Constraint mobility of fractionalized particles in quantum spin liquid

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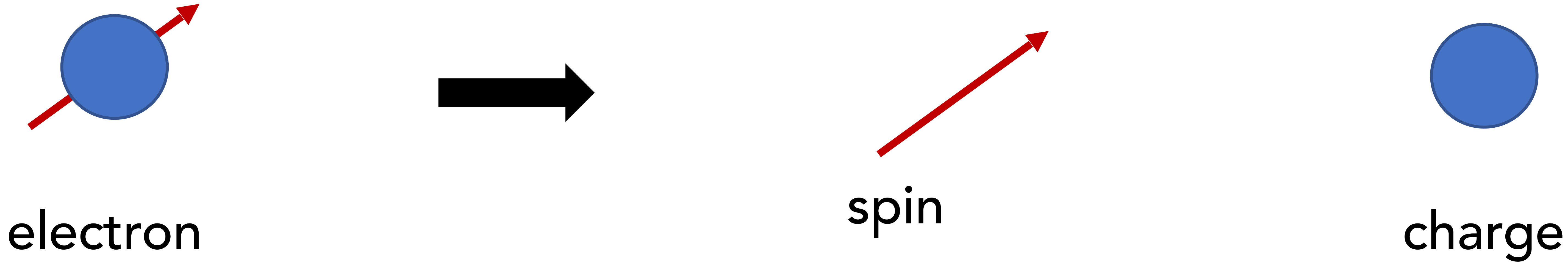
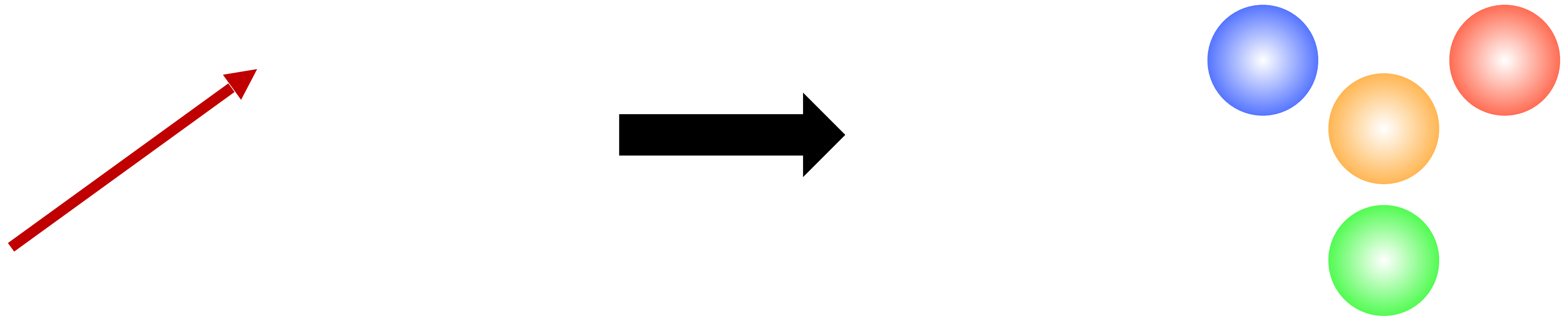
S. Feng, *A. Agarwala, S. Bhattacharjee, N. Trivedi.* *Phys. Rev. B 108, 035149 (2023)*

Fascinating Phenomena in Quantum Materials: Fractionalization



(Mott Insulator)

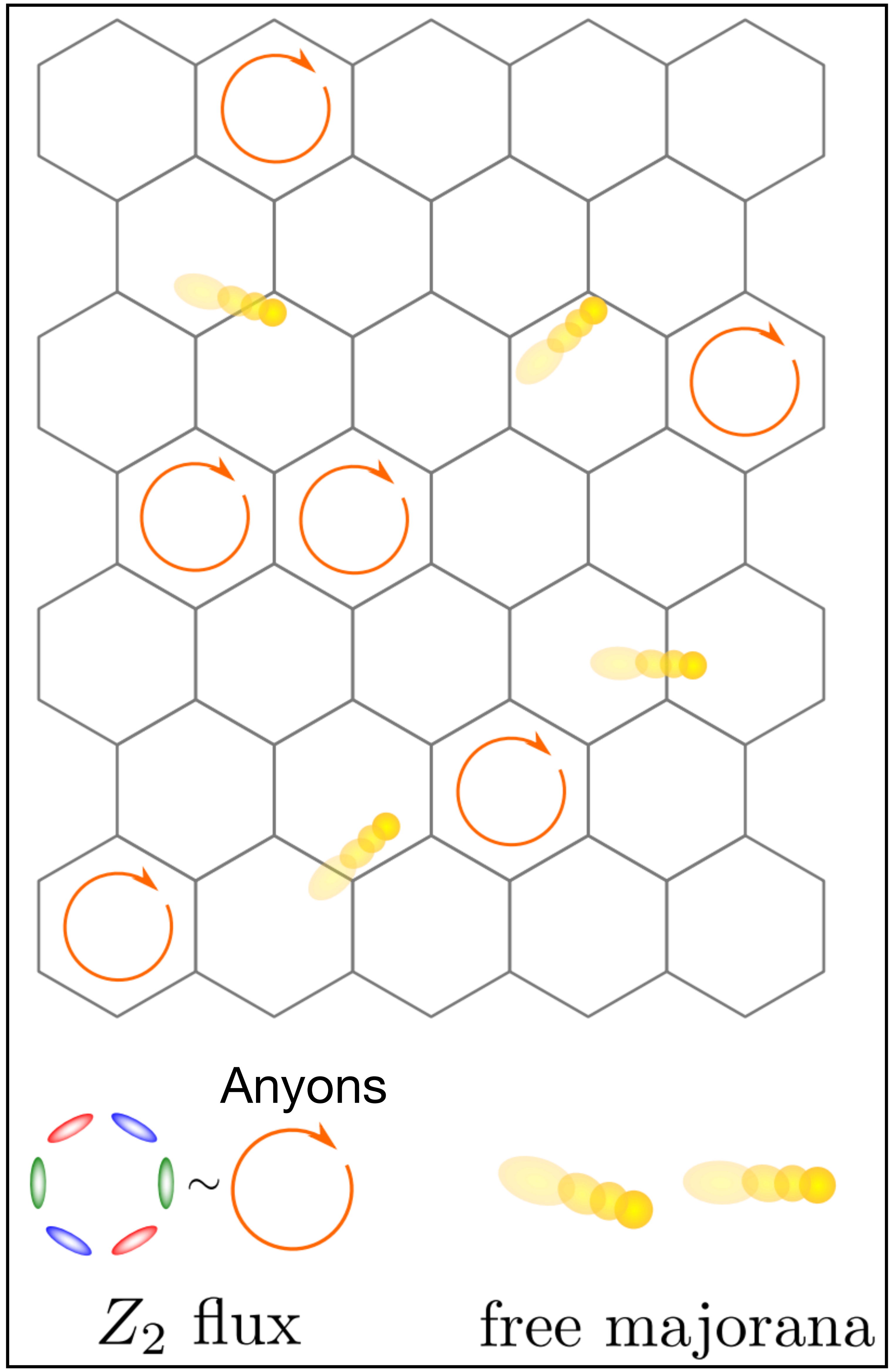


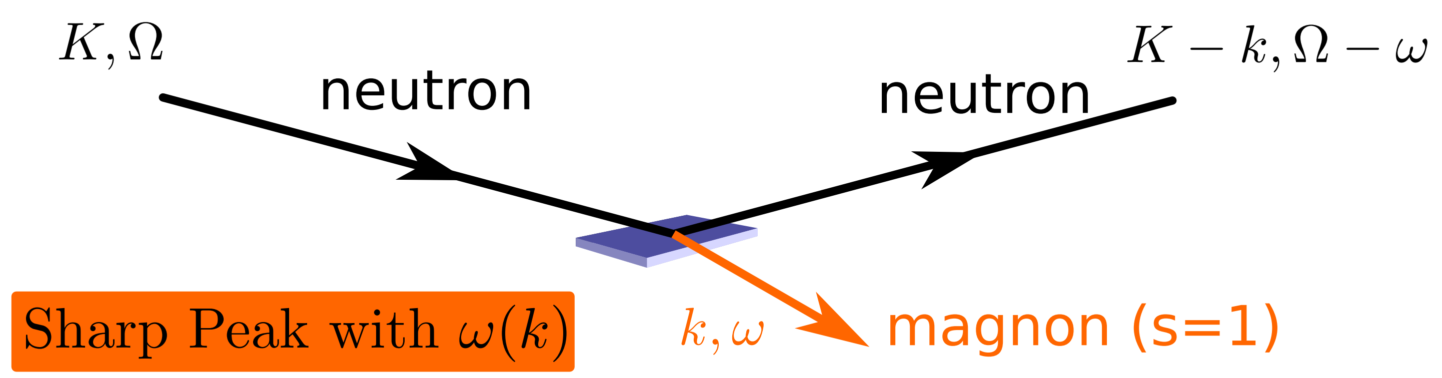
(Quantum Spin Liquid)

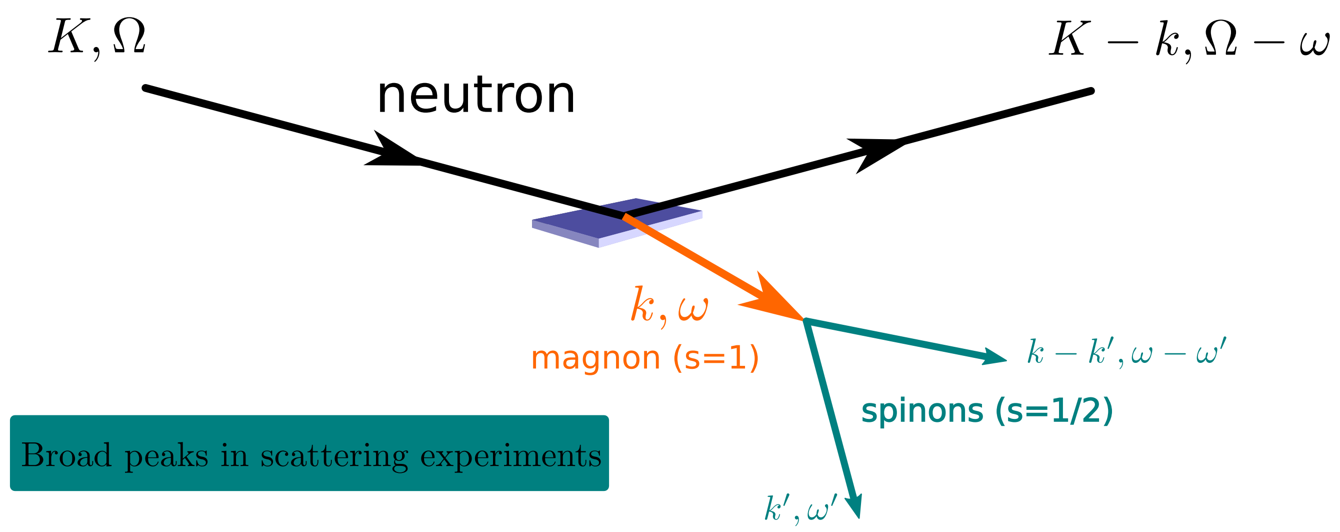
Fractionalized into anyons/majoranas /spinons

Can we detect any sharp features of fractionalized excitations?

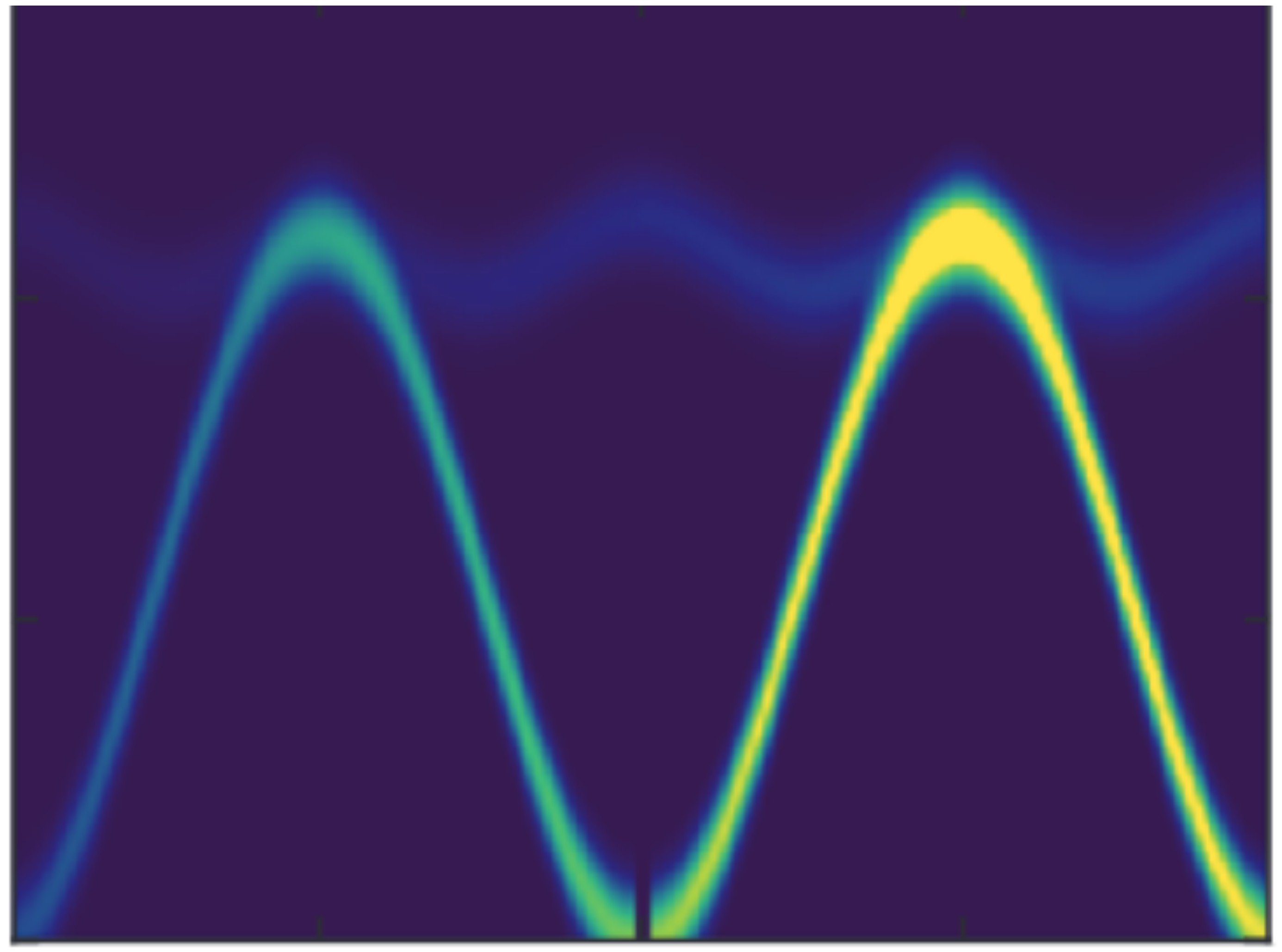
Challenge in scattering experiments for QSL



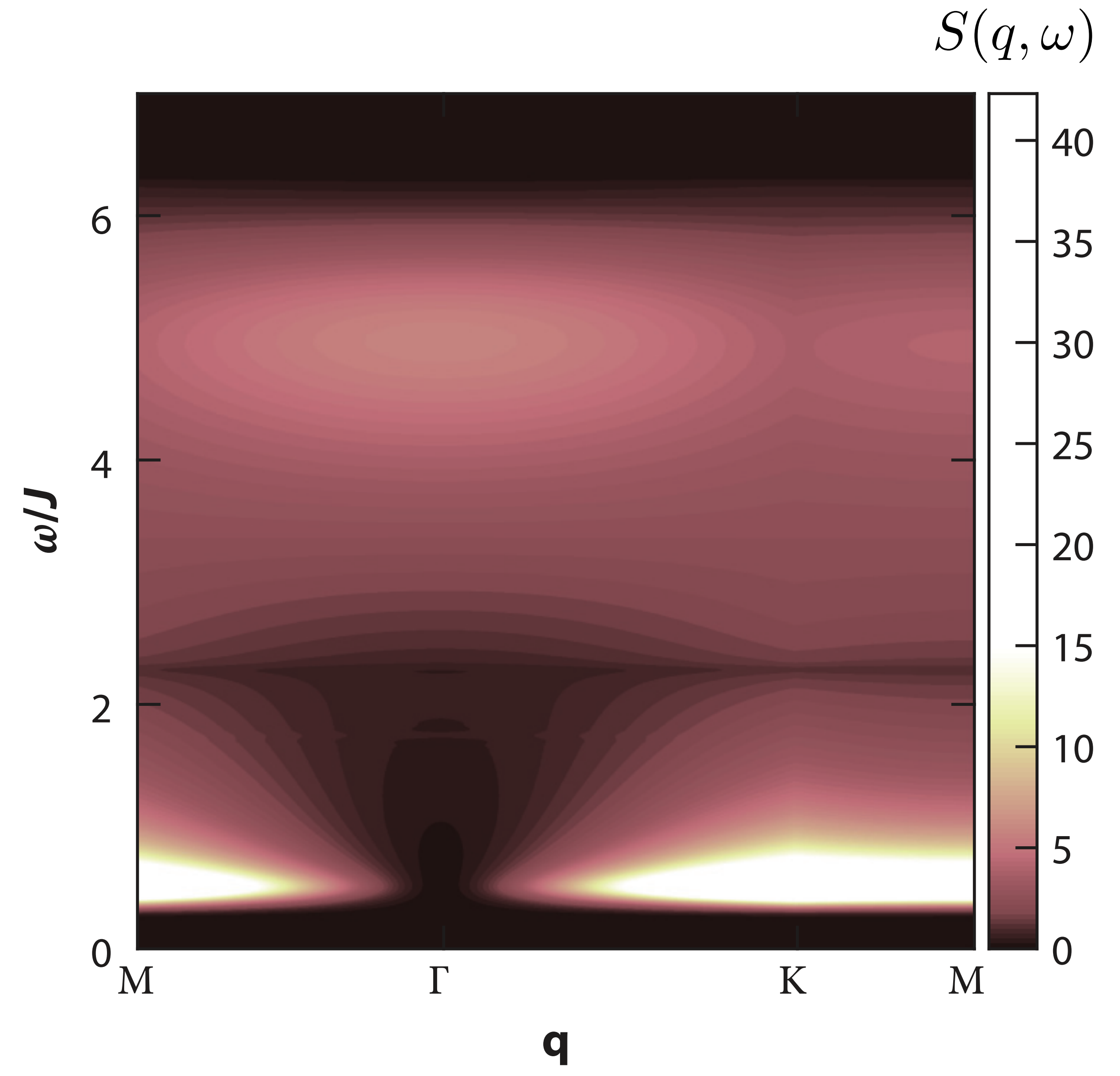




Magnon spectra of CrSBr



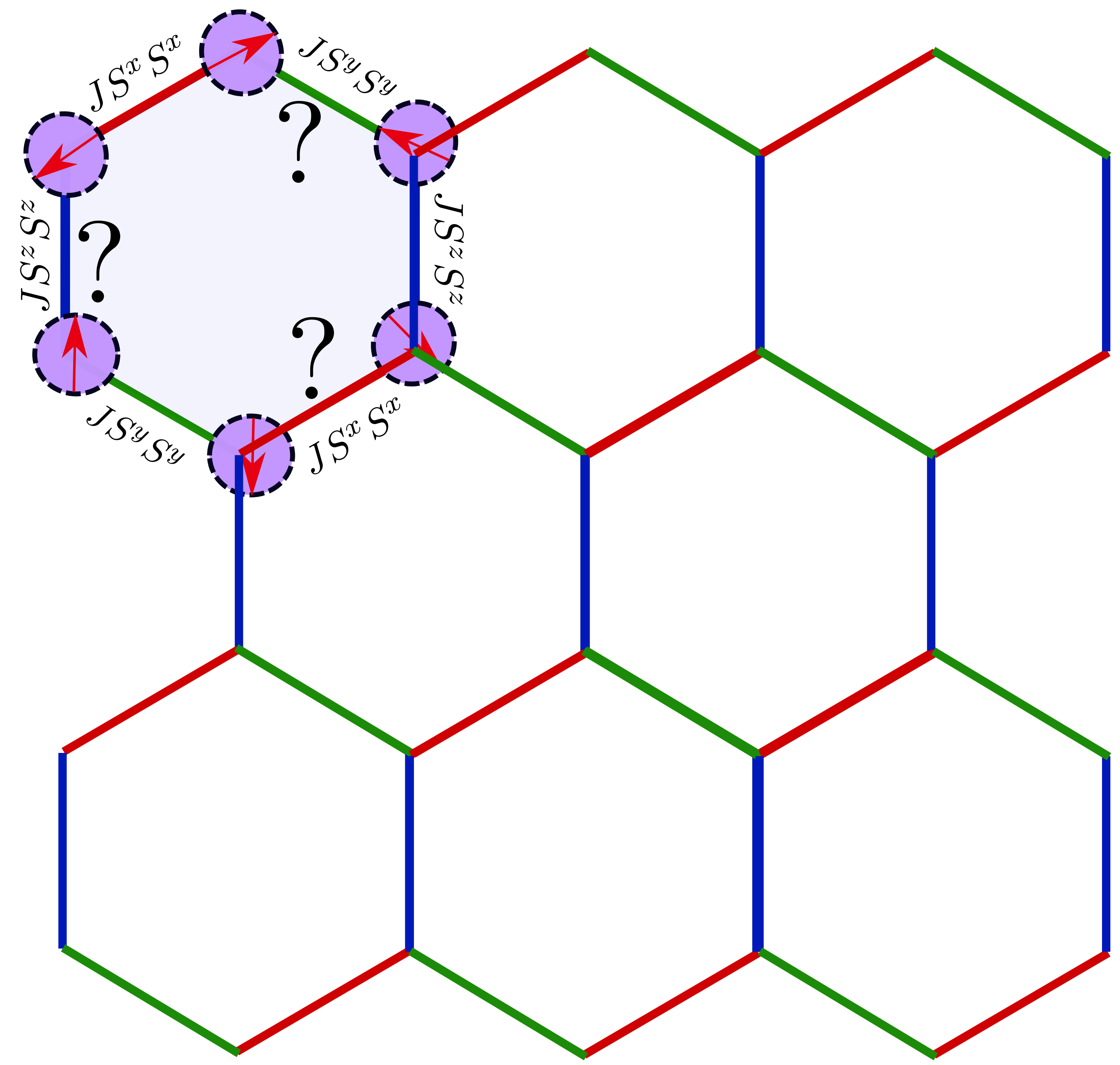
Sharp magnon modes without fractionalization



Featureless signals due to fractionalization

A. Scheie et al. advs.202202467
M. Hermanns et al. Annu. Rev. Condens. Matter Phys. 9:17-33 (2018)

2D Frustrated Magnets -> Quantum spin liquid

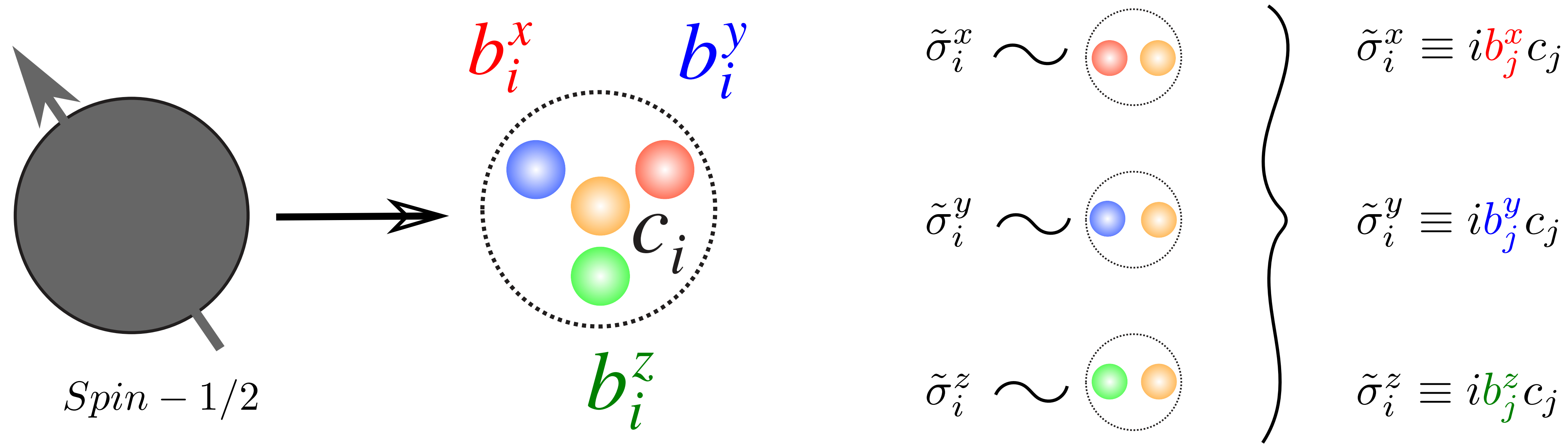


$$H = J\left(\sum_{x} S_i^x S_j^x + \sum_{y} S_i^y S_j^y + \sum_{z} S_i^z S_j^z\right)$$

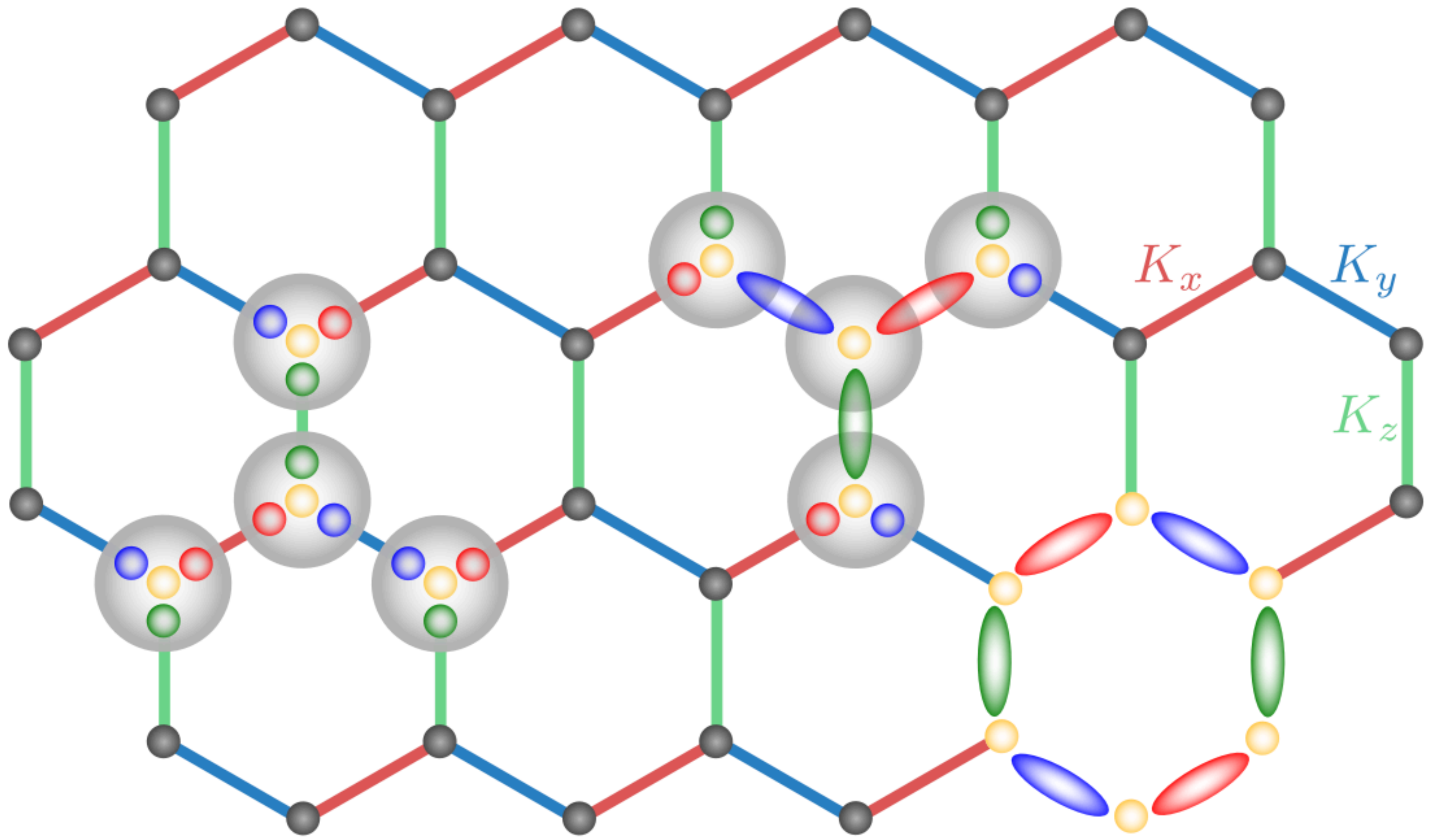
Kitaev's honeycomb model

Dynamics of fractionalized quasi-particles

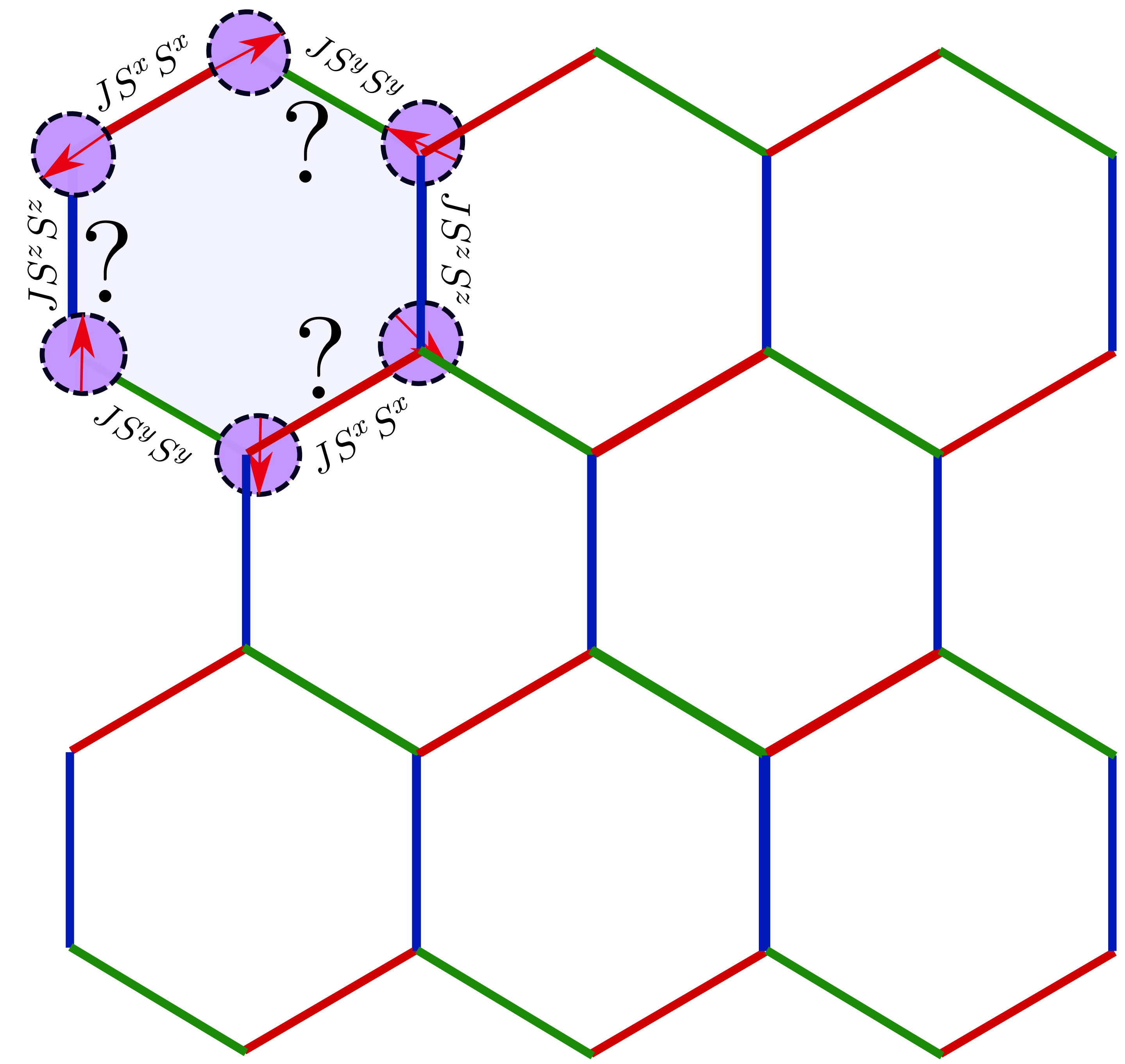
- Fractionalized particles



A. Kitaev, Annals of Physics 321 (2006) 2–111



2D Frustrated Magnets -> Quantum spin liquid



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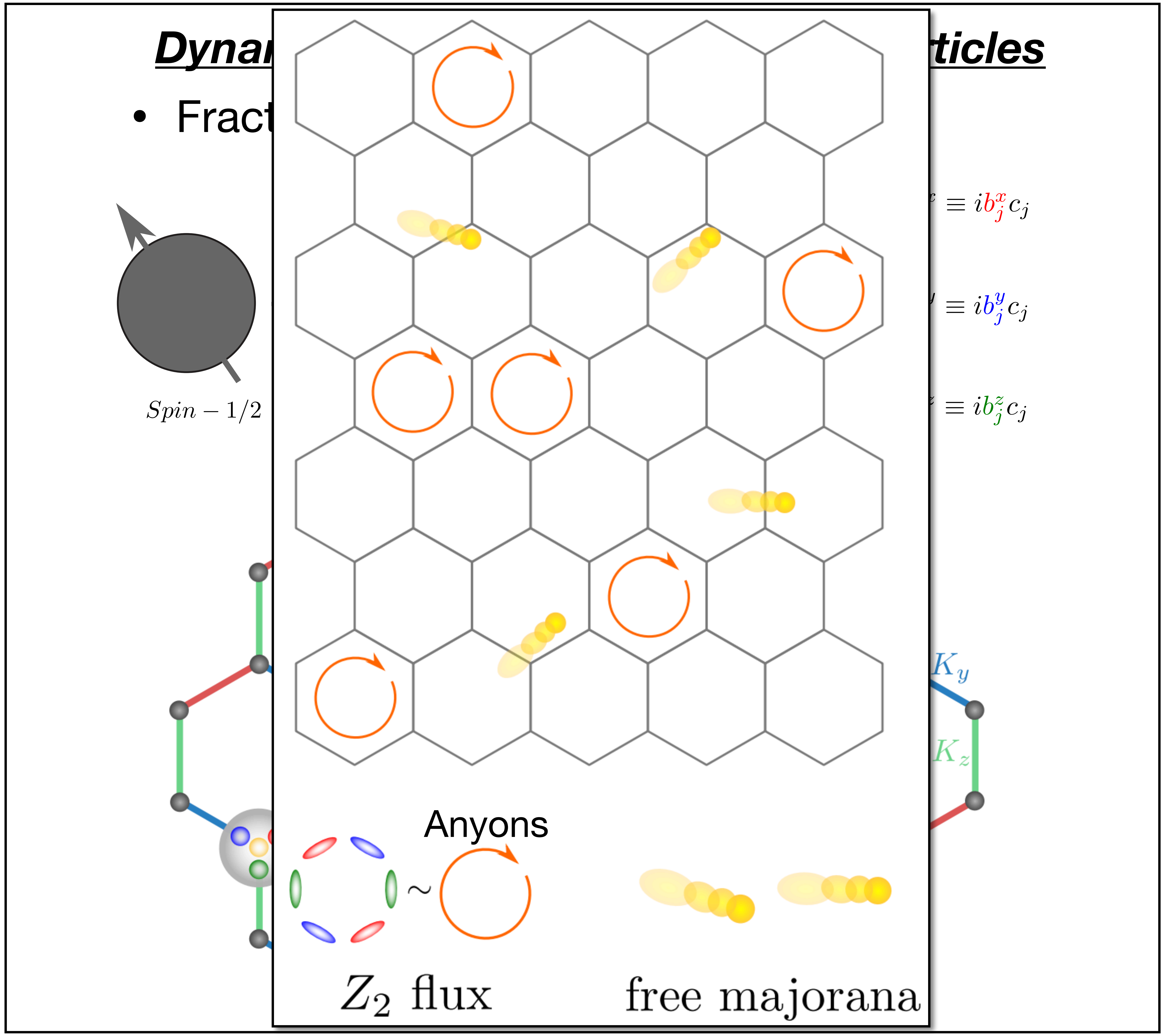
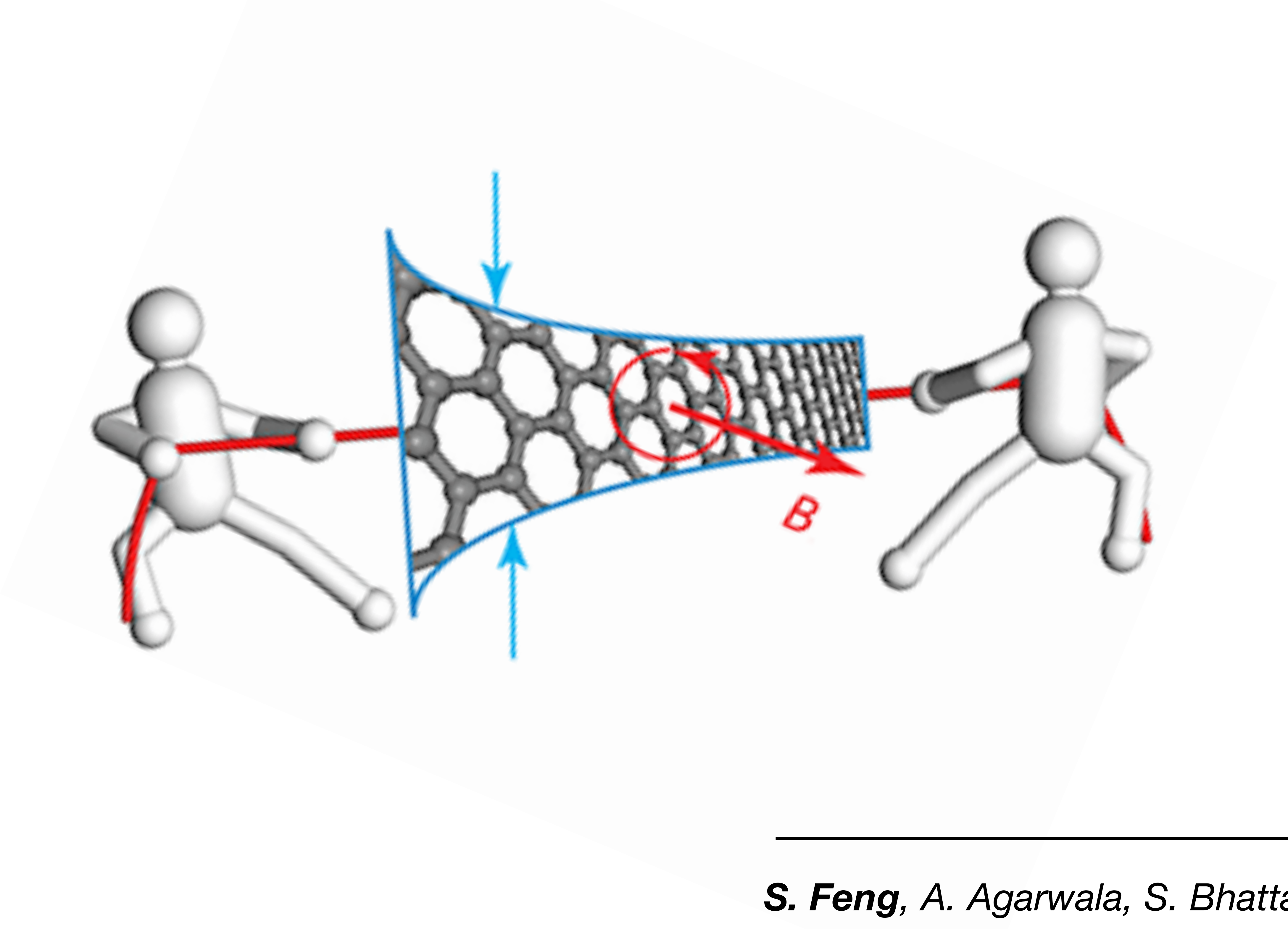
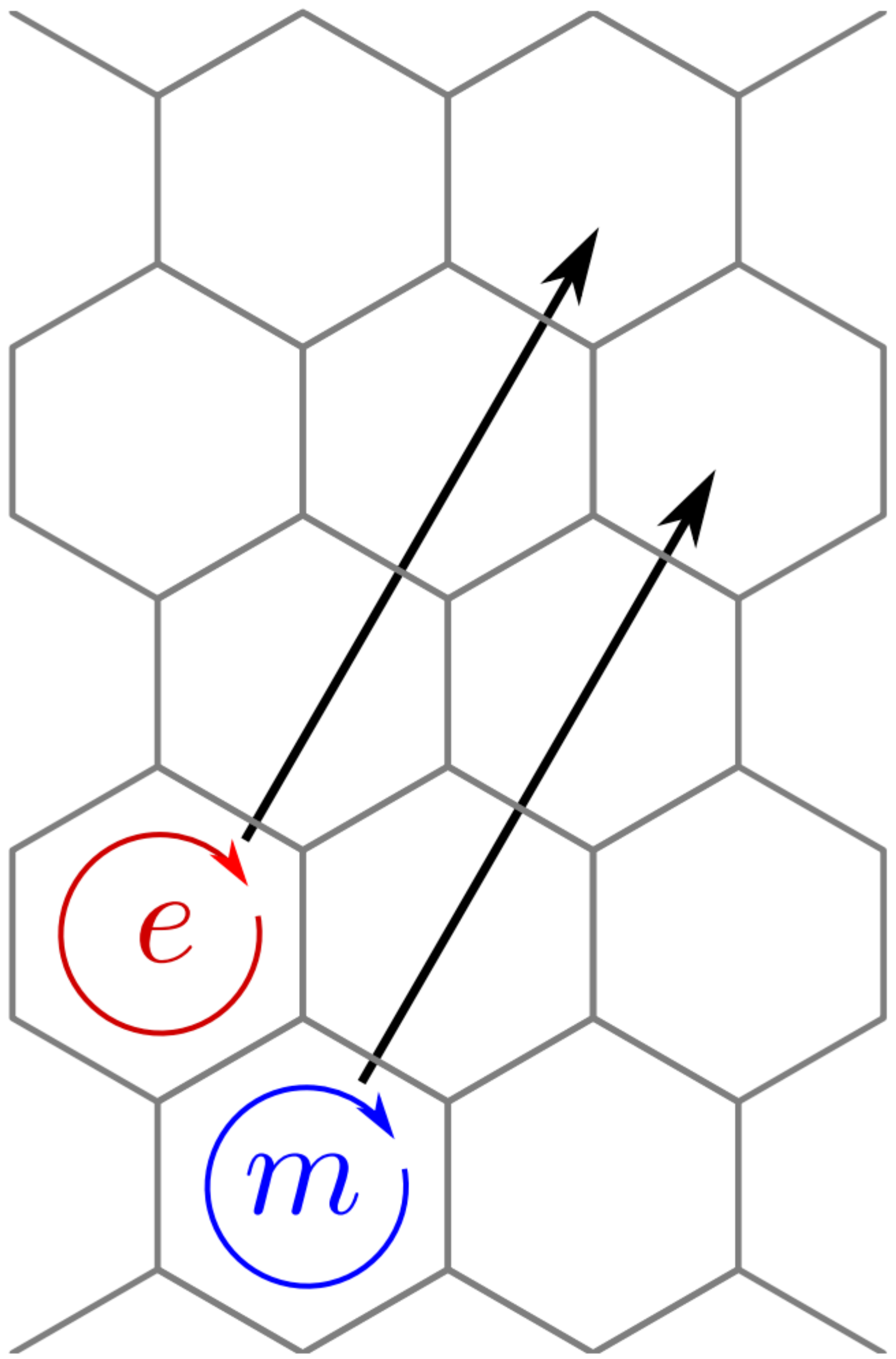
Kitaev's honeycomb model

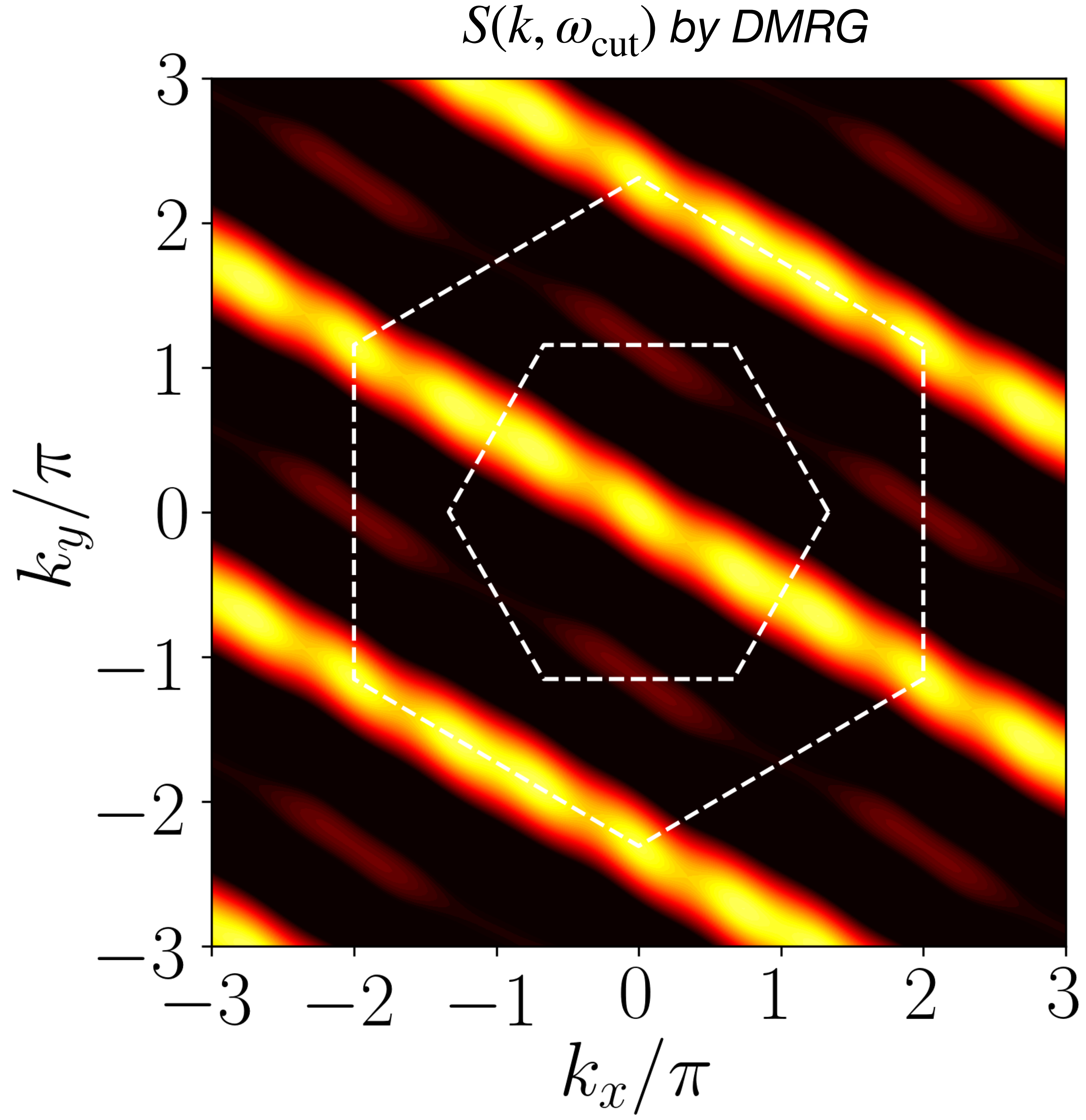


Strain + Field: *sharp* signature of anyons

$$H = \sum_{x} K_x \sigma_i^x \sigma_{i+x}^x + \sum_{y} K_y \sigma_i^y \sigma_{i+y}^y + \sum_{z} K_z \sigma_i^z \sigma_{i+z}^z - B \sum_{i} \sigma_i^{e_3}$$







1D fracton-like mobility of $\epsilon = e \times m$ anyons bound state!

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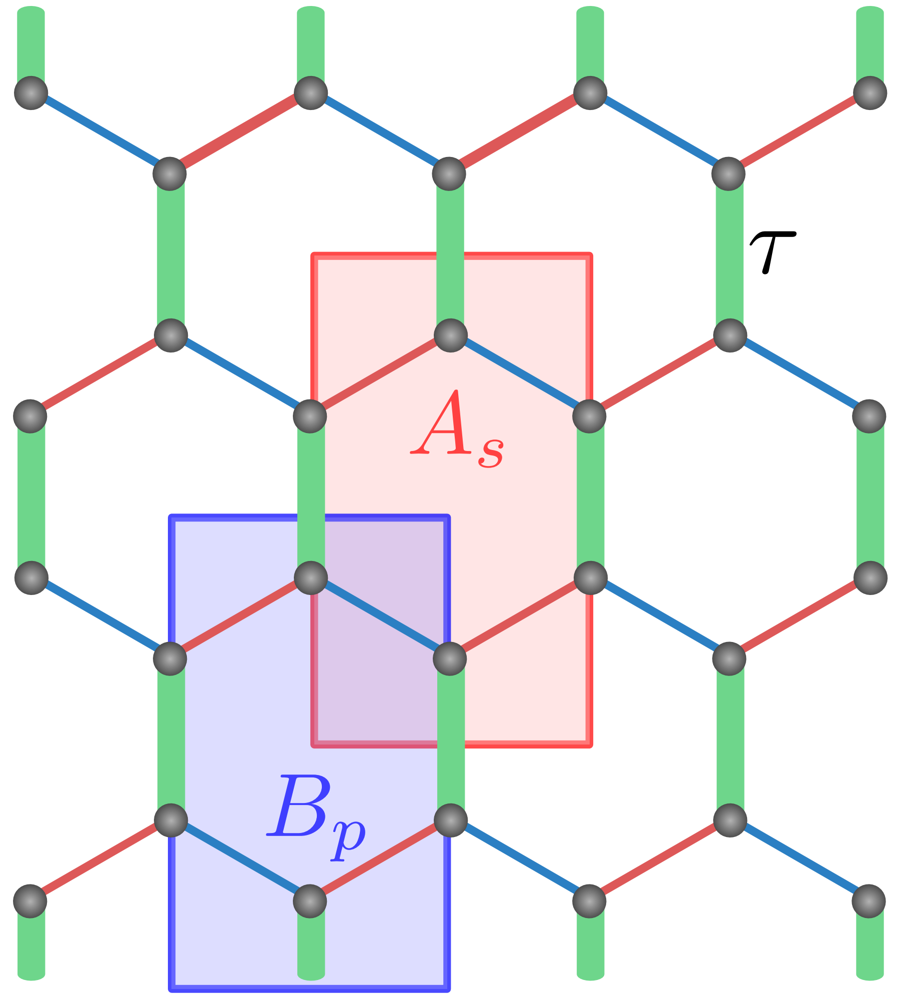
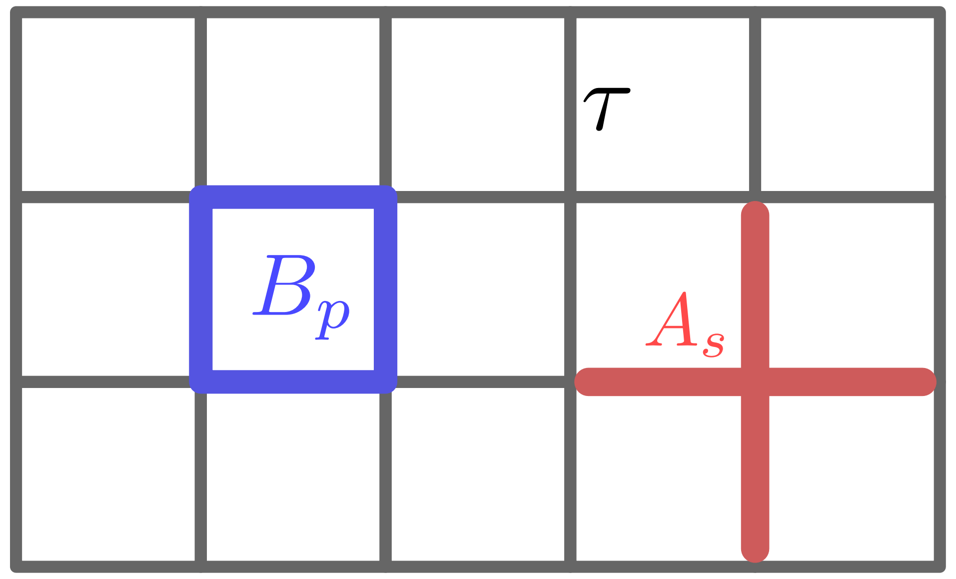
Effects of Strain → Toric Code + Majoranas

$$H_K = \sum_{x} K_x \sigma_i^x \sigma_{i+x}^x + \sum_{y} K_y \sigma_i^y \sigma_{i+y}^y + \sum_{z} K_z \sigma_i^z \sigma_{i+z}^z$$

$K_z \gg K_x, K_y$ $\quad [\,\cdot\,] \in \{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle\} \sim \tau$





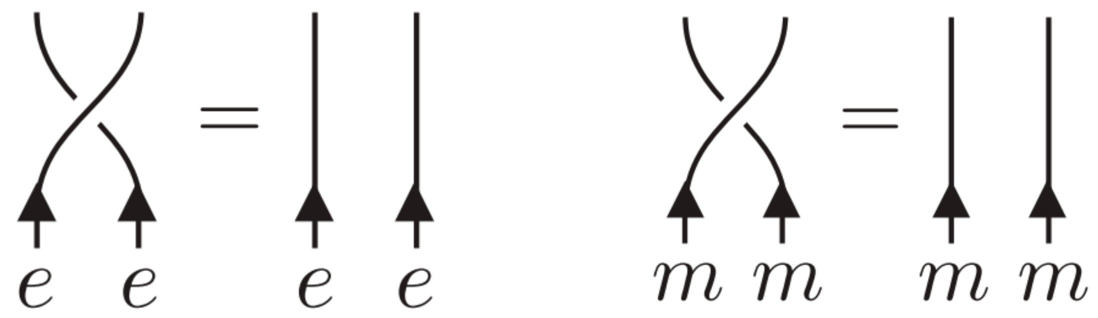
$$\mathcal{H}_{\mathrm{TC}} \sim -\sum_s A_s - \sum_p B_p$$

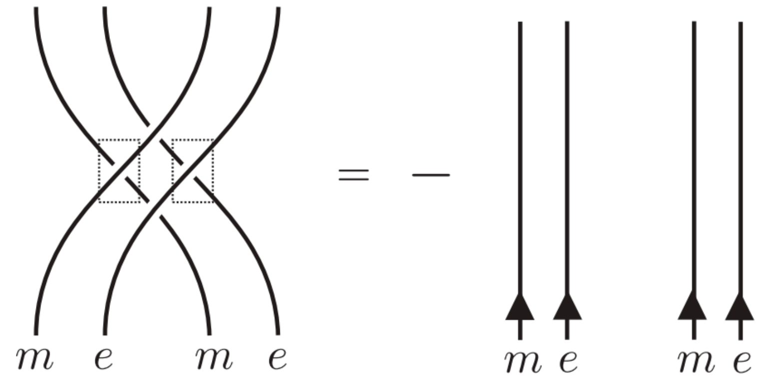
Low energy sector: Toric Code (TC) $\quad A_s = \prod_{i\in +} \tau_i^x, \quad B_p = \prod_{i\in \square} \tau_i^z, \quad [A_s, B_p] = 0$

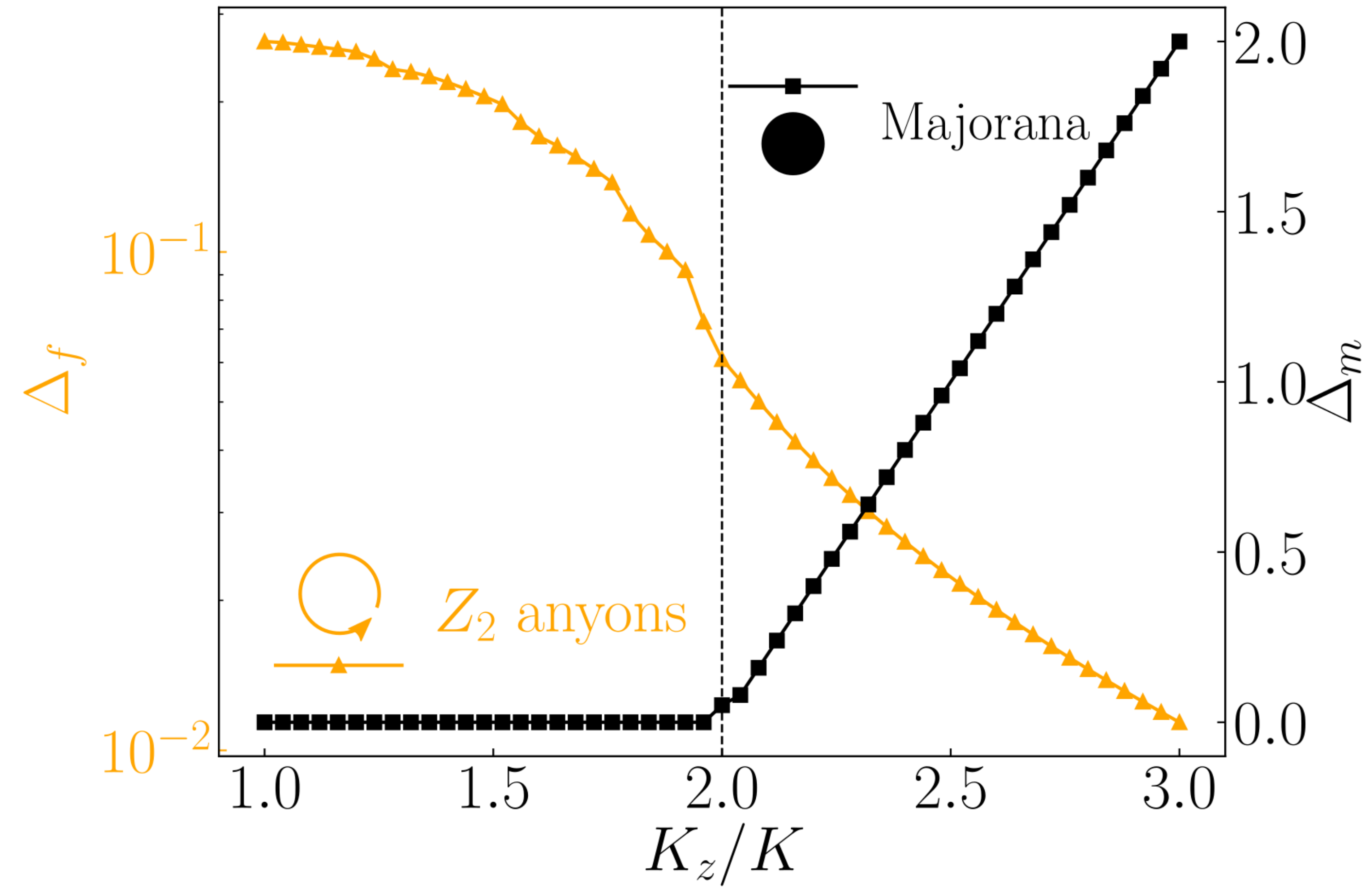
ground state : $A_s = B_p = 1$

Fractionalization:

1. Z_2 Abelian anyons:
   - e $(A_s = -1)$ boson
   - m $(B_p = -1)$ boson
   - $\epsilon = e \times m$ fermion
2. Gapped Majorana fermions







Low energy physics is dominated by anyons

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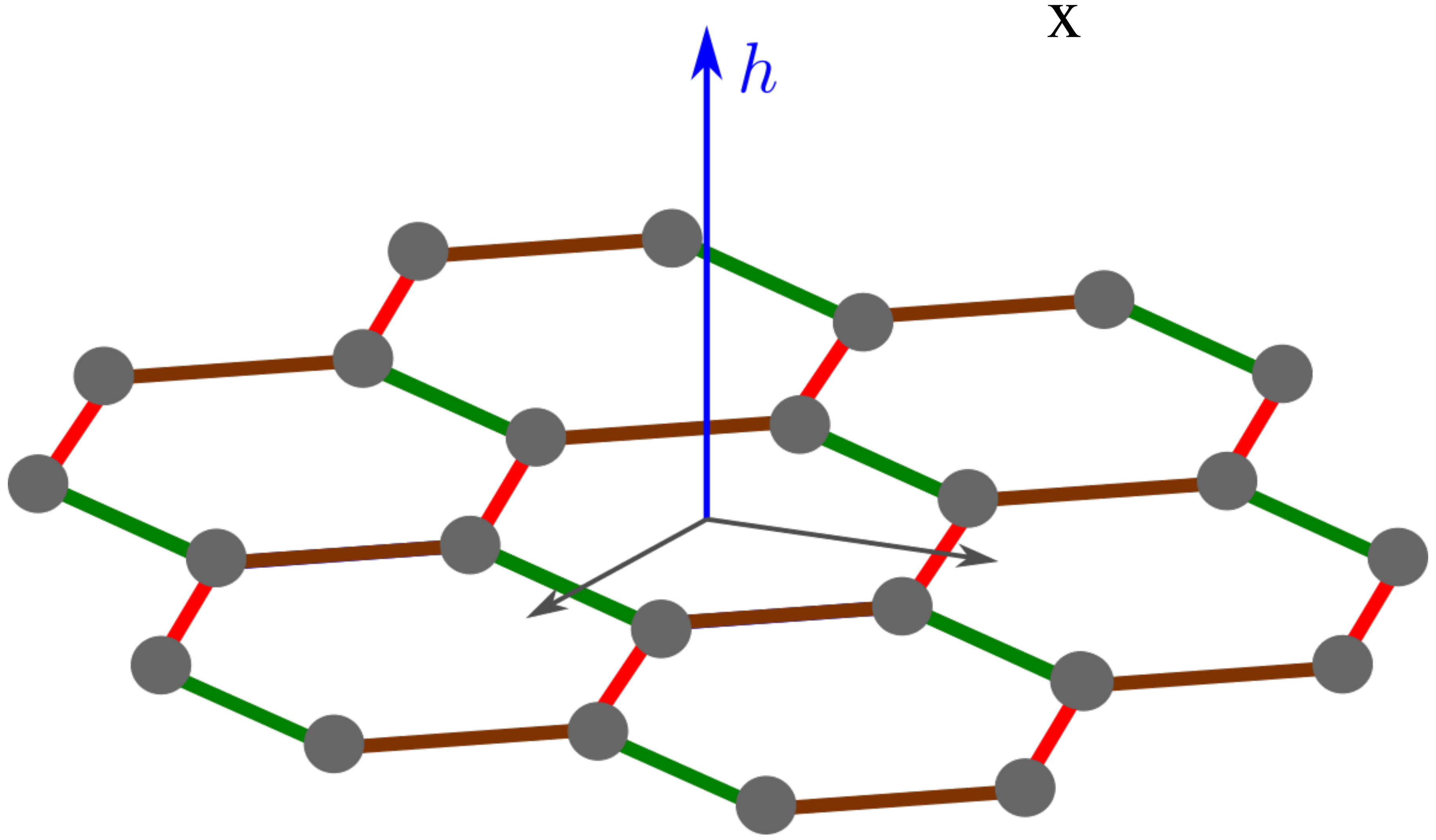
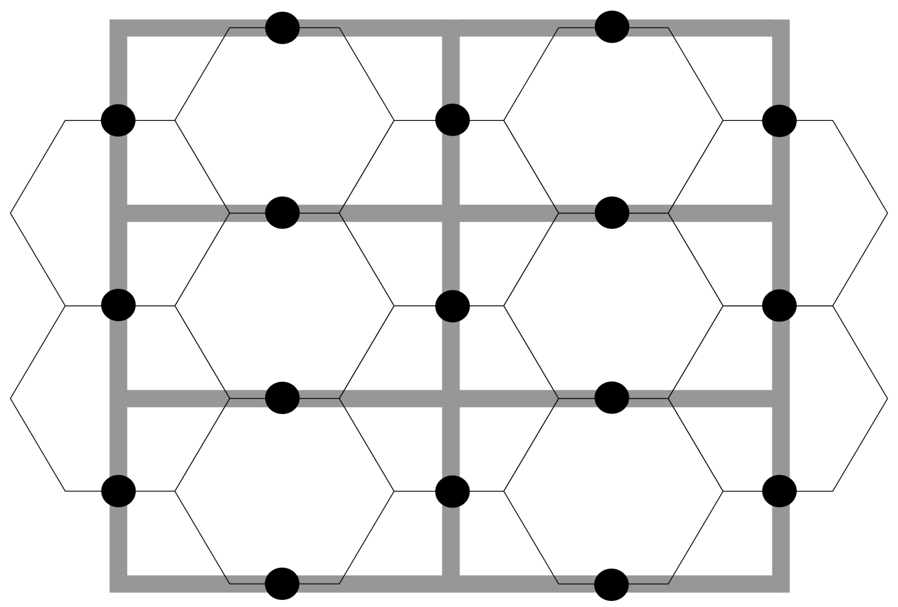
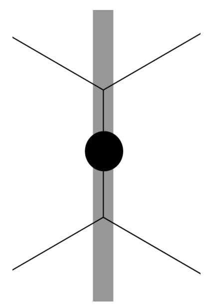
Magnetic-field-induced anyon dynamics

$$H = \sum_{x} K_x \sigma_i^x \sigma_{i+x}^x + \sum_{y} K_y \sigma_i^y \sigma_{i+y}^y + \sum_{z} K_z \sigma_i^z \sigma_{i+z}^z - h \sum_{i} \sigma_i^{e_3}$$



Second order perturbation theory:



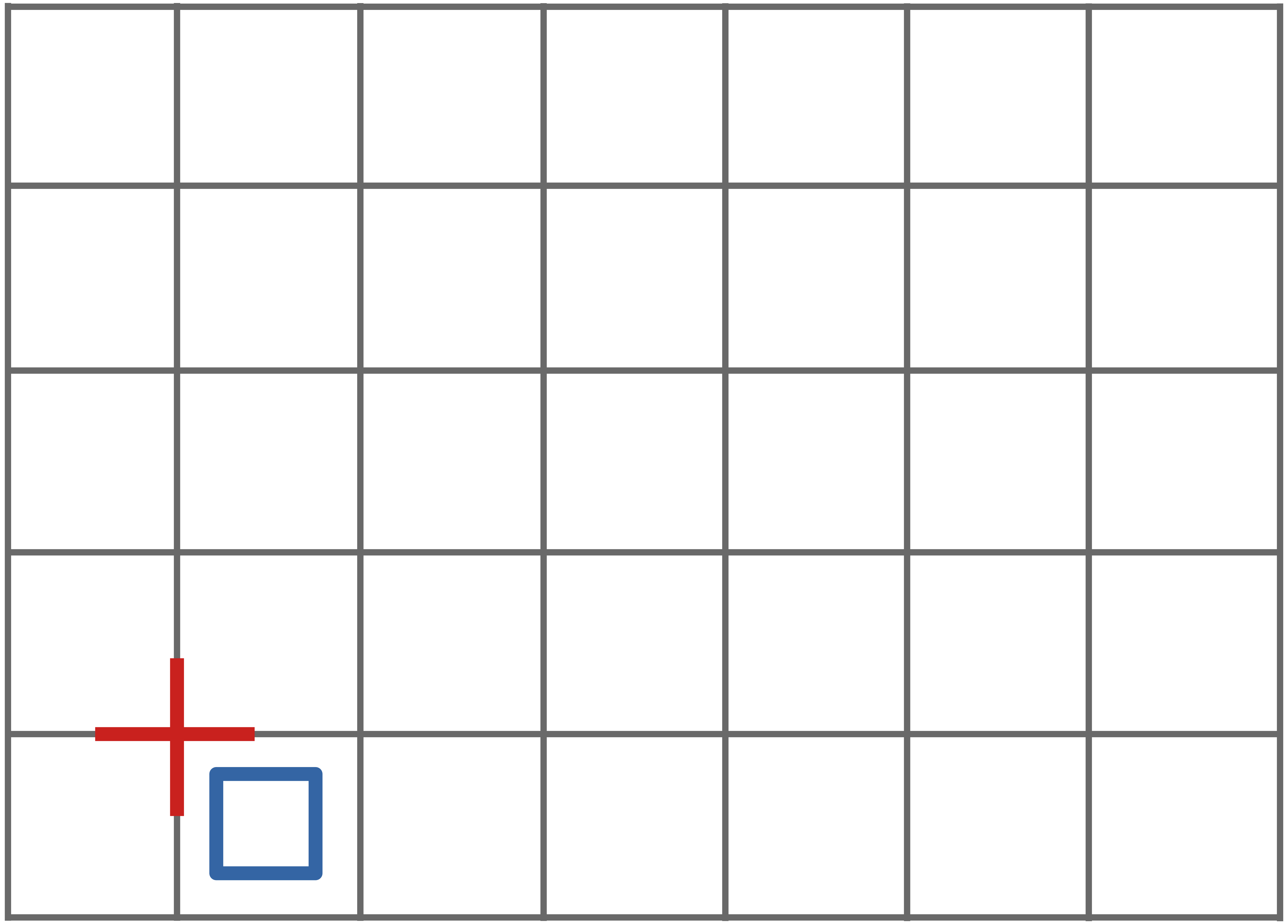
 $= |\uparrow\downarrow\rangle$ or $|\downarrow\uparrow\rangle \longrightarrow \tau$

1 spin flip→ high energy sector
2 spin flips → returns to the low energy sector

$$H_{\text{eff}} \sim -\sum_{s} A_s - \sum_{p} B_p + \sum_{i} \frac{h^2}{K_z} \tau_i^y$$

Magnetic-field-induced anyon dynamics

$$H_{\text{eff}} \sim -\sum_s A_s - \sum_p B_p + \sum_i \frac{h^2}{K_z}\tau_i^y$$



$$A_s = \prod_{i\in s} \tau_i^x$$

$$B_p = \prod_{i\in p} \tau_i^z$$

$$\tau_i^y \sim \tau_i^z \tau_i^x$$

$$[\tau_i^x, A_s] = 0, \quad [\tau_i^x, B_p] \neq 0$$

$$[\tau_i^z, B_p] = 0, \quad [\tau_i^z, A_s] \neq 0$$

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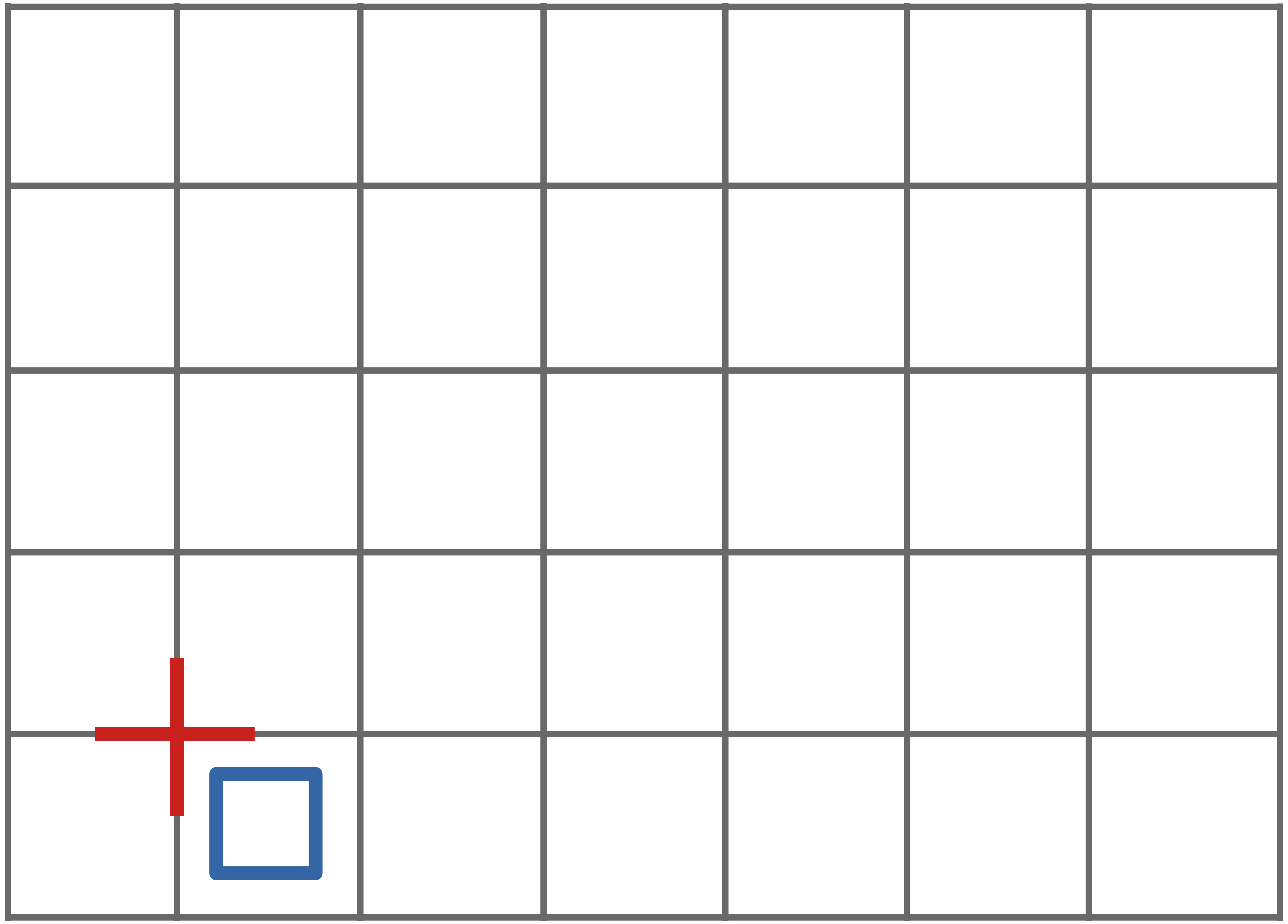

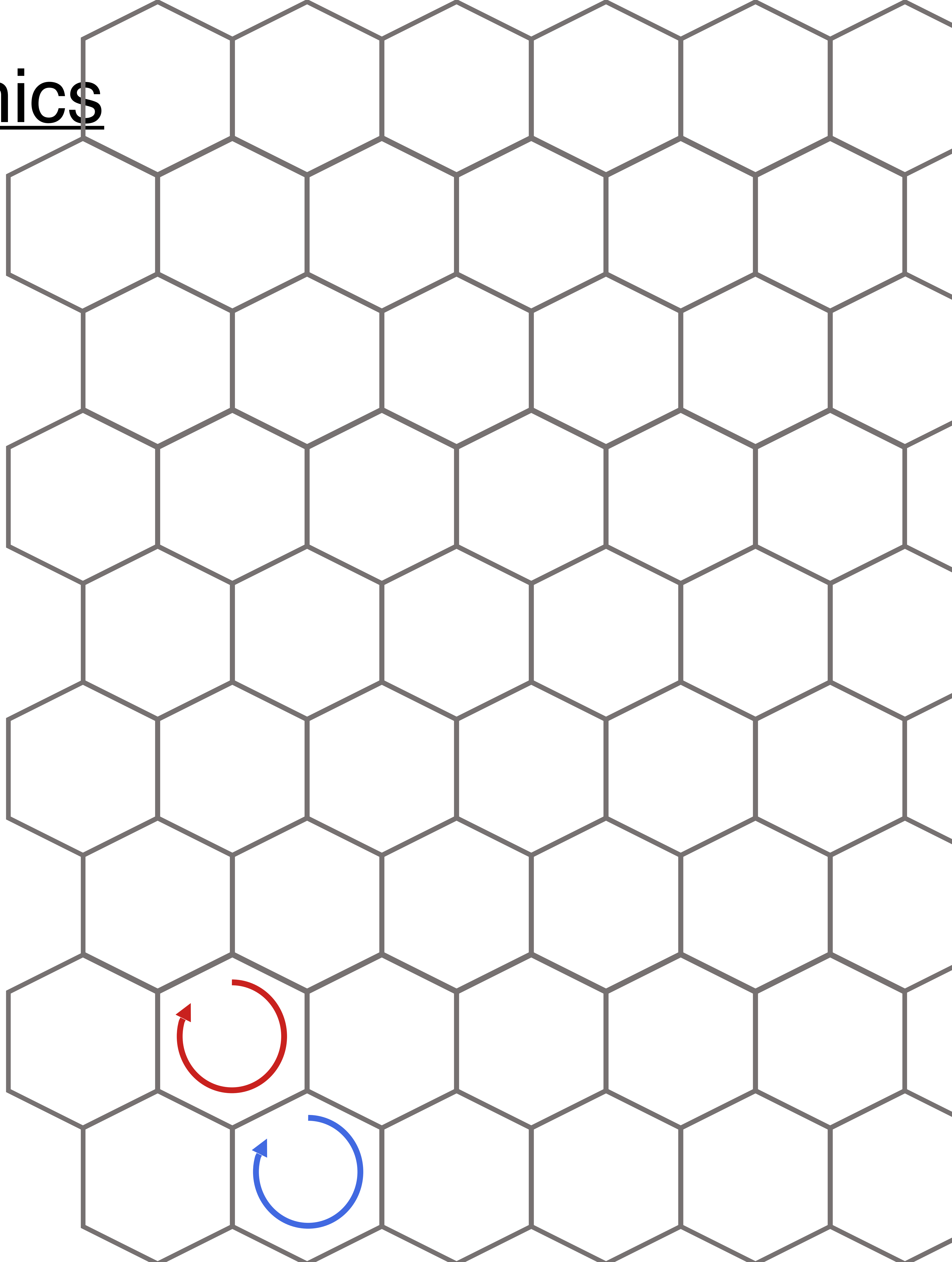

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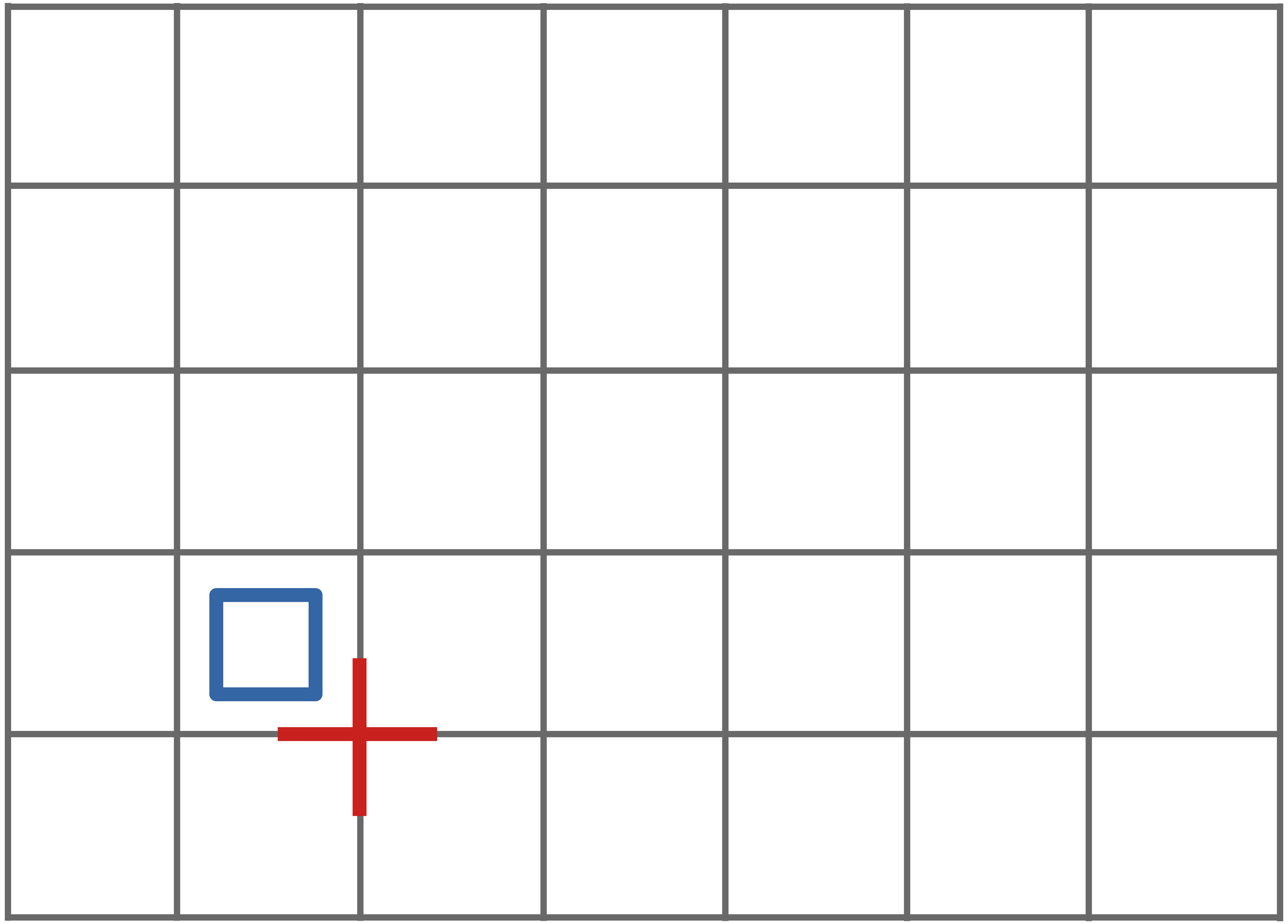

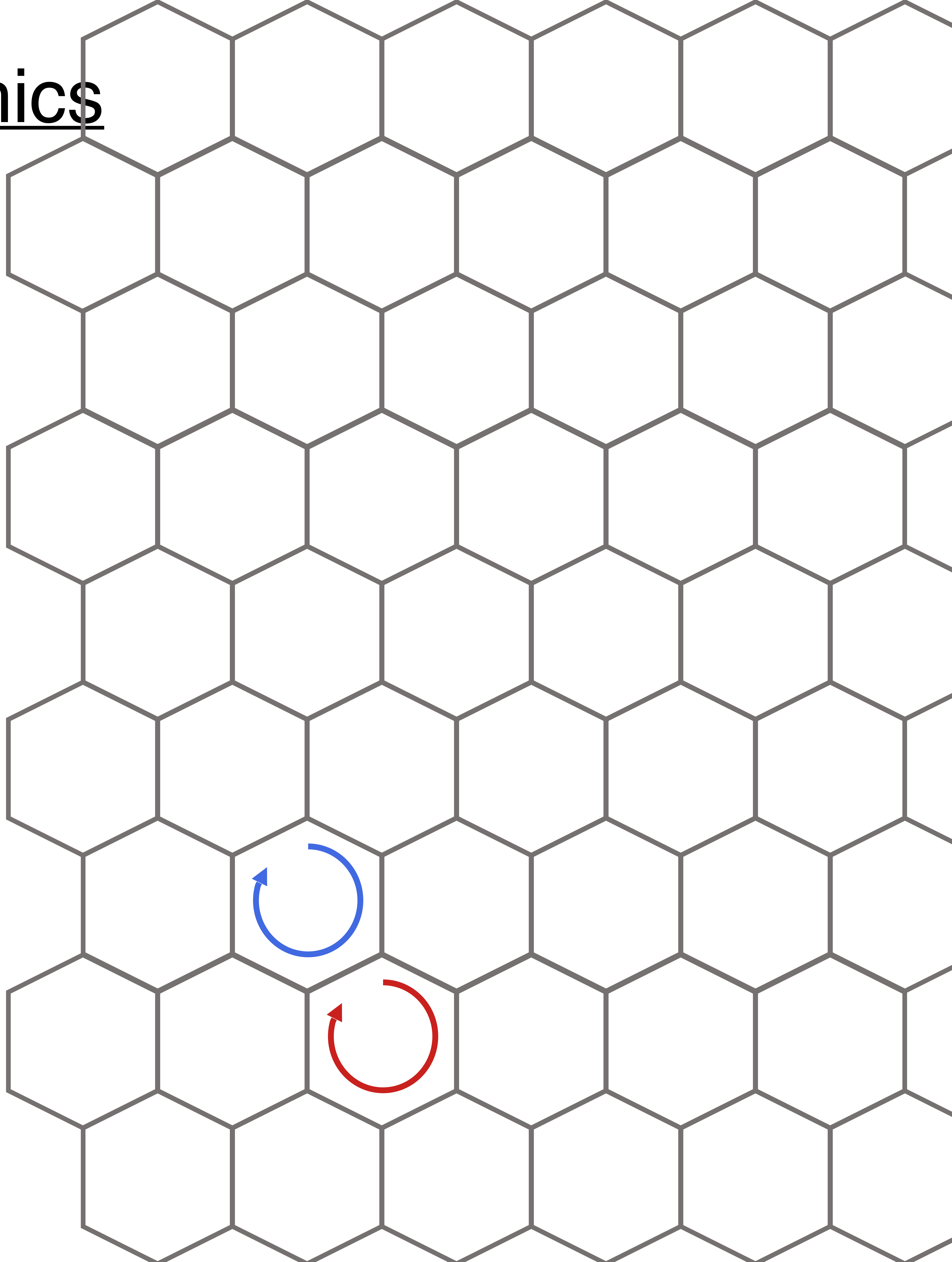

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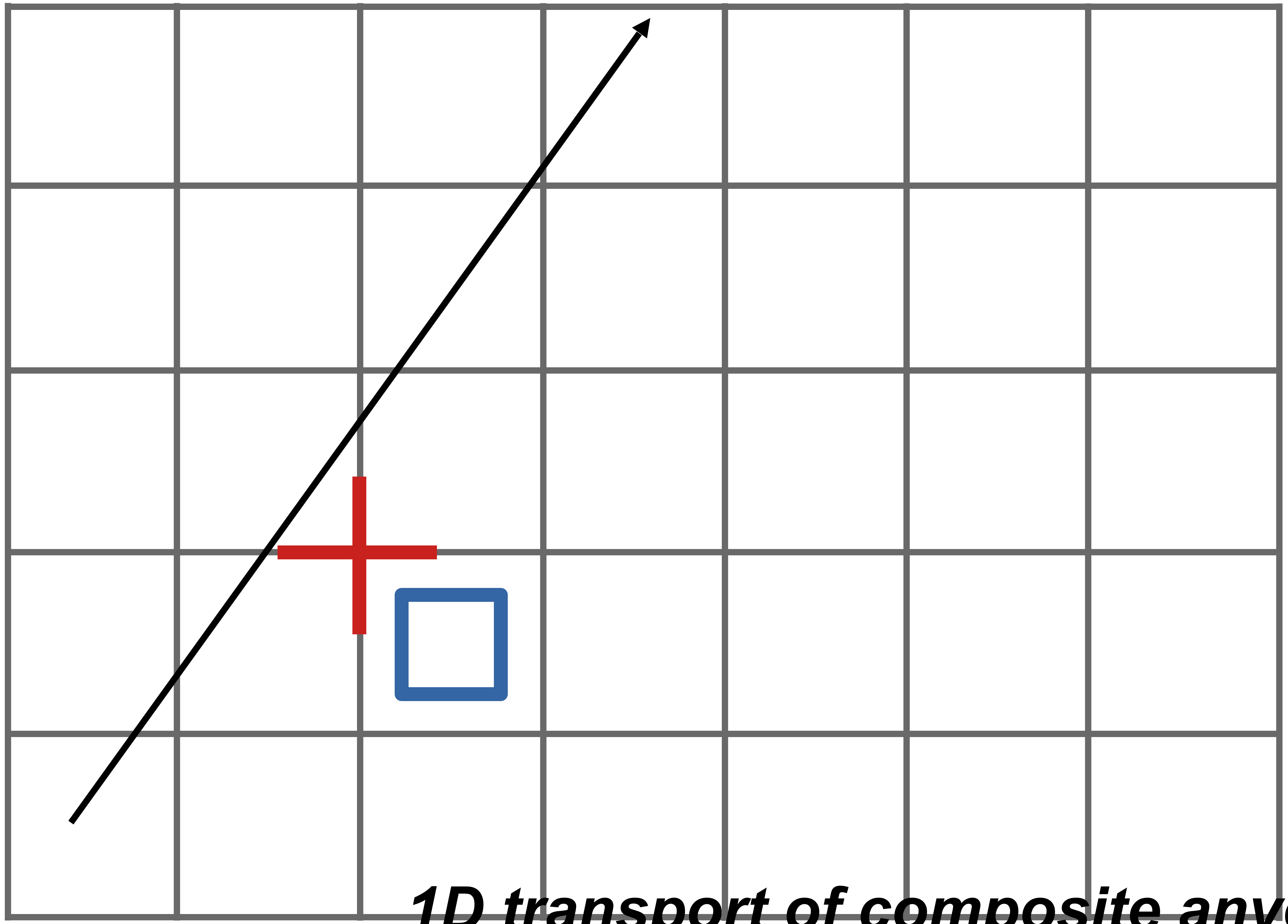
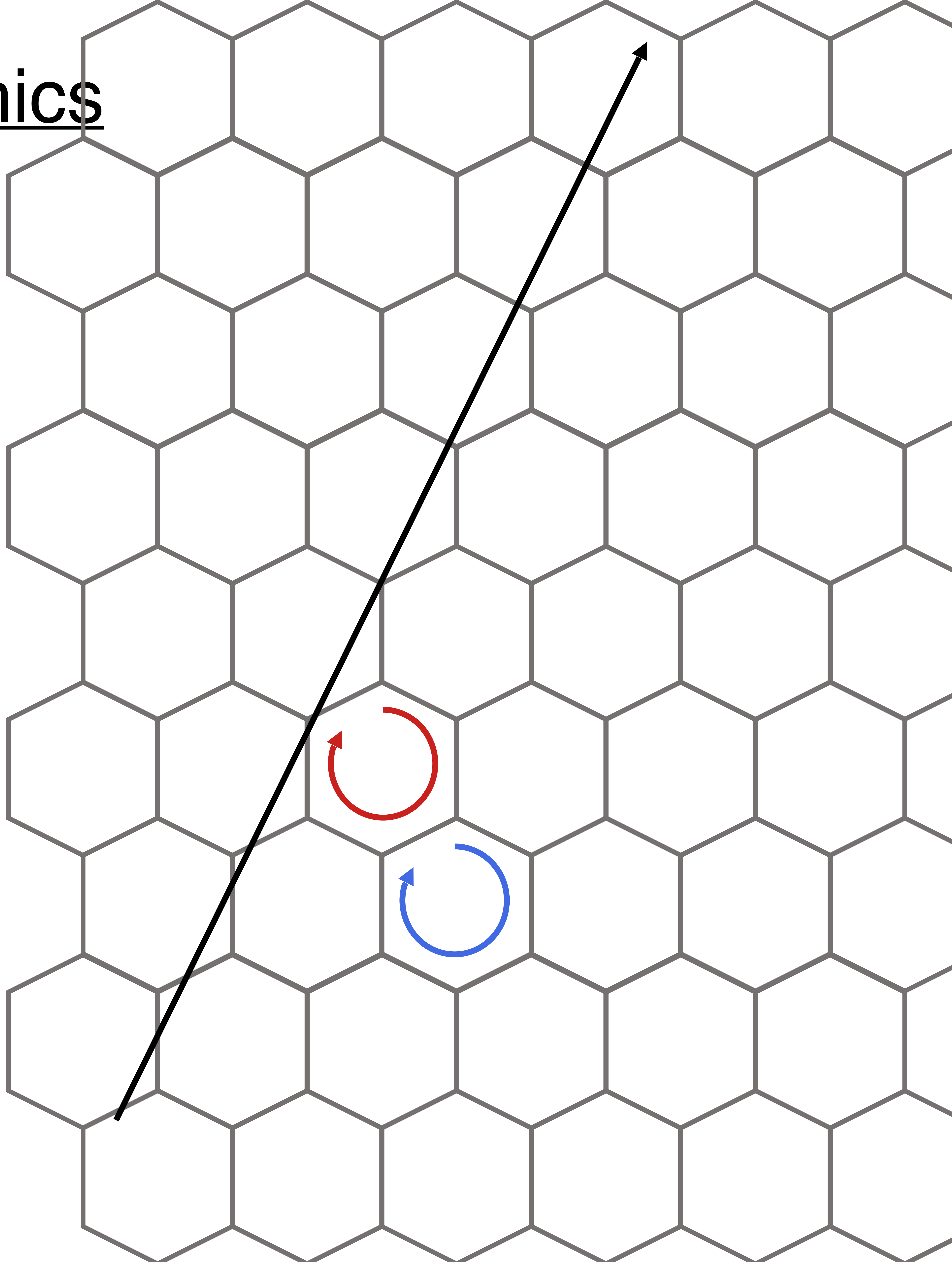
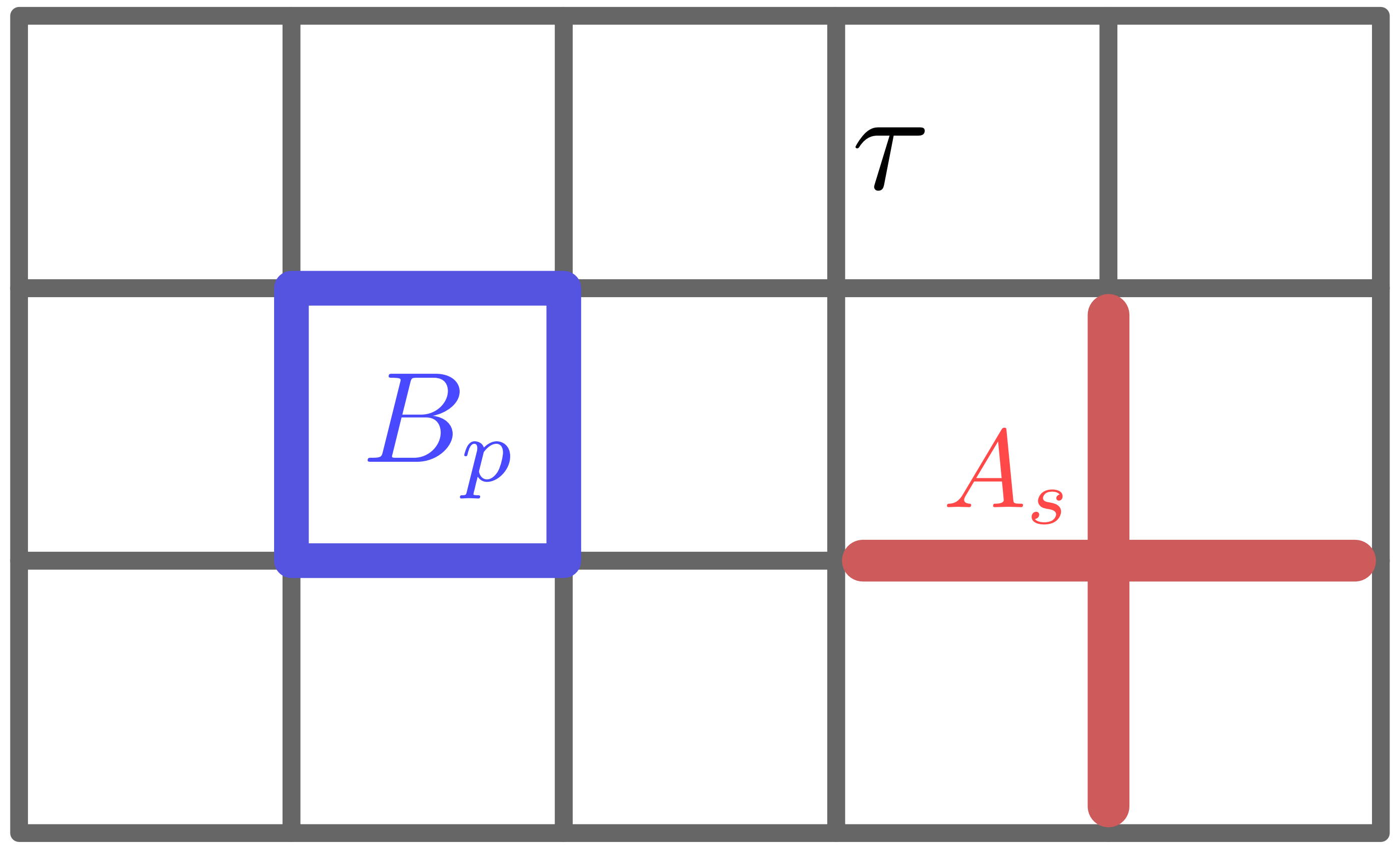




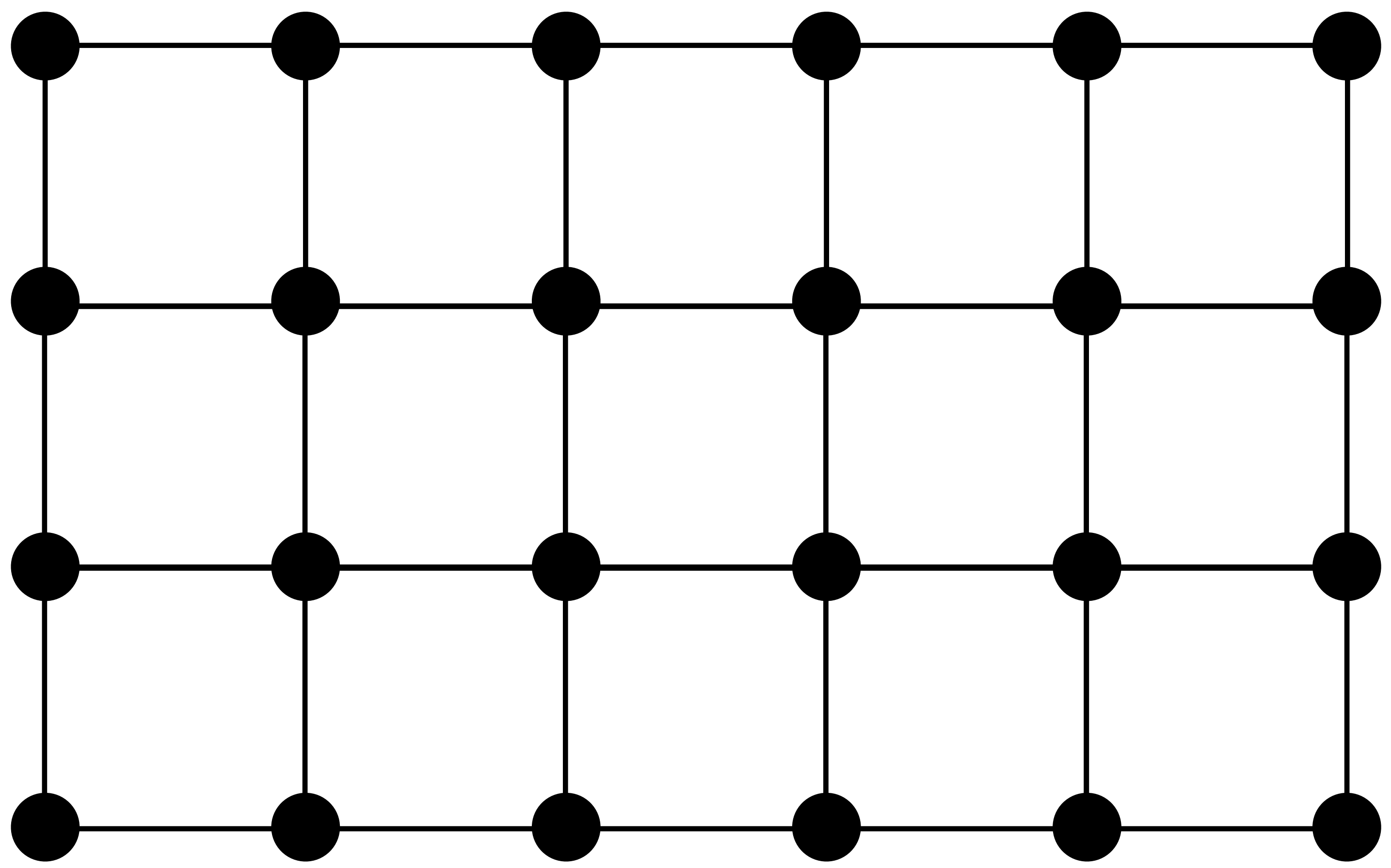
1D transport of composite anyon in a 2D model!

Fractonic Physics by Duality



$$H^{\text{eff}}_{K_z\gg K_{x,y}} = H_{\text{TC}} - \frac{2h^2}{K_z}\sum_i \tau_i^y$$

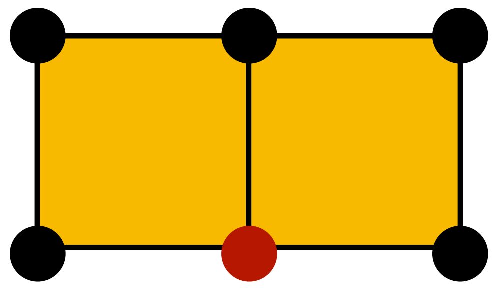
Duality Transformation



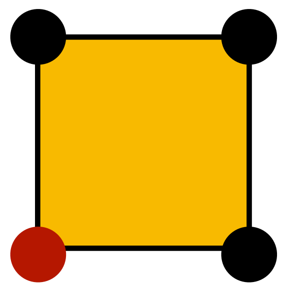
$$H_{\text{PIM}} = -\sum_{\square}\tau_i^z\tau_j^z\tau_k^z\tau_l^z - \frac{2h^2}{K_z}\sum_i\tau_i^x$$

Bp As	**2-anyon bound state with 1D mobility**
Bp or As	**Single anyon without mobility**

Duality Transformation



Constraint 1D mobility



Zero mobility

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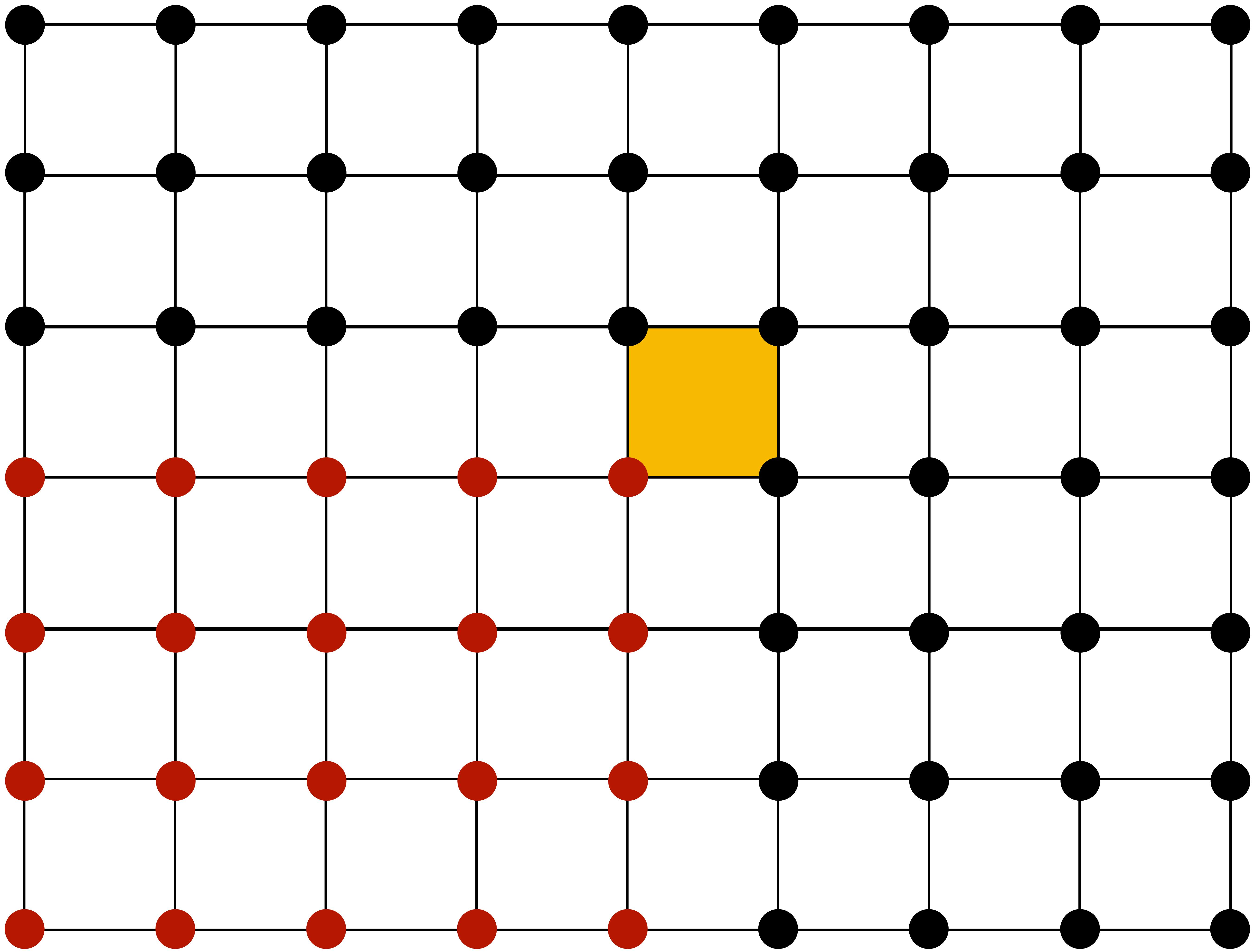
S. Feng. *Phys. Rev. B 109, 075151 (2024)*

The Plaquette Ising Model

$$H_{PIM} = -\sum_{\square} \sigma_i^z \sigma_j^z \sigma_k^z \sigma_l^z$$



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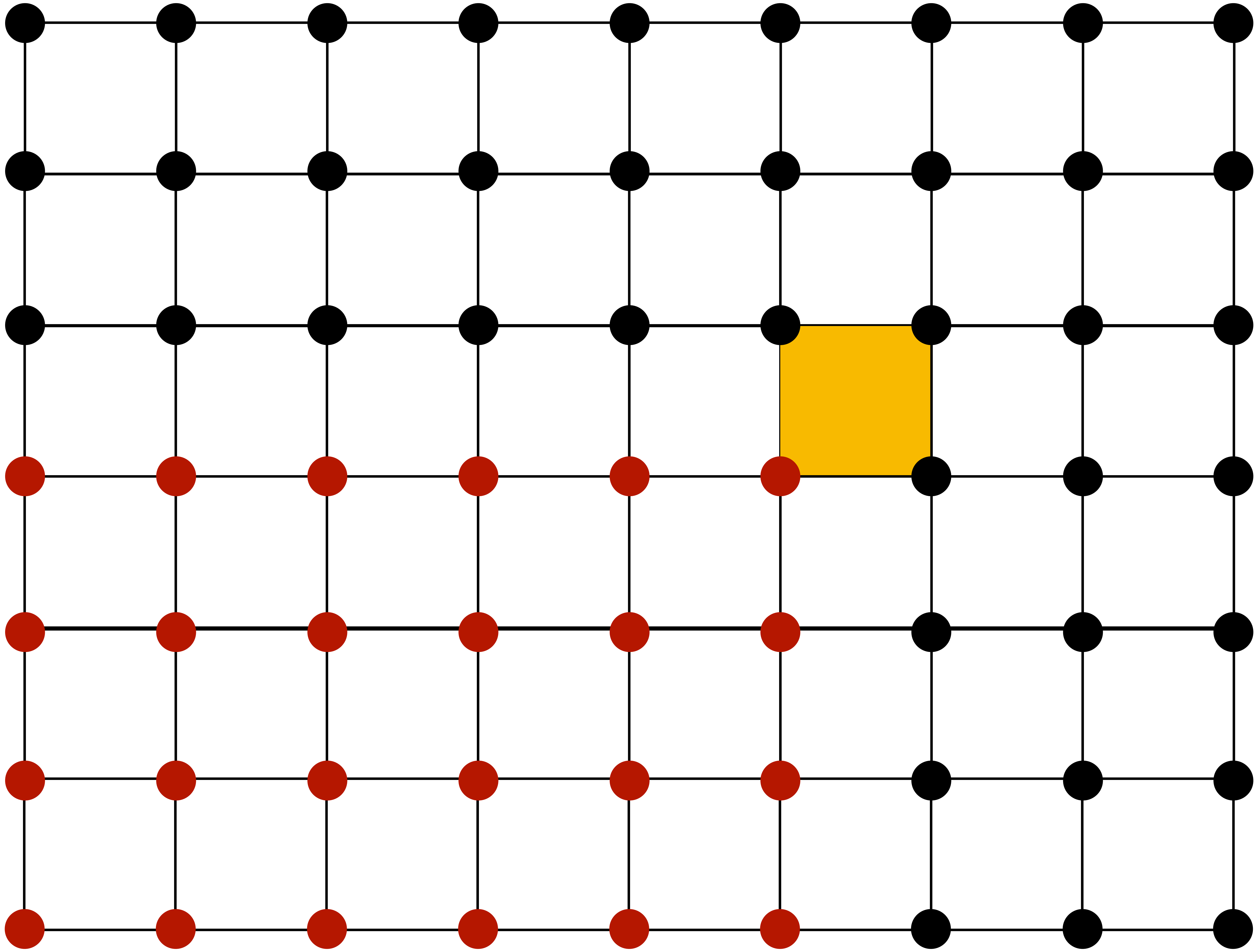

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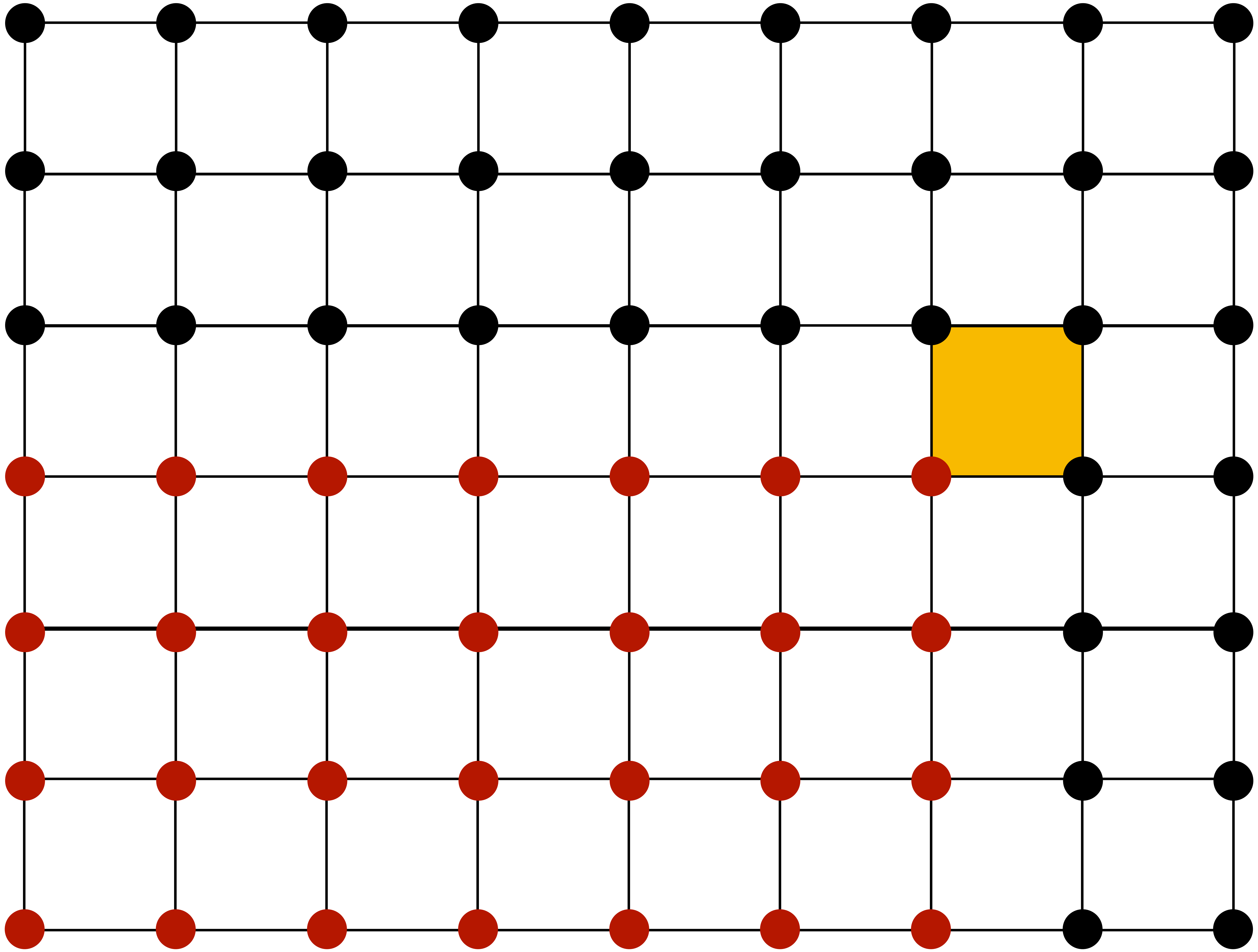

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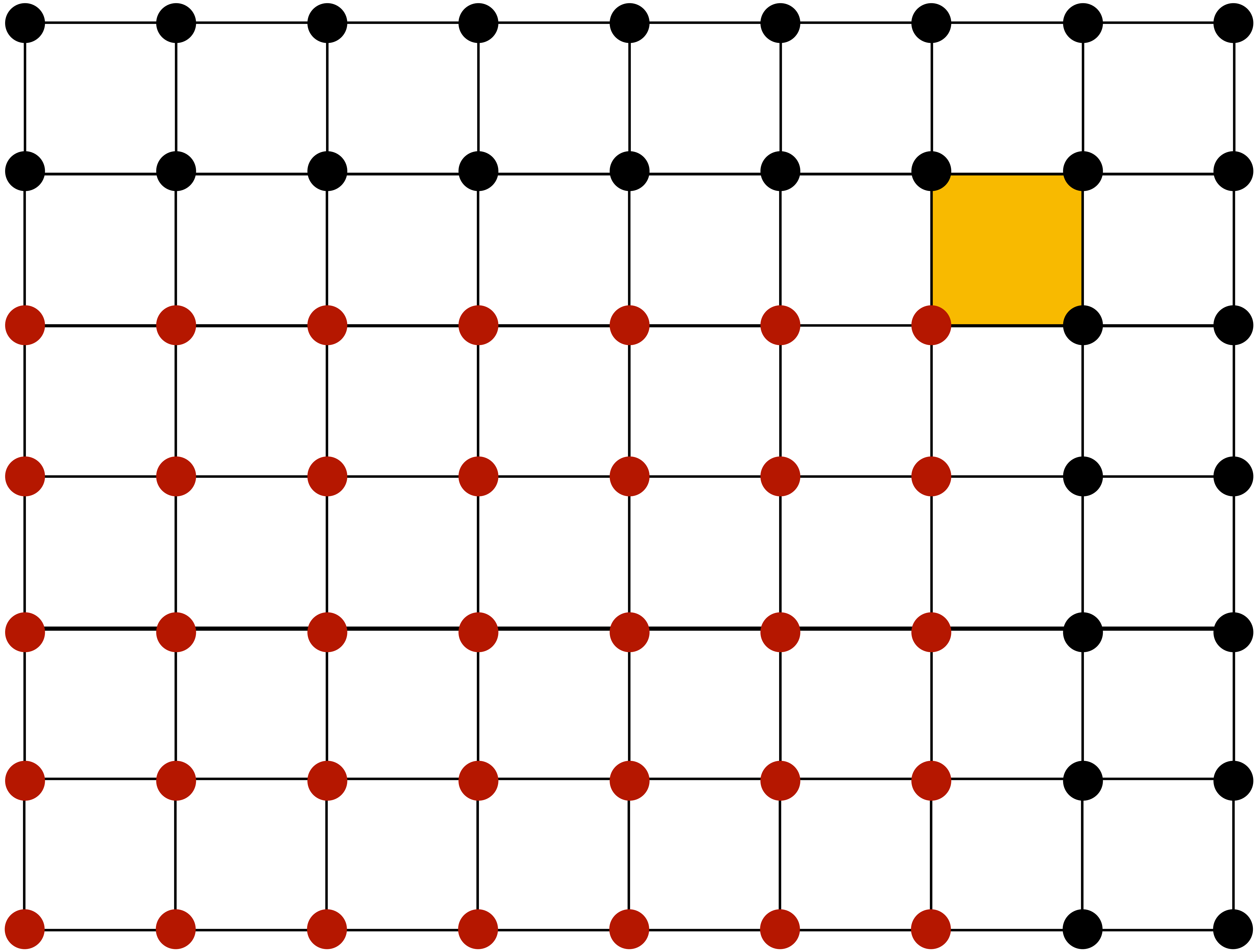

Infinite order process

The Plaquette Ising Model

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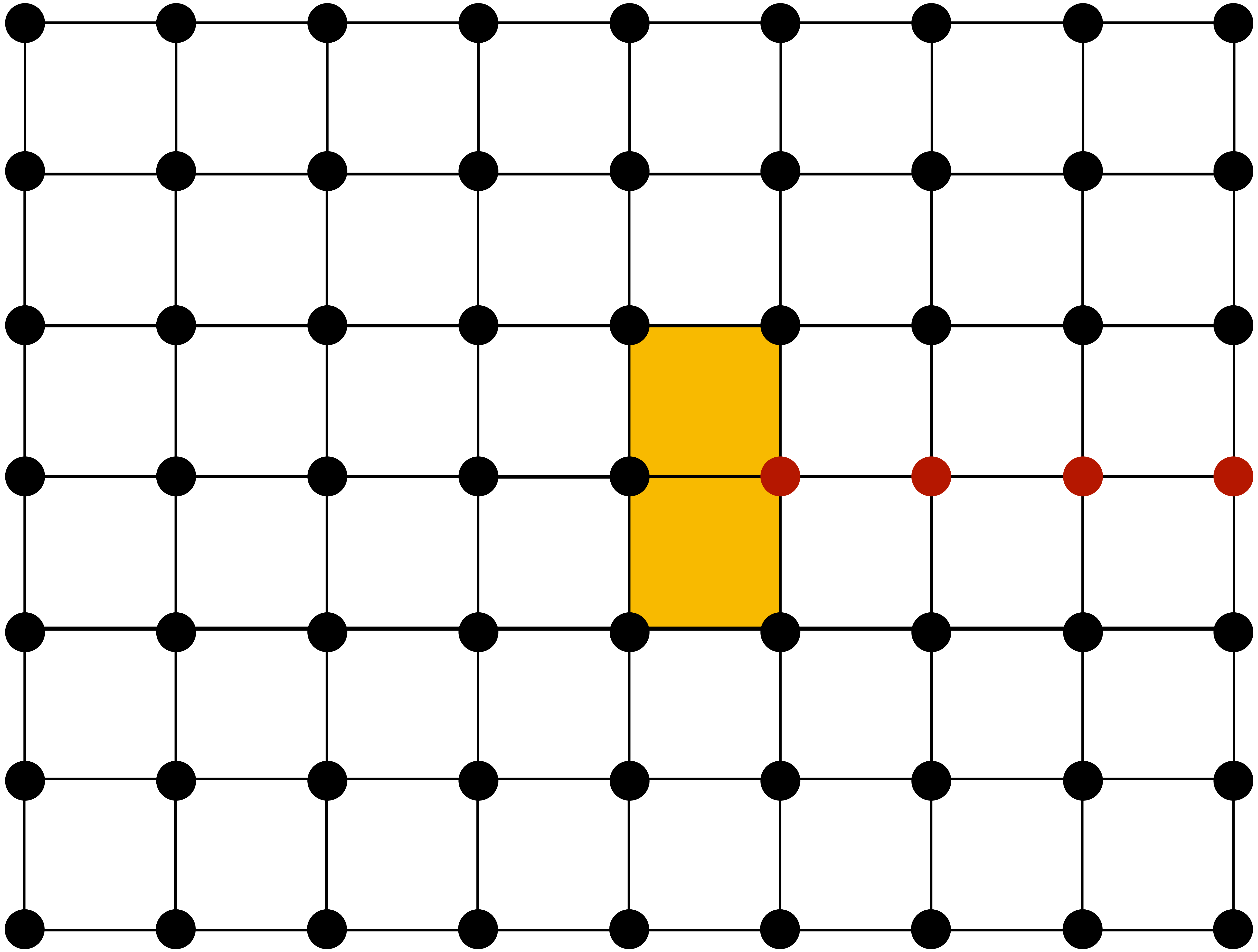

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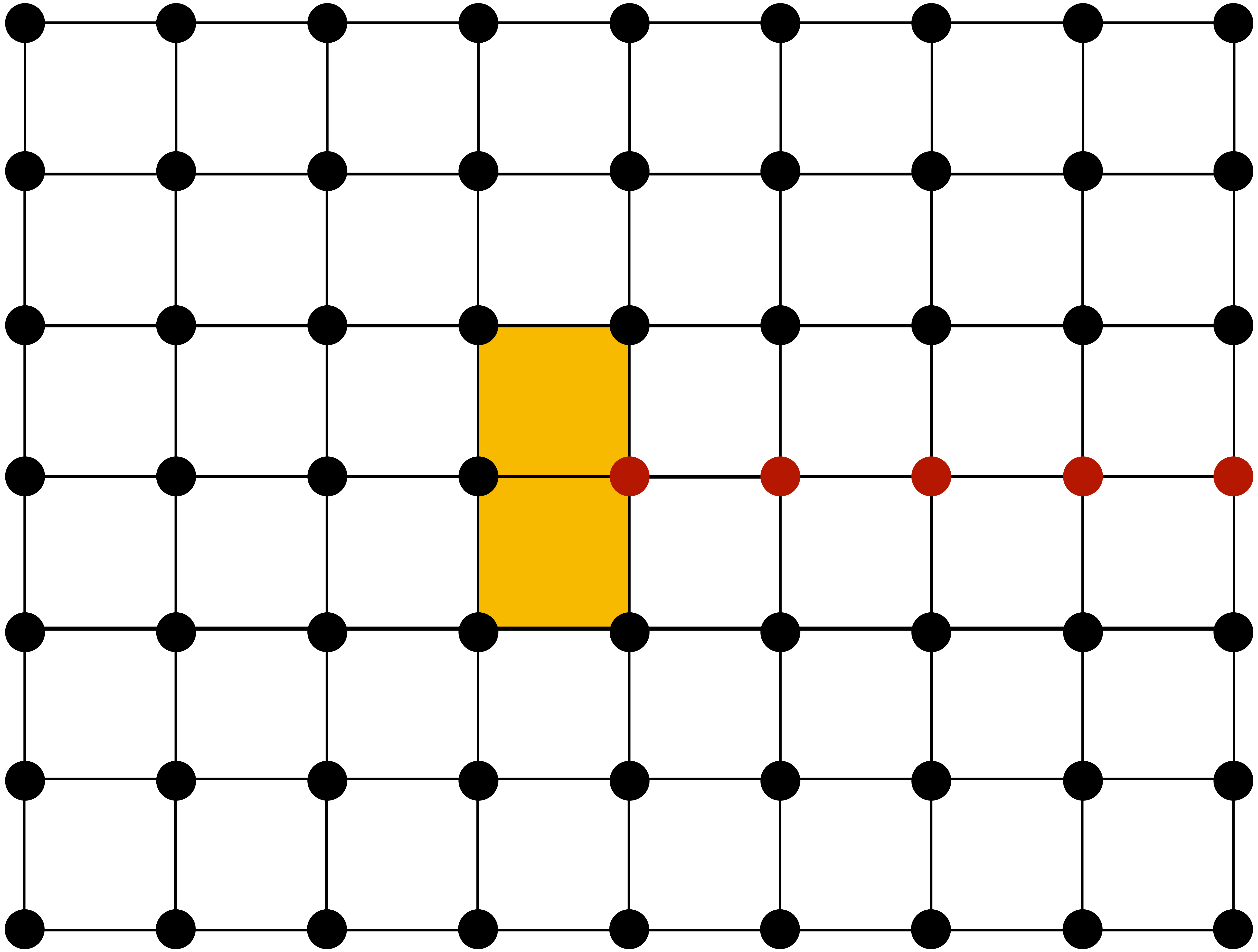

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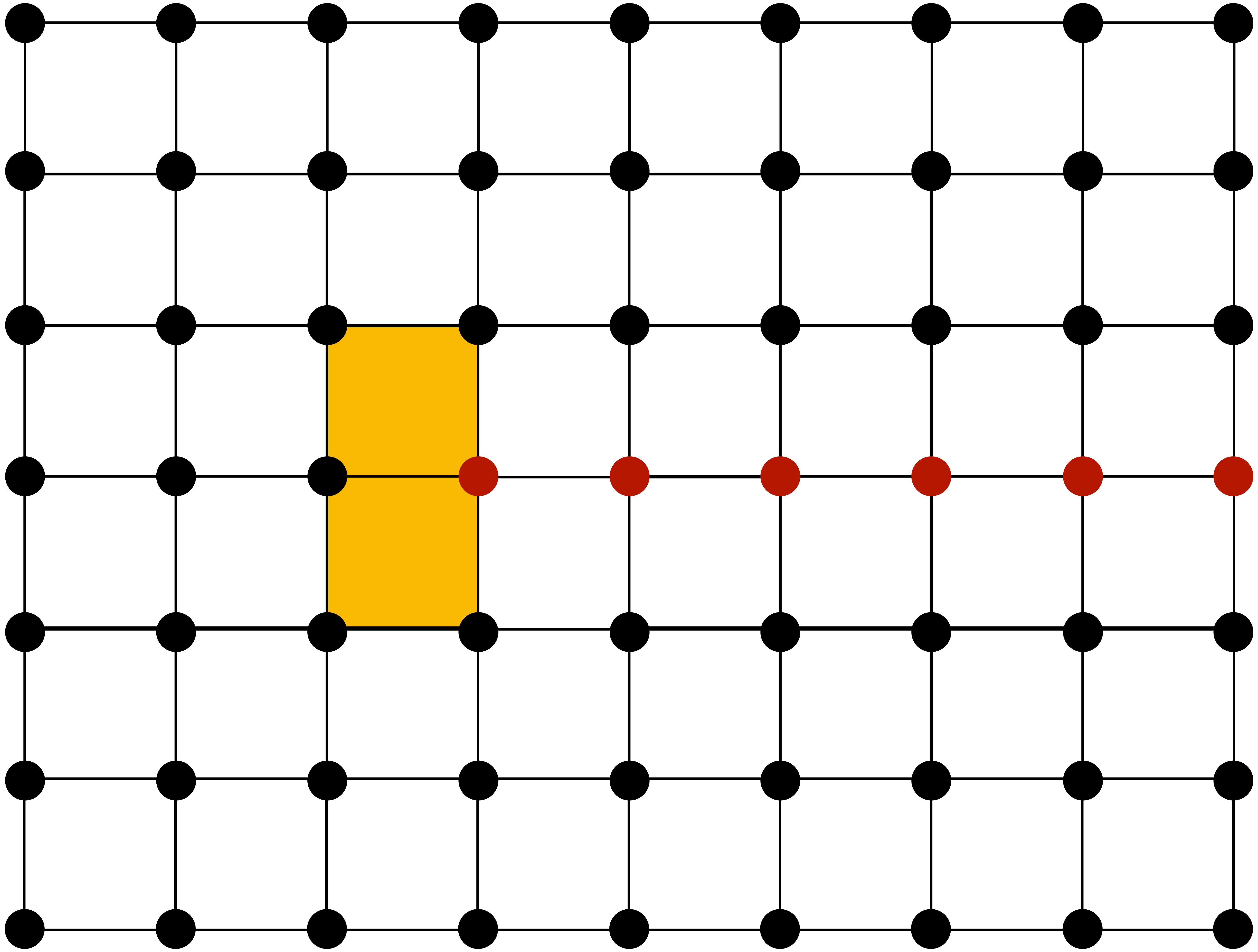

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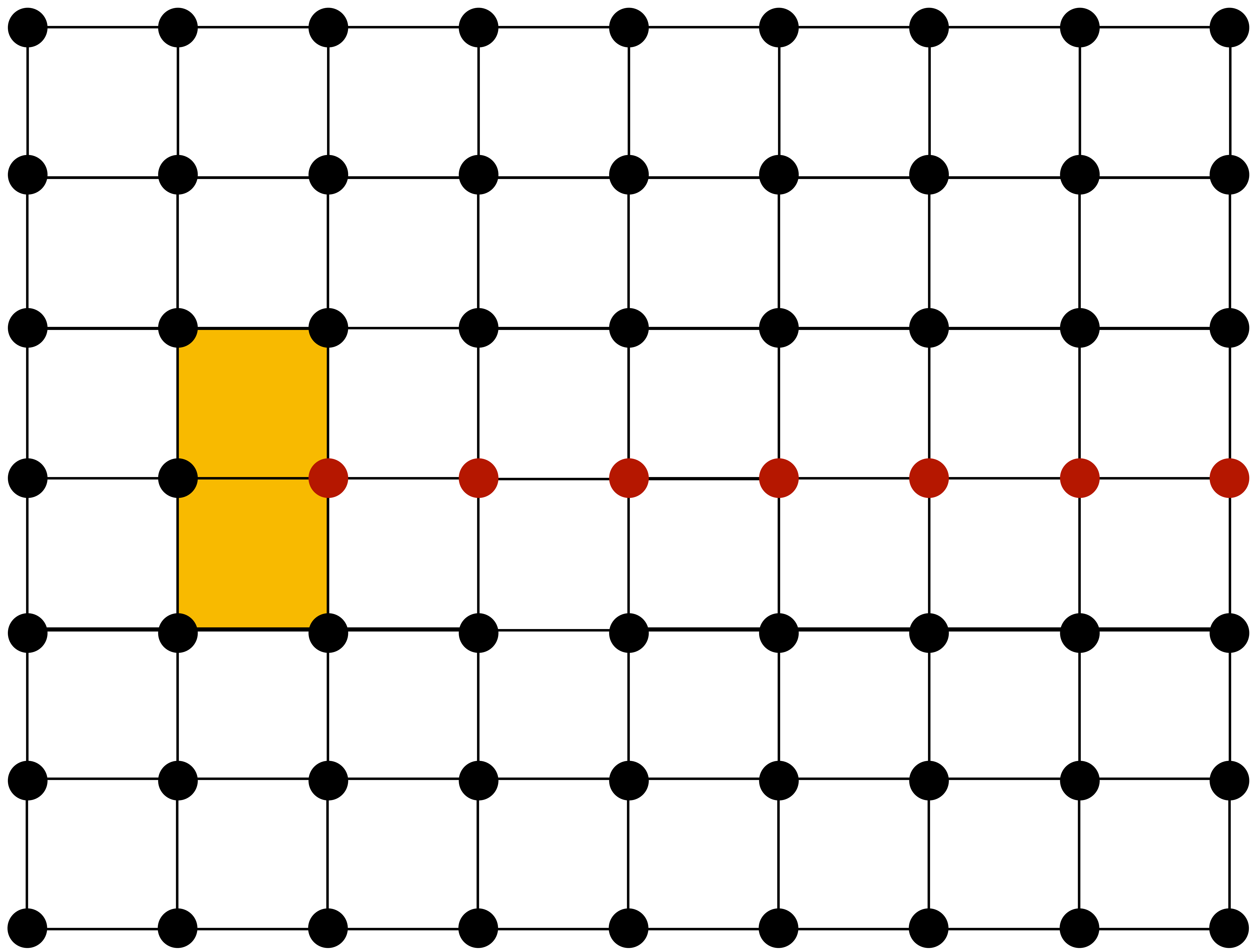
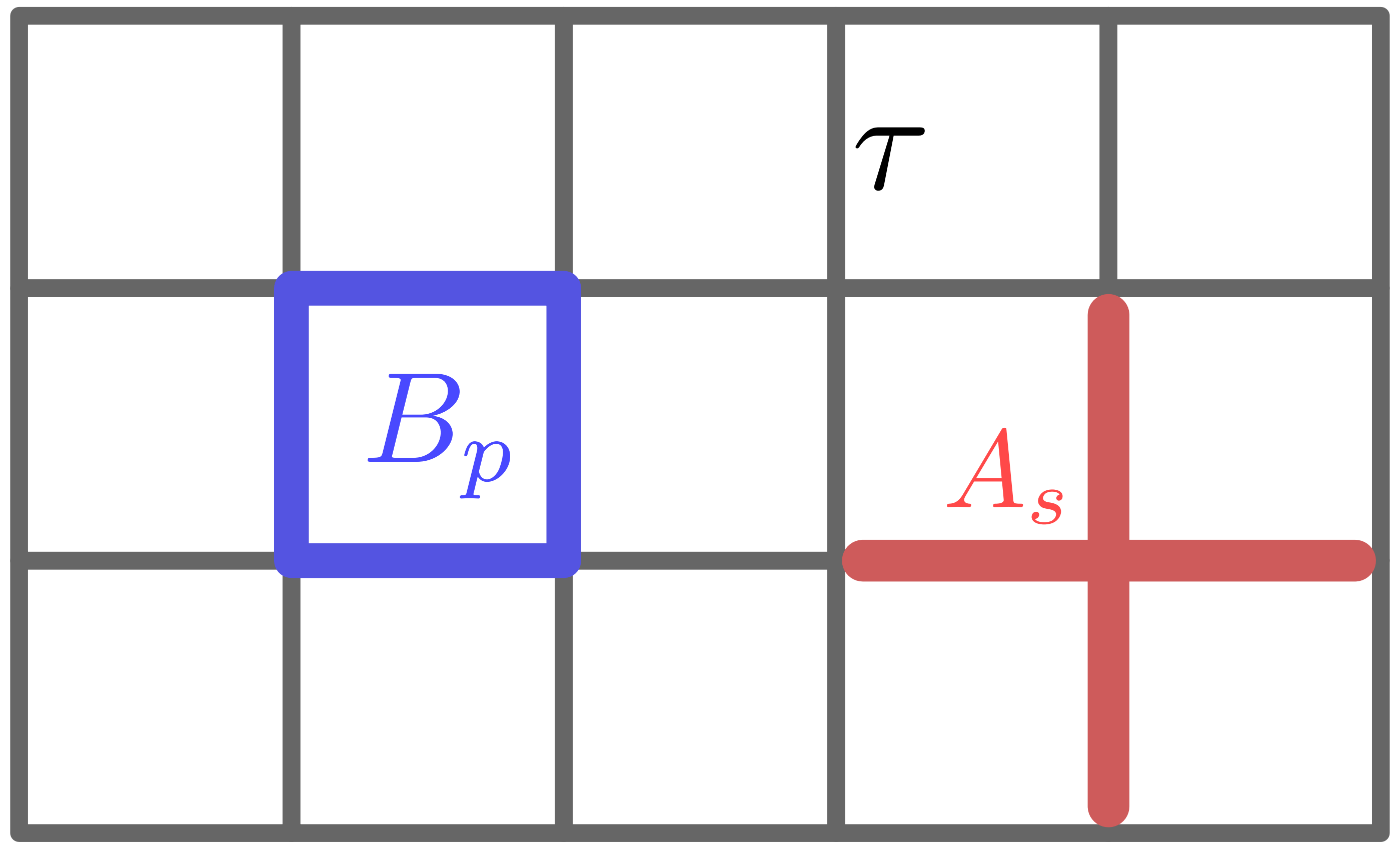
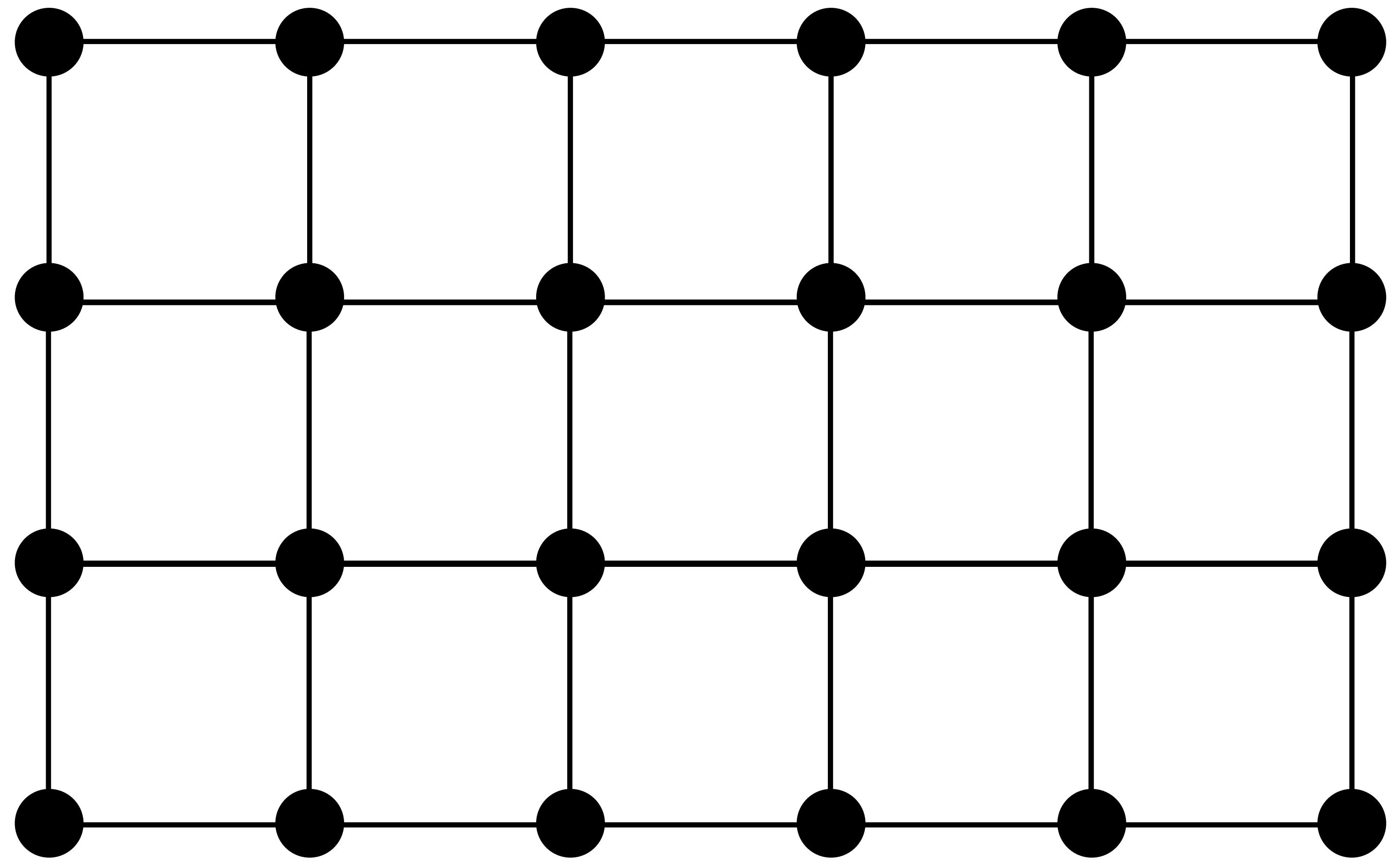


First order process

Fractonic Physics by Duality



Duality Transformation

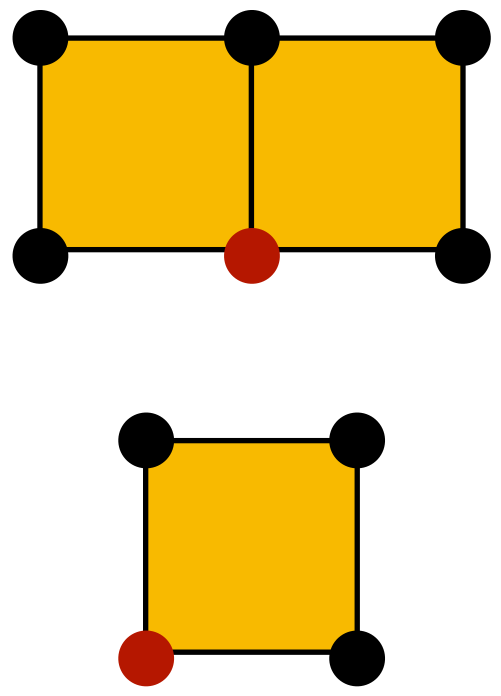


$$H^{\text{eff}}_{K_z \gg K_{x,y}} = H_{\text{TC}} - \frac{2h^2}{K_z}\sum_i \tau_i^y$$

$$H_{\text{PIM}} = -\sum_{\square} \tau_i^z \tau_j^z \tau_k^z \tau_l^z - \frac{2h^2}{K_z}\sum_i \tau_i^x$$

Bp As	2-anyon bound state with 1D mobility
Bp or As	Single anyon without mobility

Duality Transformation



(two plaquettes)	Constraint 1D mobility
(one plaquette)	Zero mobility

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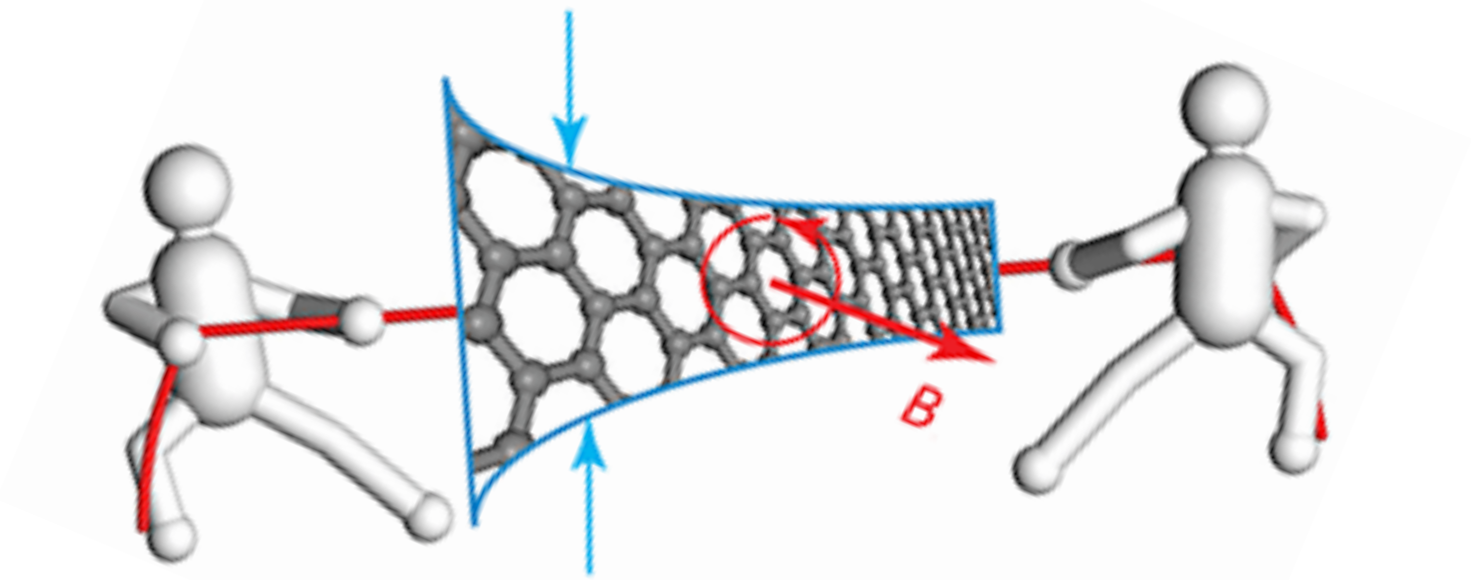
Taking away: Sharp scattering signal of fractionalization



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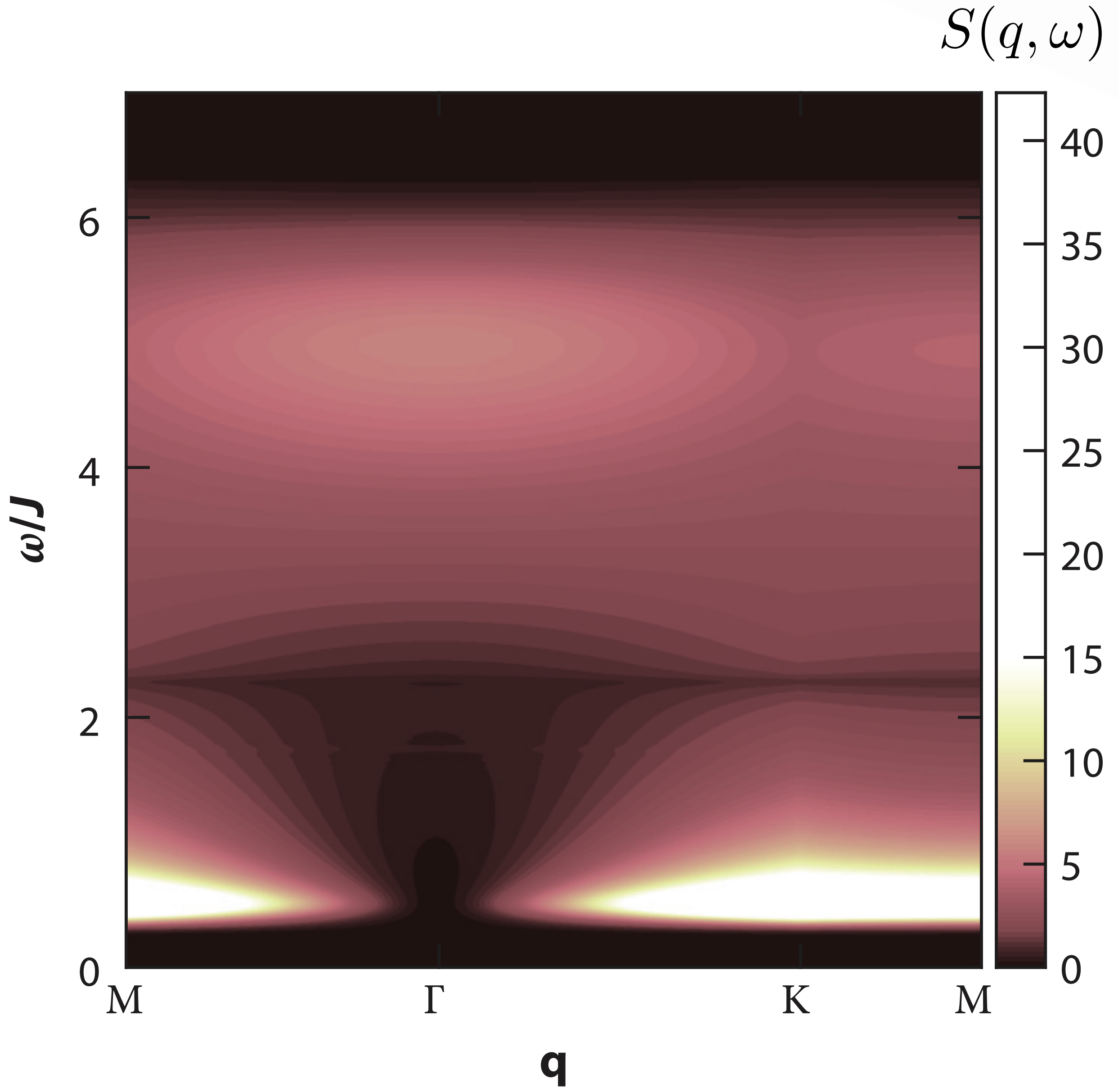
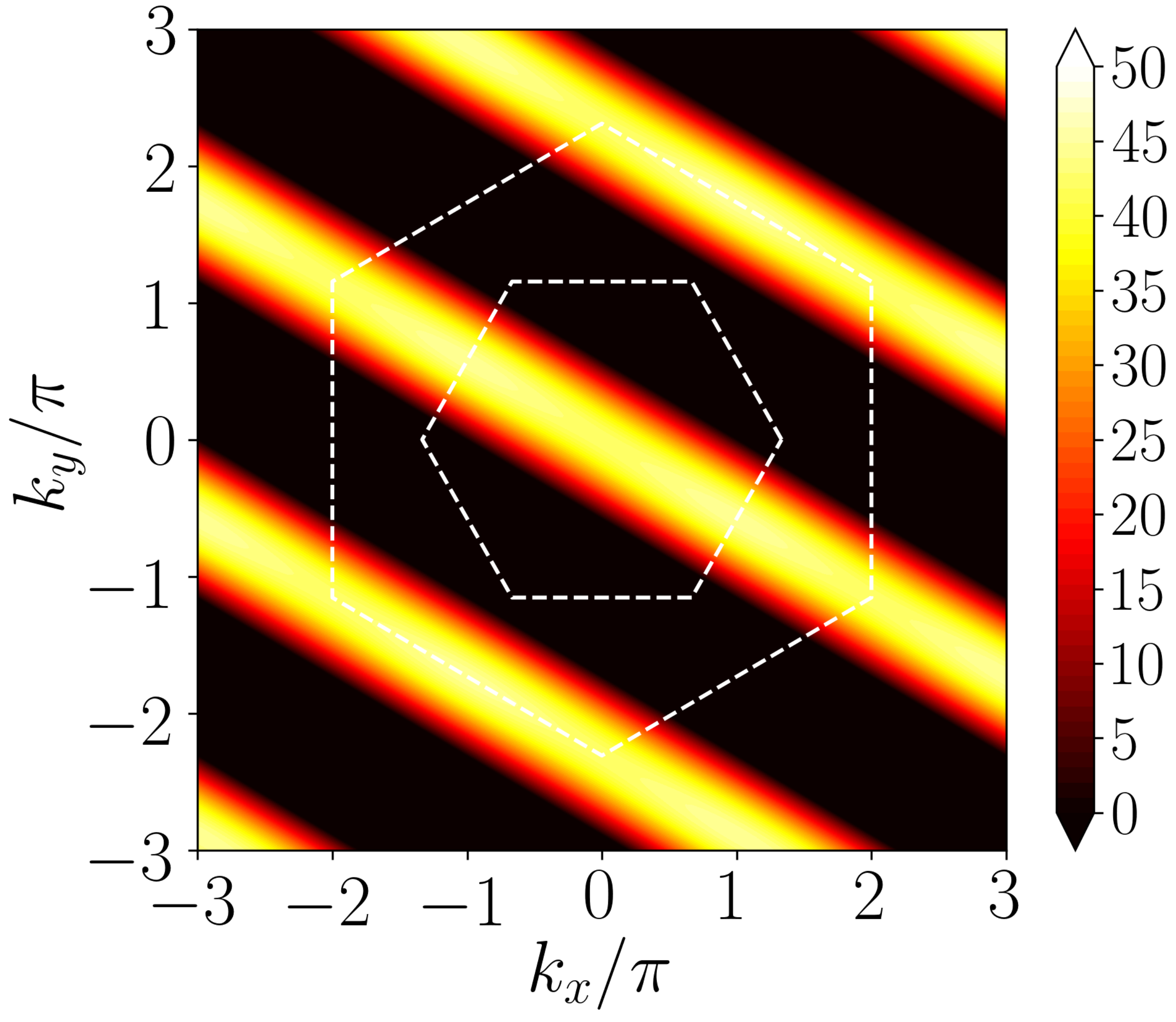


1-spin flip
fuzzy mix of fractionalized particles



2-spin flip
Sharp 1D fracton modes

	Heisenberg	**Kitaev QSL (Kz > 2)**
1 spin flip	Sharp magnon modes	Continuum of Fractionalized particles
2 spin flip	2-magnon continuum	Sharp Anyon bound state
4 spin flip	4-magnon continuum	Sharp Anyon bound state

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Thanks!