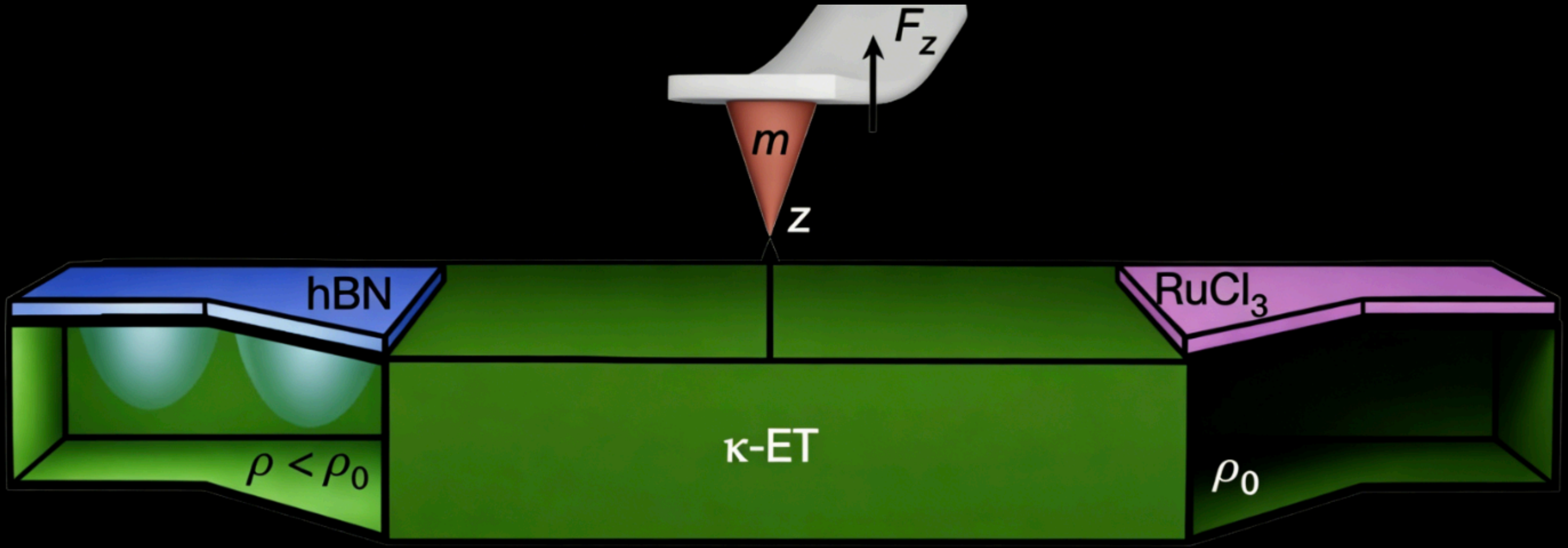
Quantum Materials? **Symmetry & Topology & Interactions**

How quantum fluctuations can Shape Matter*

* npj Nanophotonics 2, 46 (2025)



Basov group: Nature 650, 864 (2026)

Outline

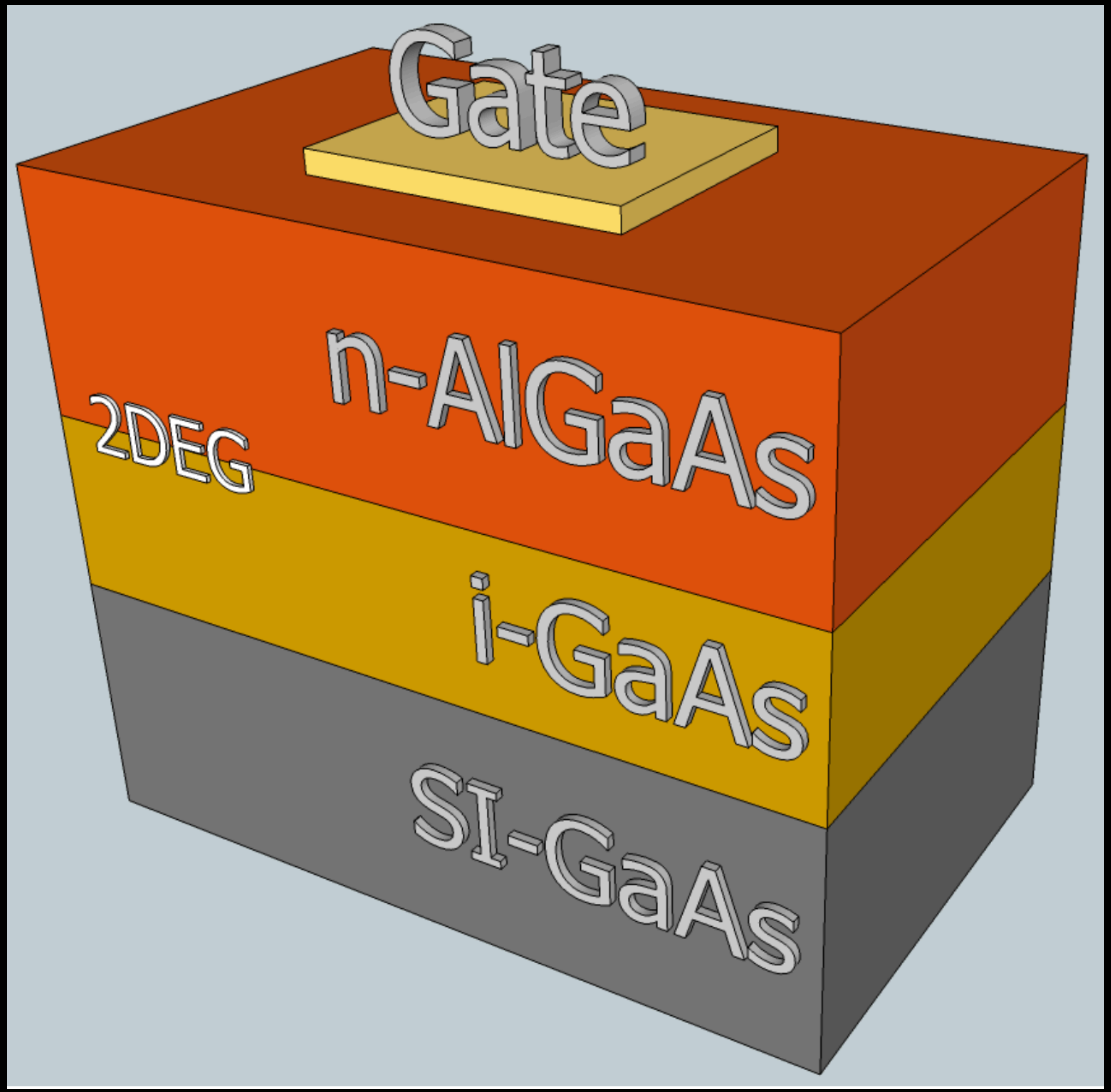
I. Vacuum modified topology

II. Vacuum renormalized band structure

III. Vacuum induced chiral spin liquids

IV. Summary and outlooks

Two dimensional electron gas



Very Clean

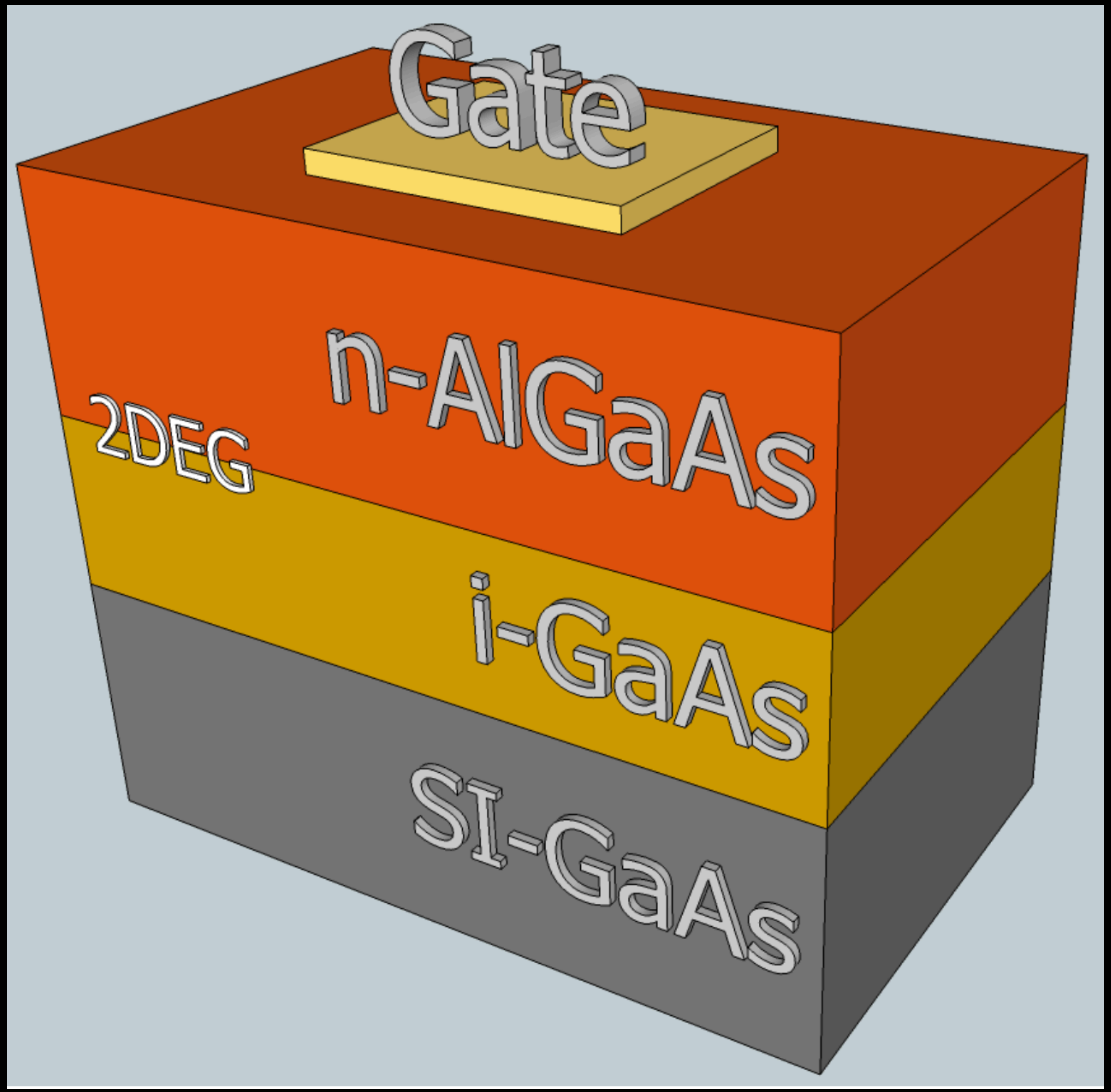
2 dimensional electron gas (2DEG)

Mean free path:

$$\ell = v_F \tau = \sqrt{2\pi n}\frac{\hbar\mu}{e} \approx 5.2\ \mu\text{m} \times \mu\ [10^6\ \text{cm}^2/\text{Vs}]\sqrt{n\ [10^{11}\ \text{cm}^{-2}]}$$

$$5.2\ \mu m \sim 10^4\ a_{lattice}$$

Two dimensional electron gas



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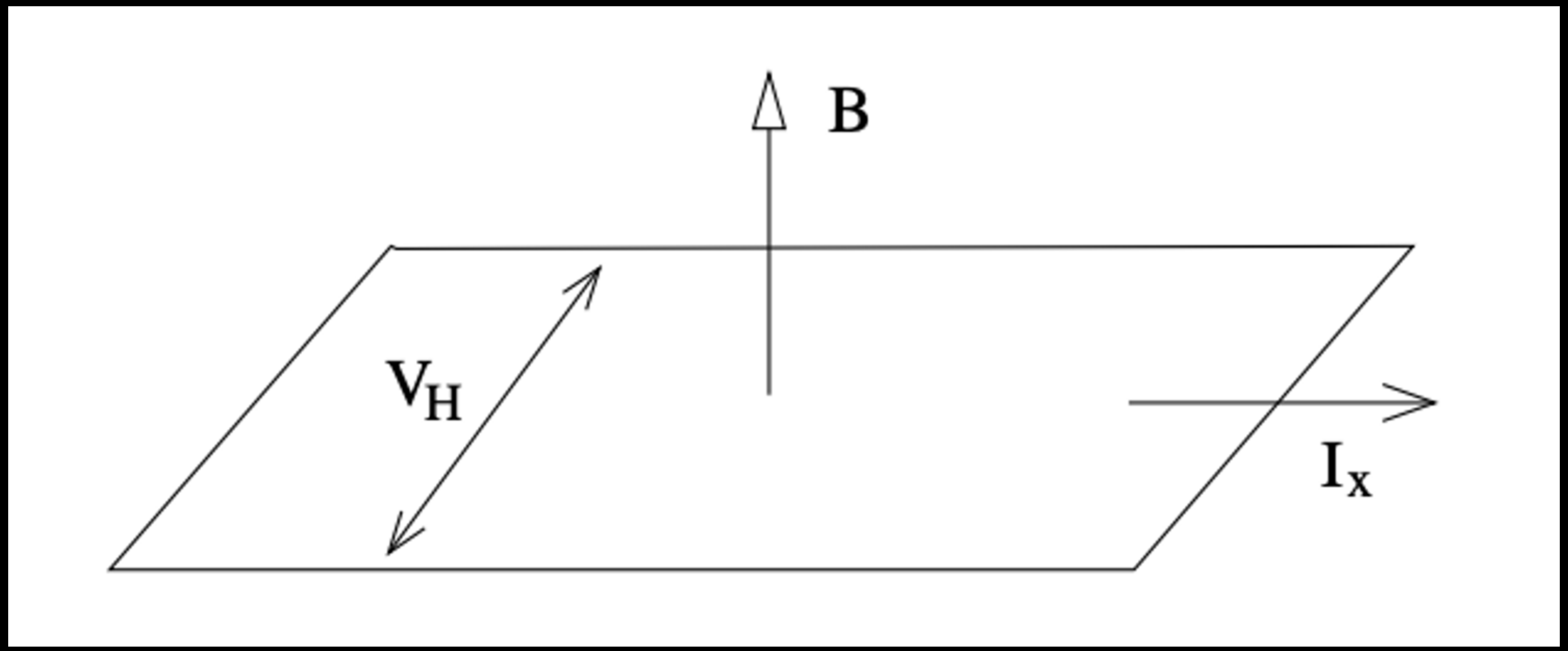
2 Nobel prizes: Quantum Hall effect
Fractional Quantum Hall effect

Quantum Hall Effect



$$m\frac{d\mathbf{v}}{dt} = -e\mathbf{v} \times \mathbf{B}$$

$$\mathrm{R}_H = h/e\text{^}2$$

David Tong, arXiv:1606.06687

Magnetic Scales

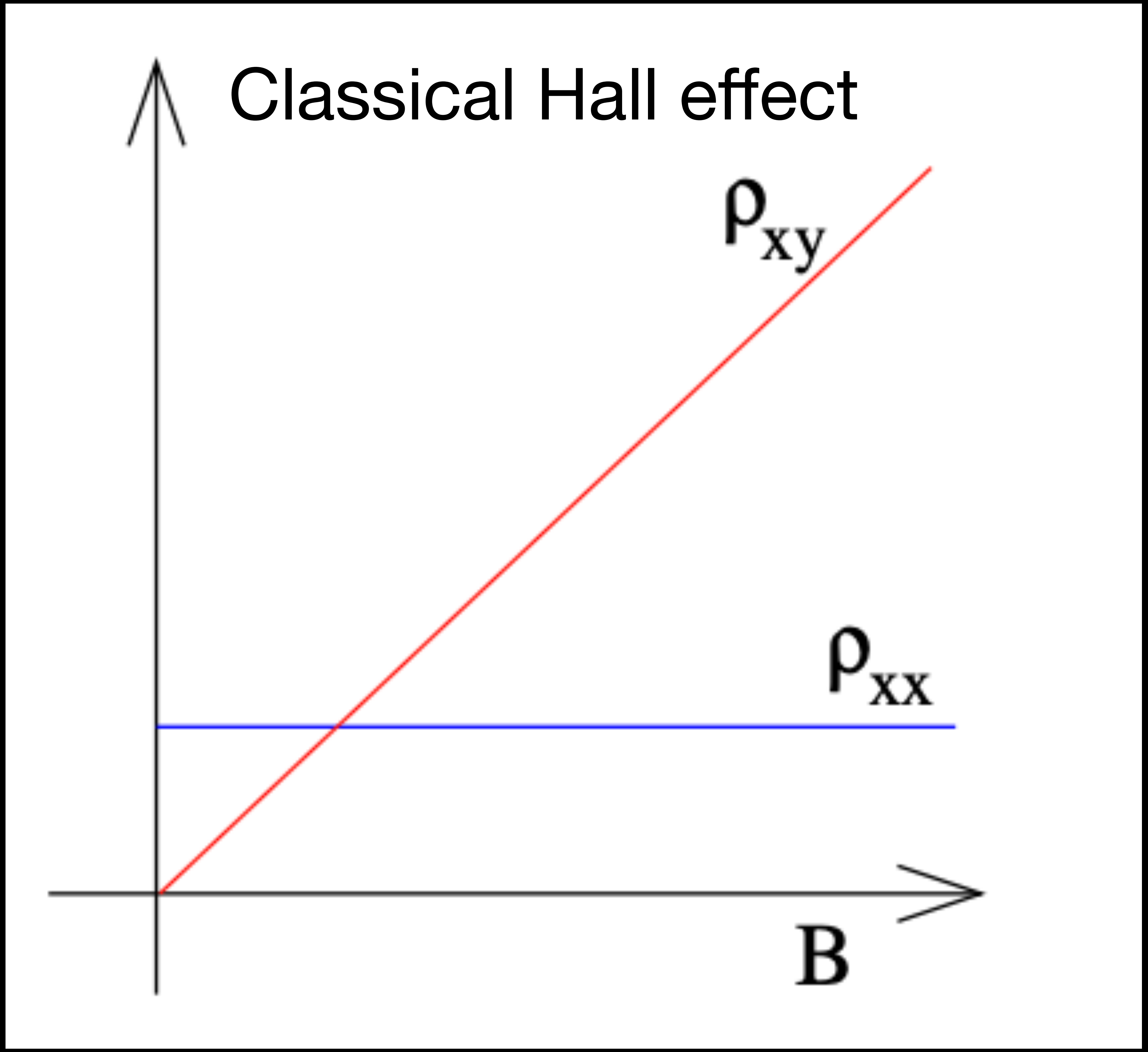
Cyclotron Frequency: $\omega_B = \frac{eB}{m}$

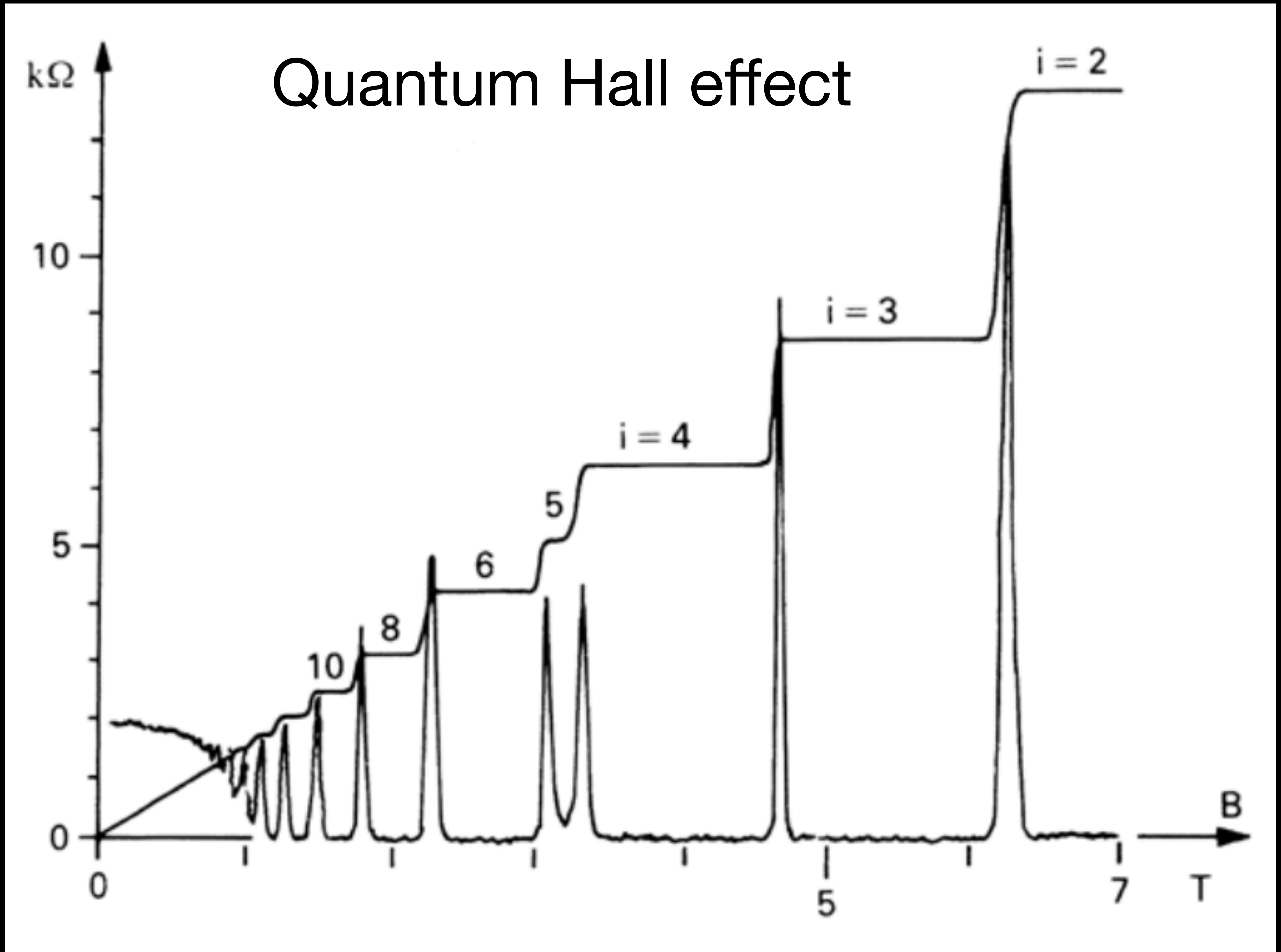
Magnetic Length: $l_B = \sqrt{\frac{\hbar}{eB}}$

Quantum of Flux: $\Phi_0 = \frac{2\pi\hbar}{e}$

Hall Resistivity: $\rho_{xy} = \frac{2\pi\hbar}{e^2}\frac{1}{\nu}$

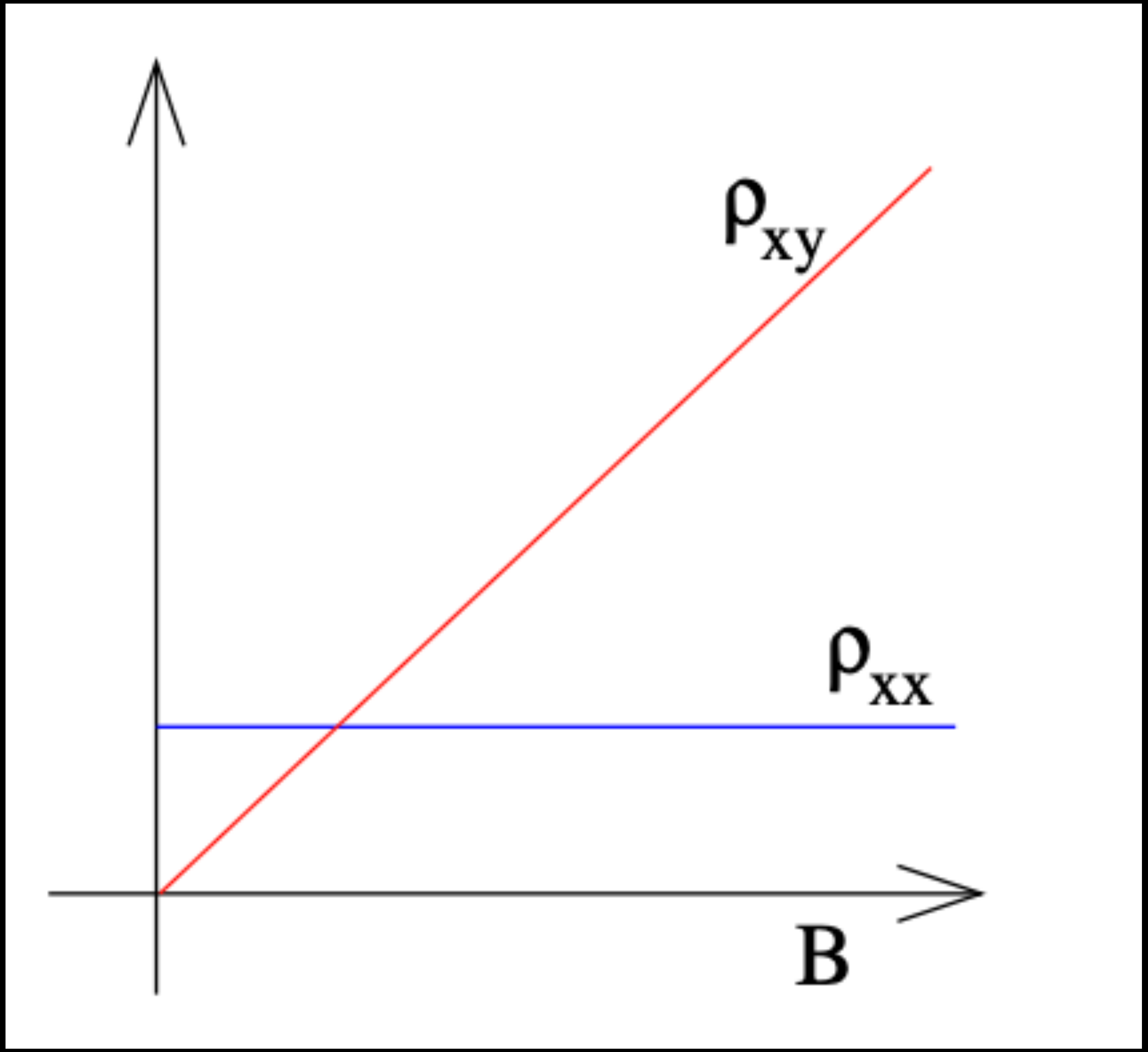
What is Quantum Hall Effect

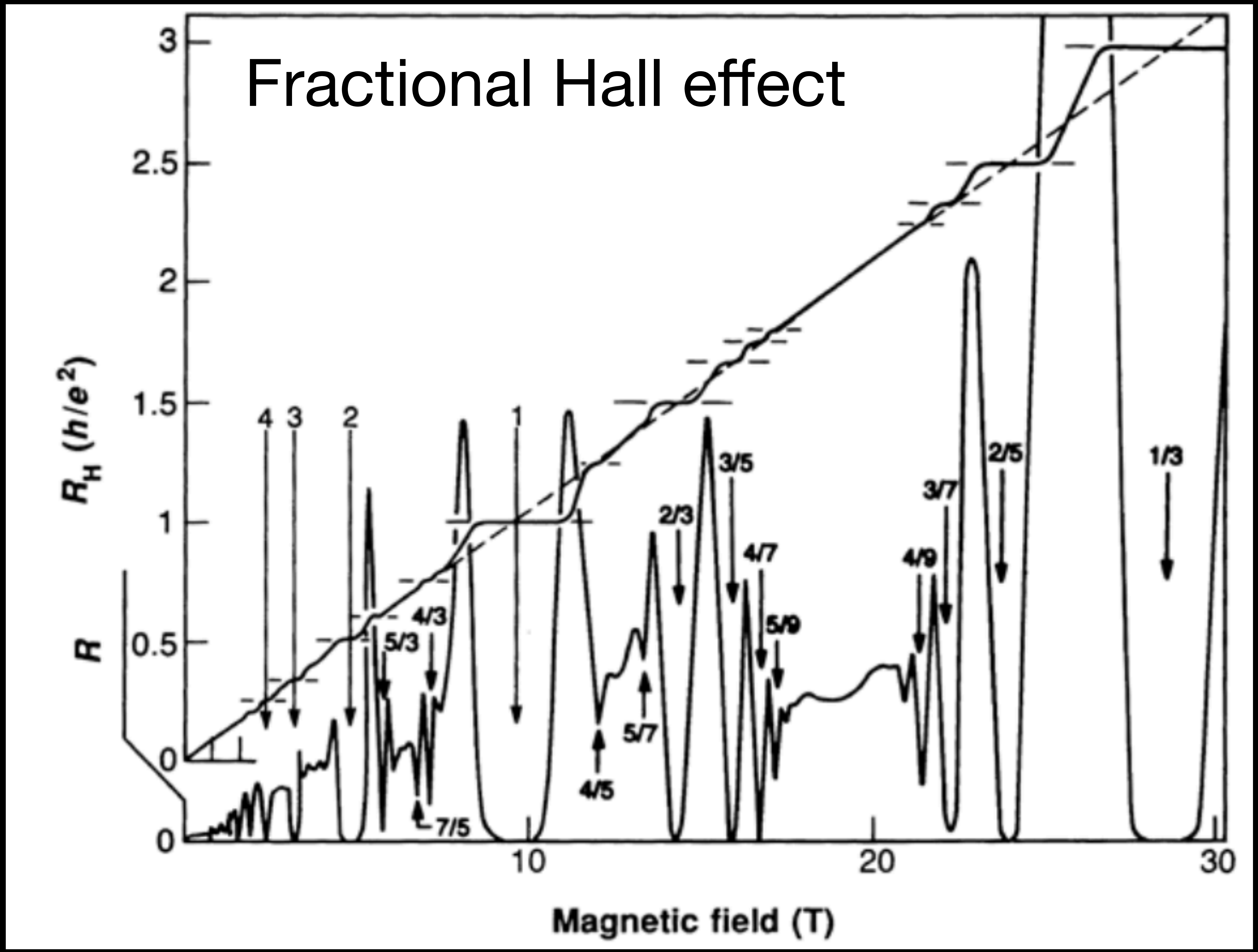




Nobel prize in physics 1985

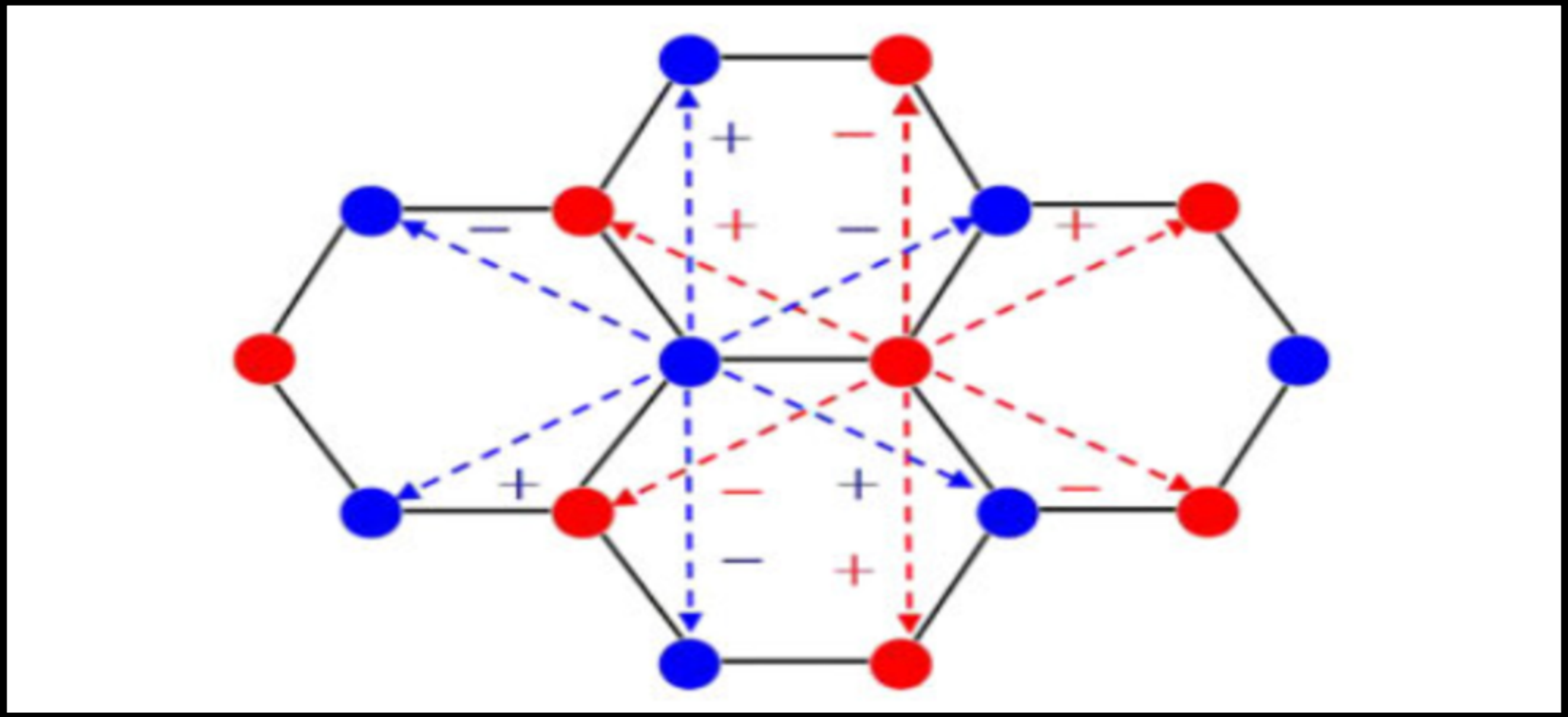
What is Quantum Hall Effect

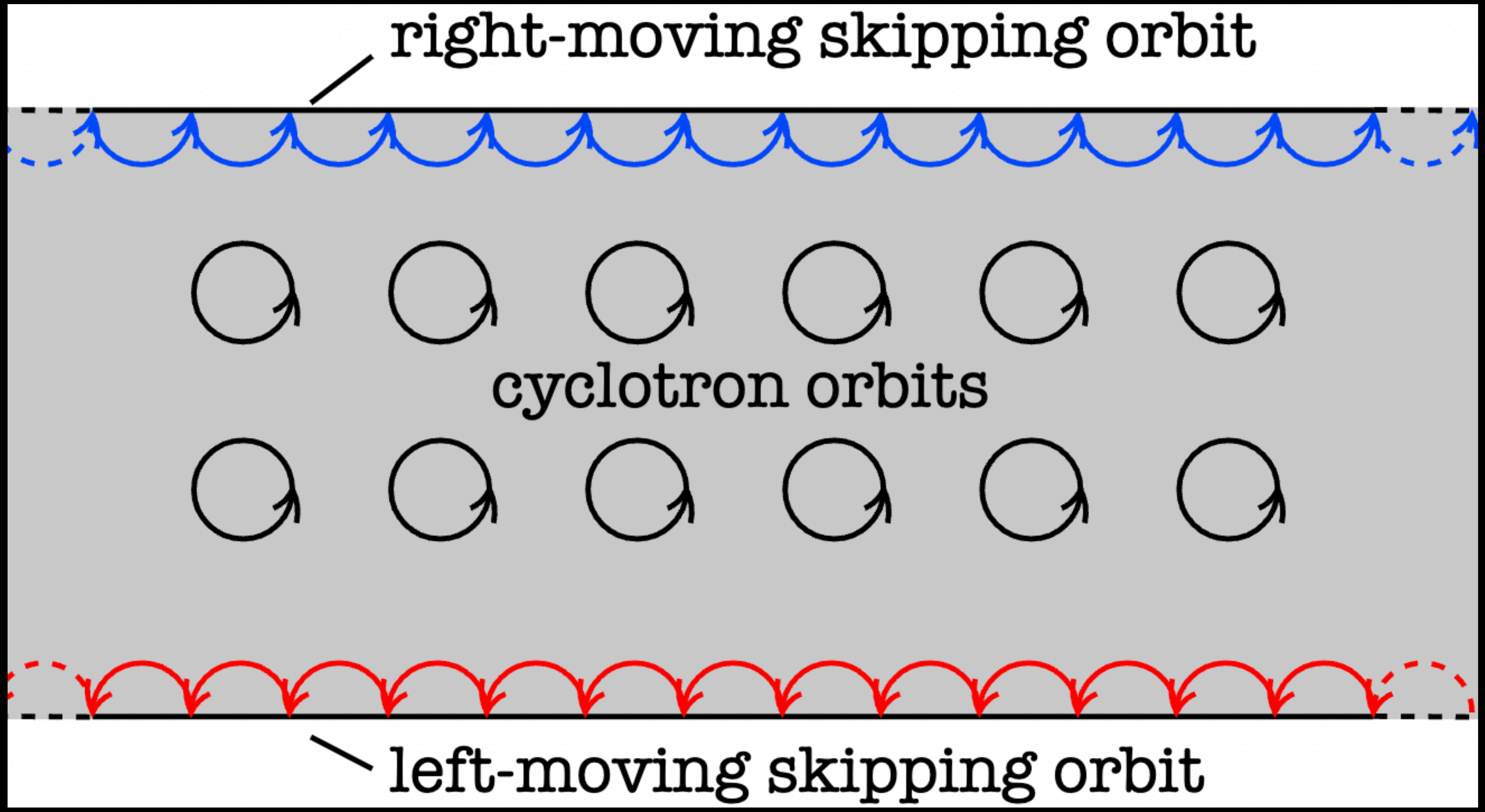




Nobel prize in physics 1998

Quantum Anomalous Hall Effect



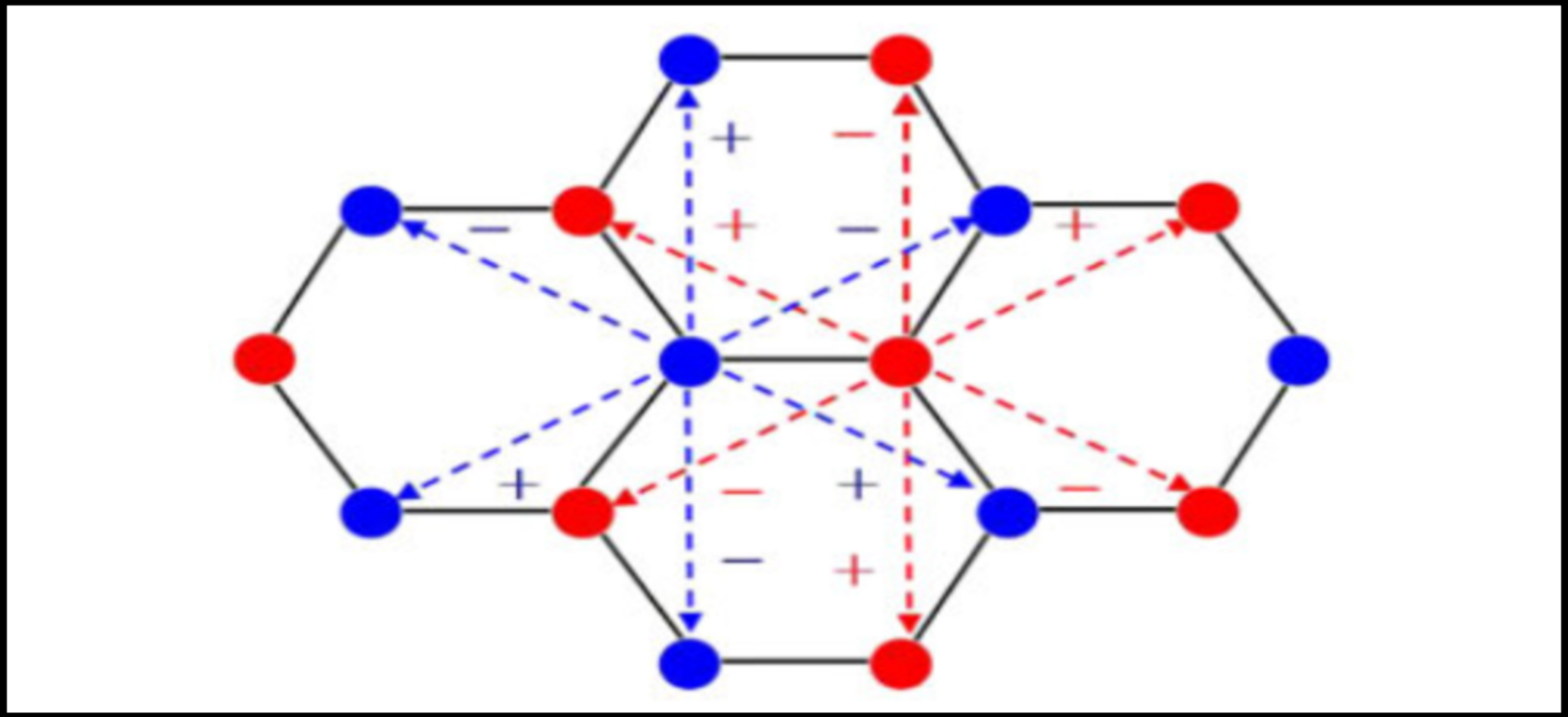


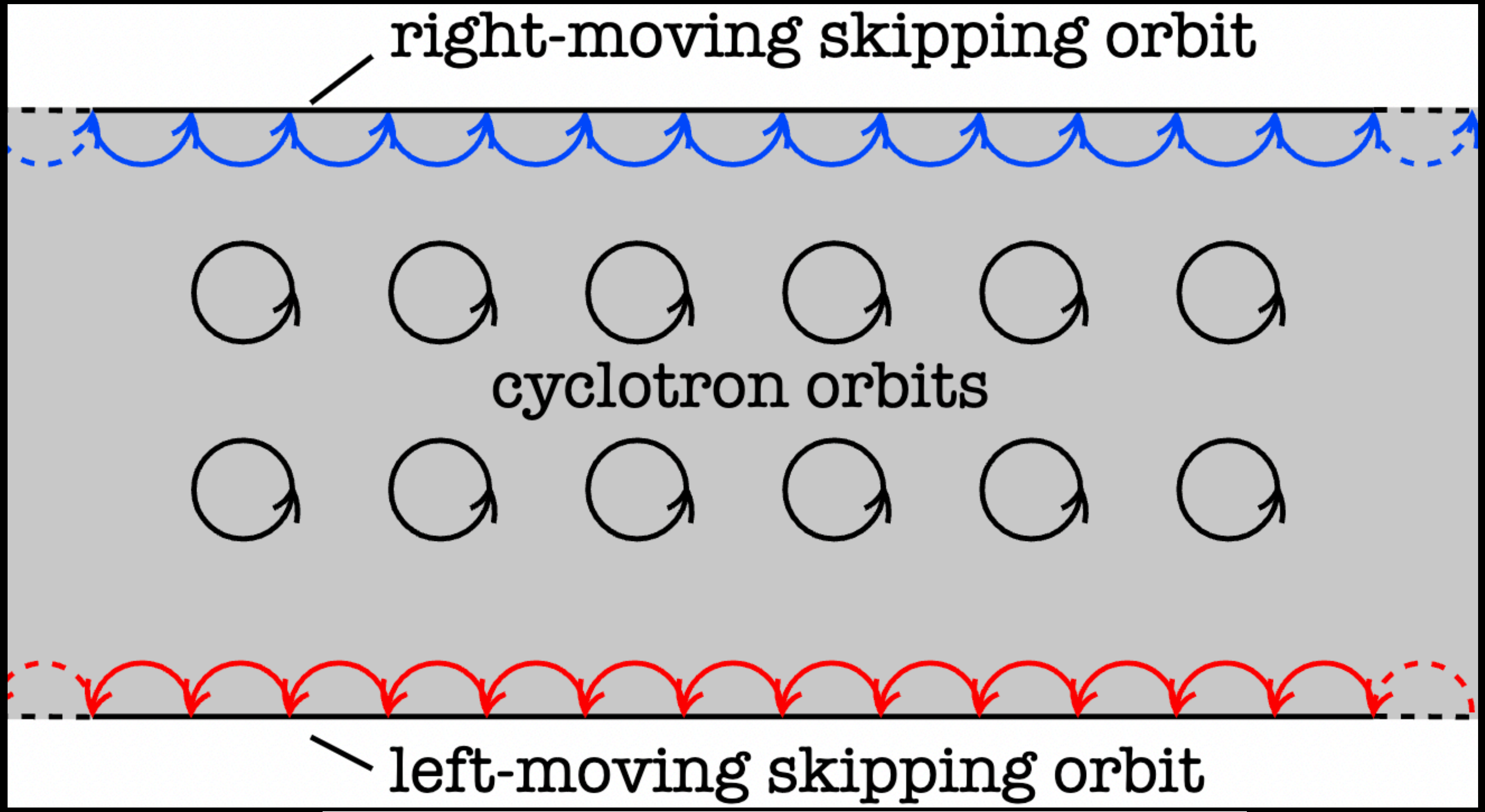
Average magnetic flux is ZERO

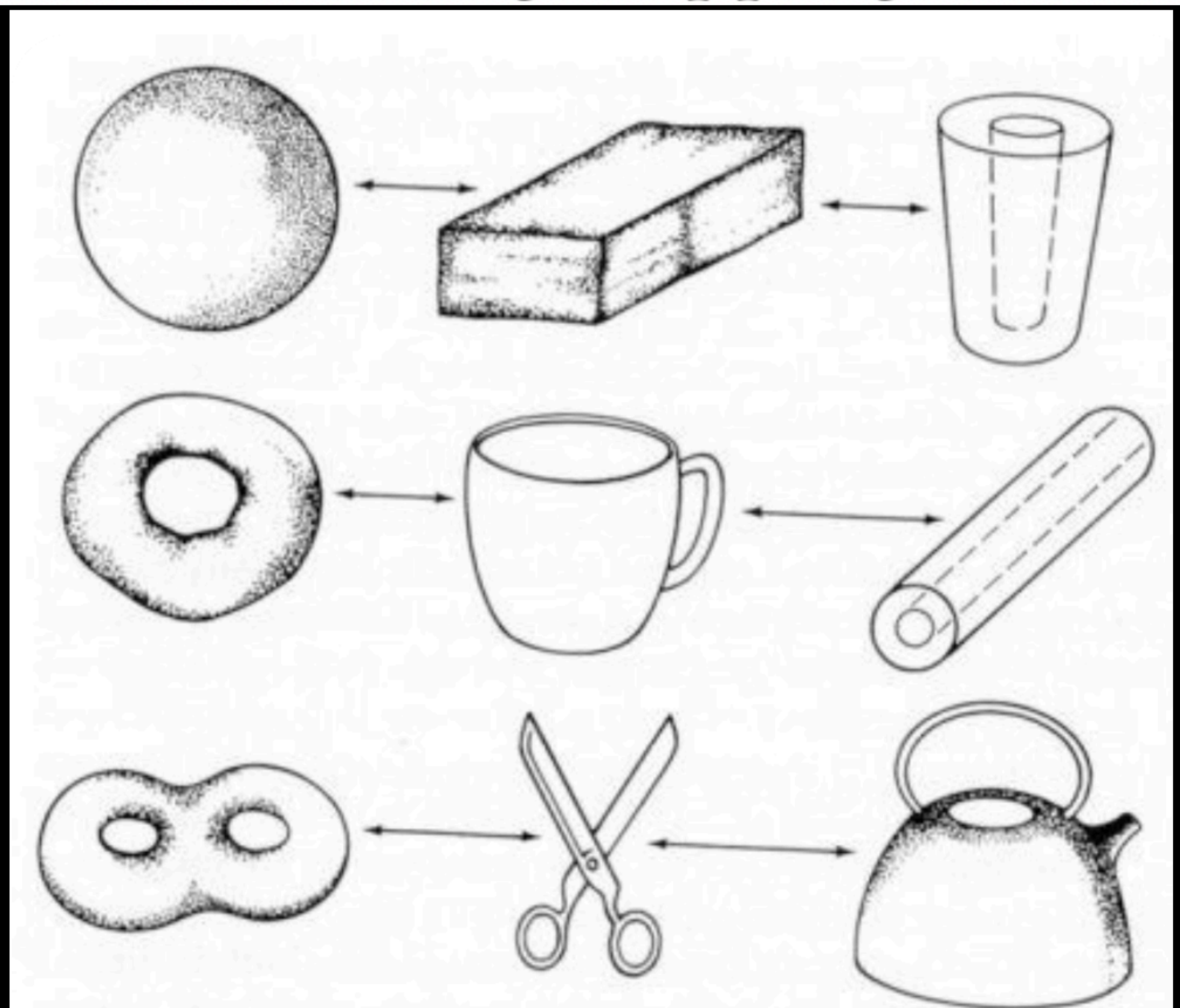
Time reversal breaking

Nobel prize in physics 2016

Quantum Anomalous Hall Effect







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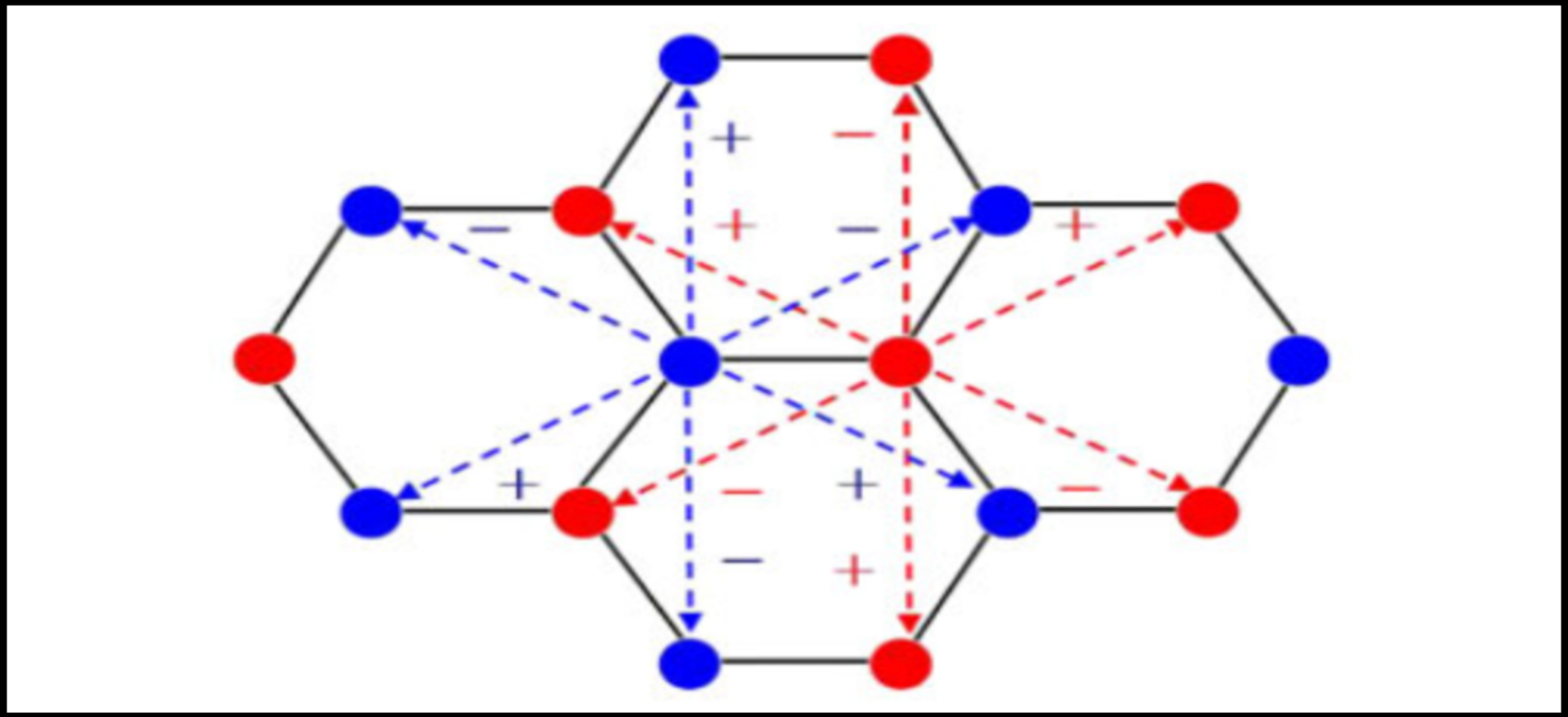

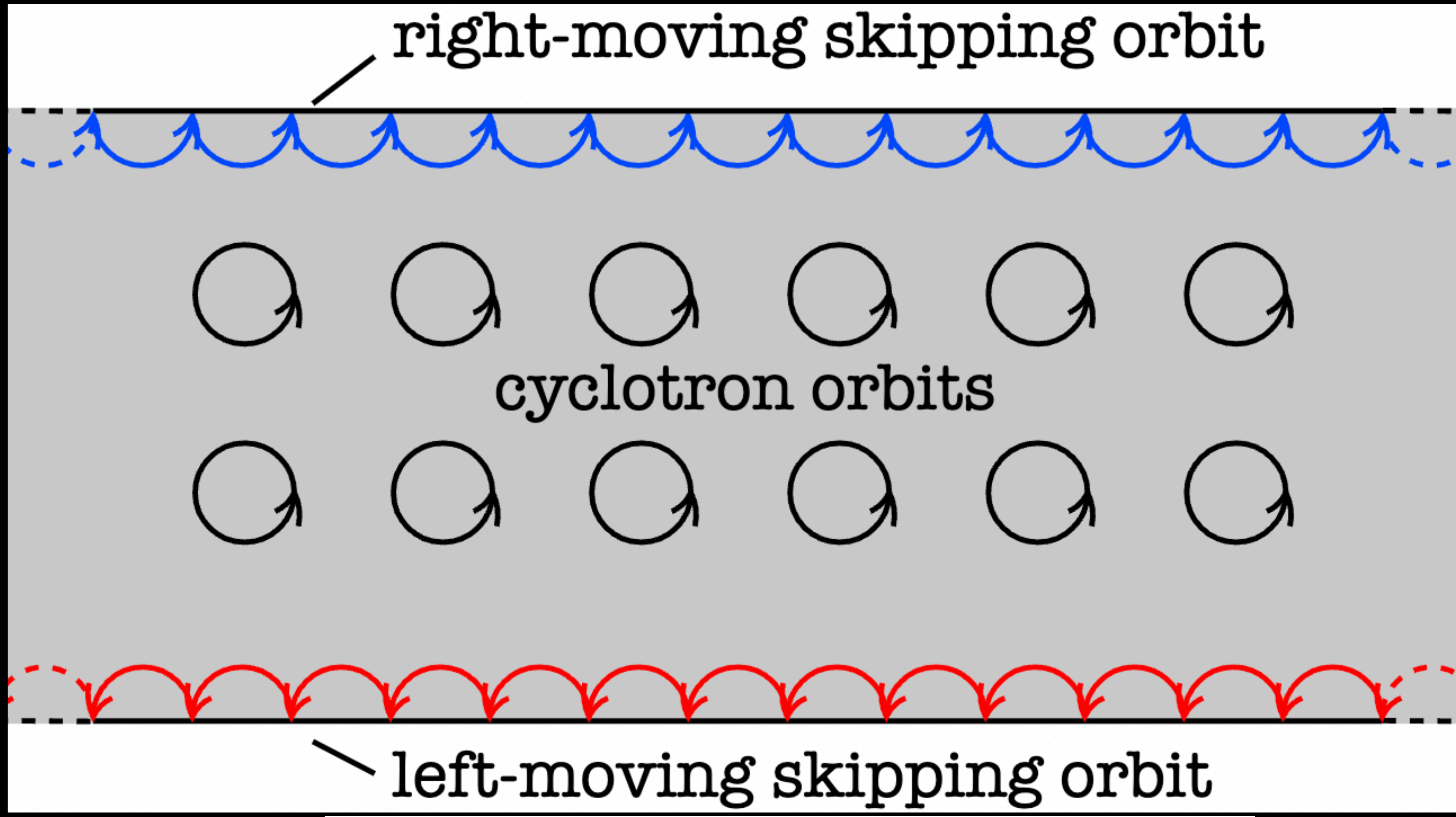

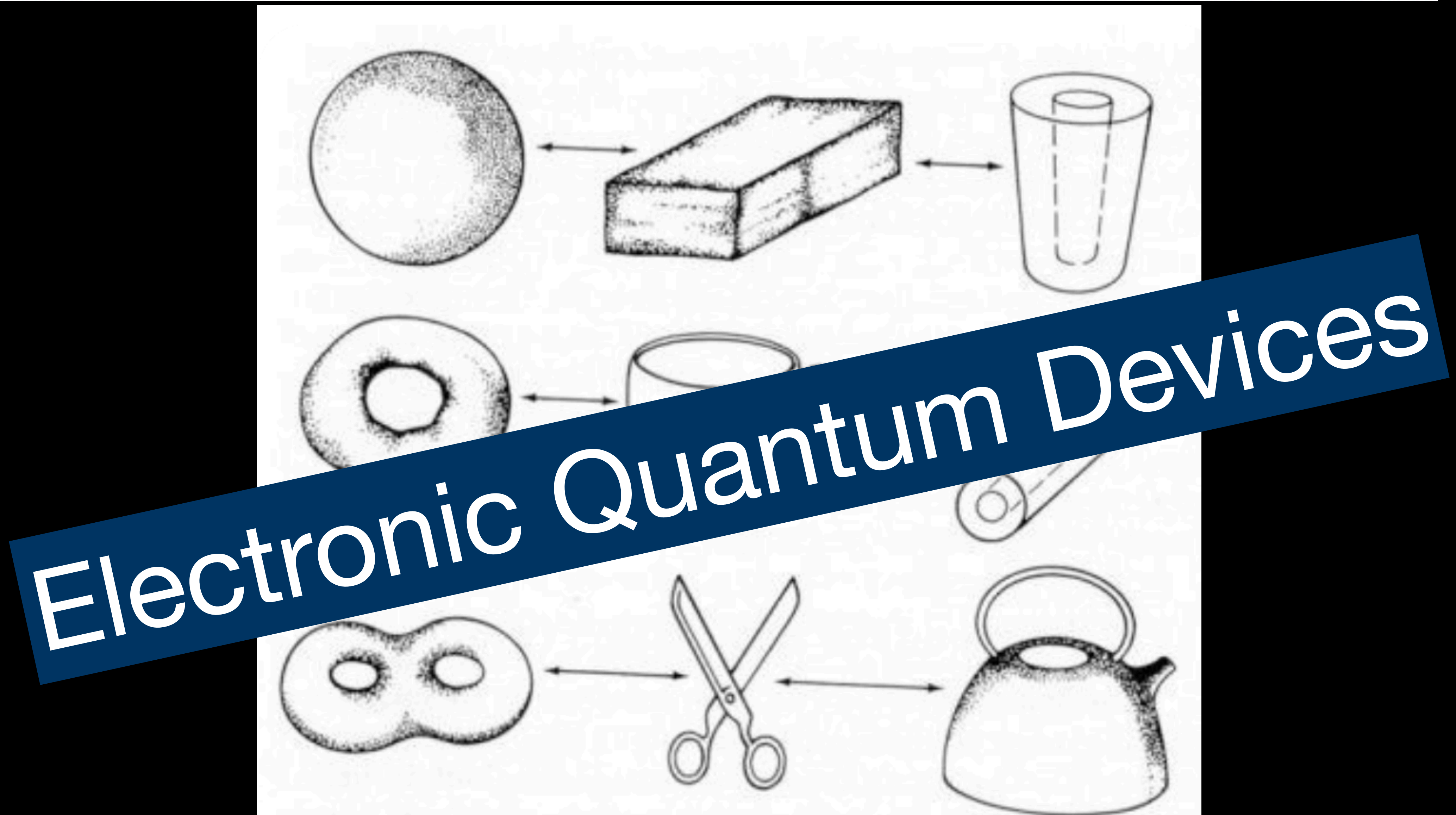

Average magnetic flux is ZERO

Time reversal breaking

Nobel prize in physics 2016

Are these quantum states robust to vacuum quantum fluctuations?

Quantum Hall effect in a cavity

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REPORT | QUANTUM OPTICS

Breakdown of topological protection by cavity vacuum fields in the integer quantum Hall effect

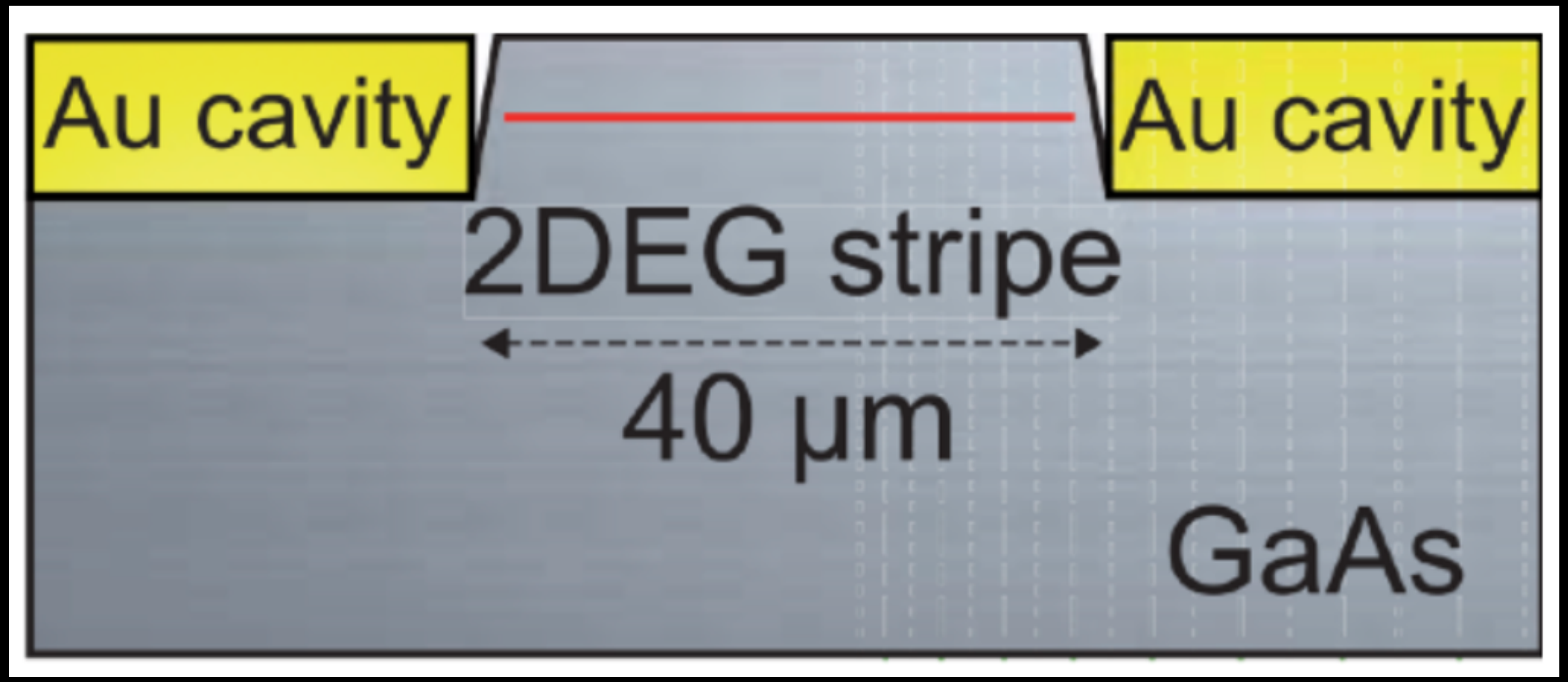
Article | Open access | Published: 14 May 2025

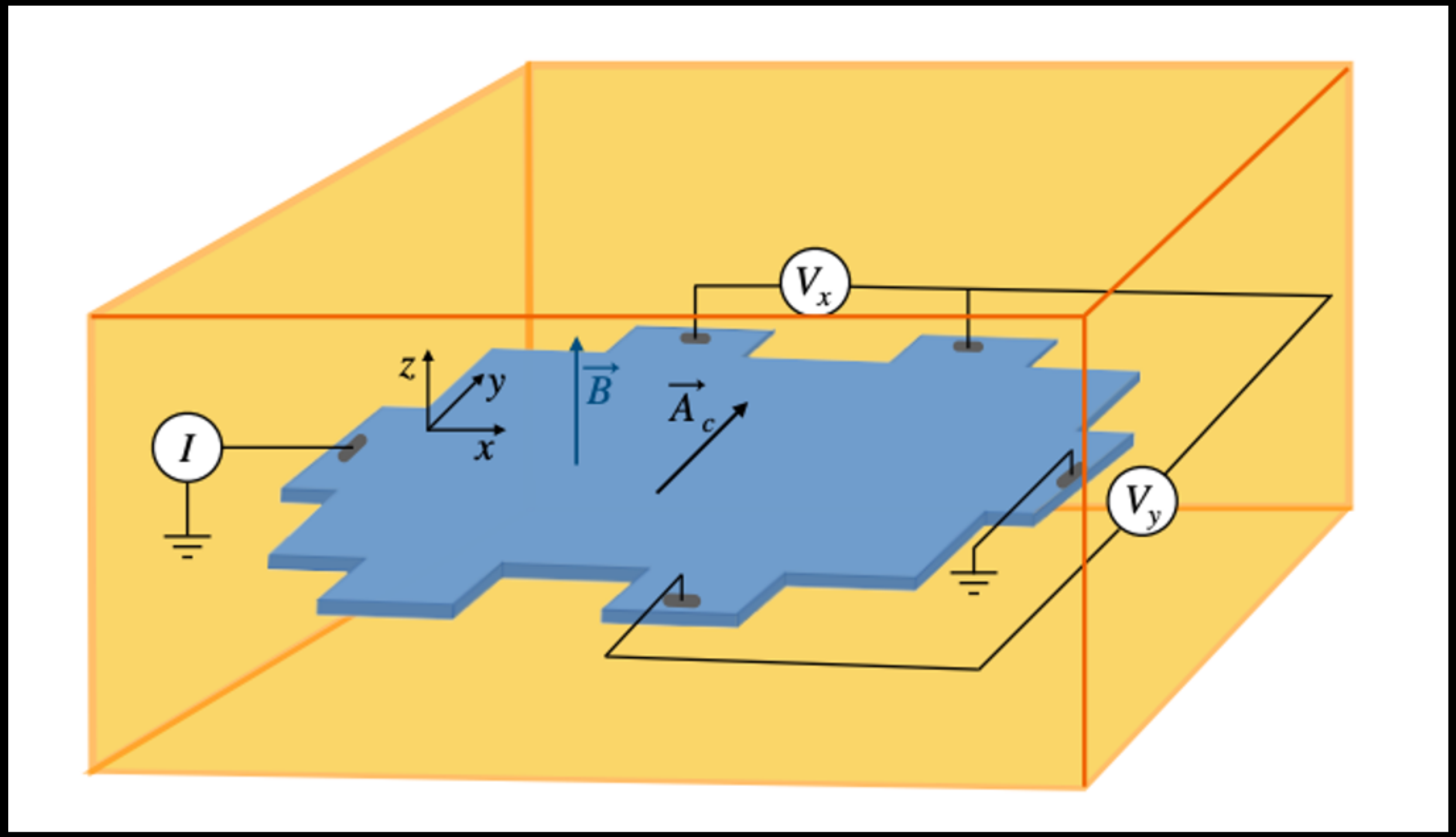
Tunable vacuum-field control of fractional and integer quantum Hall phases

Josefine Enkner, Lorenzo Graziotto, Dalin Boriçi, Felice Appugliese, Christian Reichl, Giacomo Scalari, Nicolas Regnault, Werner Wegscheider, Cristiano Ciuti & Jérôme Faist

Nature **641**, 884–889 (2025) | Cite this article

Quantum Hall effect in a cavity





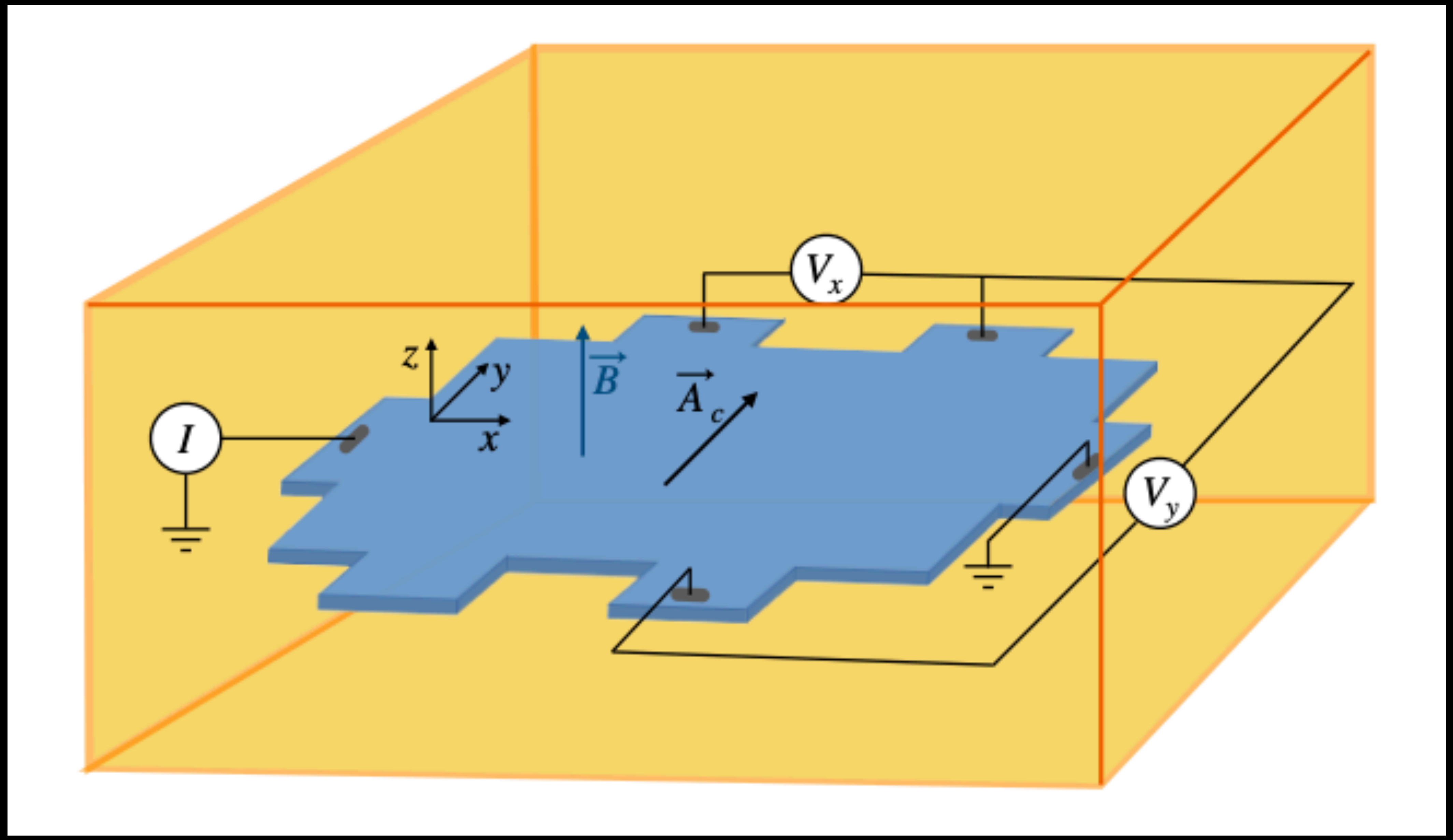
Effective field theory for QHE

$$S_{\text{eff}}[A] = \frac{\nu e^2}{4\pi\hbar} \int dt d^2x \epsilon^{\mu\nu\lambda} A_\mu \partial_\nu A_\lambda$$

$$j^\mu = \frac{\delta S_{\text{eff}}}{\delta A_\mu} = \frac{\nu e^2}{2\pi\hbar} \epsilon^{\mu\nu\lambda} \partial_\nu A_\lambda$$

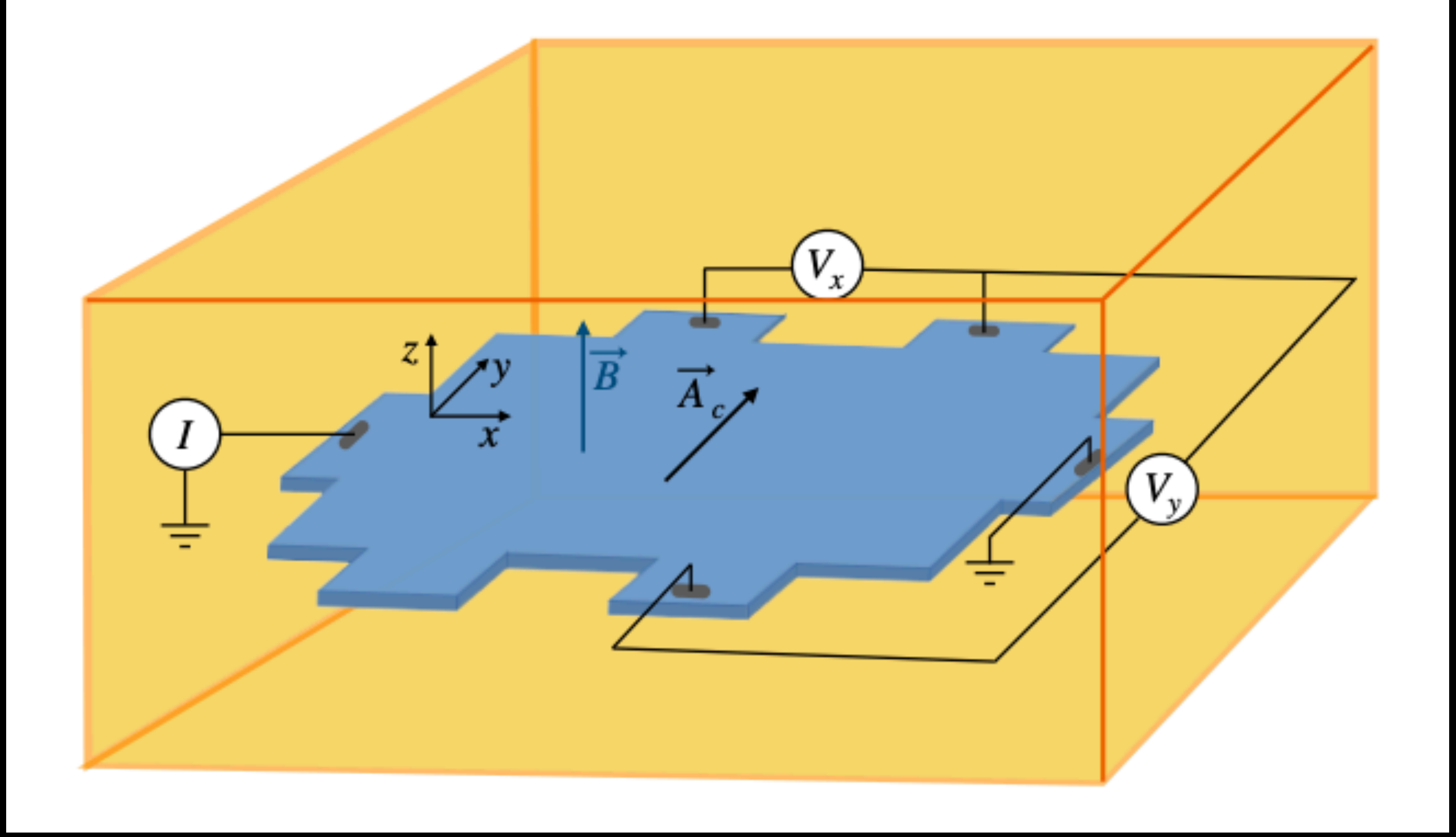
$$S[b, A] = \int d^3x \left[\frac{1}{4\pi\nu} \epsilon^{\mu\nu\lambda} b_\mu \partial_\nu b_\lambda + \frac{e}{2\pi} \epsilon^{\mu\nu\lambda} A_\mu \partial_\nu b_\lambda \right]$$

Cavity Quantum Hall Hydrodynamics



$$\mathcal{L}_H = -\frac{m}{4\pi}\epsilon^{\mu\nu\rho} b_\mu \partial_\nu b_\rho - \frac{e}{2\pi}\epsilon^{\mu\nu\rho} A_\mu \partial_\nu b_\rho + \frac{m}{4\pi\omega_B}\vec{E}_b^2 - \frac{u}{2}B_b^2,$$

Cavity Quantum Hall Hydrodynamics

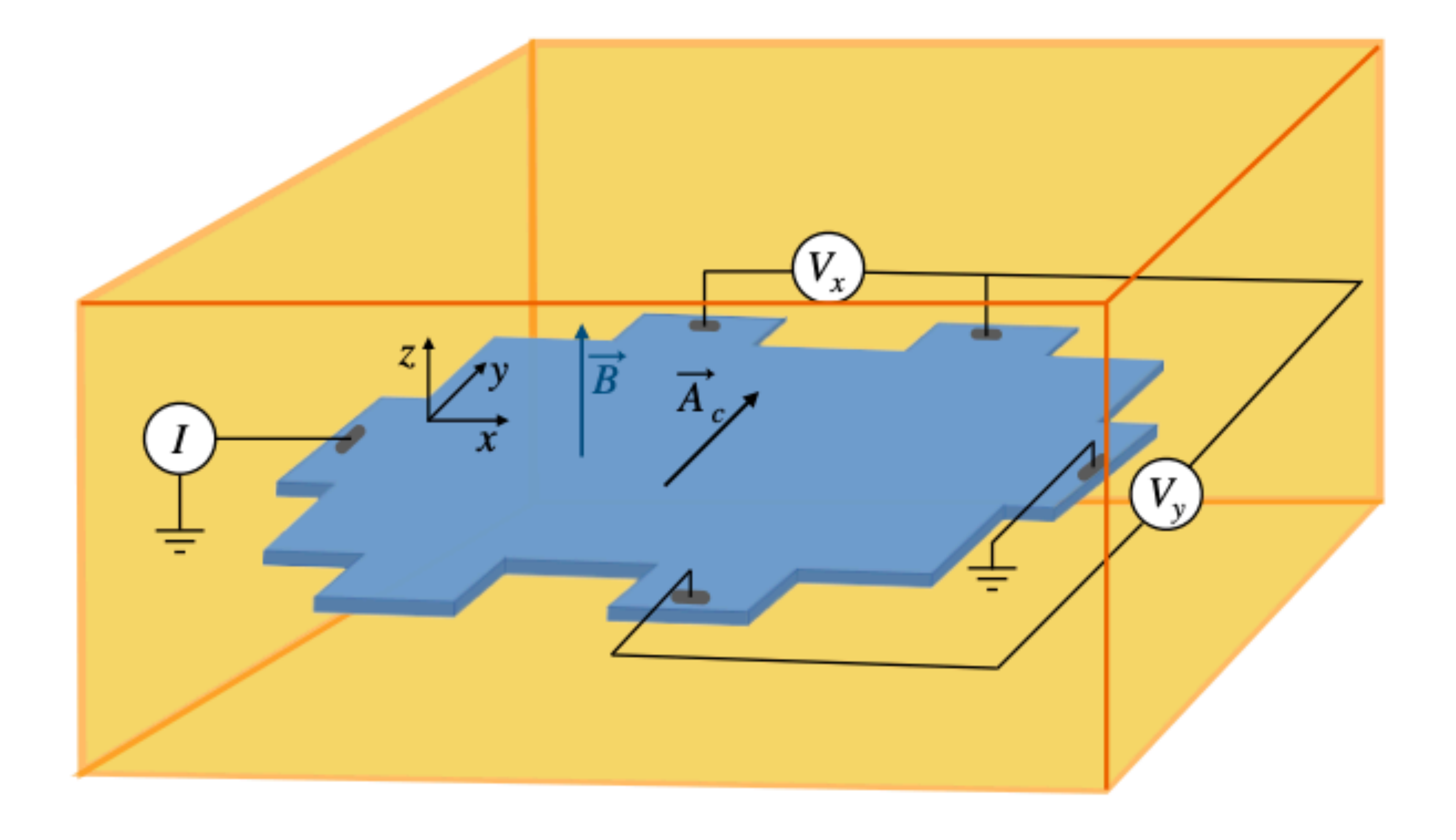


Result 1: Longitudinal conductance

$$j^x(\omega) = \frac{e^2}{2\pi}\frac{1}{m}E_y(\omega) + \frac{e^2}{2\pi}\frac{1}{m^2}\frac{2\alpha}{L_{\rm eff}}\frac{i\omega}{\omega^2-\omega_c^2}E_x(\omega),$$

$$j^y(\omega) = -\frac{e^2}{2\pi}\frac{1}{m}E_x(\omega)\,,$$

Cavity Quantum Hall Hydrodynamics



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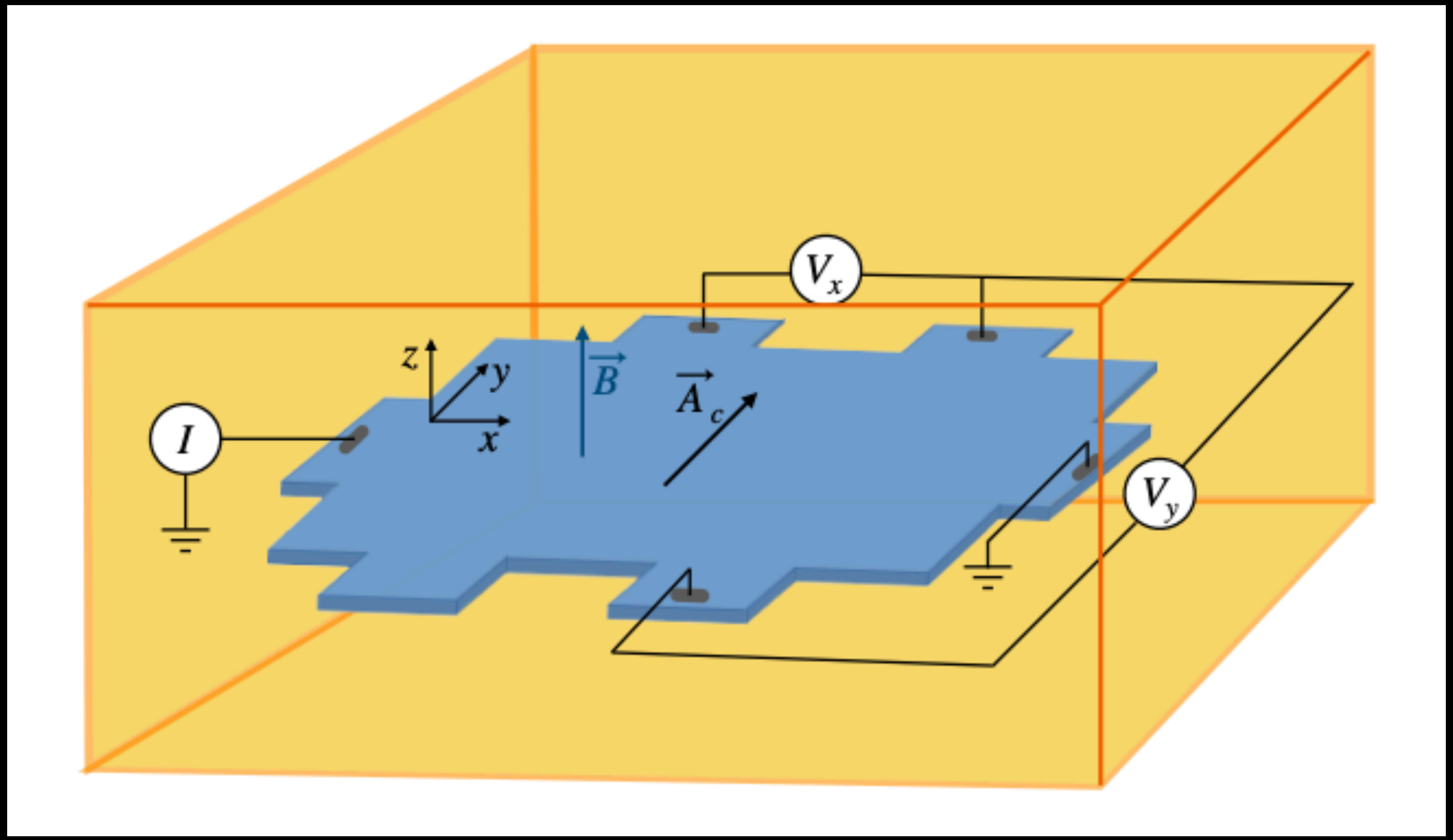
Result 2: Kohn mode frequency

$$\omega = \omega_B + \frac{1}{m}\frac{\alpha}{L_{\text{eff}}}.$$

Cavity Quantum Hall Hydrodynamics



G. Cardoso, L. Yang, T. H. Hansson, QDJ, Phys. Rev. B 113, 045108; Phys. Rev. B 113, 045109 (2026)

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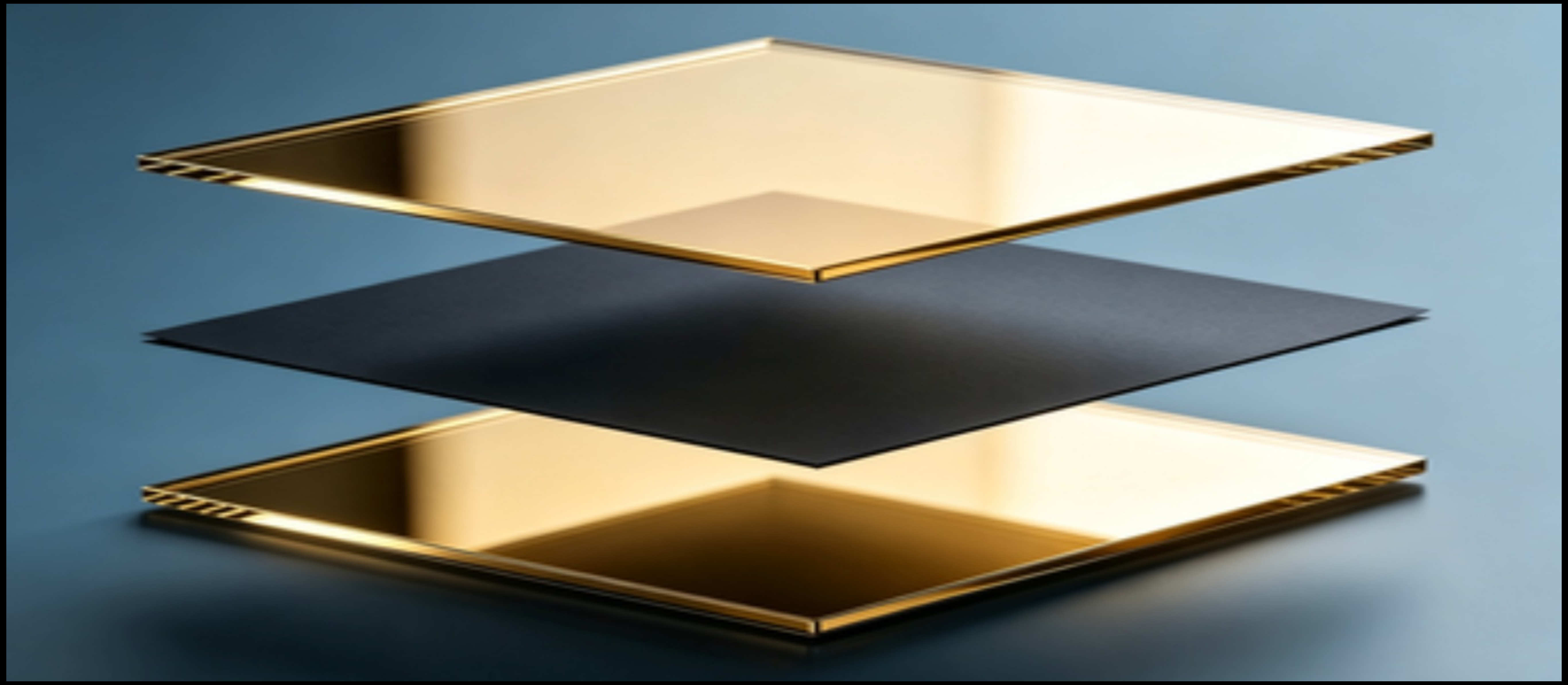
Result 3: Photon electron mixing

Quantum Hall breaks down when $\omega_c \sim \omega_B$

Vacuum modification of QHE



$$\rho_L = \frac{1}{2} Z_0 \qquad \rho_H = R_K/\nu \quad \Rightarrow \quad \sigma = \rho^{-1} = \frac{1}{\rho_{xx}^2 + \rho_{xy}^2} \begin{pmatrix} \rho_{xx} & -\rho_{xy} \\ \rho_{xy} & \rho_{xx} \end{pmatrix}$$

$$\sigma_H = 1/\rho_H \times \left[1 - (\rho_L/\rho_H)^2\right]$$

T. H. Hansson, QDJ, S. A. Kivelson, T. Klein Kvorning, arXiv:2604.26014

Vacuum modification of QHE

$$S_b = \int d^3x \left[-\frac{\nu}{4\pi}\epsilon^{\mu\nu\sigma} b_\mu \partial_\nu b_\sigma + \frac{e}{2\pi}\epsilon^{\mu\nu\sigma}\left(A_\mu + Q_\mu\right)\partial_\nu b_\sigma + j_\nu^\mu b_\mu \right]$$

$$\mathcal{S}_M = \frac{1}{2}\int \frac{d^4p}{(2\pi)^4}\left\{ \overrightarrow{Q}(-p)\left[(\omega/c)^2\varepsilon(\overrightarrow{p},\omega) - q^2 - p_z^2\right]\cdot \overrightarrow{Q}(p) + Q_0(-p)\varepsilon(\overrightarrow{p},\omega)p^2 Q_0(p) \right\}$$

↓

$$\varepsilon(\overrightarrow{p},\omega) = \varepsilon_0 - \frac{\tilde{\sigma}}{i\omega - Dp^2}$$

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$$\varepsilon(\overrightarrow{p}, \omega) = \varepsilon_0 - \frac{\tilde{\sigma}}{i\omega - Dp^2}$$

$$S_{tot} = \int \frac{d^3p}{(2\pi)^3} \left[\frac{\alpha}{4\pi} \frac{i\omega^2}{\sqrt{\omega^2 + i\tilde{\sigma}\omega}} \delta^{ij} b_i b_j - \frac{\nu}{4\pi} i\omega \epsilon^{ij} b_i b_j - \frac{e}{2\pi} \epsilon^{ij} b_i E_j \right]$$

Vacuum modification of QHE

$$S_{tot} = \int \frac{d^3p}{(2\pi)^3} \left[\frac{\alpha}{4\pi} \frac{i\omega^2}{\sqrt{\omega^2 + i\tilde{\sigma}\omega}} \delta^{ij} b_i b_j - \frac{\nu}{4\pi} i\omega \epsilon^{ij} b_i b_j - \frac{e}{2\pi} \epsilon^{ij} b_i E_j \right]$$

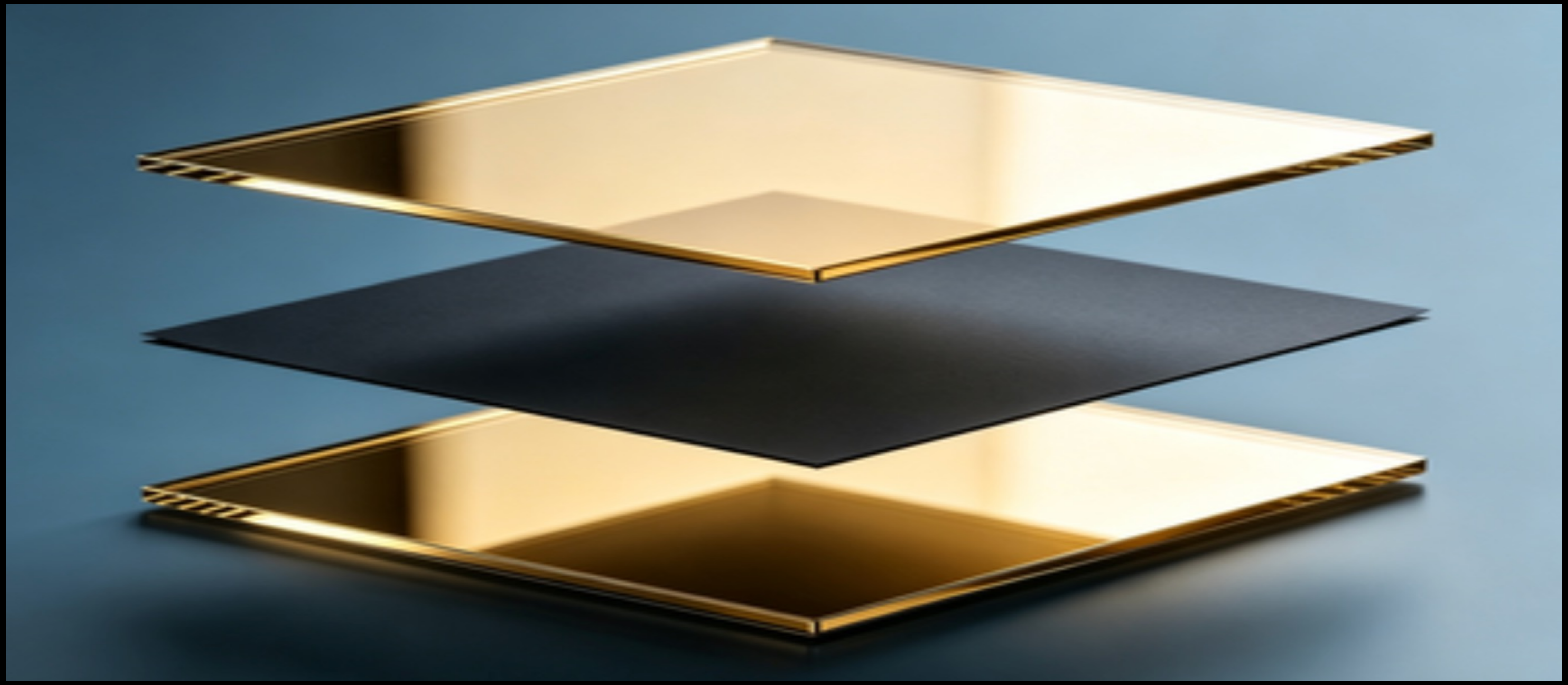
↓

$$\frac{\alpha}{2\pi} \frac{i\omega^2}{\sqrt{\omega^2 + i\tilde{\sigma}\omega}} b^i - \frac{\nu}{2\pi c} i\omega \epsilon^{ij} b_j - \frac{e}{2\pi} \epsilon^{ij} E_j = 0$$

↓

$$-\frac{\alpha}{e} \frac{\omega}{\sqrt{\omega^2 + i\tilde{\sigma}\omega}} \delta^{ij} J_j - \frac{\nu}{e} \epsilon^{ij} J_j + \frac{e}{2\pi} E^i = 0$$

Vacuum modification of QHE



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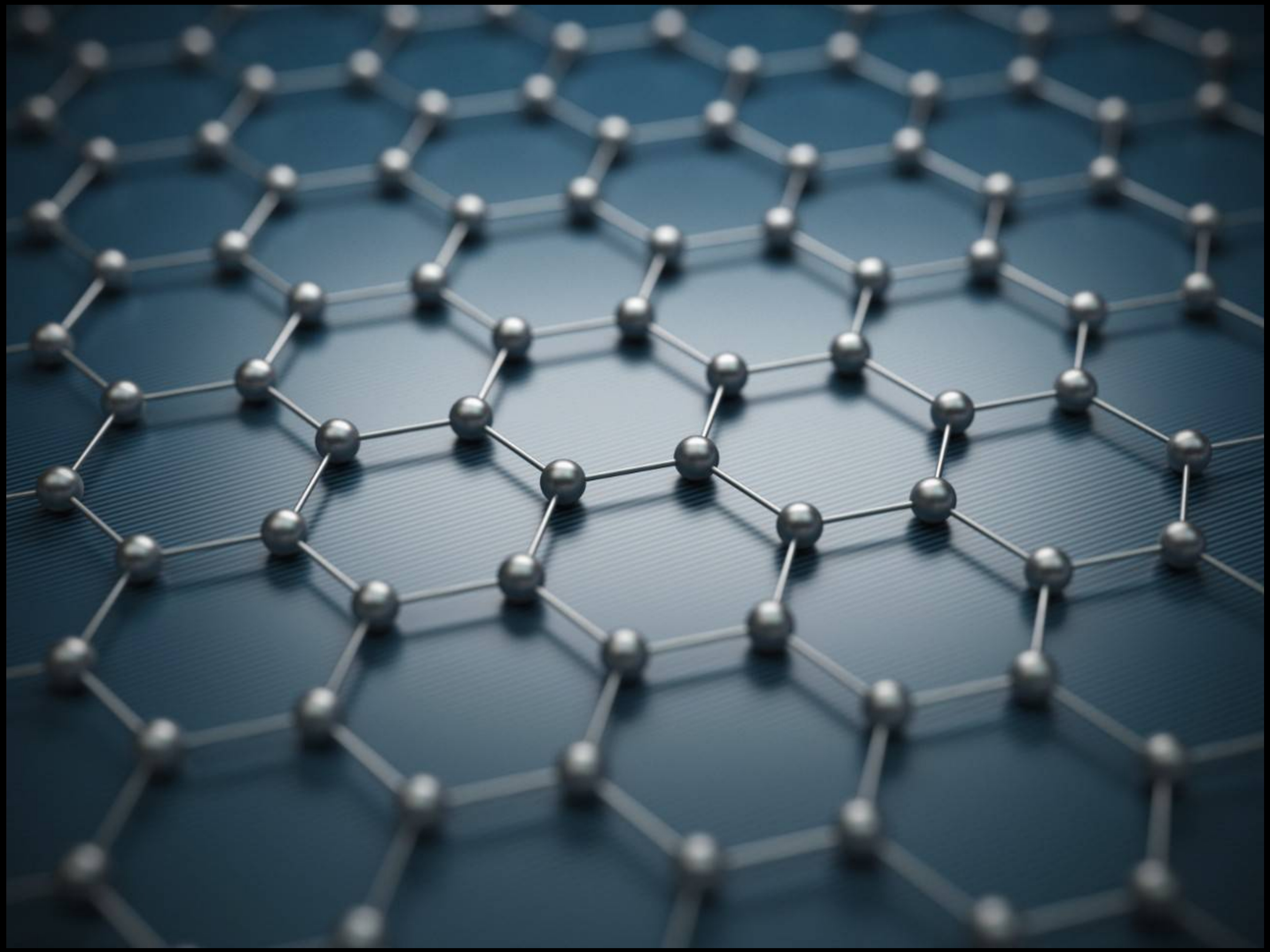
T. H. Hansson, QDJ, S. A. Kivelson, T. Klein Kvorning, arXiv:2604.26014

Quantum Anomalous Hall in a chiral cavity

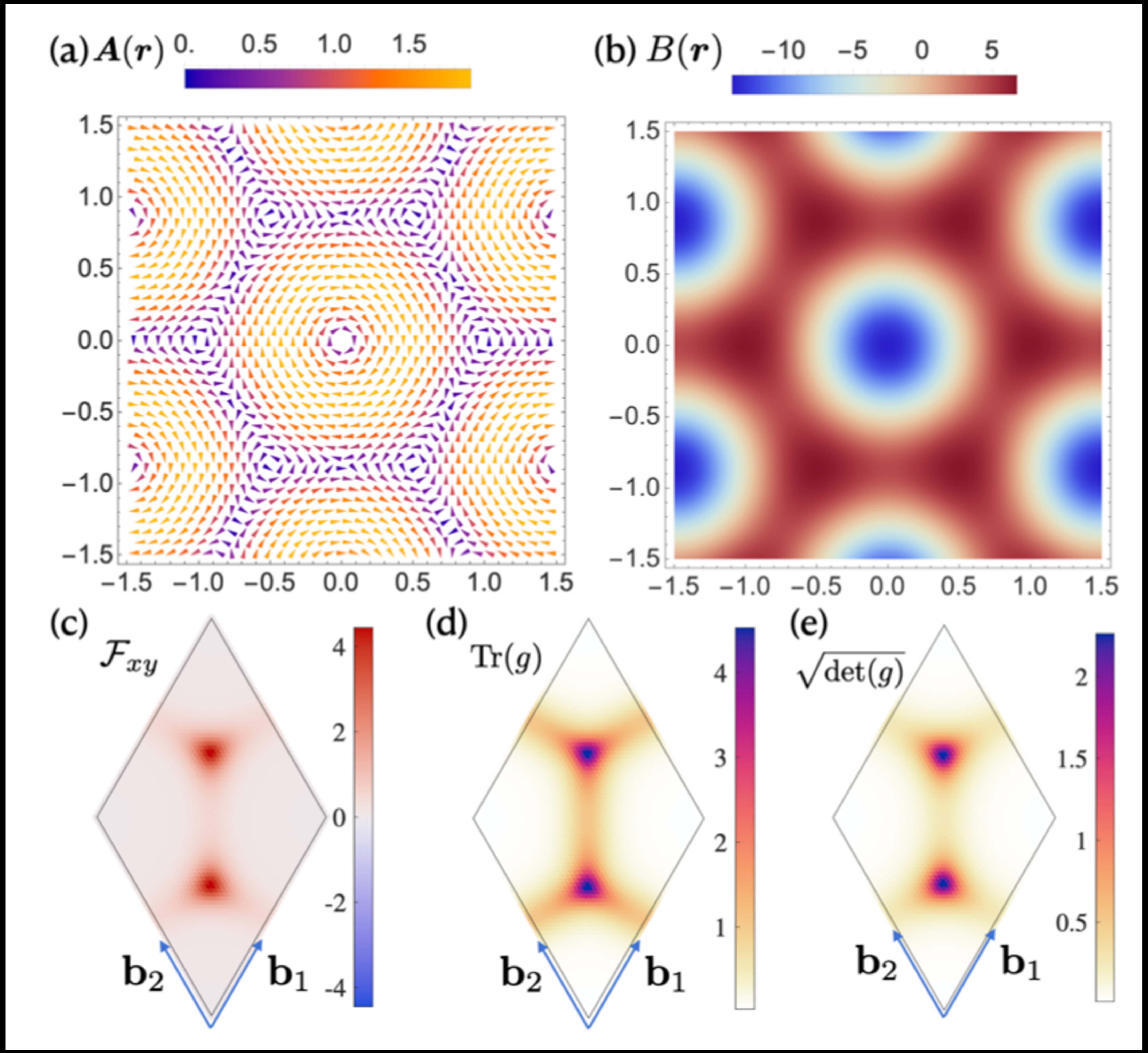
Emergent Haldane model



$$\hat{H}^C = \frac{(\hat{\boldsymbol{p}} + e\hat{\mathbf{A}})^2}{2m} + V(\boldsymbol{r}) + \hbar\omega_c \left(\hat{a}^\dagger \hat{a} + \frac{1}{2}\right)$$

$$\hat{\mathbf{A}} = A_0 \left(\boldsymbol{\epsilon}\hat{a} + \boldsymbol{\epsilon}^* \hat{a}^\dagger\right)$$

Graphene in a chiral cavity



Liu Yang and QDJ, Comm. Phys. 8, 126 (2025)

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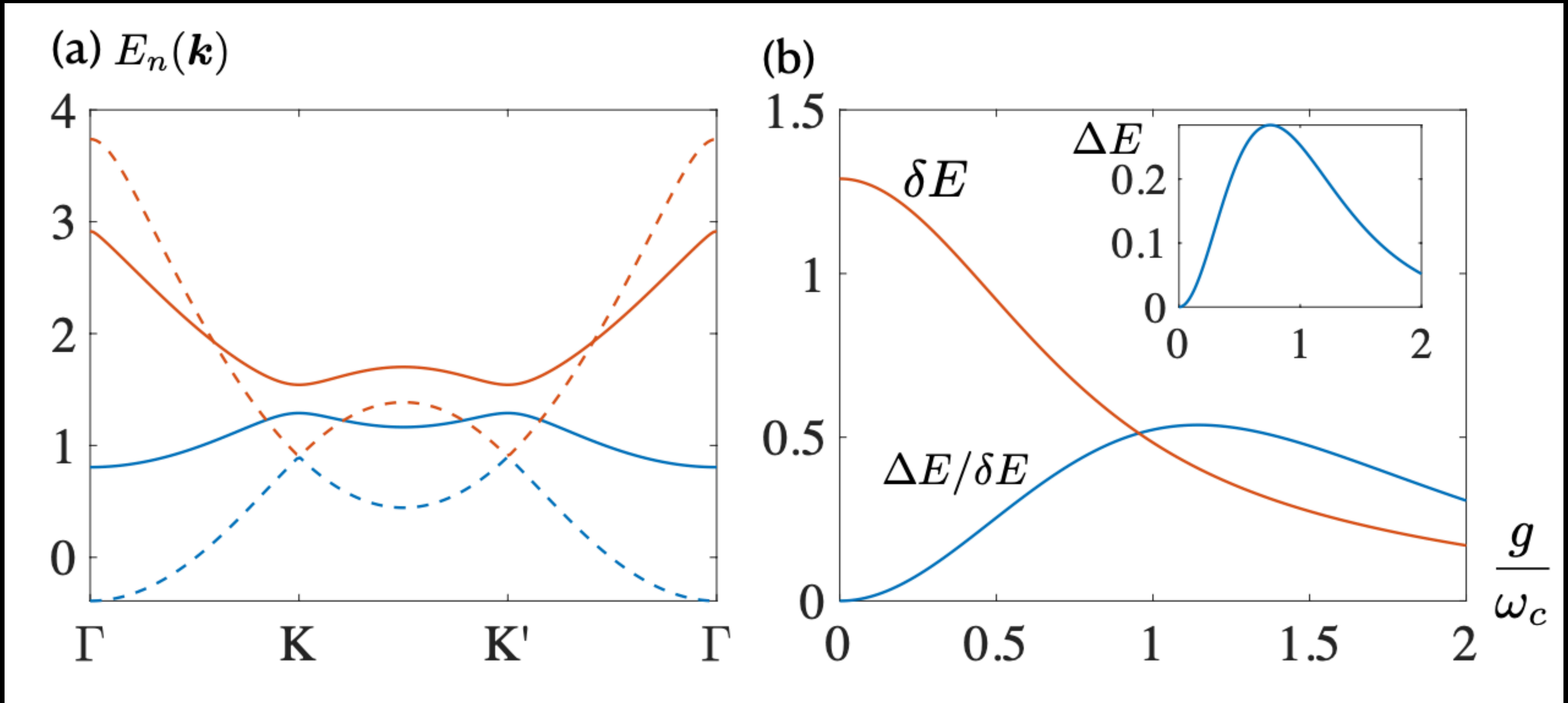
$$\hat{\mathbf{A}} = A_0\left(\boldsymbol{\epsilon}\hat{a} + \boldsymbol{\epsilon}^*\hat{a}^\dagger\right)$$

$$\hat{H}^U = \langle 0_{\text{photon}}|\hat{U}^\dagger\hat{H}^C\hat{U}|0_{\text{photon}}\rangle = \frac{\hat{p}^2}{2m_{\text{eff}}} + \widetilde{V}\left(\boldsymbol{r} + \frac{\xi^2}{2\hbar}\hat{\mathbf{p}} \times \boldsymbol{e}_z\right)$$

$$\hat{H}^U \approx \frac{[\hat{\boldsymbol{p}} + e\boldsymbol{A}(\boldsymbol{r})]^2}{2m_{\text{eff}}} + V_{\text{eff}}(\boldsymbol{r})$$

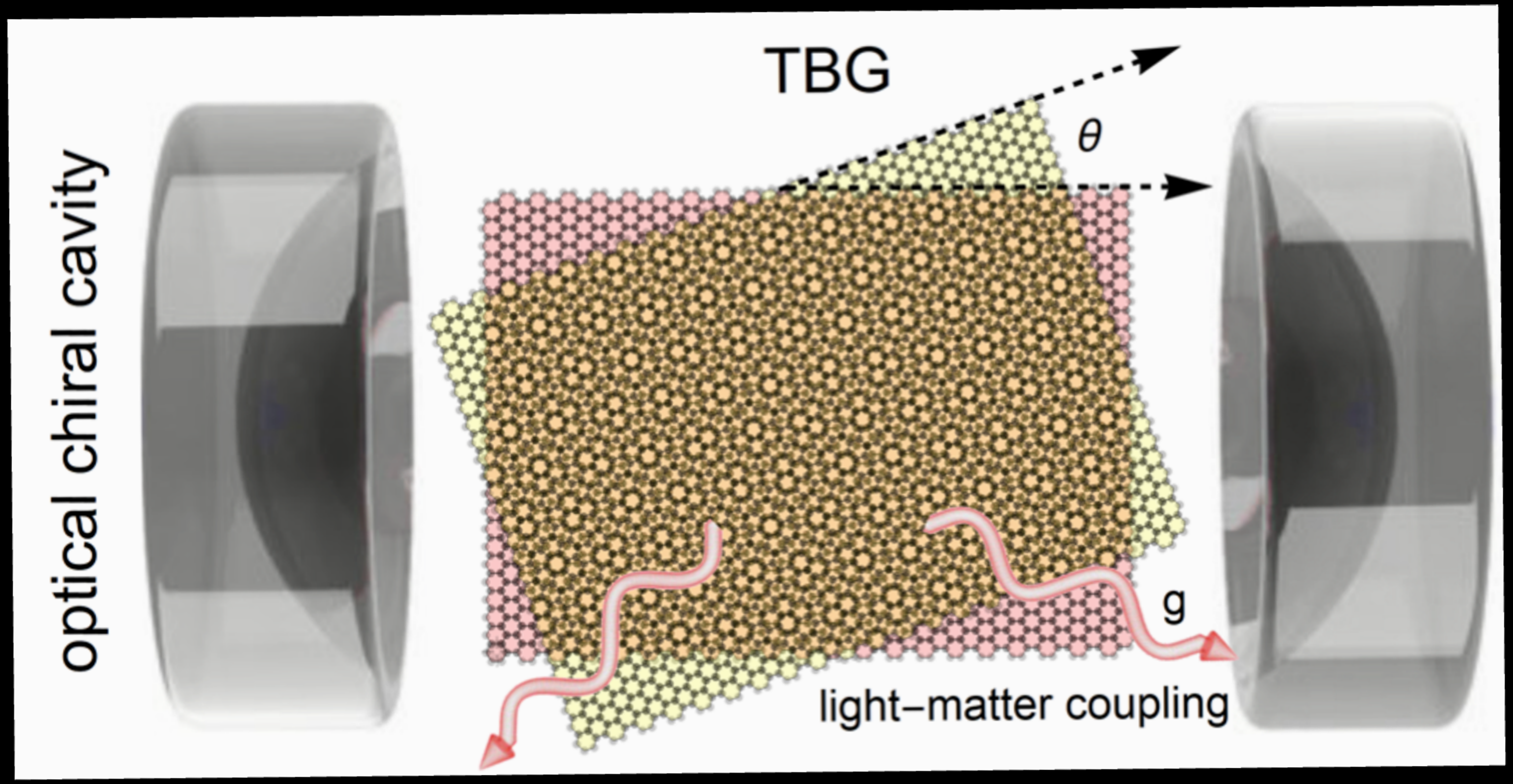
Graphene in a chiral cavity

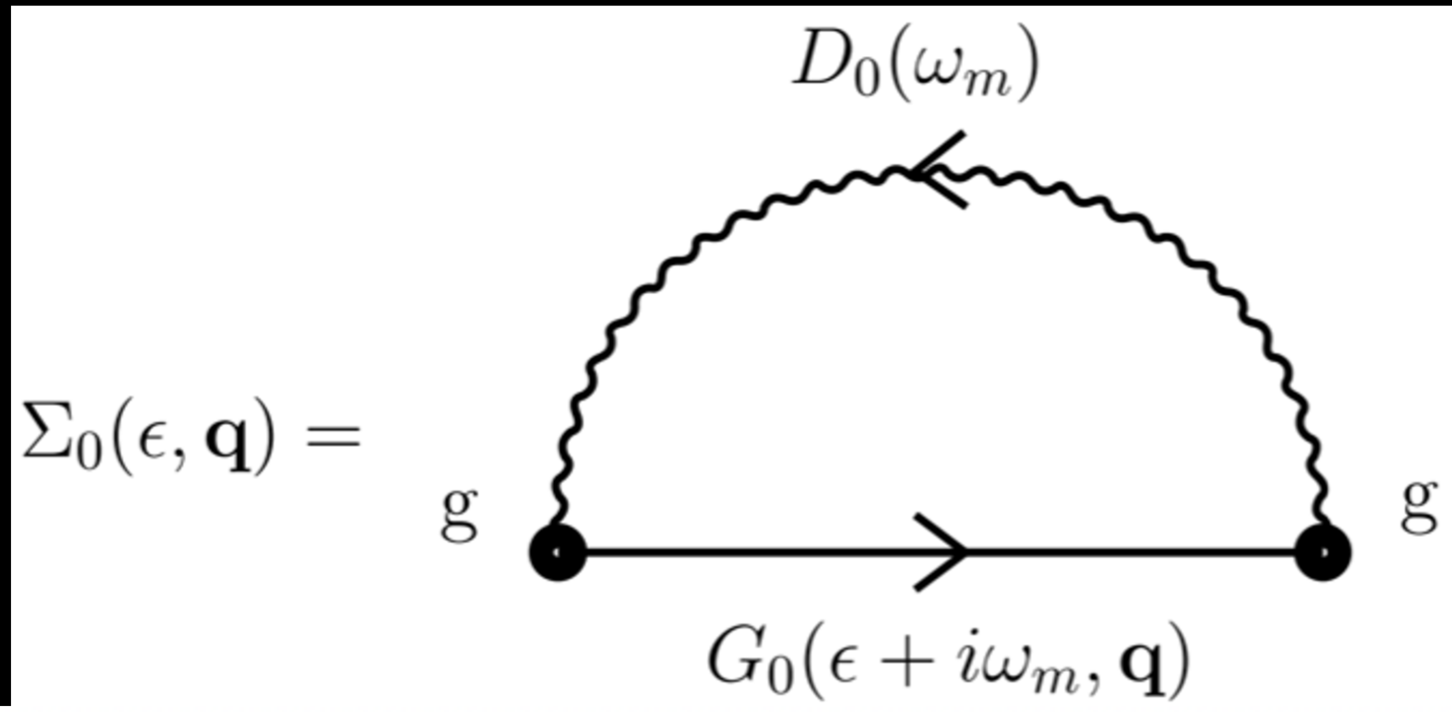


$$n_p(\boldsymbol{k}) = \langle \hat{a}^\dagger \hat{a} \rangle_C = \frac{\beta T_{\boldsymbol{k}}}{\hbar \omega_c},$$

Liu Yang and QDJ, Comm. Phys. 8, 126 (2025)

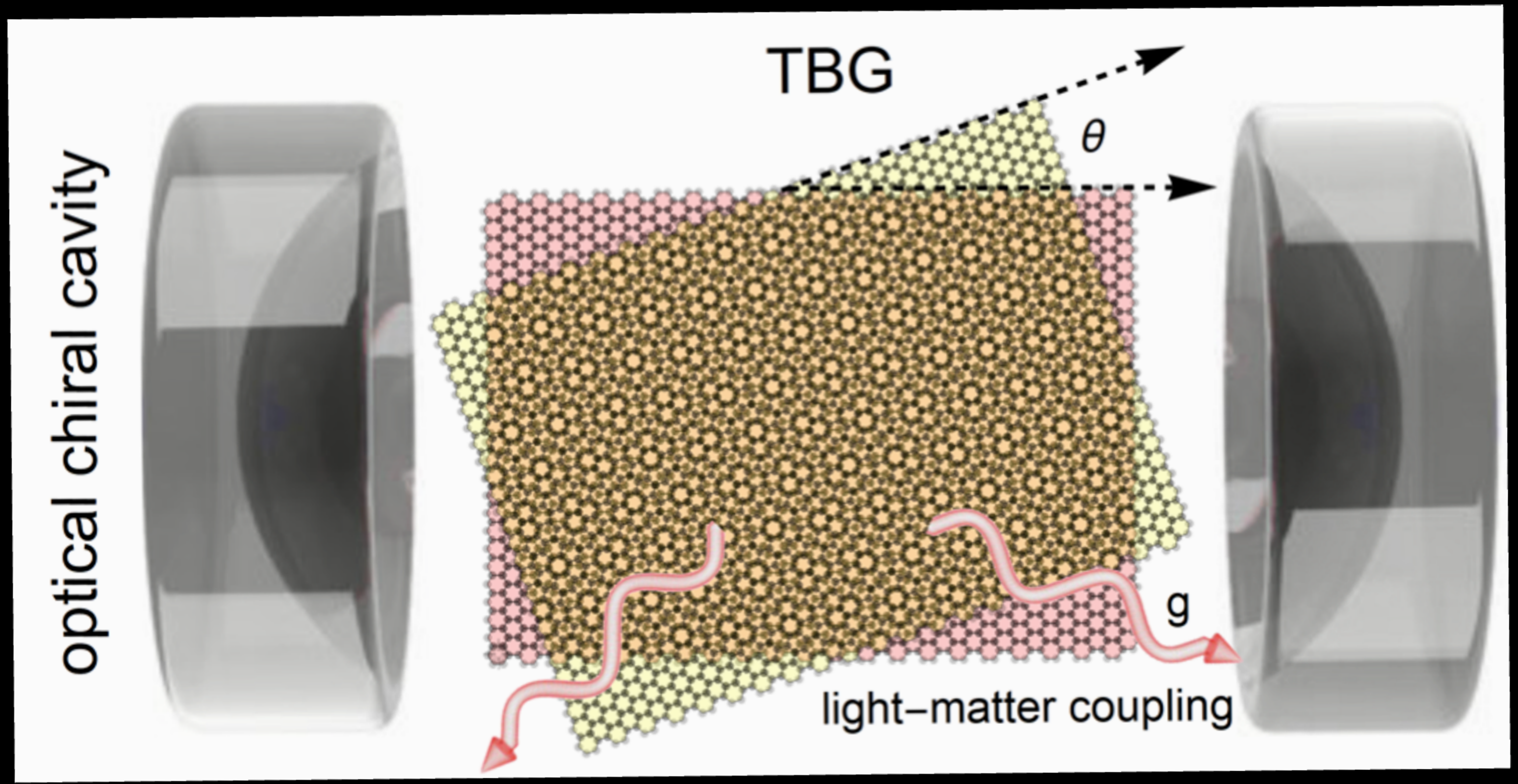
Vacuum to engineer band structure of 2D materials

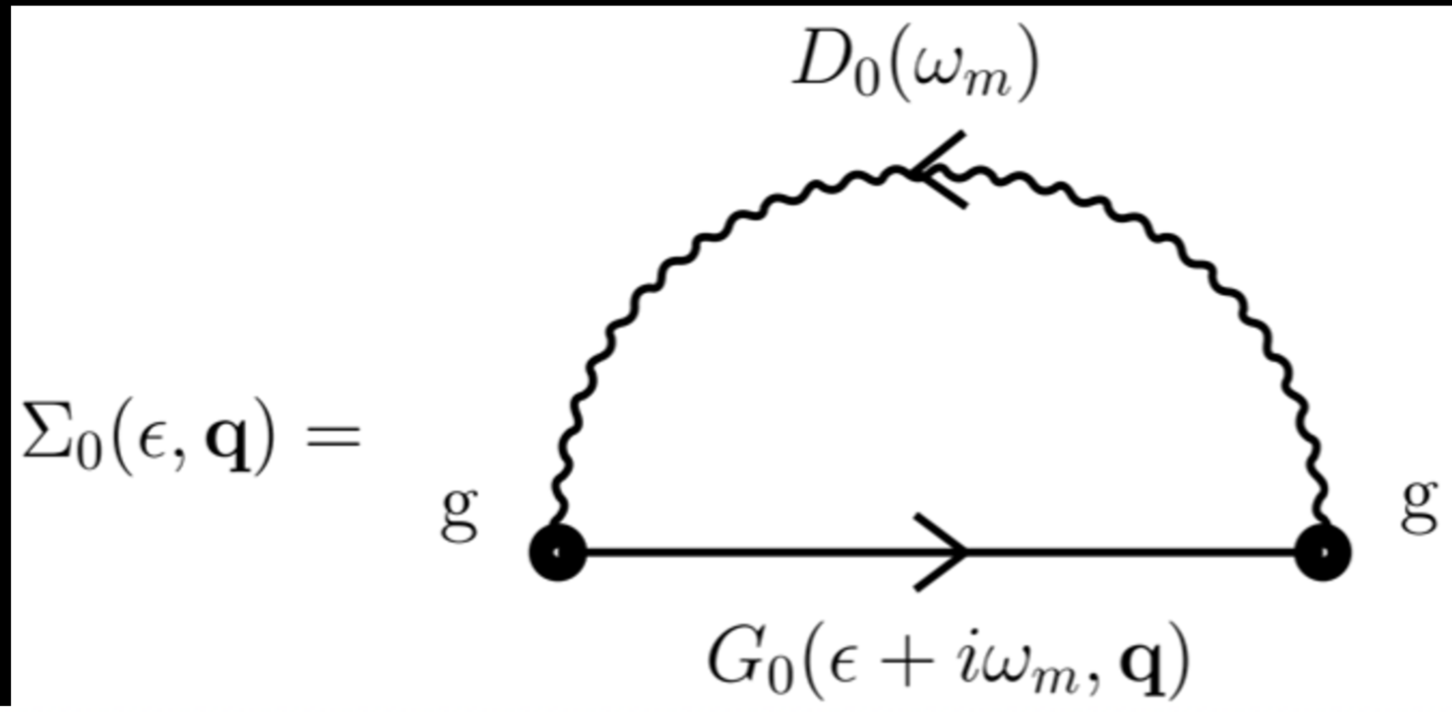




$$\Sigma_0(\epsilon, \mathbf{q}) = -\frac{g^2}{\beta} \sum_{m=1}^{\infty} G_0(\epsilon + i\omega_m, \mathbf{q}) D_0(\omega_m).$$

Vacuum to engineer band structure of 2D materials





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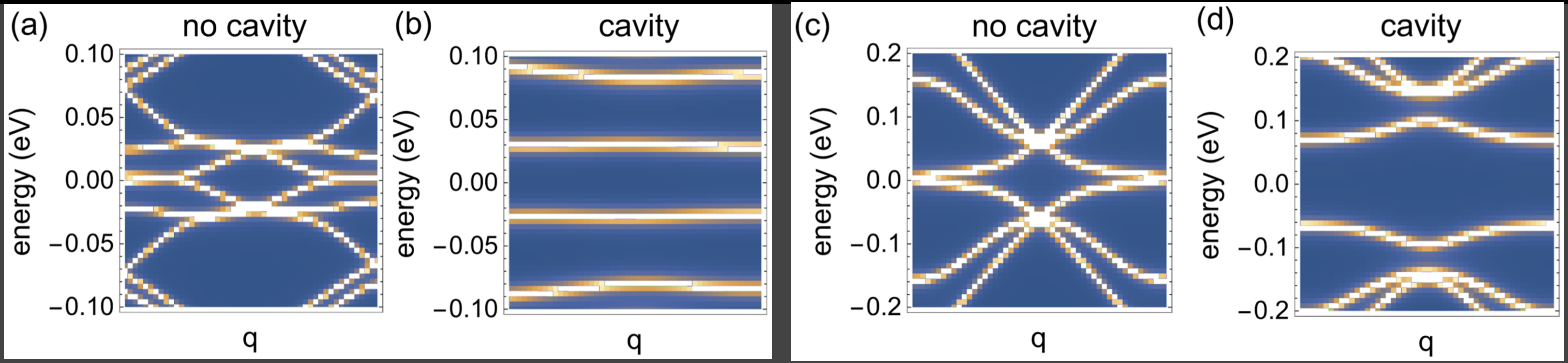
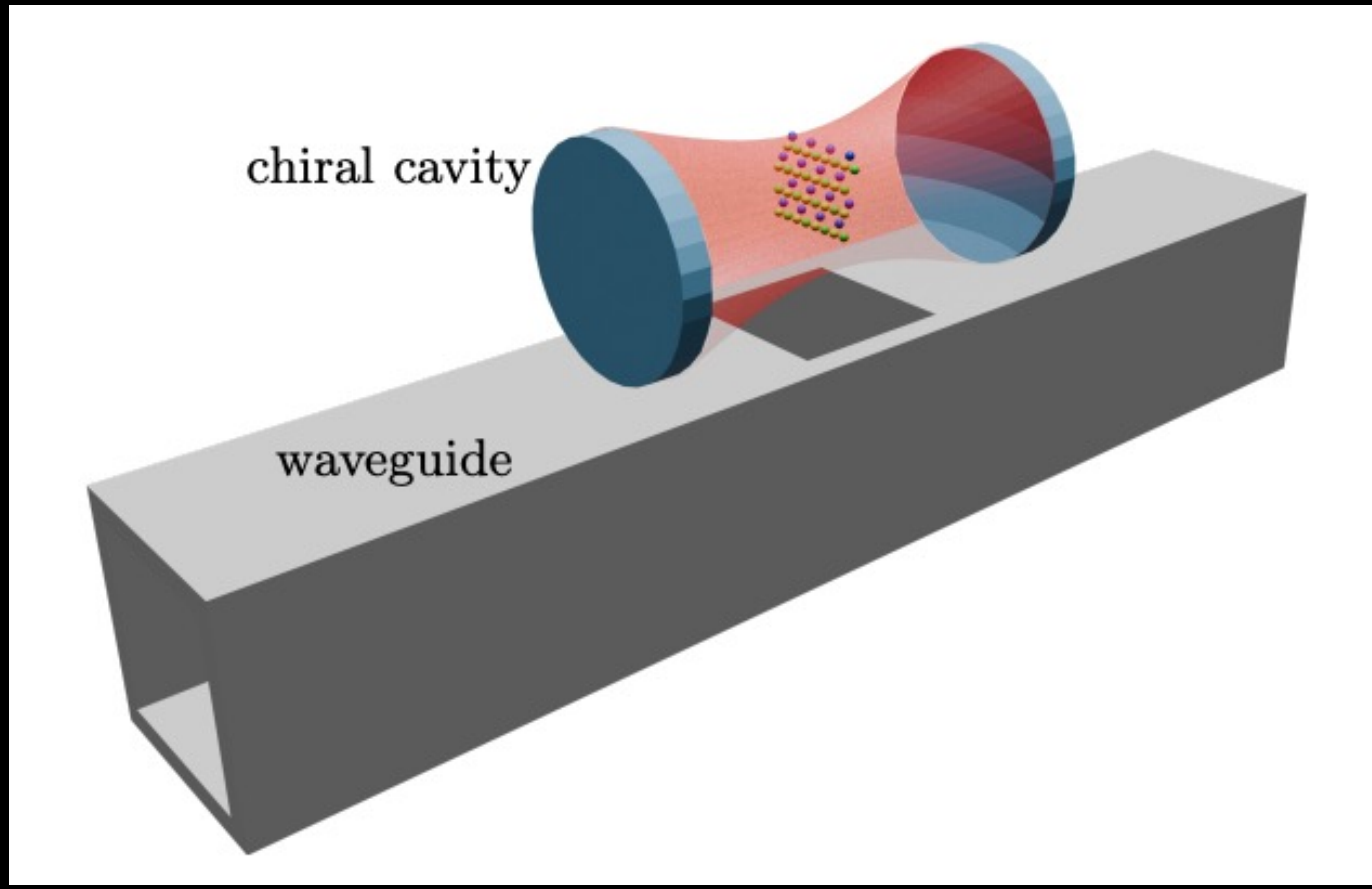
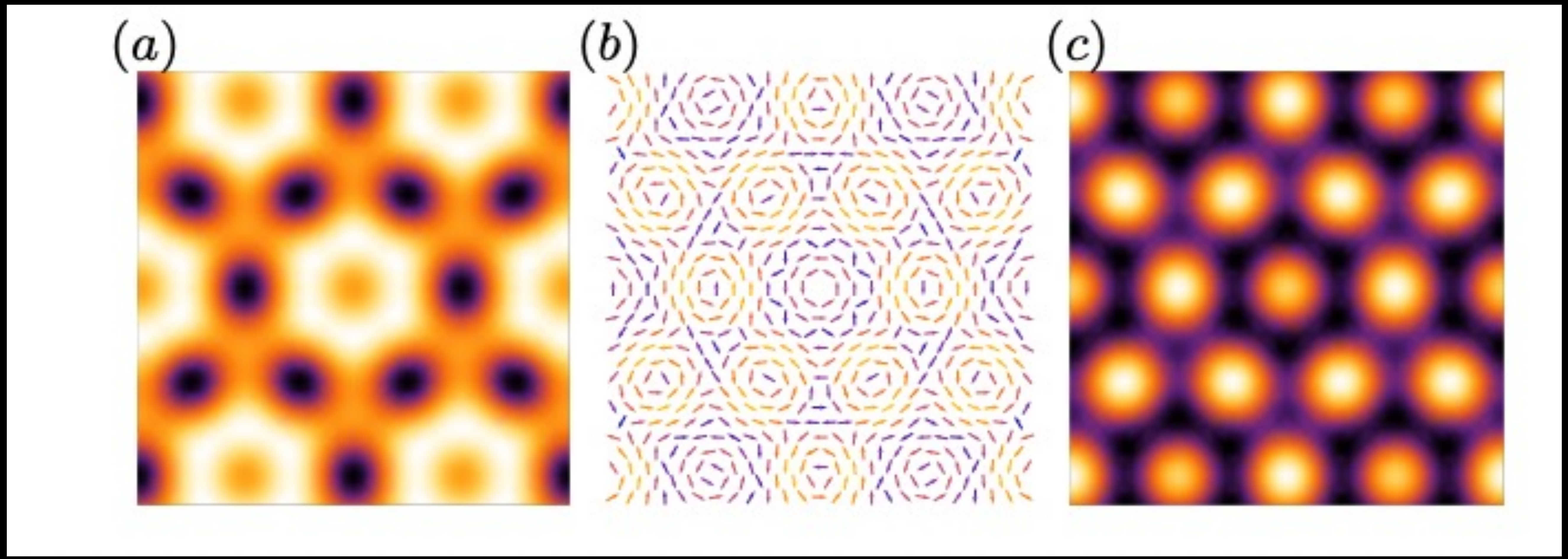


Cunyuan Jiang, Matteo Baggioli, and QD Jiang, PRL **132**, 166901 (2024)

Chiral virtual photons induce chiral spin liquid





$$H_{\mathrm{AD}} = -\sum_{i,j,\sigma} t e^{i\varphi_{ij}} c_{i\sigma}^{\dagger} c_{j\sigma} + U' \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_i B(n_{i\uparrow} - n_{i\downarrow})$$

$$H_{\mathrm{eff}} = \sum_{\bullet\!-\!\bullet} \frac{2|t_{ij}|^2}{U'}(P_{ij} - 1) + \sum_{\triangle} \frac{6\,\mathrm{Im}(t_{ij}t_{jk}t_{ki})}{U'^2} i(P_{ijk} - h.c.).$$

Chenan Wei, Liu Yang and QDJ, PRL 135, 236901 (2025)

李政道研究所
TSUNG-DAO LEE INSTITUTE

Quantum Connections in Sweden-16
Summer School

Lecture 1: Renormalization and Casimir Physics

Lecture 2: Casimir Torque, Friction and Spectra

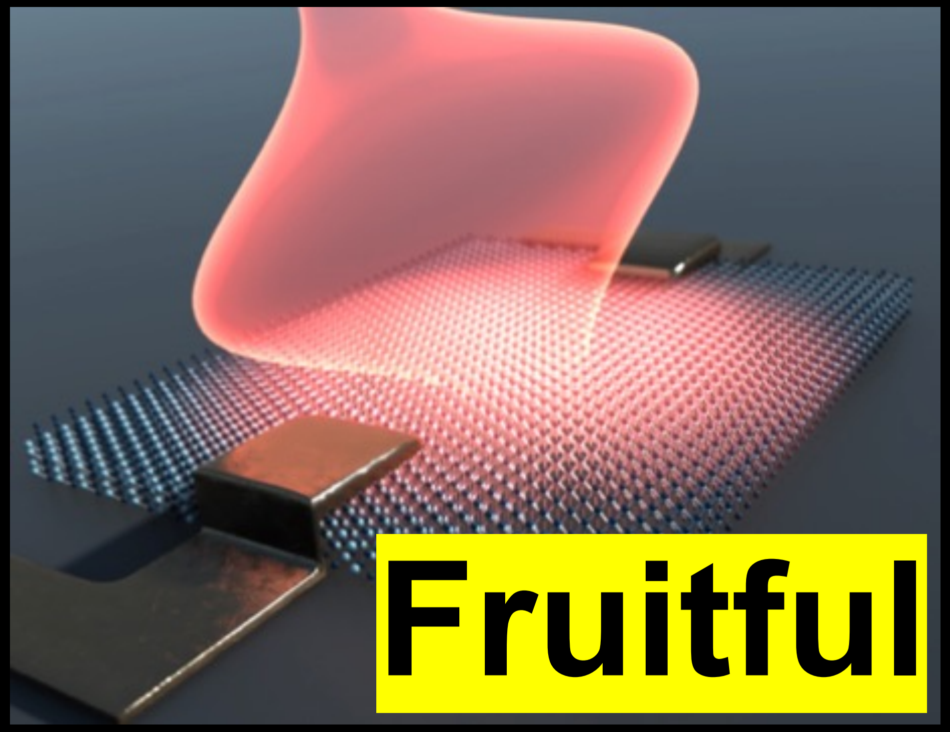
Lecture 3: Quantum atmosphere

Lecture 4: Cavity Quantum Materials

The Rise of Vacuumronics

N

Photon number

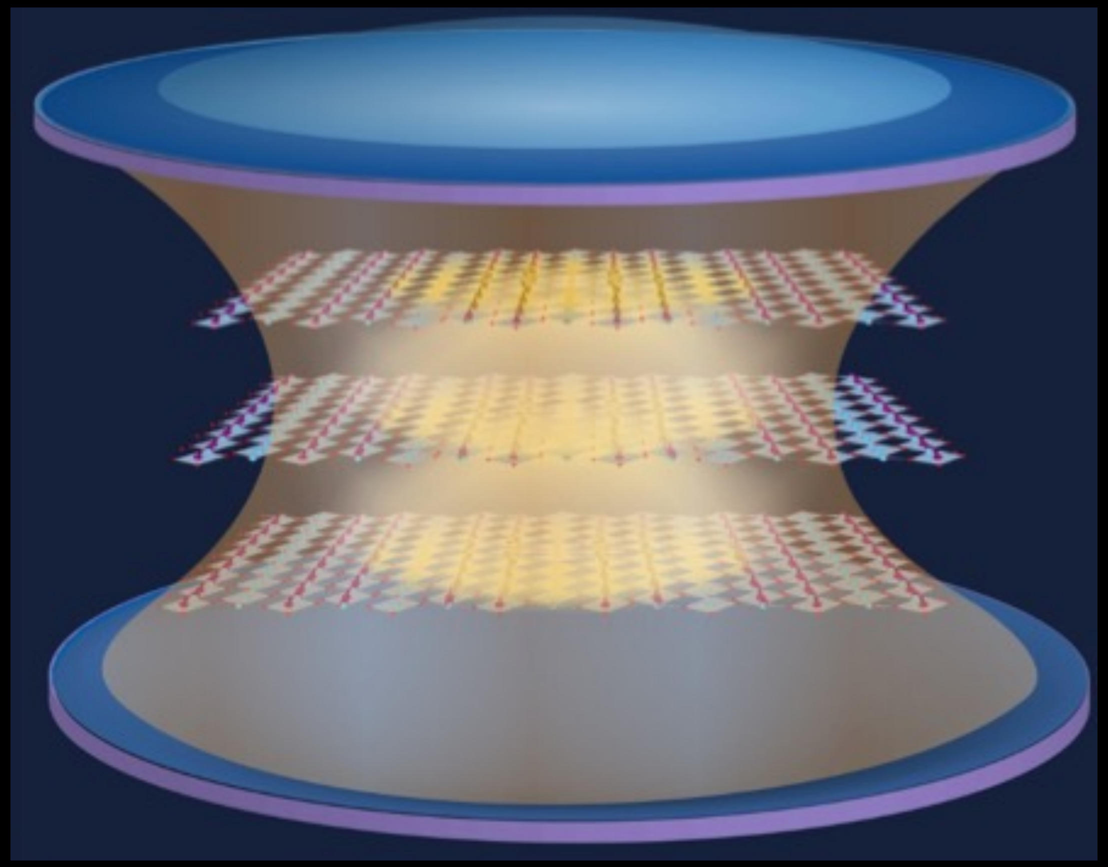


SOMETIMES

Less is More,

when more is too much.

— Frank Lloyd Wright



Vacuum fluctuation strength

Advantages

- No heating
- Equilibrium approach
- Strong coupling

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Summary