UNIVERSITY of WASHINGTON

IQuS InQubator for Quantum Simulation

Random measurements and entanglement for nuclear and particle physics exploration

Niklas Mueller
University of Washington

based on work with Jacob Bringewatt, Jon Kunjummen, arXiv:2303.15519
and Torsten Zache, Robert Ott, Phys. Rev. Lett. 129 (2022) 011601

ECT*, June 8, 2023

Shout-out and related developments

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- Quantum simulation of nuclear physics problems getting off the ground

Quantum simulating gauge theories:

Savage, Zohar, Stryker, Meurice, Singh, Yao, Hauke, Gonzales Cuadra, Ott

Quantum Simulation of Lattice Gauge Theories in more than 1+1 D — *Erez Zohar*

next: 2+1d?

*Aula Renzo Leonardi, ECT** — Tuesday — 10:10 - 10:50

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Does entanglement in equilibrium

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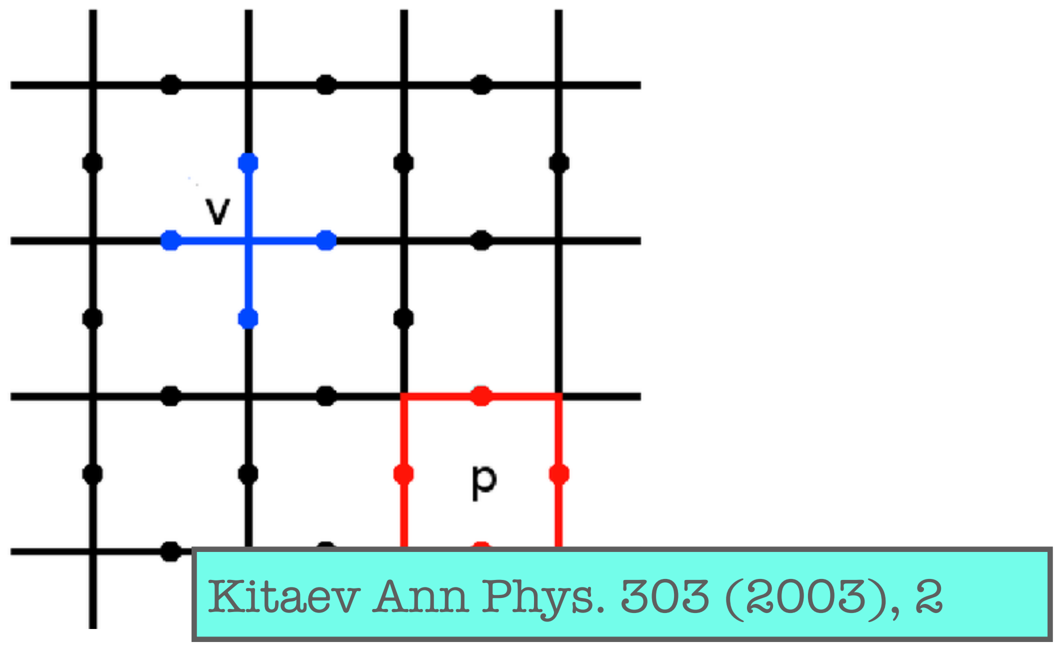
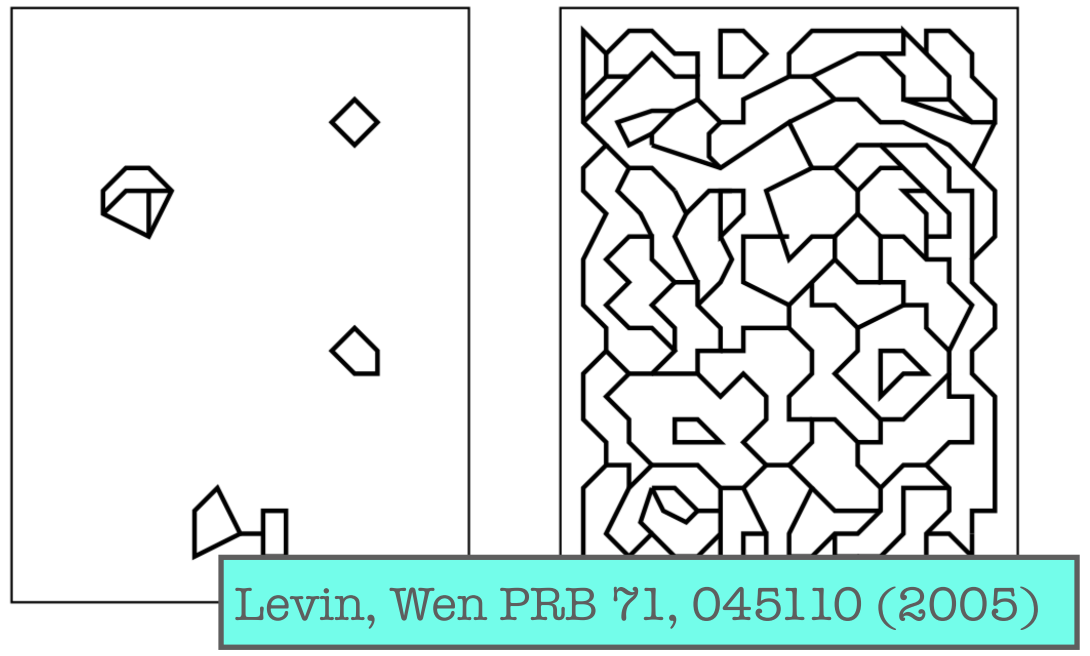
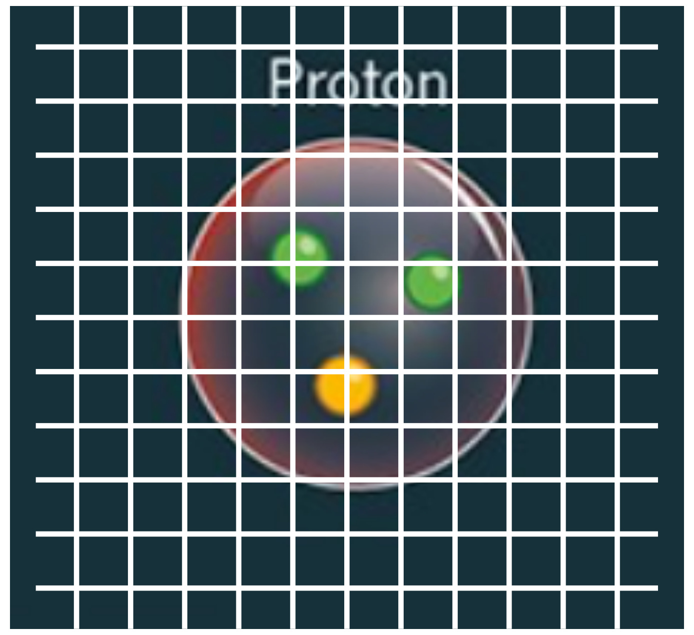


quantum information science and technology



condensed matter



high energy and nuclear physics

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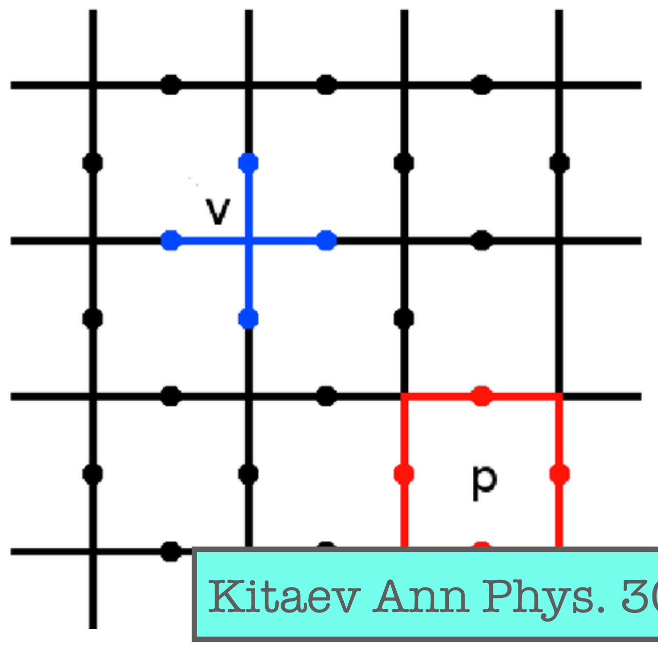

Kitaev Ann Phys. 303 (2003), 2

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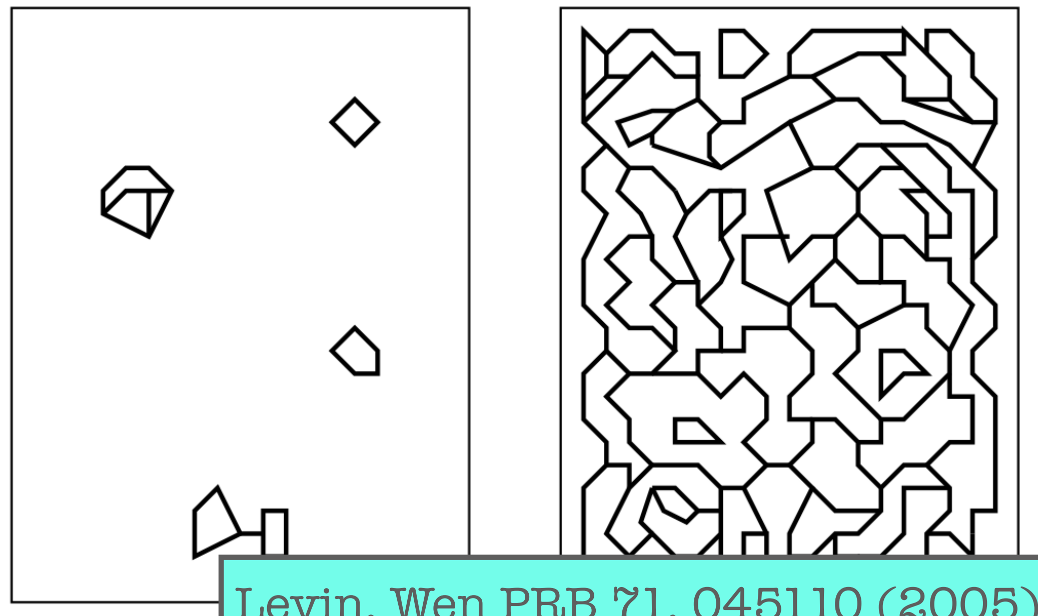

Levin, Wen PRB 71, 045110 (2005)

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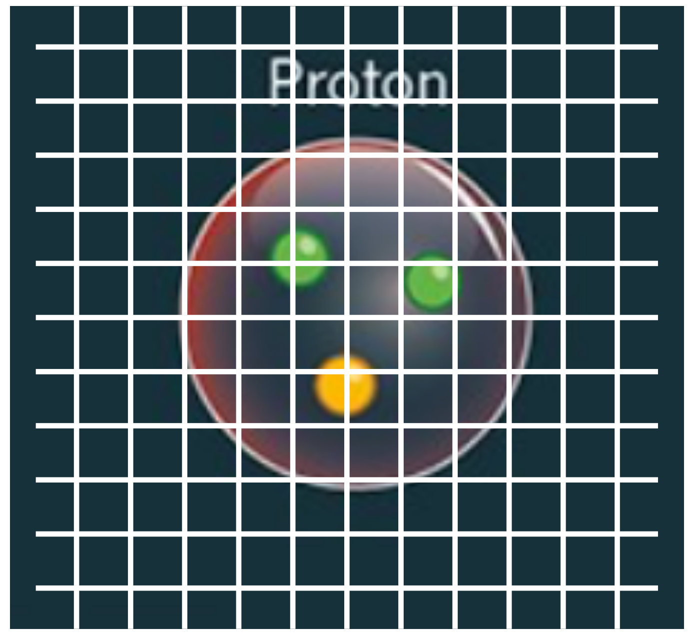

high energy and nuclear physics

Quantum Error Correction with Gauge Symmetries *Abhishek Rajput*

Wednesday

*Aula Renzo Leonardi, ECT** 10:10 - 10:50

Entanglement

quantum phases

non-equilibrium problems
e.g. scattering, thermalization

Entanglement: Quantum Phases

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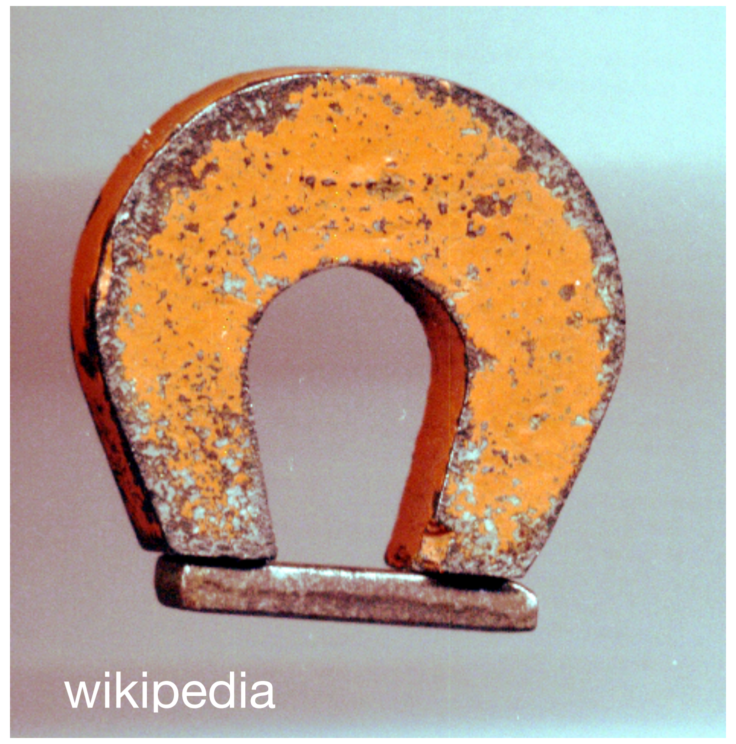
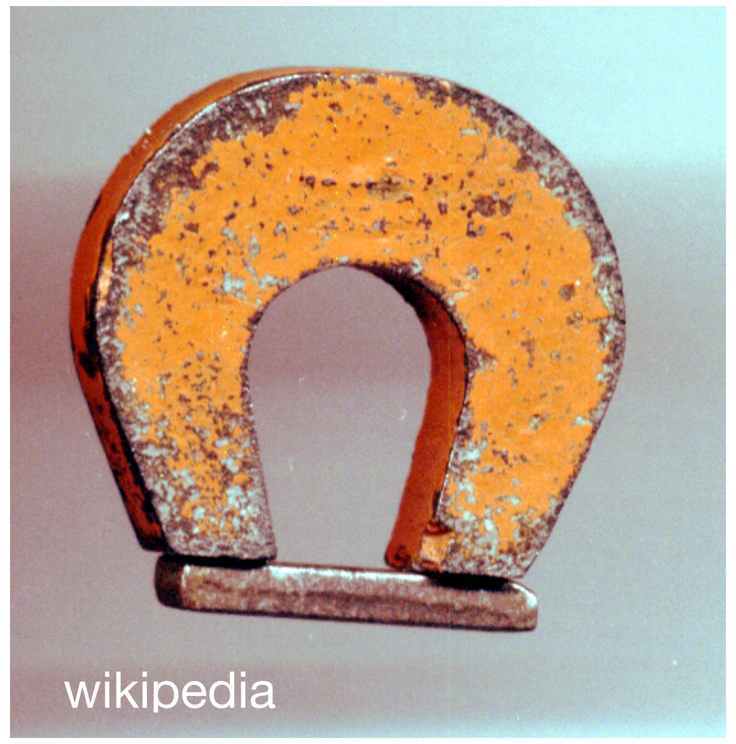


Local Order Parameter: Landau theory of phase transitions

Entanglement: Quantum Phases



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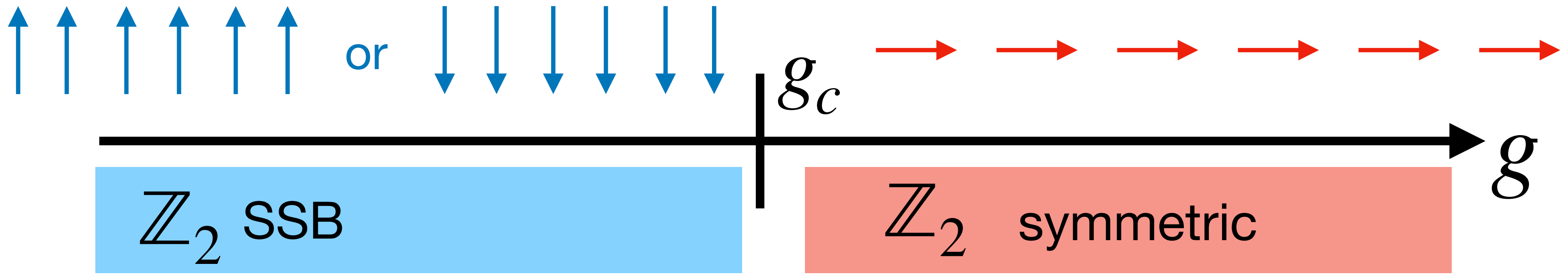

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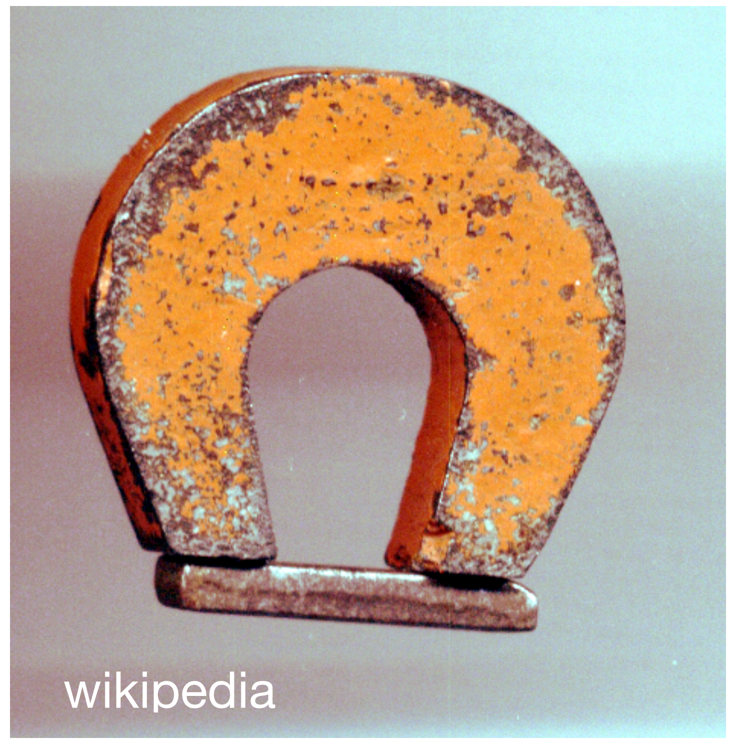

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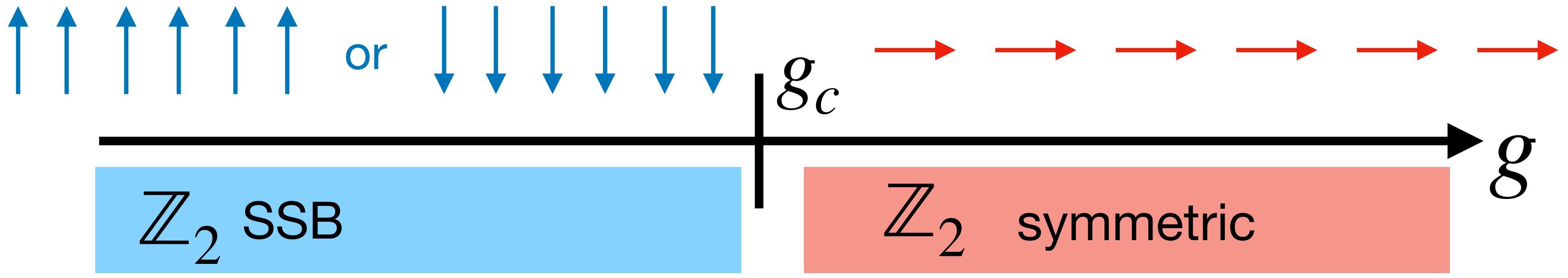

- **Symmetry protected**

Topological Insulators — Kane, Mele, PRL 95 (2005) 226801; Bernevig, Zhang, PRL 96 (2006) 106802

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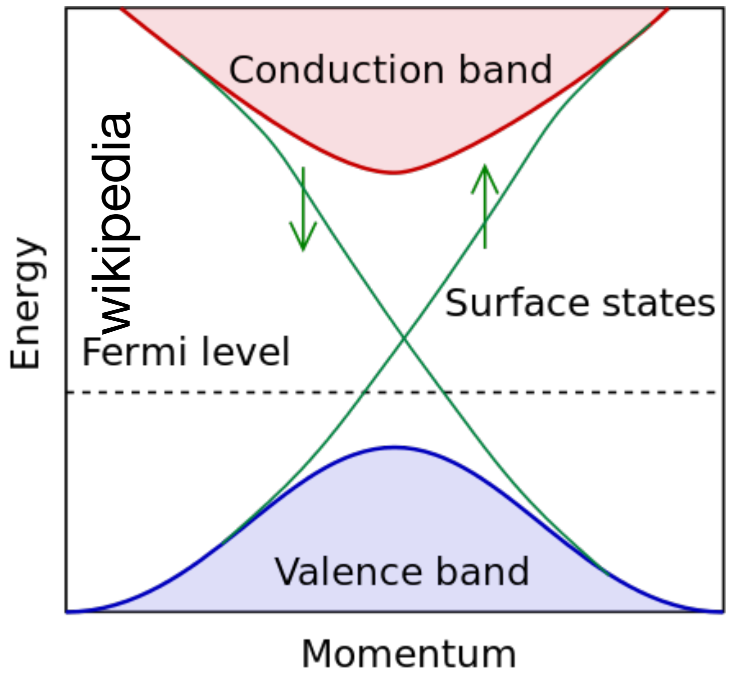

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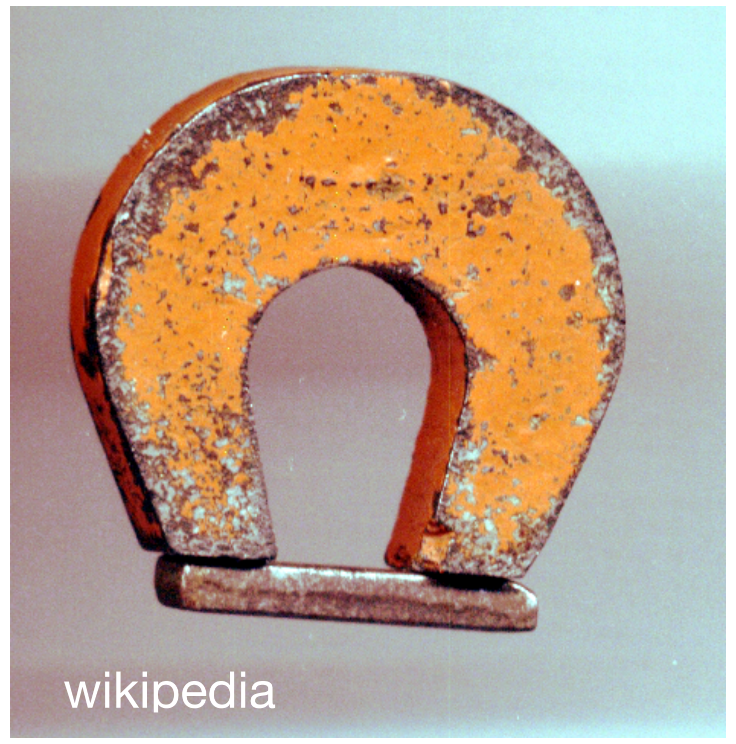

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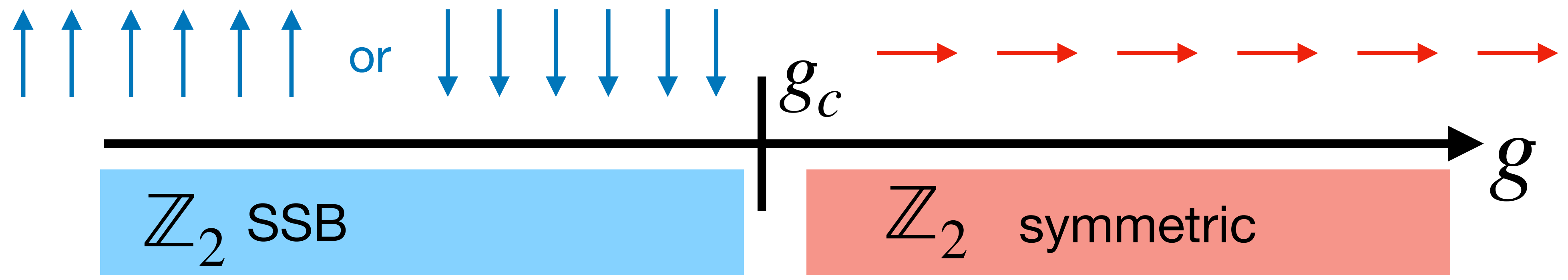

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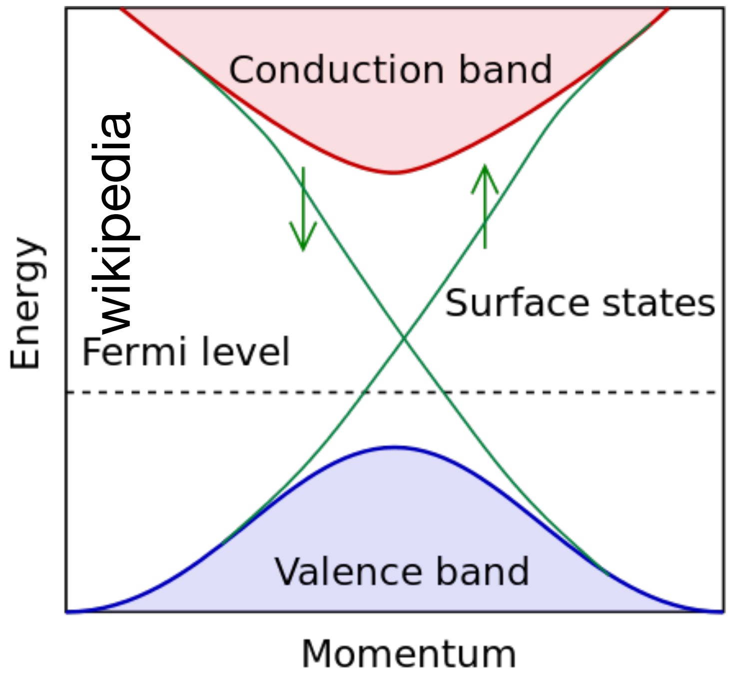

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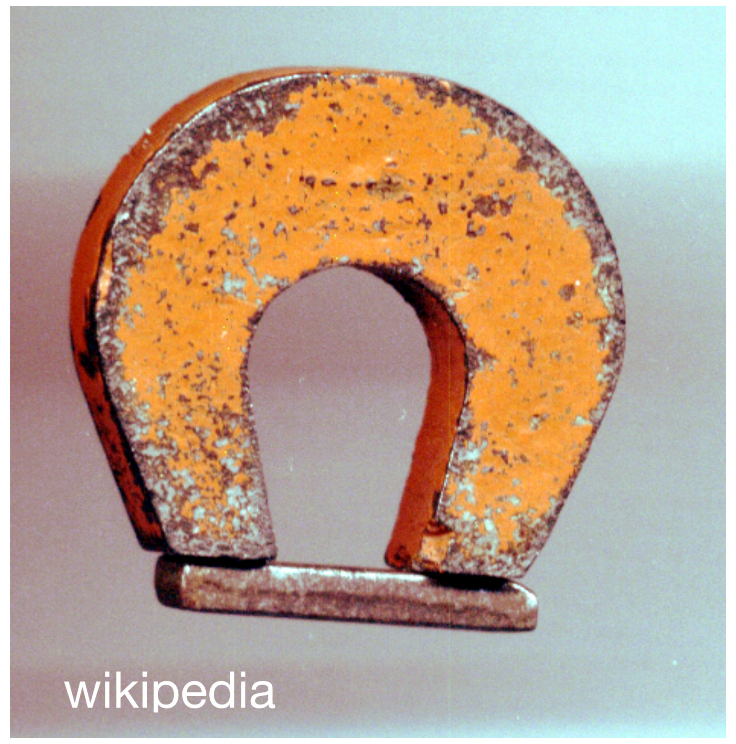

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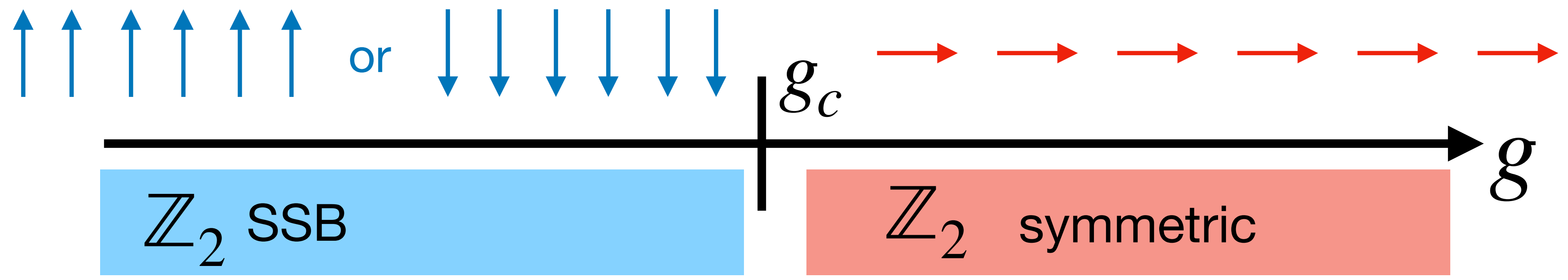

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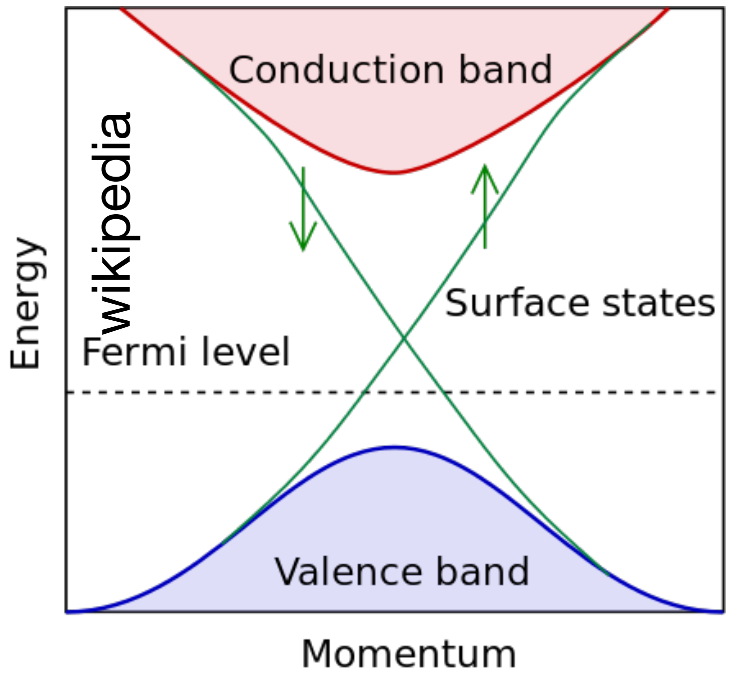

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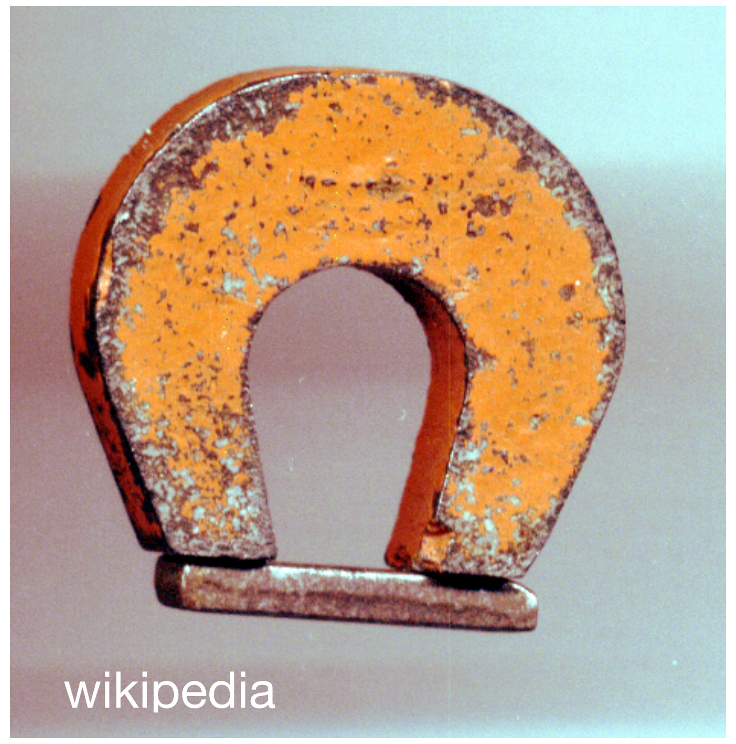

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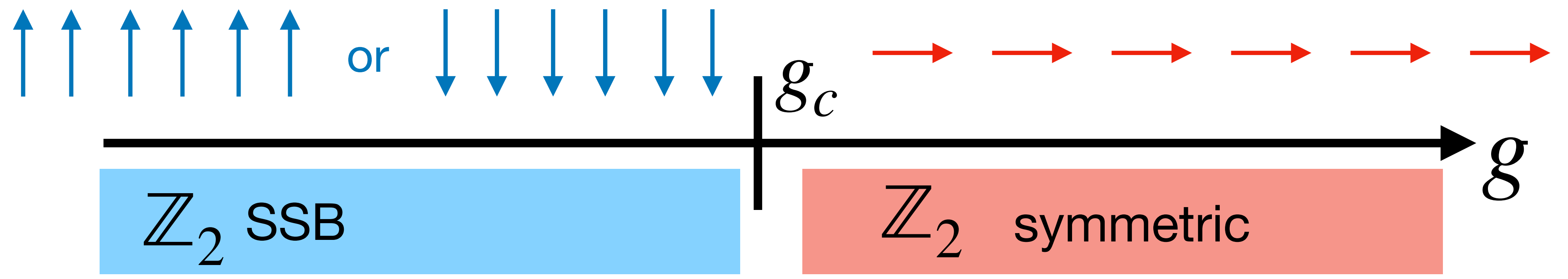

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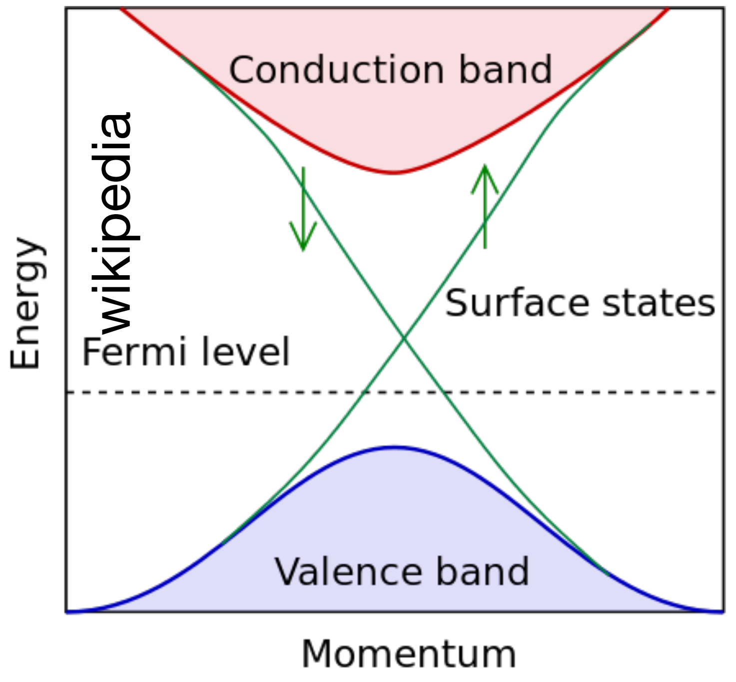

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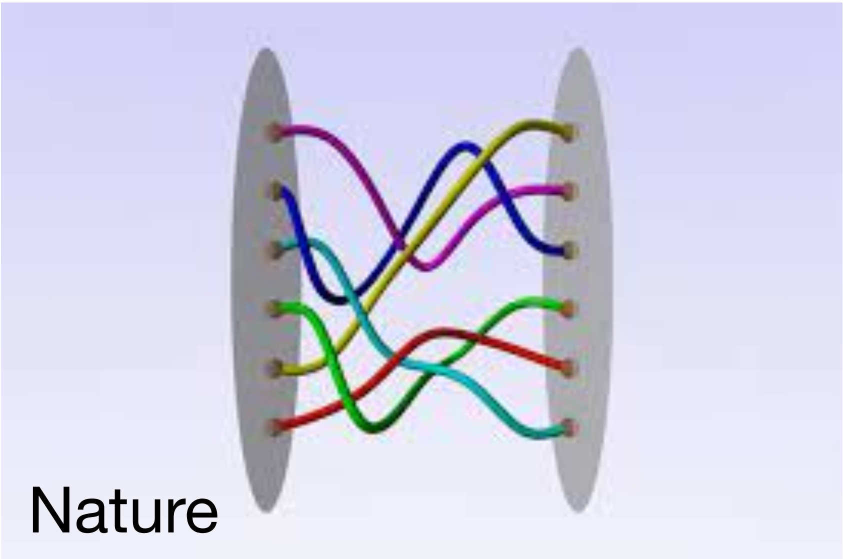

anyonic / fractional excitations

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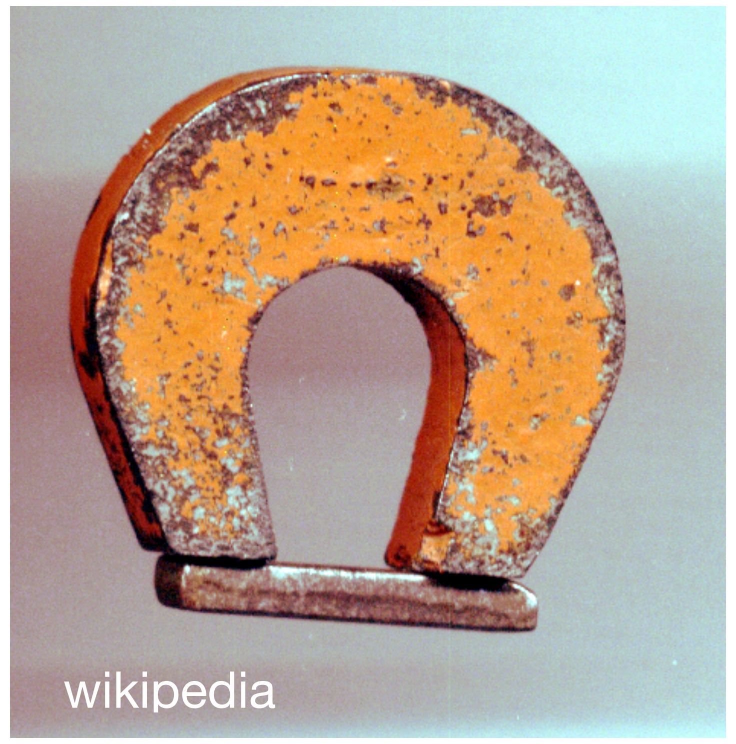

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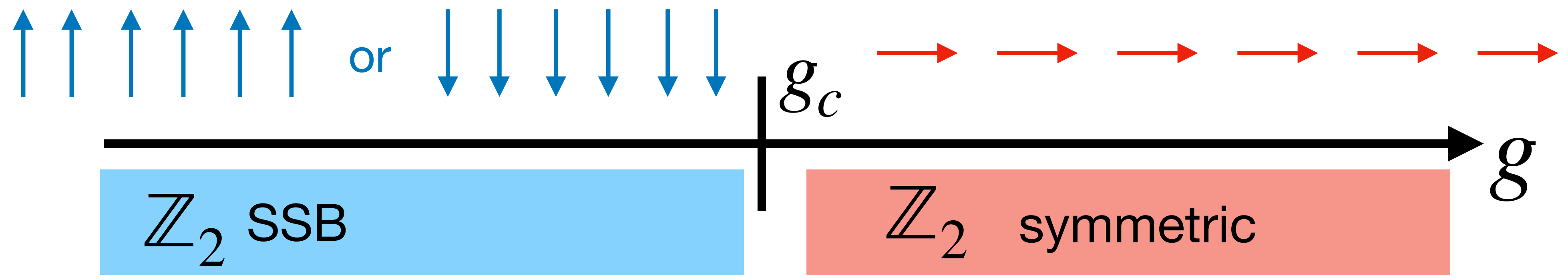

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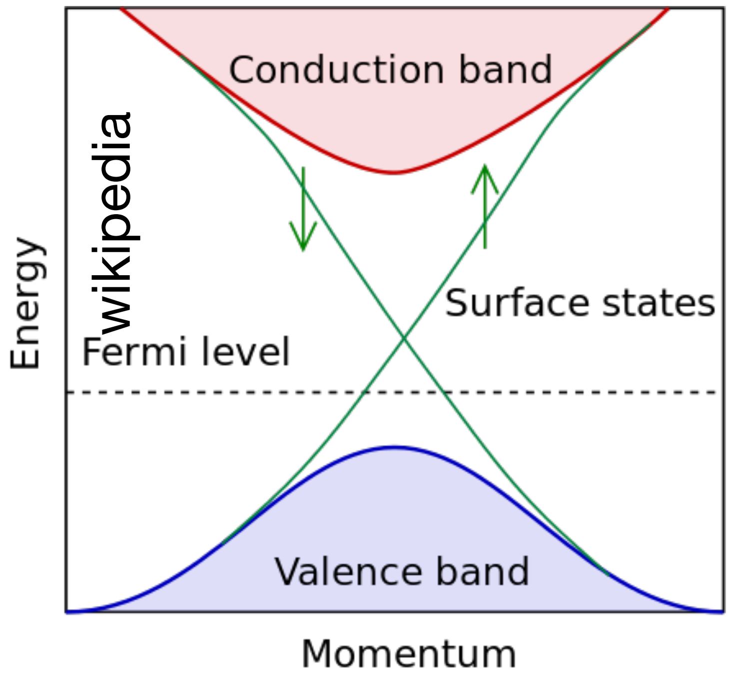

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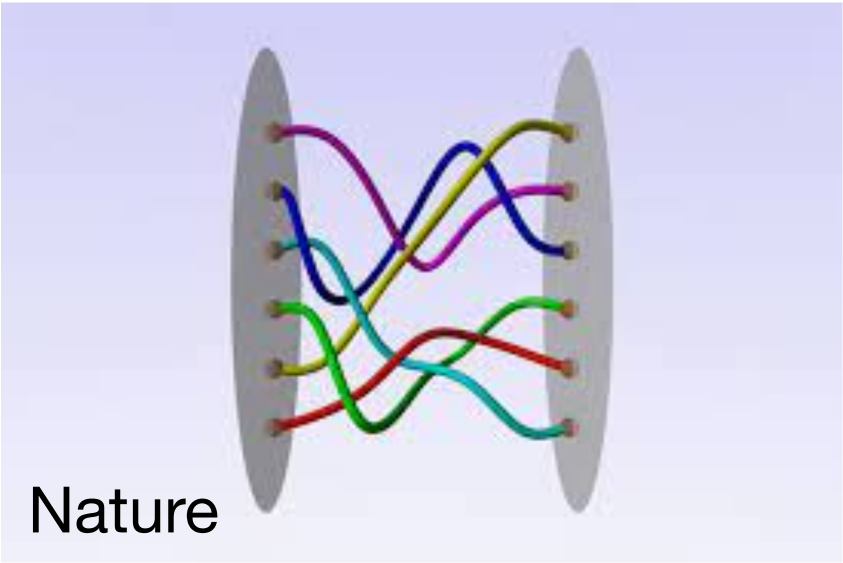

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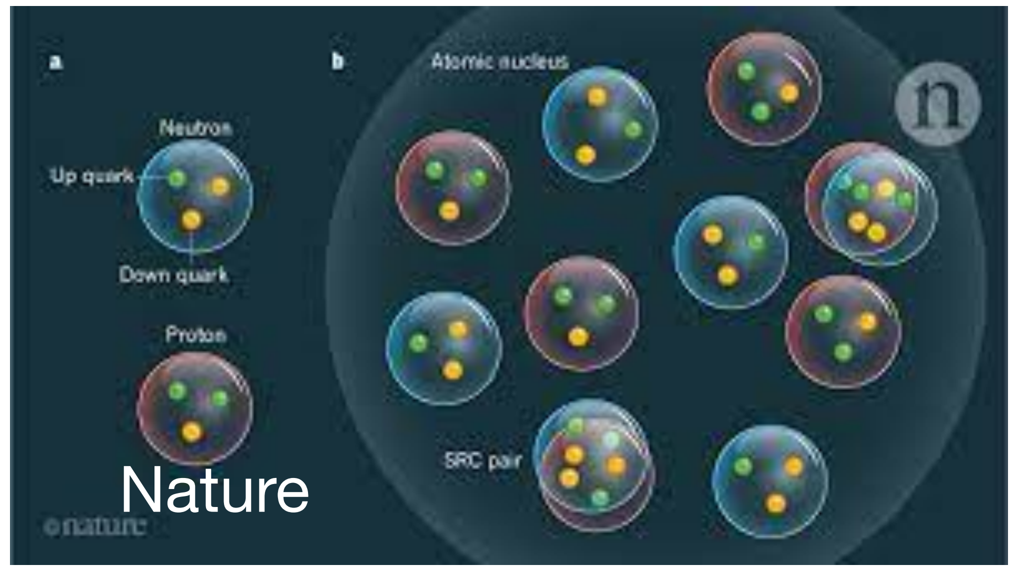

emergent gauge fields

Entanglement: Non-equilibrium problems

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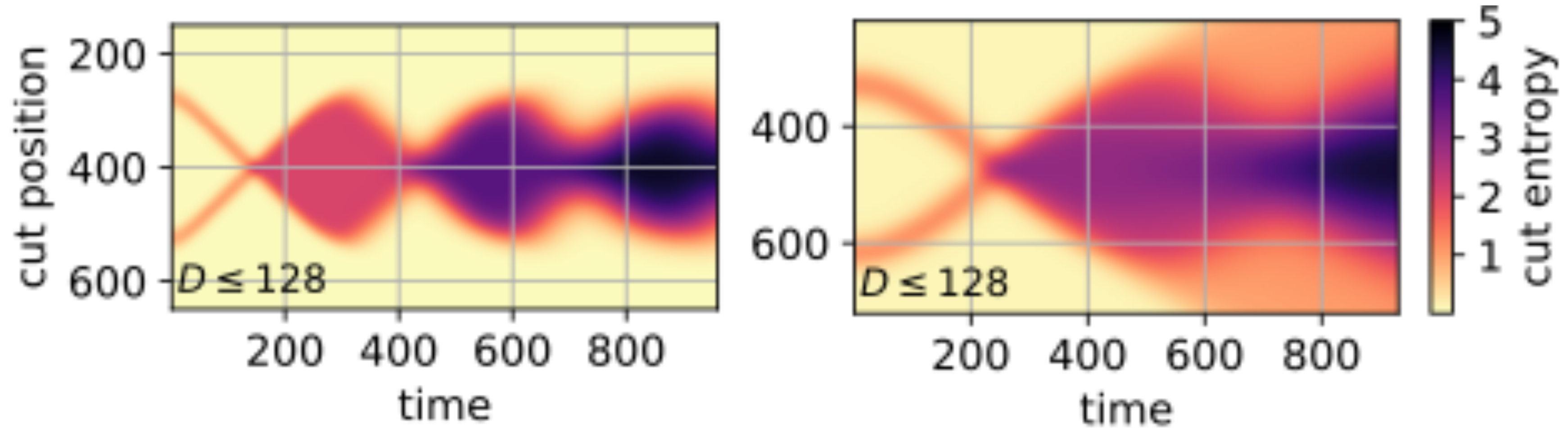

Milsted et al, PRX Quantum 3, 020316 (2022)

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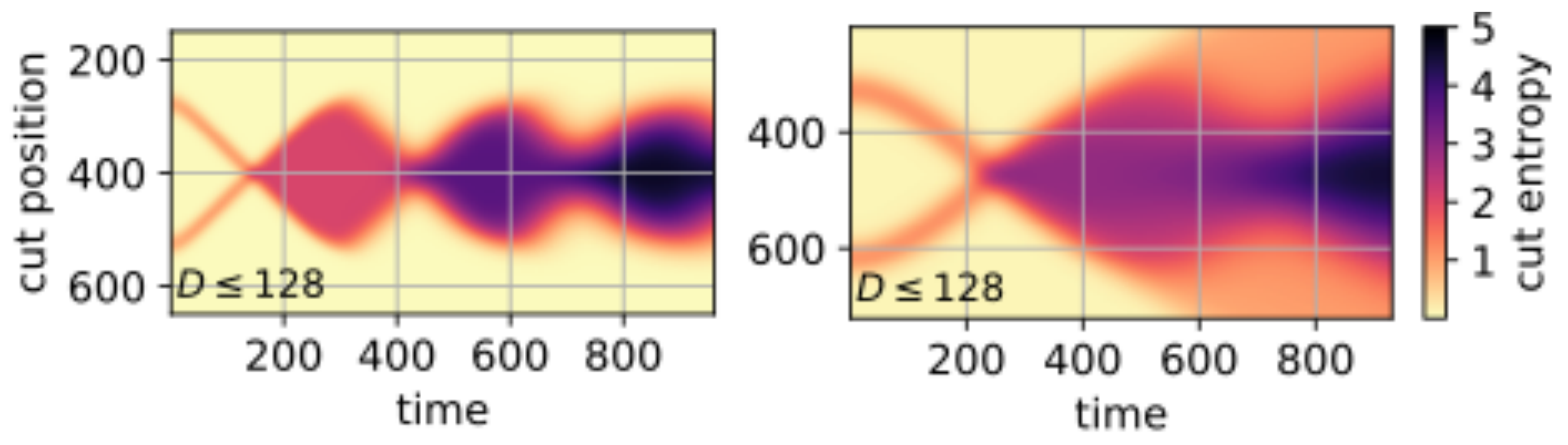

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Baker, Kharzeev PRD 98, 054007 (2018)
Beane, Ehlers MPL A 35, 2050048 (2020)
Beane, Kaplan, Klco, Savage PRL 122, 102001 (2019)
Beane, Farell, Varma IKMP A, 2150205 (2021)

in nuclear and high energy physics

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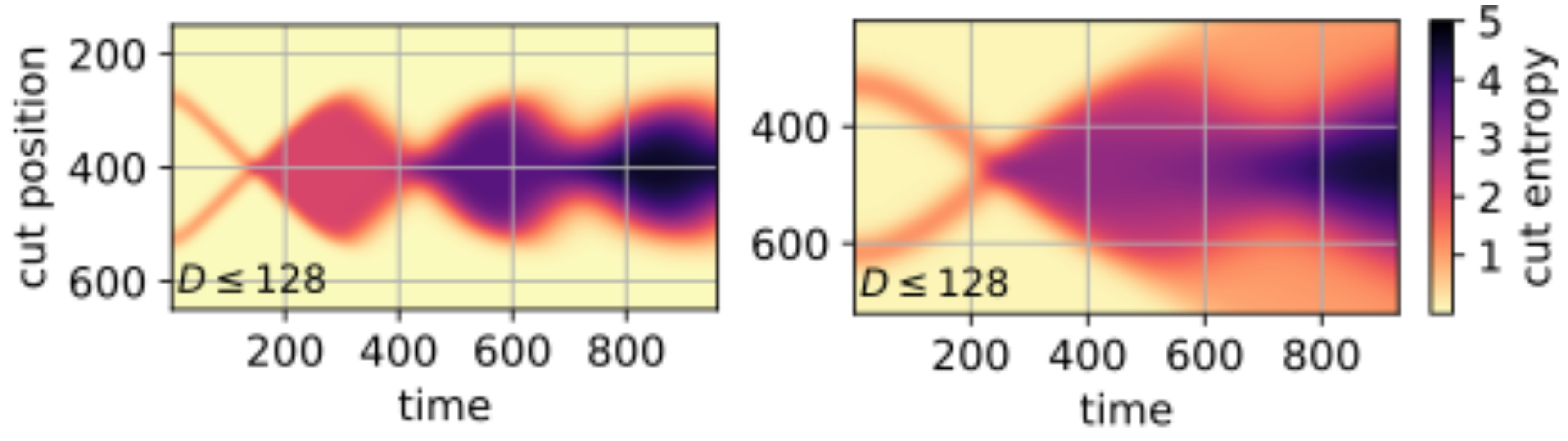

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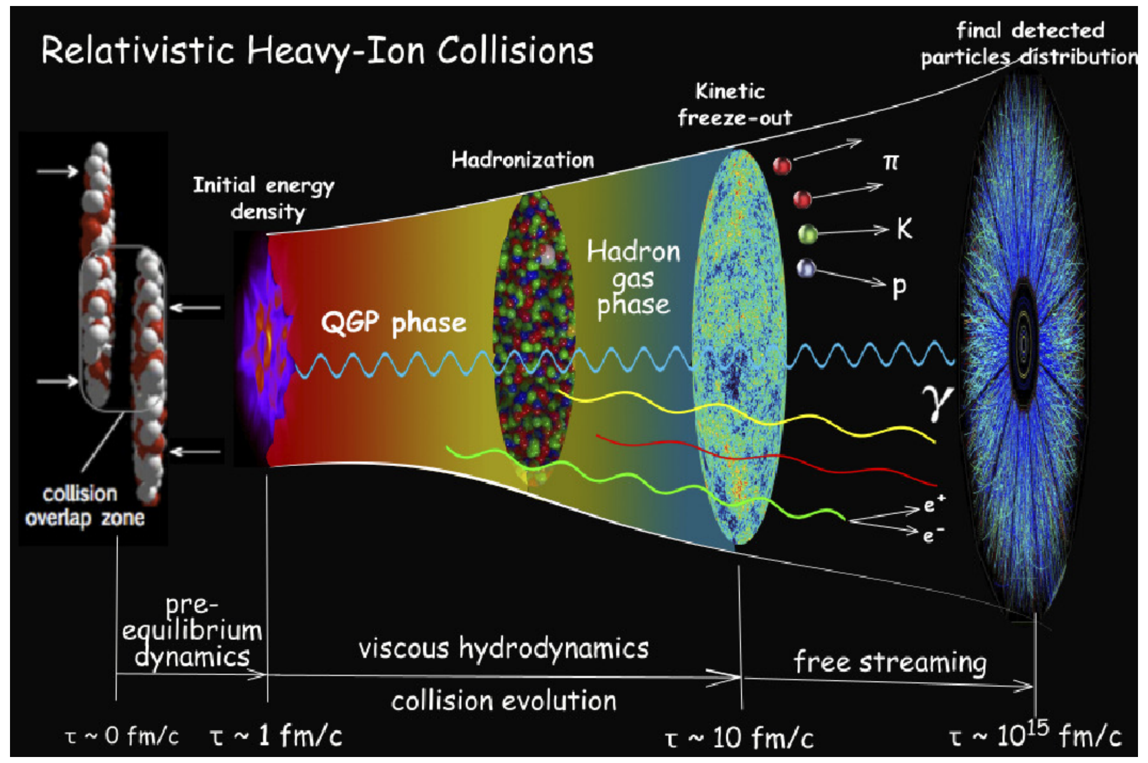

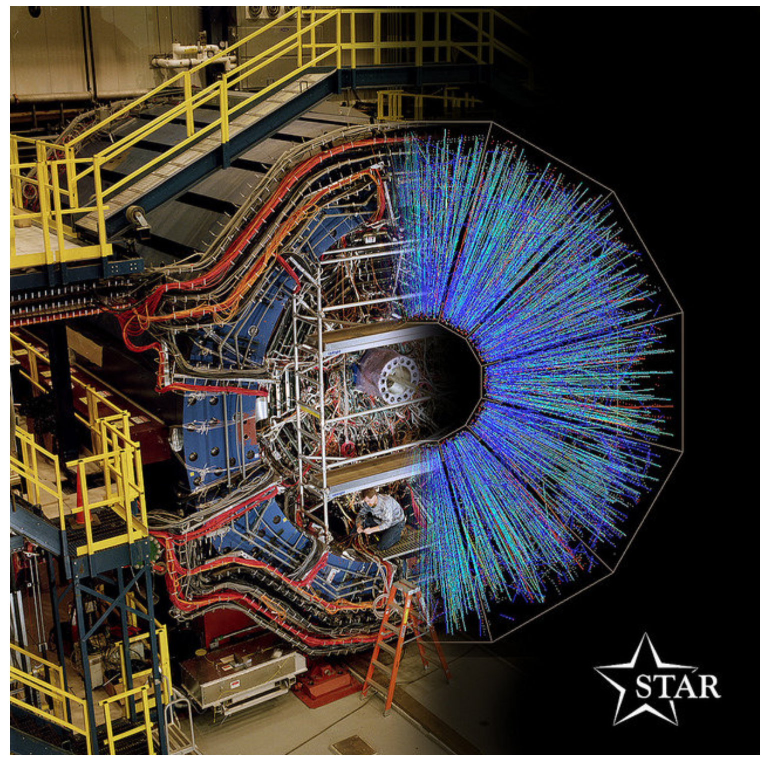

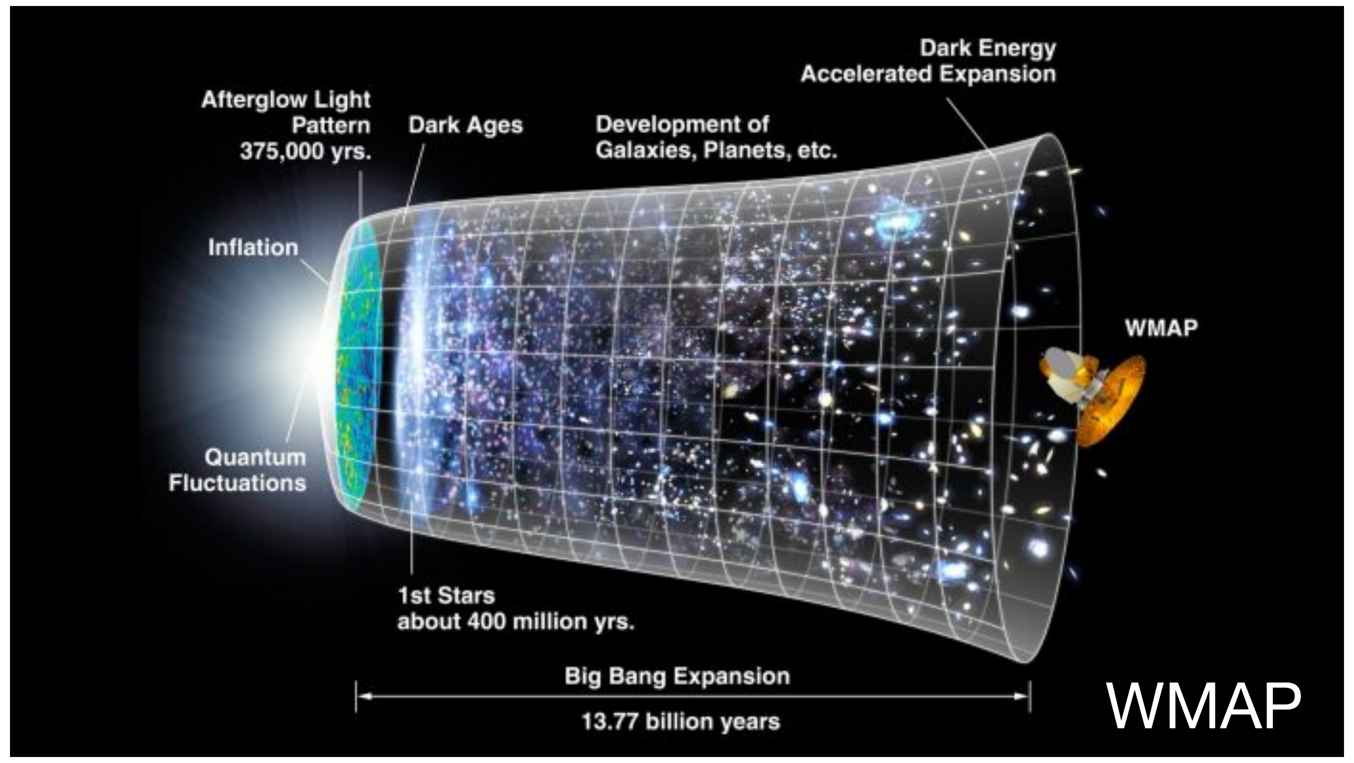

Arnold, Moore, Yaffe; JHEP 11 (2000) & 05 (2003)
Baier, Mueller, Schiff, Son; PLB 502, 51 (2001)
Berges, Heller, Mazeliauskas, Venugopalan, Rev. Mod. Phys. 93 (2021), 035003
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Entanglement: From topological order to Lattice Gauge theories

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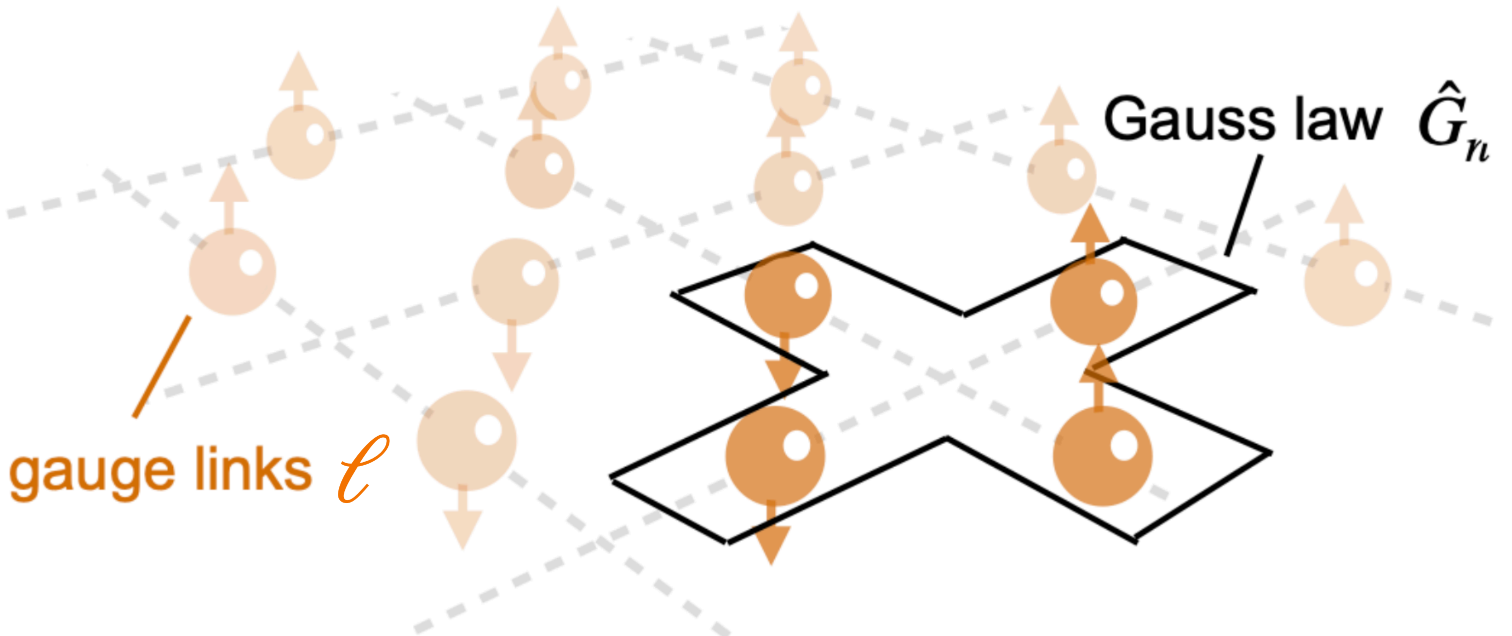

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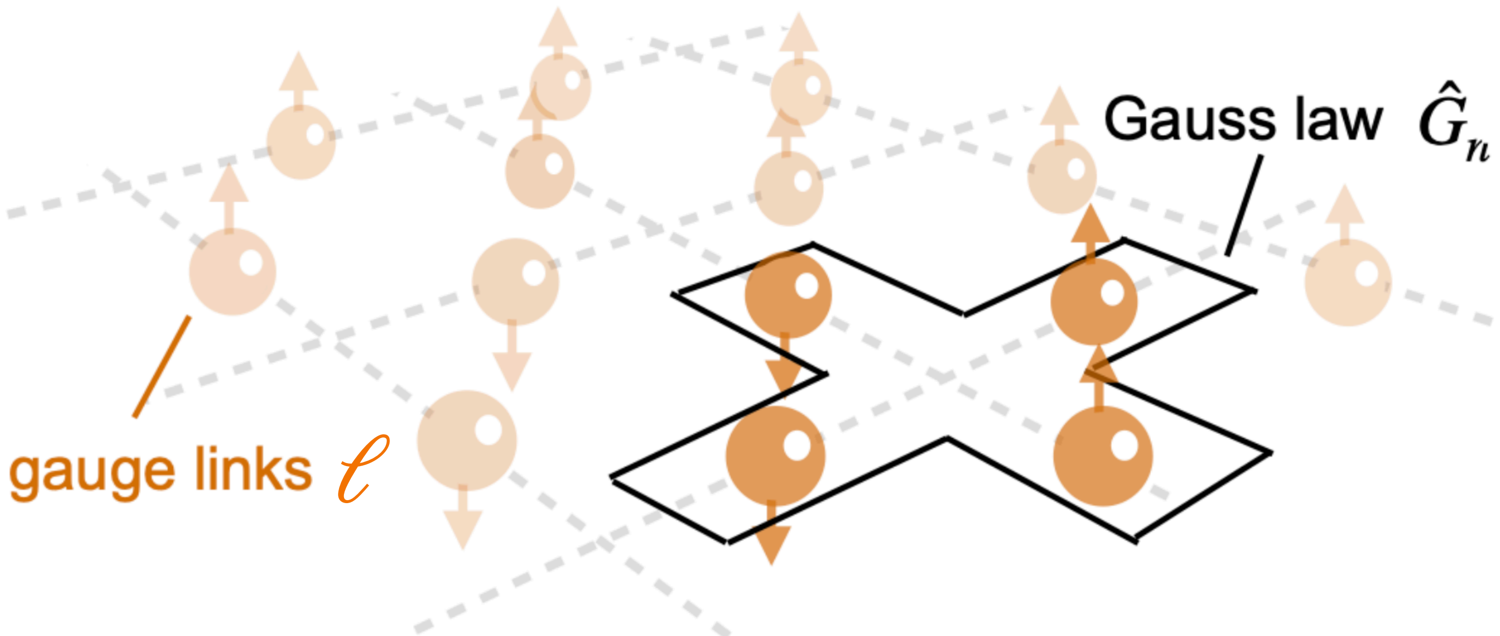

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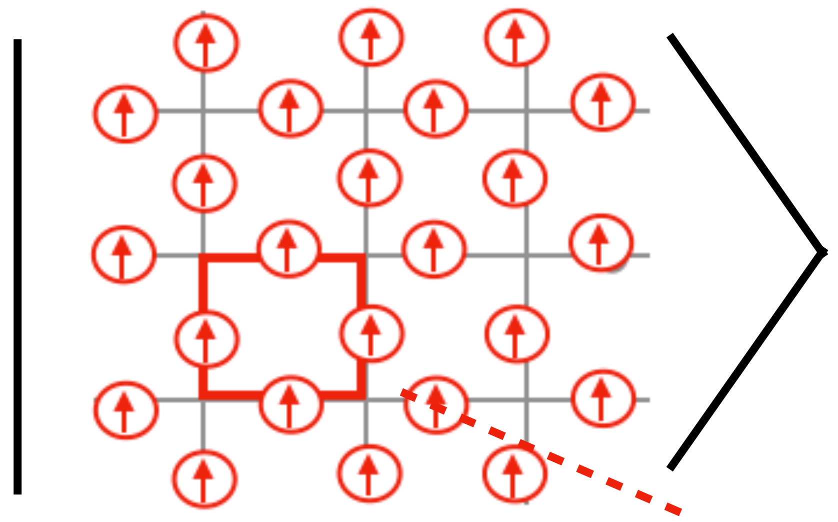

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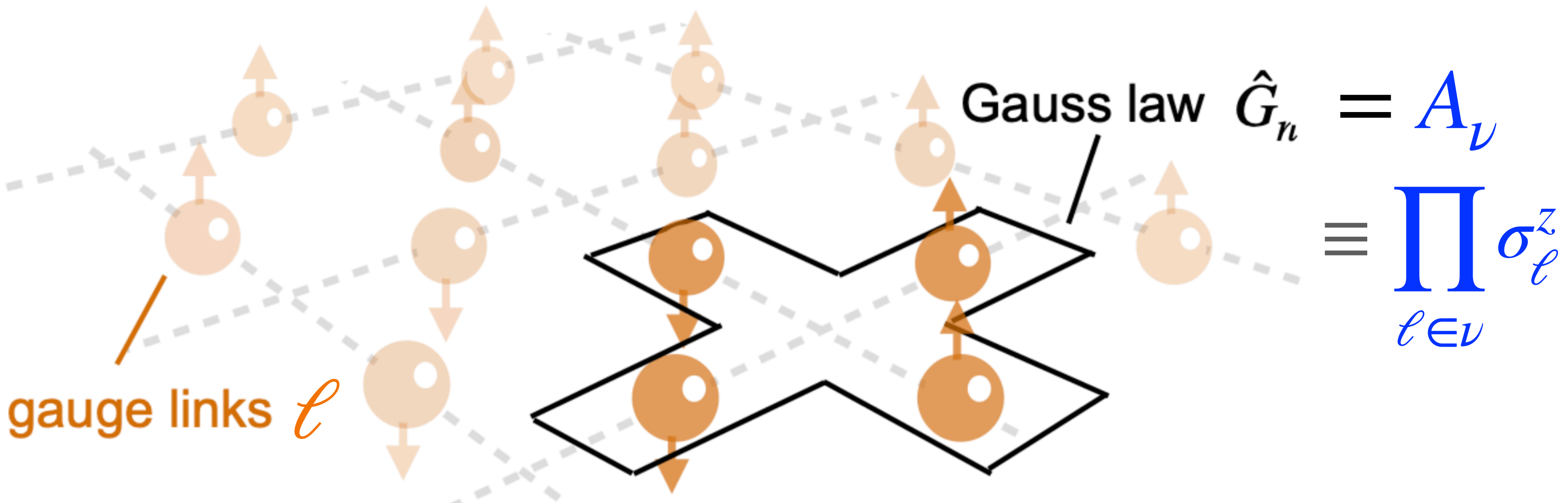

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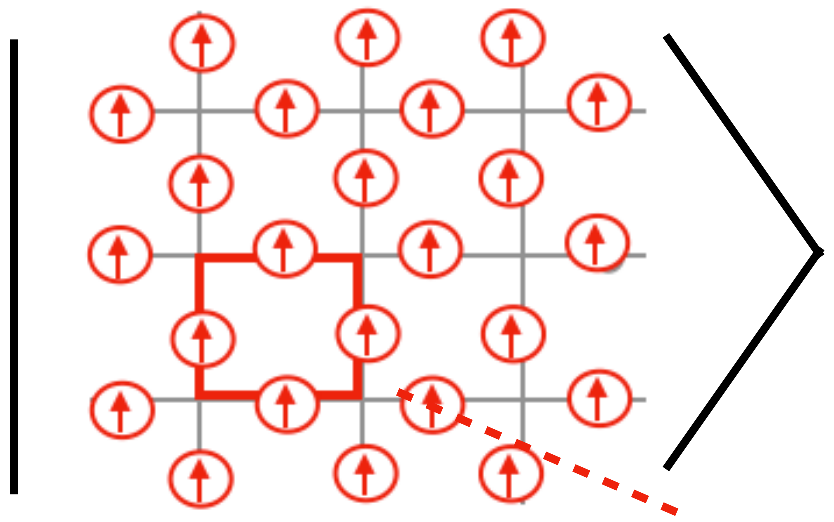

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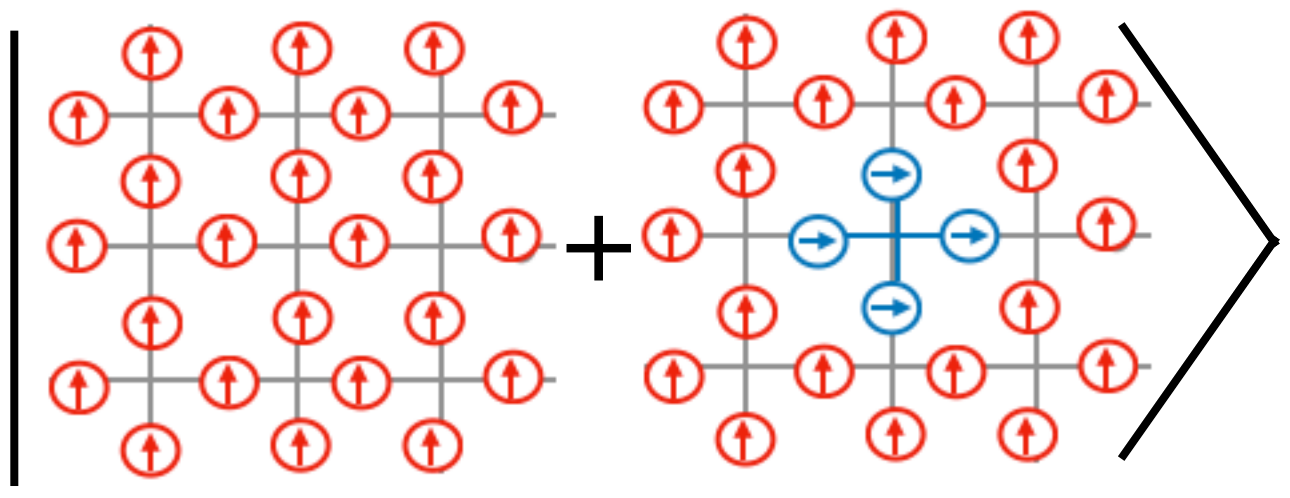
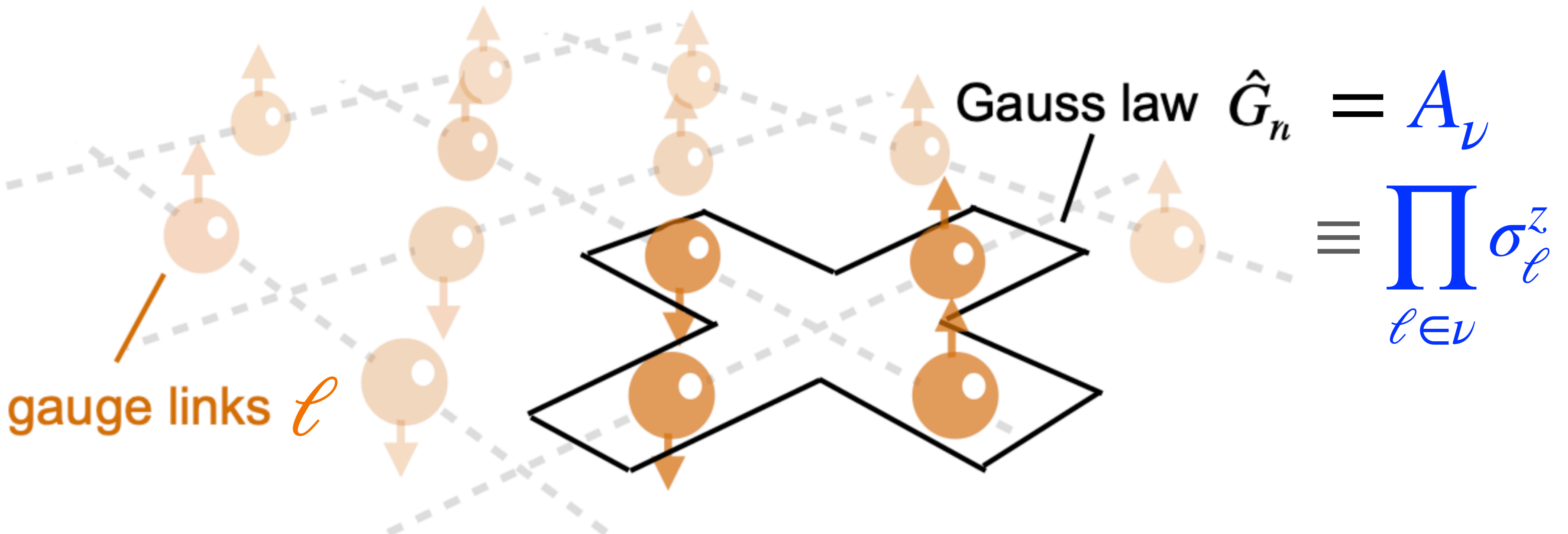


$$(1 + A_\nu)|G_p\rangle$$

Entanglement: From topological order to Lattice Gauge theories



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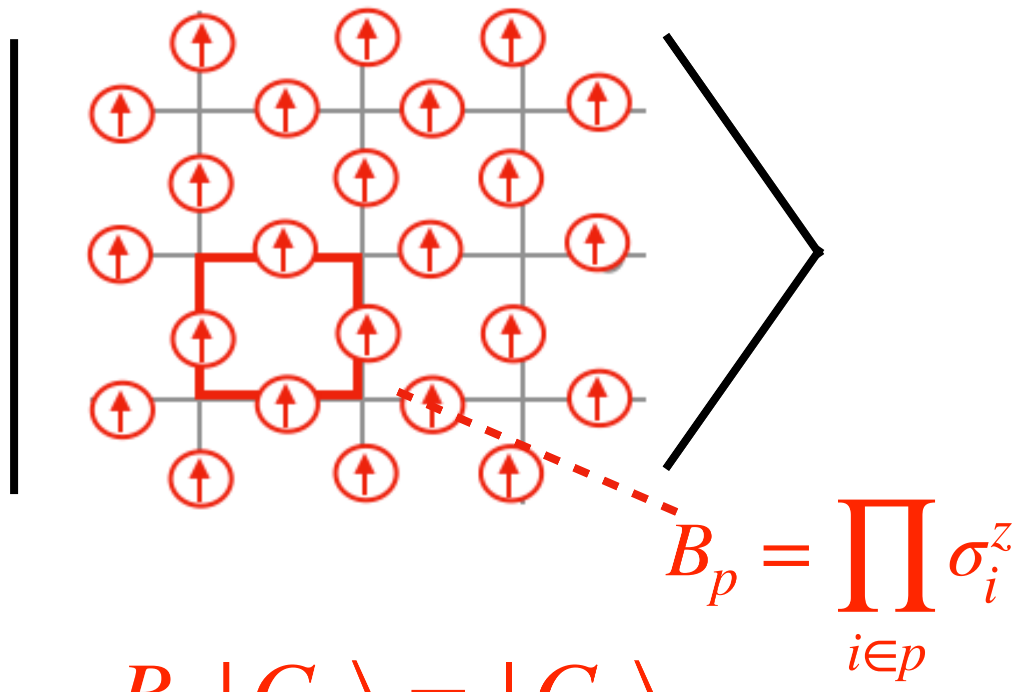

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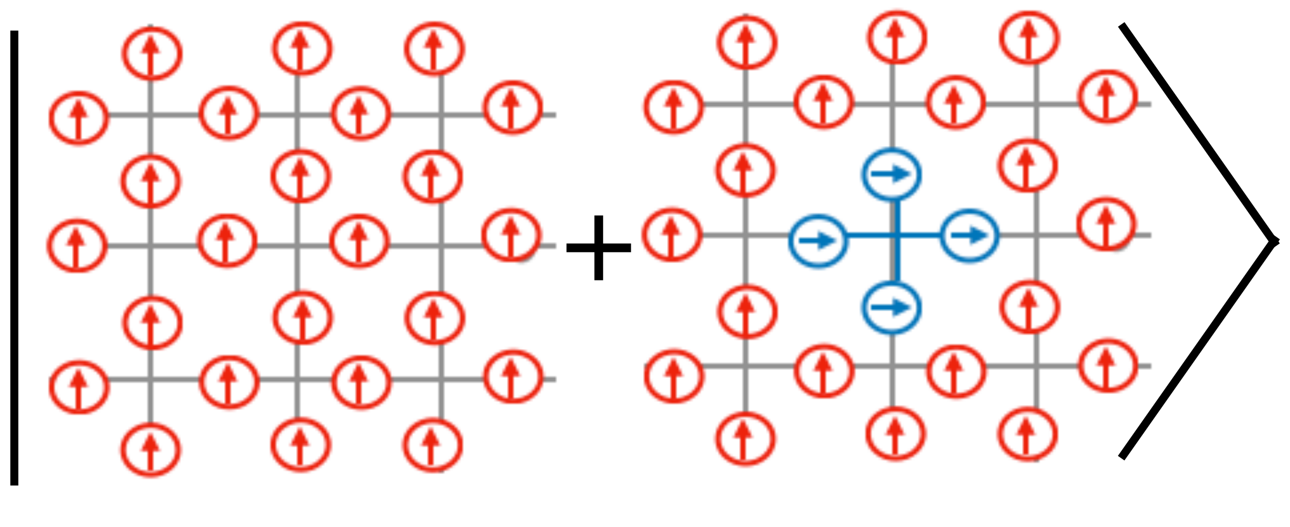

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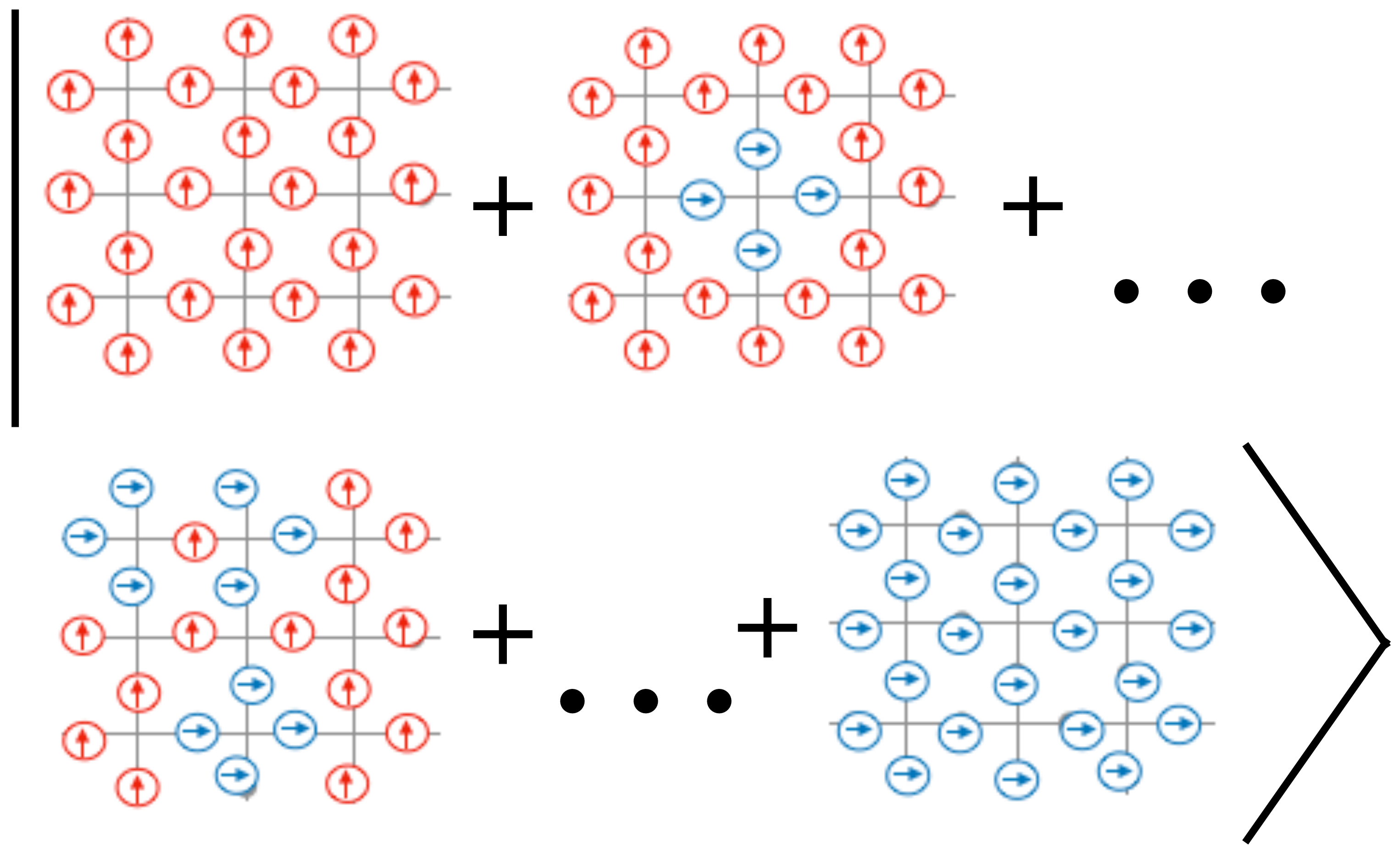

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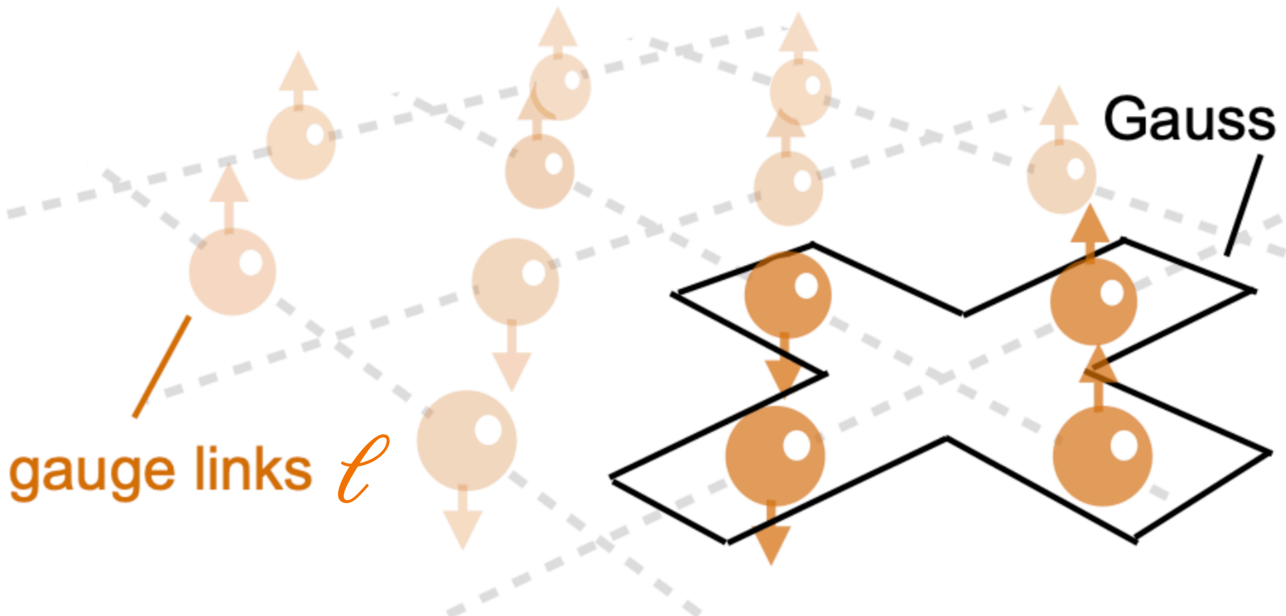

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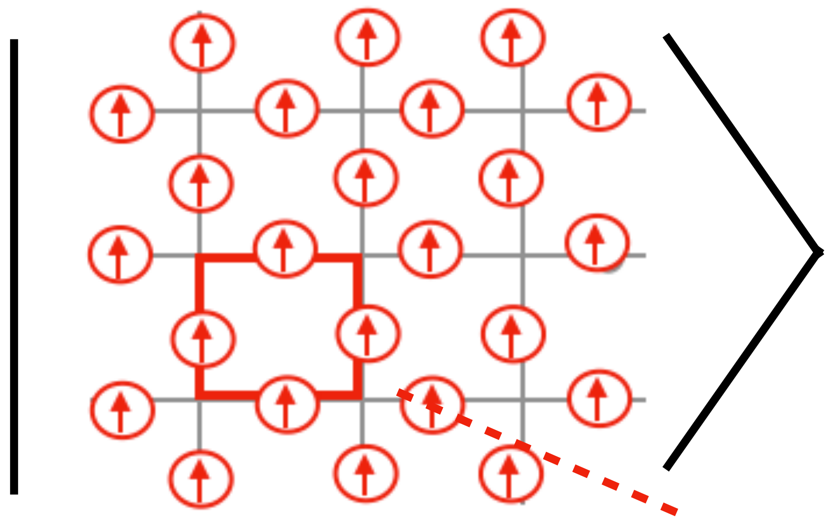

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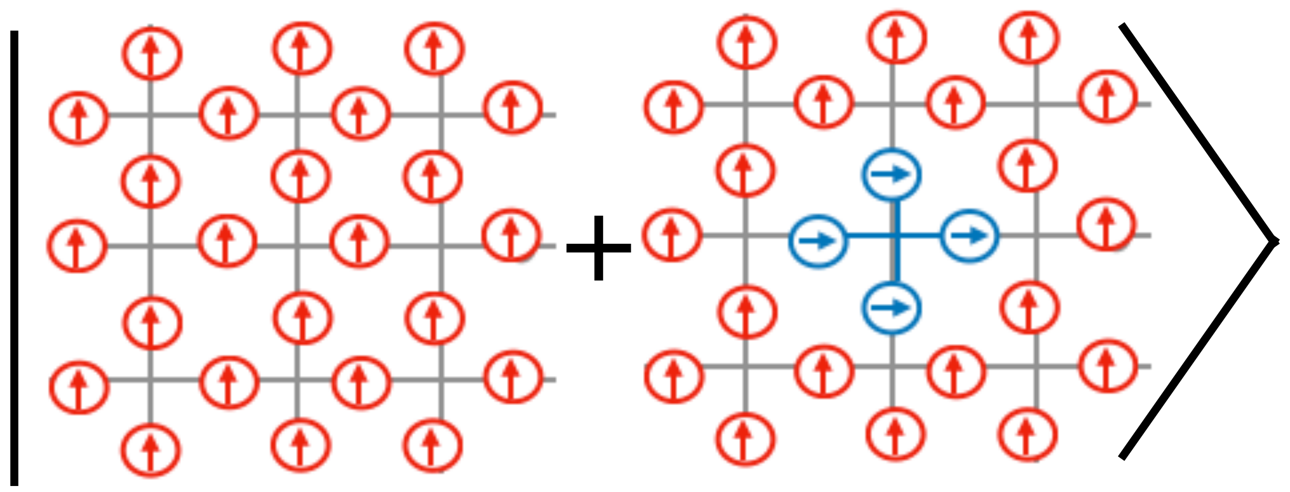
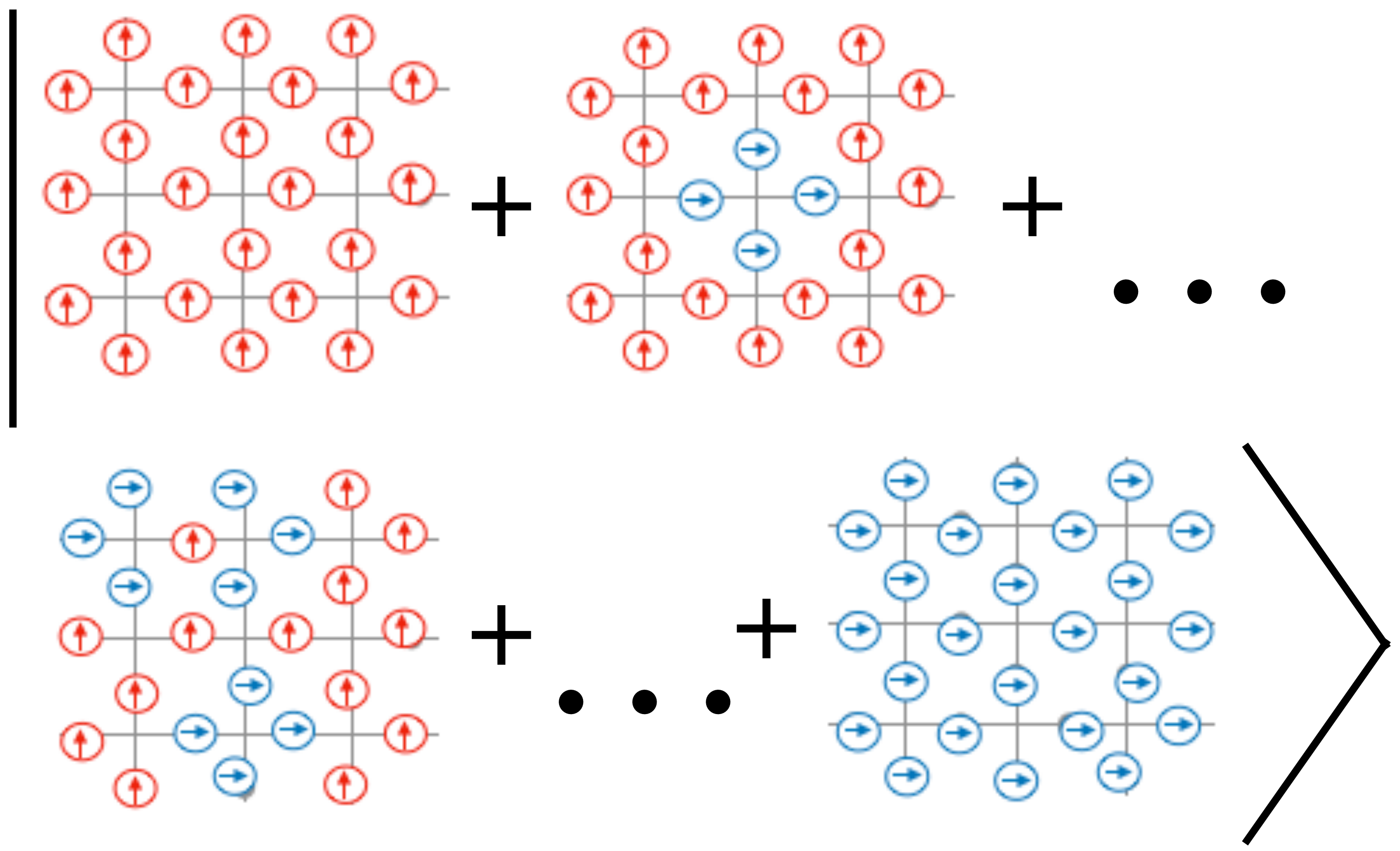


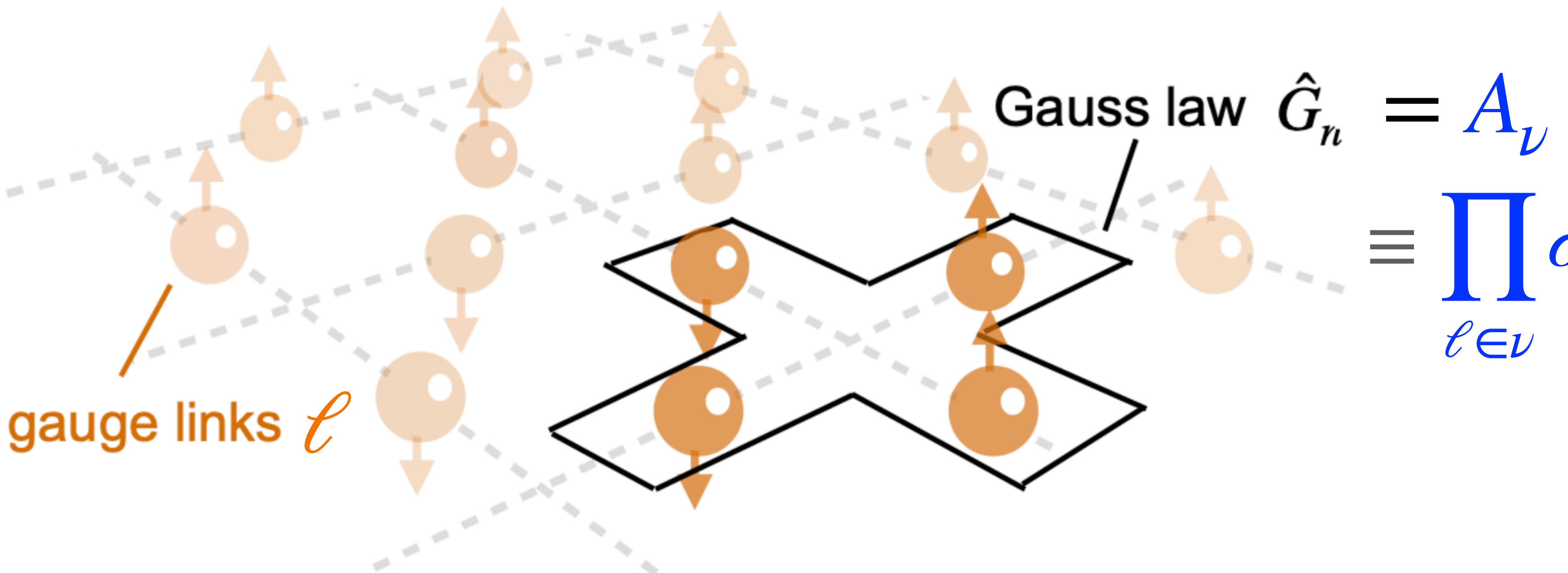
$$(1 + A_\nu) | G_p \rangle$$



$$| G \rangle \propto \prod_p (1 + B_p) | G_\nu \rangle$$

$$= \prod_\nu (1 + A_\nu) | G_p \rangle$$

Entanglement: From topological order to Lattice Gauge theories



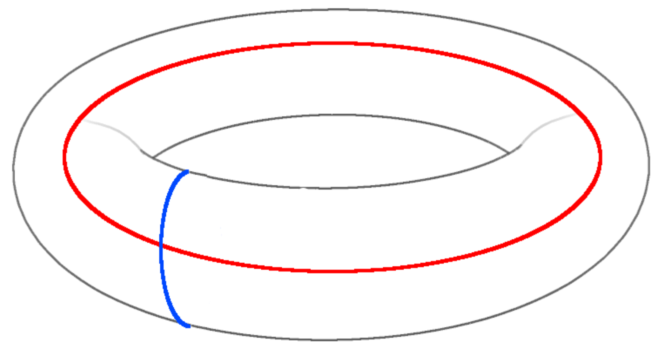
$$\hat{G}_n = A_\nu \equiv \prod_{\ell \in \nu} \sigma^z_\ell$$

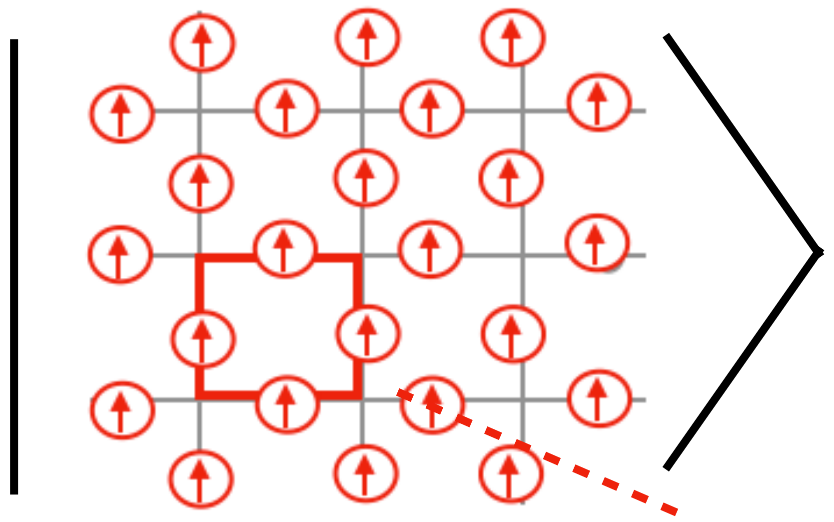
$$H = -\epsilon \sum_{\ell} \sigma^z - \sum_{p} B_p \qquad [A_\nu, B_p] = 0$$

$$B_p \equiv \prod_{\ell \in p} \sigma^x_\ell$$

Classified by

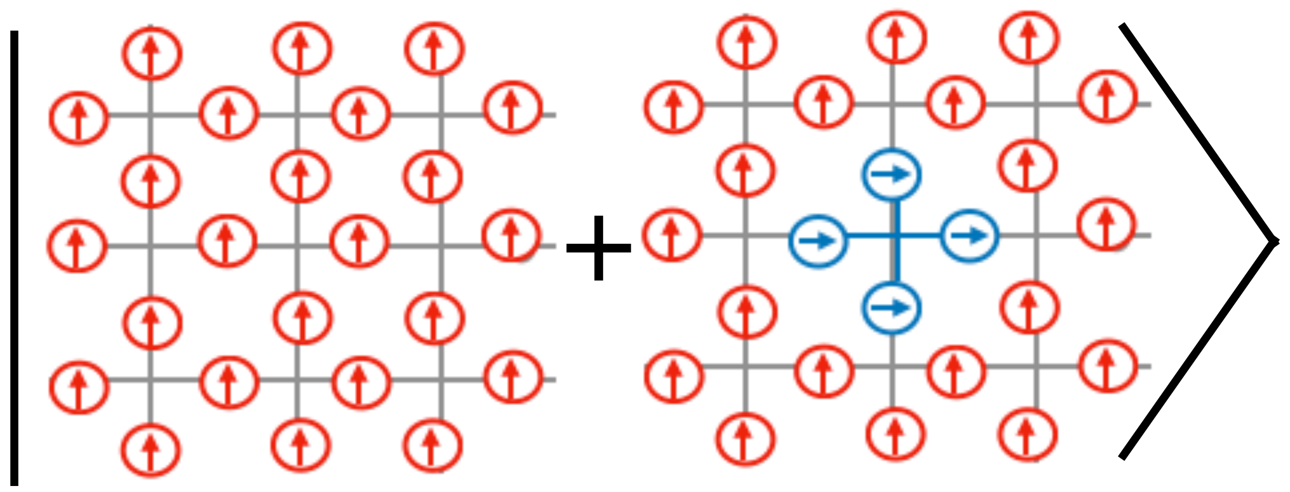
- ground state degeneracy (torus)
- anyonic excitations and ….



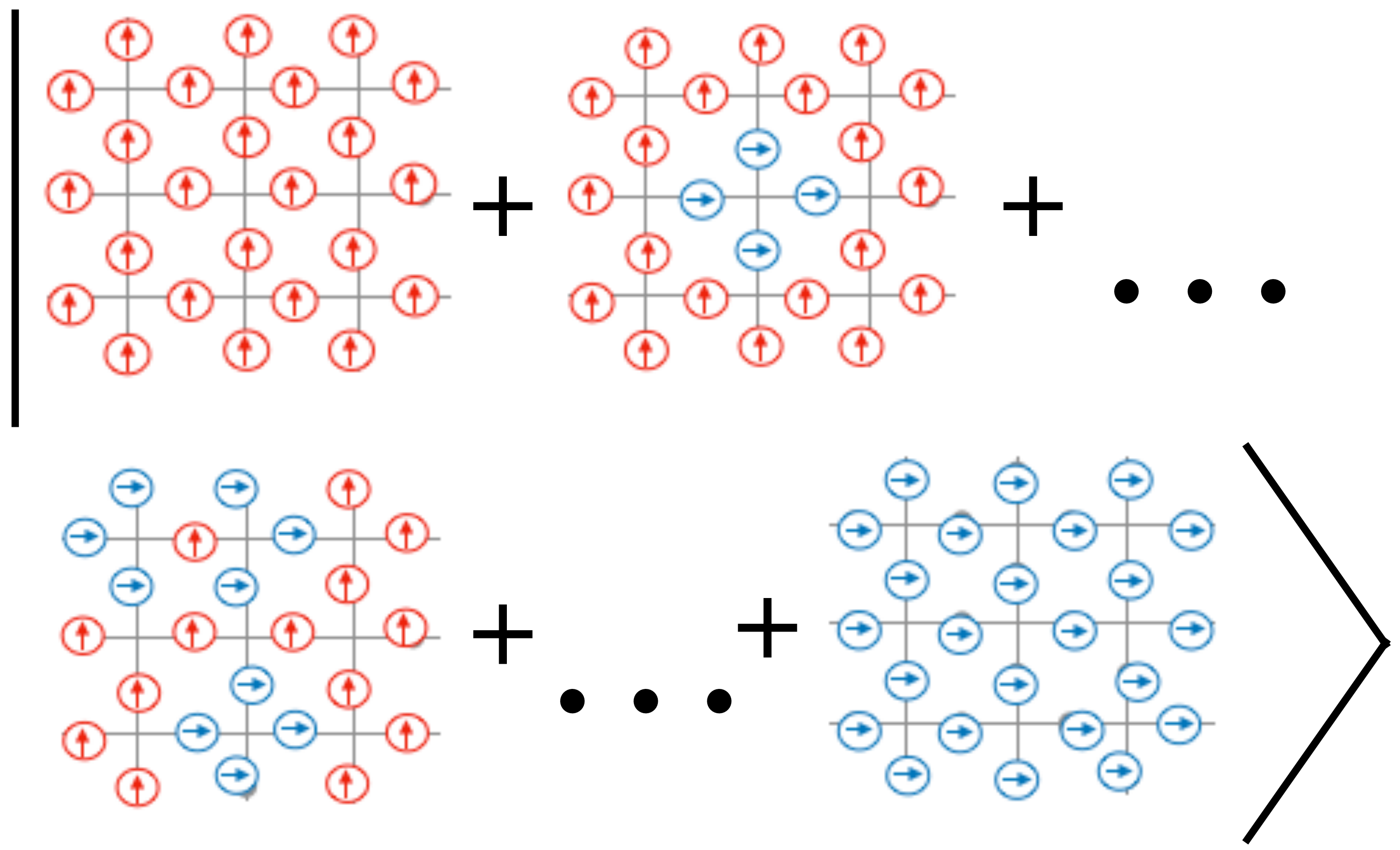


$$B_p = \prod_{i \in p} \sigma^z_i$$

$$B_p | G_p \rangle = | G_p \rangle$$



$$(1 + A_\nu) | G_p \rangle$$



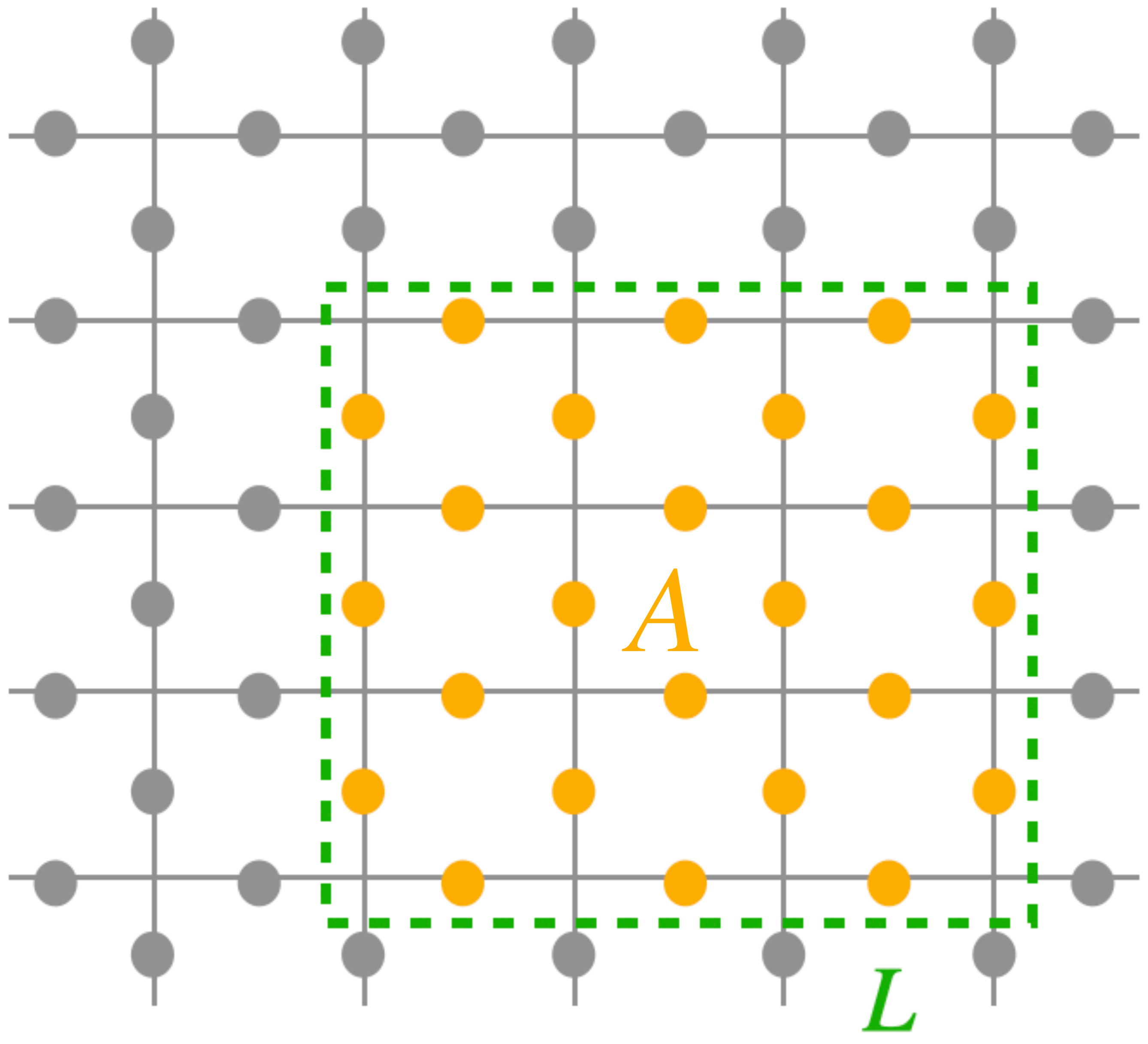
$$| G \rangle \propto \prod_p (1 + B_p) | G_\nu \rangle = \prod_\nu (1 + A_\nu) | G_p \rangle$$

Entanglement: From topological order to Lattice Gauge theories

… by Entanglement

Entanglement: From topological order to Lattice Gauge theories

… by Entanglement



Entanglement: From topological order to Lattice Gauge theories

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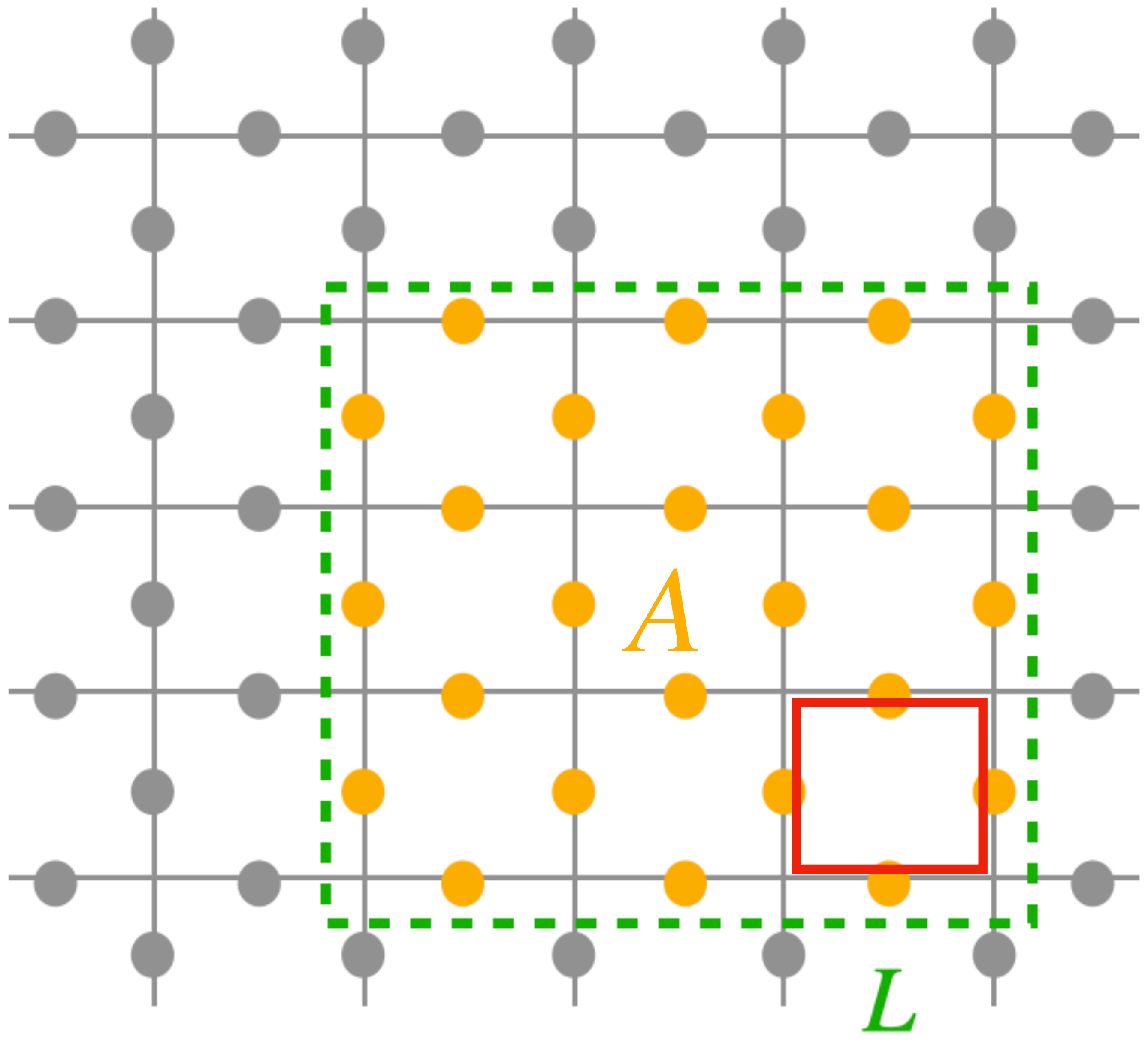
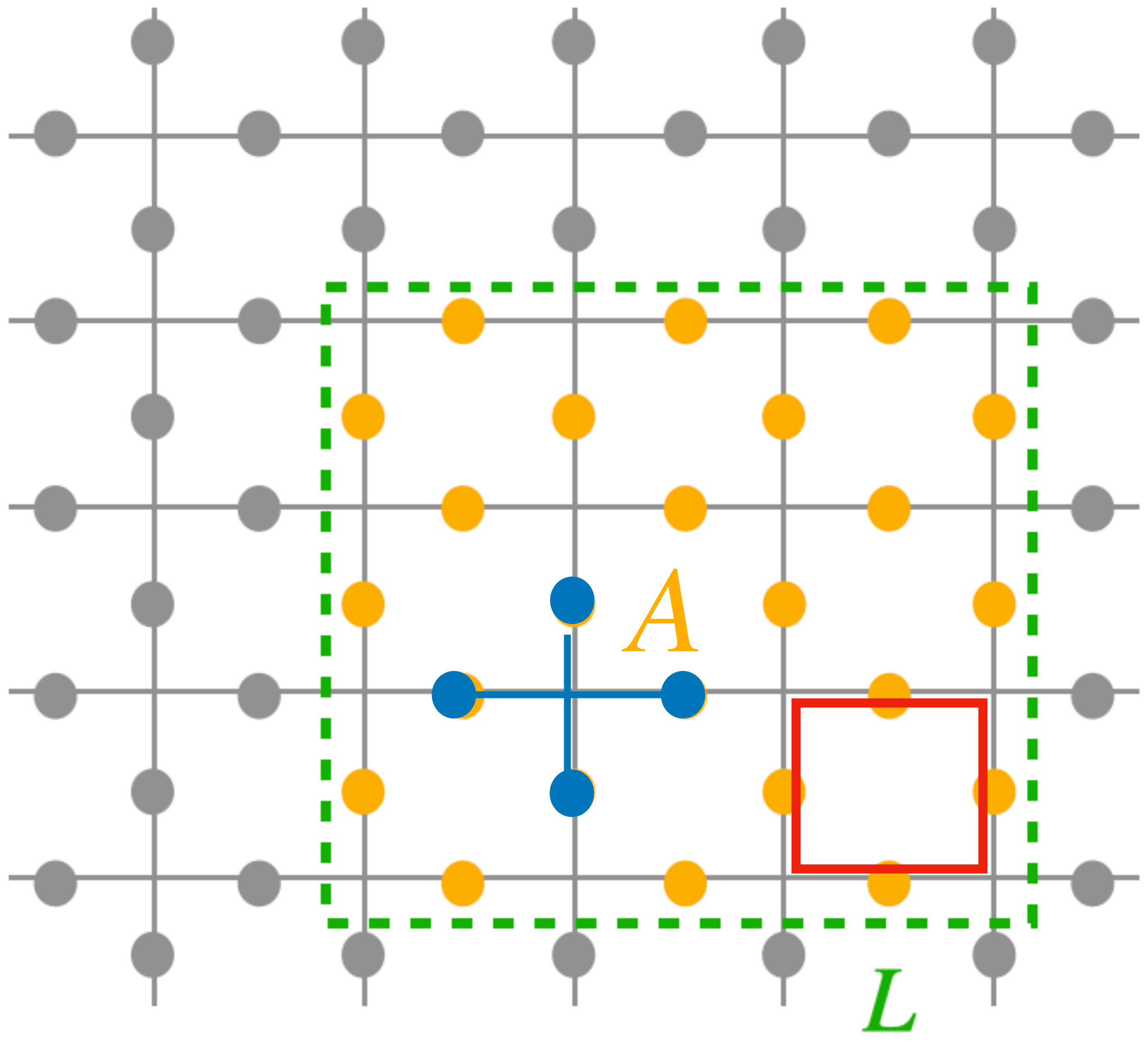


$$\propto \prod_{p \in \mathscr{A}} (1 + B_p)$$

Entanglement: From topological order to Lattice Gauge theories

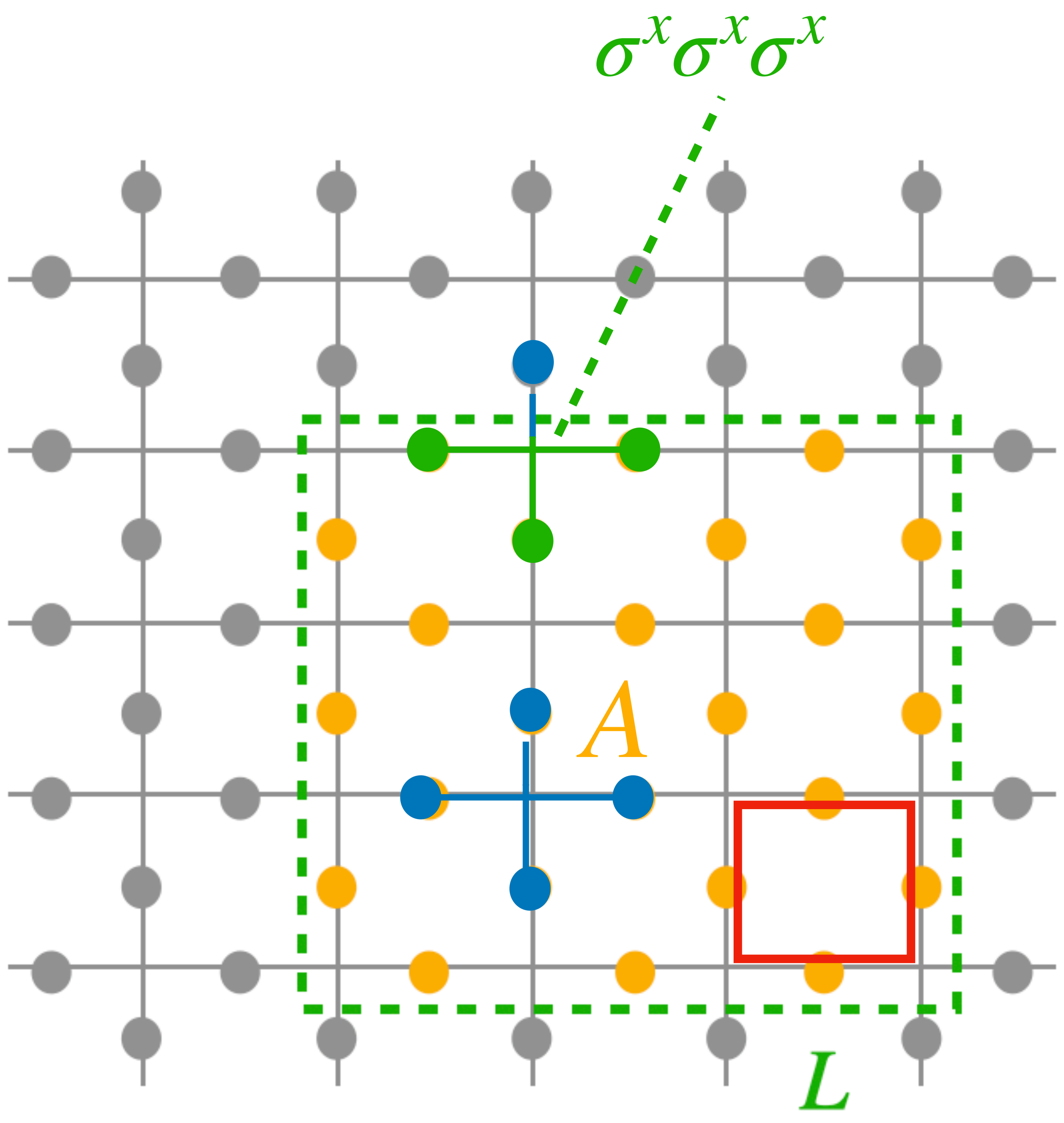
… by Entanglement



$$\propto \prod_{p\in\mathcal{A}}(1+B_p)\prod_{v\in\mathcal{A}}(1+A_v)$$

Entanglement: From topological order to Lattice Gauge theories

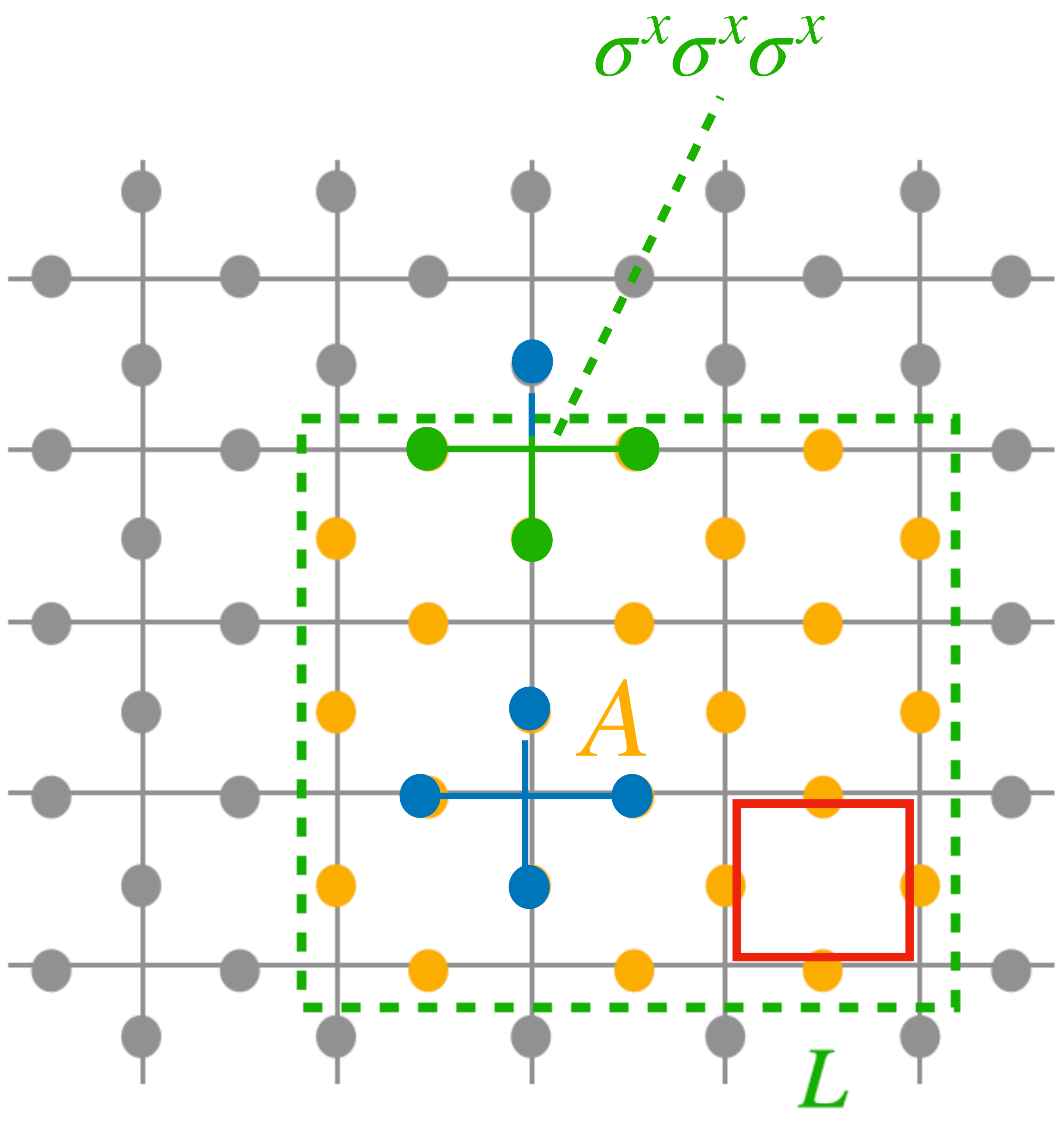
… by Entanglement



$$\propto \prod_{p\in\mathscr{A}}(1+B_p)\prod_{\nu\in\mathscr{A}}(1+A_\nu)$$

Entanglement: From topological order to Lattice Gauge theories

… by Entanglement

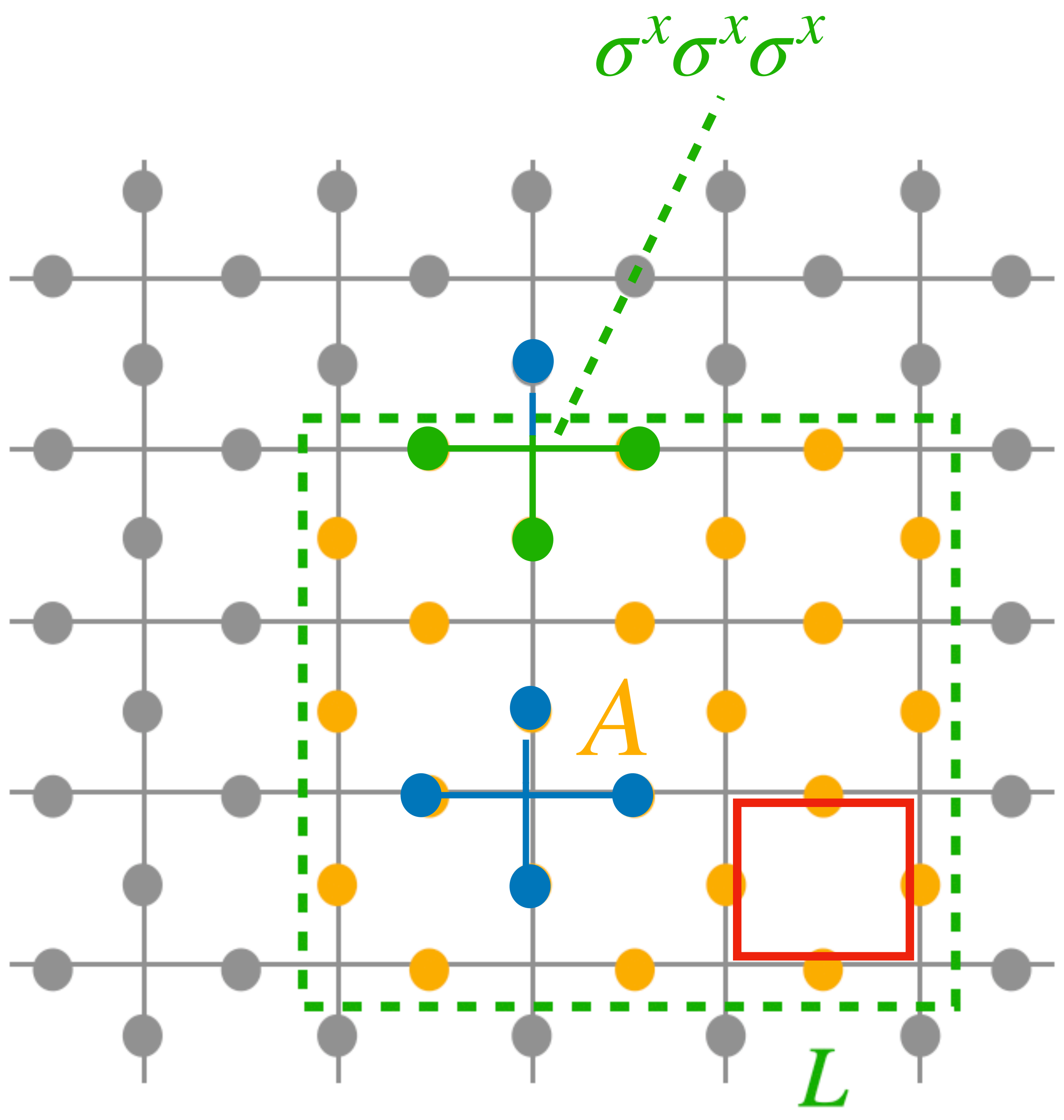


$$[\rho_A, \sigma^x\sigma^x\sigma^x] = 0$$

$$\propto \prod_{p\in\mathcal{A}} (1+B_p) \prod_{\nu\in\mathcal{A}} (1+A_\nu)$$

Entanglement: From topological order to Lattice Gauge theories

… by Entanglement



$$[\rho_A, \sigma^x\sigma^x\sigma^x] = 0$$

$$\rho_A = \begin{pmatrix} \square & \cdots & \\ \vdots & \square & \\ & \cdots & \ddots \end{pmatrix}$$

$$\propto \prod_{p\in\mathscr{A}} (1+B_p) \prod_{\nu\in\mathscr{A}} (1+A_\nu)$$

Entanglement: From topological order to Lattice Gauge theories

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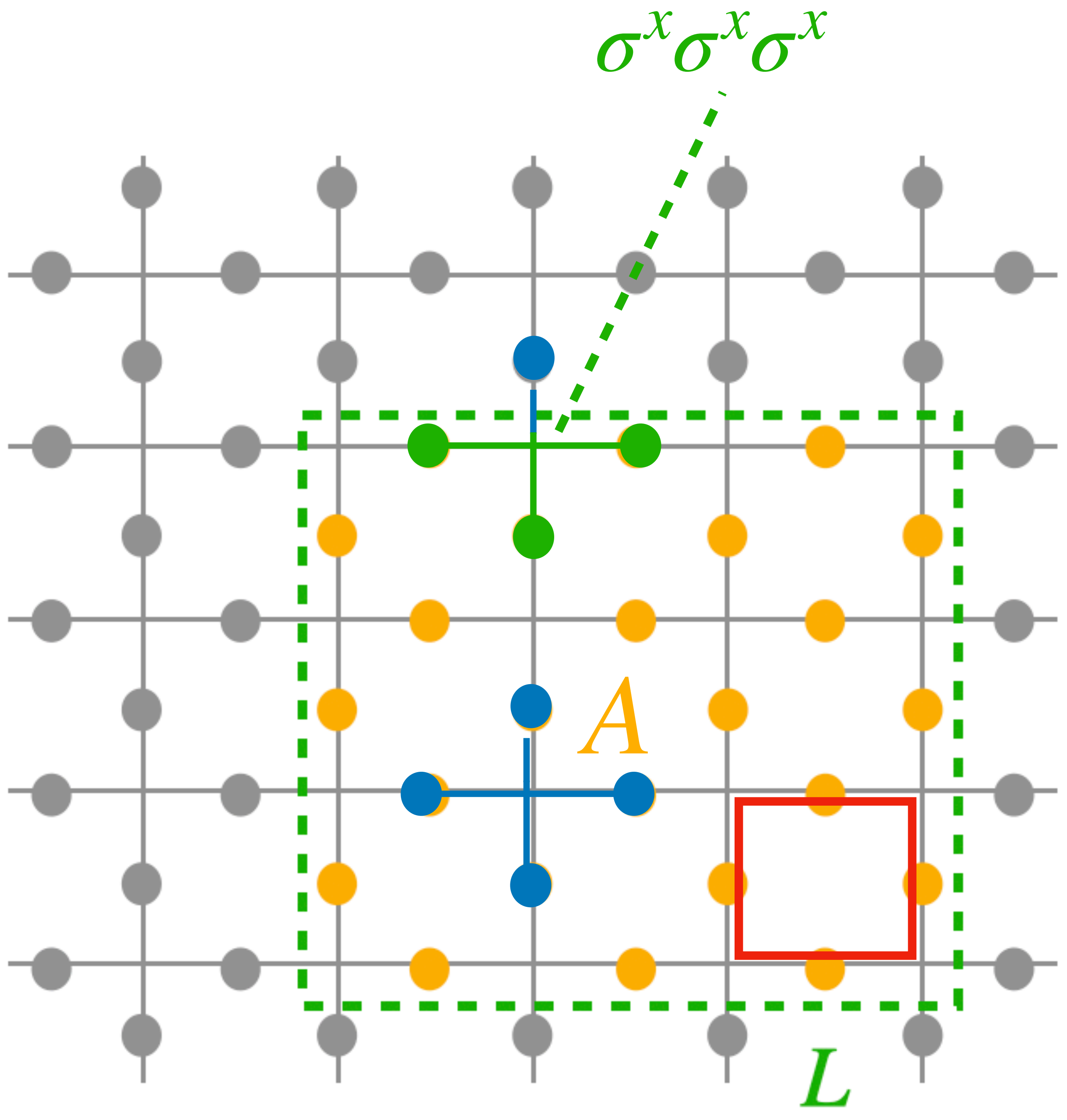

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$$\propto \prod_{p\in\mathcal{A}} (1+B_p) \prod_{\nu\in\mathcal{A}} (1+A_\nu) \quad \frac{\mathbb{1}}{2^{\#}}$$

Entanglement: From topological order to Lattice Gauge theories

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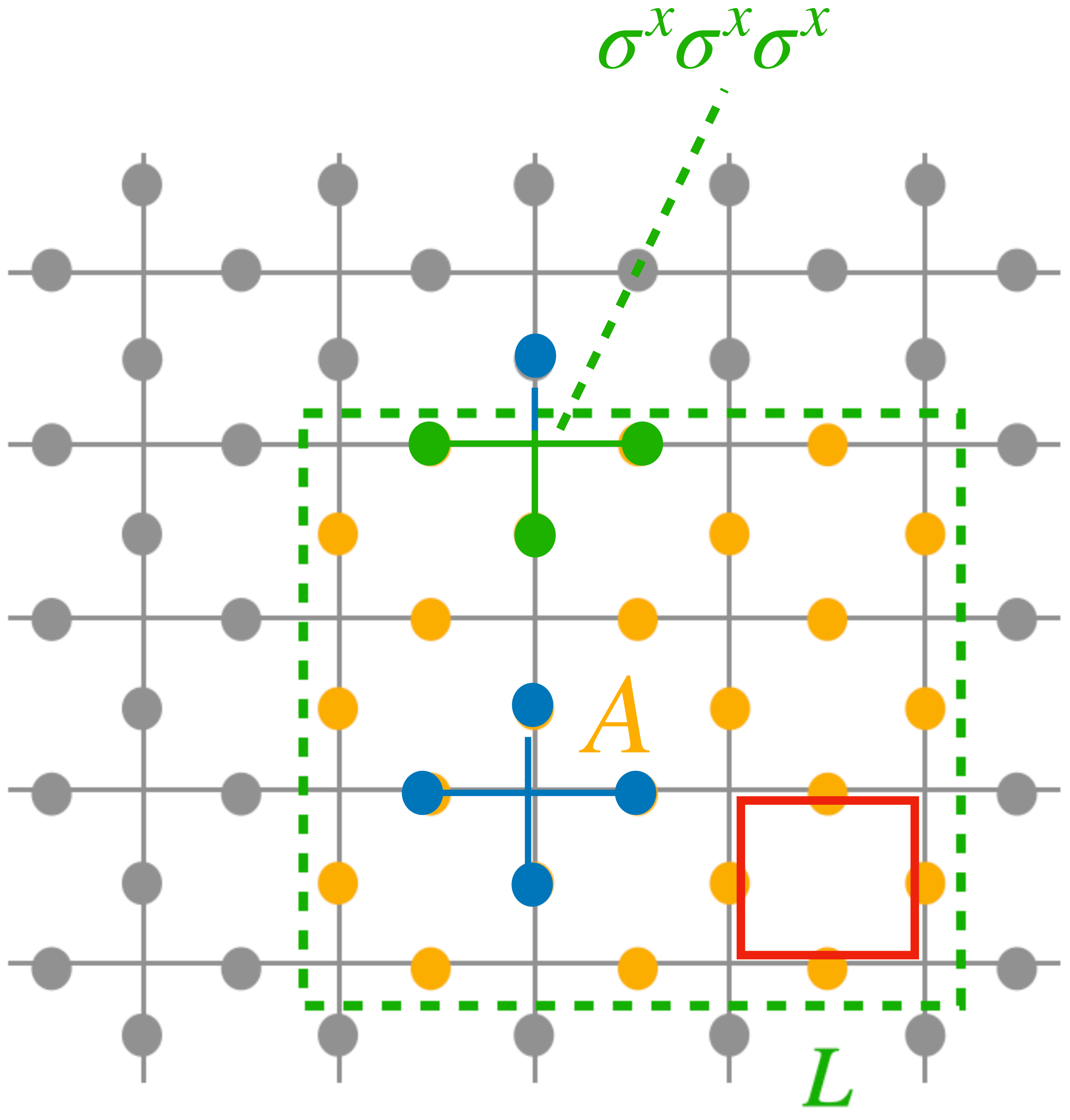


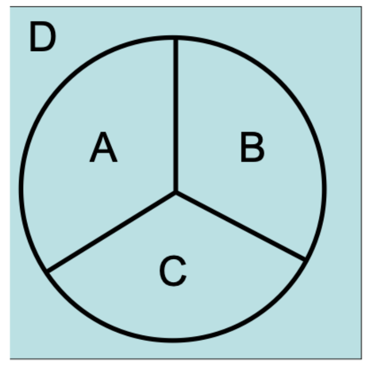
$$[\rho_A, \sigma^x\sigma^x\sigma^x] = 0$$

$$\rho_A = \begin{pmatrix} \square & \cdots & \\ \vdots & \square & \\ & \cdots & \ddots \end{pmatrix}$$

$$\propto \prod_{p\in\mathscr{A}} (1+B_p) \prod_{v\in\mathscr{A}} (1+A_v) \; \frac{\square}{2^{\#}}$$

Topological Entanglement Entropy

$$\prod_{v\in\partial A} A_v^{\top} = 1 \qquad \# = L - 1$$



$$S = L\log(2) - \gamma$$

$$\gamma = \log(2)$$

Kitaev, Preskill PRL 96 (2006) 110404
Levin, Wen PRL 96, 110405 (2006)

Entanglement: From topological order to Lattice Gauge theories

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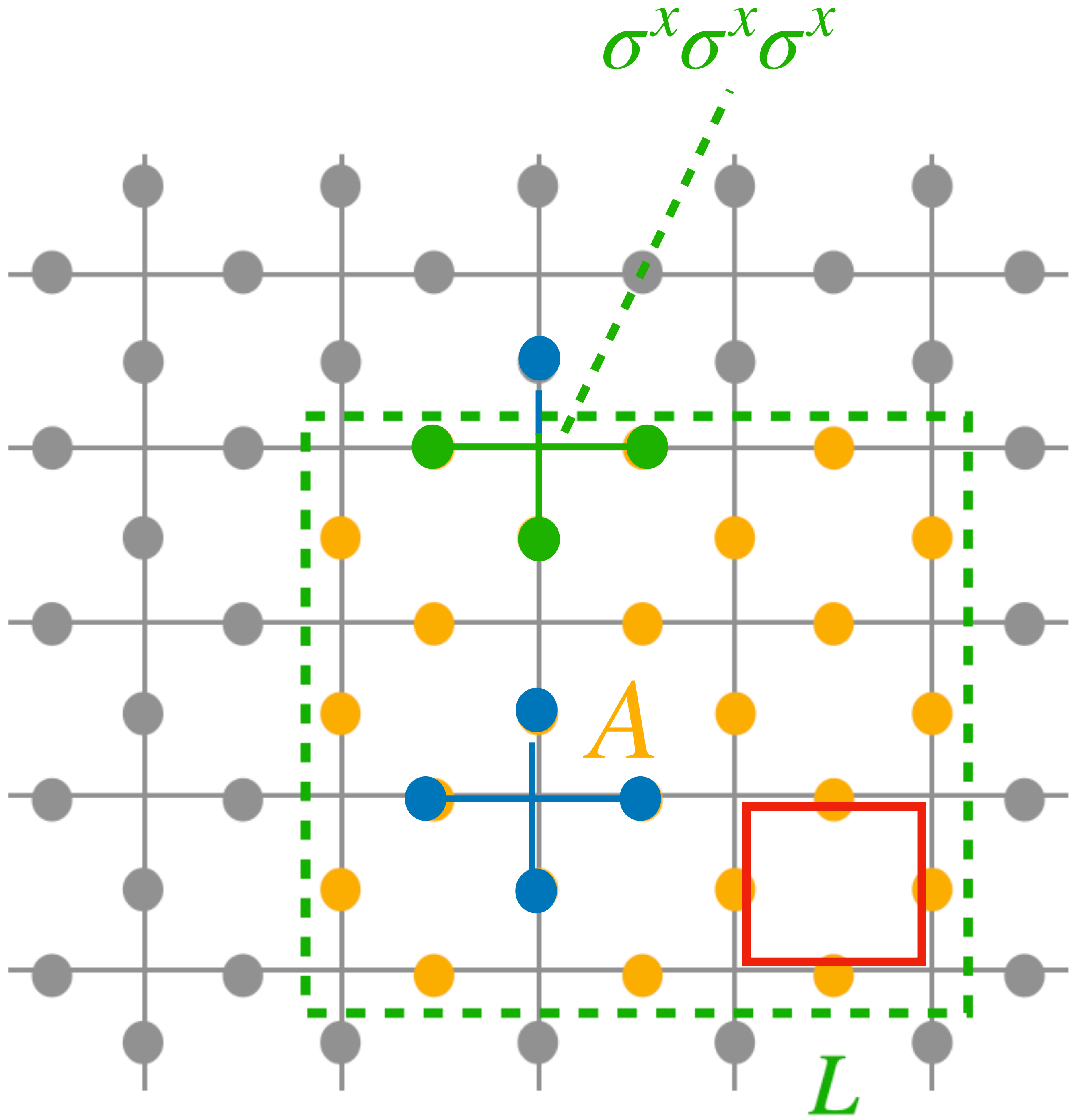


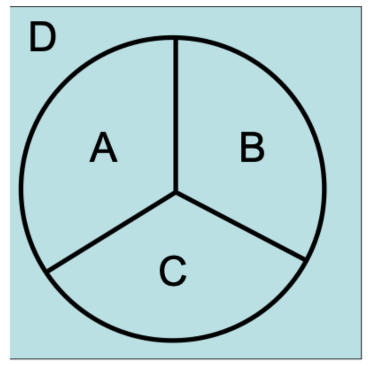
$$[\rho_A, \sigma^x\sigma^x\sigma^x] = 0$$

$$\rho_A = \begin{pmatrix} \square & \cdots & \\ \vdots & \square & \\ & \cdots & \ddots \end{pmatrix}$$

$$\propto \prod_{p\in\mathcal{A}} (1+B_p) \prod_{\nu\in\mathcal{A}} (1+A_\nu) \, \frac{\square}{2^{\#}}$$

Topological Entanglement Entropy

$$\prod_{\nu\in\partial A} A_\nu^\top = 1 \qquad \# = L-1$$



$$S = L\log(2) - \gamma$$

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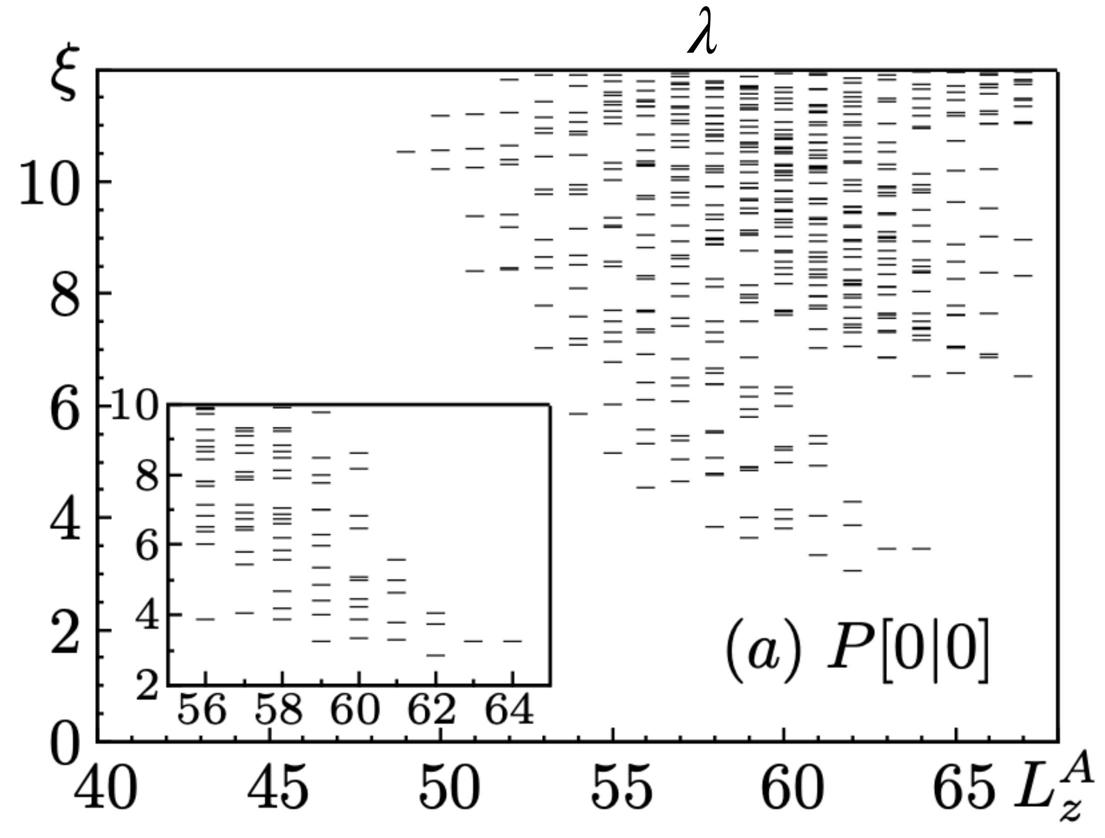
Kitaev, Preskill PRL 96 (2006) 110404
Levin, Wen PRL 96, 110405 (2006)

Entanglement Spectrum

$$\rho_A = \exp\{-H_A\} = \sum_\lambda e^{-\xi_\lambda} |\lambda\rangle\langle\lambda|$$



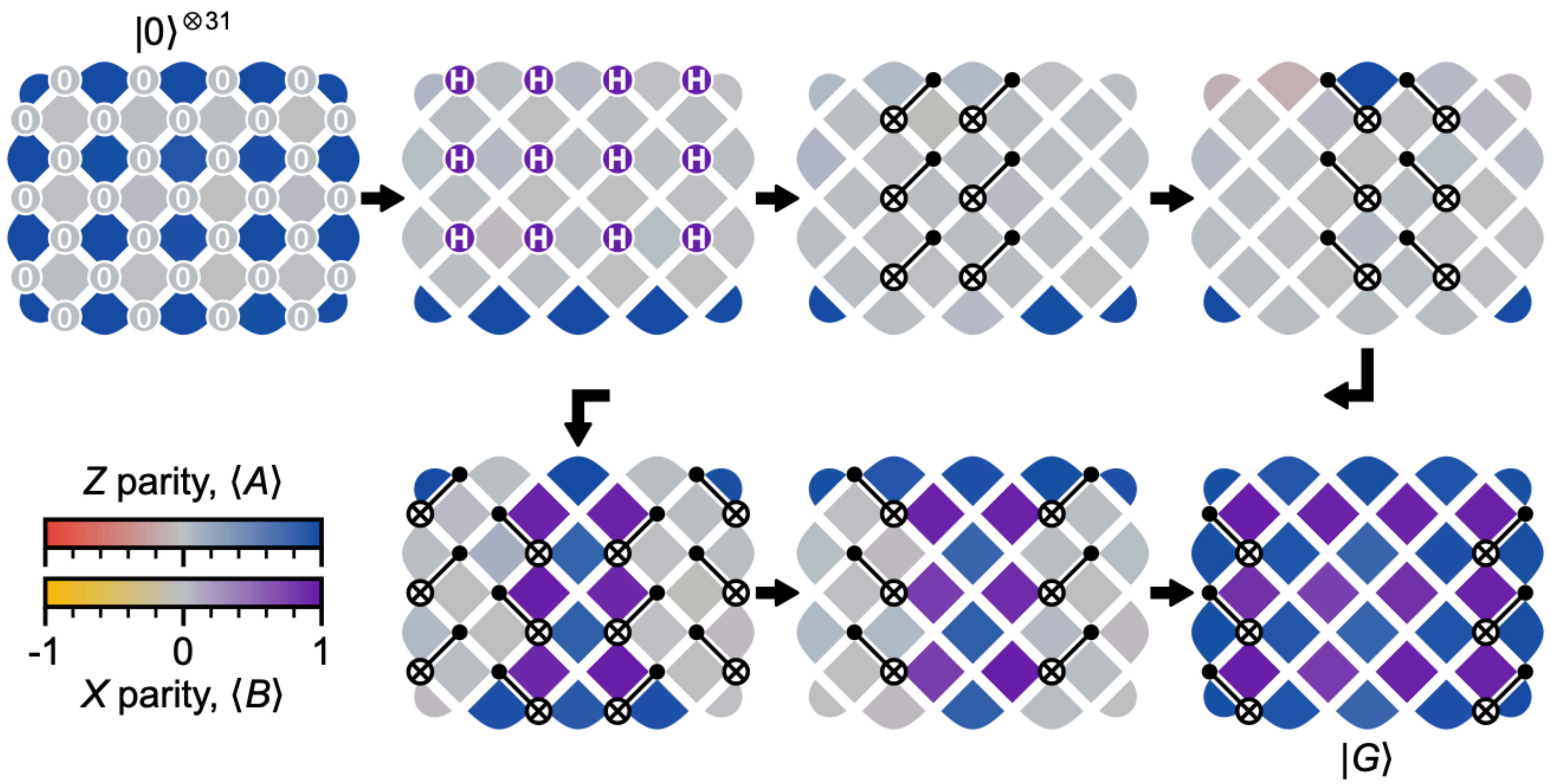
Li Haldane, PRL 101 01504 (2008)

Topological Order

Experimental realization

Topological Order

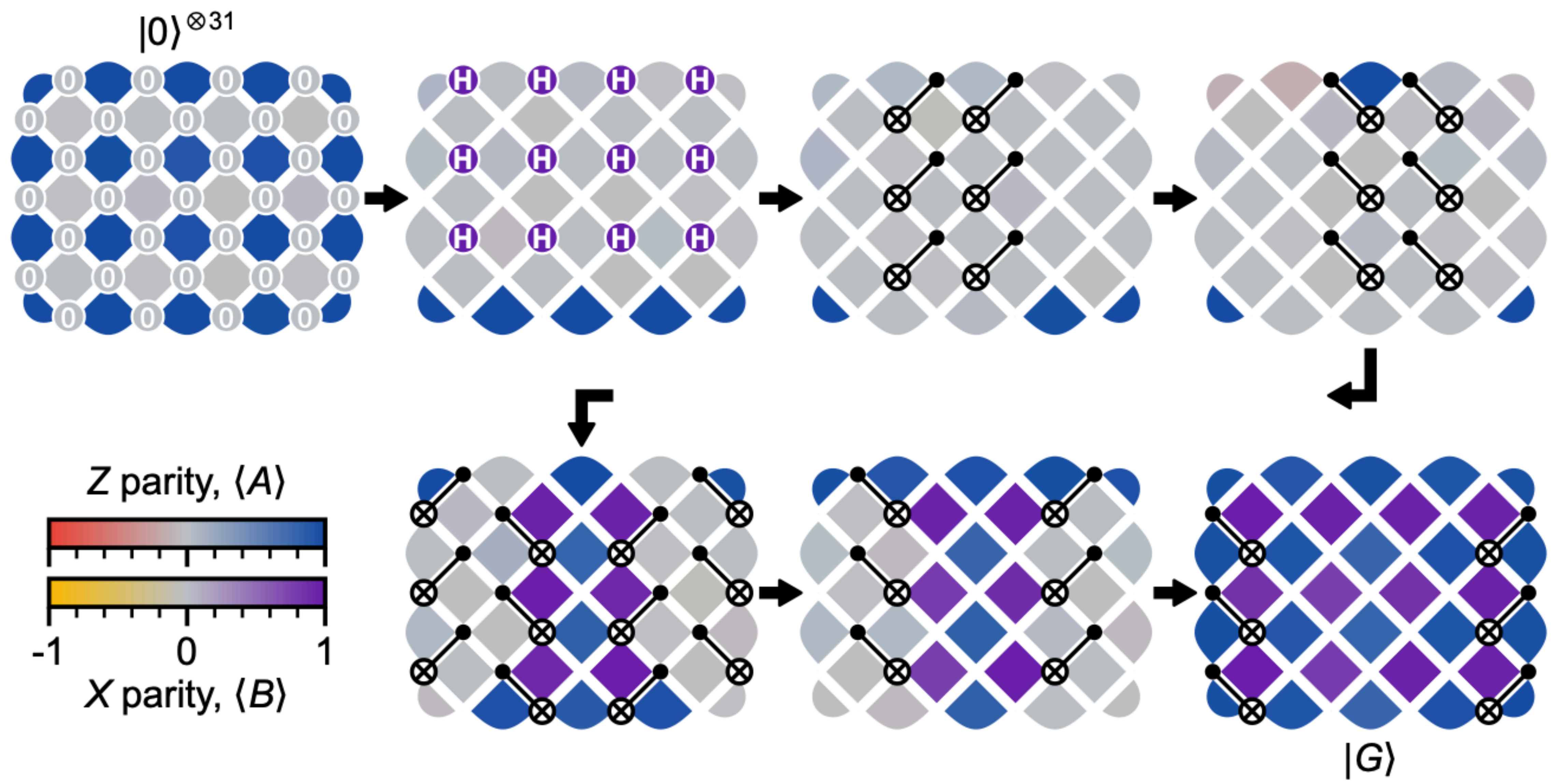
Experimental realization



Satzinger et al., Pollmann, Roushan Science 374, 123701241

Topological Order

Experimental realization



Satzinger et al., Pollmann, Roushan Science 374, 123701241

- **see also: Spin liquid states with Rydberg arrays**

  Semeghini et al Science 374, 1242

  chiral spin liquids with cold atoms

  Sun, Goldman, Aidelsburger, Bukov, PRX Quantum 4, 020329

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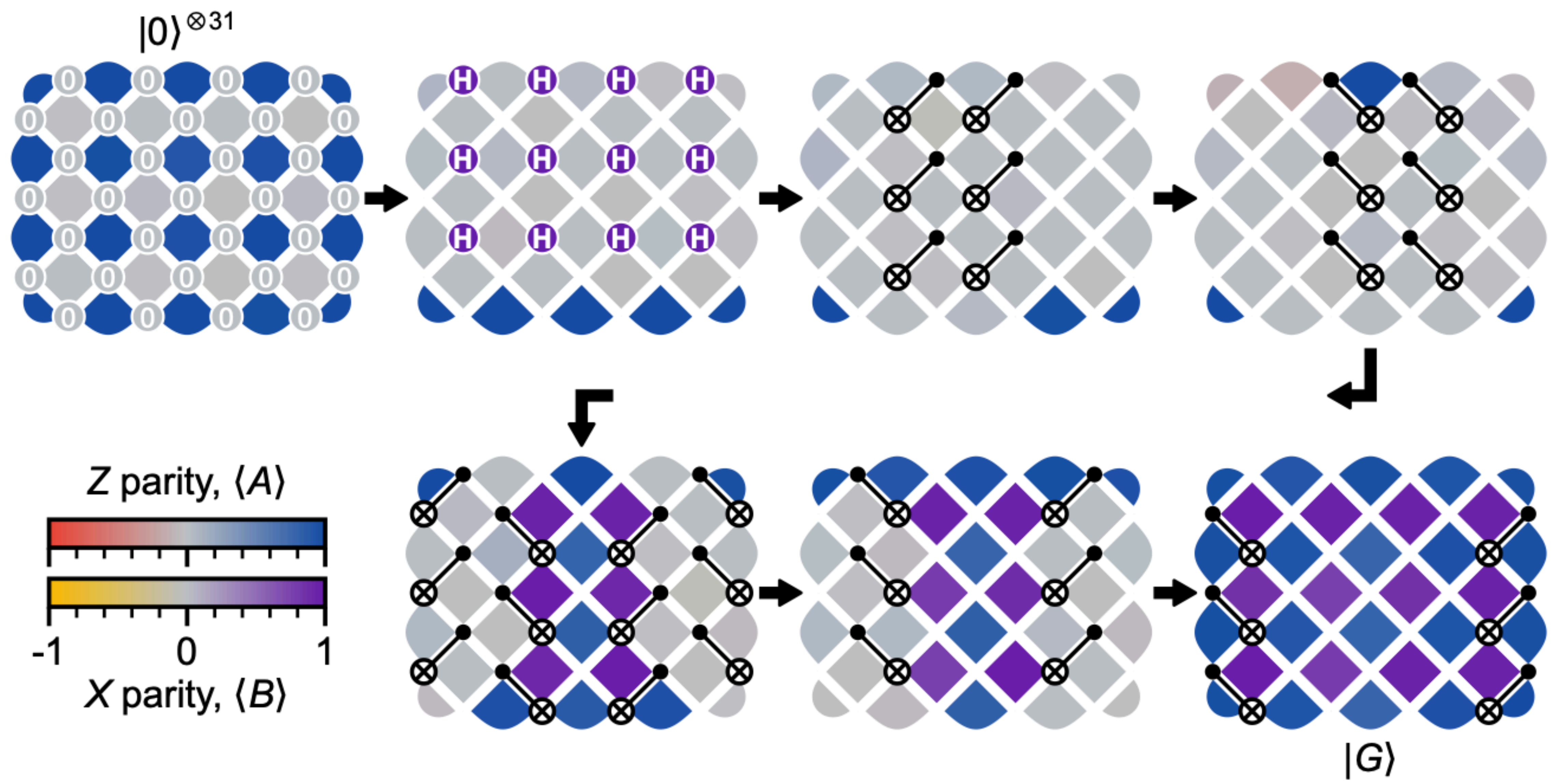

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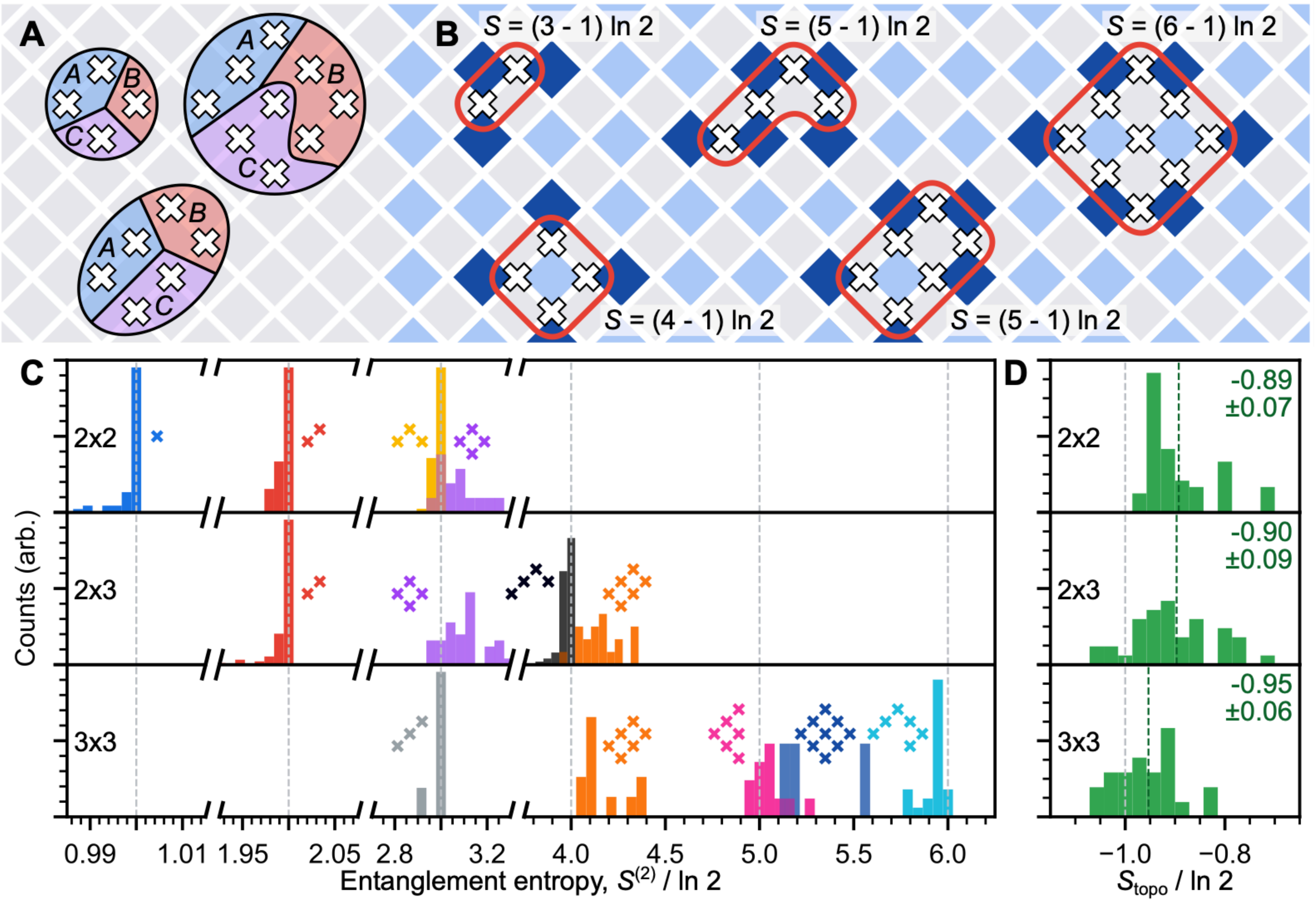

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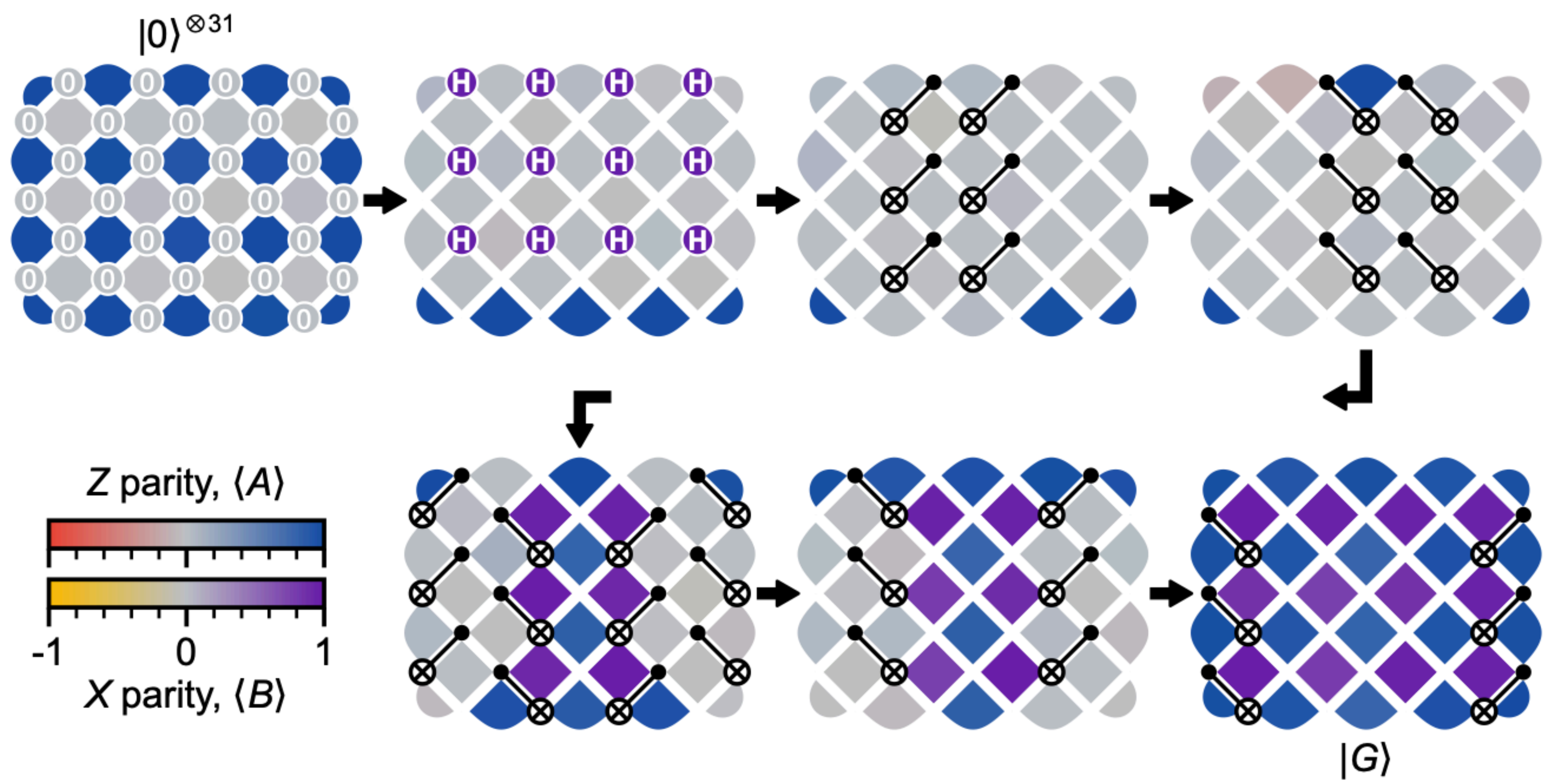

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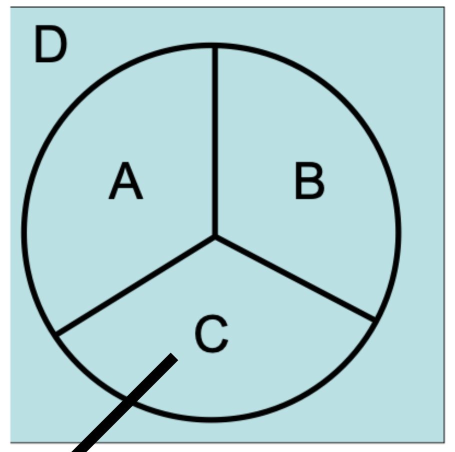

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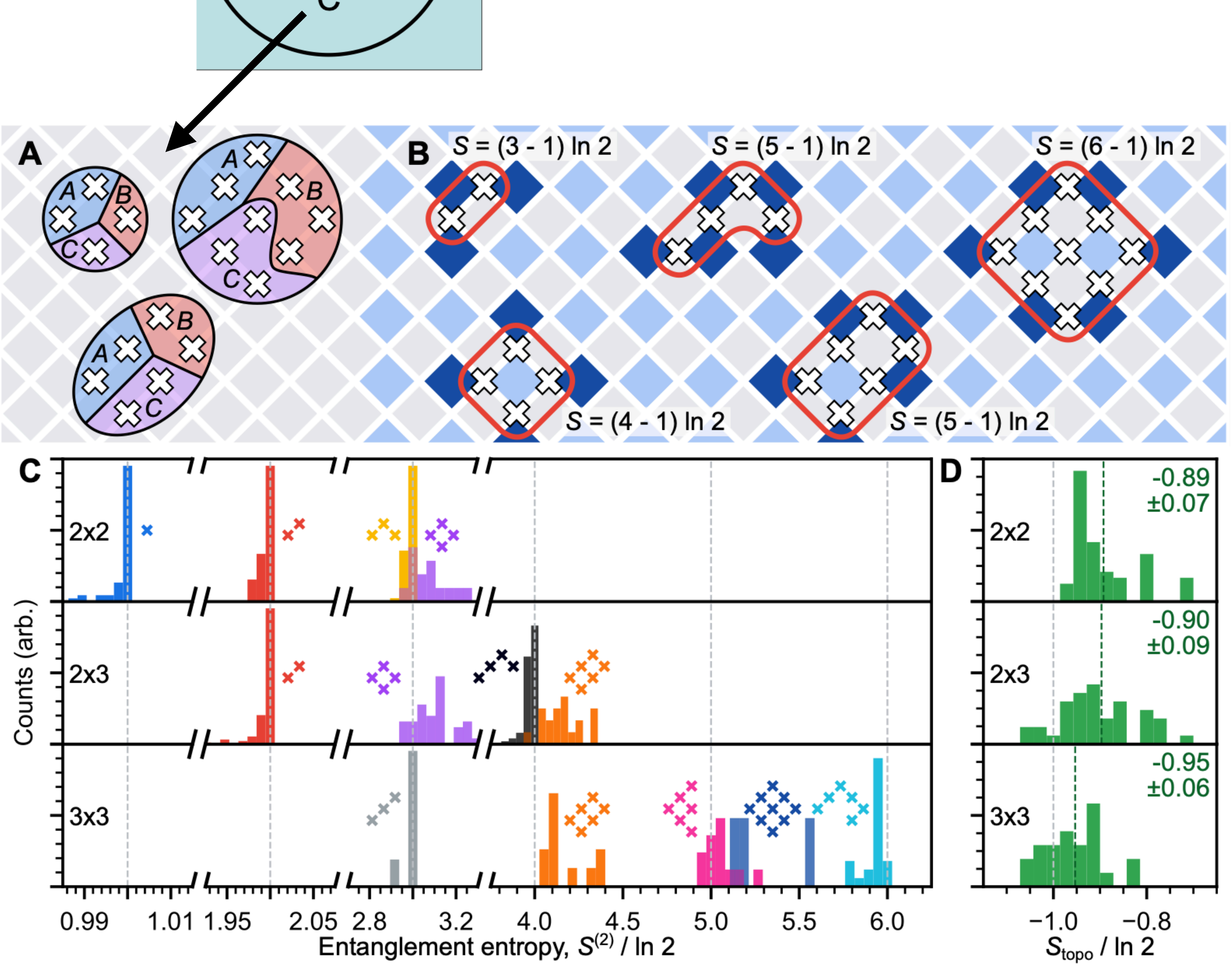

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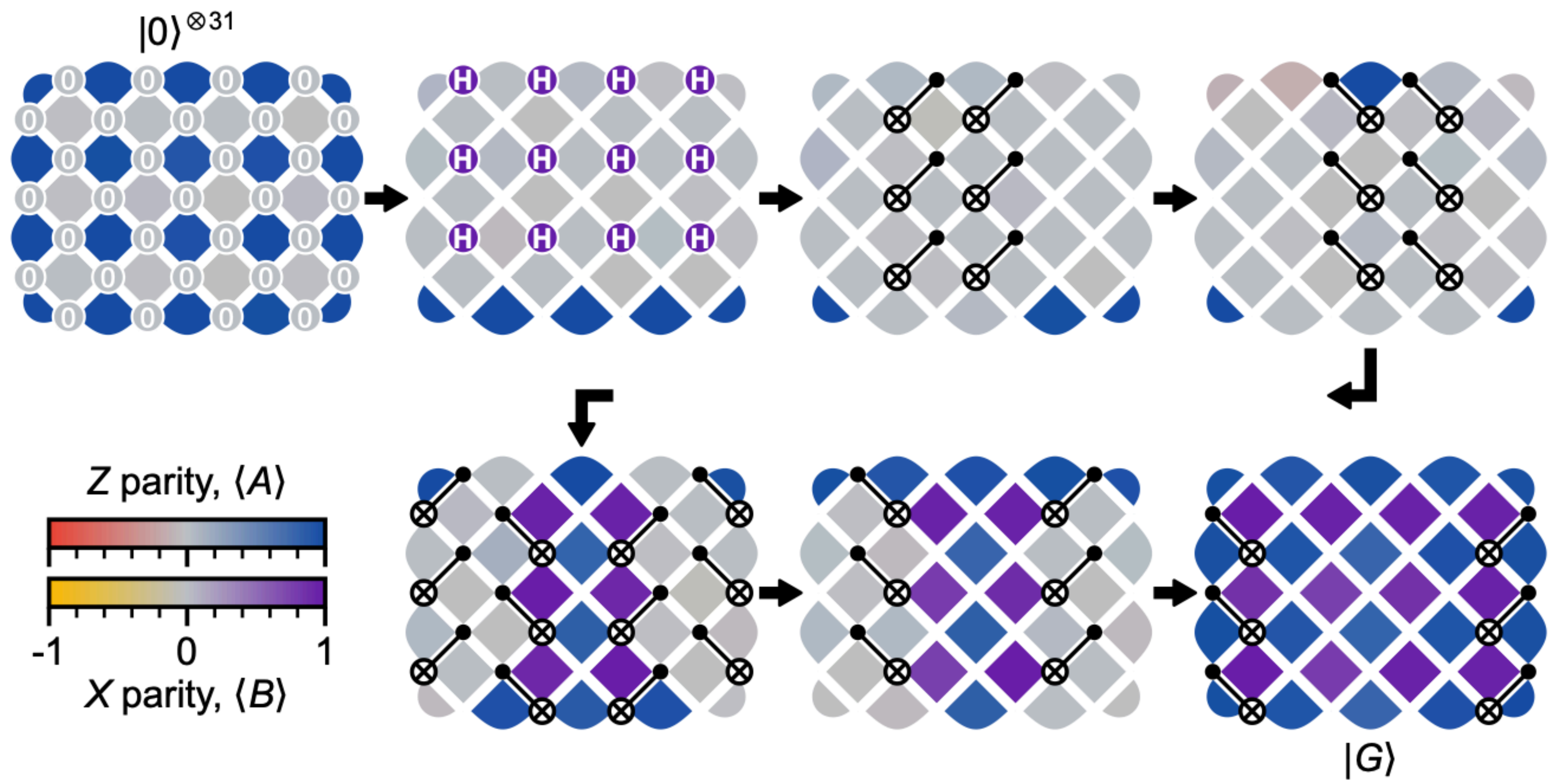

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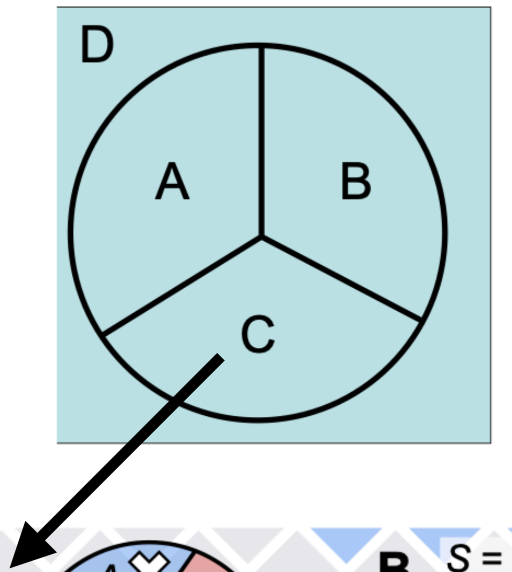

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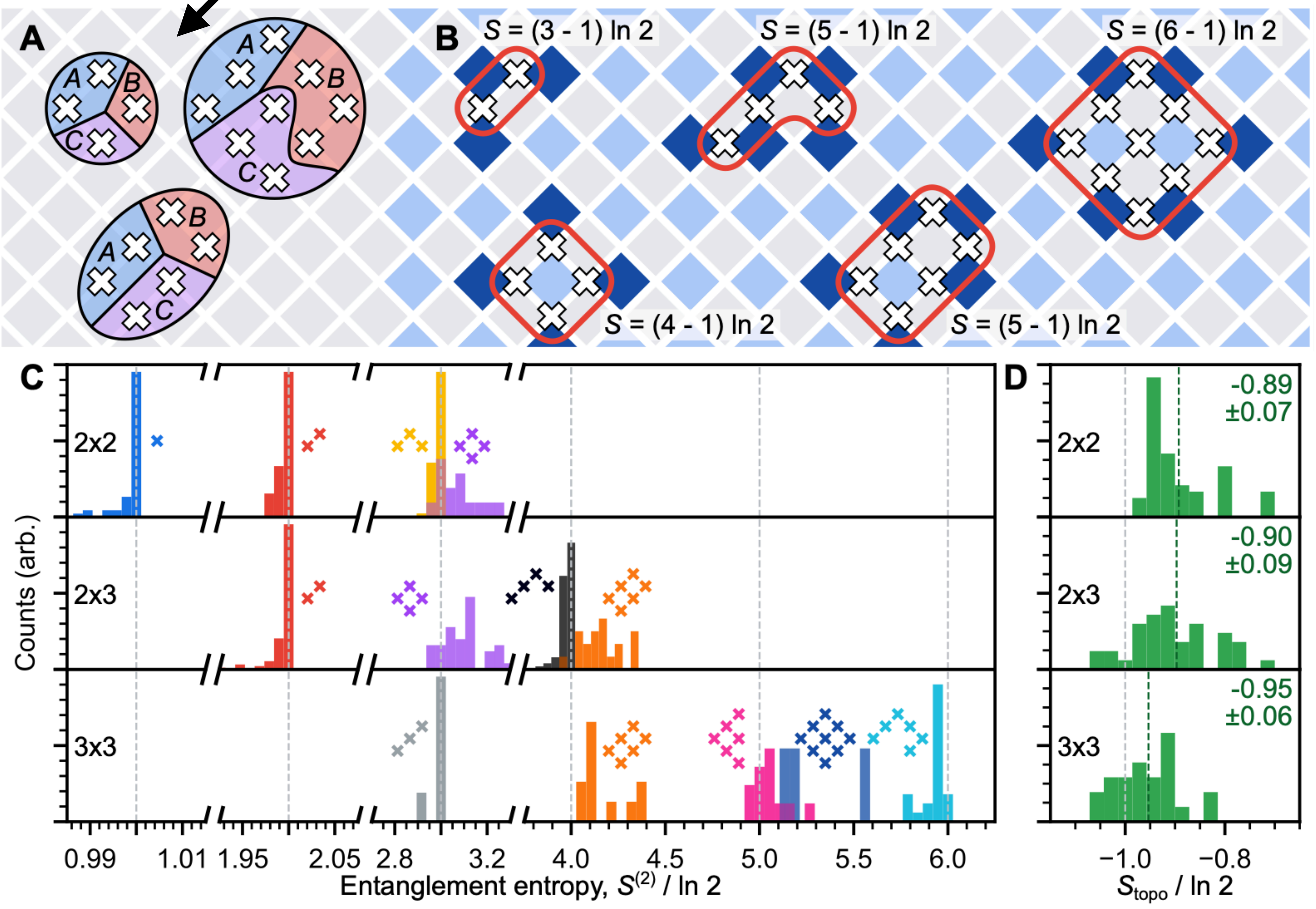
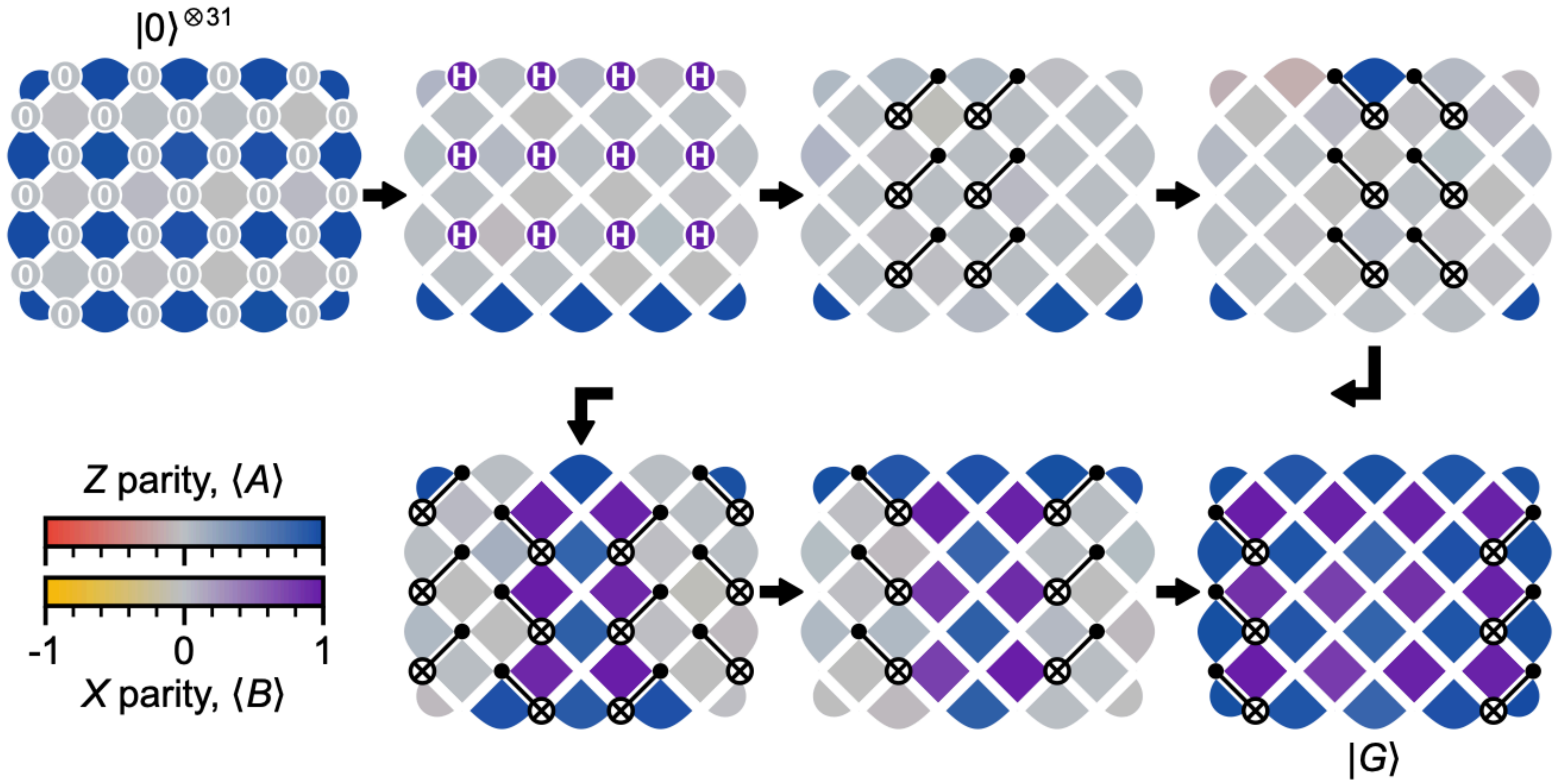


random measurement protocols

Brydges et al, Science 364, 260 (2019)

Topological Order

Experimental realization



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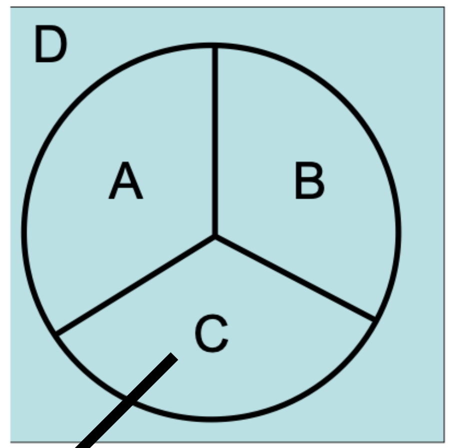

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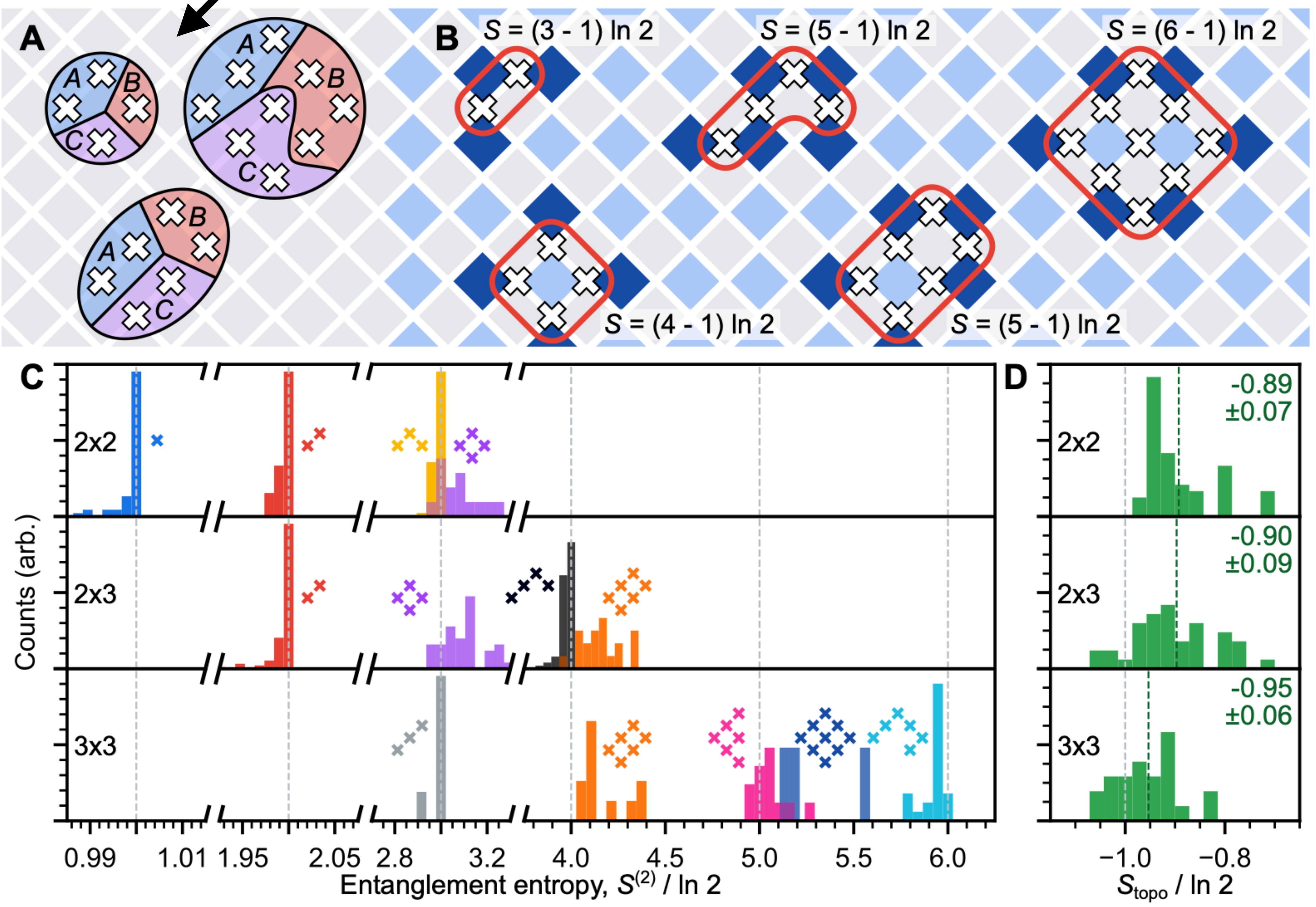

random measurement protocols

Brydges et al, Science 364, 260 (2019)

van Enk, Benenakker, PRL 108, 110503 (2012)
Dalmonte, Vermersch, Zoller, Nature Phys. 14, 827 (2018)
Elben, Vermersch, Dalmonte, Cirac, Zoller, PRL 120, 050406 (2018)
Brydges, Elben, Jurcevic, Vermersch, Maier, Lanyon, Zoller, Blatt, Roos, Science 364, 260
Huang, Kueng, Preskill, Nature Phys 16, 1050 (2020) (2019)
Elben et al, PRA 97, 023604 (2018)
Paini, Kalev arXiv1910.10543 (2019)
Elben, et al PRL 125 200501 (2020)
Zhou et al, PRL 125, 200502 (2020)
Huang, Kueng, Preskill, PRL 127, 030503 920210 (2021)
Kokaill, van Bijnen, Elben, Vermersch, Zoller, Nature Phys 17, 936 (2021)
Hu, Choi, You, arXiv:2107.04817
Zhao, Rubin, Miyake, PRL 110504 (2021)
Kokail et al, PRL 127, 170501 (2021), Rath et al, PRL 127 200503 (2021)
Kunjummen, Tran, Carney, Taylor, arXiv:2110.03629 (2021)
Levy, Luo Clark, arXiv.2110.02965 (2021)
Helsen et al, arXiv.2110.13178 (2021)
Huang et al.,, Science 376, 1182 (2021)
Low, arXiv.2208.08964
Huang, Nat. Rev, Phys. 4, (2022)

Random Measurement: Entanglement

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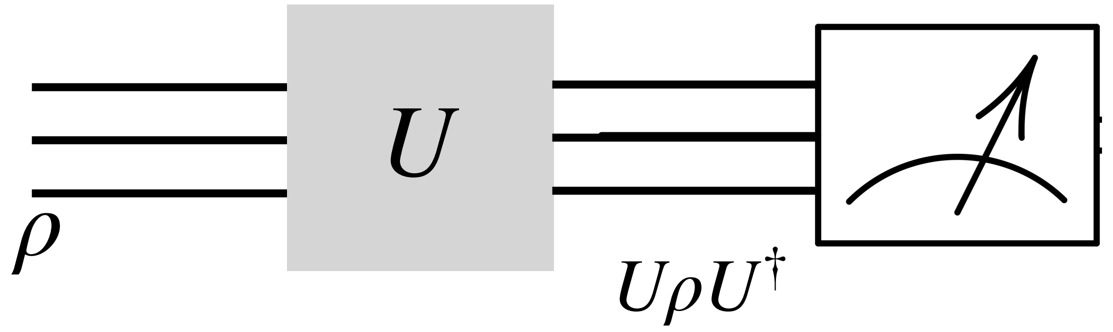
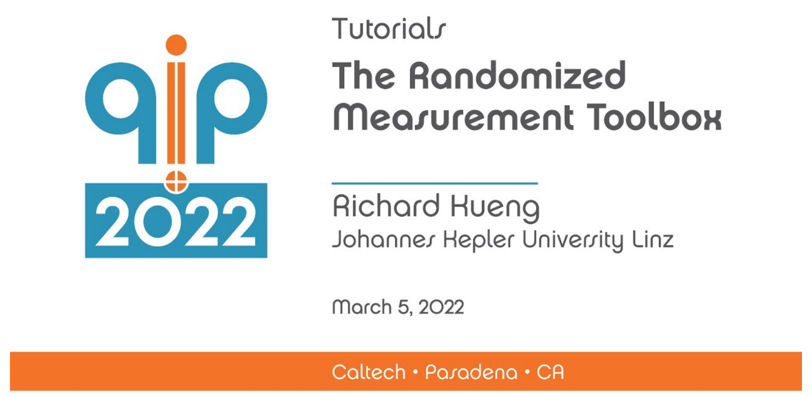
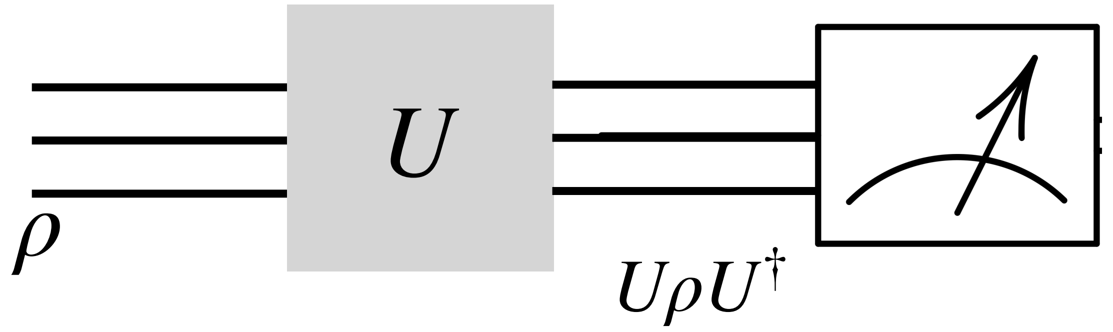


Random Measurement: Entanglement

good intro: Richard Küng
https://youtube.com/watch?v=FXdJoJ0qcZY





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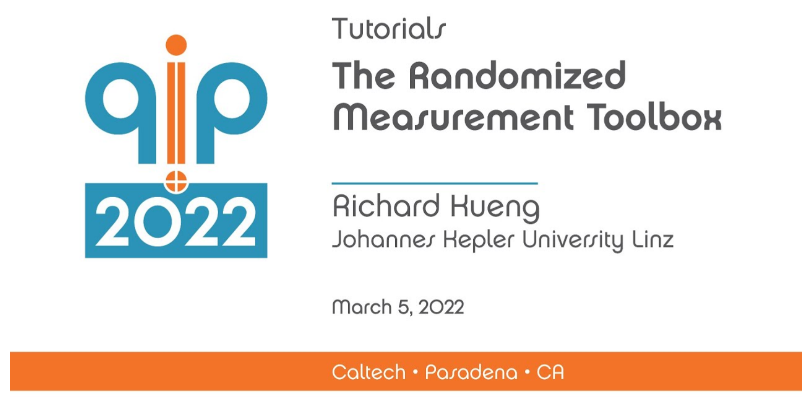

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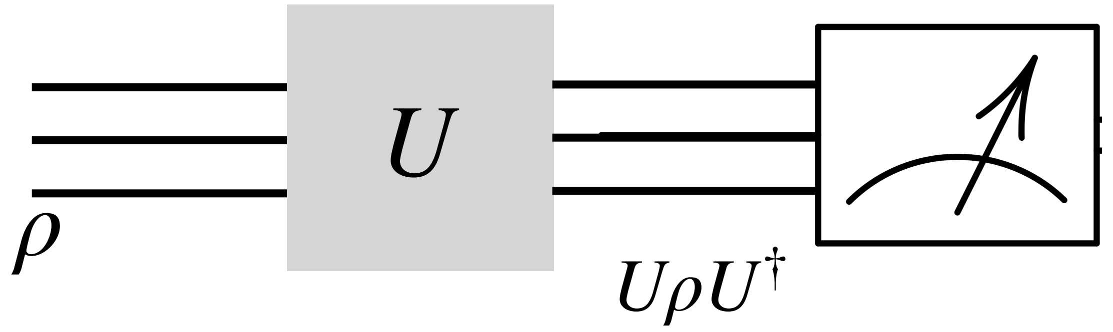
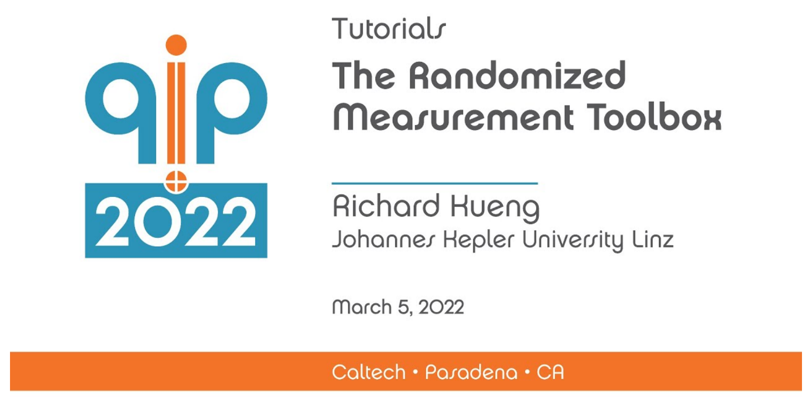


VQE type algorithms
device verification
predict many observables from few measurements

Random Measurement: Entanglement



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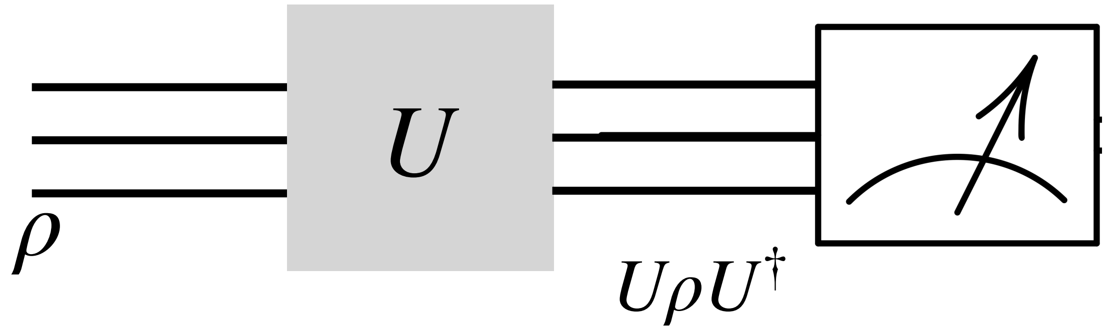

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Entanglement Tomography: "k-designs give k-entropies"

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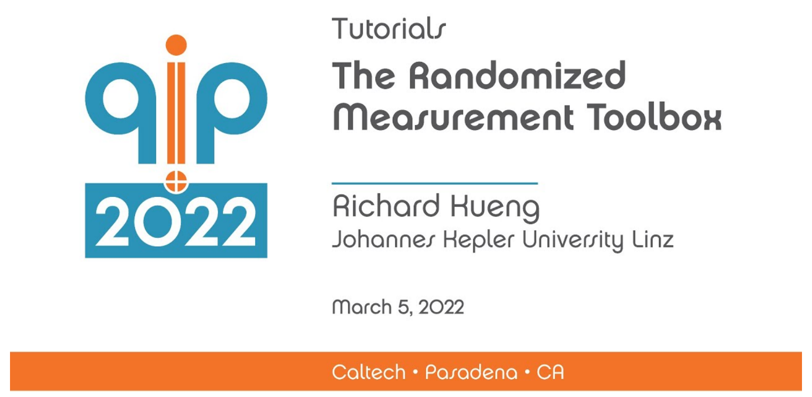

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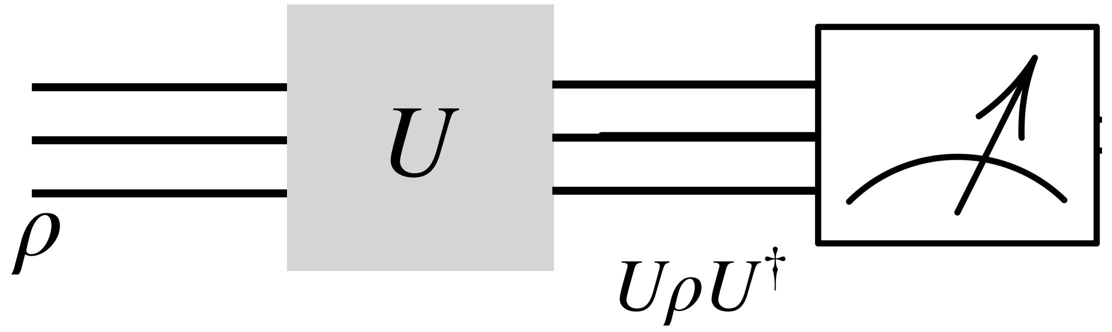

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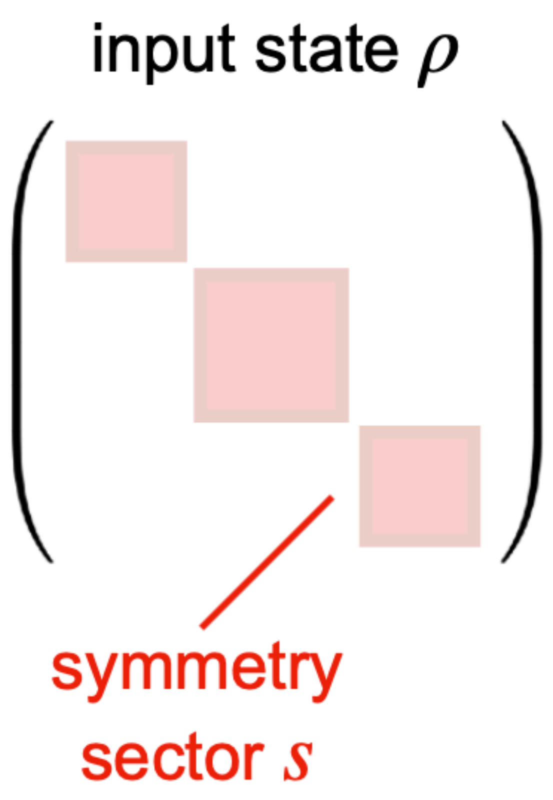
Symmetry ignorant versus conscious



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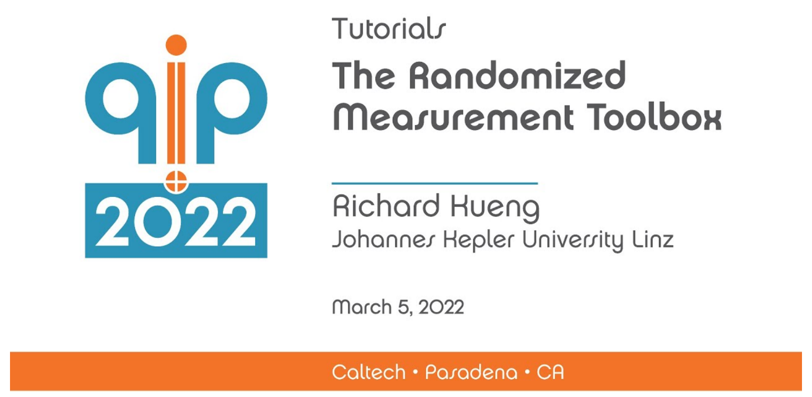

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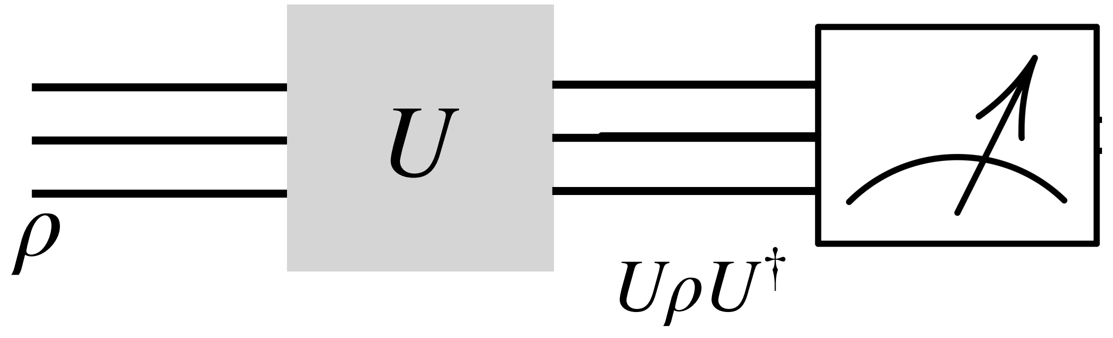

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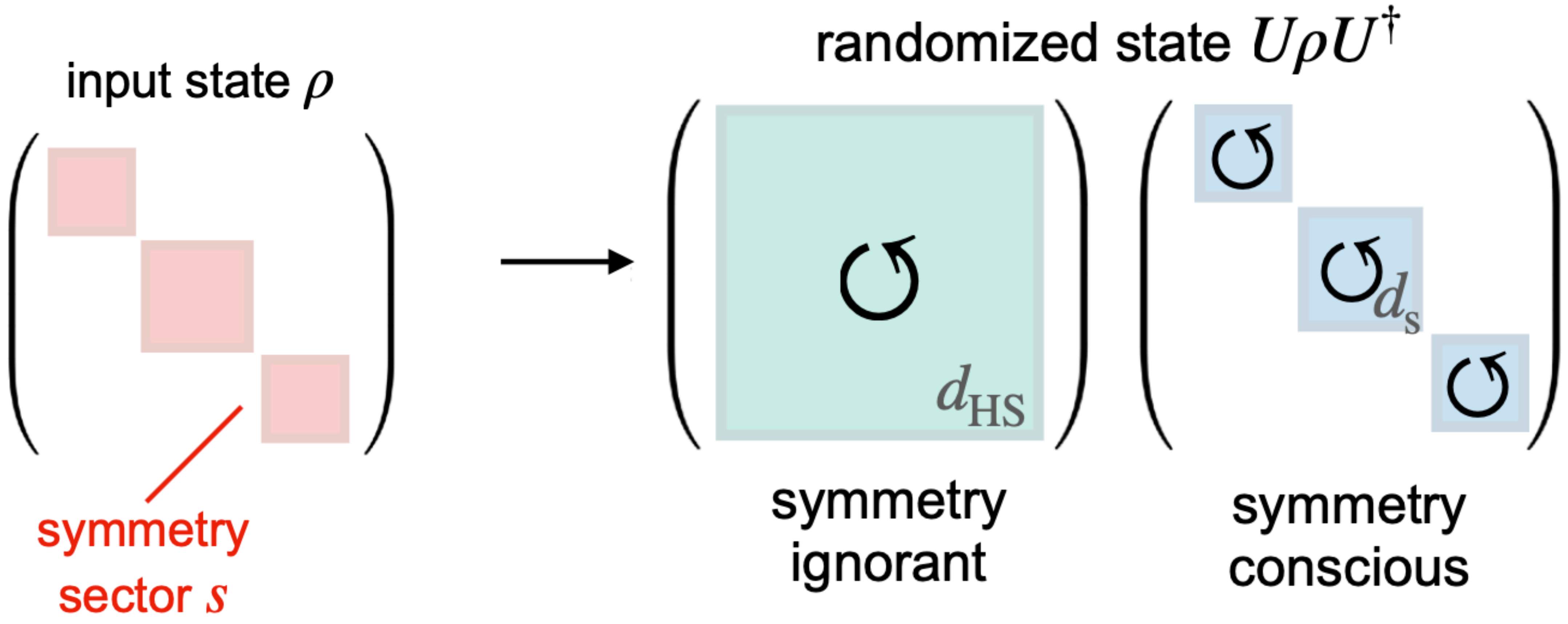

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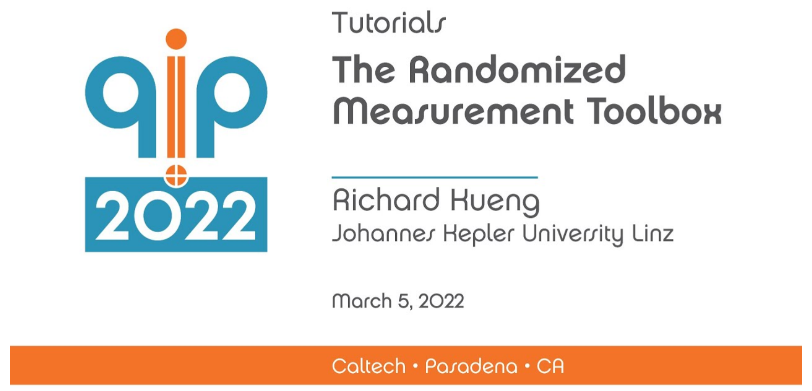

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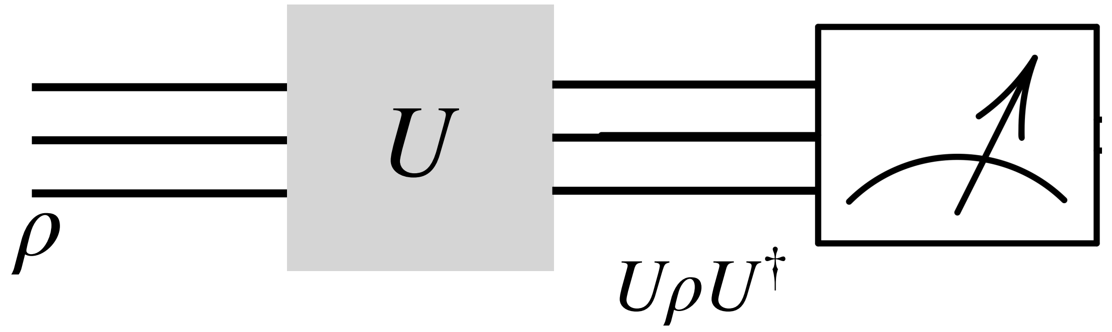

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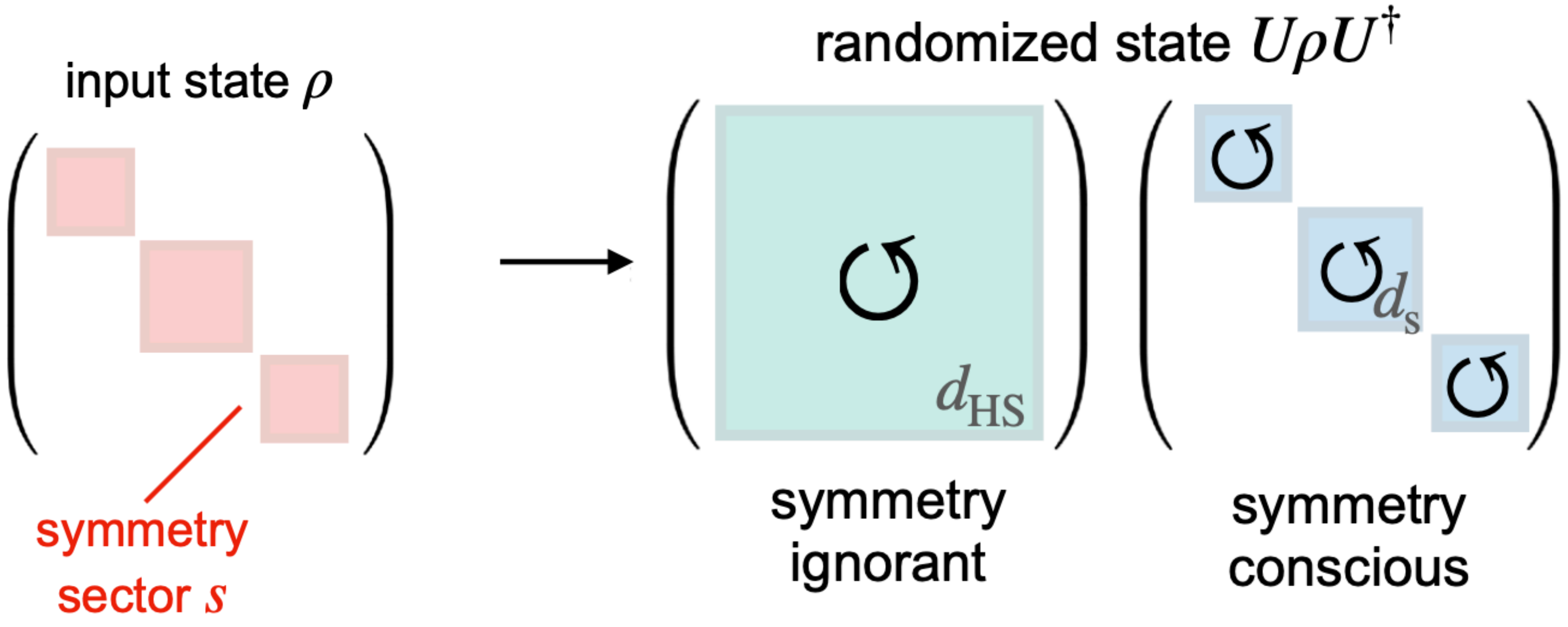

$ cost reduction

ϵ symmetry-based error mitigation

entanglement structure

Random Measurement: Entanglement

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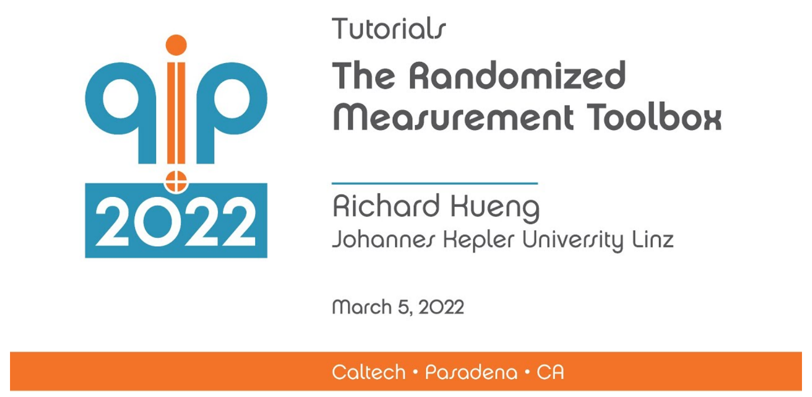

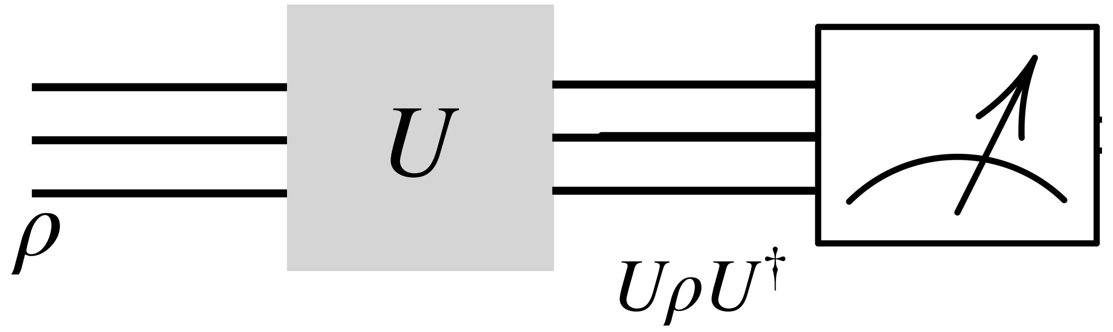

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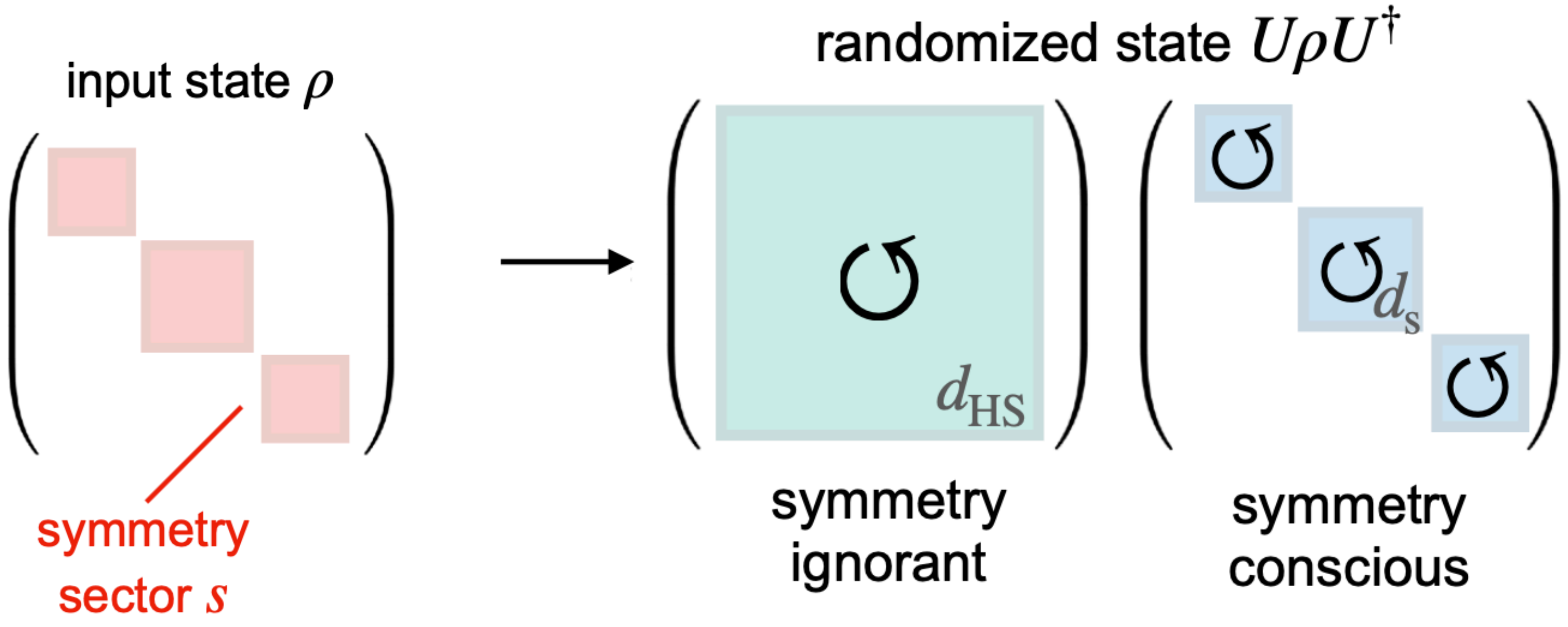
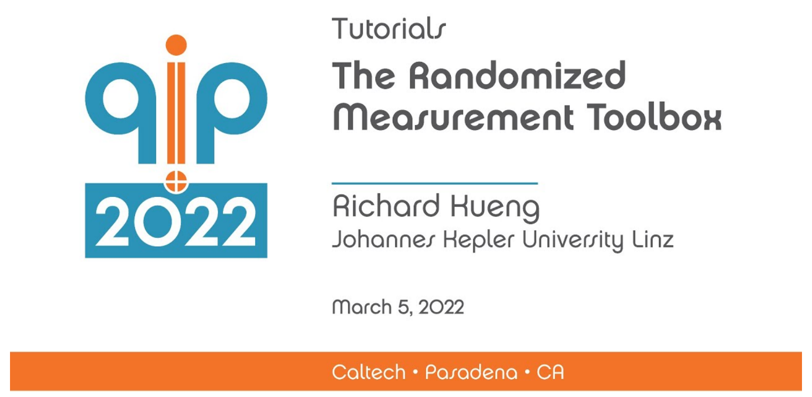


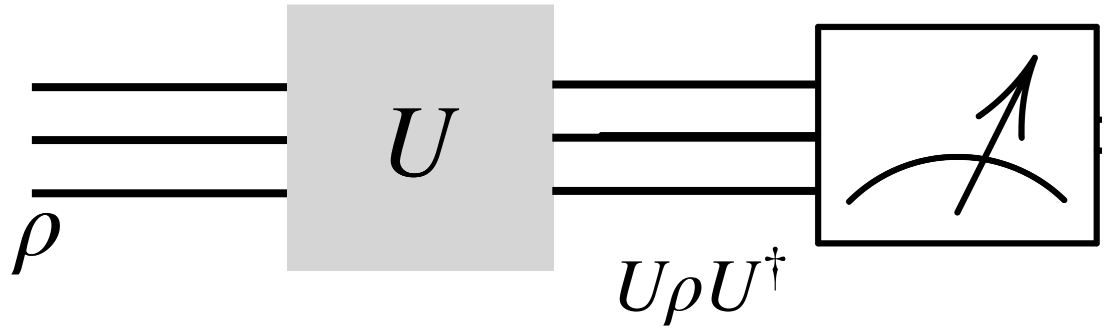
- \$ cost reduction
- ϵ symmetry-based error mitigation
- entanglement structure

d_s vs. d_{HS} (Z2: $2^V/2^{2V} = 2^{-V}$)

Random Measurement: Entanglement



good intro: Richard Küng
https://youtube.com/watch?v=FXdJoJ0qcZY



VQE type algorithms
device verification
predict many observables from few measurements
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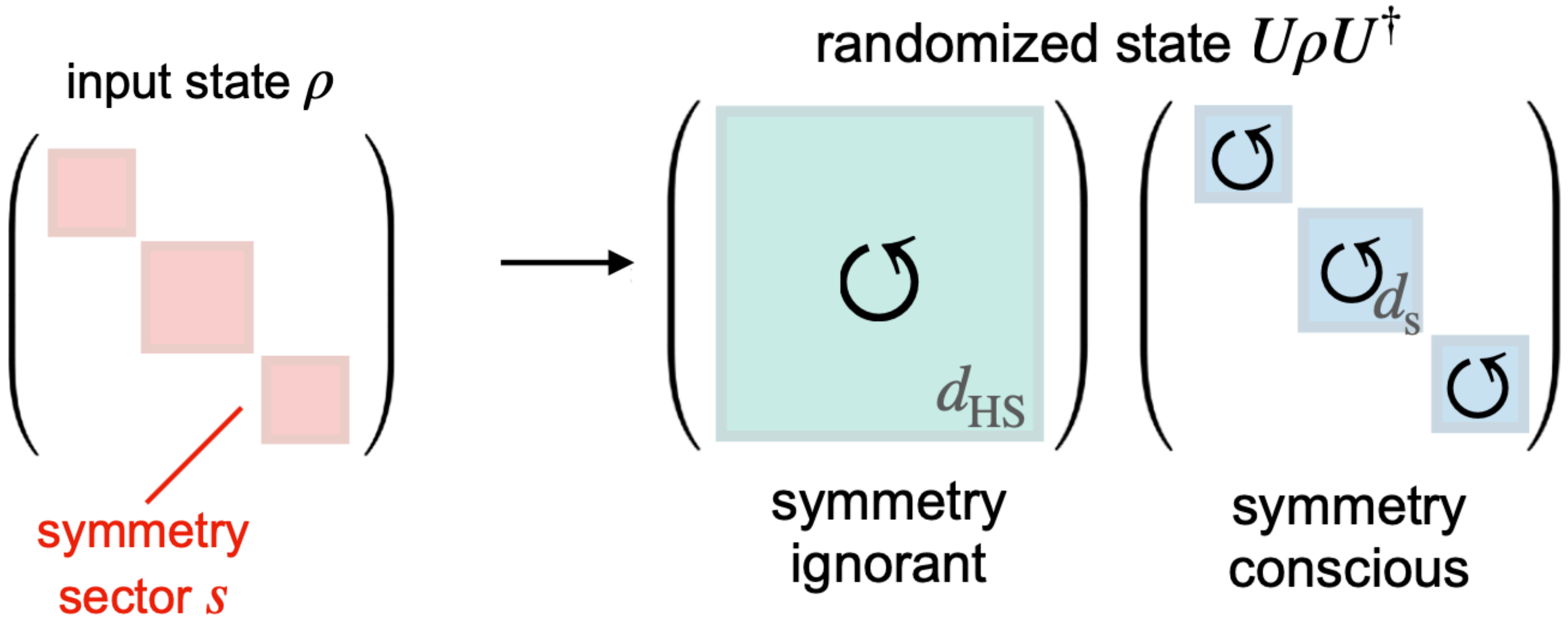

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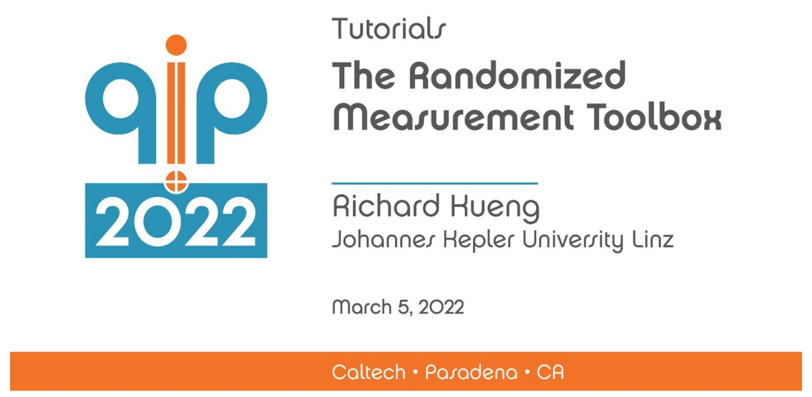
Nuguyen et al. Davoudi, Linke
PRX Quantum 3, 023024 (2022)

Random Measurement: Entanglement



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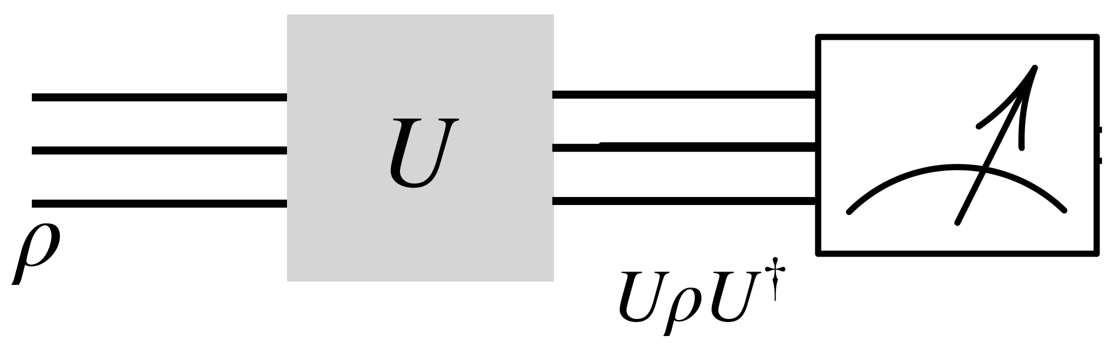

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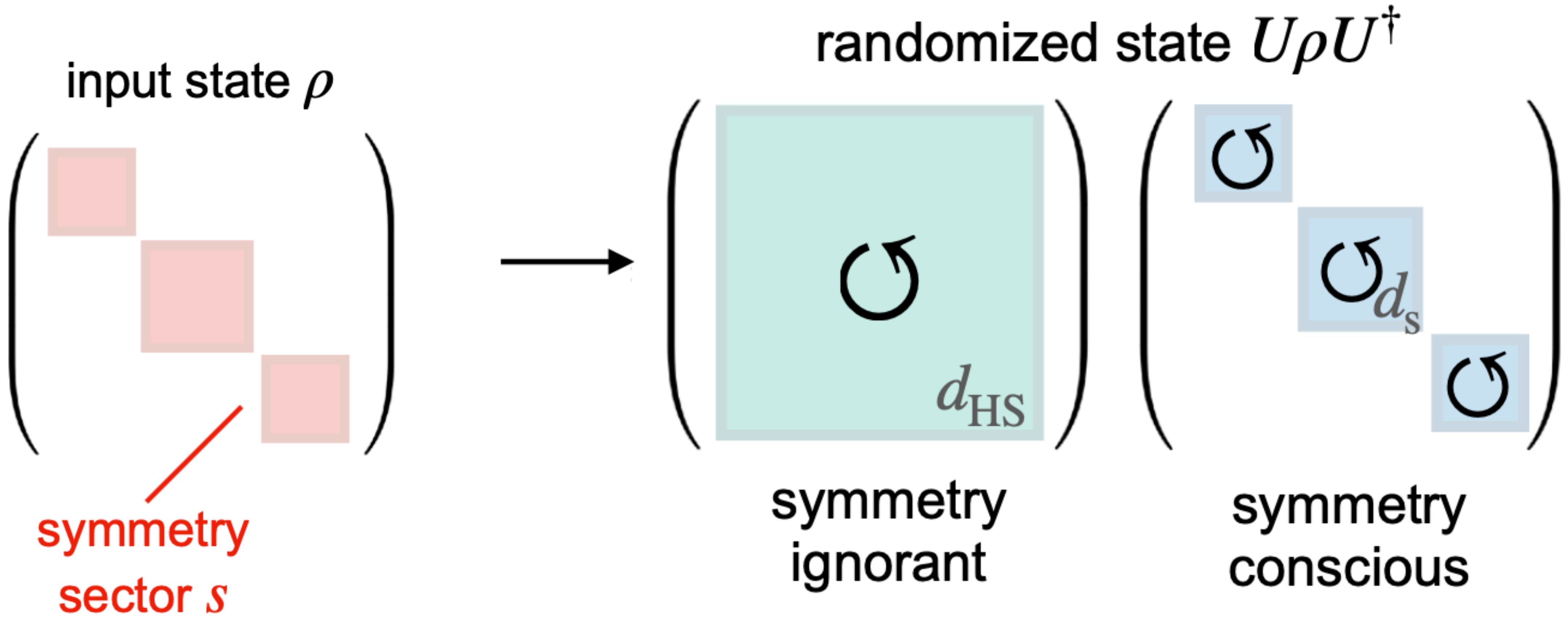

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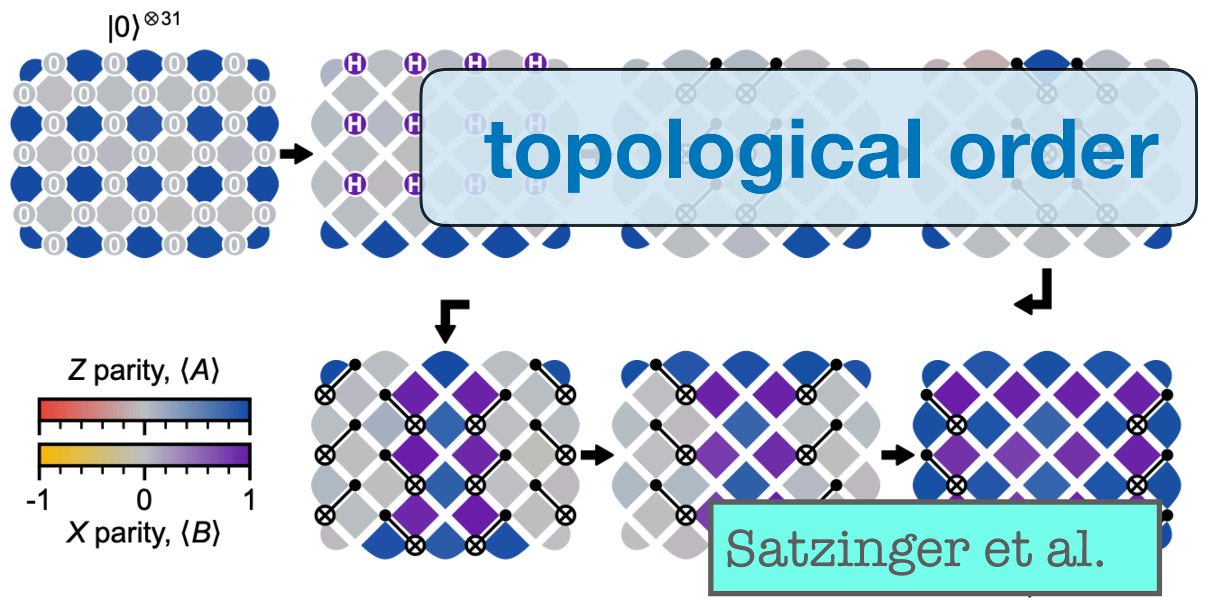
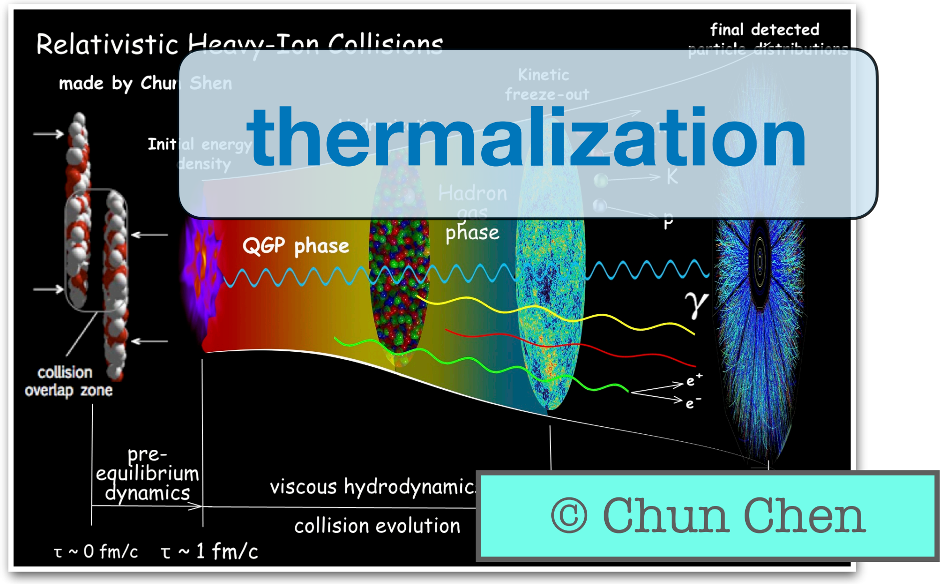
ϵ symmetry-based error mitigation — Nuguyen et al. Davoudi, Linke PRX Quantum 3, 023024 (2022)

entanglement structure — this talk!





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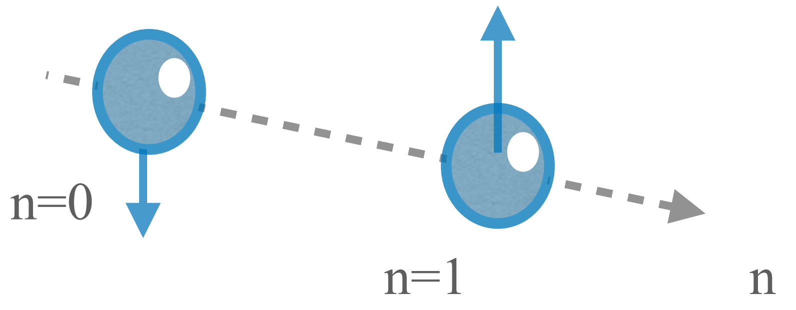

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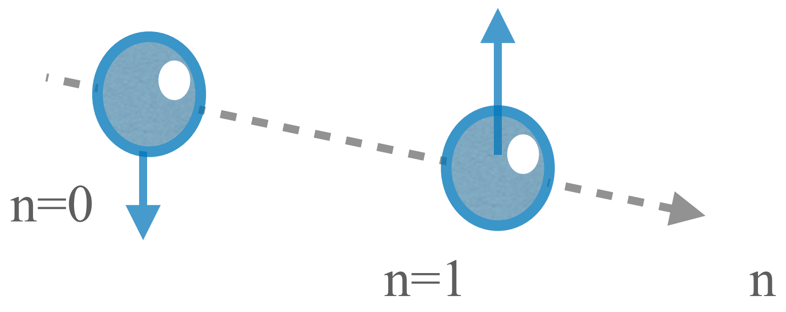

$$\rho = \begin{pmatrix} \rho_2 & & \\ & [\rho_1] & \\ & & \rho_0 \end{pmatrix}$$

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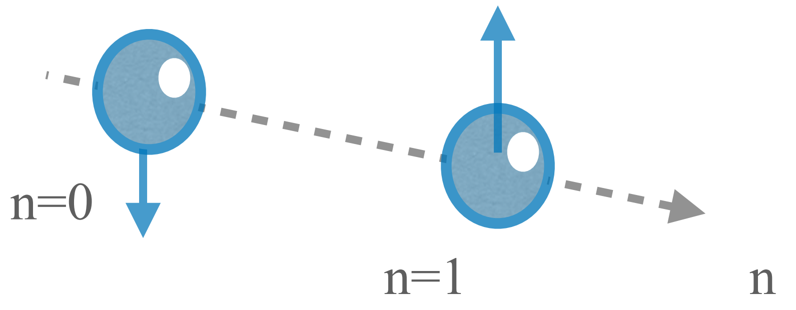

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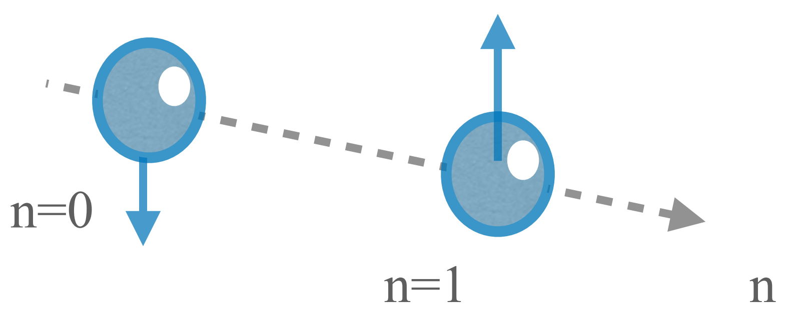

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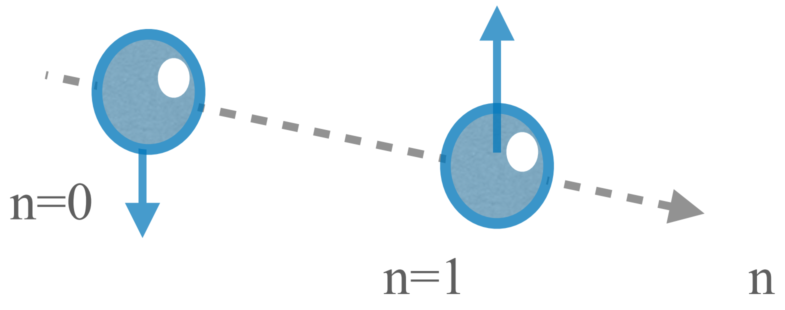

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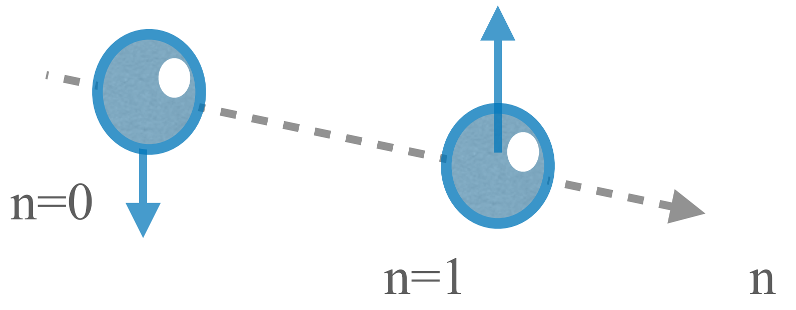

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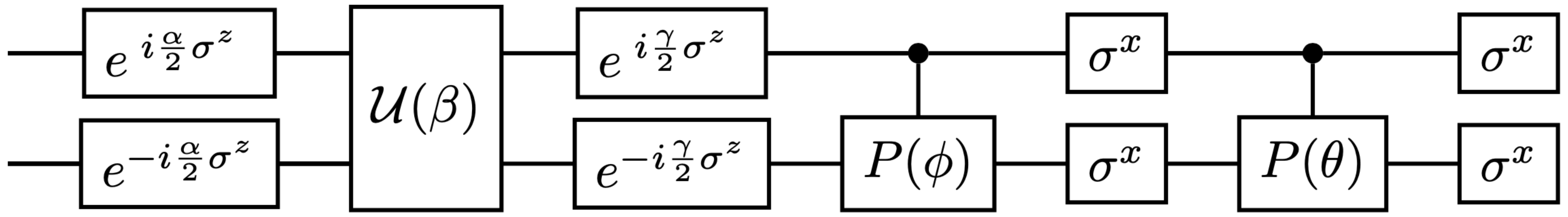

$$\mathcal{U}_{j_1,j_2}(\beta) \equiv \exp\{i\tfrac{\beta}{2}(\sigma^y_{j_1}\sigma^x_{j_2} - \sigma^x_{j_1}\sigma^y_{j_2})\}$$

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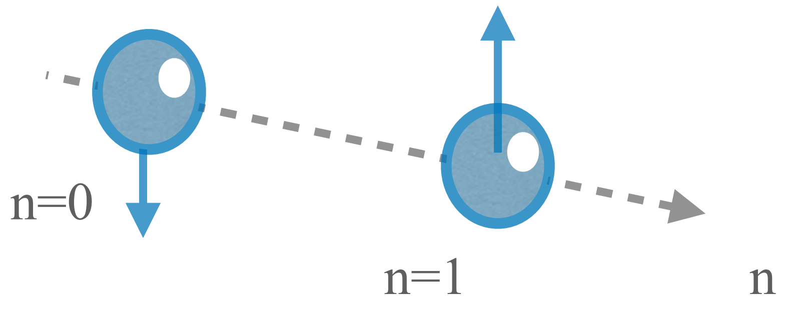

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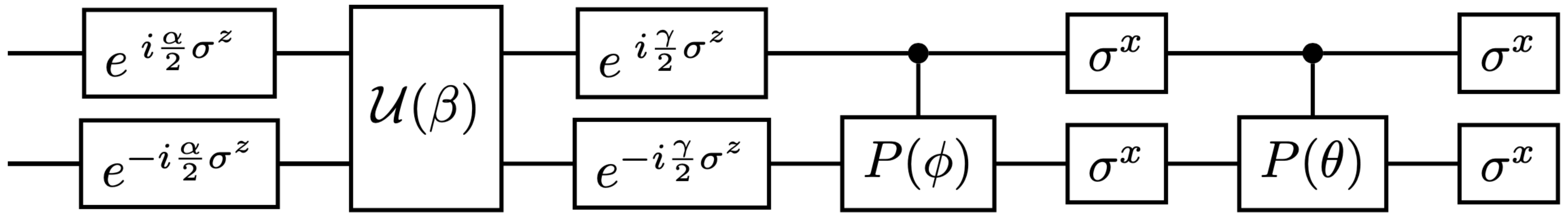

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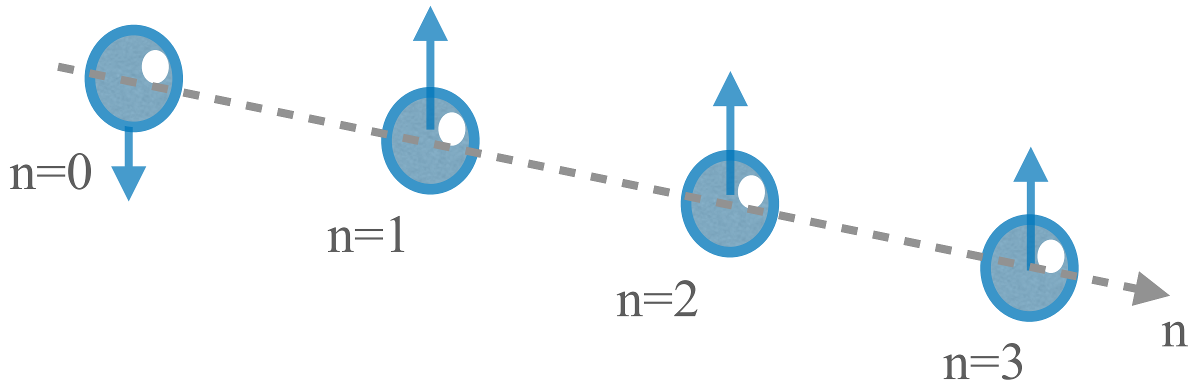

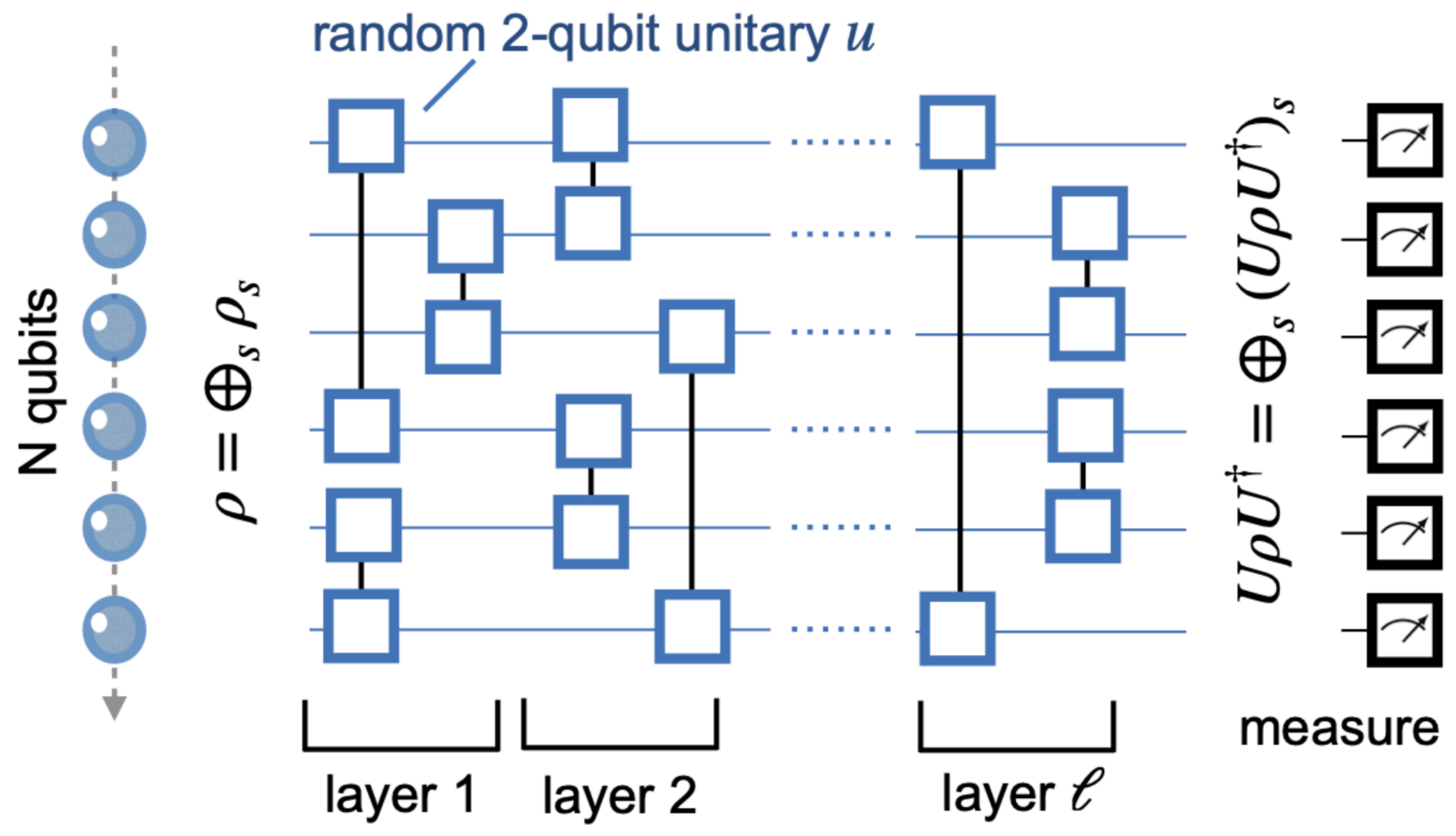

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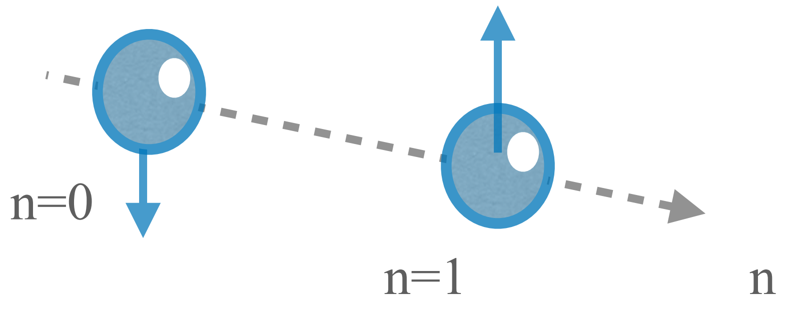

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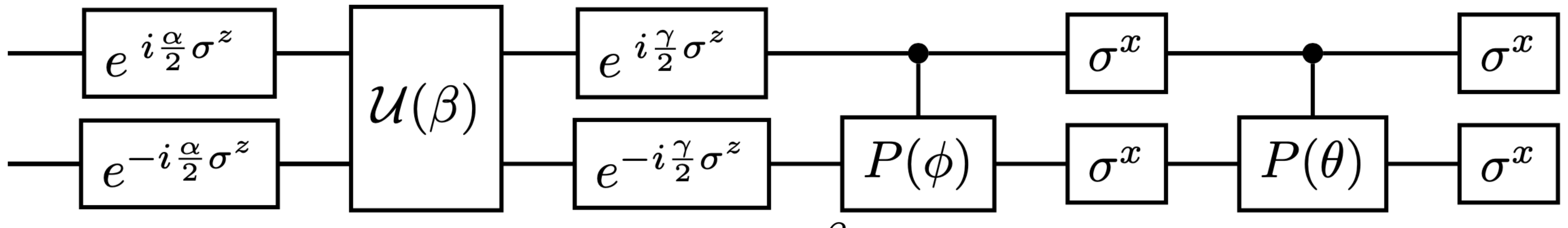

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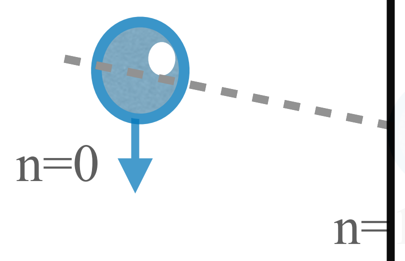

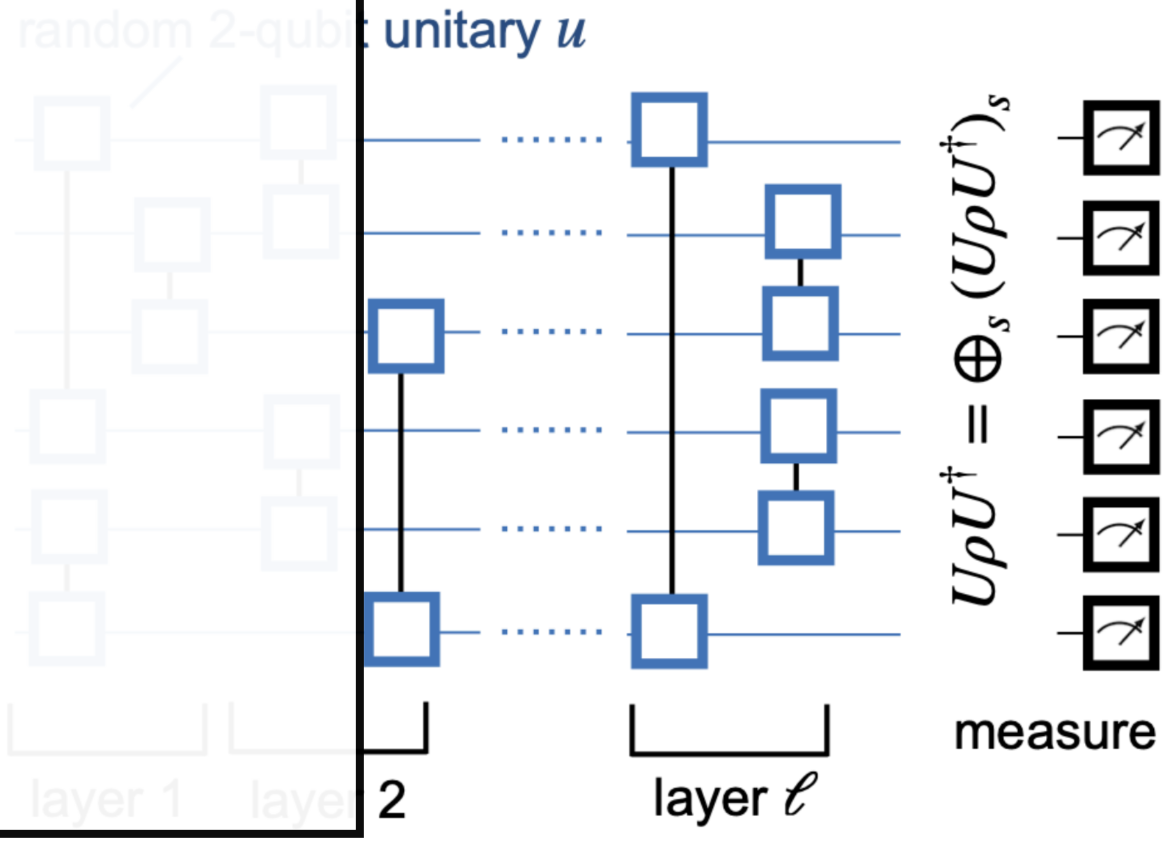

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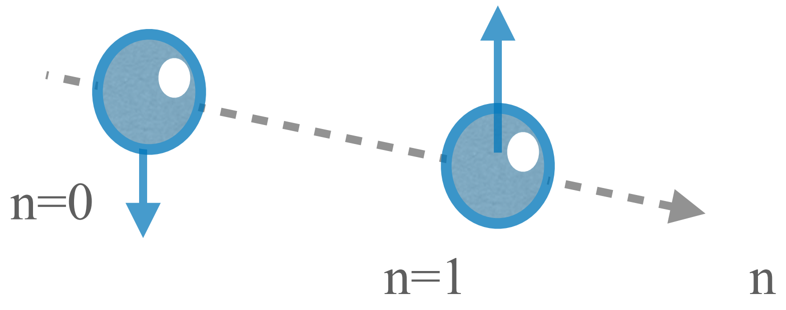

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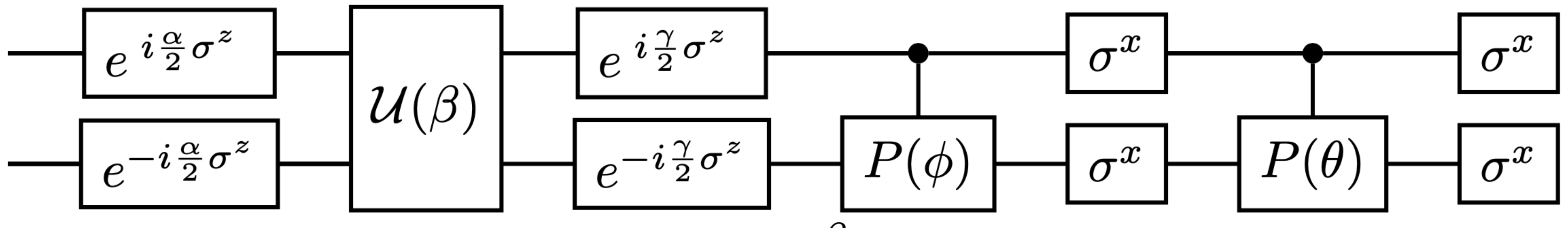

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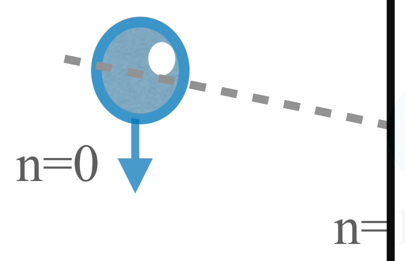
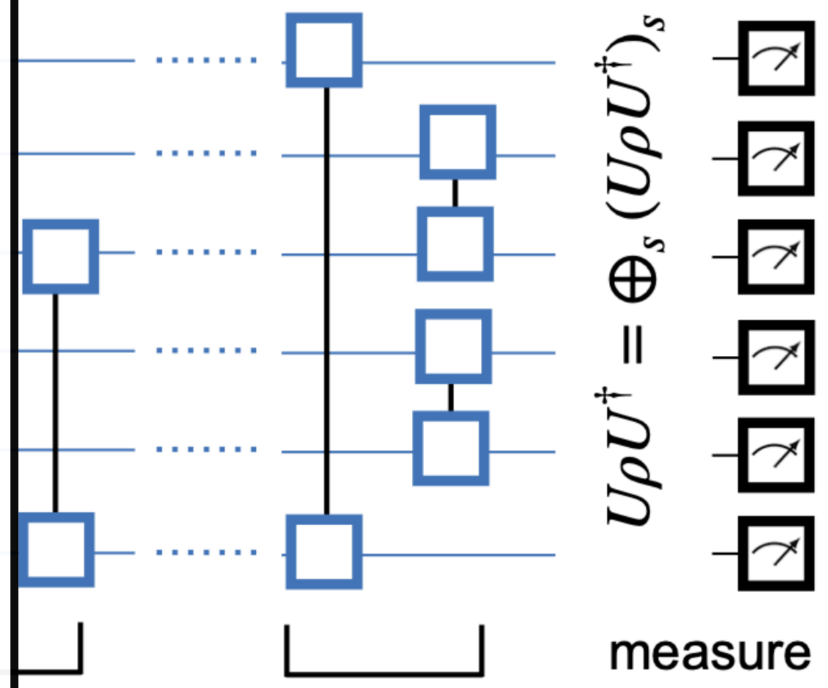
$$-\frac{d_s^2}{d_s^2-1}\left[(\mathcal{A}^s)^{i'j'}_{ij}(\mathcal{A}^s)^{k'l'}_{kl} + (\mathcal{A}^s)^{k'l'}_{ij}(\mathcal{A}^s)^{i'j'}_{kl}\right]$$

$$(\mathcal{B}^s)^{i'j'k'l'}_{ijkl} = -\frac{\delta_{ii'}\delta_{kk'}\delta_{jl'}\delta_{lj'} + \delta_{ik'}\delta_{ki'}\delta_{jj'}\delta_{ll'}}{d_s(d_s^2-1)}$$





Elben, Vermersch, Dalmonte, Cirac, Zoller, PRL 120, 050406 (2018)
Vermersch, Elben, Dalmonte, Cirac, Zoller, PRA 97, 023604 (2018)

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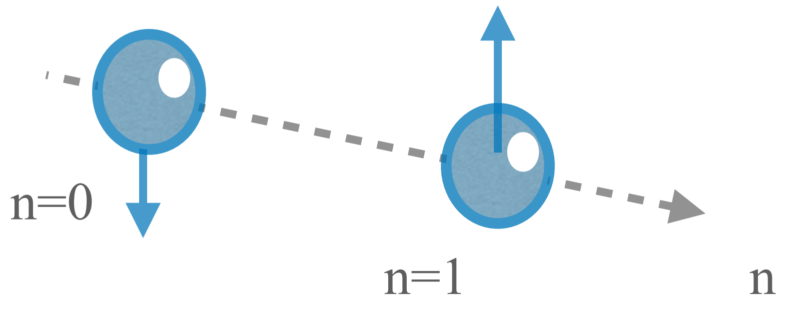

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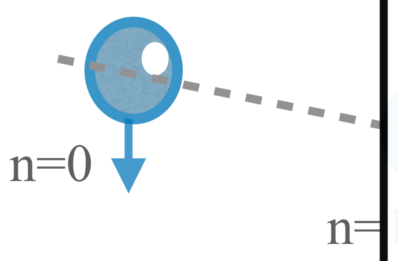

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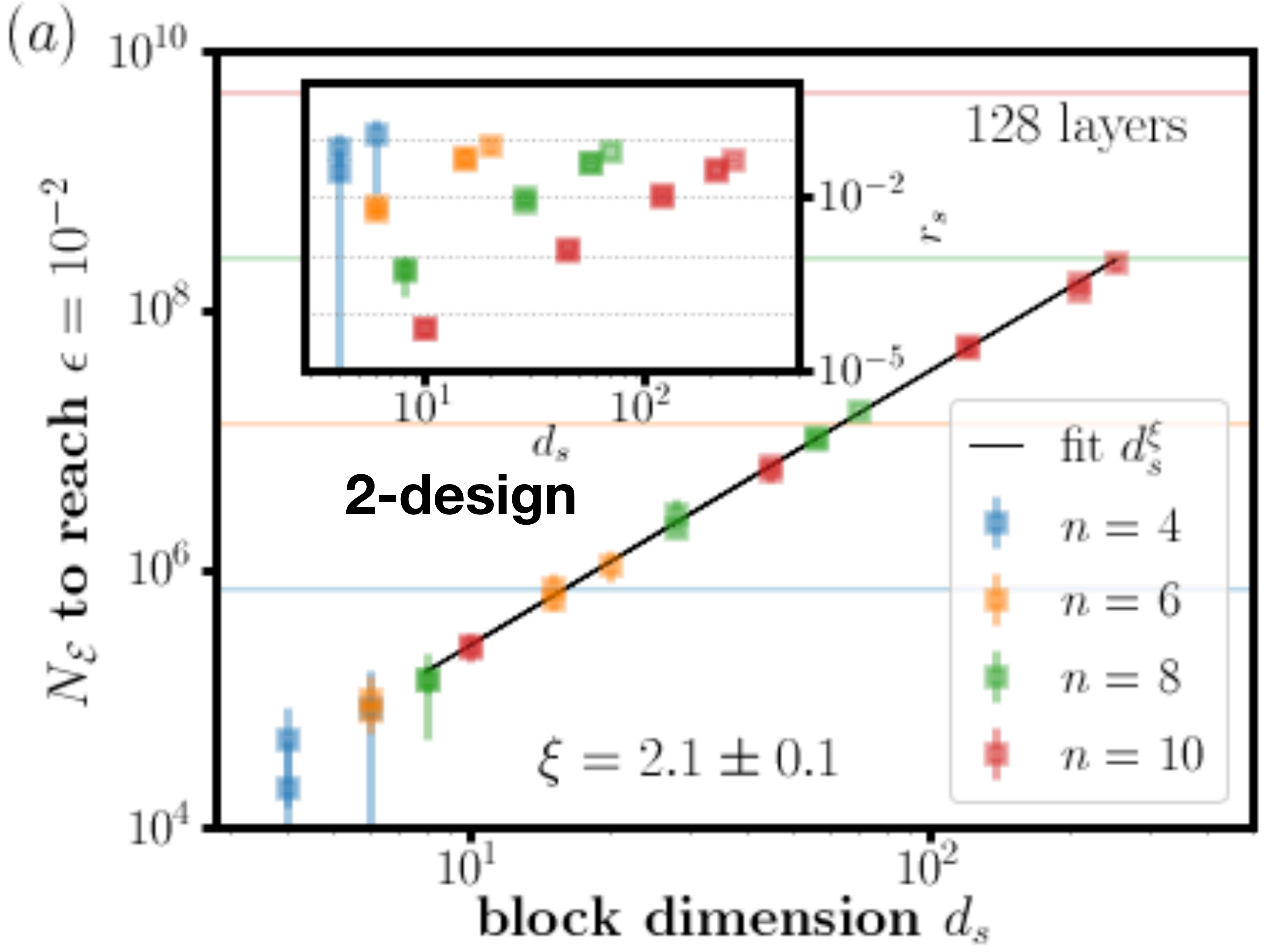

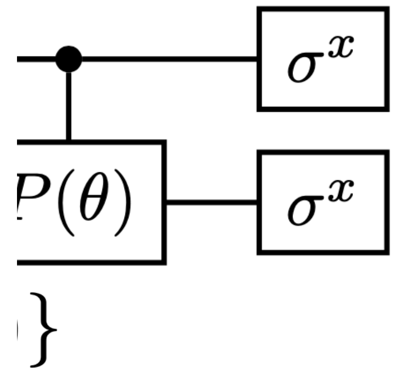

Jake Bringewatt, Jon Kunjummen, NM, arXiv:2303.15519

Symmetry-conscious Random Measurement

Lattice Gauge Theories

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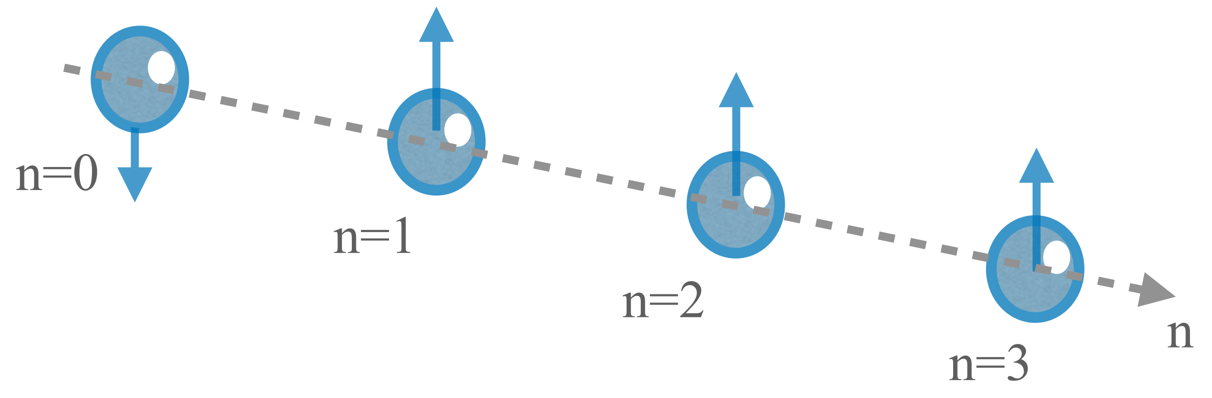

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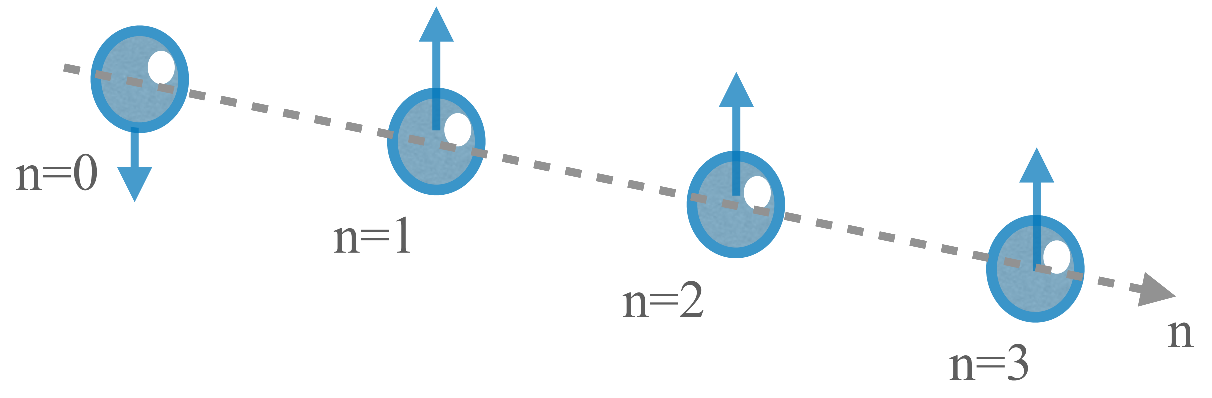

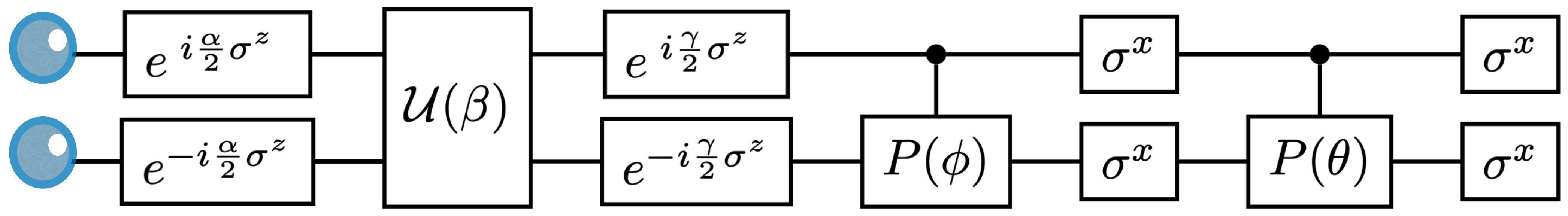

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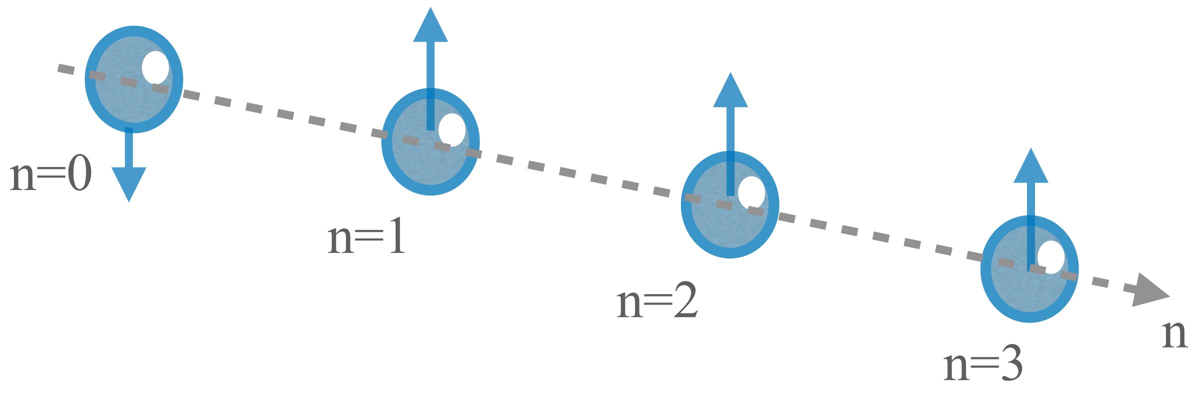

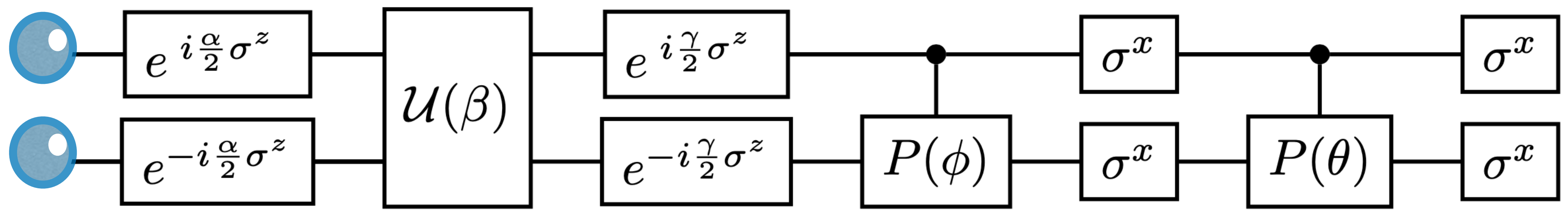

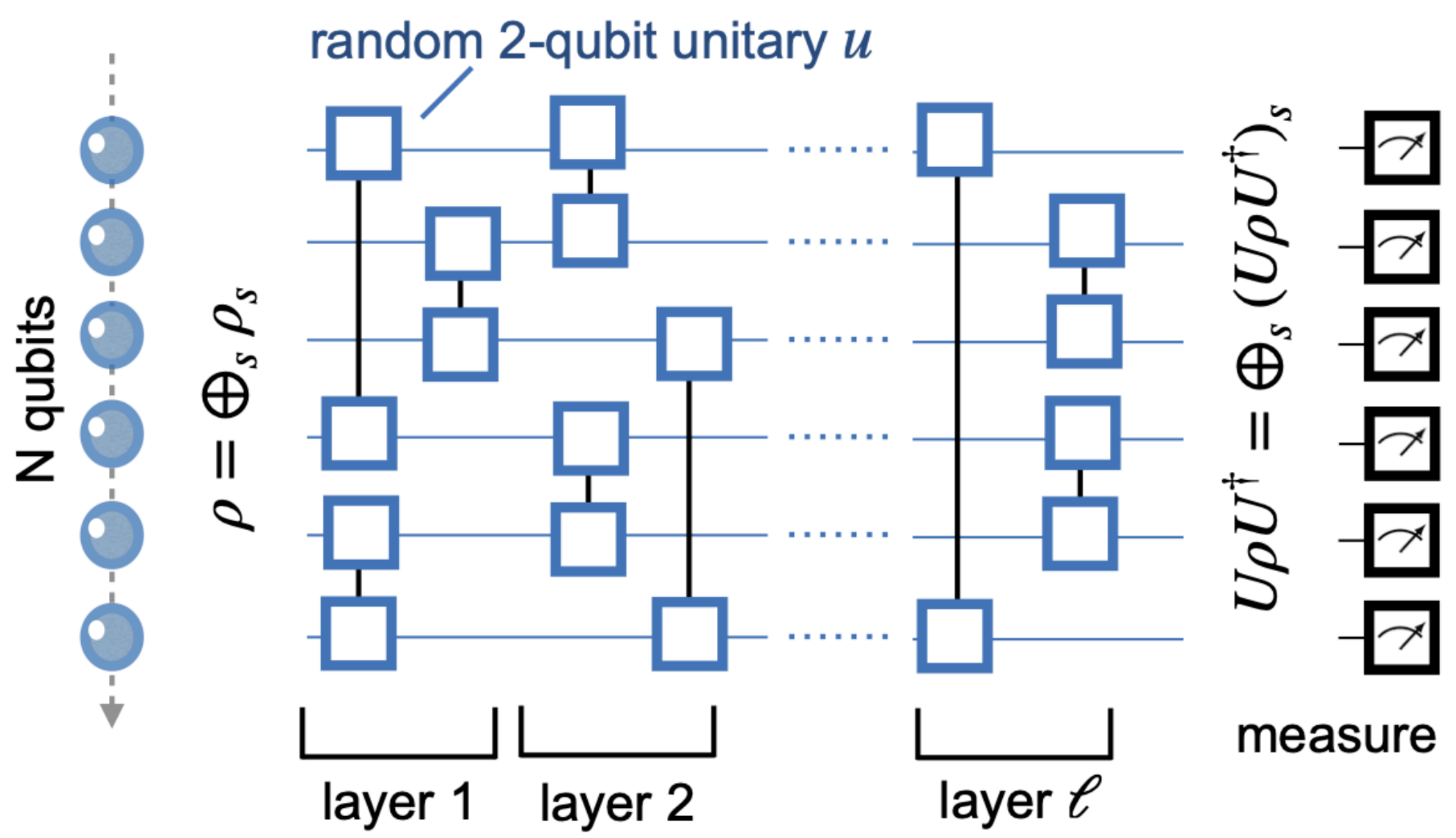

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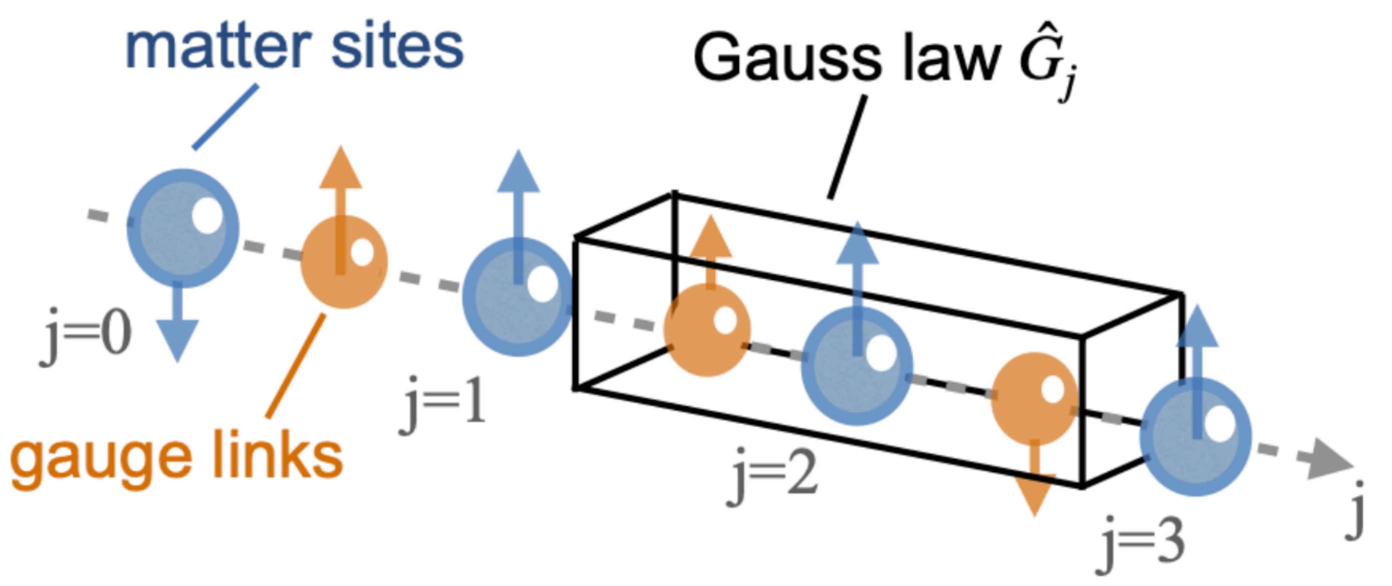

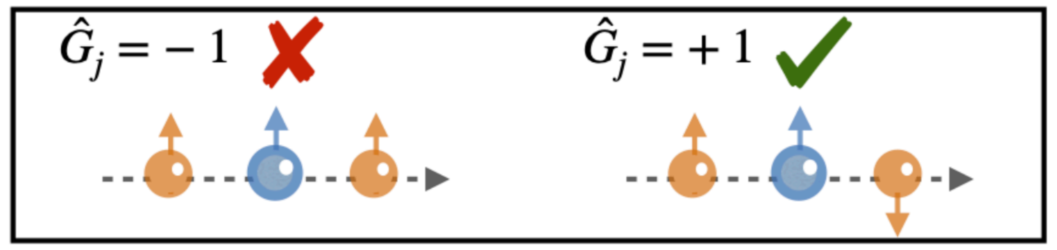

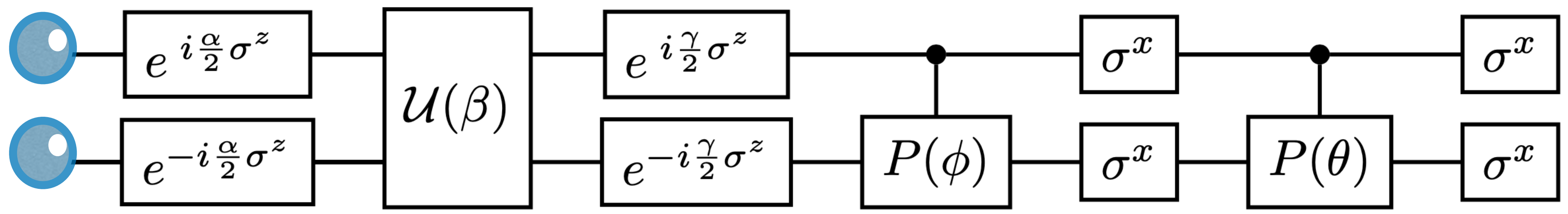

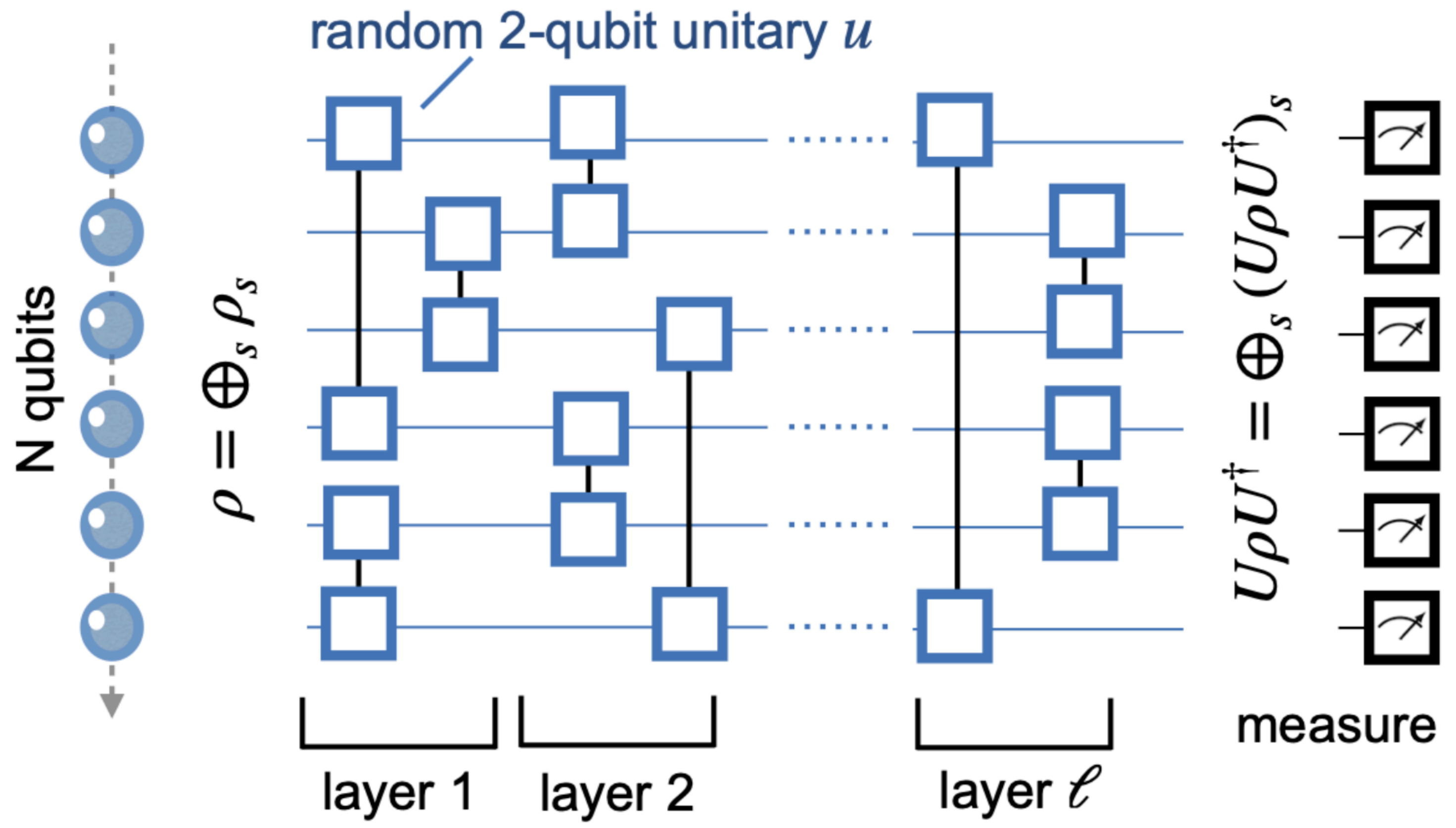

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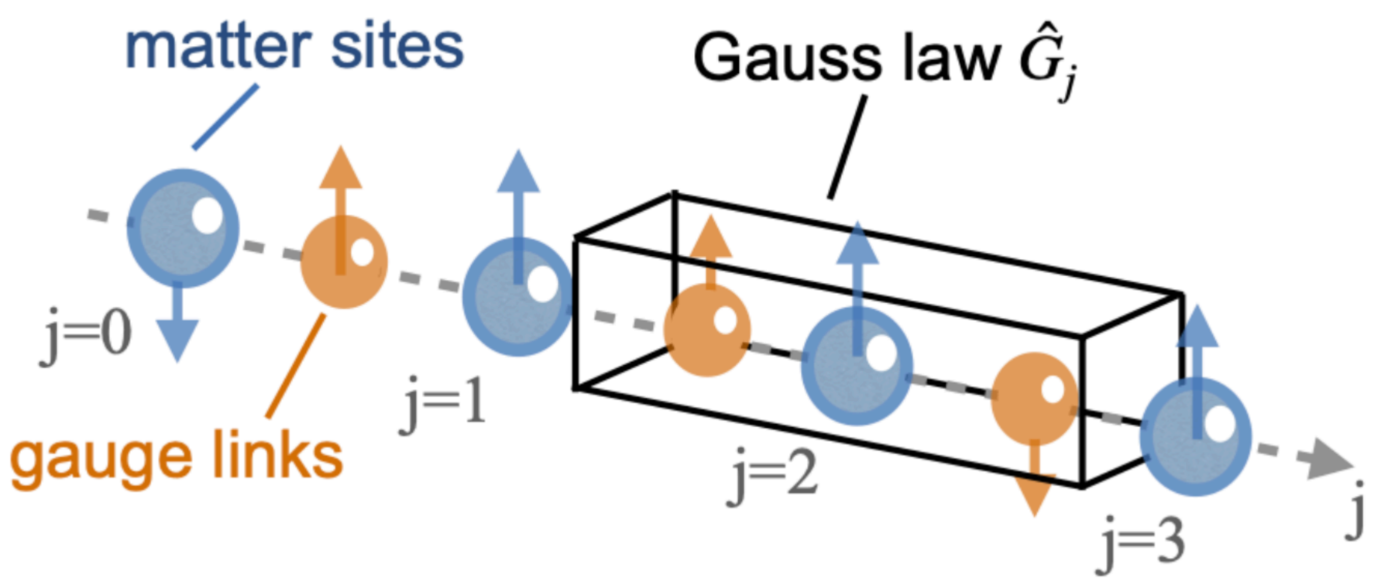
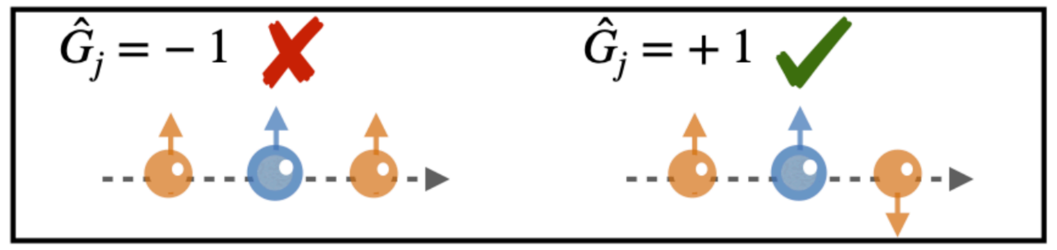
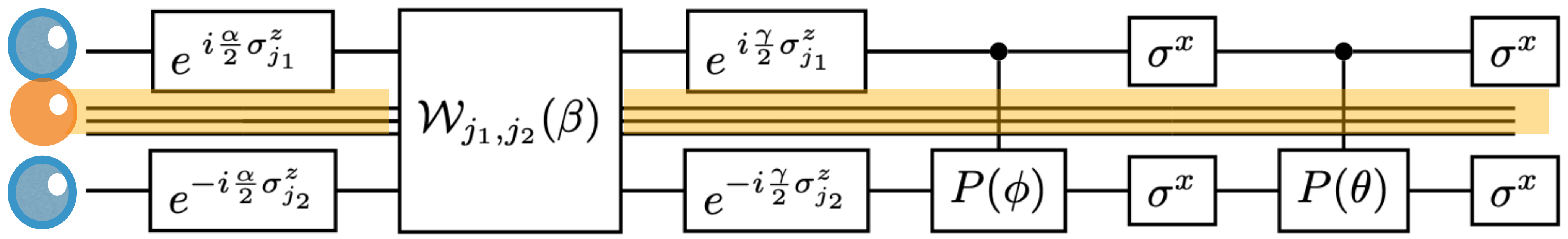
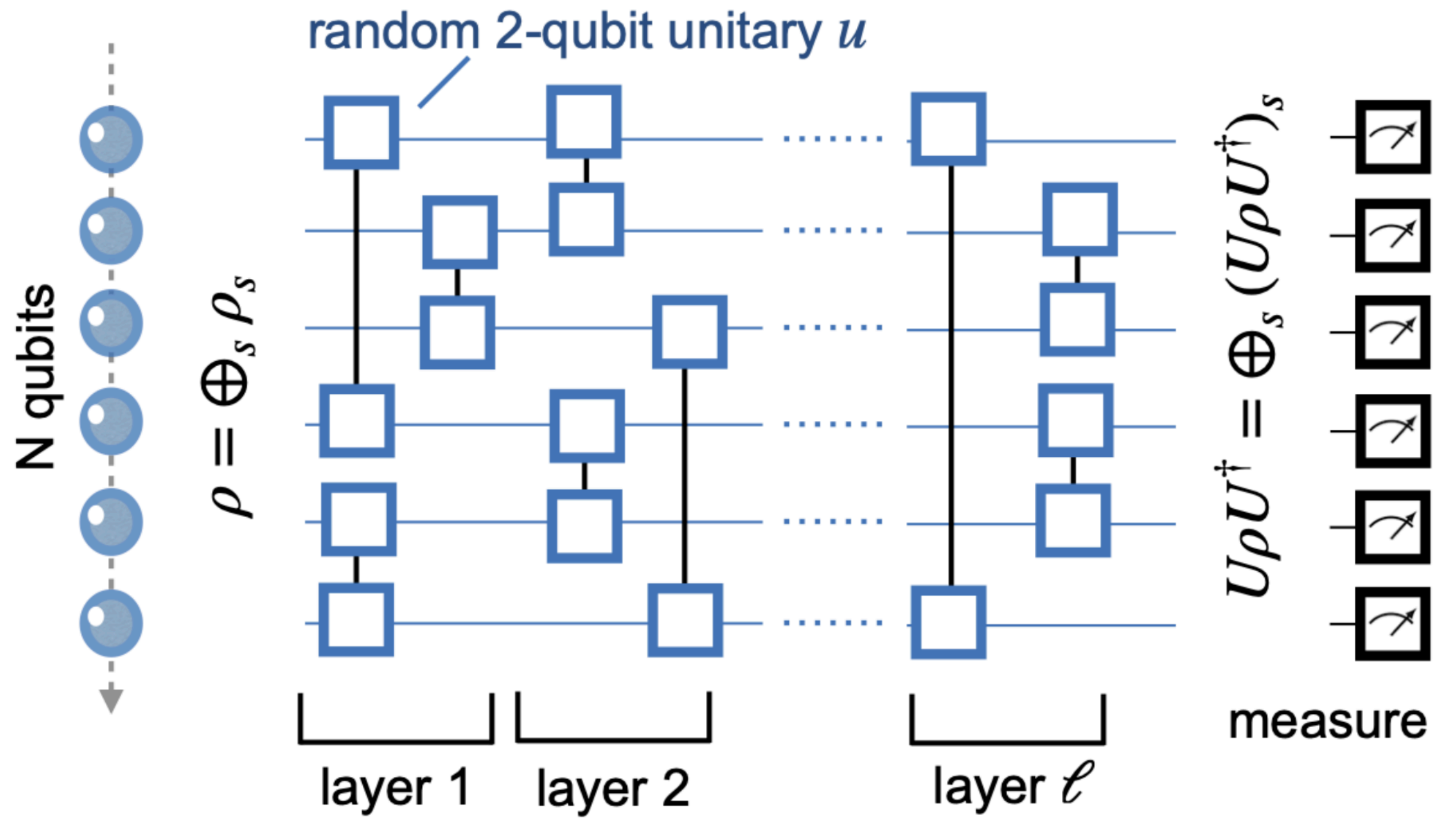






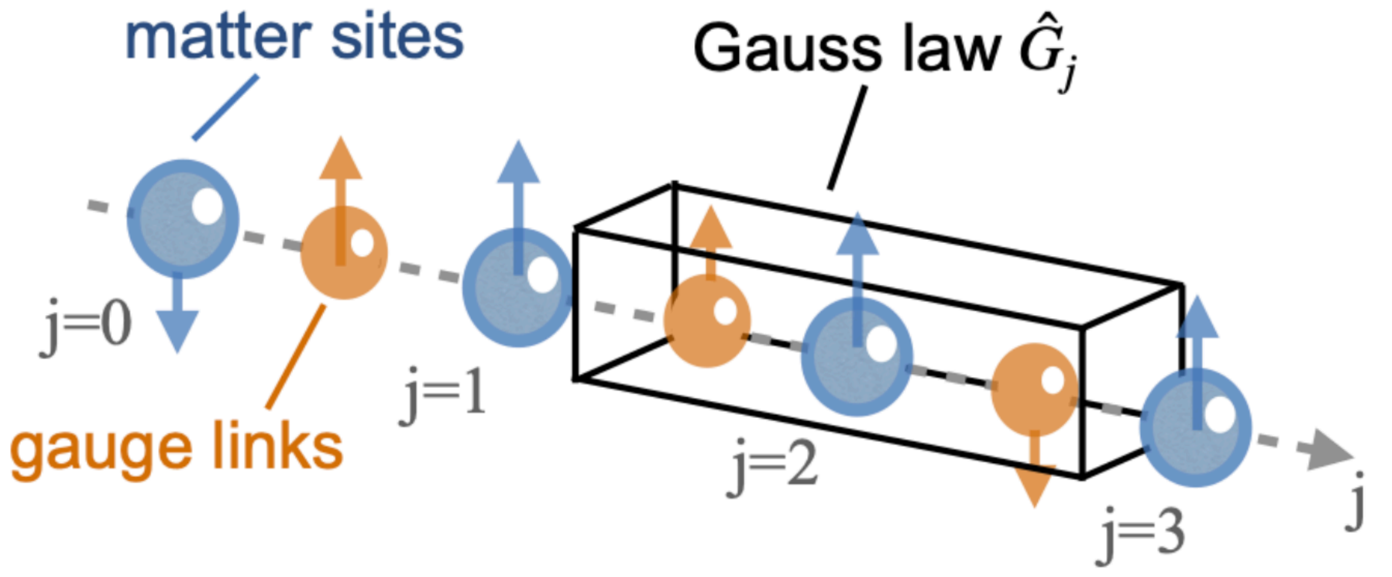
$$\mathscr{W}_{j_1,j_2}(\beta) \equiv \exp\{i\frac{\beta}{2}(\sigma^y_{j_1} W_{j_1,j_2} \sigma^x_{j_2} - \sigma^x_{j_1} W_{j_1,j_2} \sigma^y_{j_2})\}$$

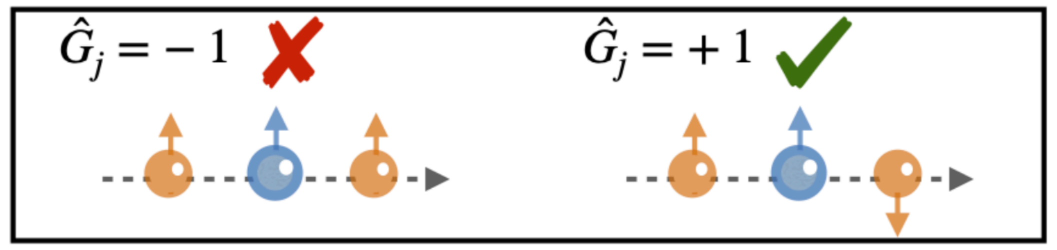
$$W_{j_1,j_2} \equiv \prod_{j=j_1}^{j_2-1} \tilde{\sigma}^x_{j,j+1}$$

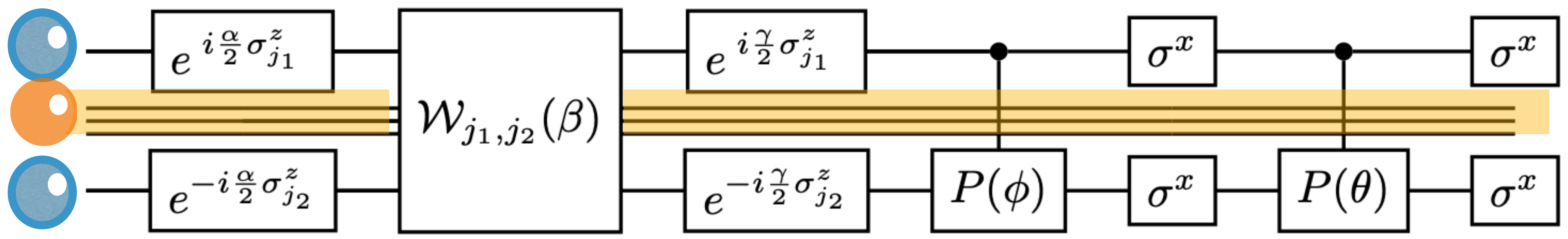


Symmetry-conscious Random Measurement

Lattice Gauge Theories

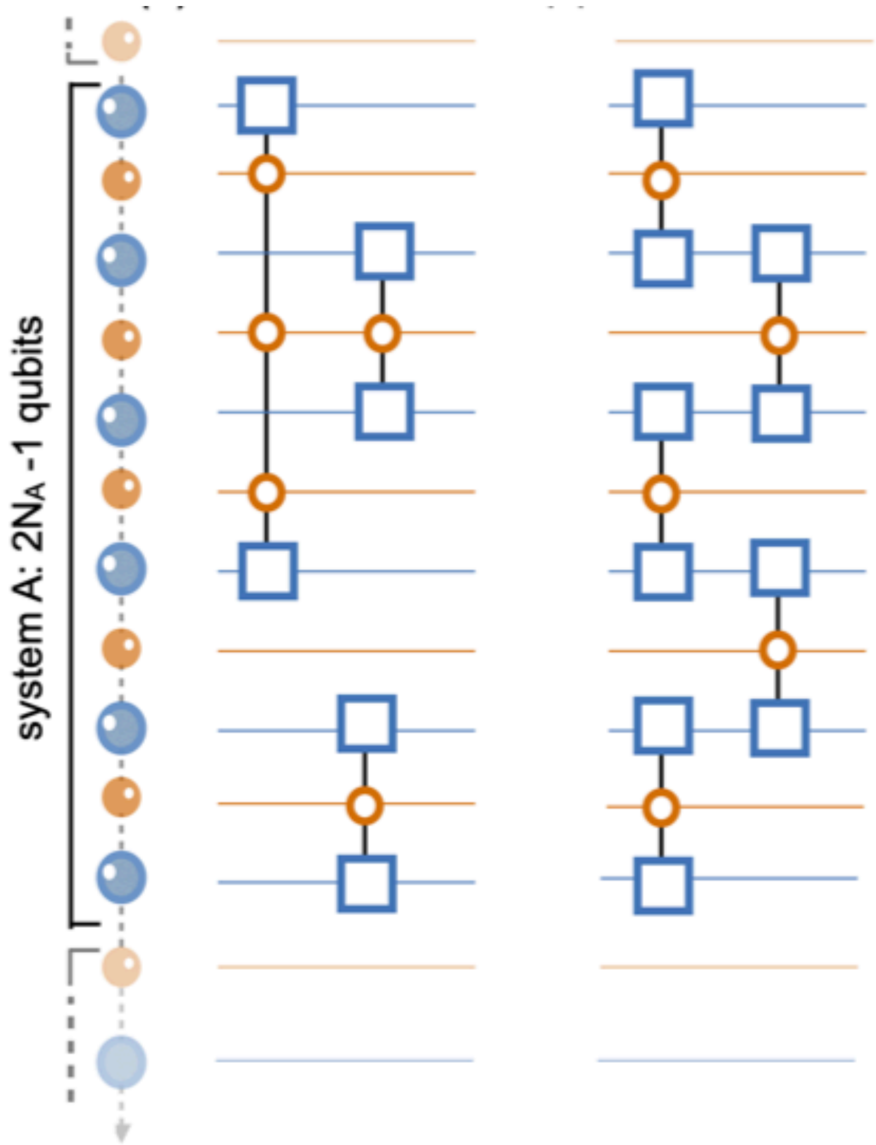






$$\mathscr{W}_{j_1,j_2}(\beta) \equiv \exp\{i\frac{\beta}{2}(\sigma^y_{j_1}W_{j_1,j_2}\sigma^x_{j_2} - \sigma^x_{j_1}W_{j_1,j_2}\sigma^y_{j_2})\}$$

$$W_{j_1,j_2} \equiv \prod_{j=j_1}^{j_2-1} \tilde{\sigma}^x_{j,j+1}$$



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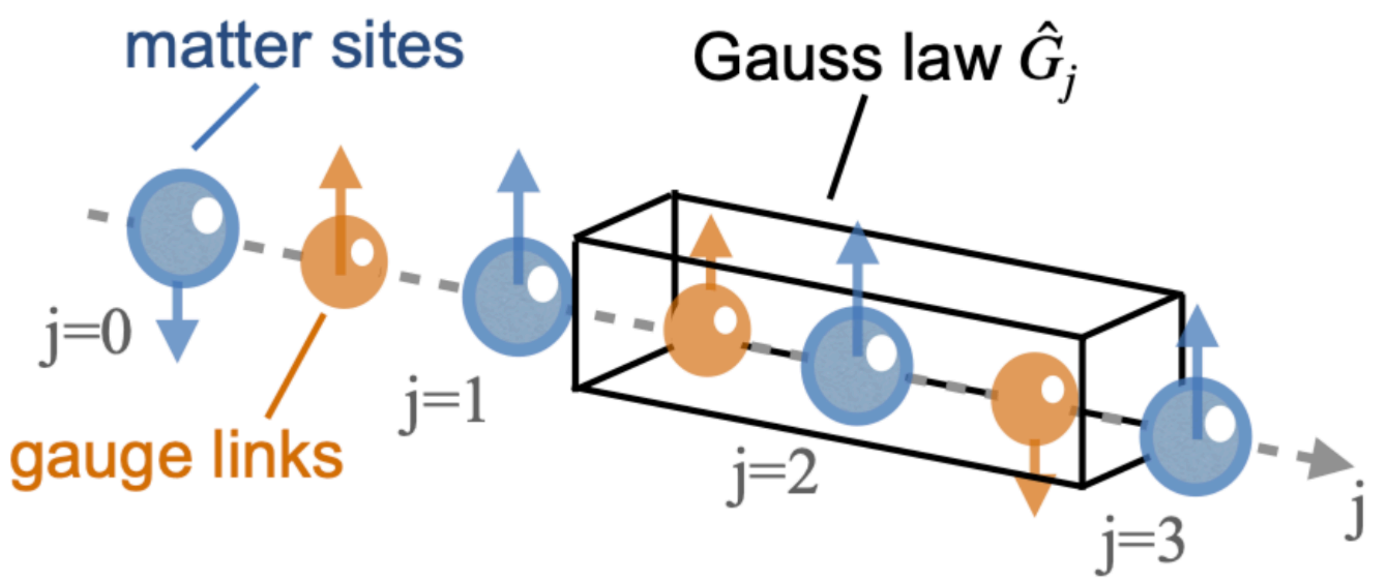
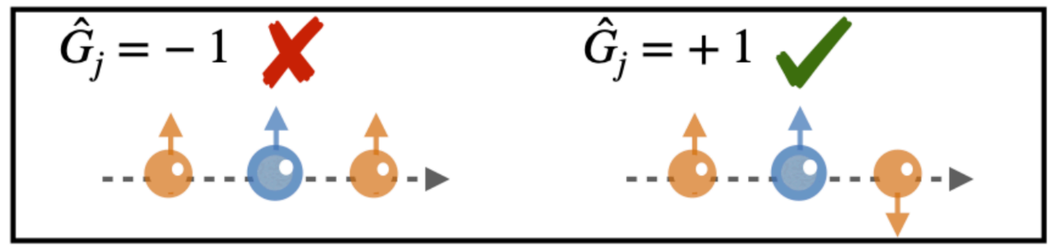
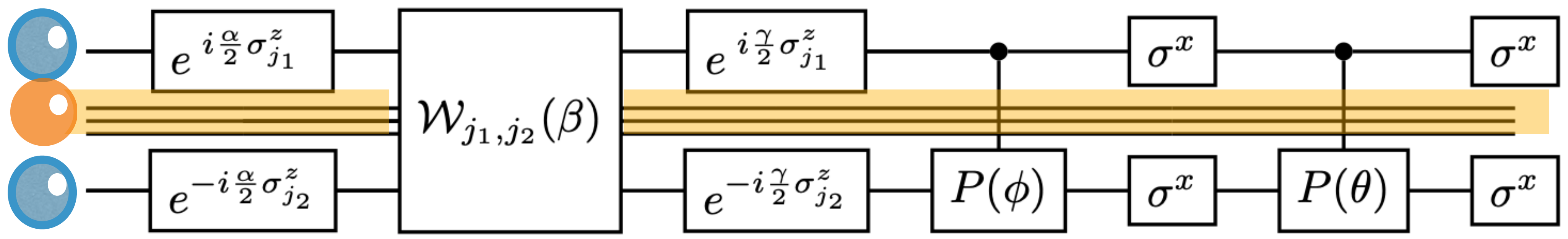
Lattice Gauge Theories







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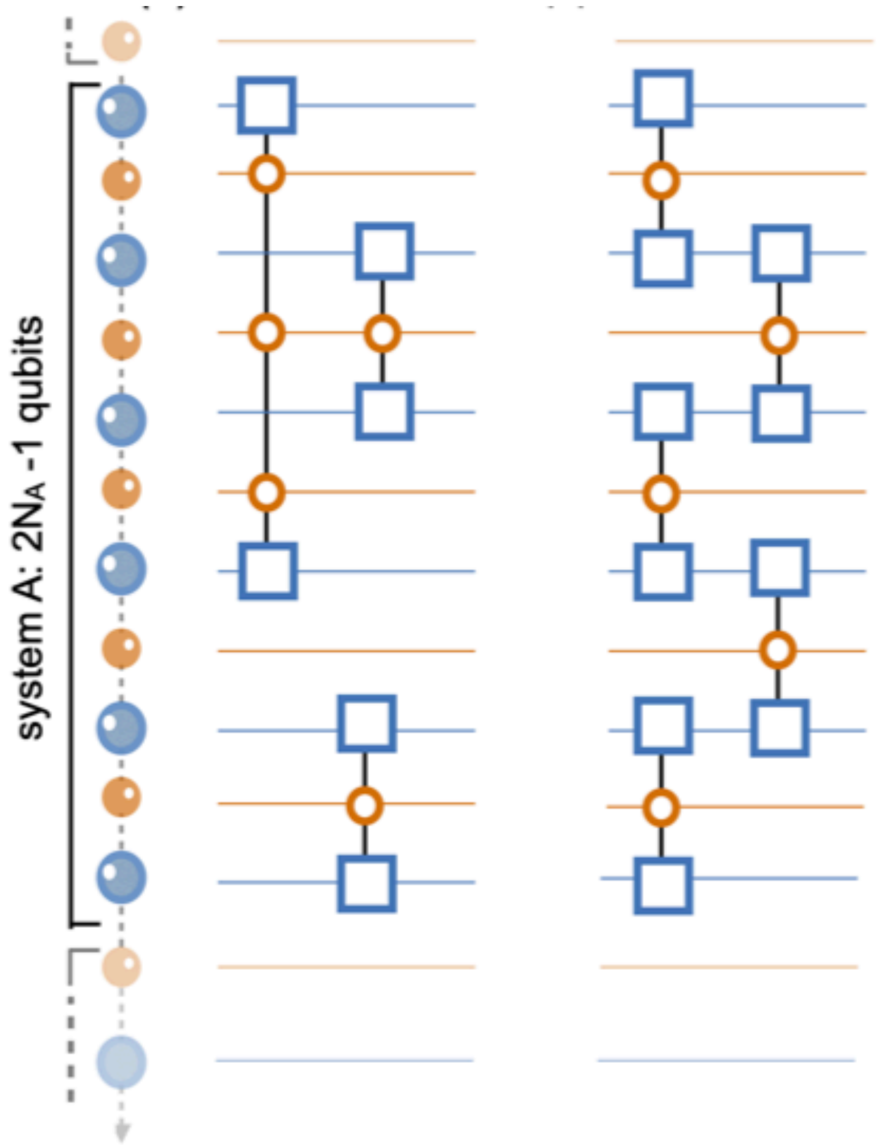
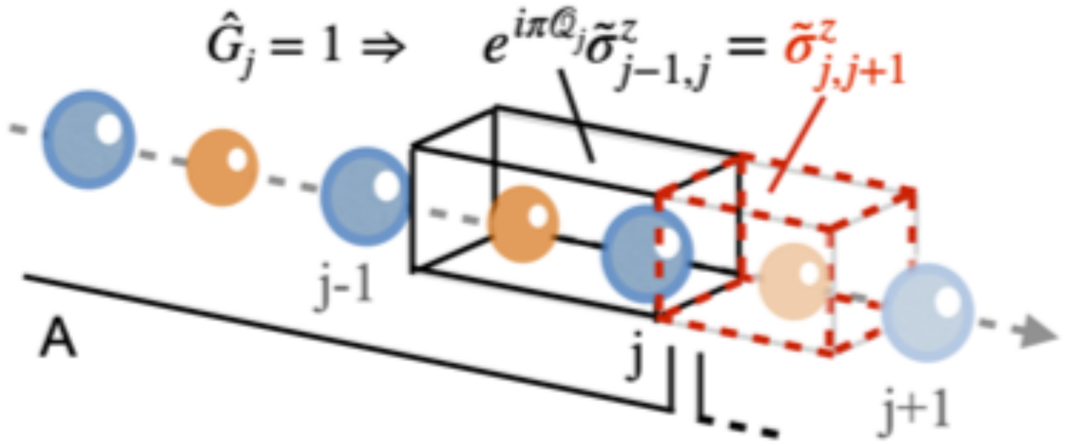
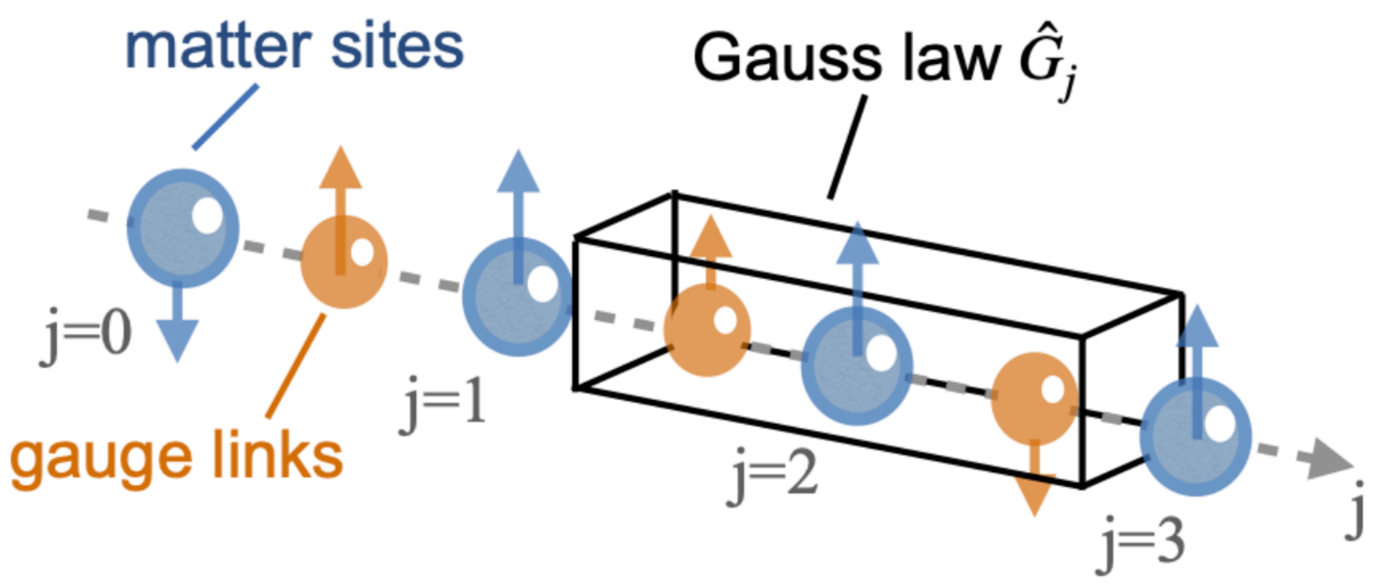


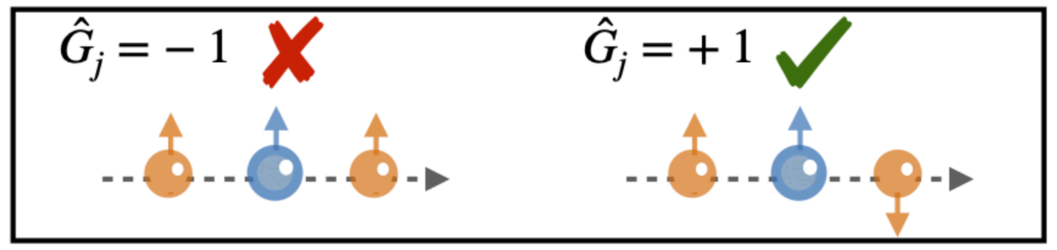


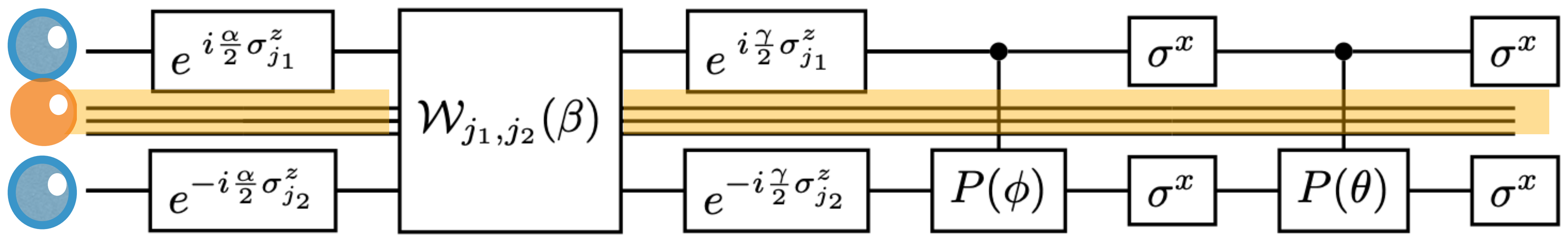
$$\rho = \bigoplus_s \rho_s$$

Symmetry-conscious Random Measurement

Lattice Gauge Theories







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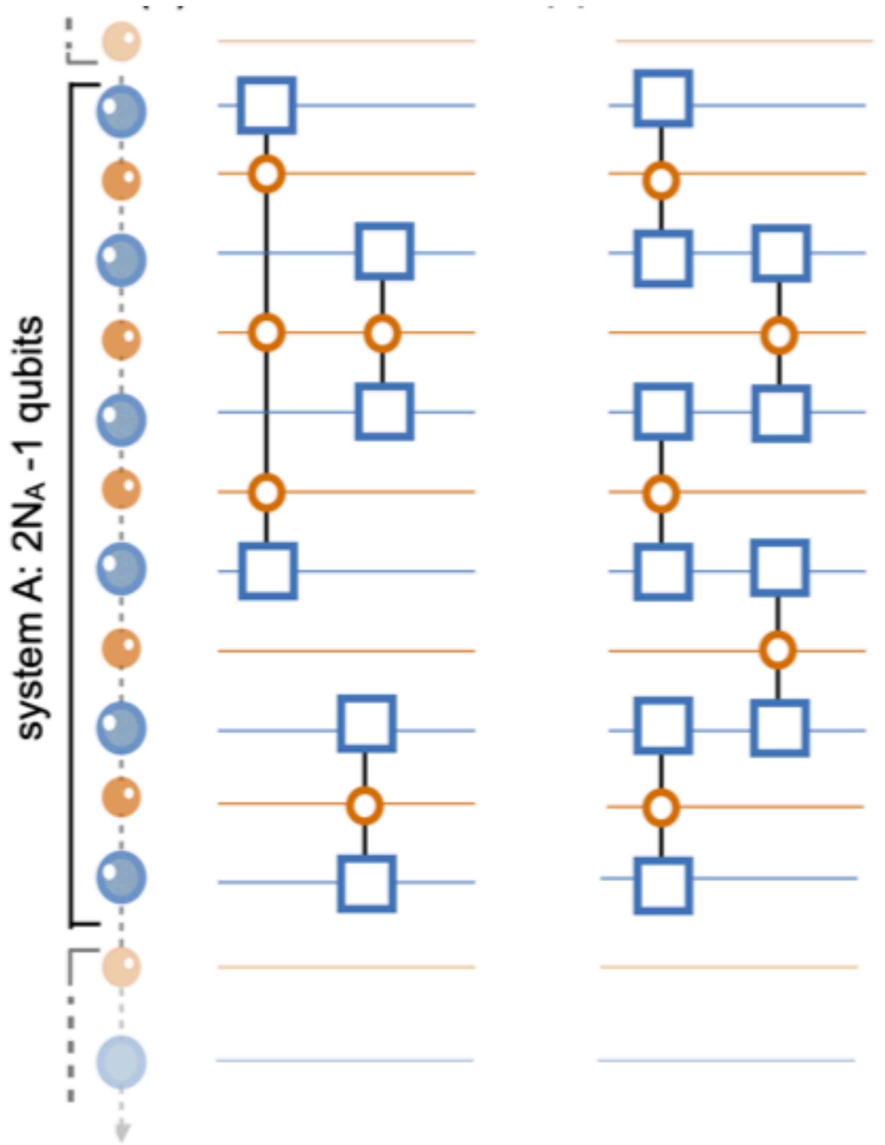

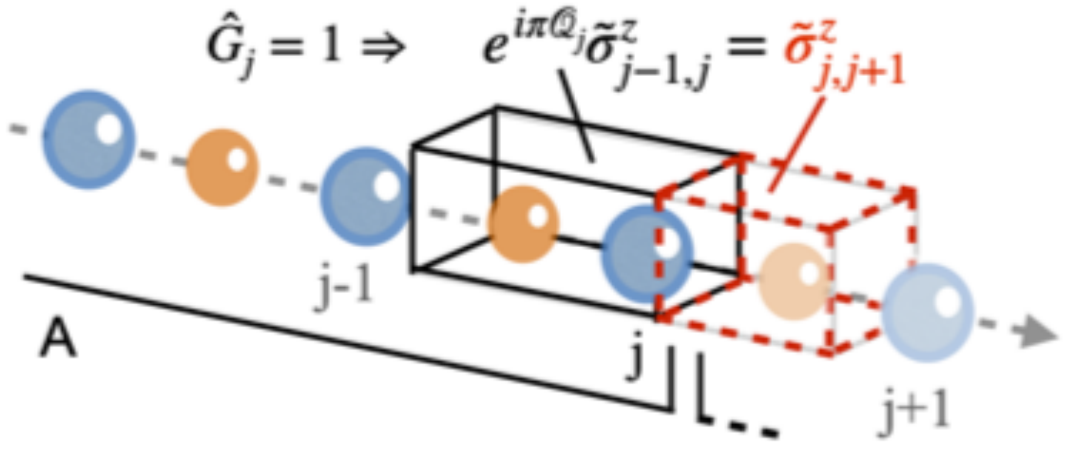

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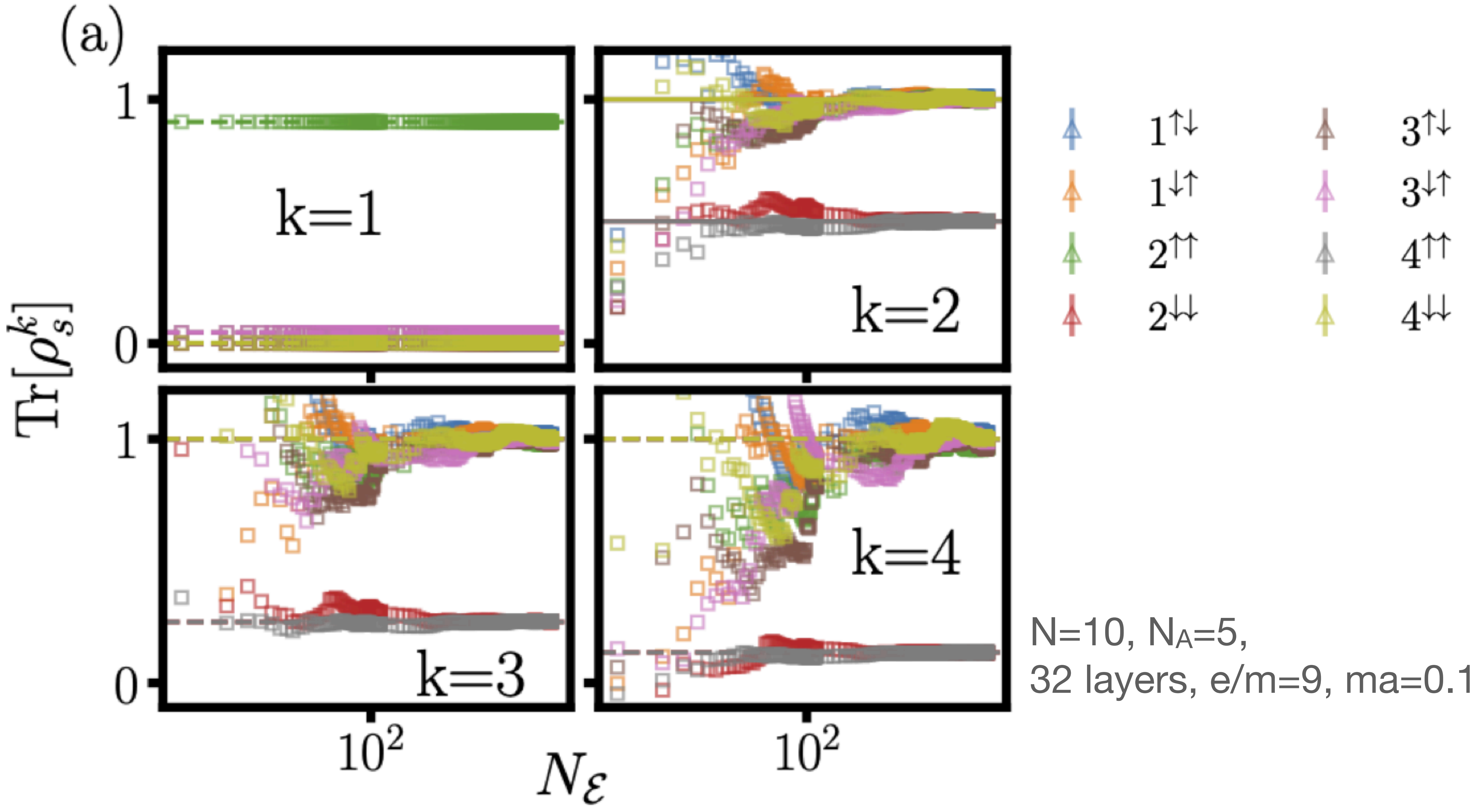


N=10, N_A=5,
32 layers, e/m=9, ma=0.1

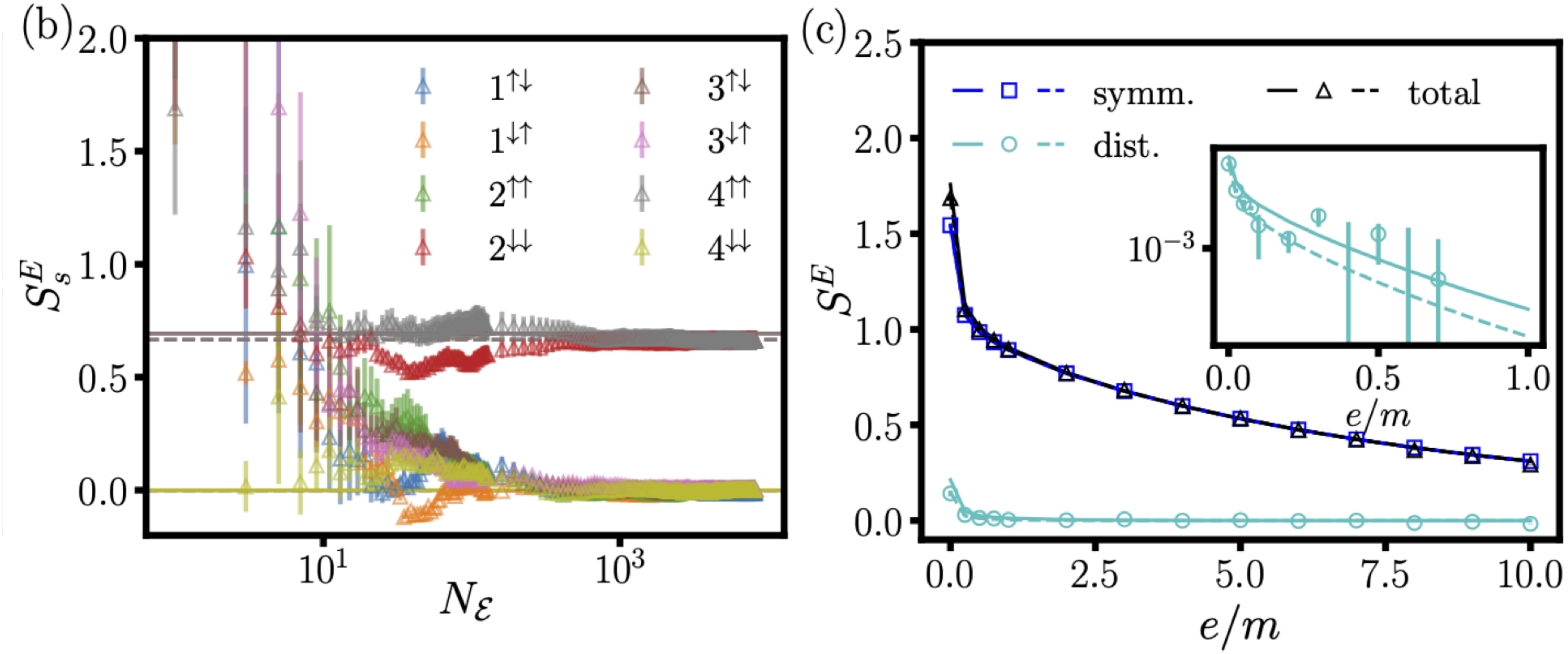
Jake Bringewatt, Jon Kunjummen, NM, arXiv:2303.15519

Symmetry-conscious Random Measurement

Lattice Gauge Theories

Measure distillable Entanglement Entropy

$$S^E = -\sum_s p_s \log(p_s) + \sum_s p_s S^E_s \qquad p_s \equiv \mathrm{Tr}_s(\rho_s)$$



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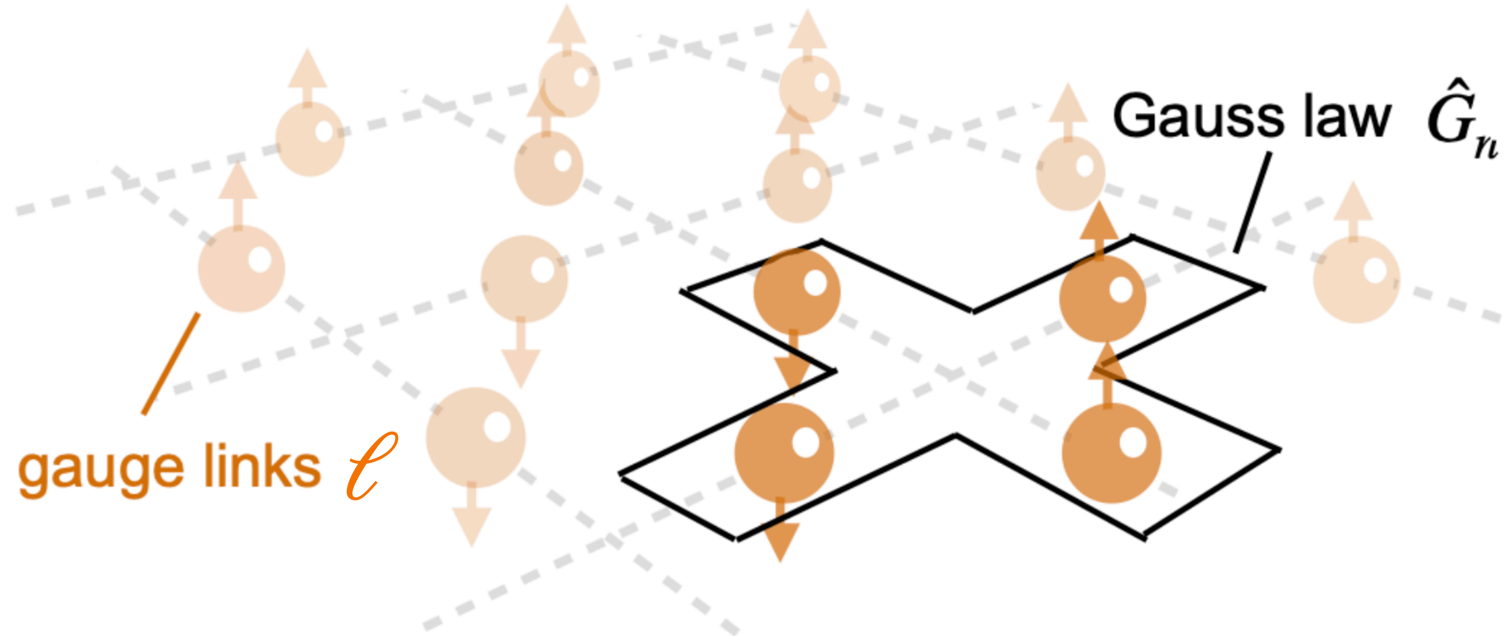
Symmetry-conscious Random Measurement

Lattice Gauge Theories

Symmetry-conscious Random Measurement

Lattice Gauge Theories

- **Z_2 Lattice Gauge Theory**



$$\hat{G}_n = A_\nu \equiv \prod_{\ell \in \nu} \sigma_\ell^z$$

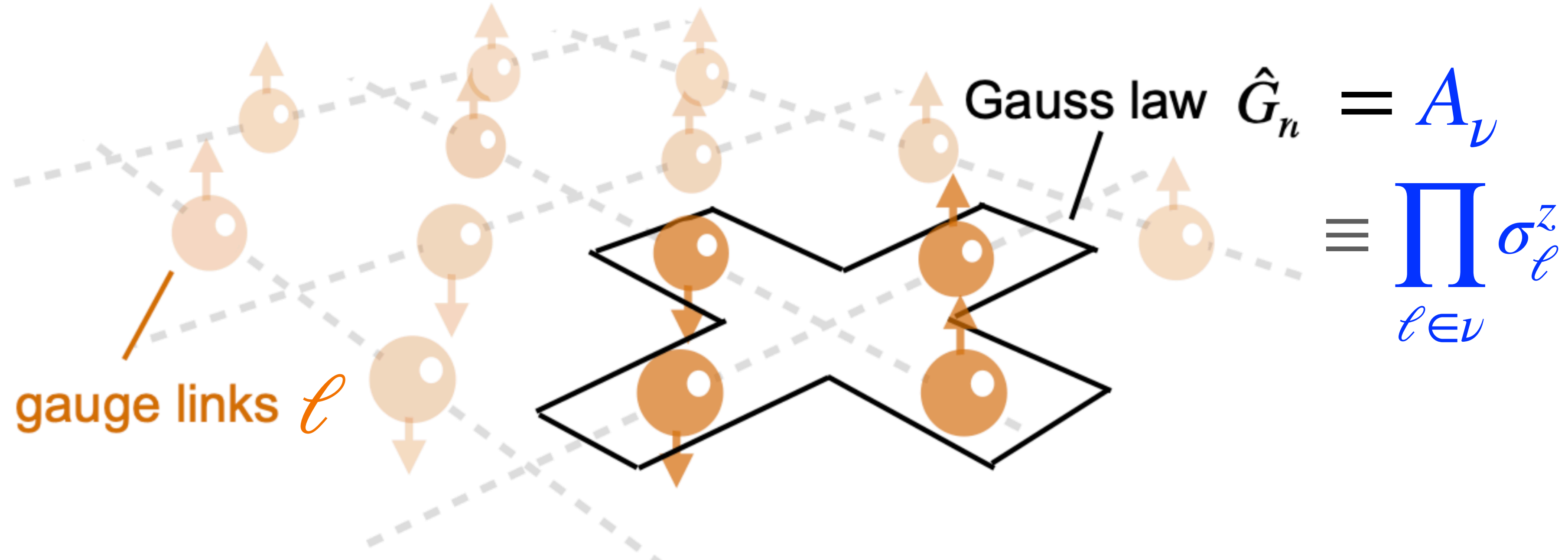
$$H = -\epsilon \sum_{\ell} \sigma^z - \sum_p B_p$$

$$B_p \equiv \prod_{\ell \in p} \sigma_\ell^x$$

Symmetry-conscious Random Measurement

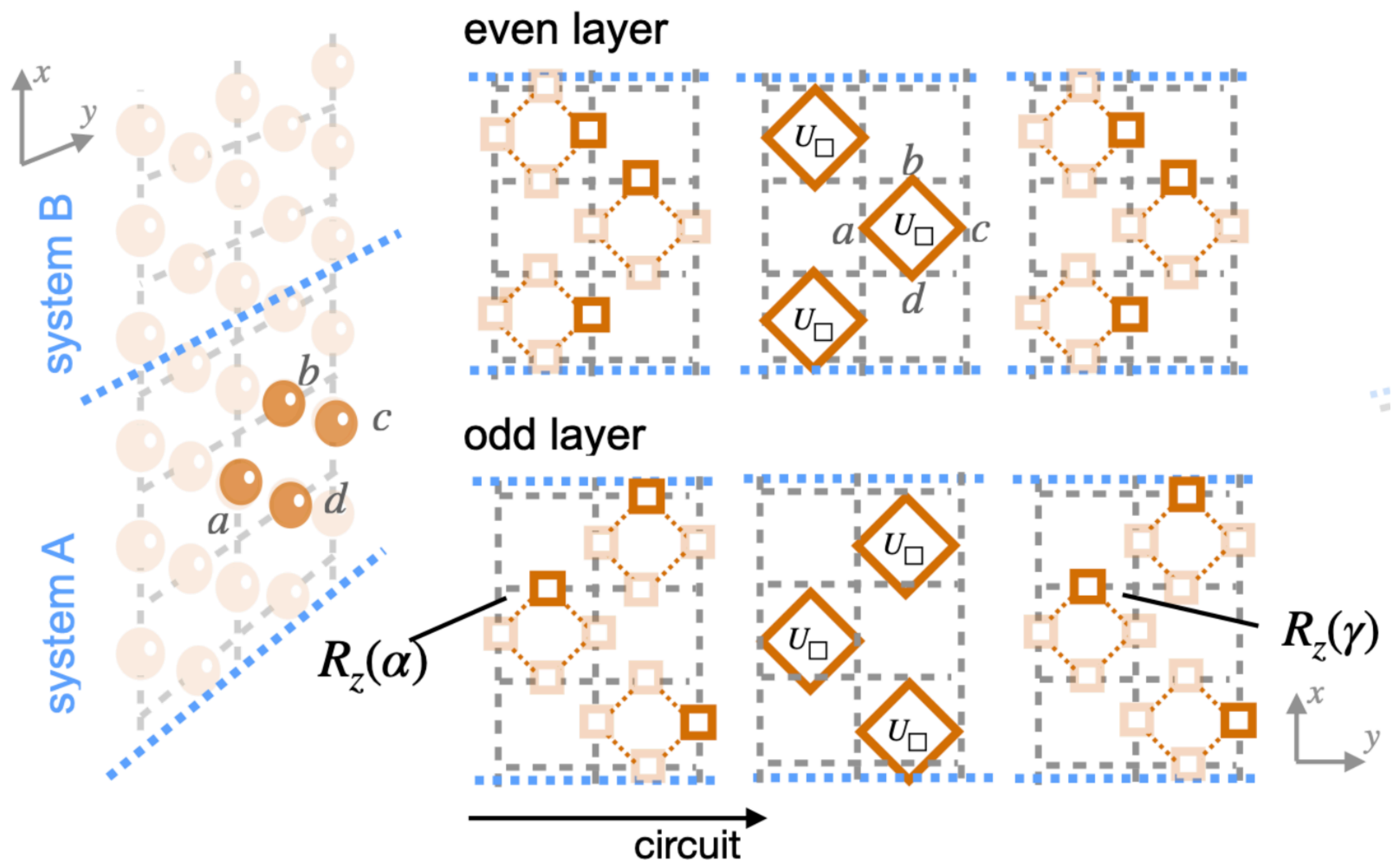
Lattice Gauge Theories

- **Z_2 Lattice Gauge Theory**



$$H = -\epsilon \sum_{\ell} \sigma^z - \sum_{p} B_p \qquad B_p \equiv \prod_{\ell \in p} \sigma^x_\ell$$

Recipe: symmetry-conscious k-design



Symmetry-conscious Random Measurement

Lattice Gauge Theories

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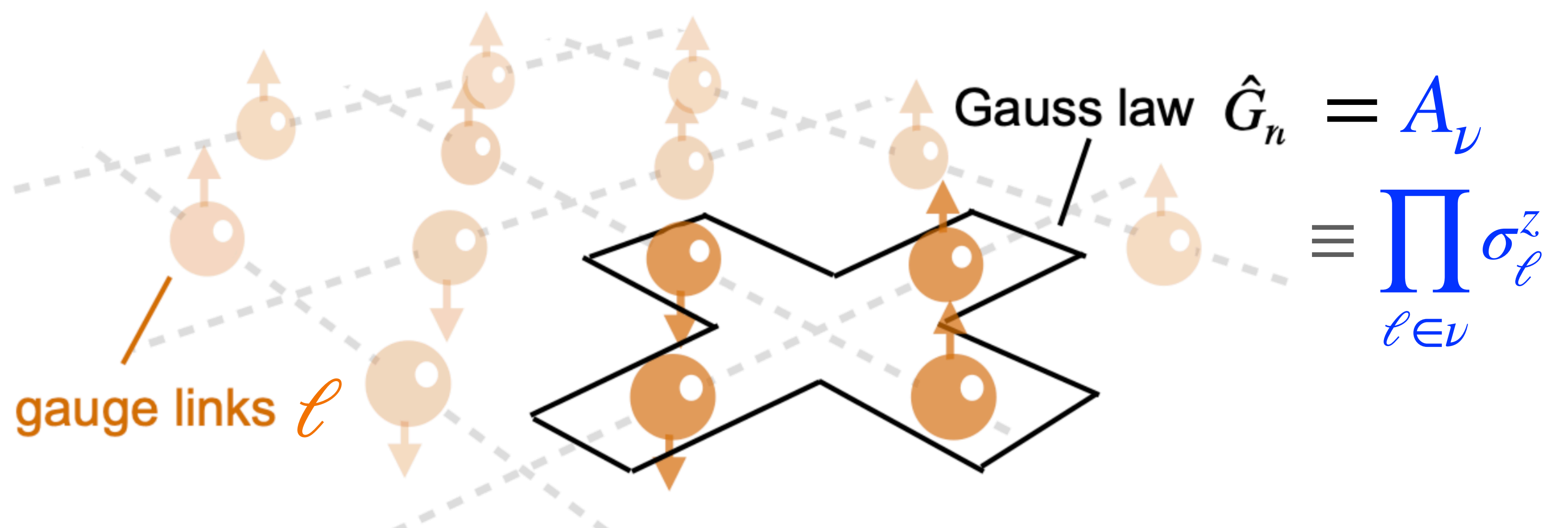
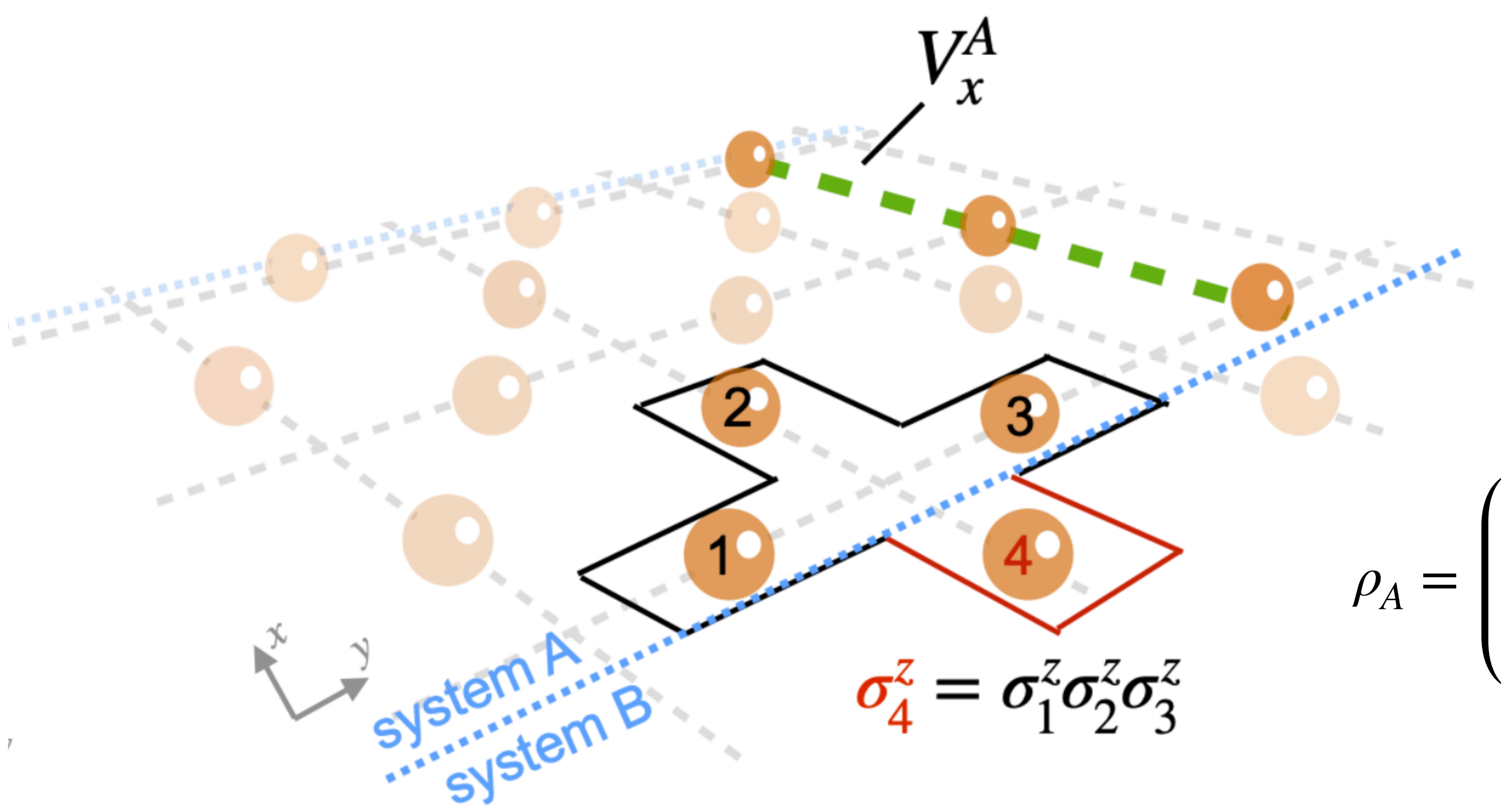
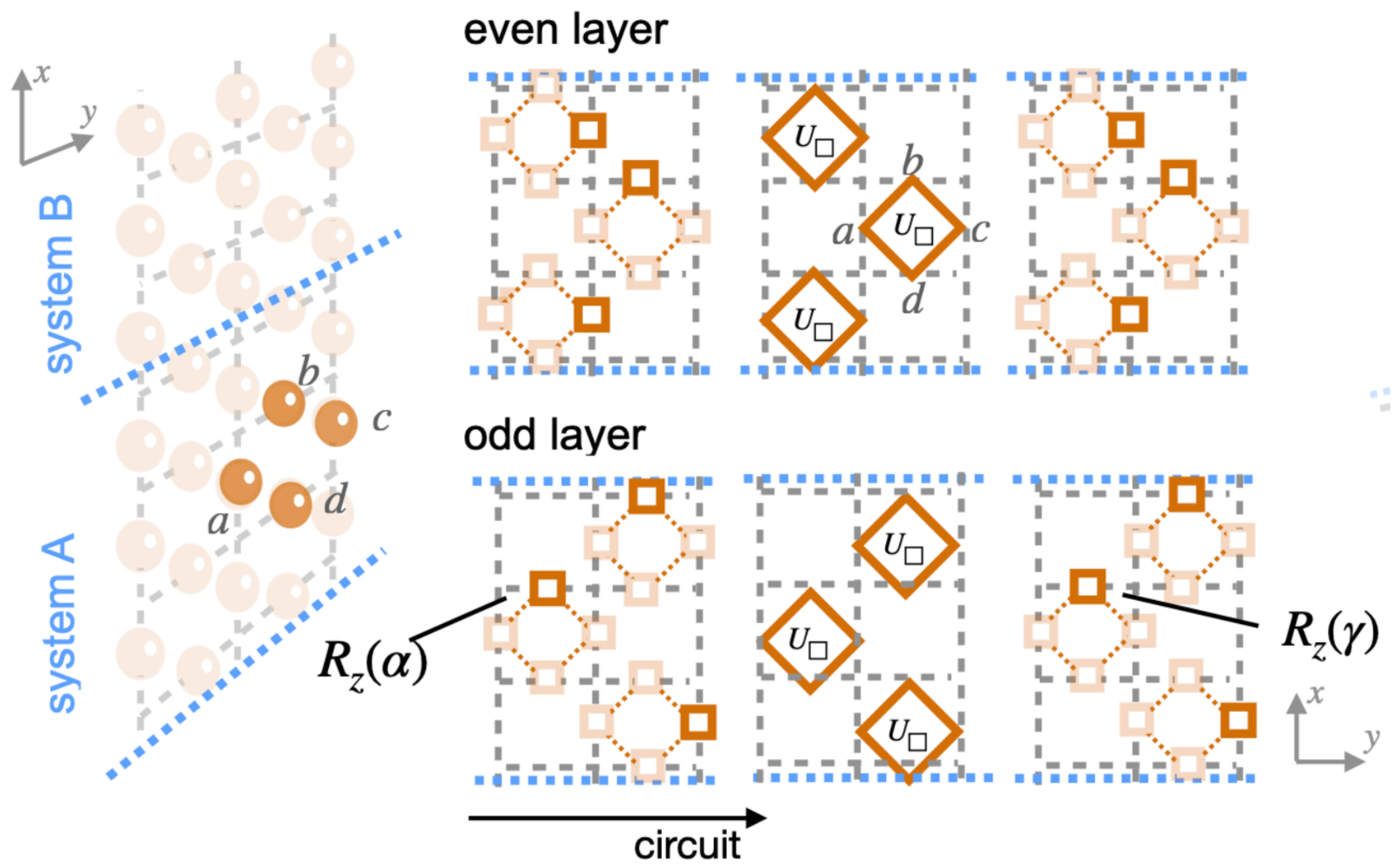


$$H = -\epsilon \sum_\ell \sigma^z - \sum_p B_p \equiv \prod \sigma^x_\ell$$



$$\rho_A = \begin{pmatrix} \square & \cdots & \\ \vdots & \square & \\ & \cdots & \ddots \end{pmatrix}$$

Recipe: symmetry-conscious k-design



Symmetry-conscious Random Measurement

Lattice Gauge Theories

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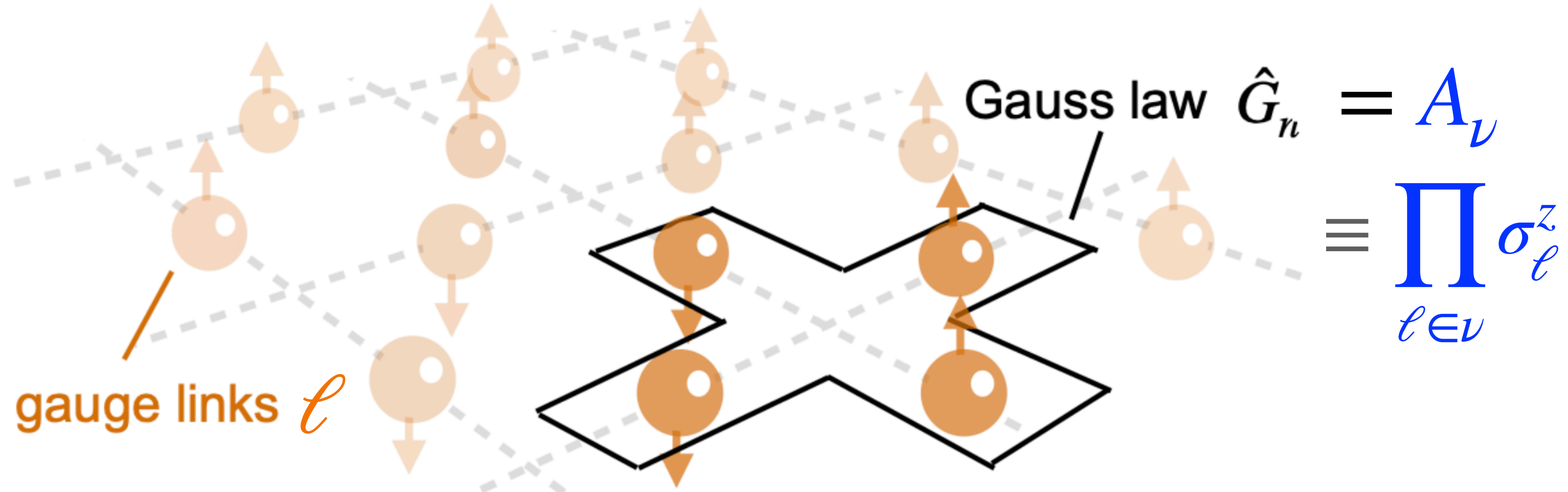

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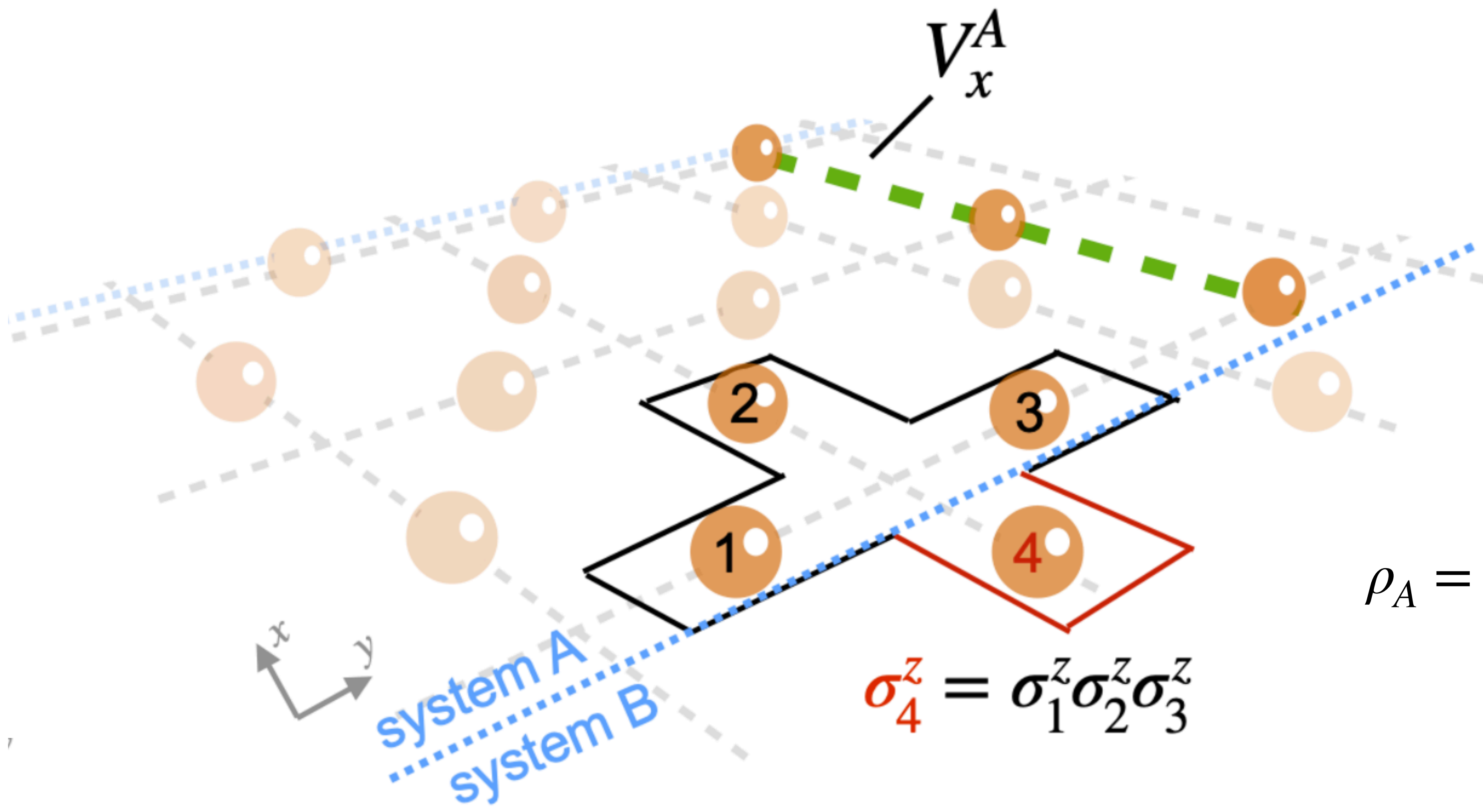

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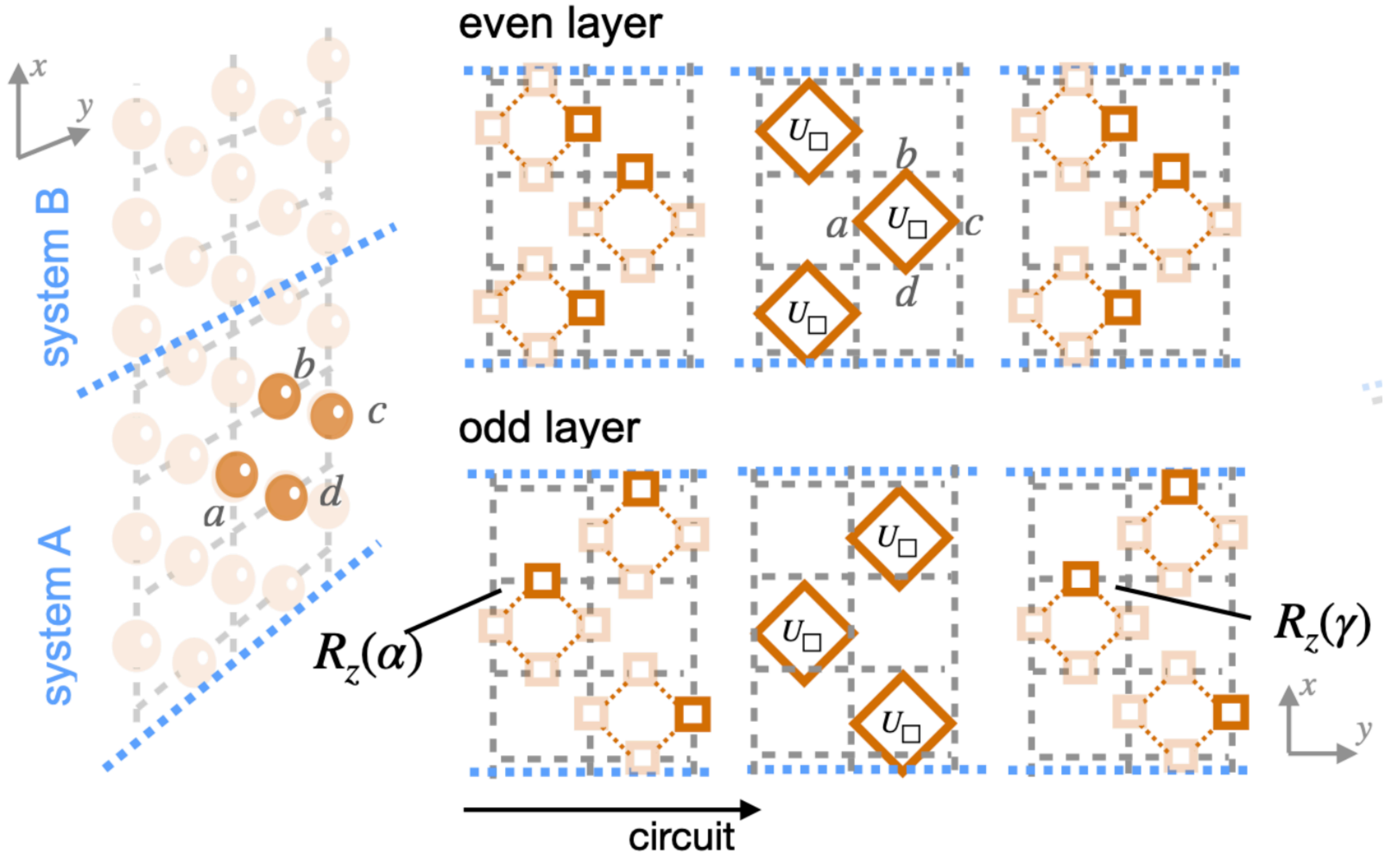


(for every plaquette p)

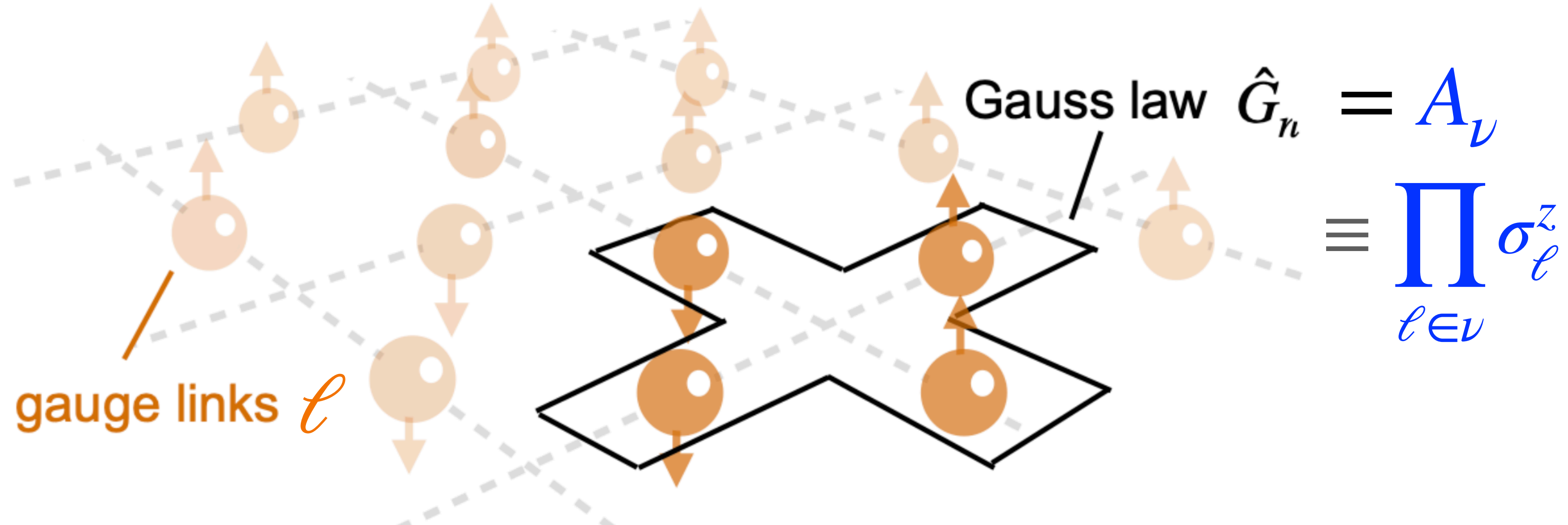
1. Draw α, β, γ randomly from 1-qubit CUE

$$u_1 = = \exp\{i\gamma\sigma^z\}\ \exp\{i\beta\sigma^x\}\ \exp\{i\alpha\sigma^z\}$$

Symmetry-conscious Random Measurement

Lattice Gauge Theories

- **Z_2 Lattice Gauge Theory**



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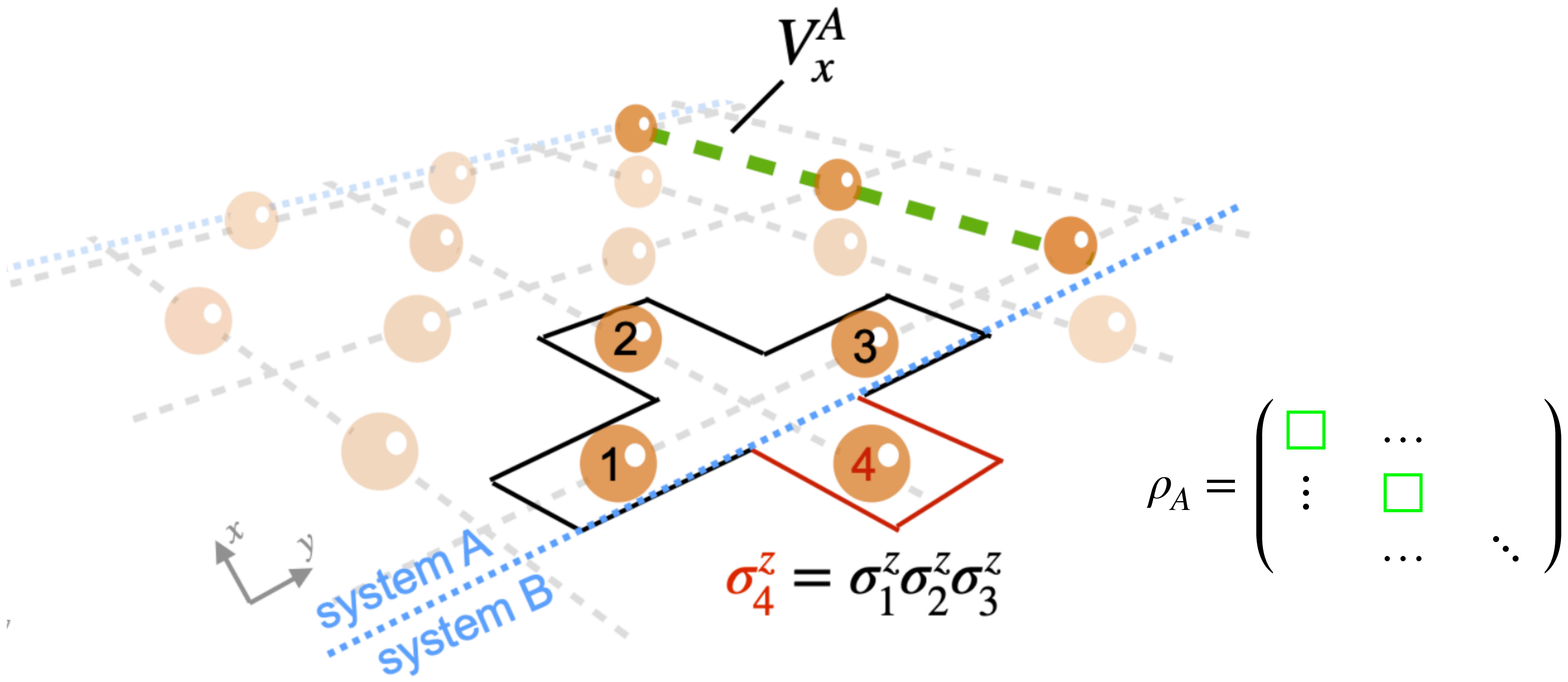

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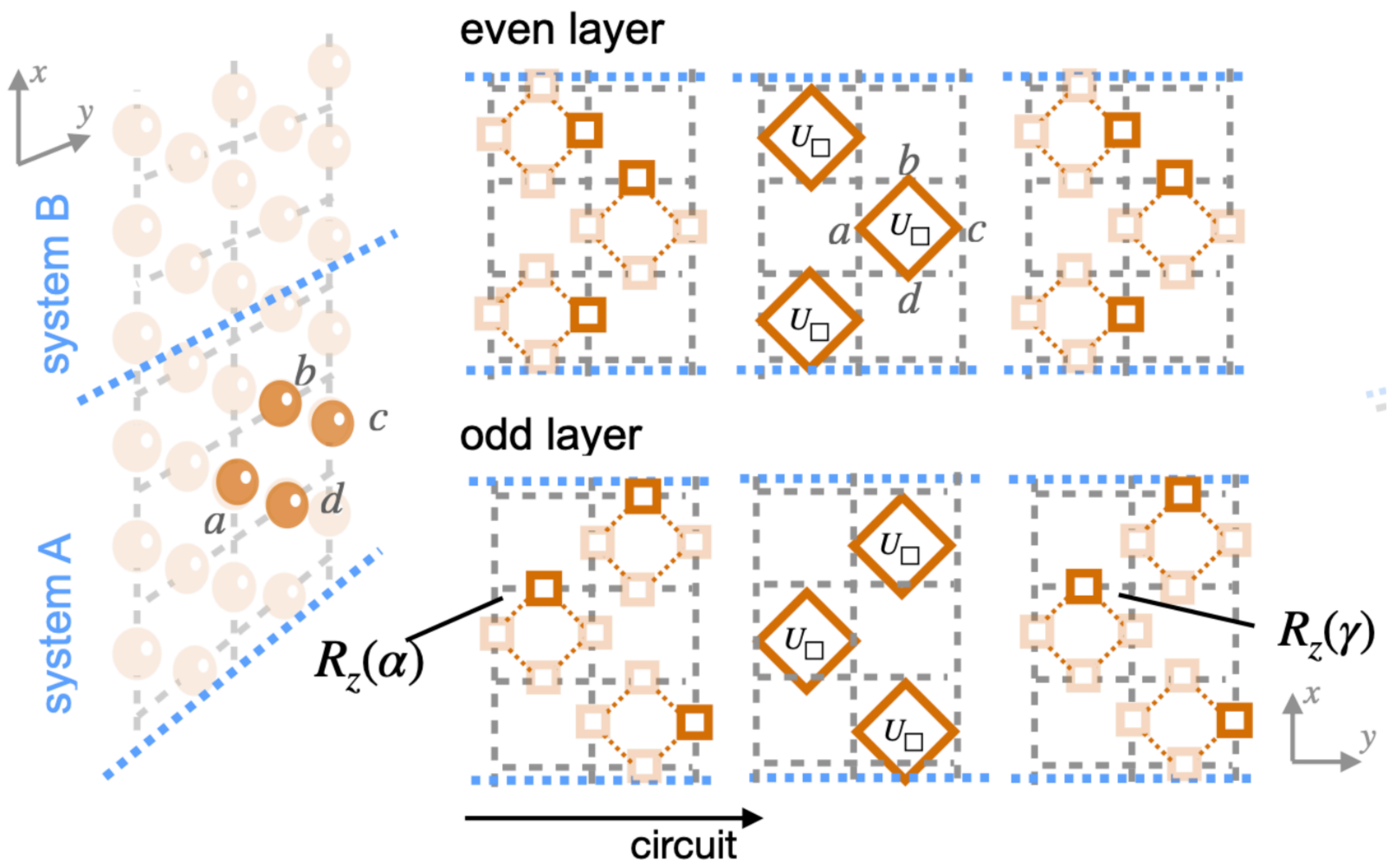

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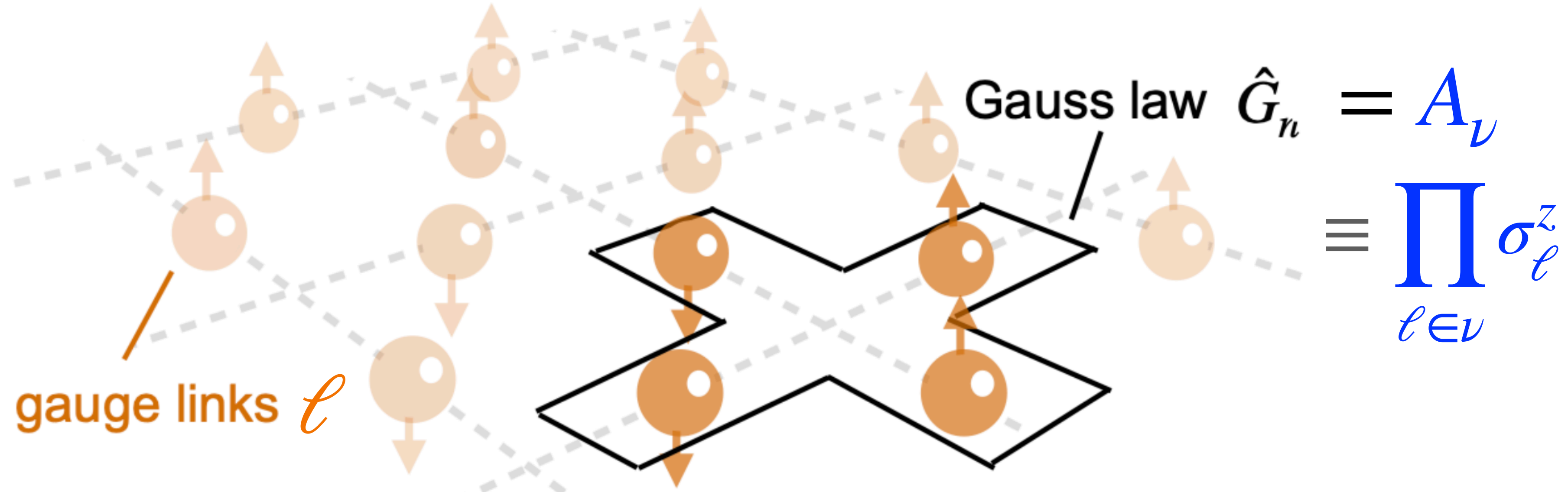
Symmetry-conscious Random Measurement

Lattice Gauge Theories

- **Z_2 Lattice Gauge Theory**



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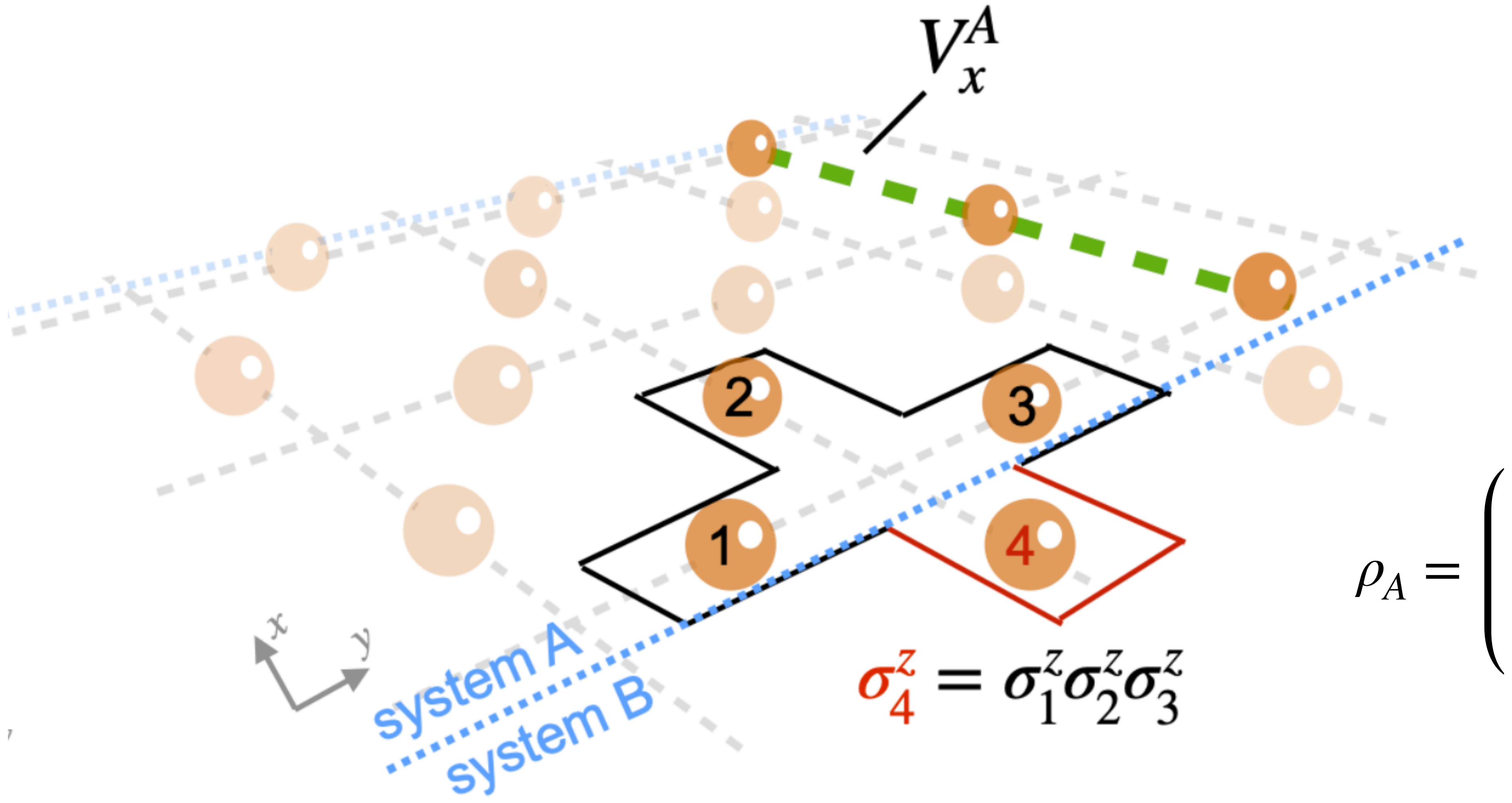

$\sigma^z_4 = \sigma^z_1 \sigma^z_2 \sigma^z_3$

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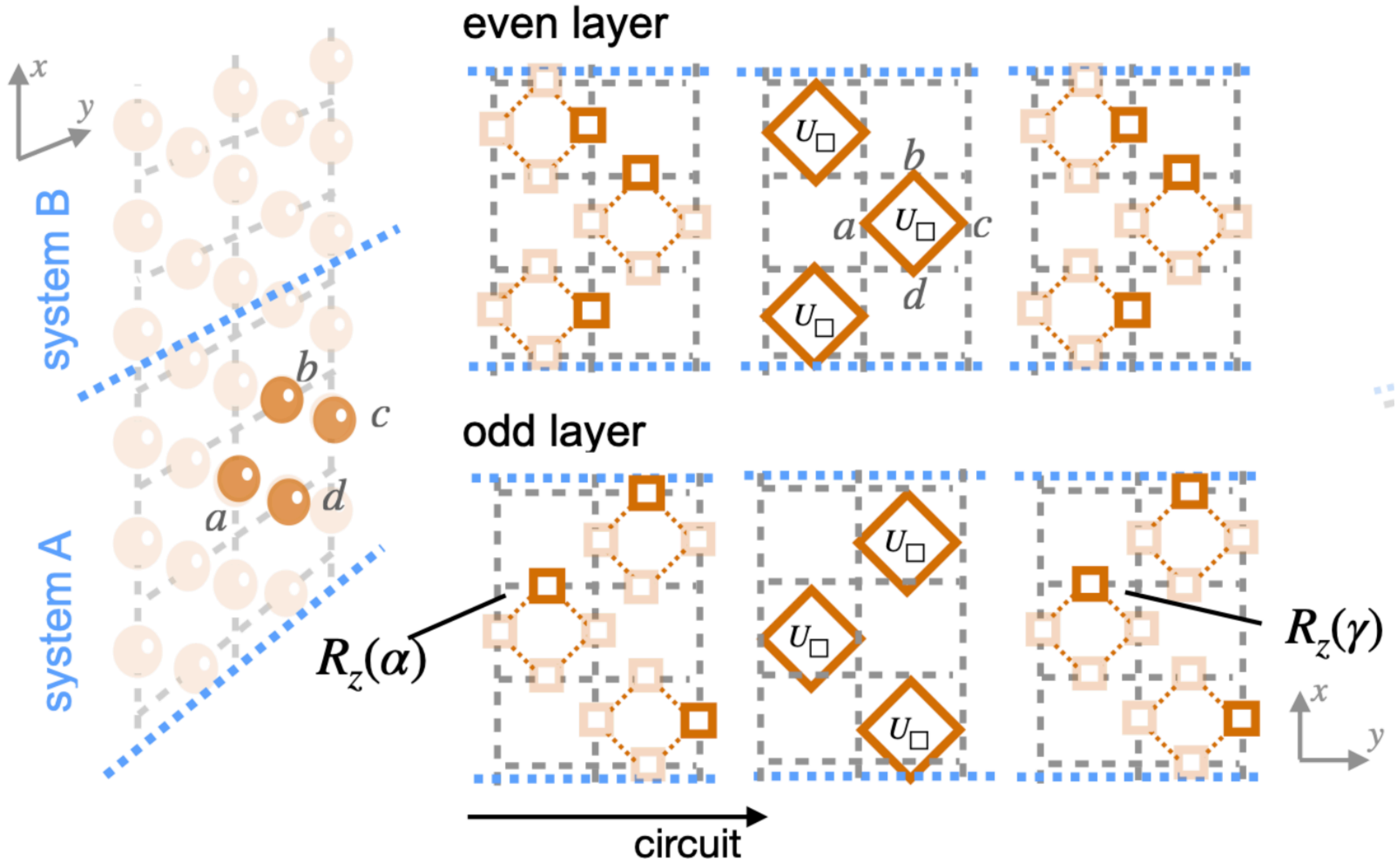

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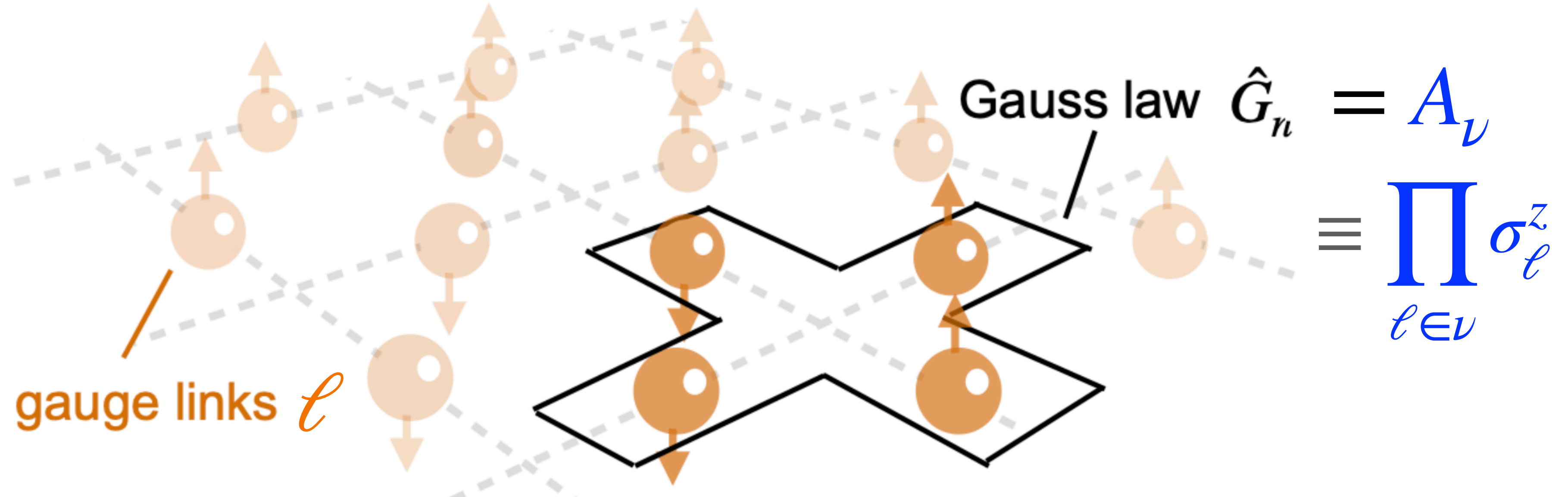
Symmetry-conscious Random Measurement

Lattice Gauge Theories

- **Z_2 Lattice Gauge Theory**



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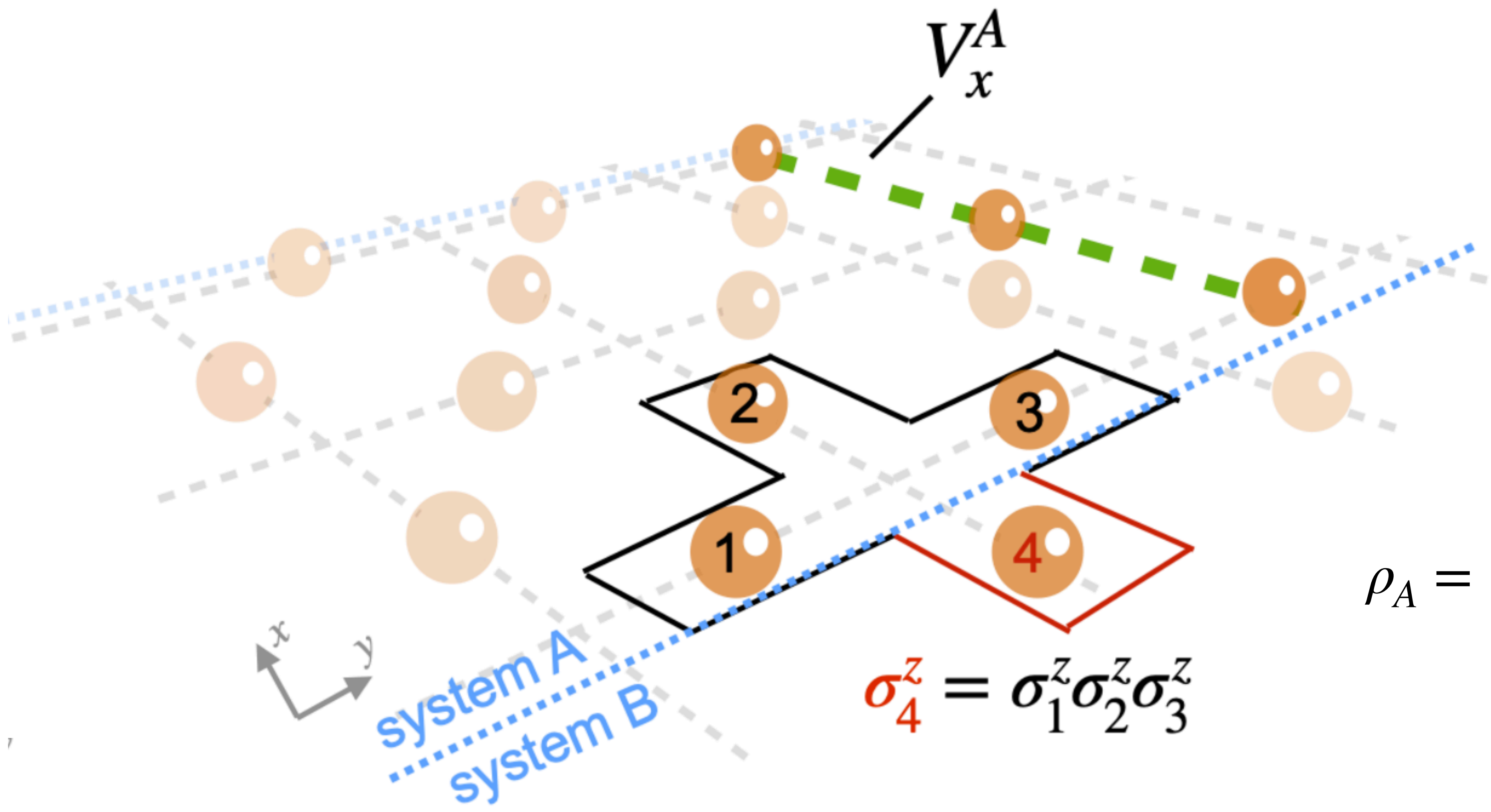

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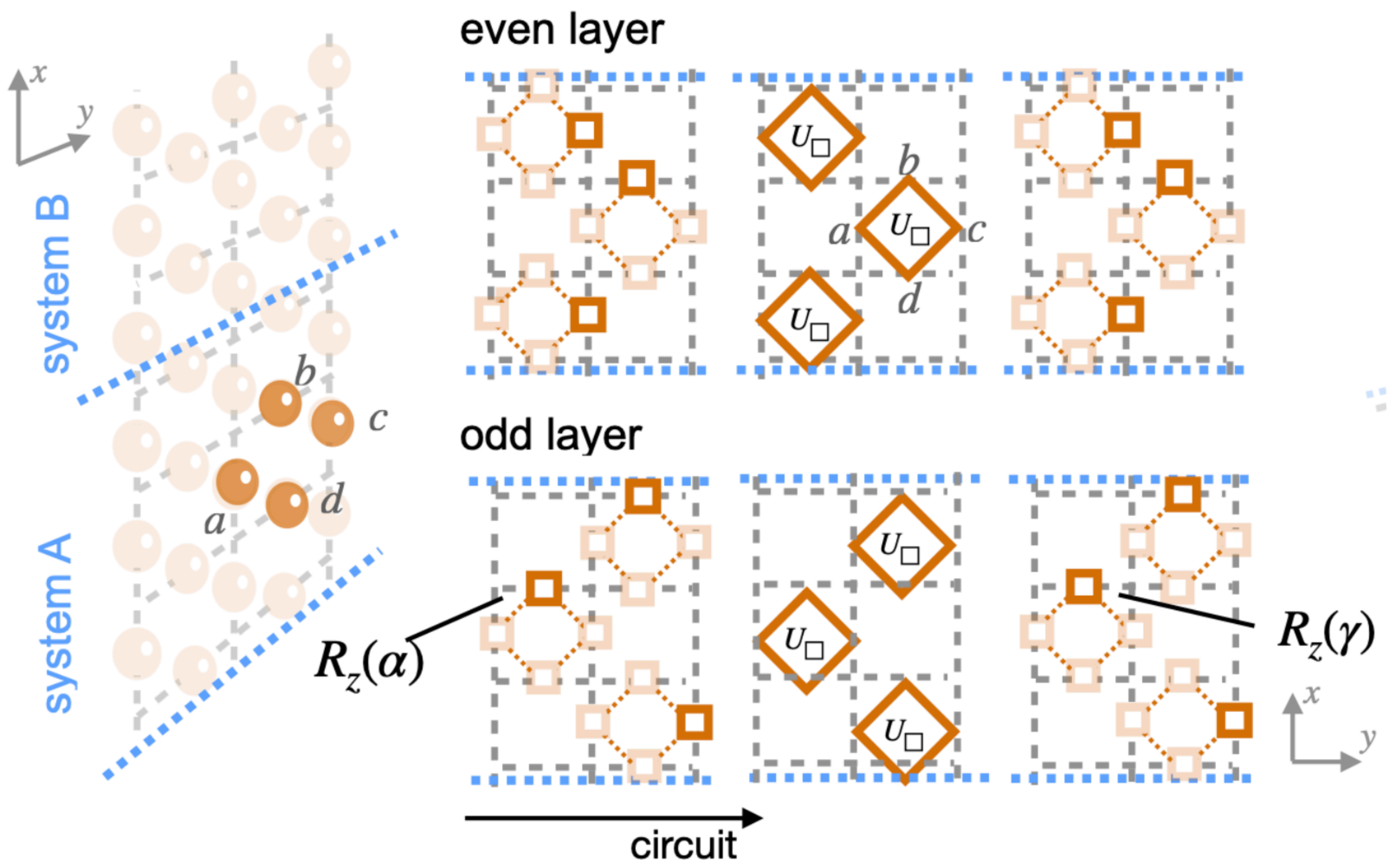

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Symmetry-conscious Random Measurement

Lattice Gauge Theories

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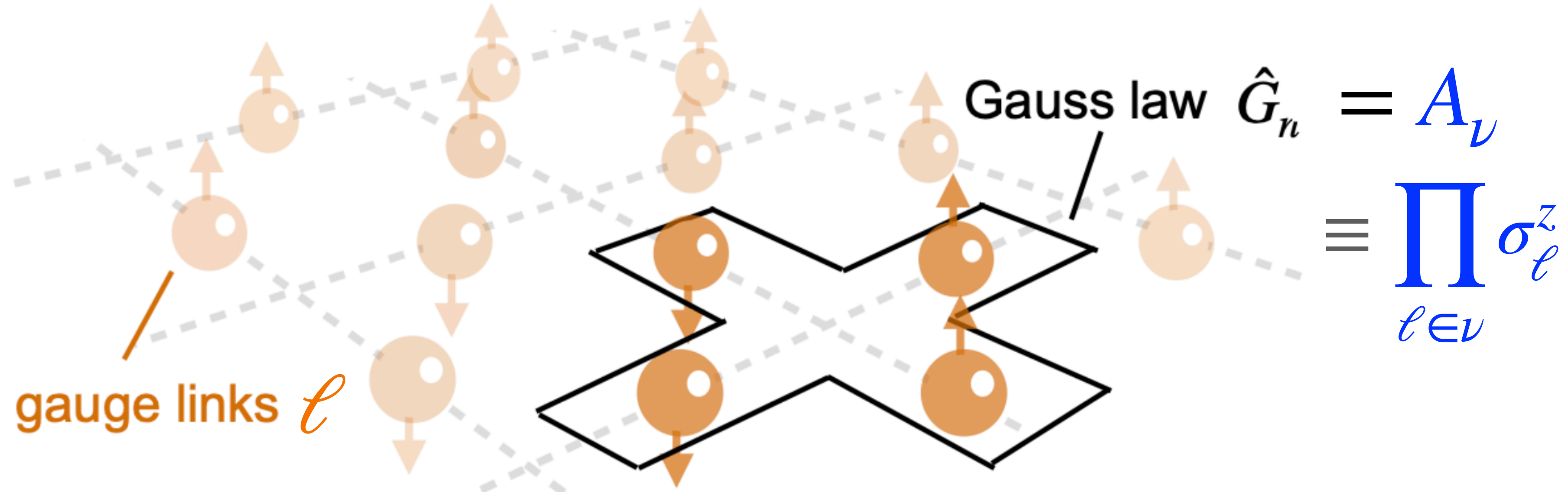

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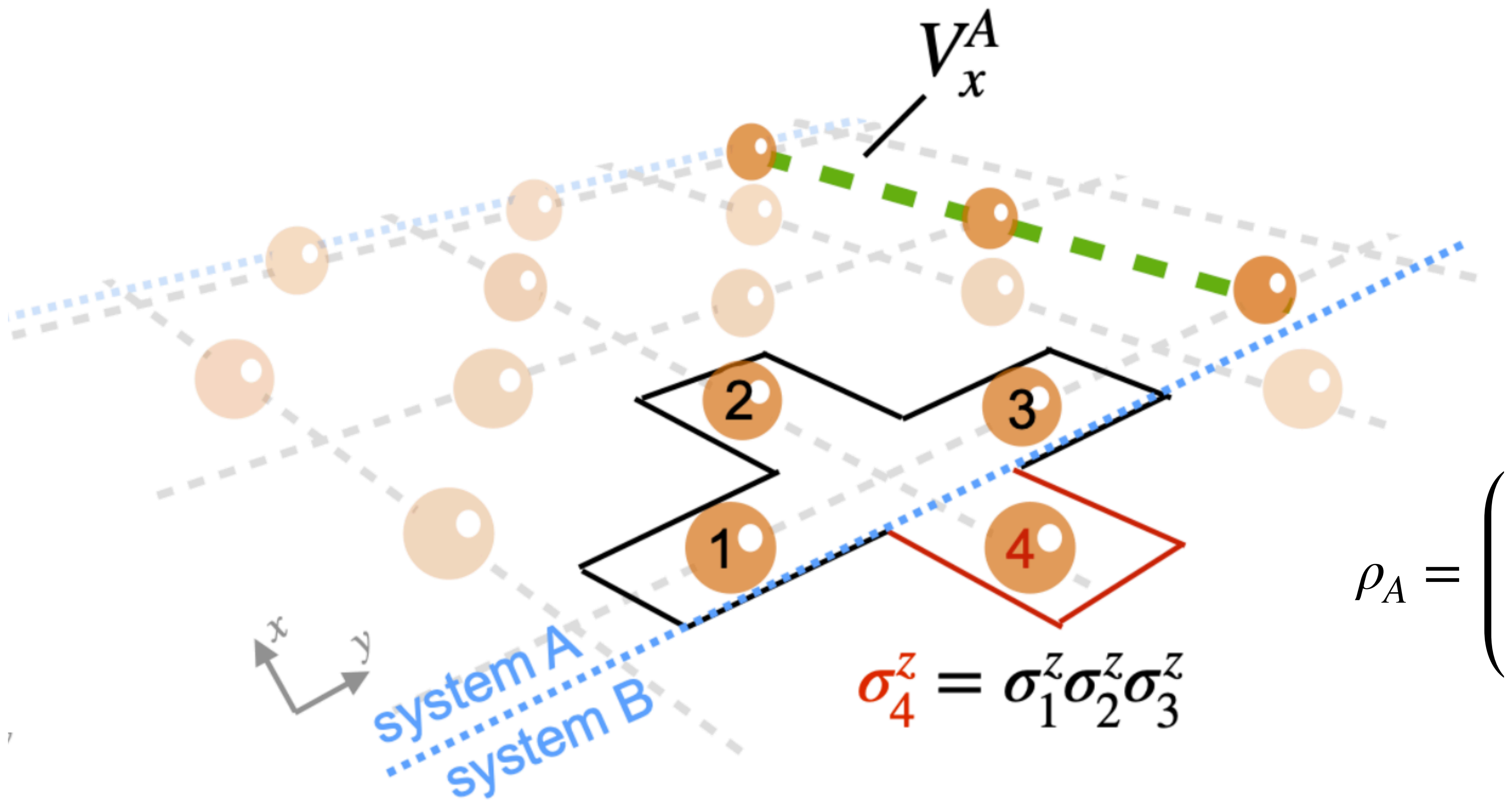

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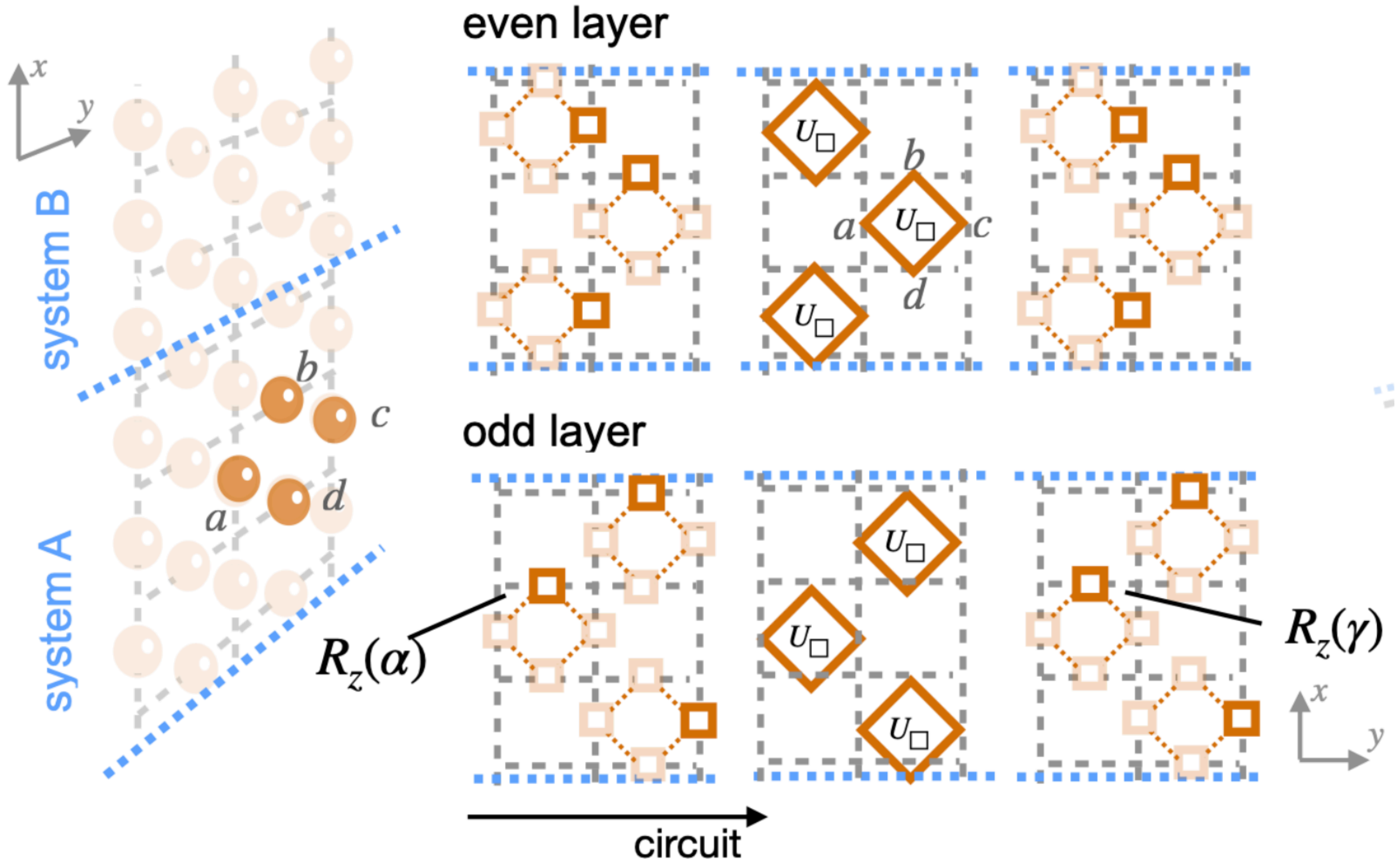

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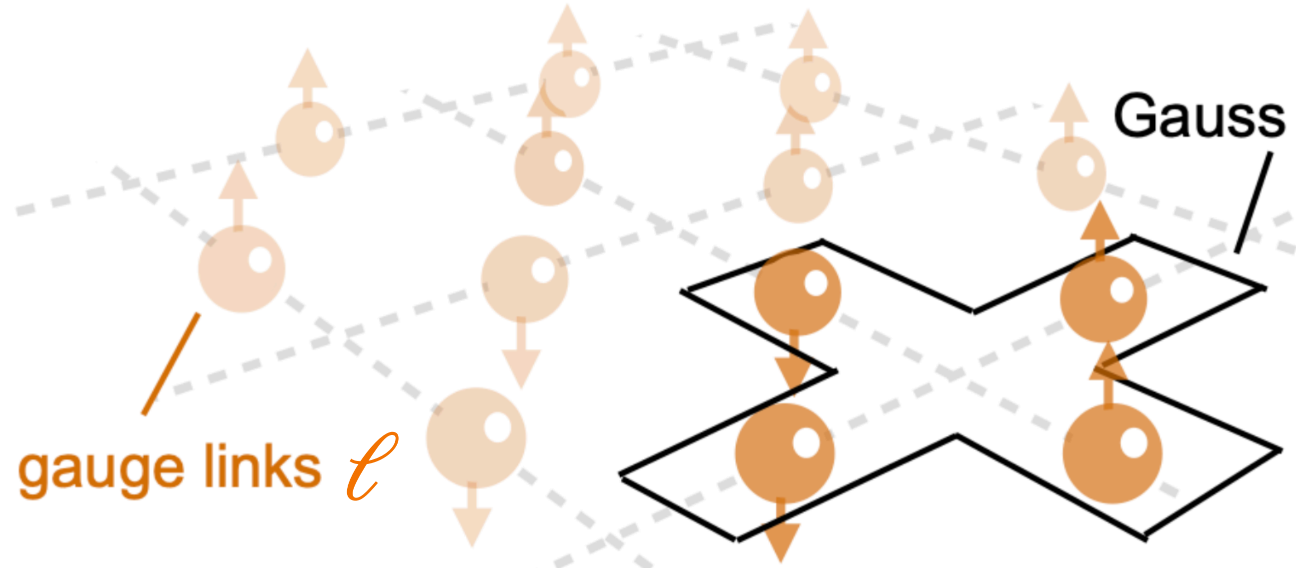
Symmetry-conscious Random Measurement

Lattice Gauge Theories

- **Z_2 Lattice Gauge Theory**



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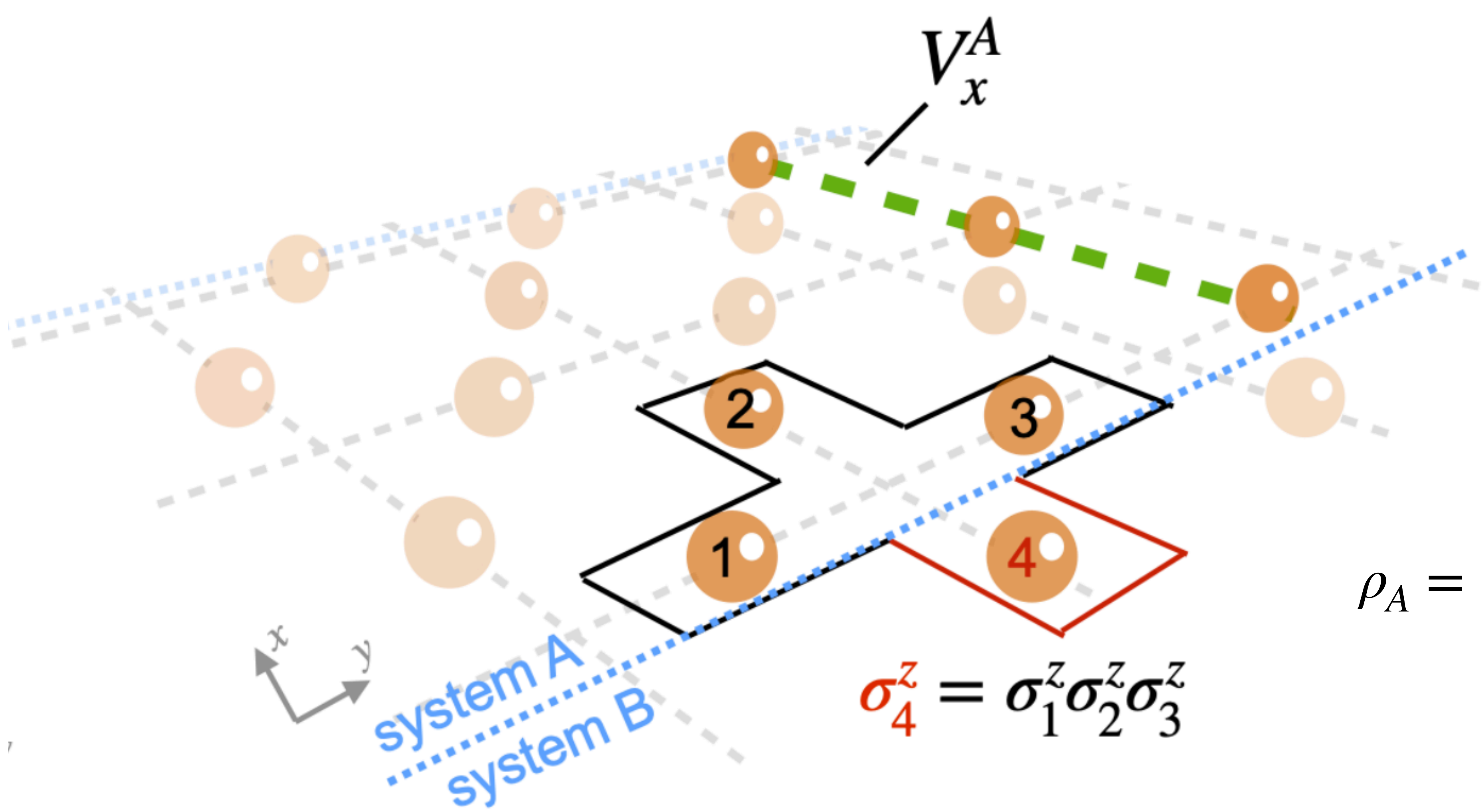

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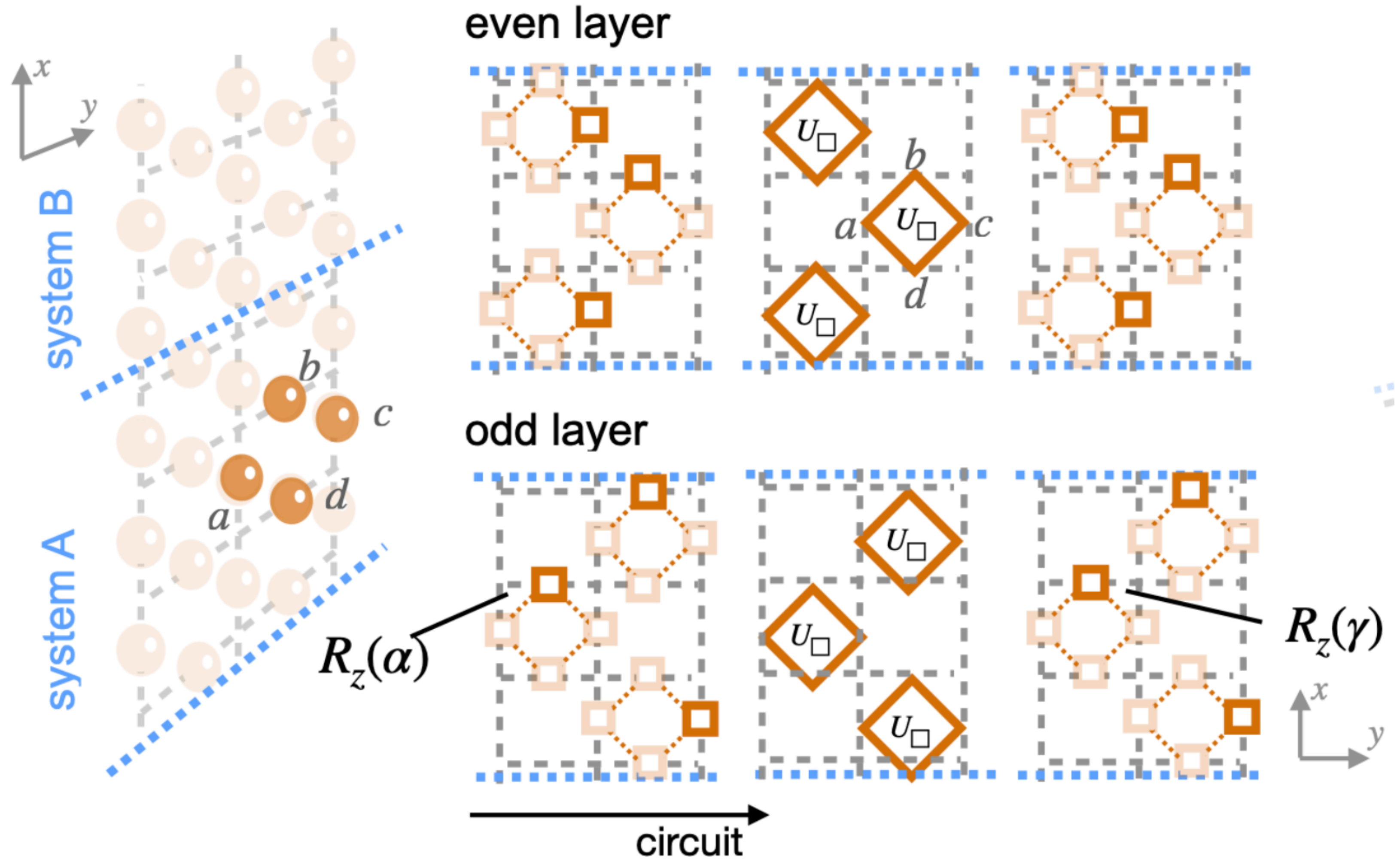

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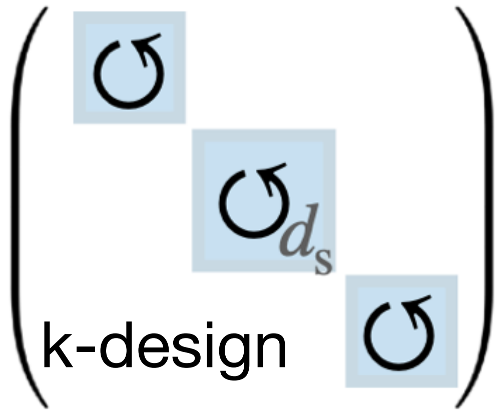

symmetry conscious

Symmetry-conscious Random Measurement

Lattice Gauge Theories

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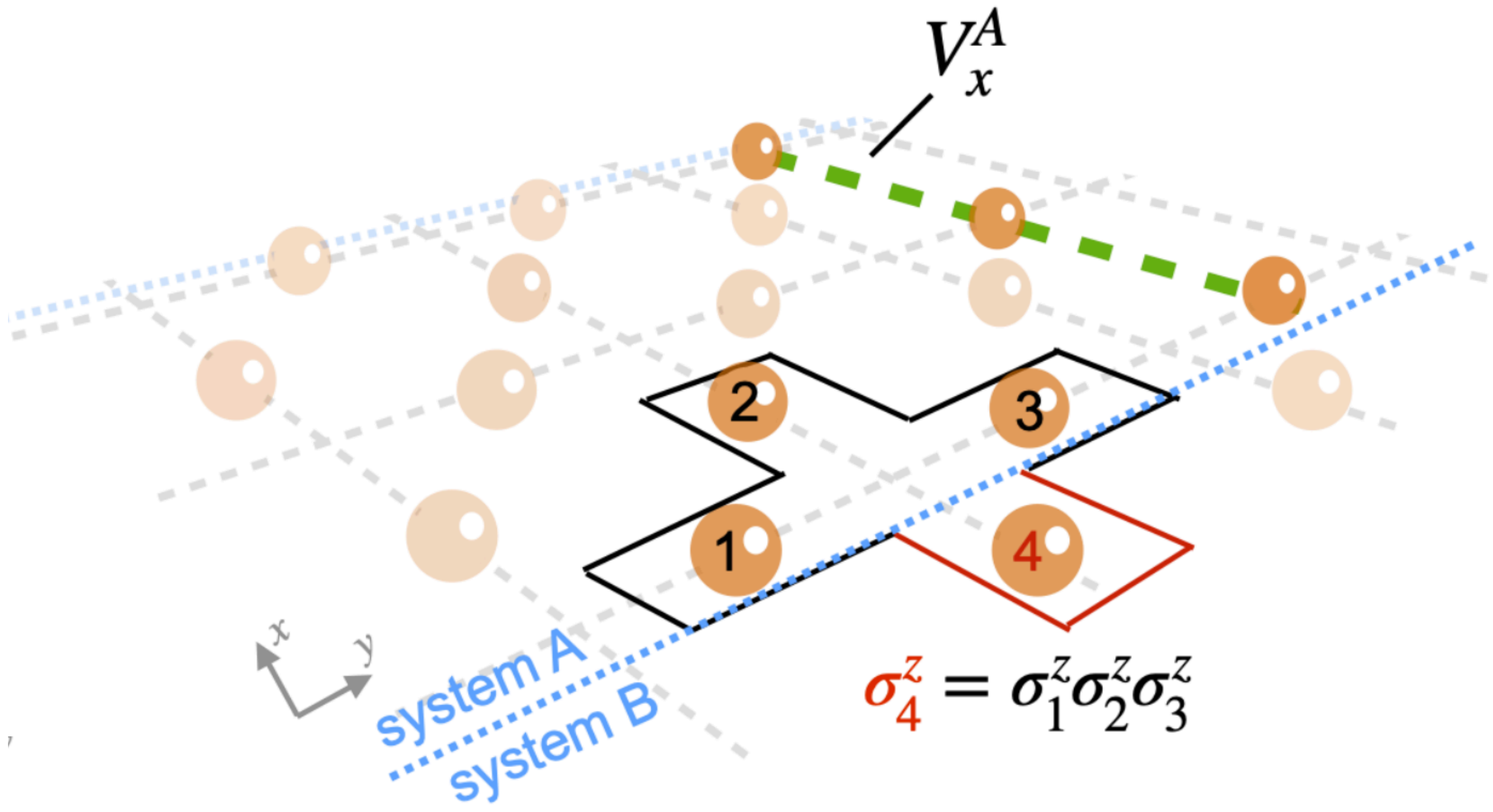
Lattice Gauge Theories



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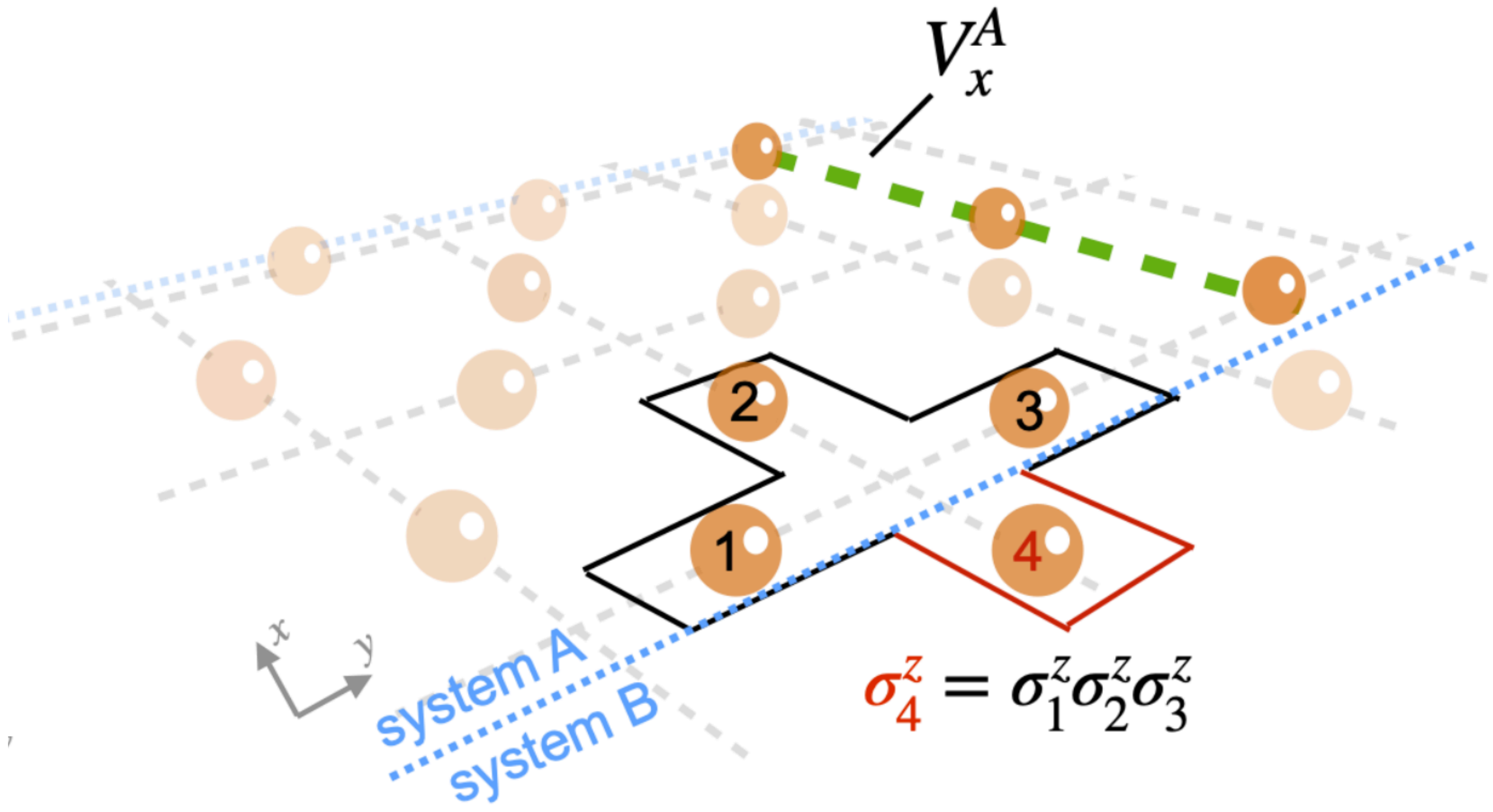

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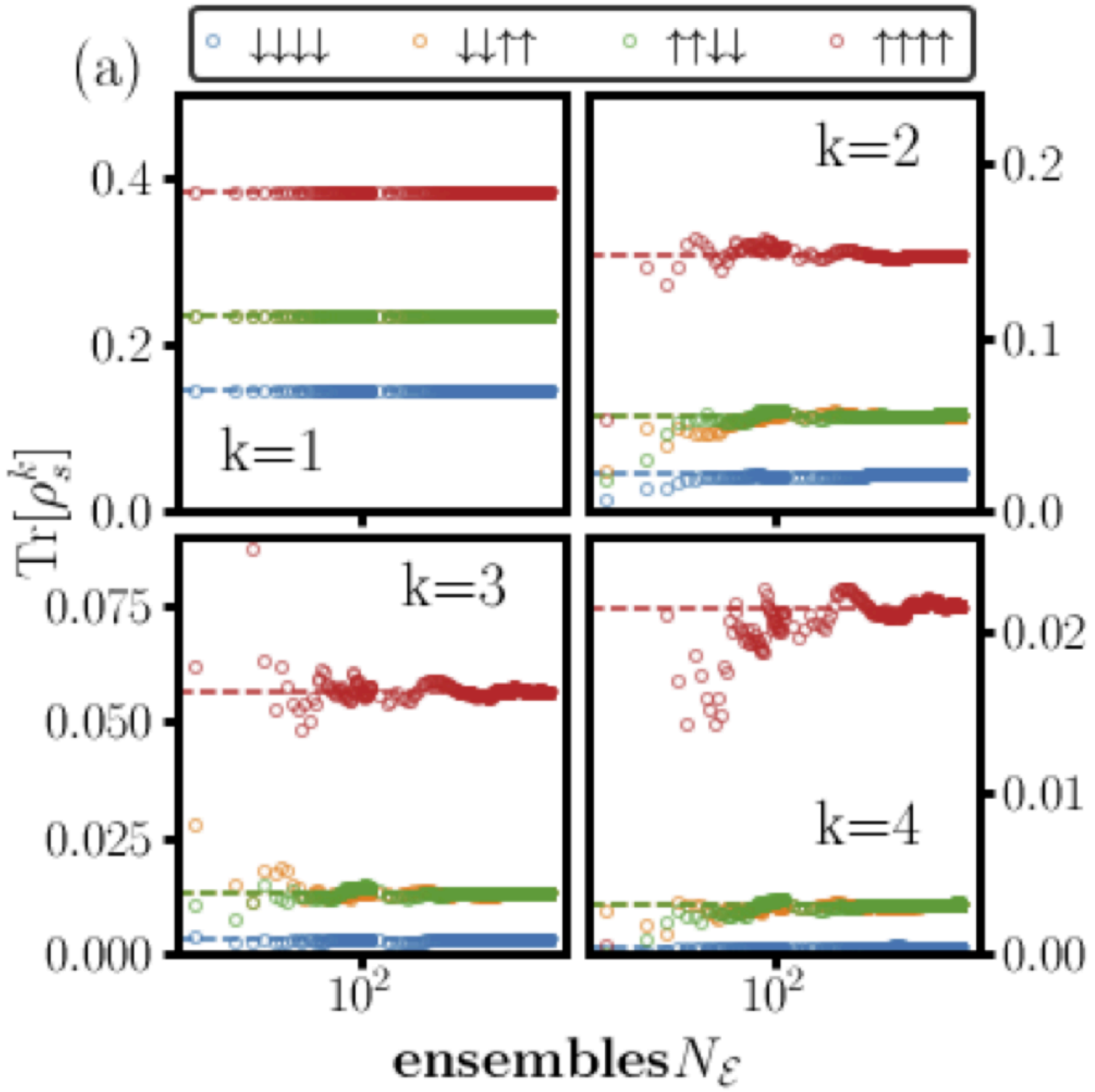
k-designs give k-Renyi entropies



Jake Bringewatt, Jon Kunjummen, NM, arXiv:2303.15519

Symmetry-conscious Random Measurement

Lattice Gauge Theories

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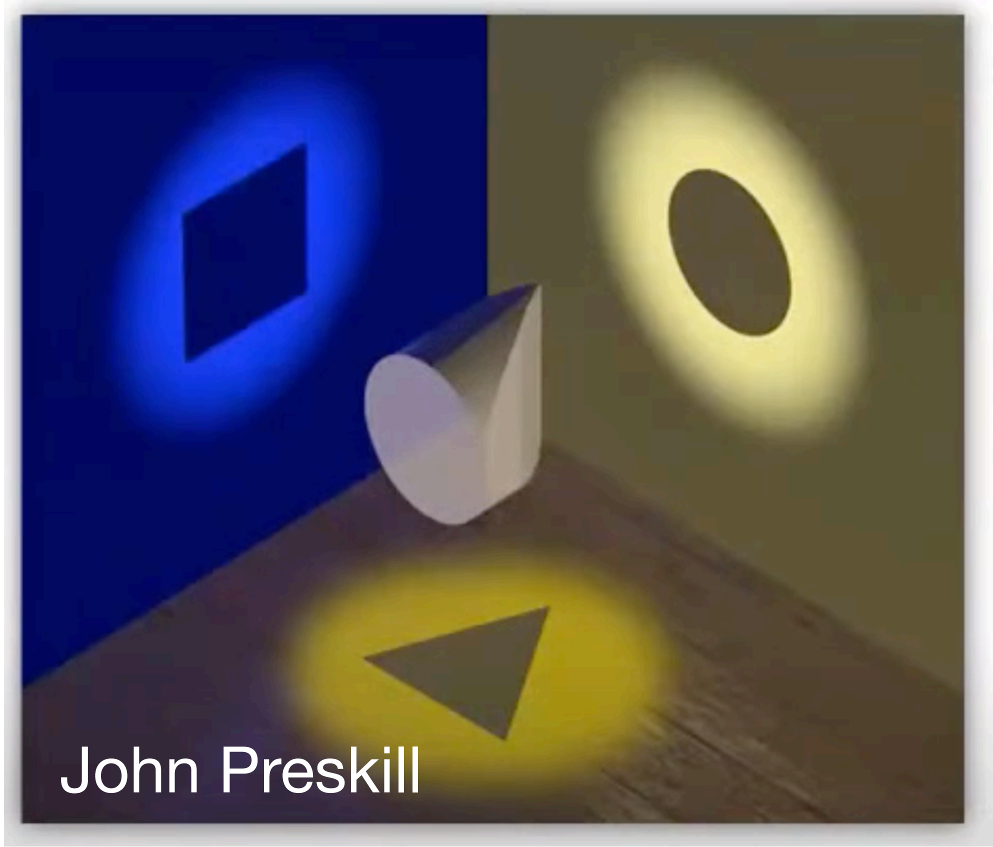
Lattice Gauge Theories

- **Shadows**



Huang, Kueng, Preskill,
Nat. Phys. 16 (2020), 1050

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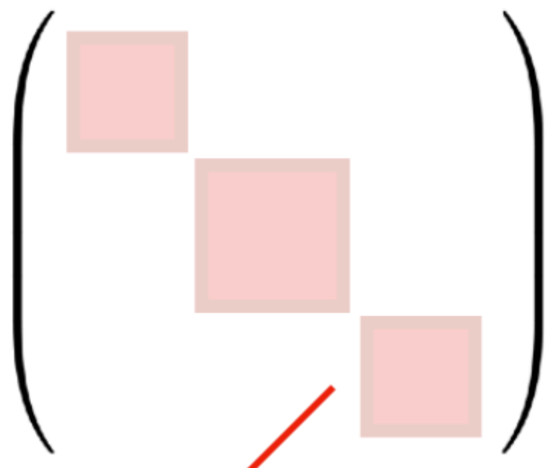

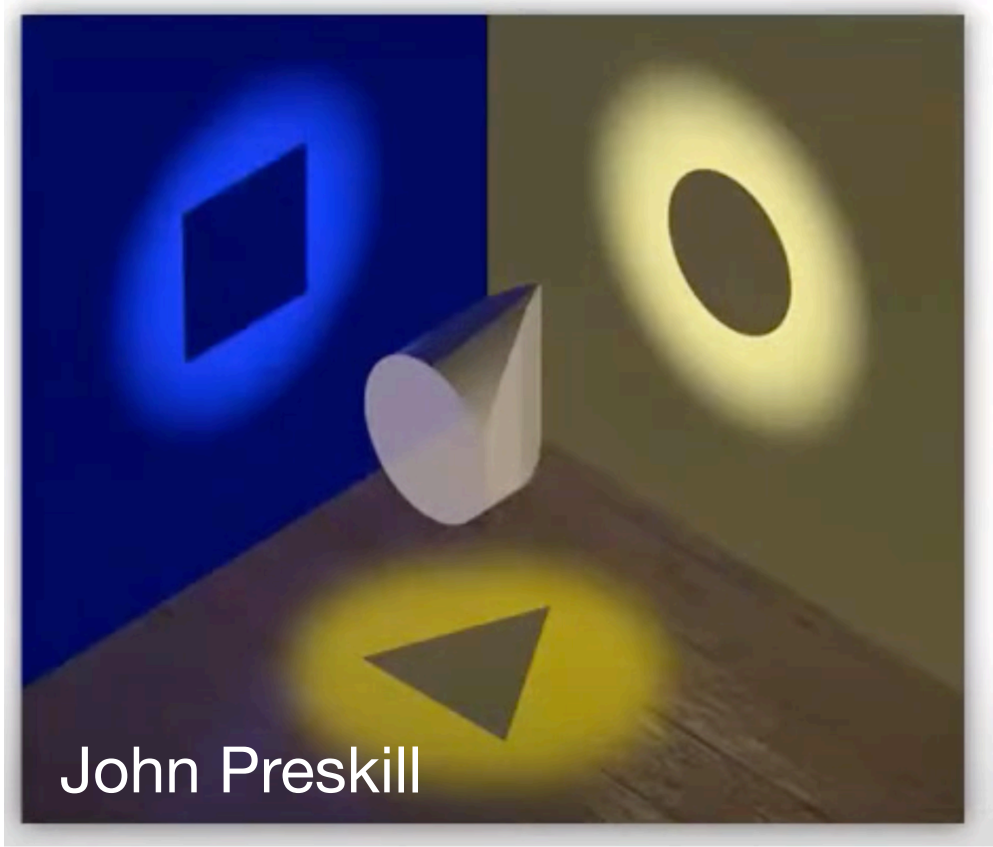

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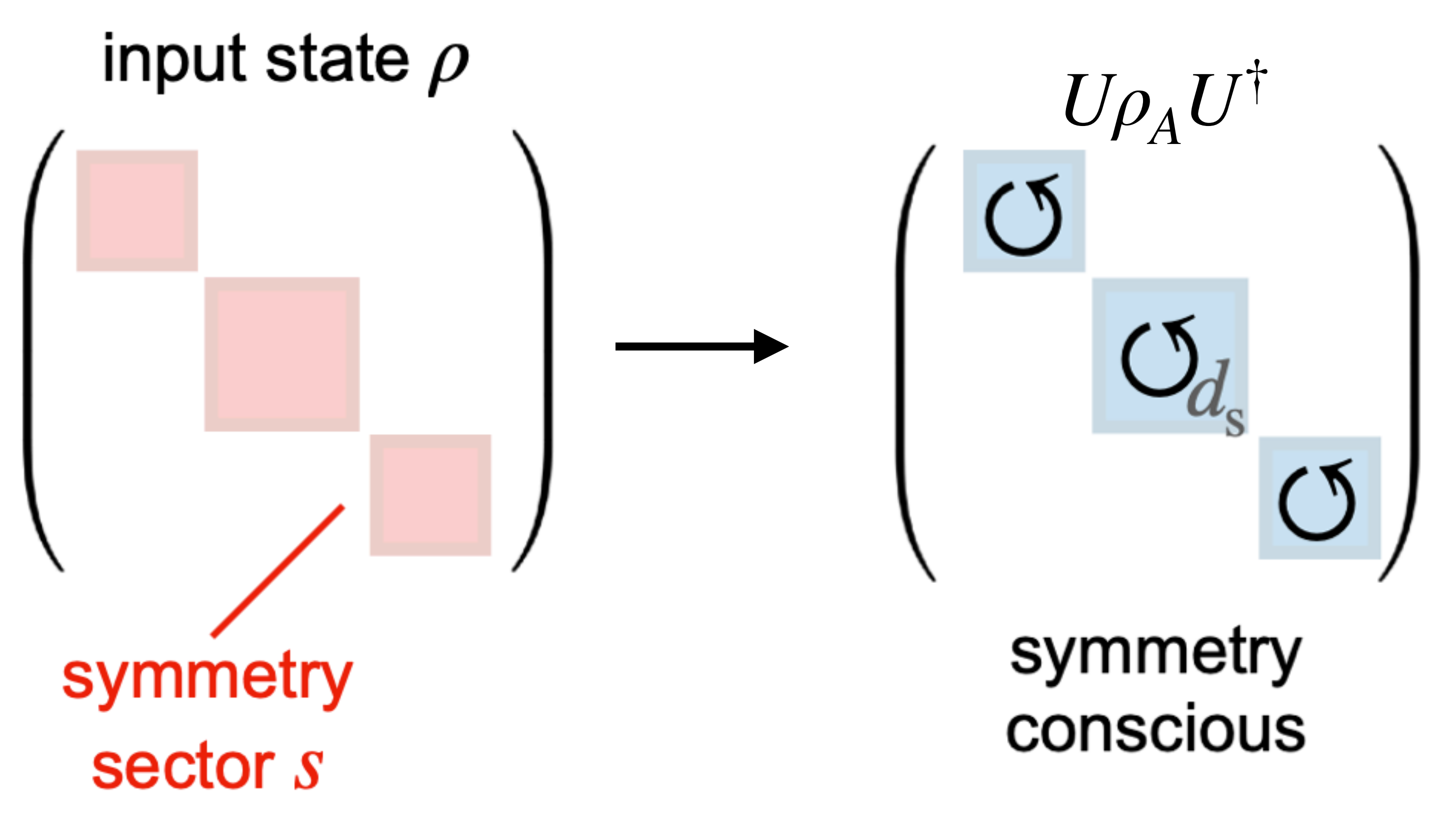

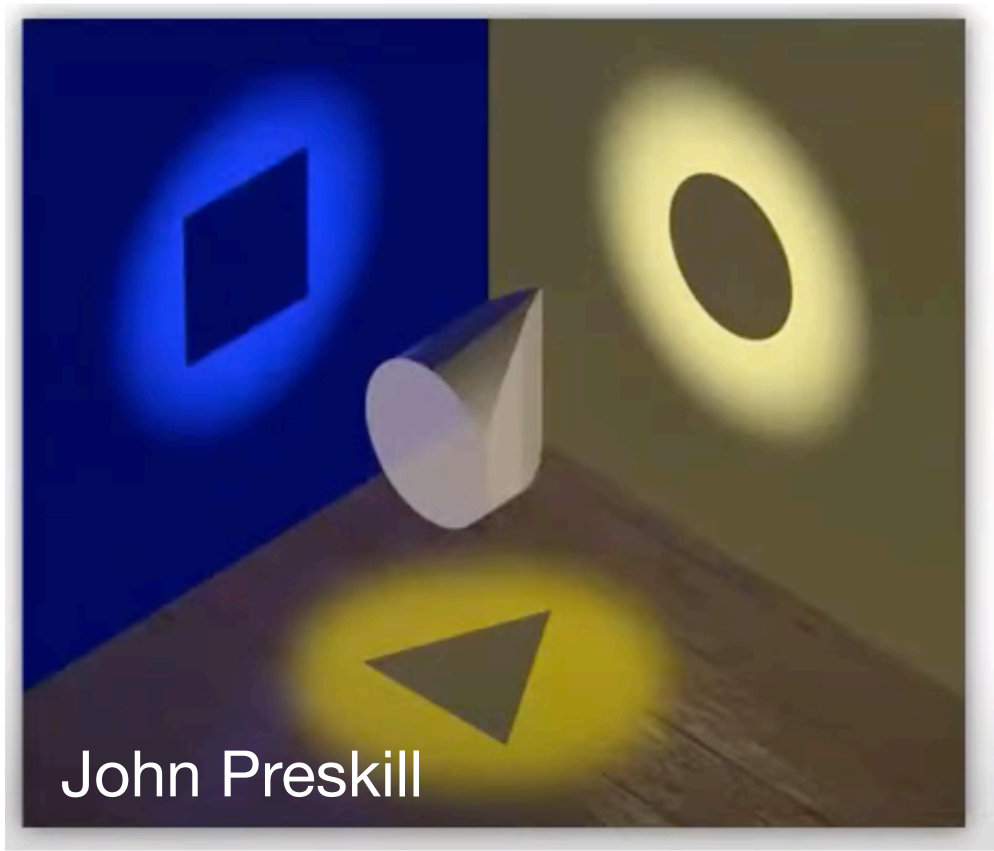

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Lattice Gauge Theories

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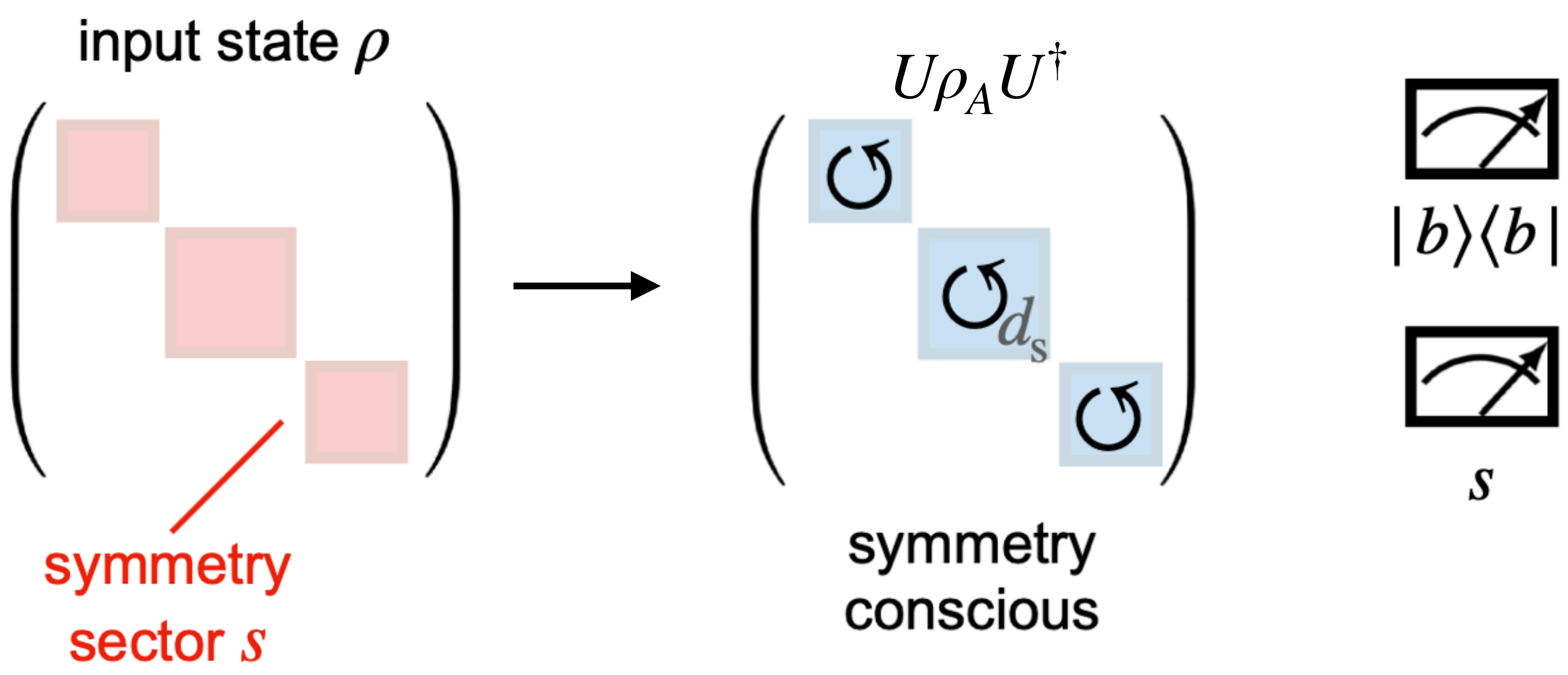

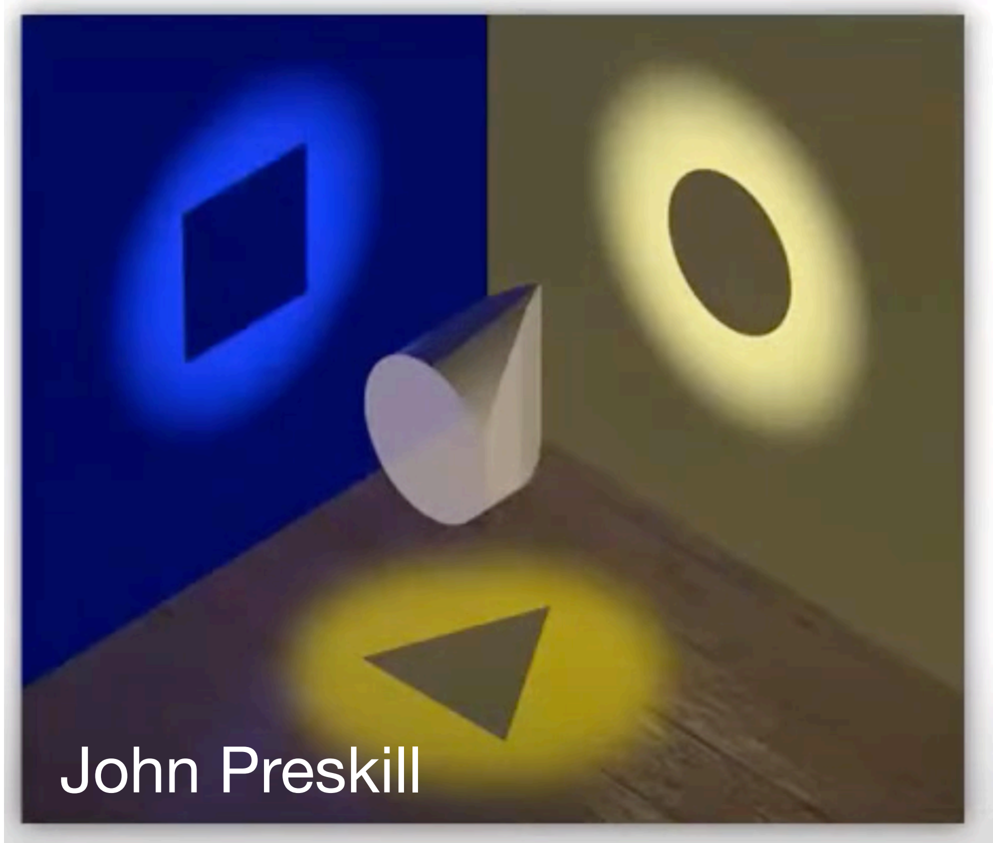

Huang, Kueng, Preskill,
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Symmetry-conscious Random Measurement

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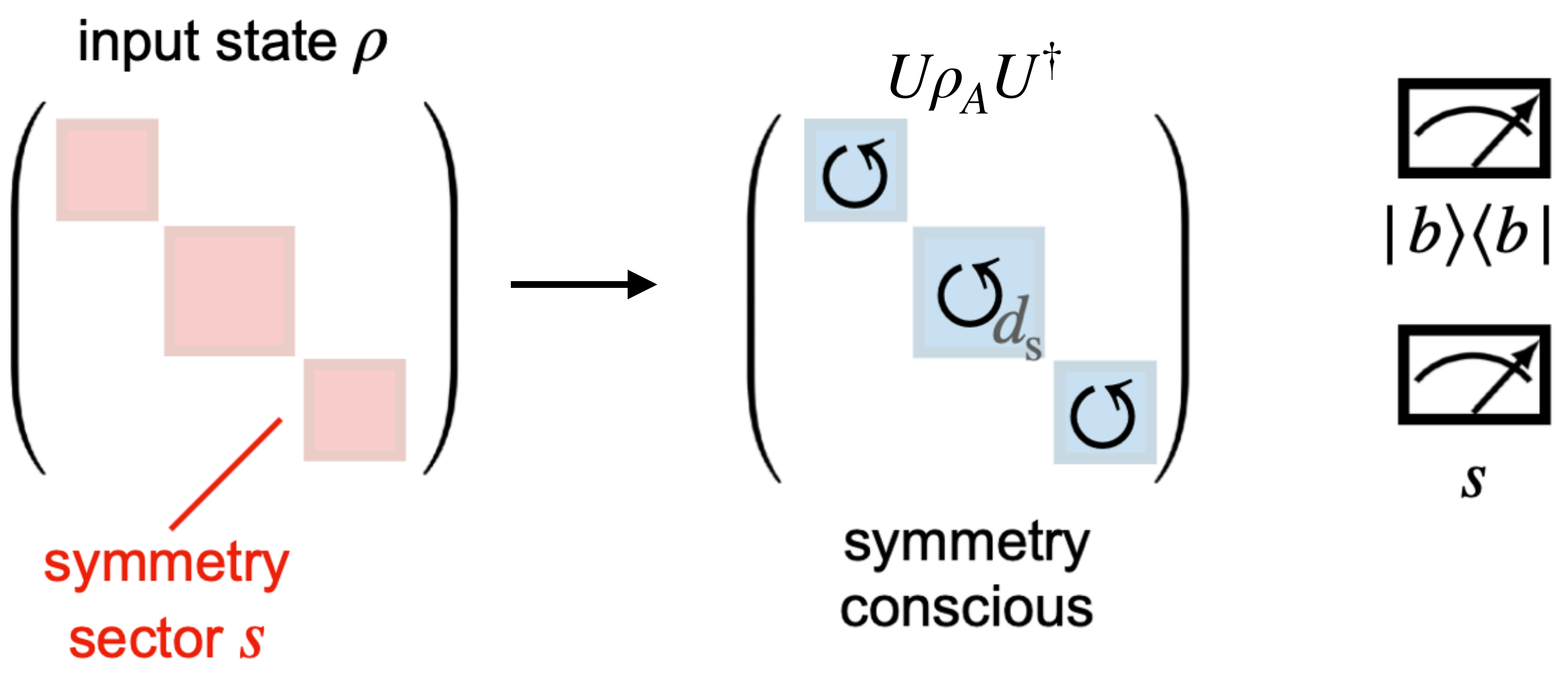
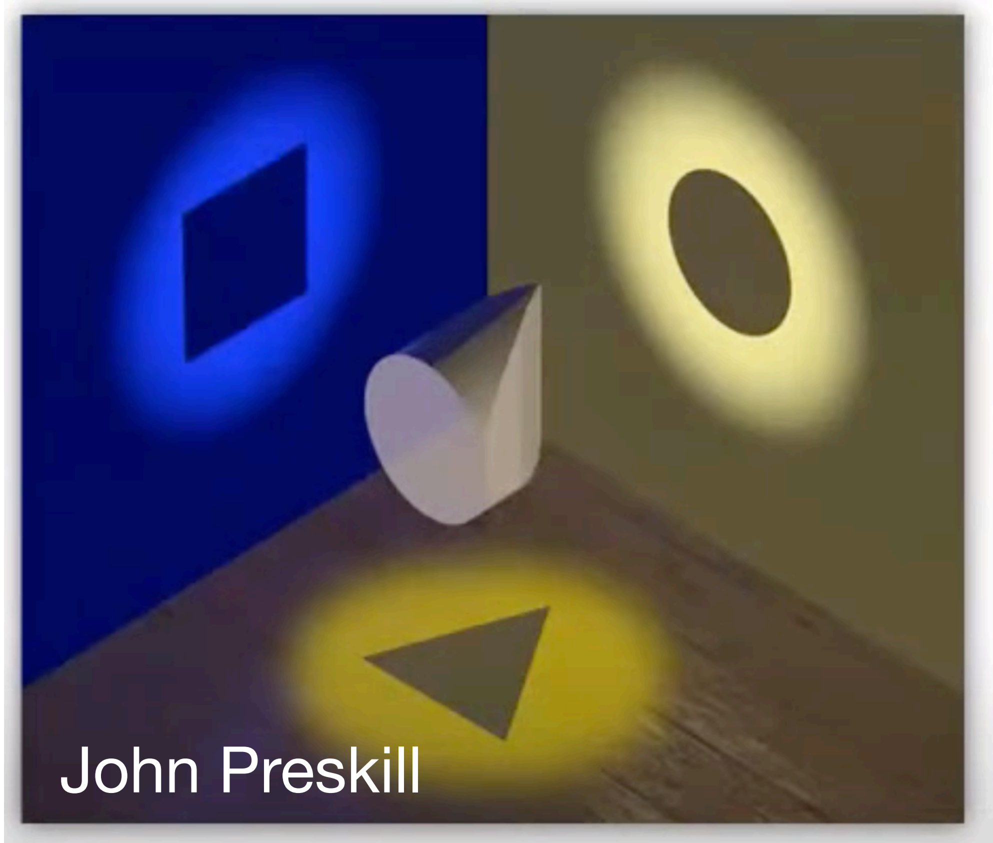


$U_s^\dagger |b, s\rangle\langle b, s| U_s$

classical shadow



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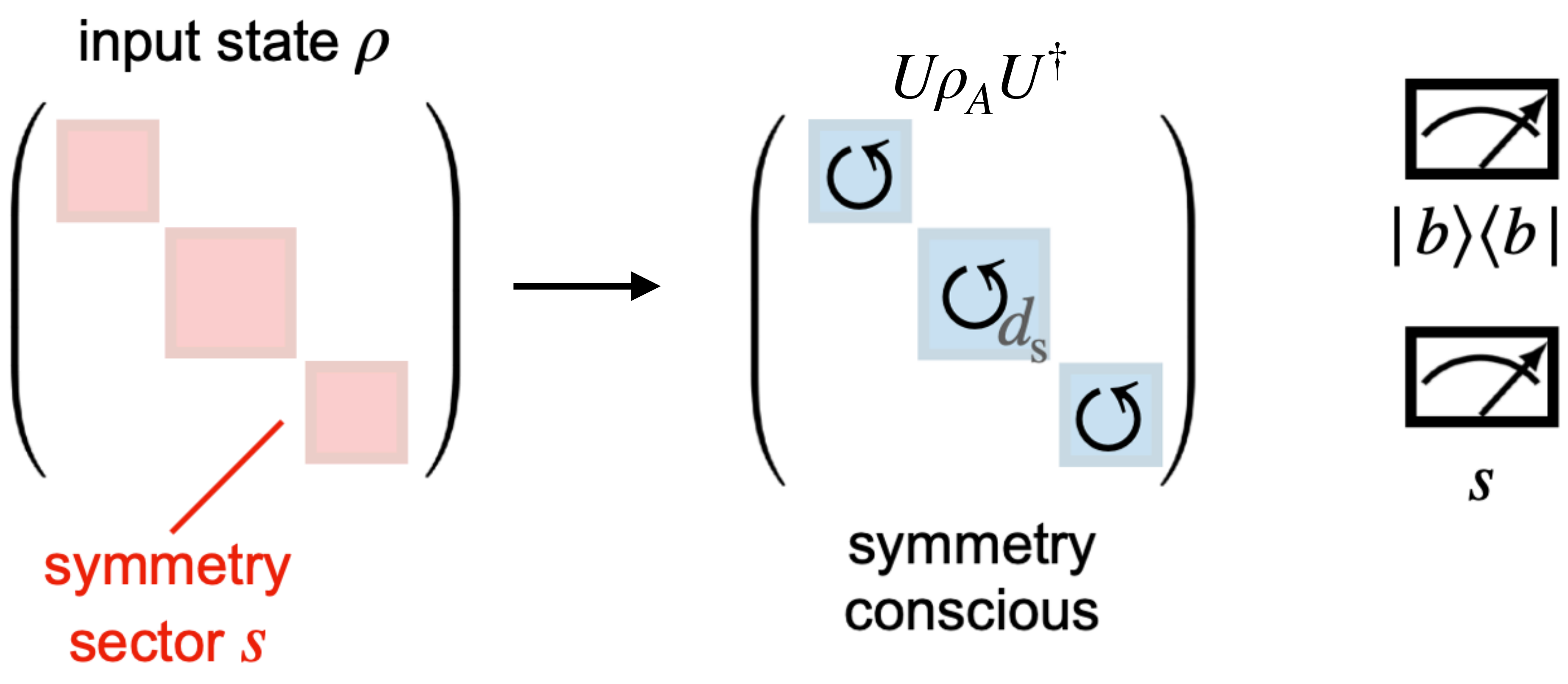

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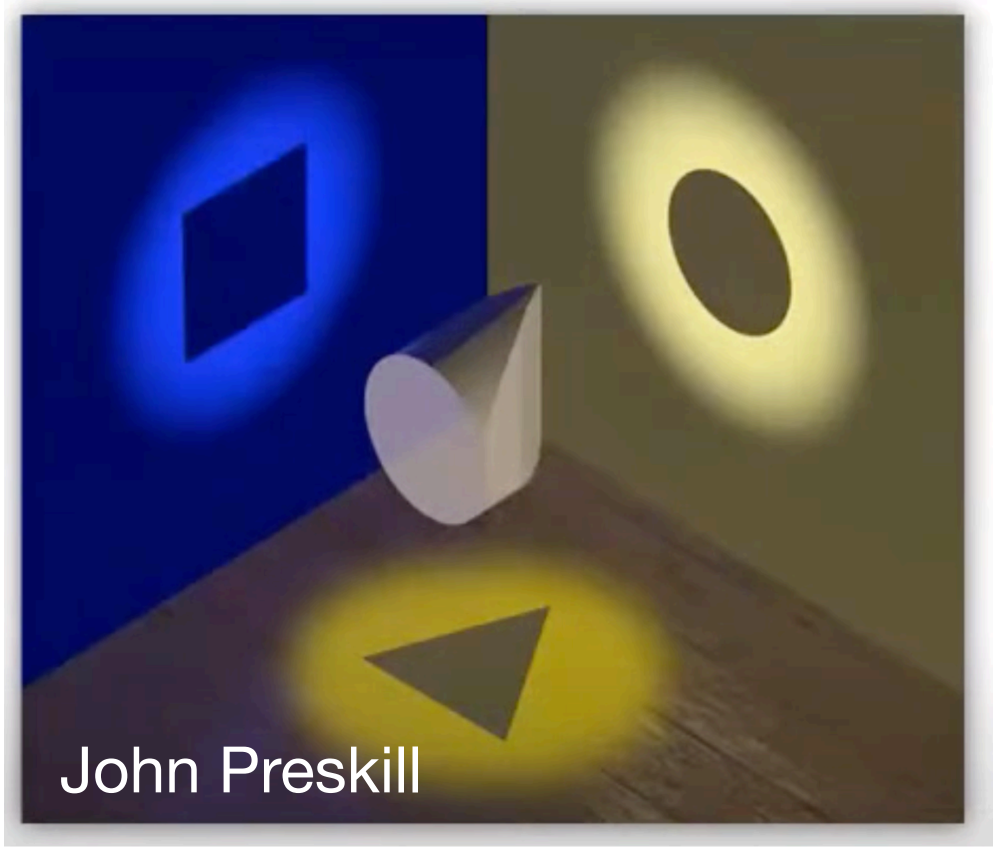

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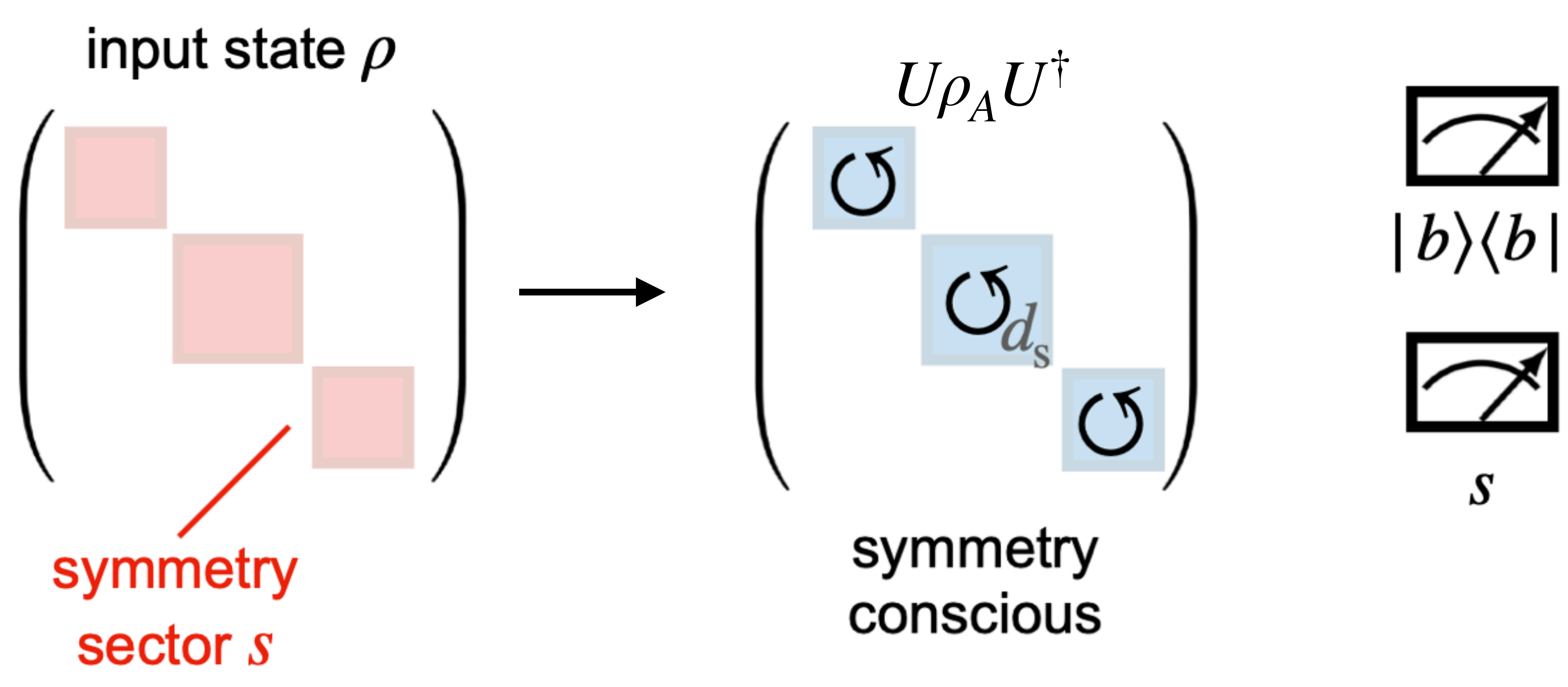

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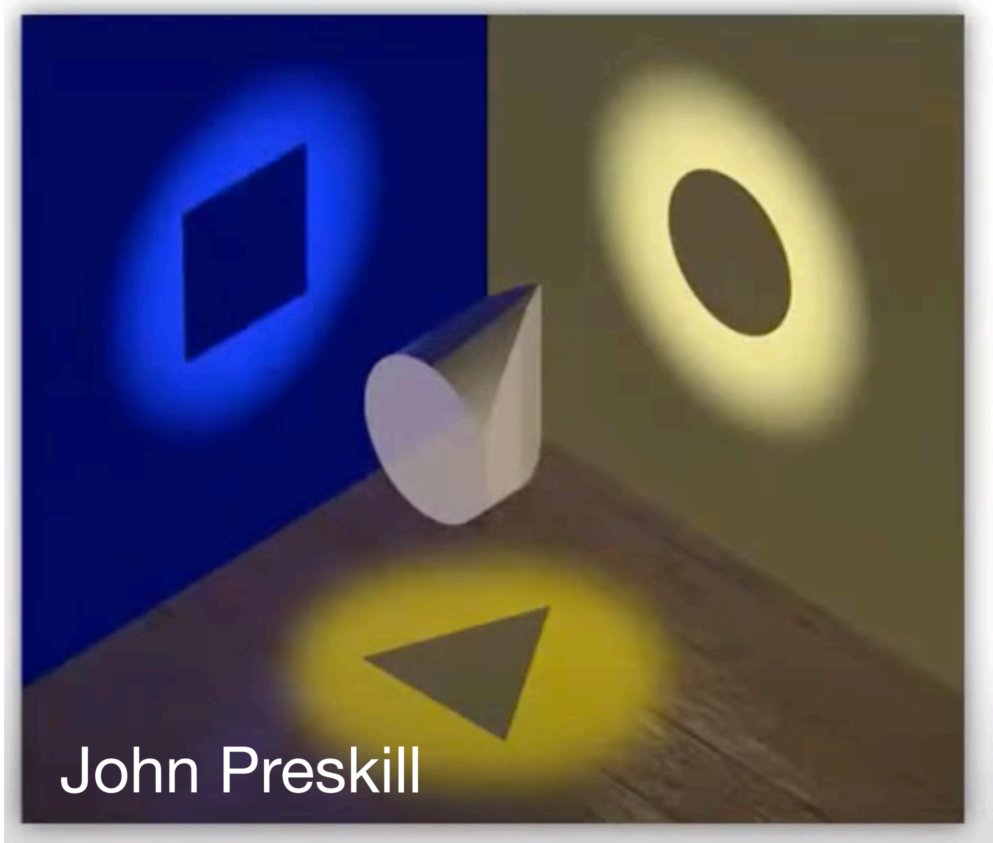

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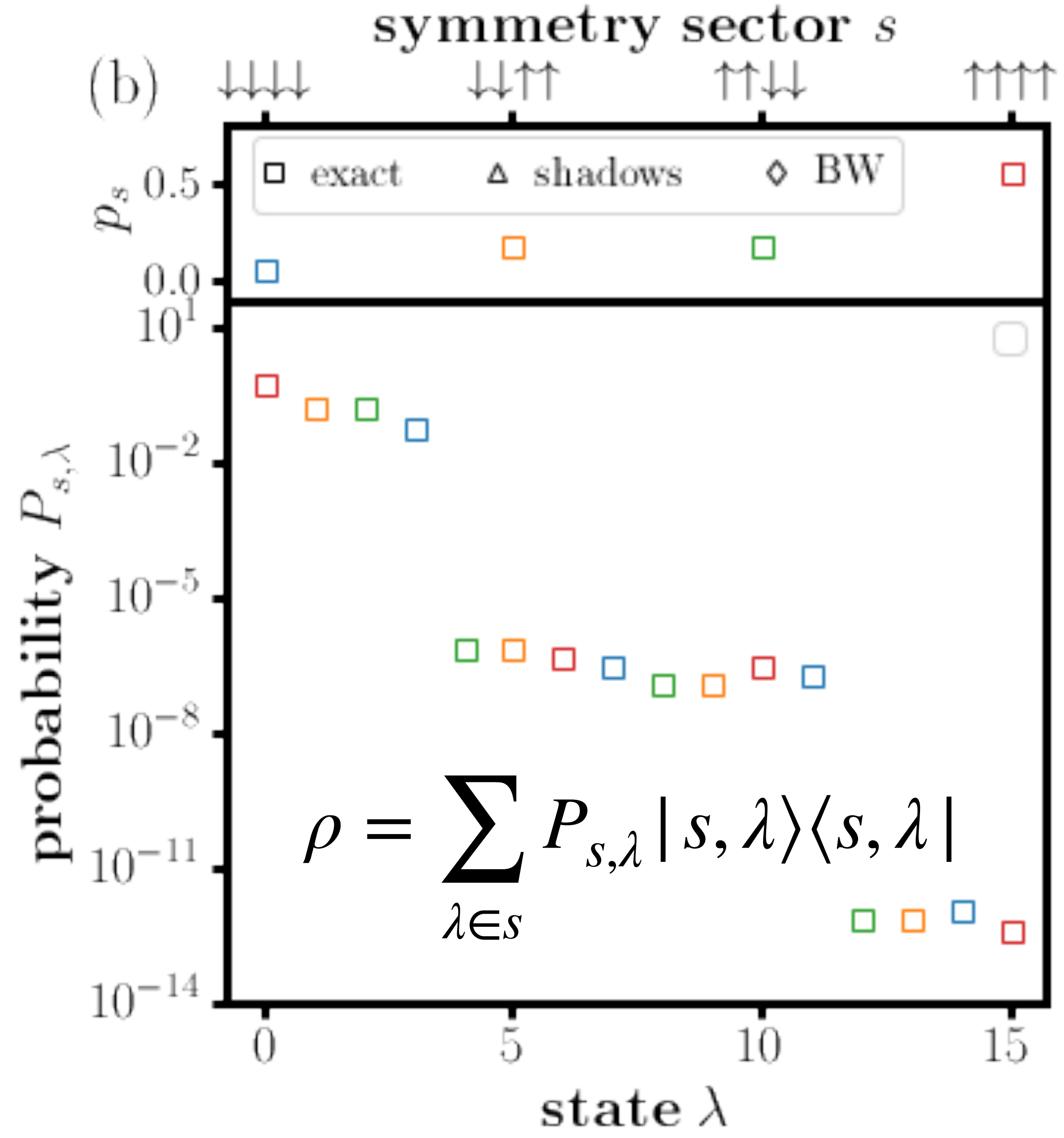

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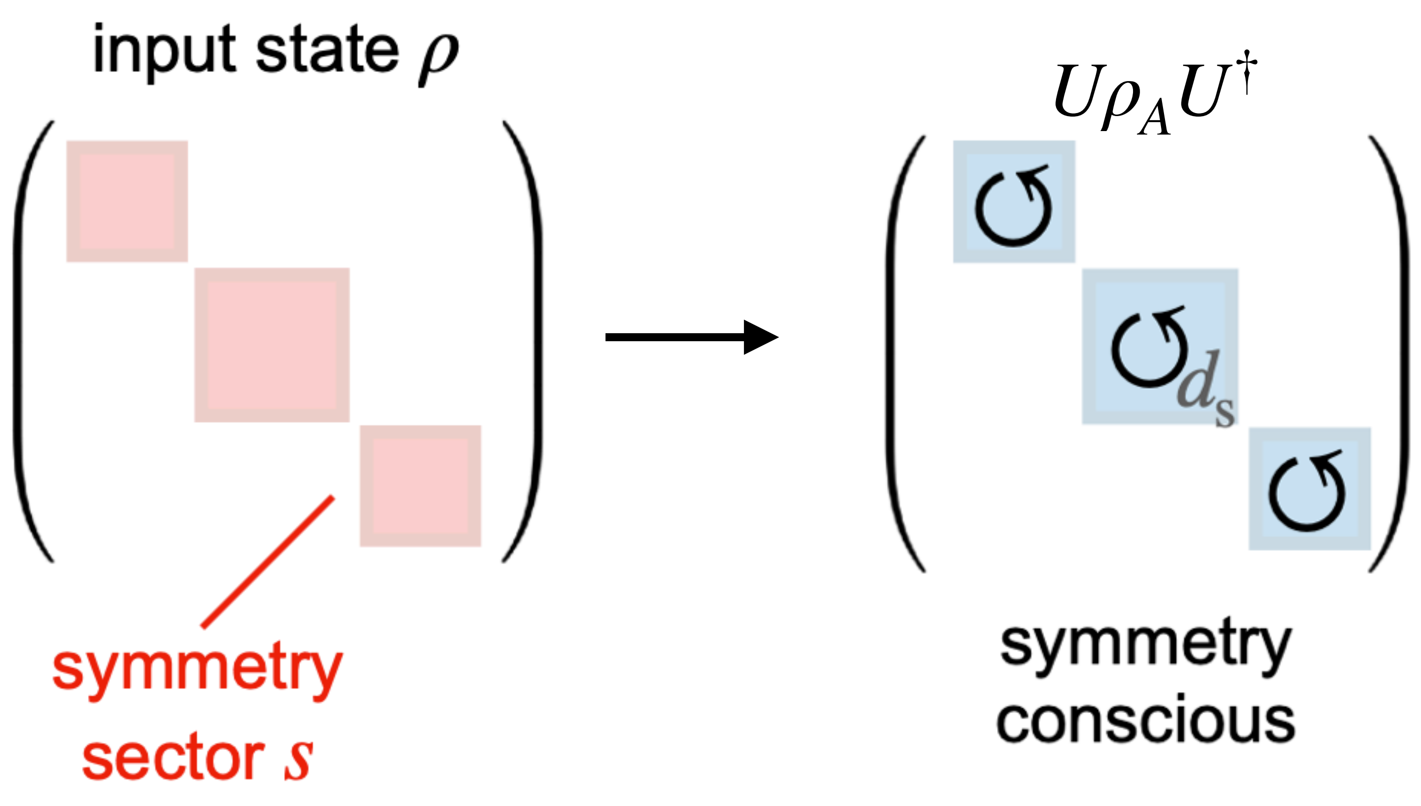

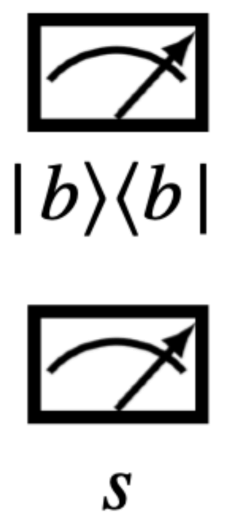

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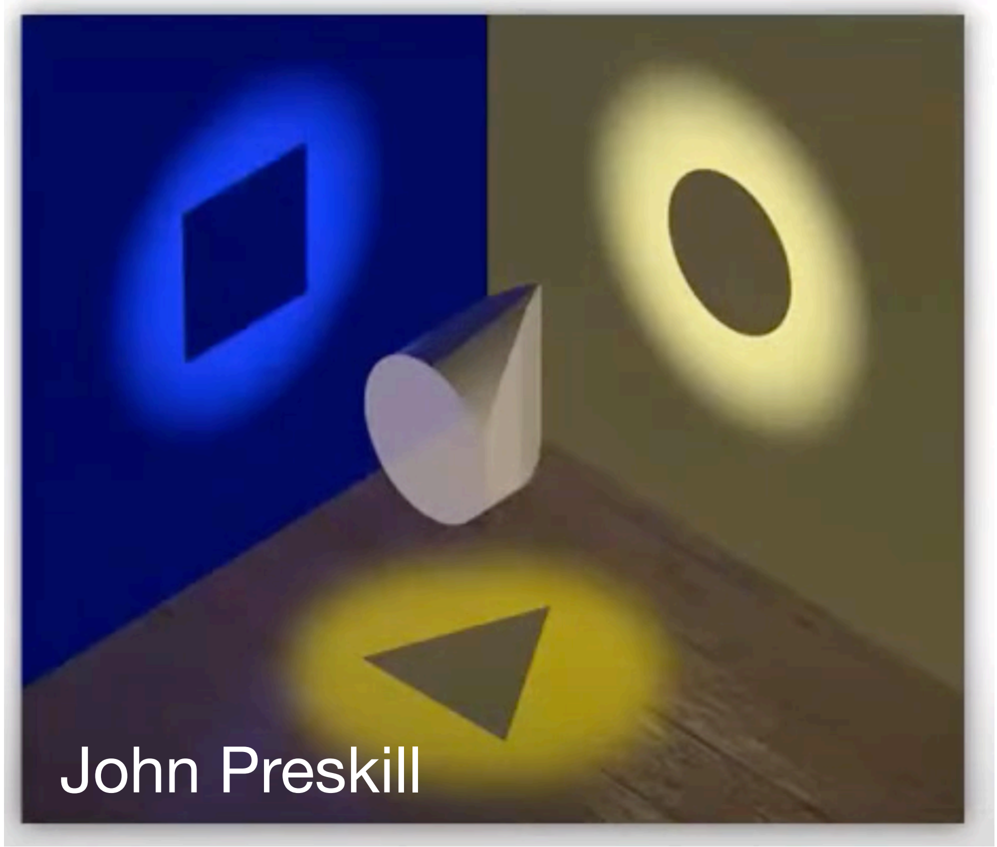

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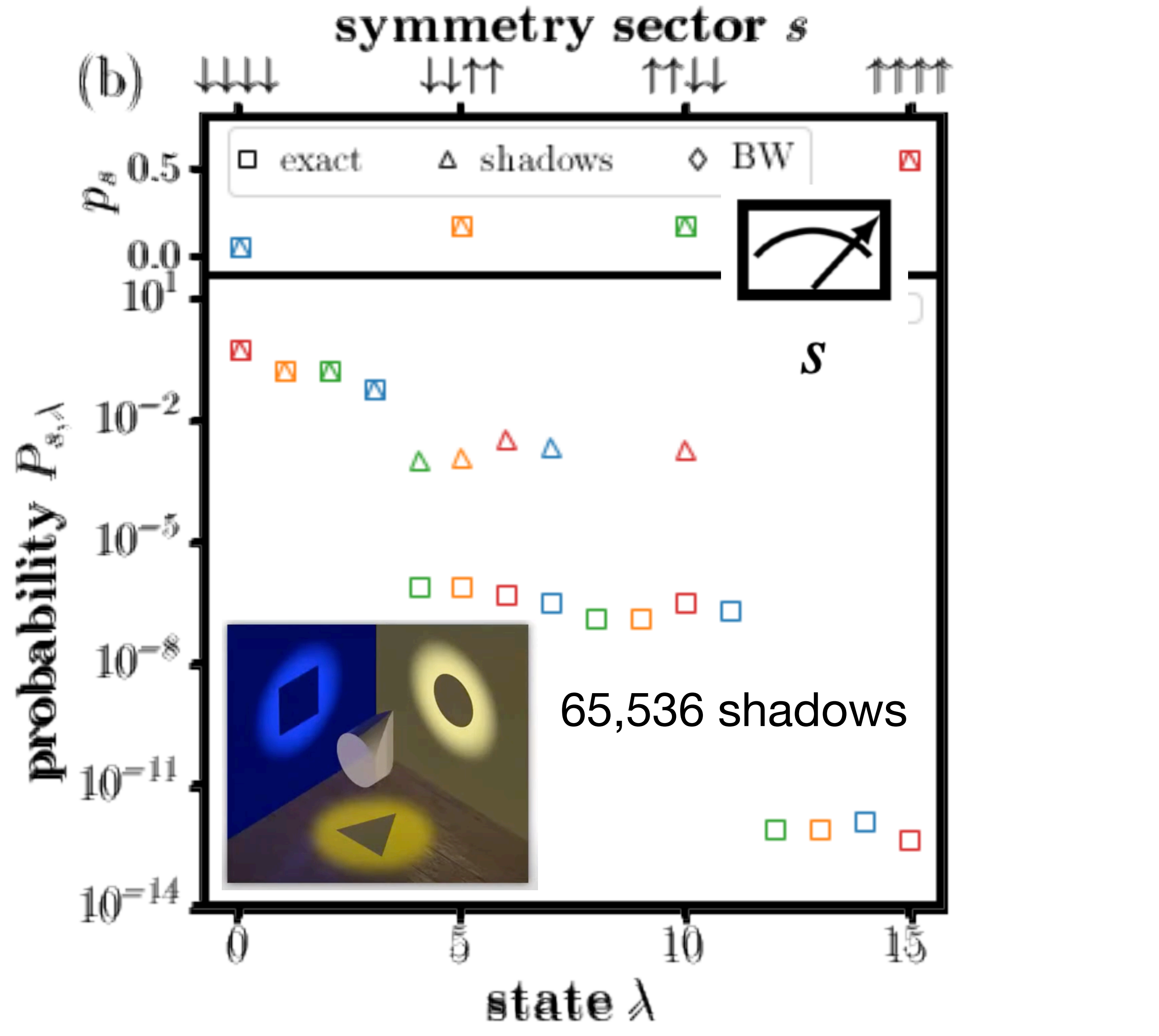

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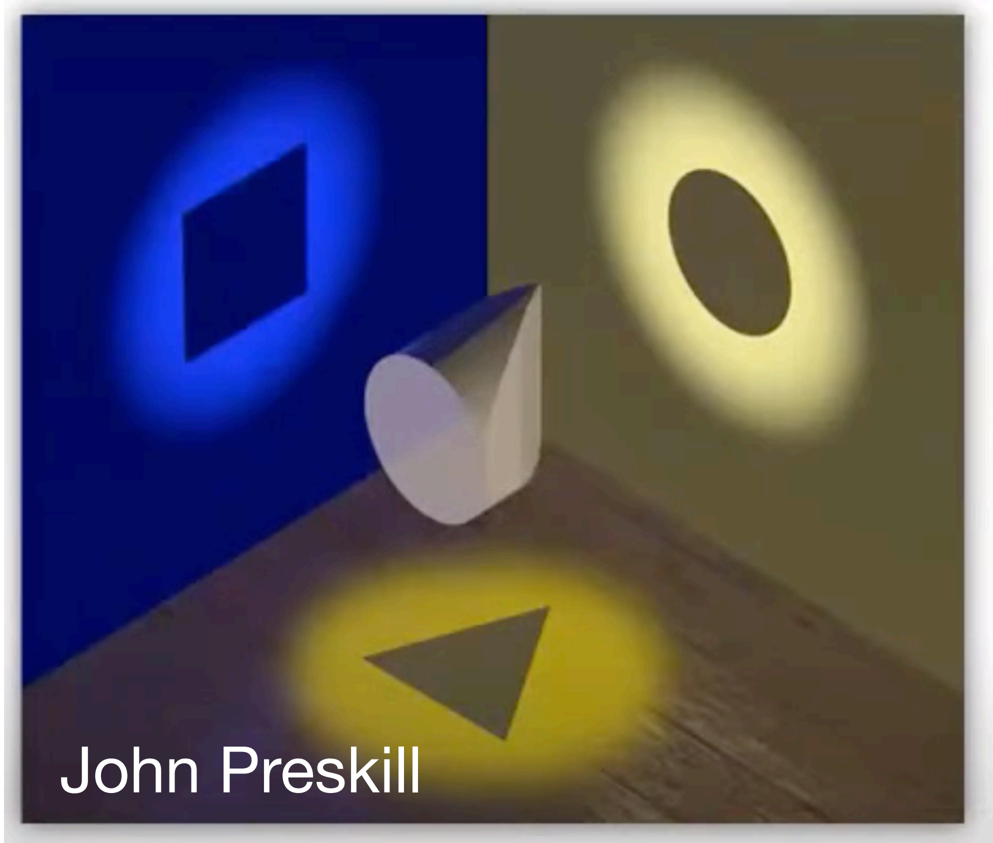

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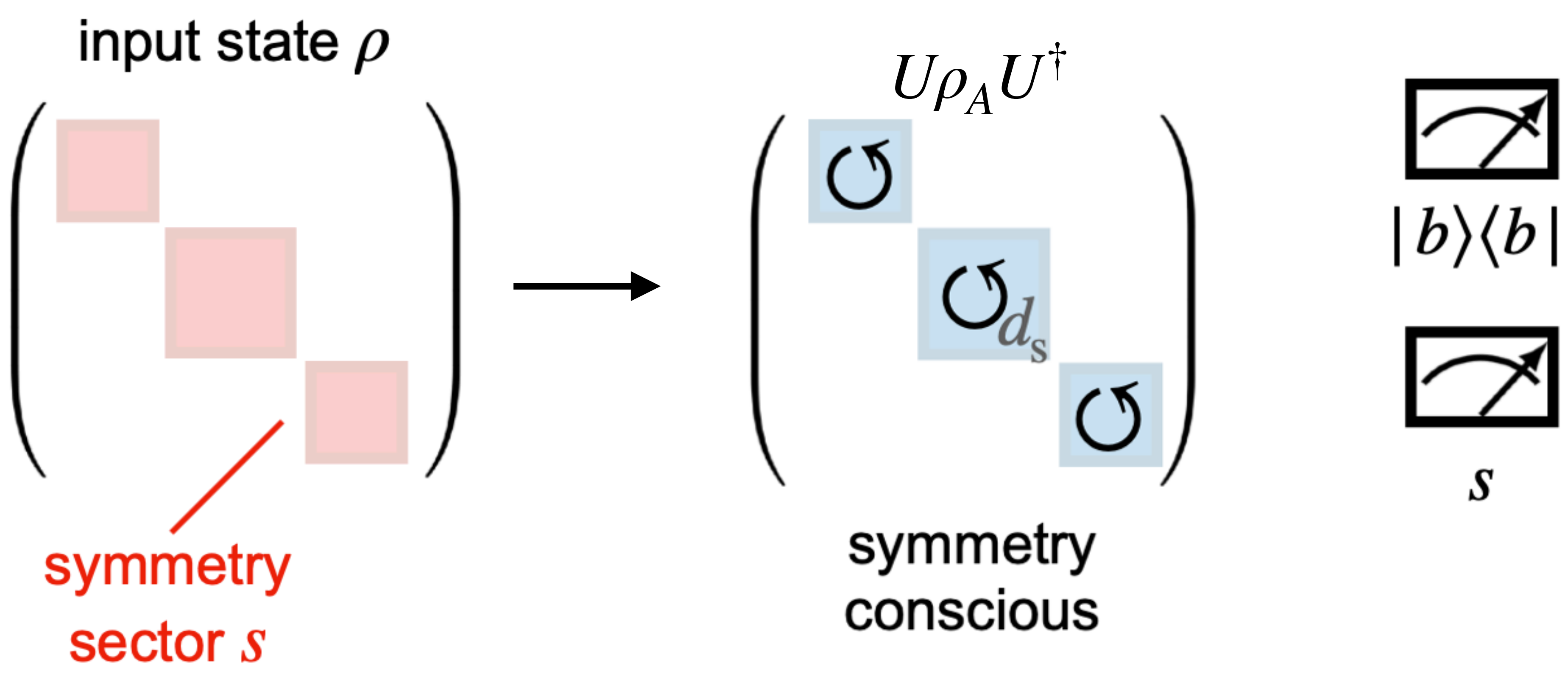

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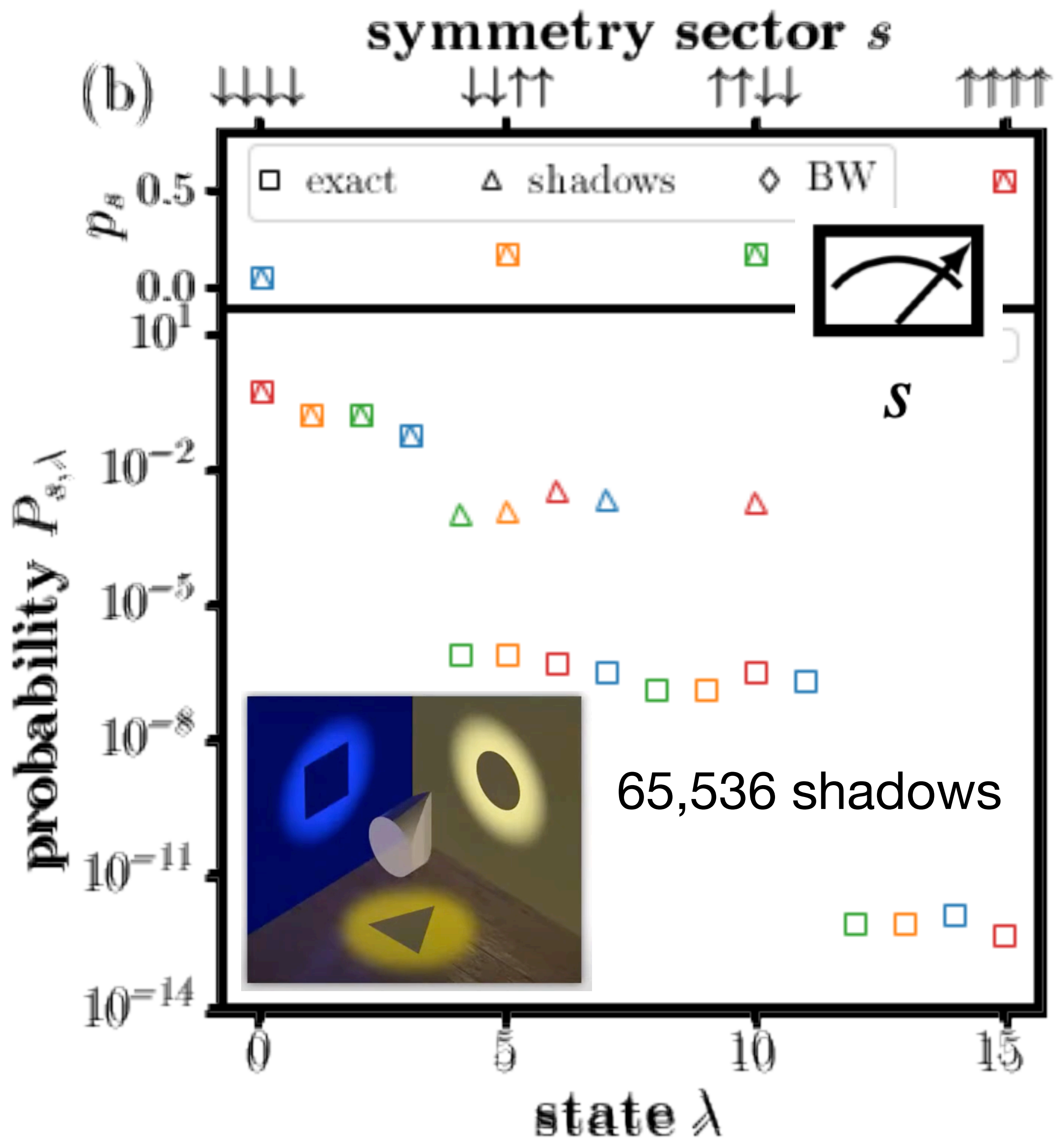
Bisognano, Wichmann, J Math Phys 16, 985 (1975) & 17, 303 (1976)
Dalmonte, Vermersch, Zoller, Nature 14 2018 827-831



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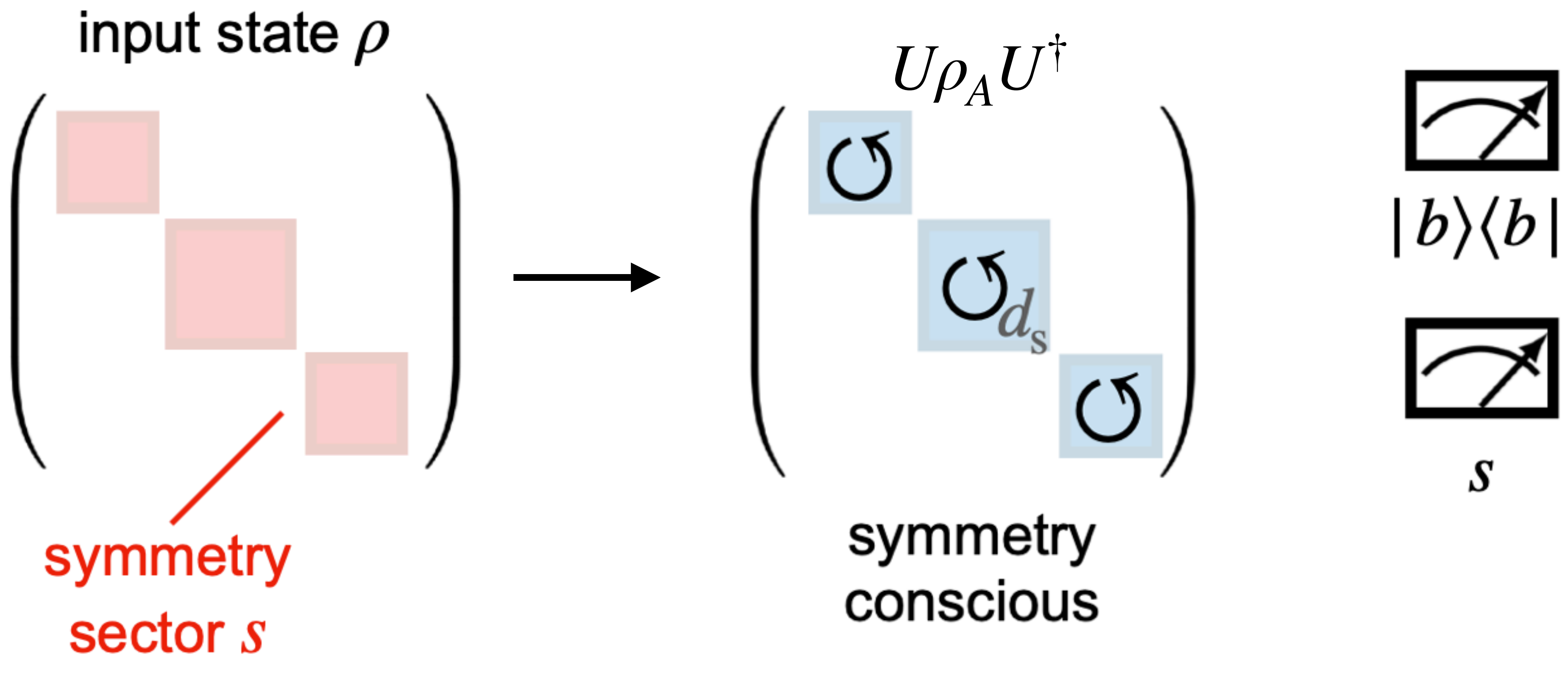

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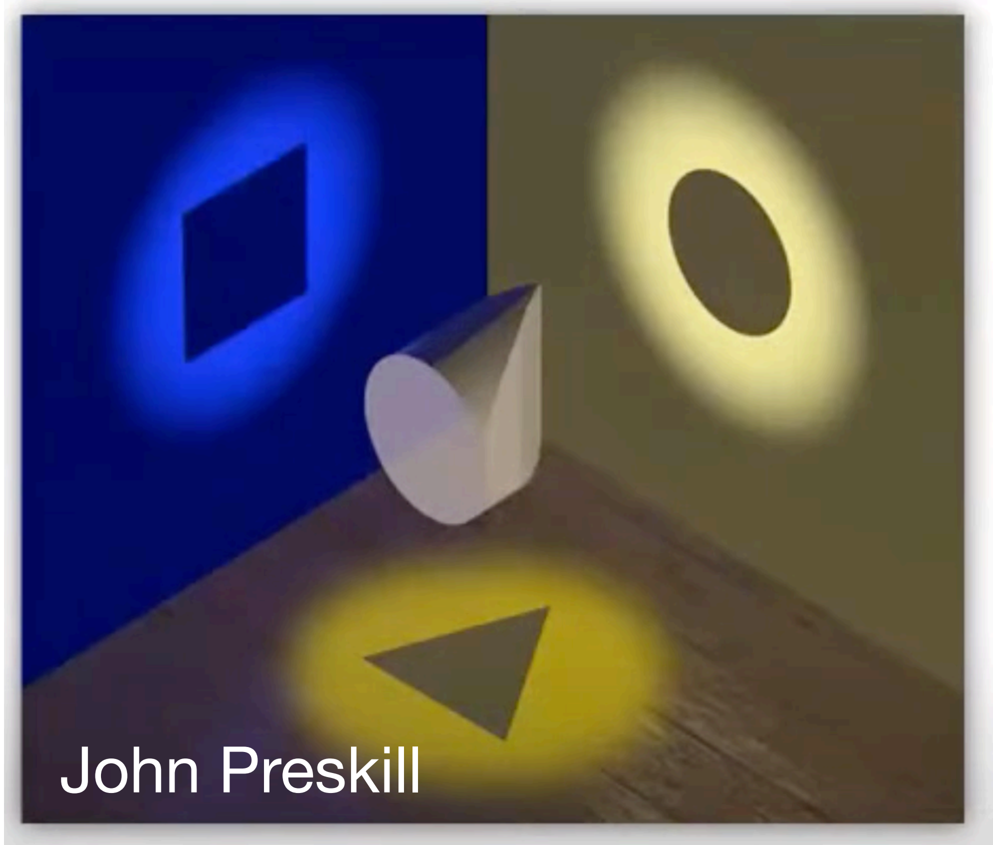

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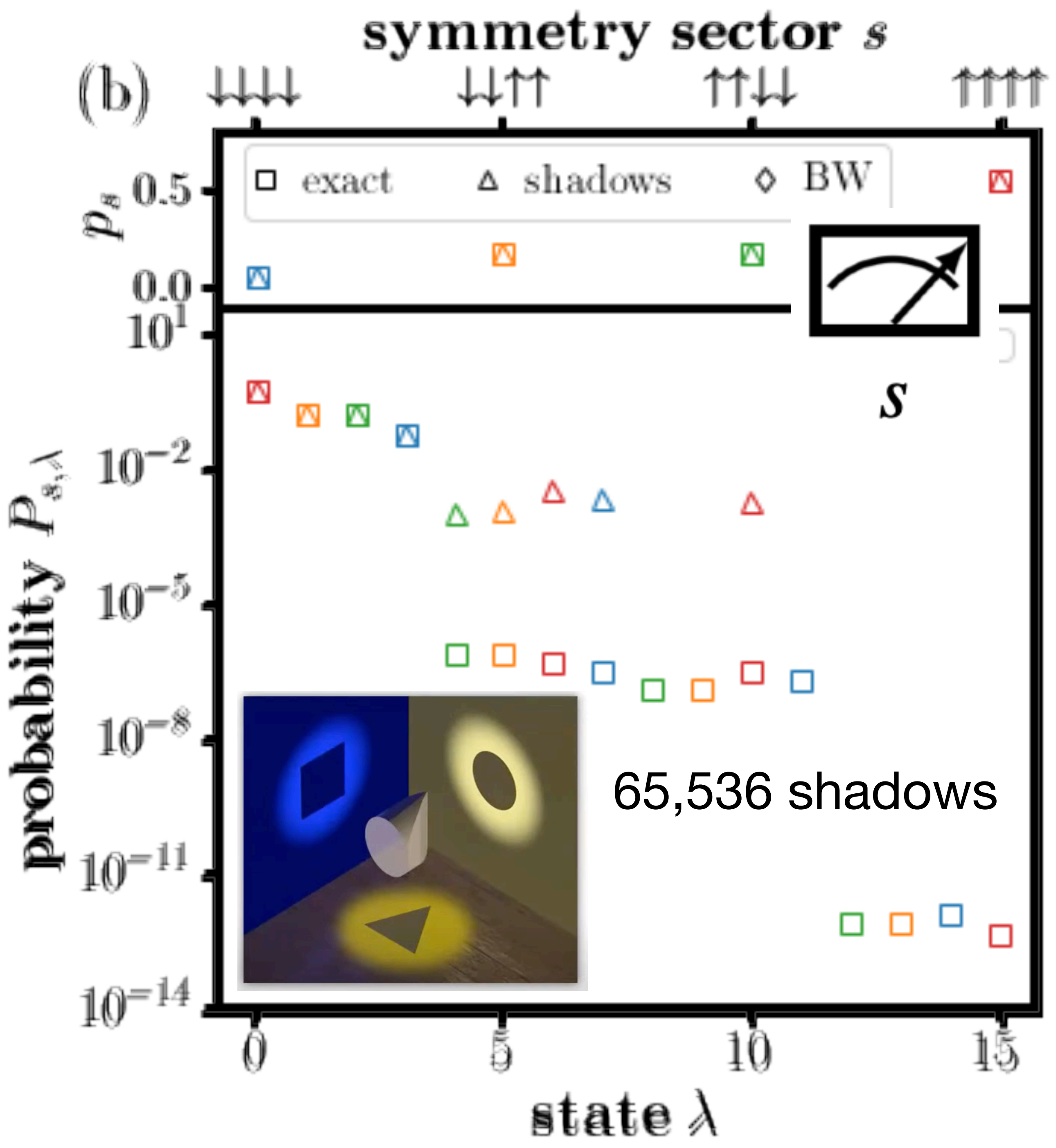

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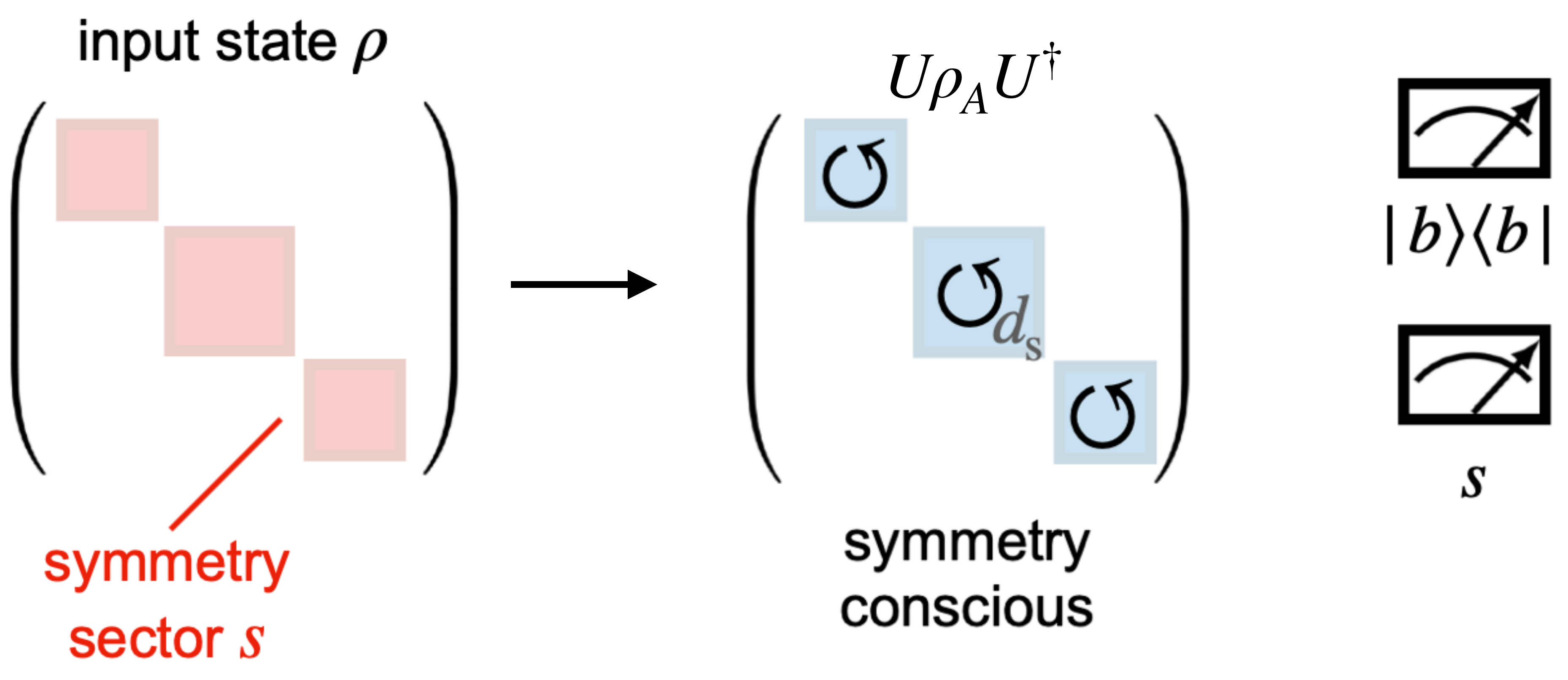

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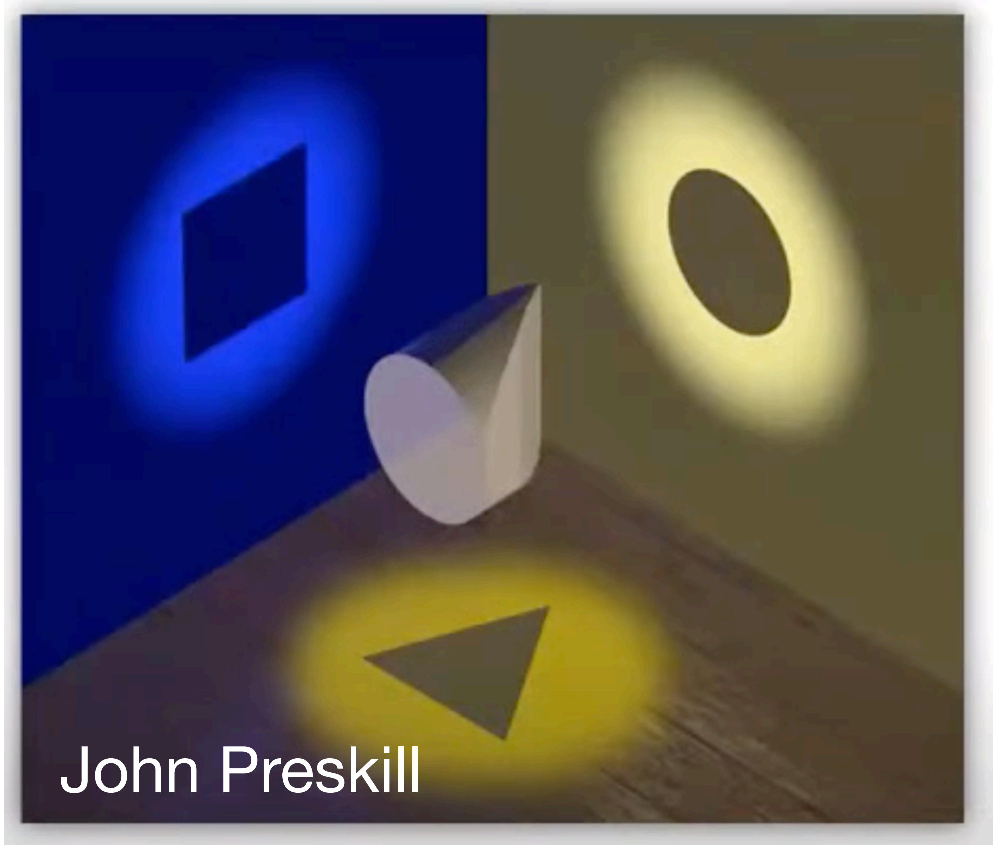

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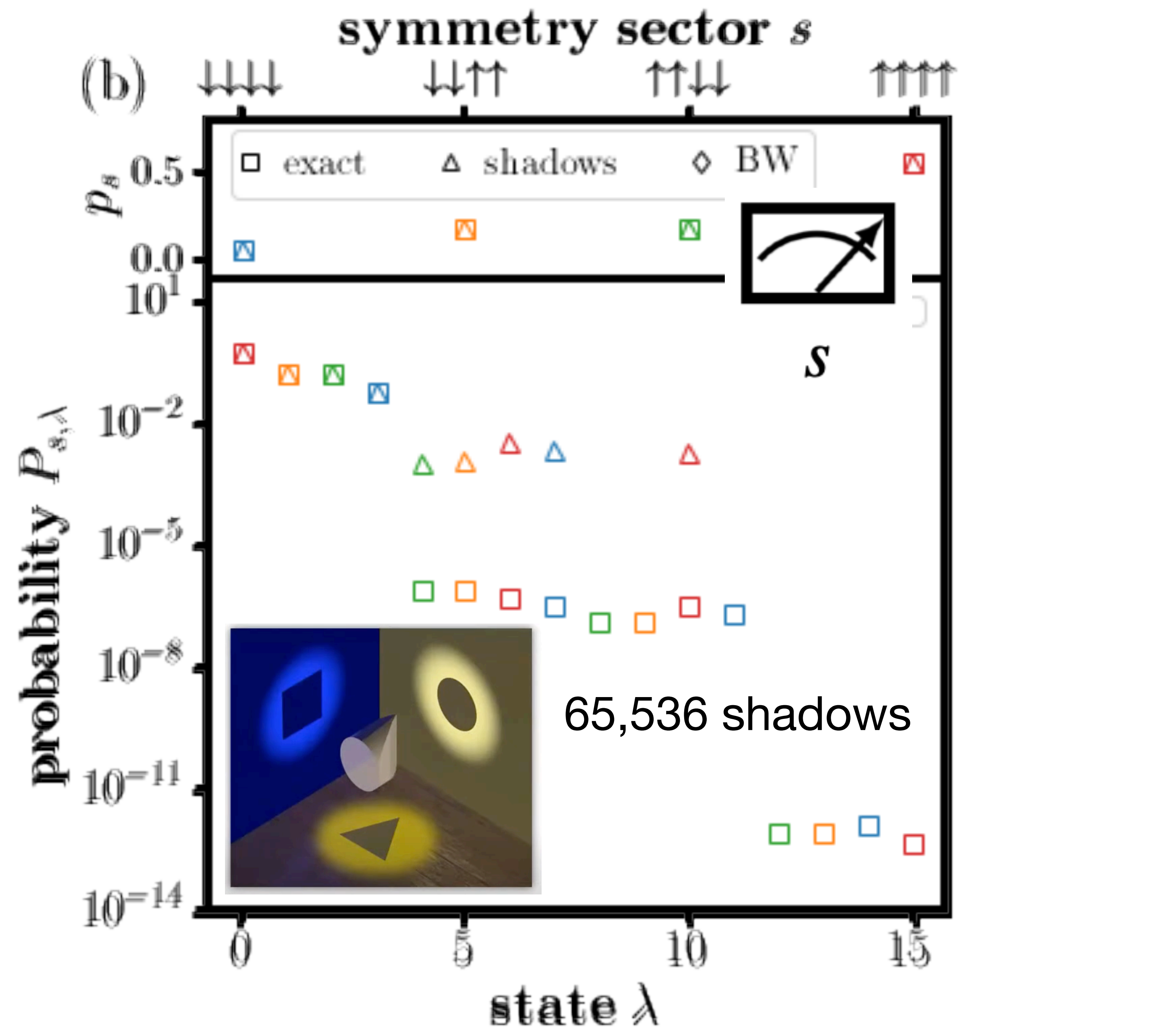

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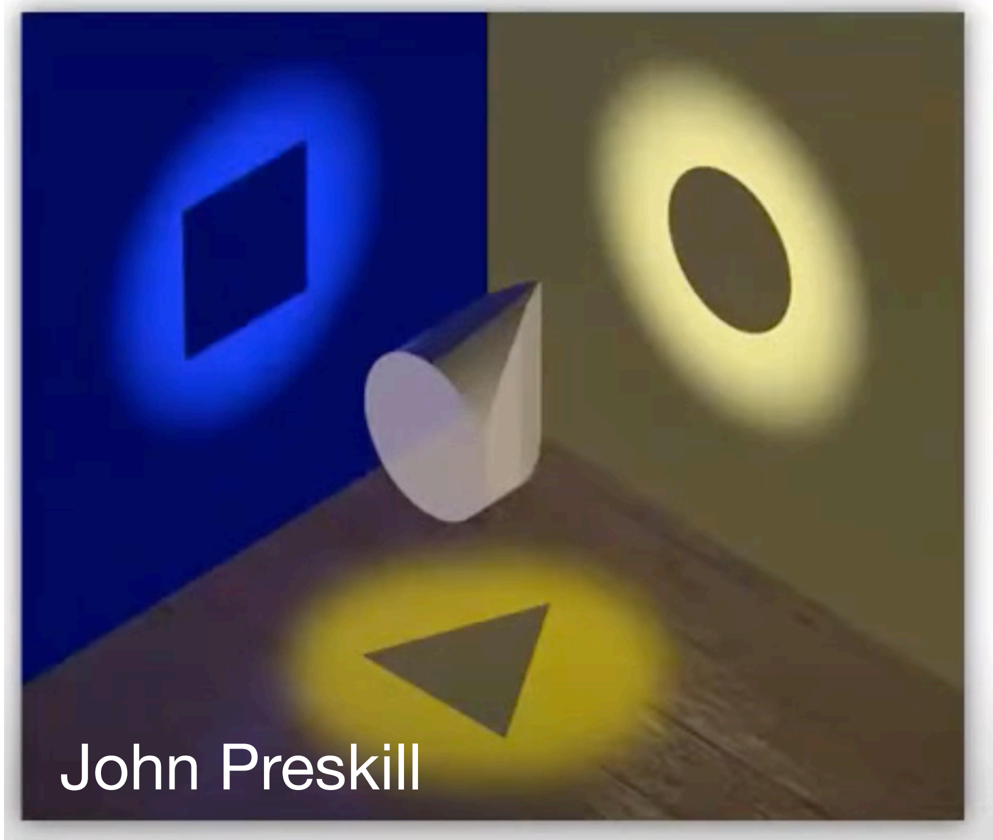

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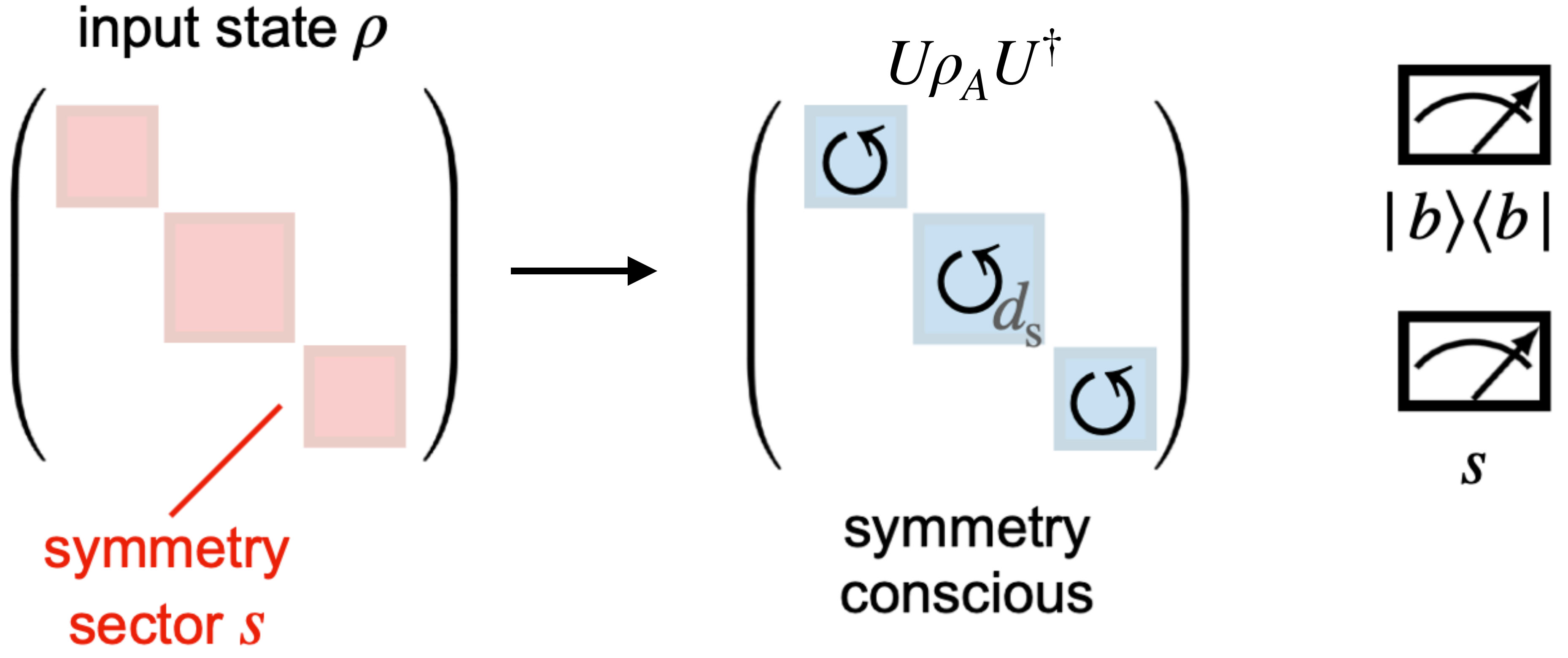

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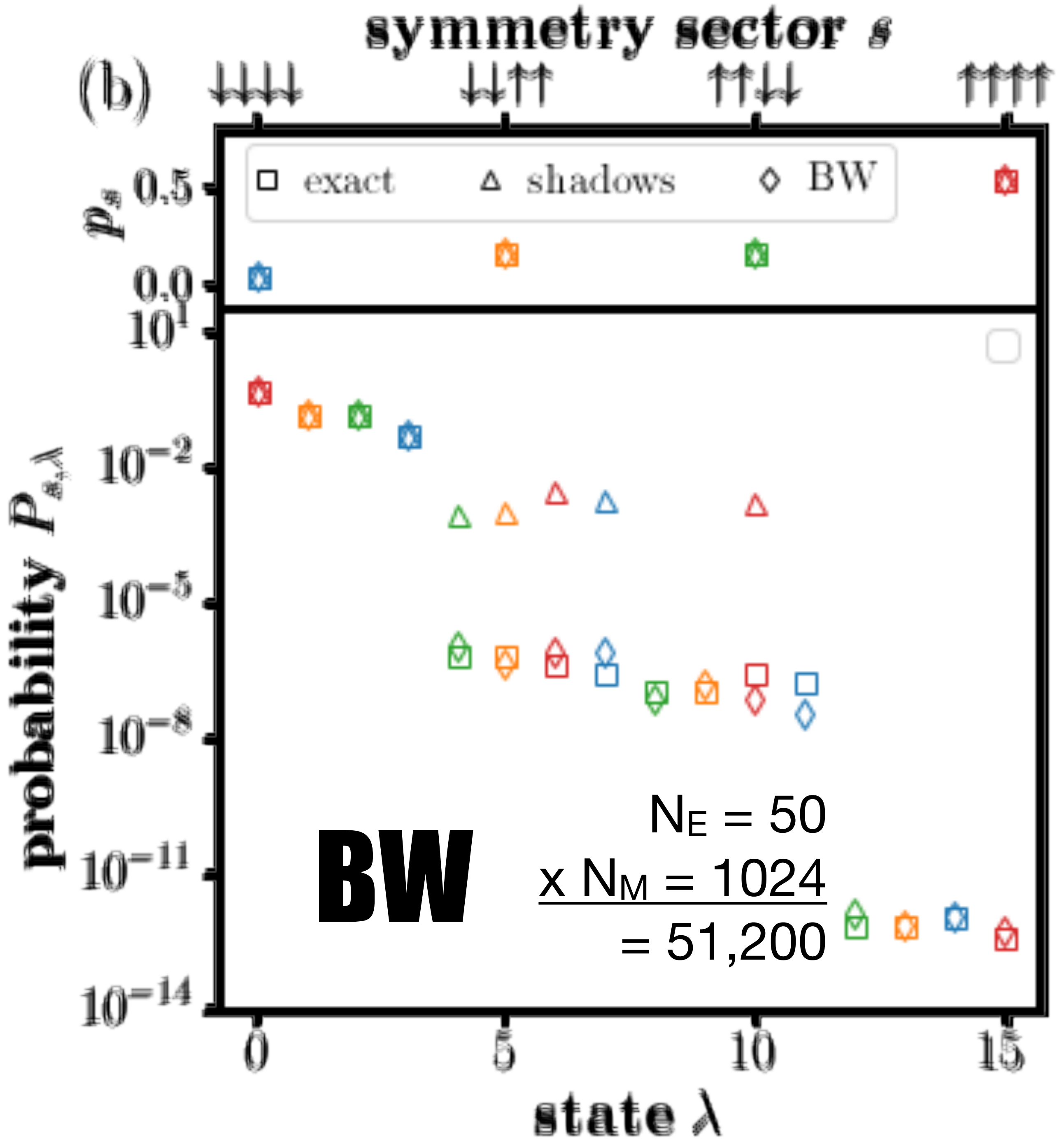

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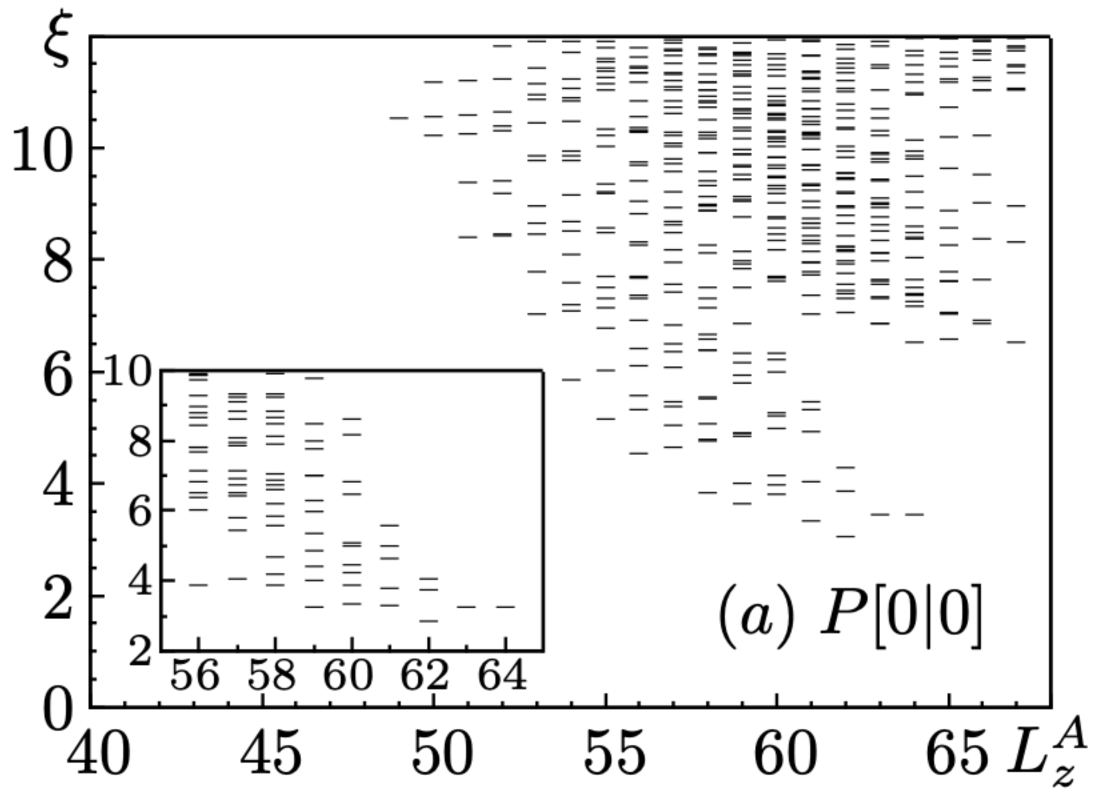
Symmetry-conscious Random Measurement

Detecting Topological Order



Li Haldane, PRL 101 01504 (2008)

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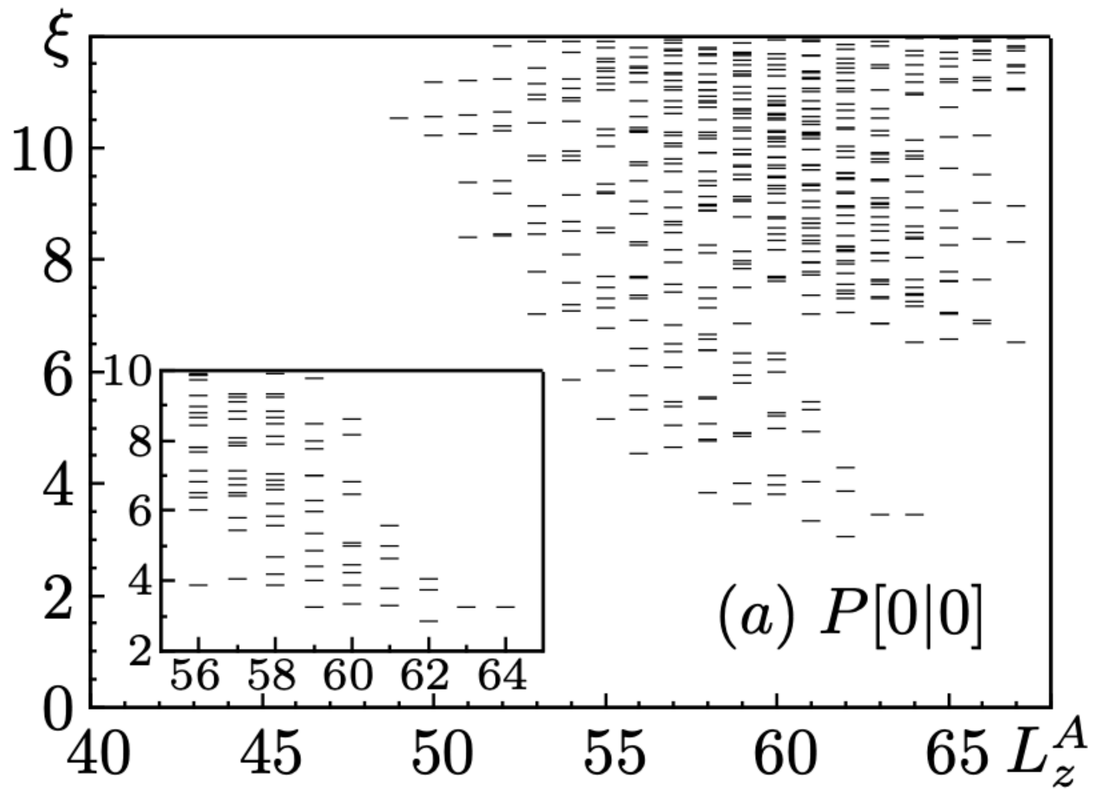

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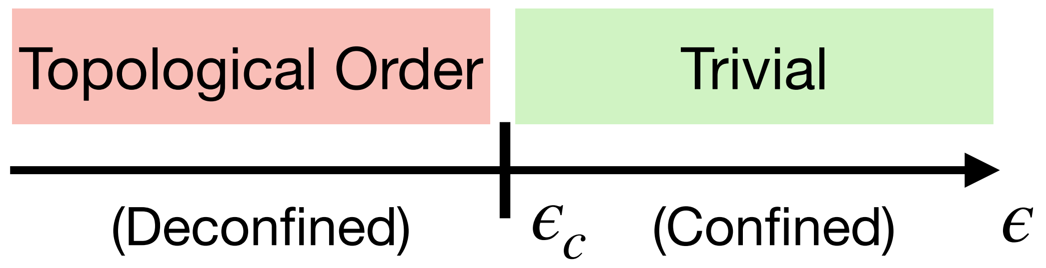

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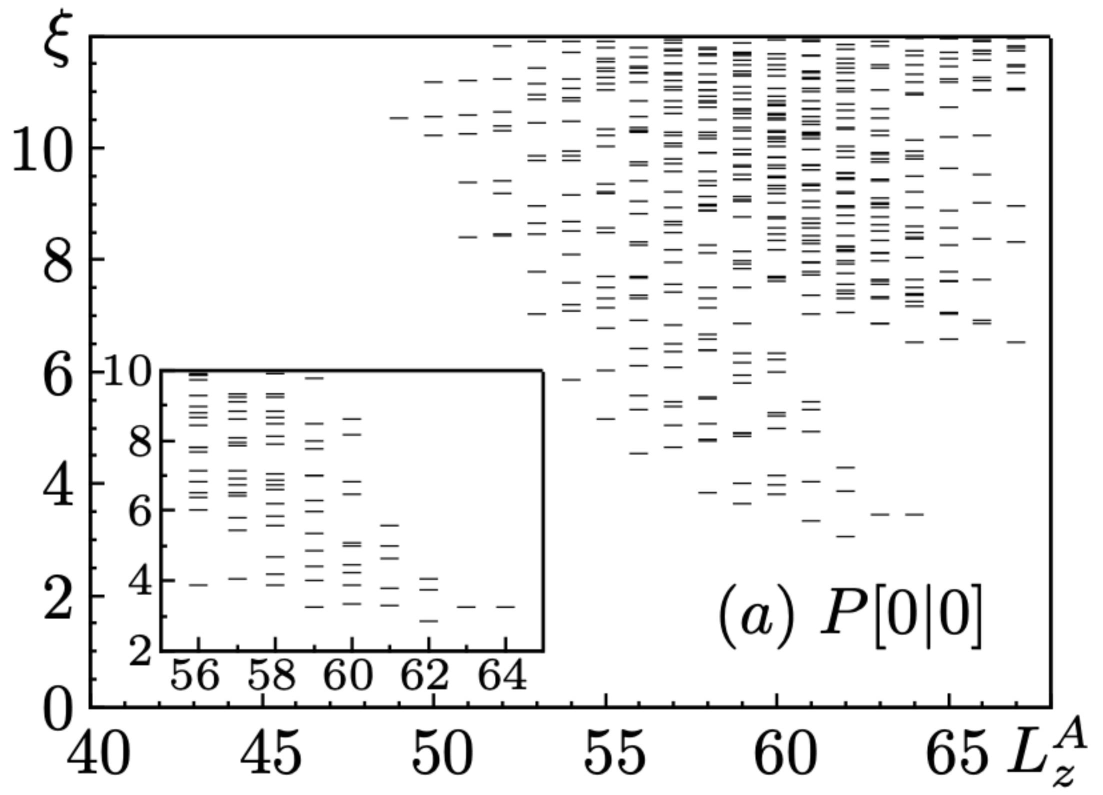

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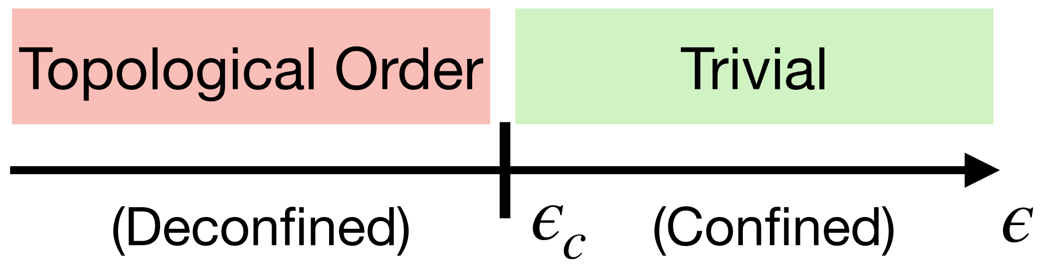

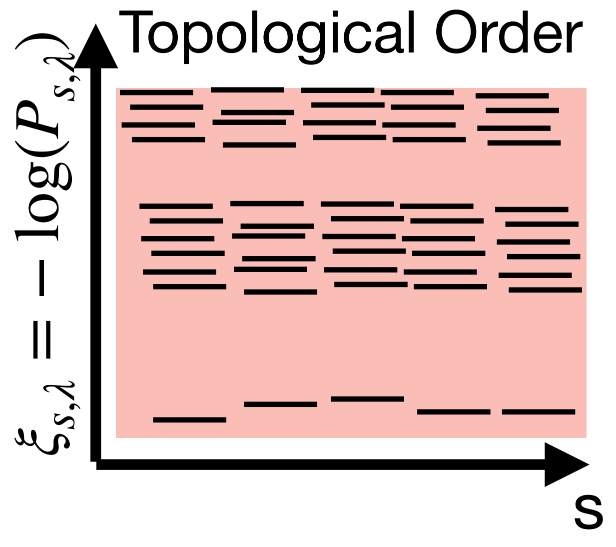

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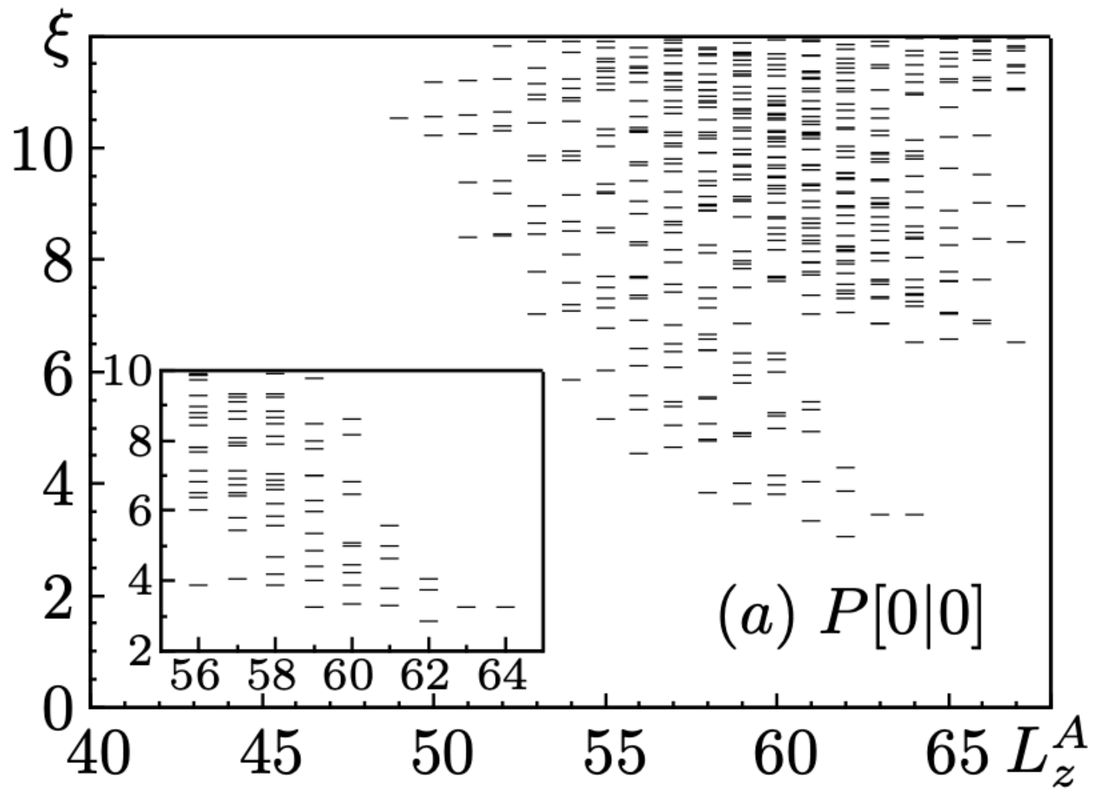

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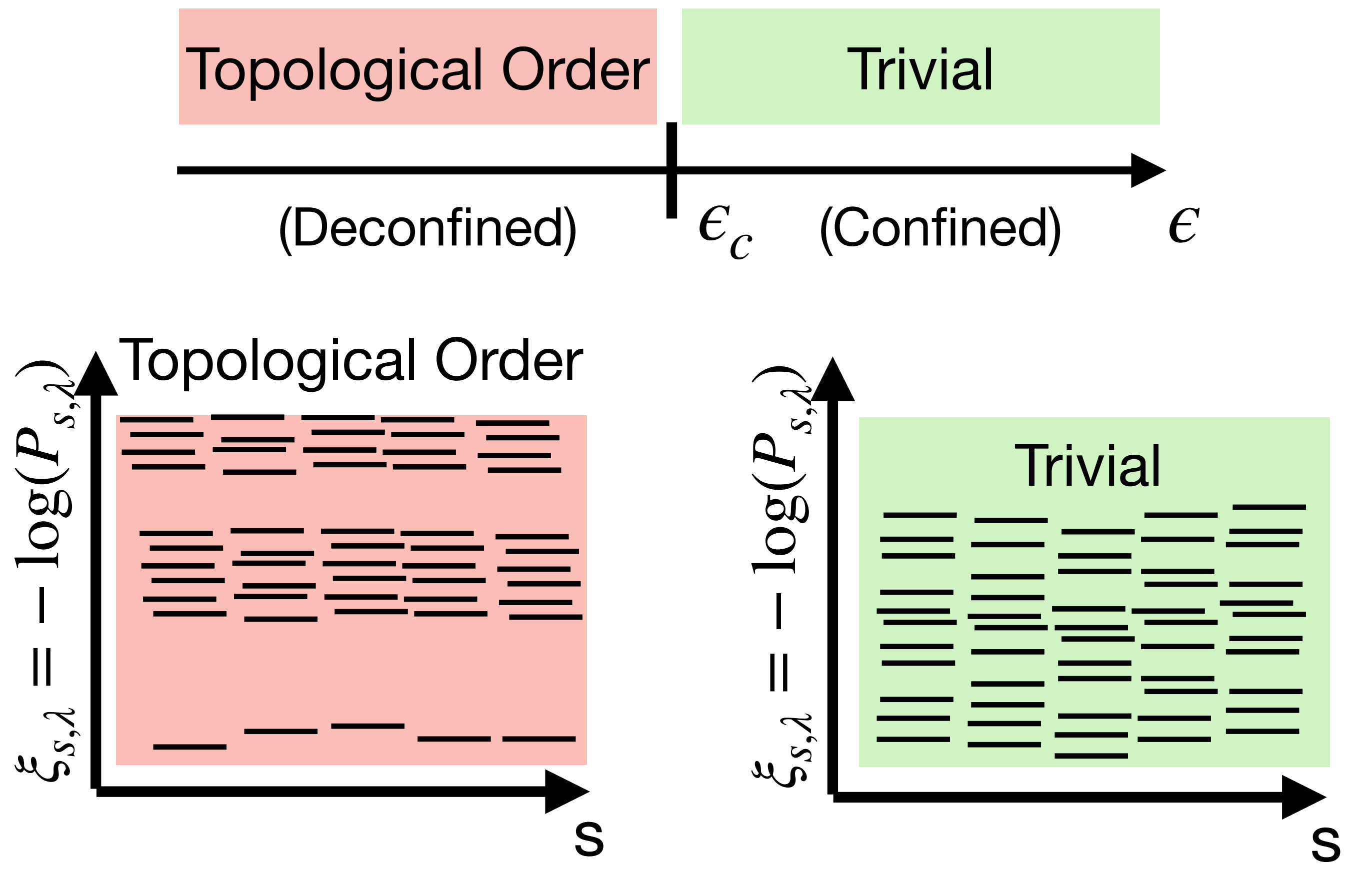

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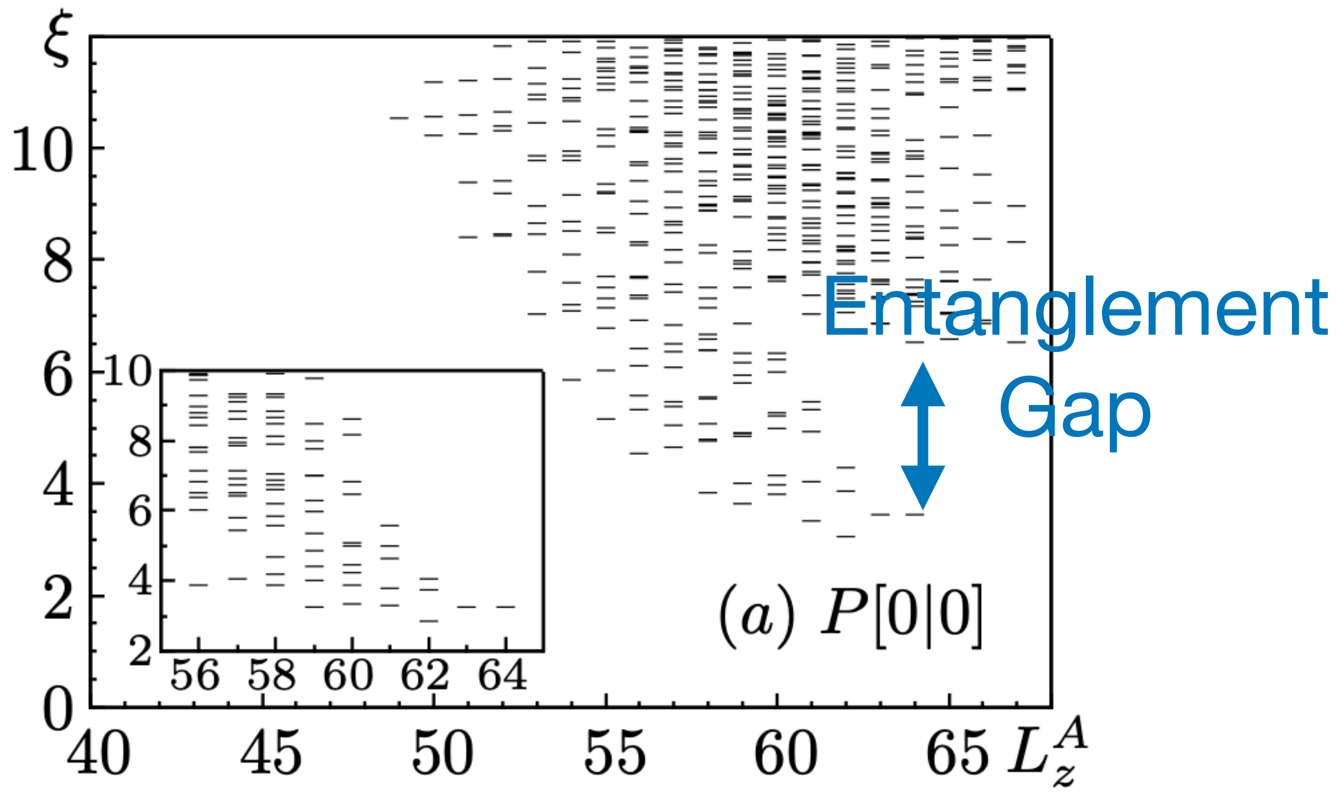

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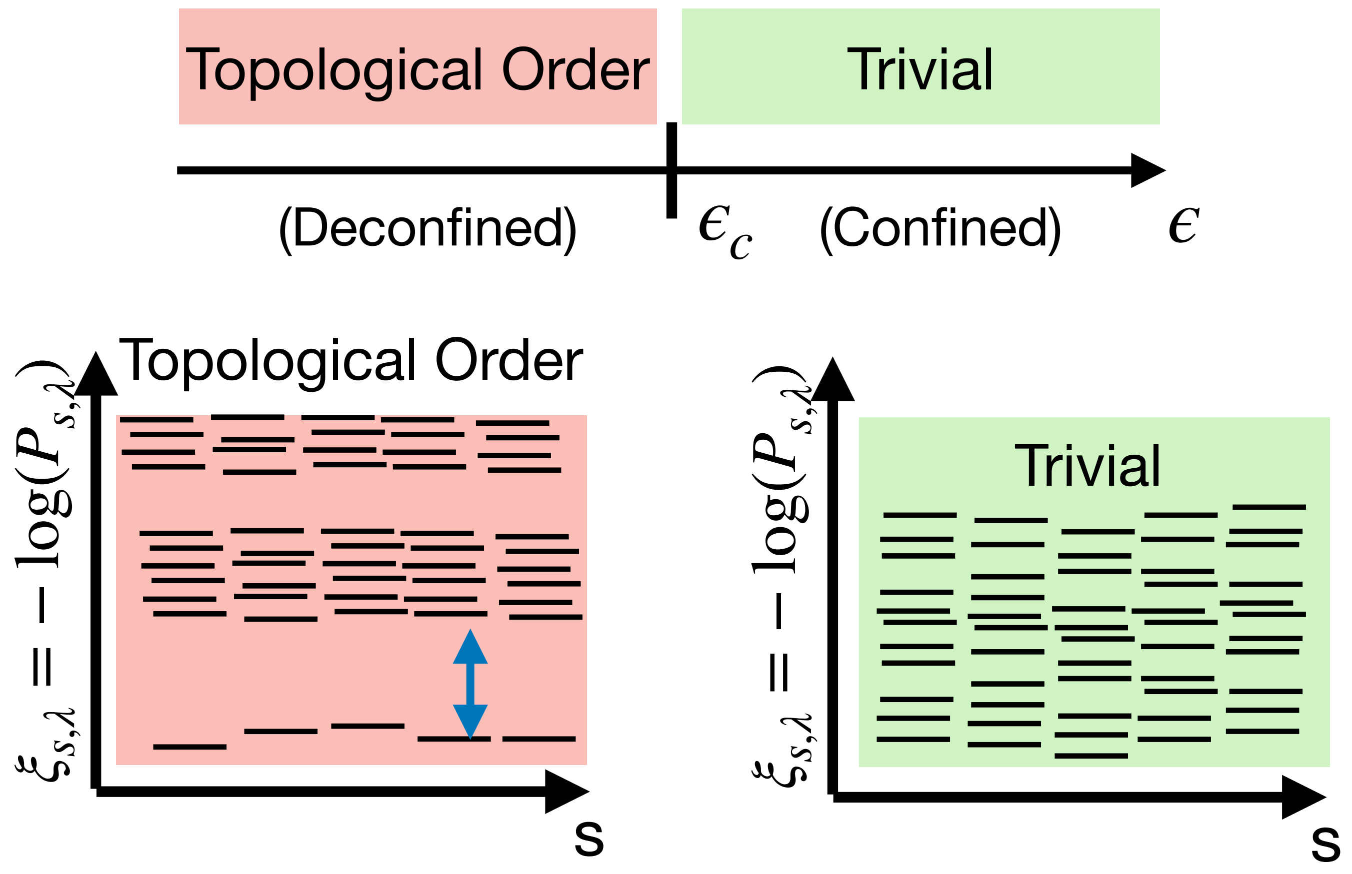

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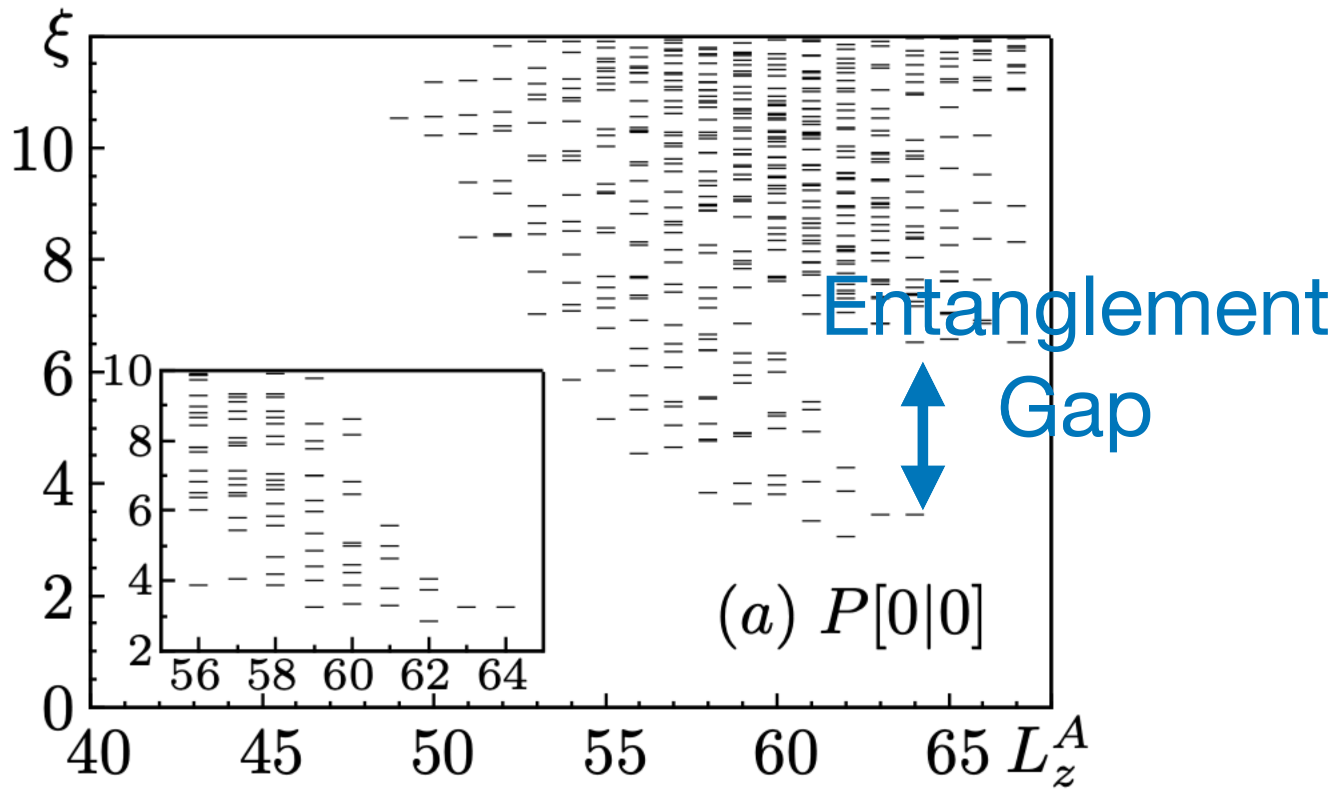

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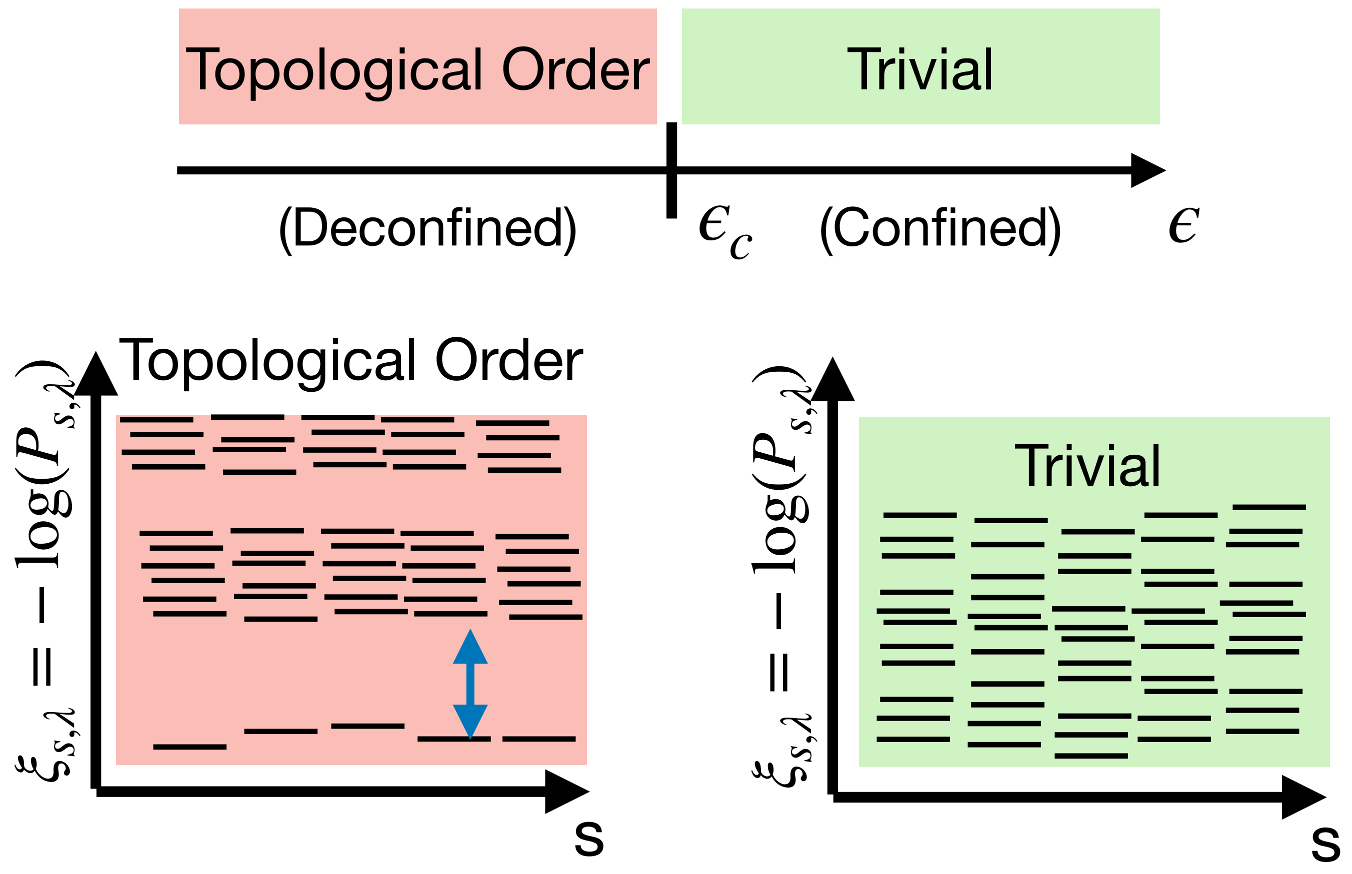

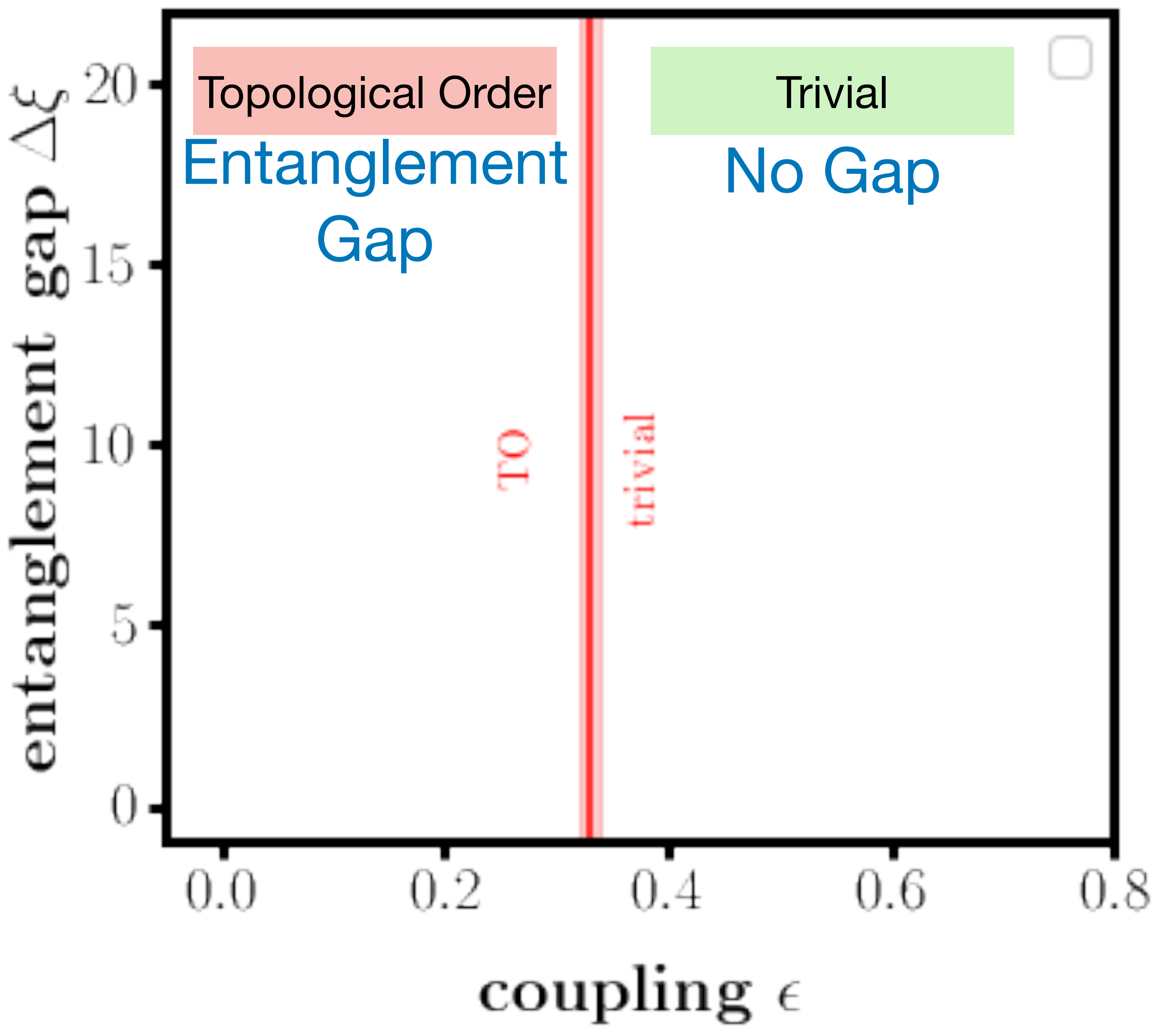

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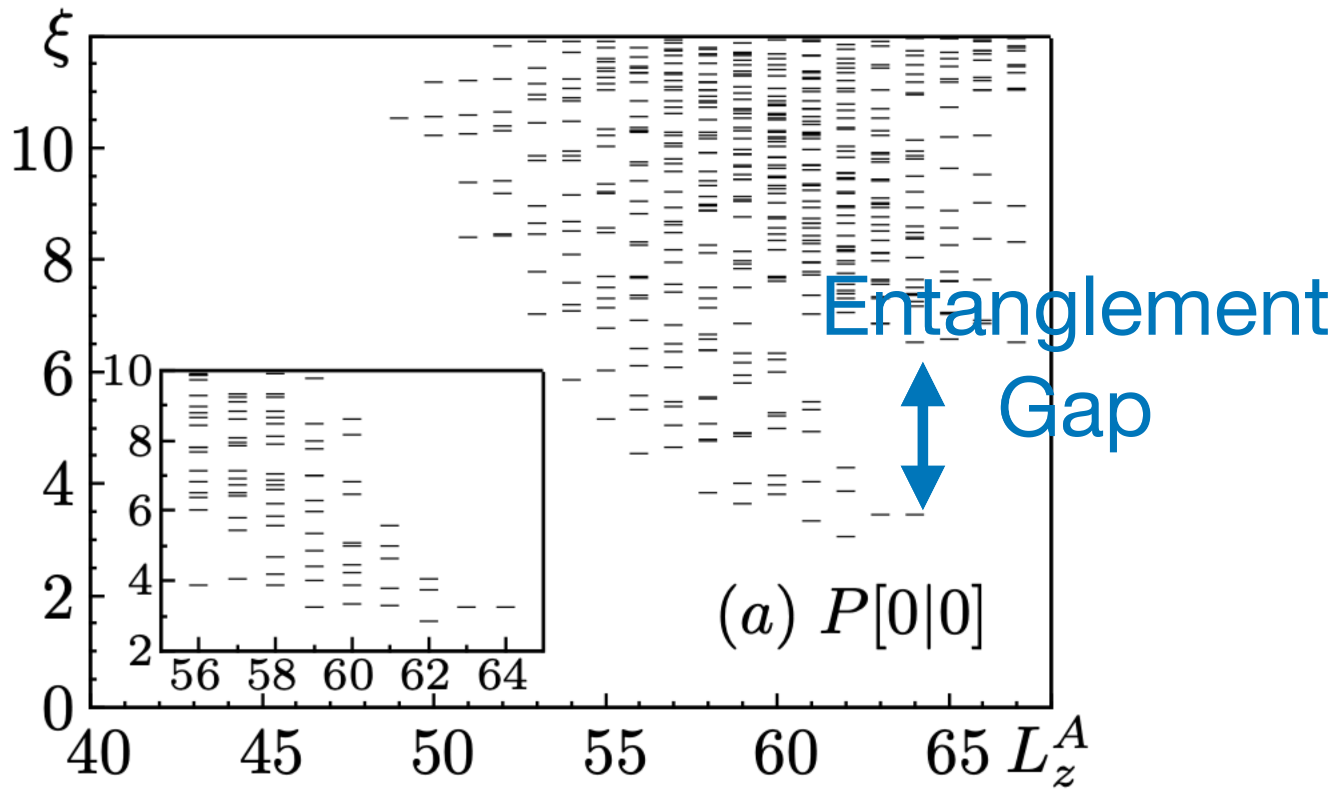

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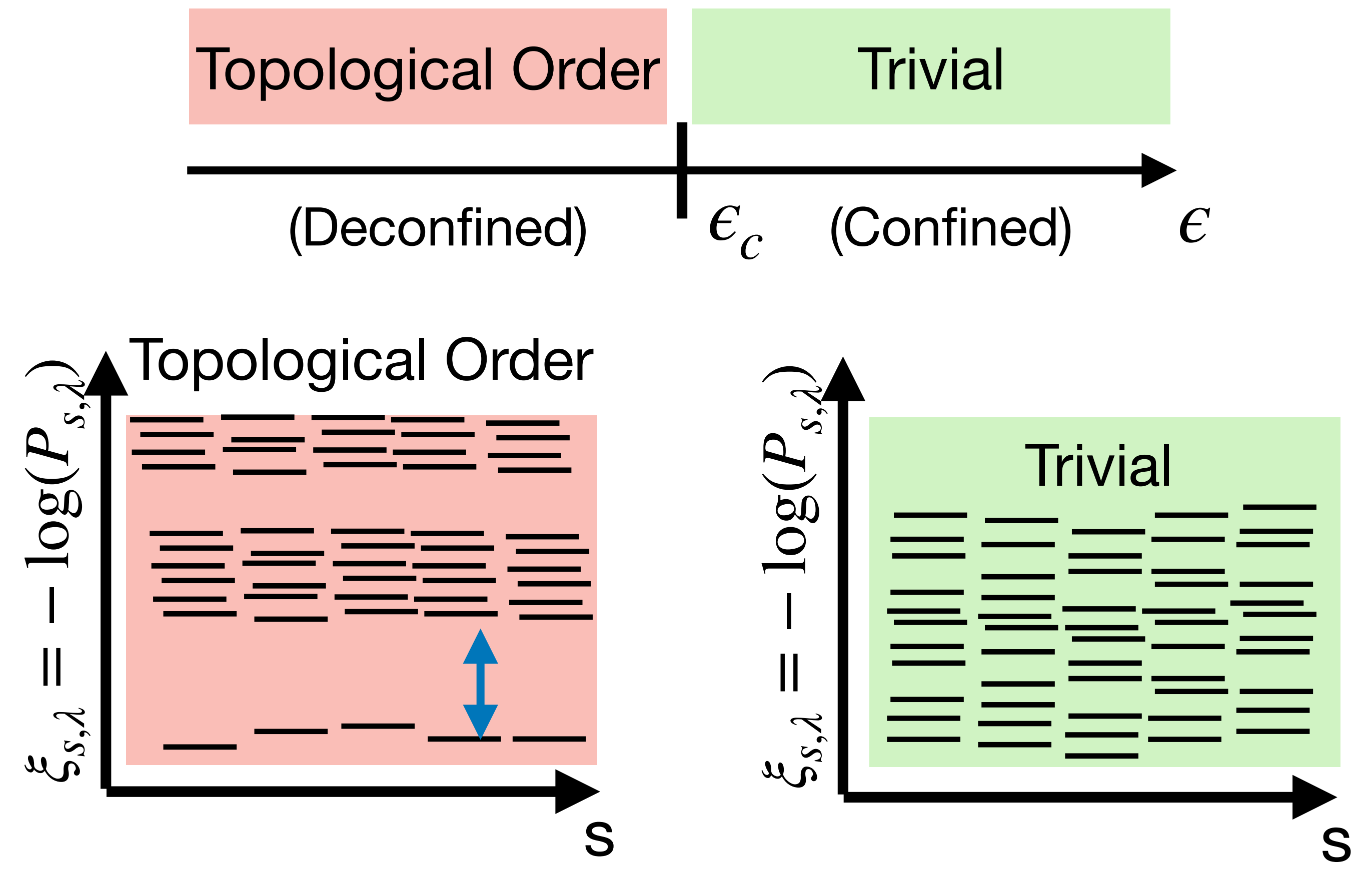
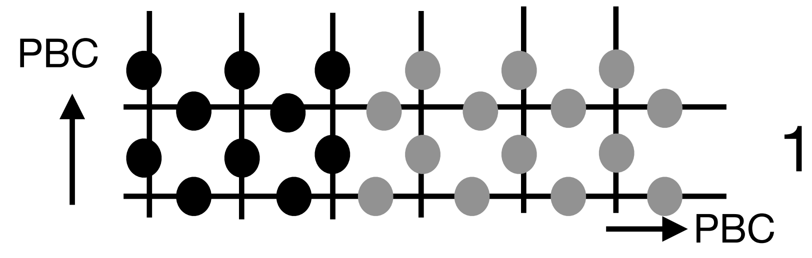
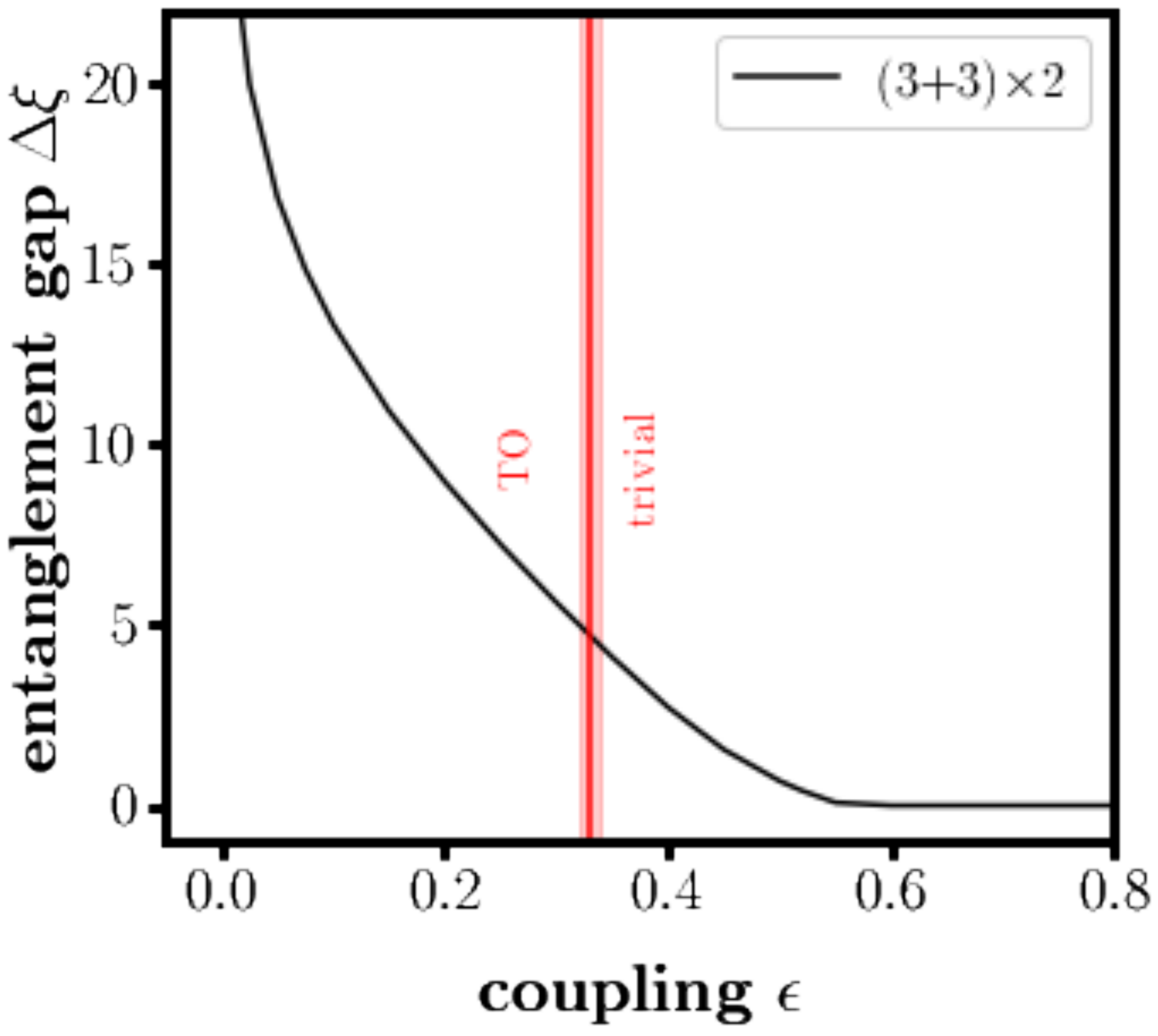




10+14=28 qubits



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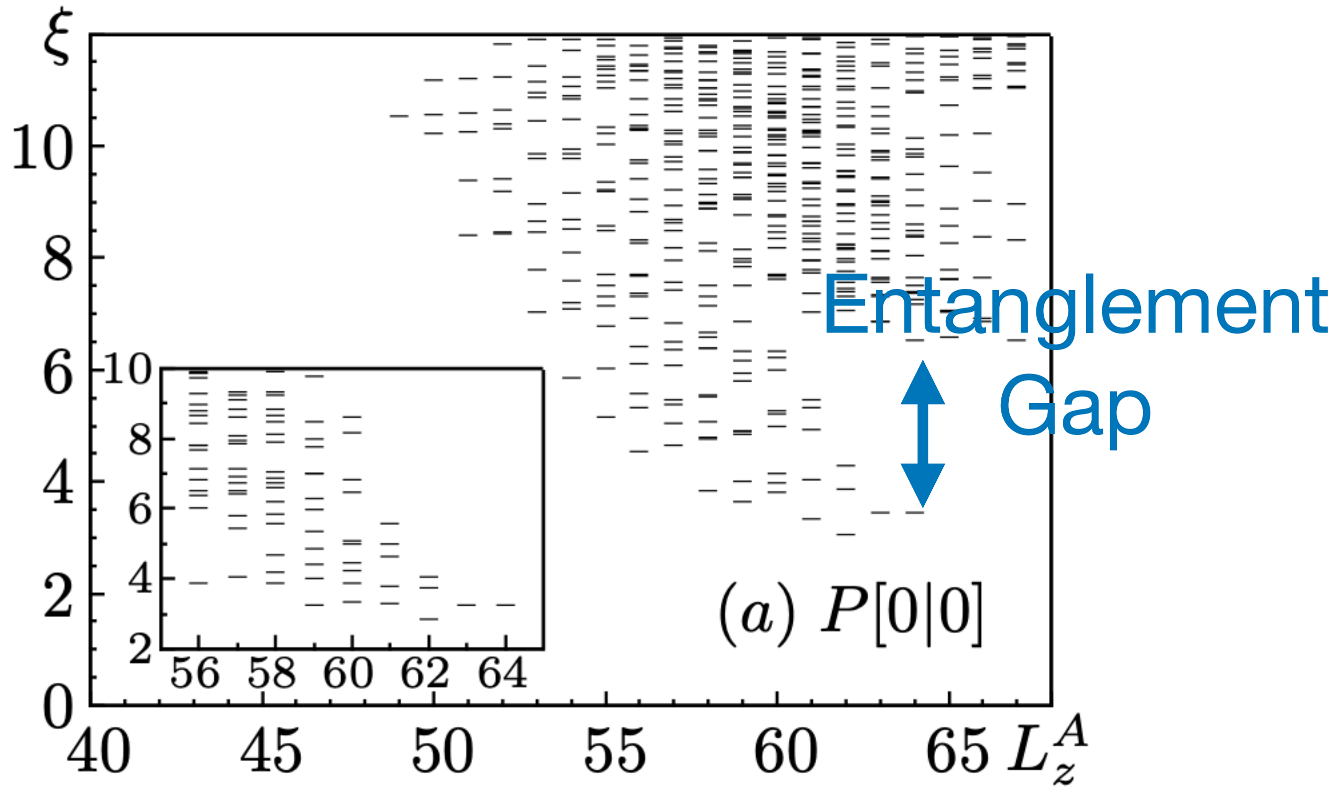

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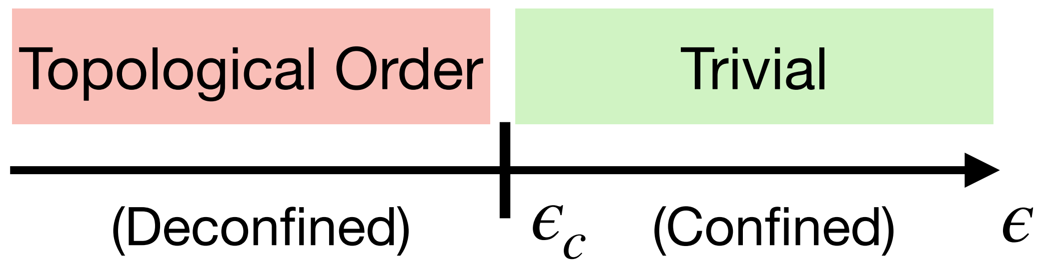

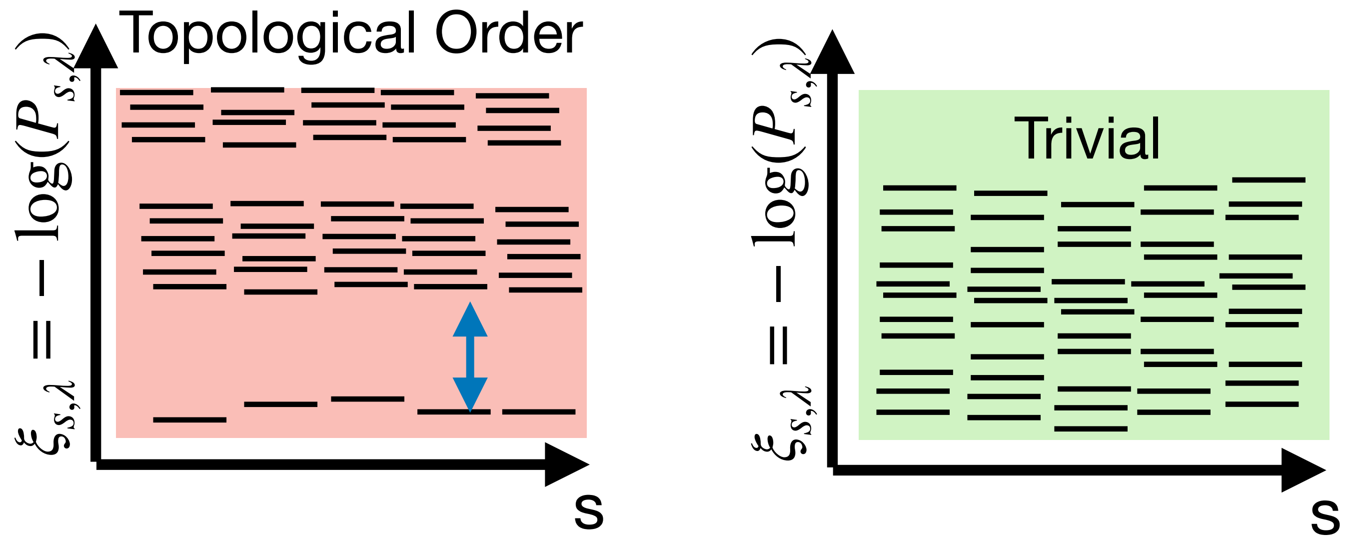

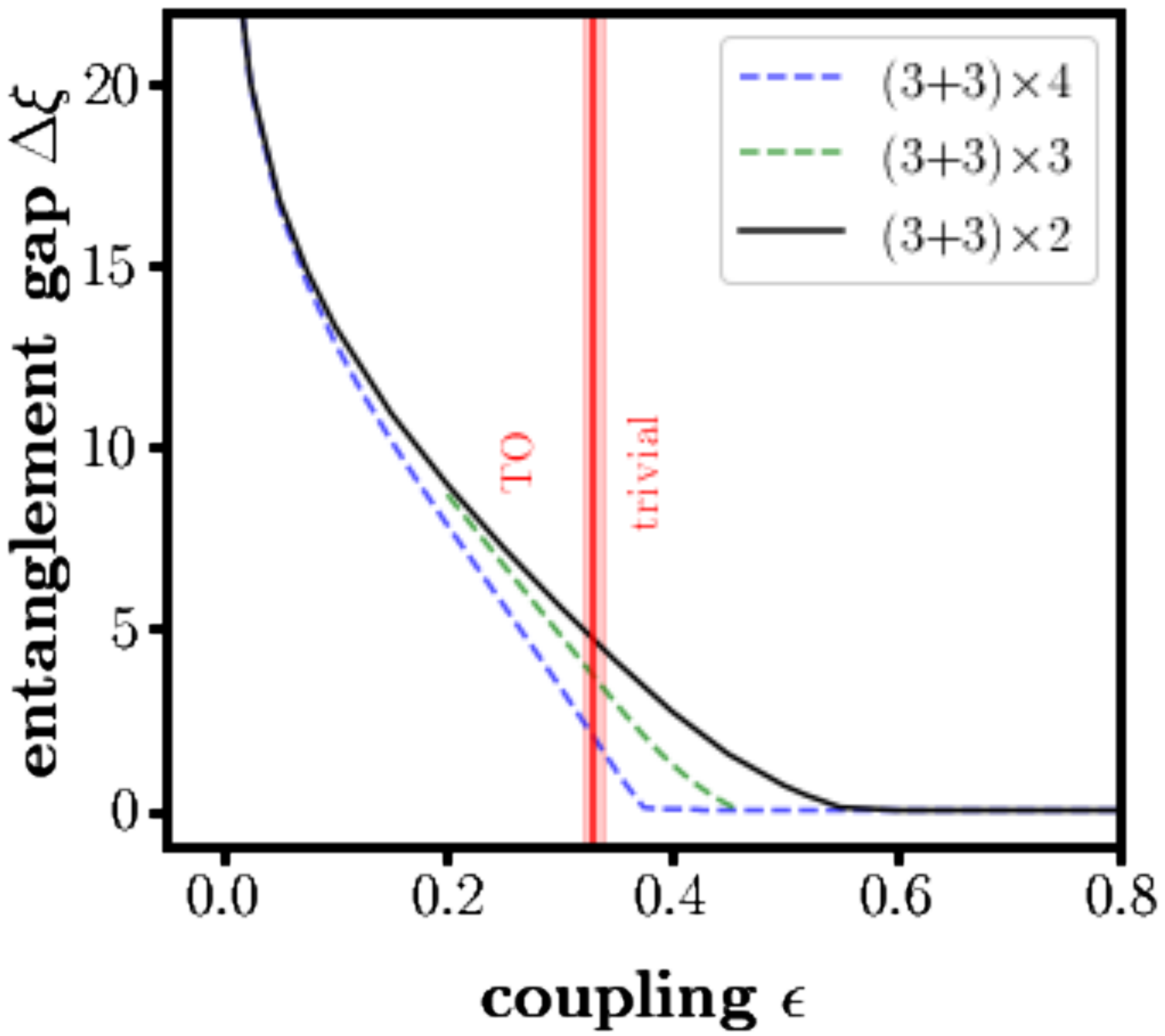

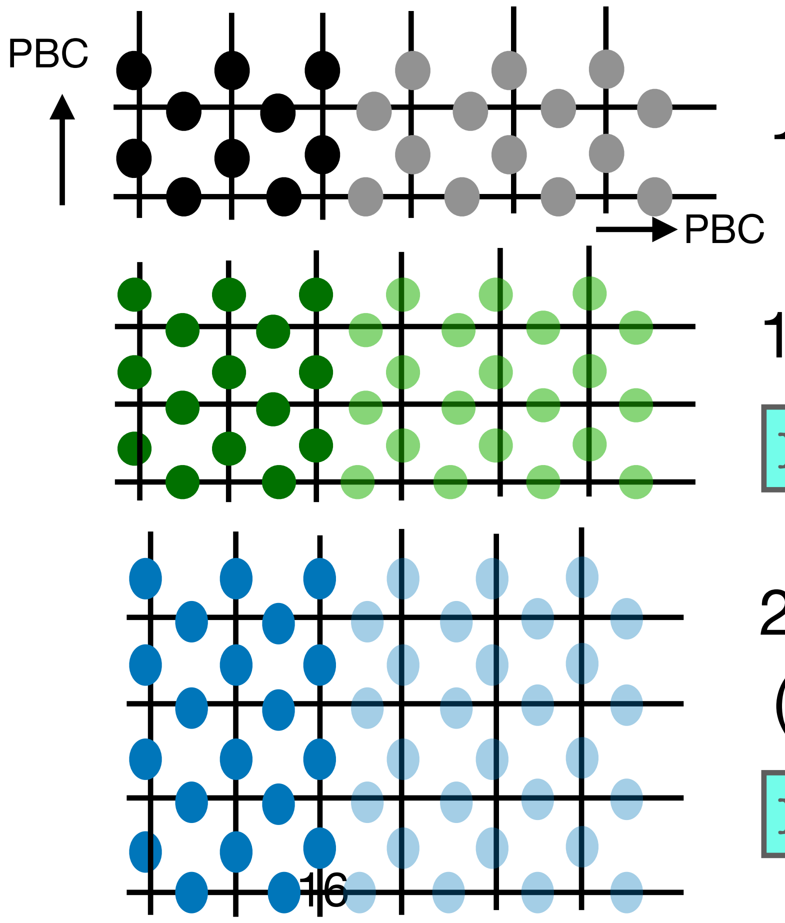

10+14=28 qubits

15+21=36 qubits (dual)

NM, Zache, Ott, PRL129 (2022) 1

20+28=48 qubits (dual)

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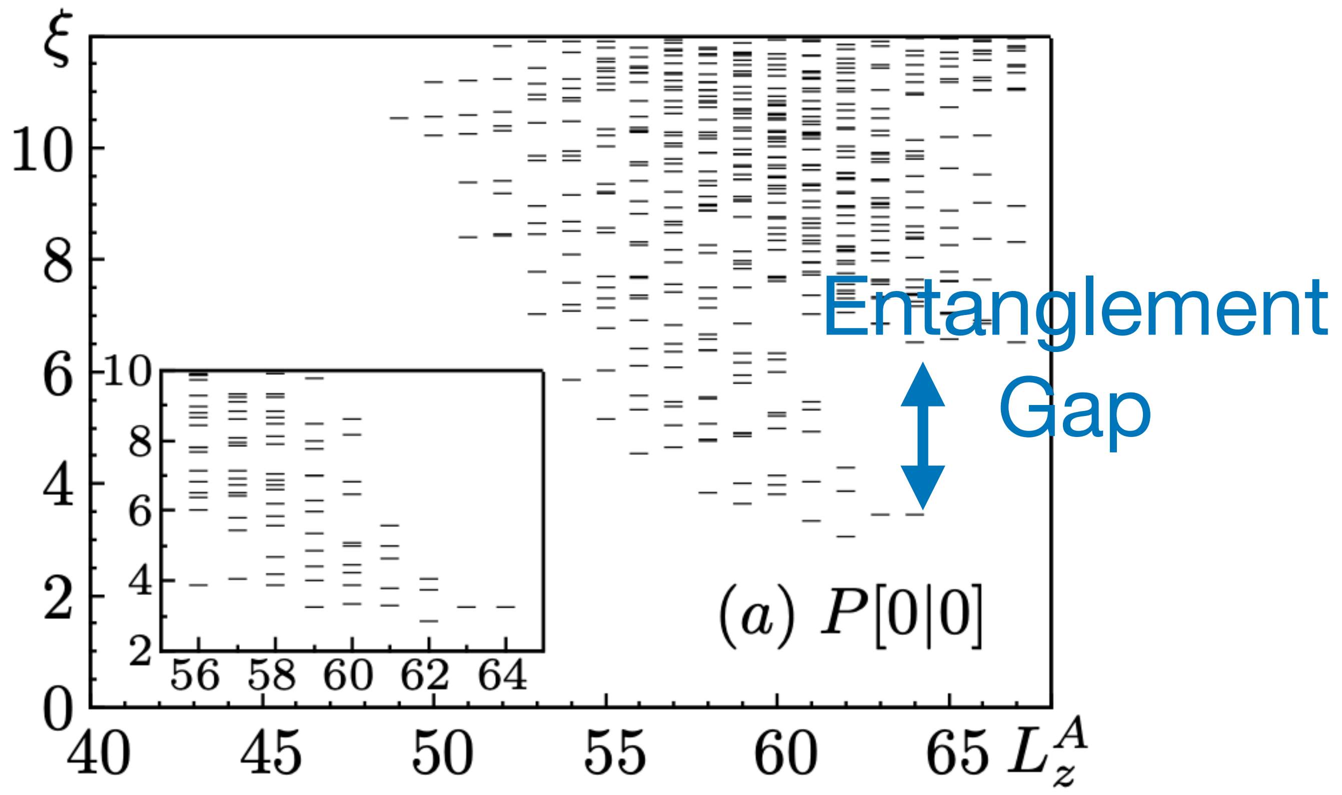

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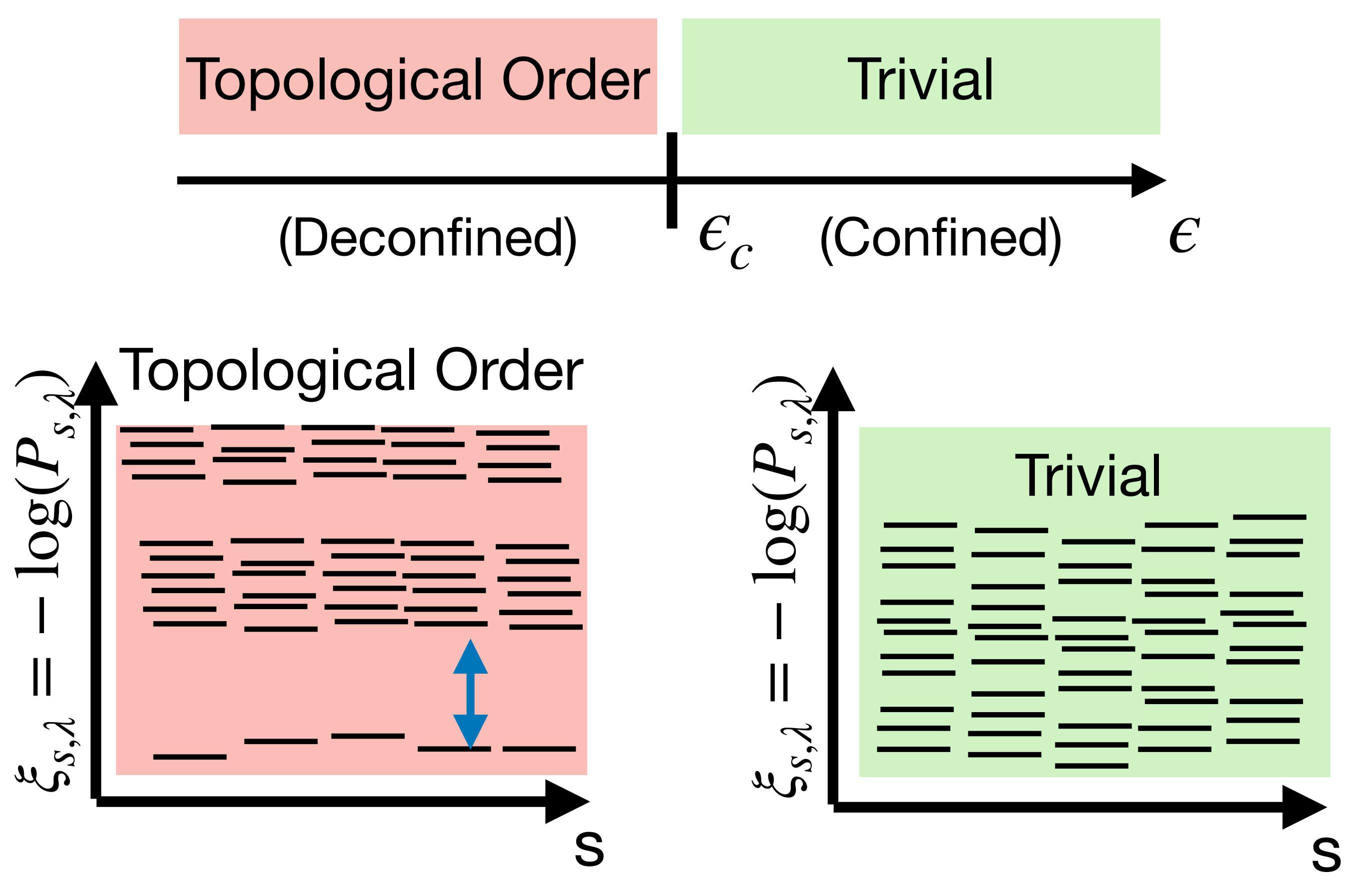
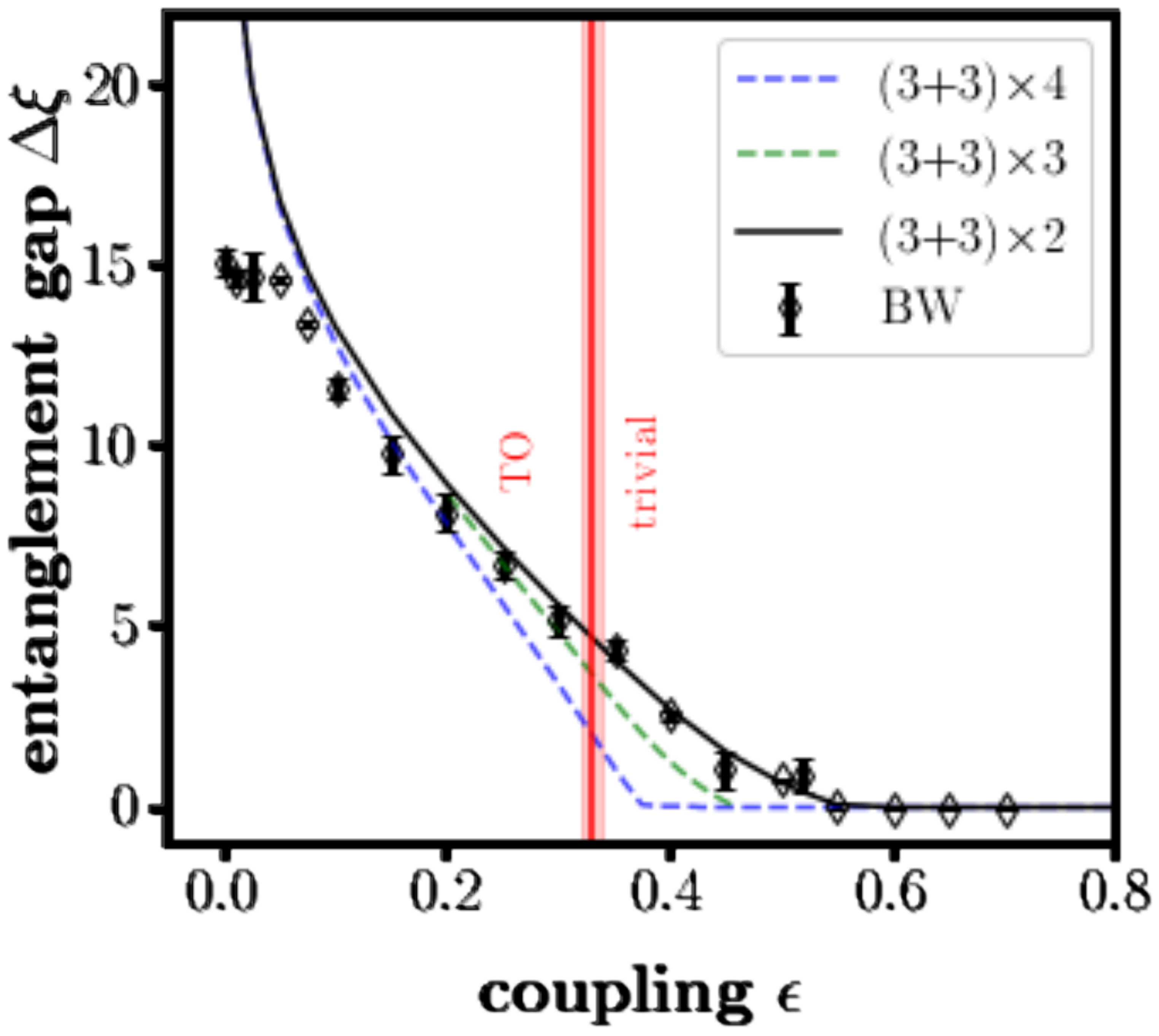


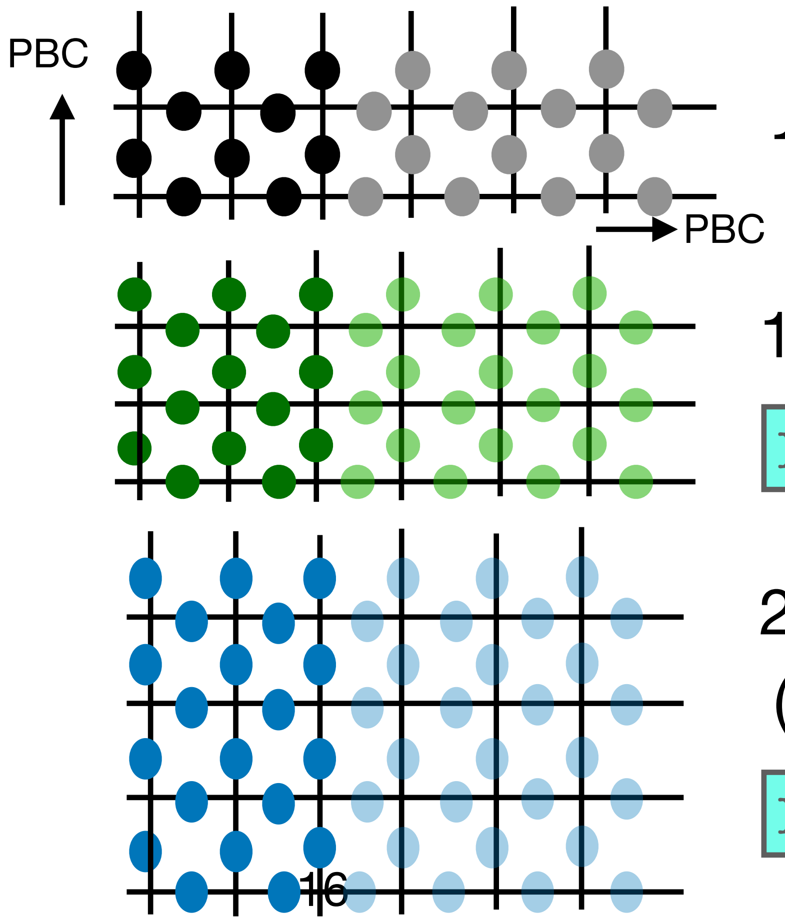


- **Measure Topological Order**

BW

	sampling cost	circuit layer
	$N_E = 50$	64 layers
	$\times N_M = 1024$	
	$= 51{,}200$	

(overkill, because we can)



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NM, Zache, Ott, PRL129 (2022) 1

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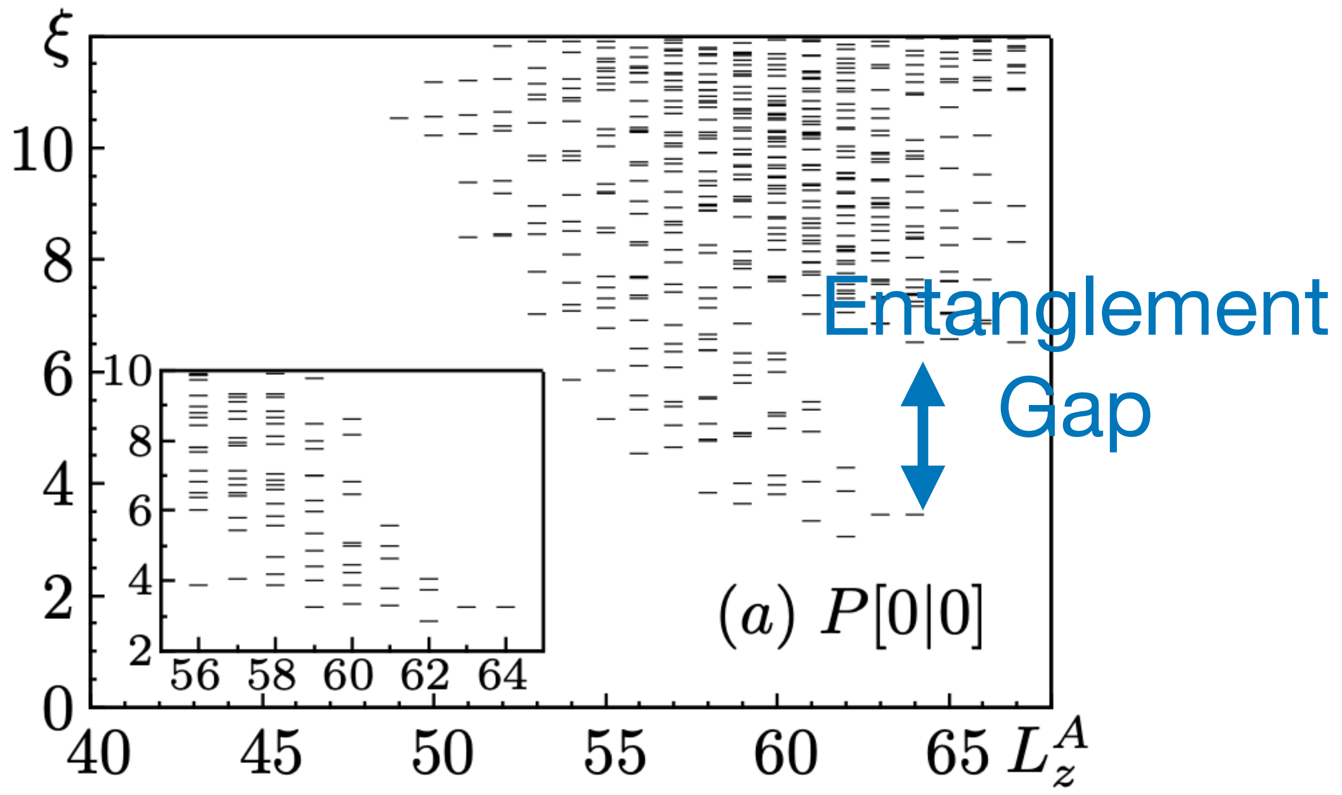
NM, Zache, Ott, PRL129 (2022) 1

Jake Bringewatt, Jon Kunjummen, NM, arXiv:2303.15519

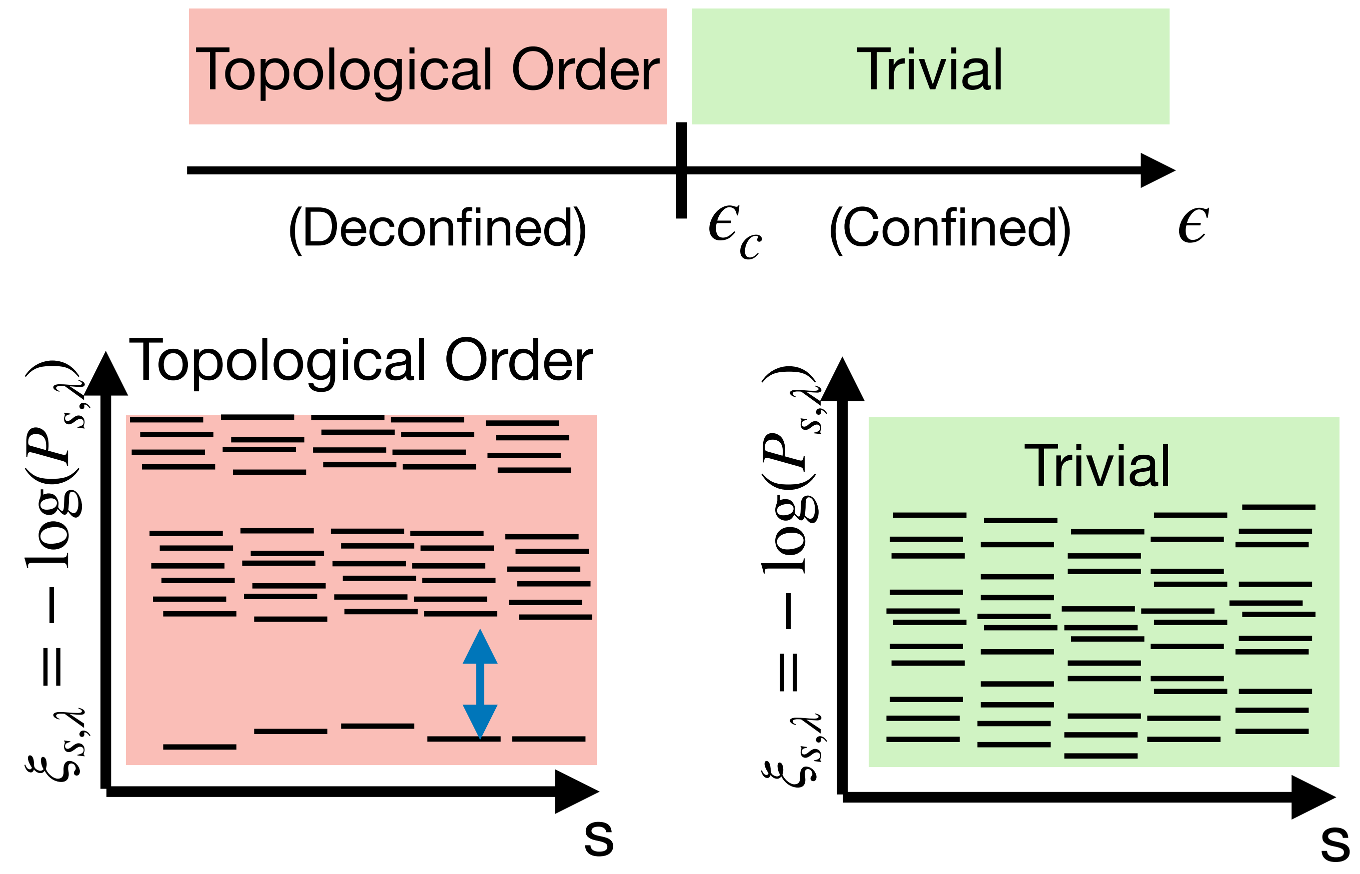
Symmetry-conscious Random Measurement

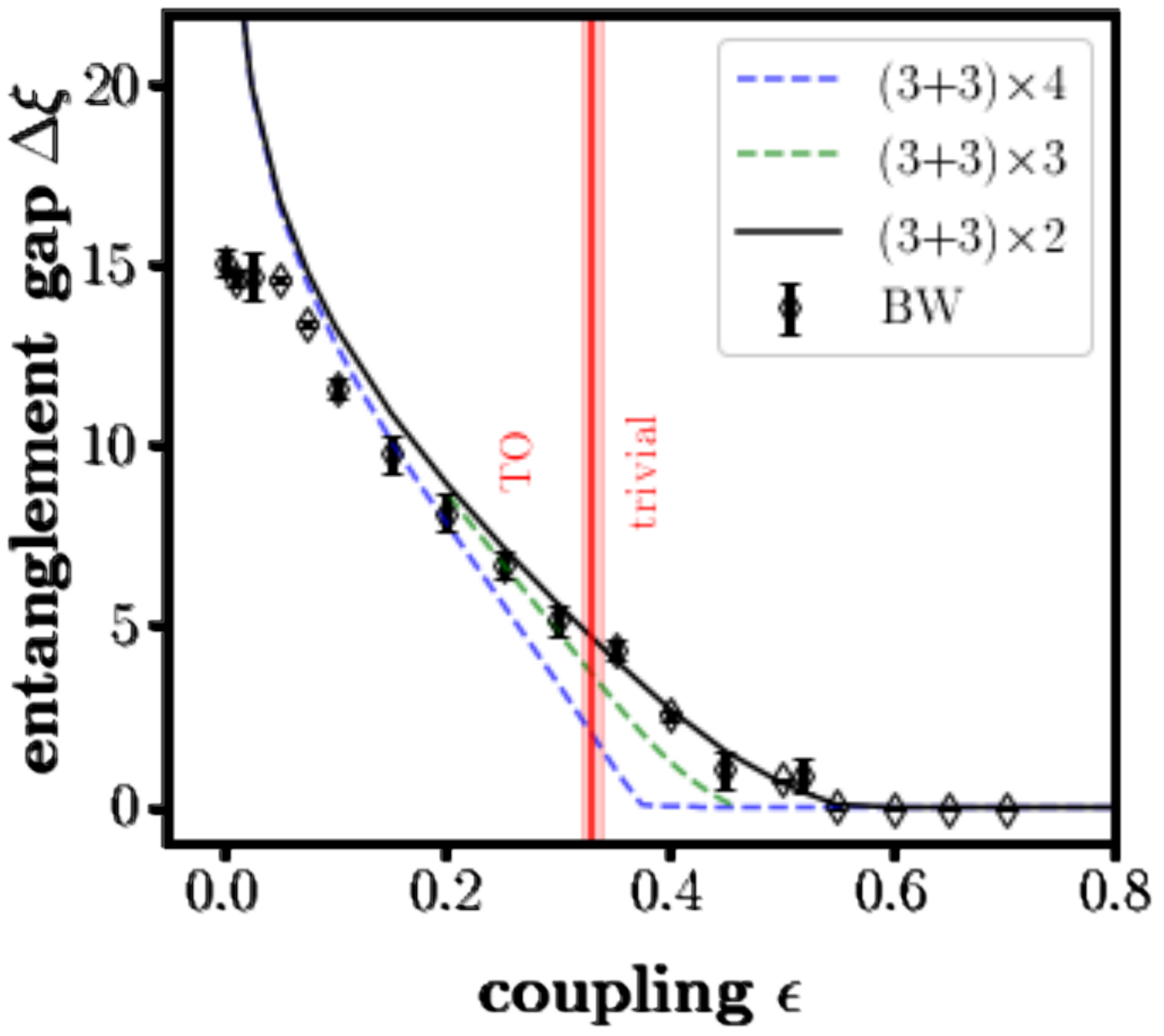
Detecting Topological Order



Li Haldane, PRL 101 01504 (2008)

$$H = -\epsilon \sum_{\ell} \sigma^z - \sum_p B_p$$

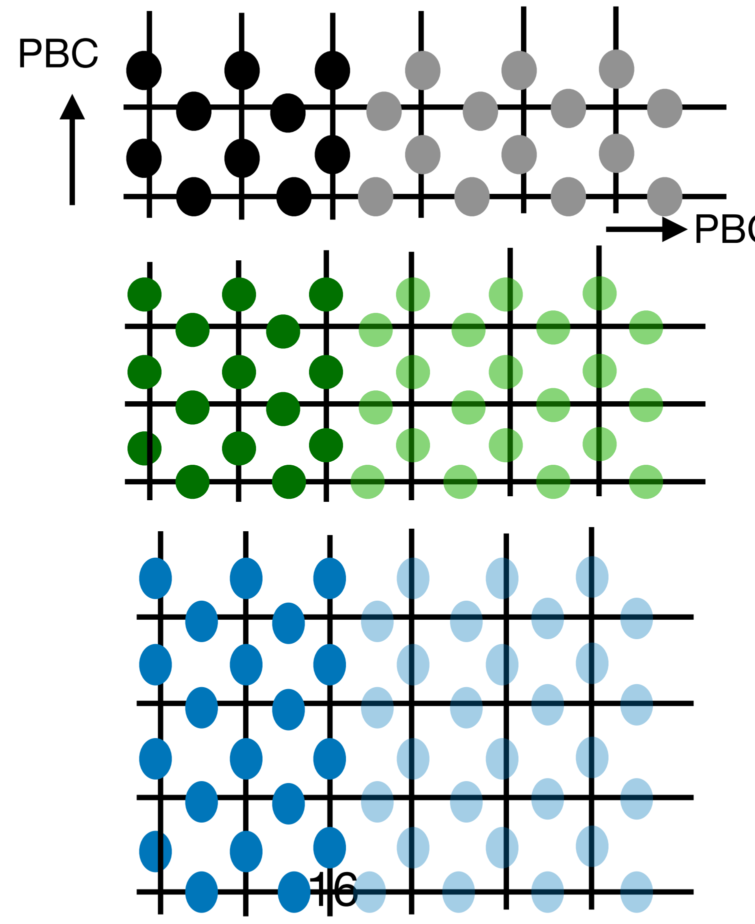




- **Measure Topological Order**

BW	sampling cost	circuit layer
	$N_E = 50$ x $N_M = 1024$ = 51,200	64 layers

(overkill, because we can)



10+14=28 qubits

15+21=36 qubits (dual)

NM, Zache, Ott, PRL129 (2022) 1

20+28=48 qubits (dual)

NM, Zache, Ott, PRL129 (2022) 1

$d_A = 2^{20} = 1{,}048{,}576$

$d_s = 2^8 = 256$

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Thermalization of Gauge Theories

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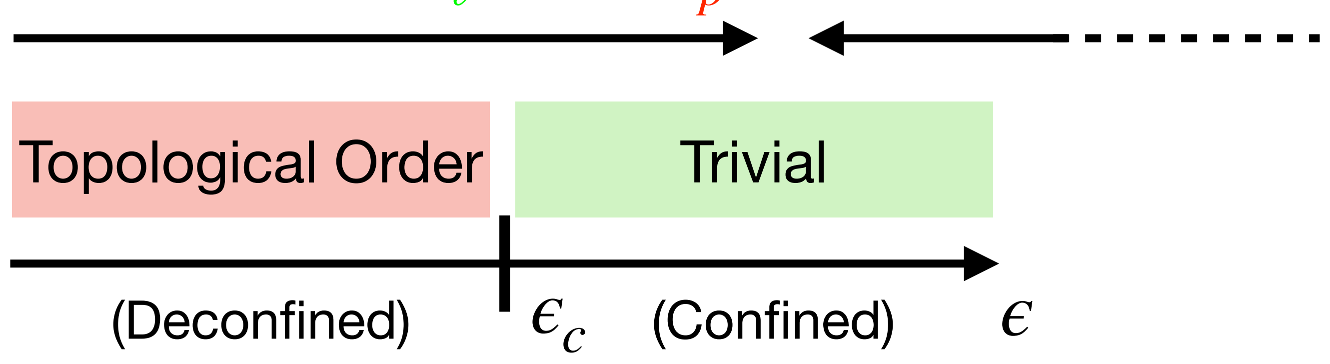

Quantum Quench

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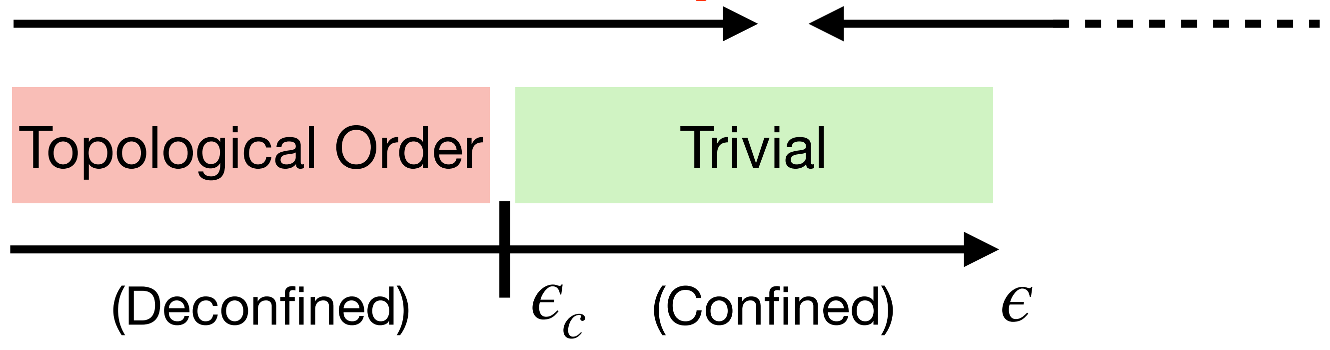

Quantum Quench

from Entanglement Structure

universität innsbruck

IQI

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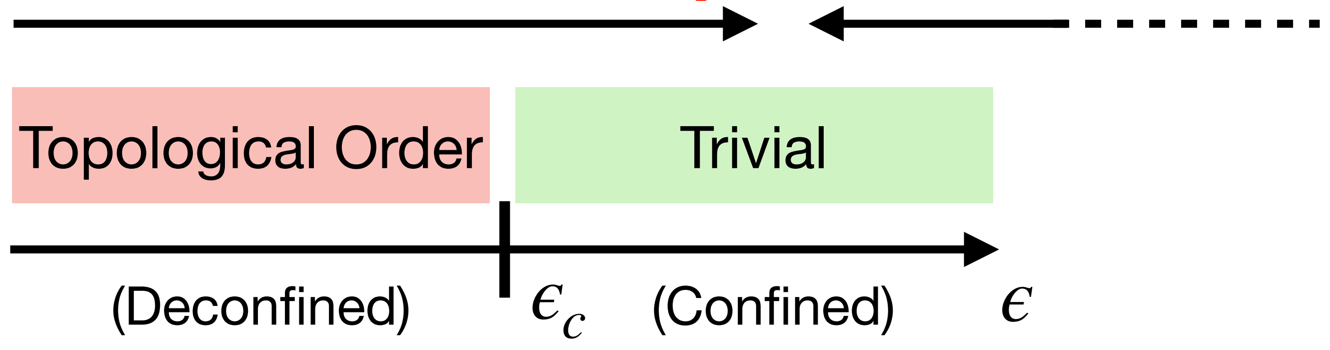

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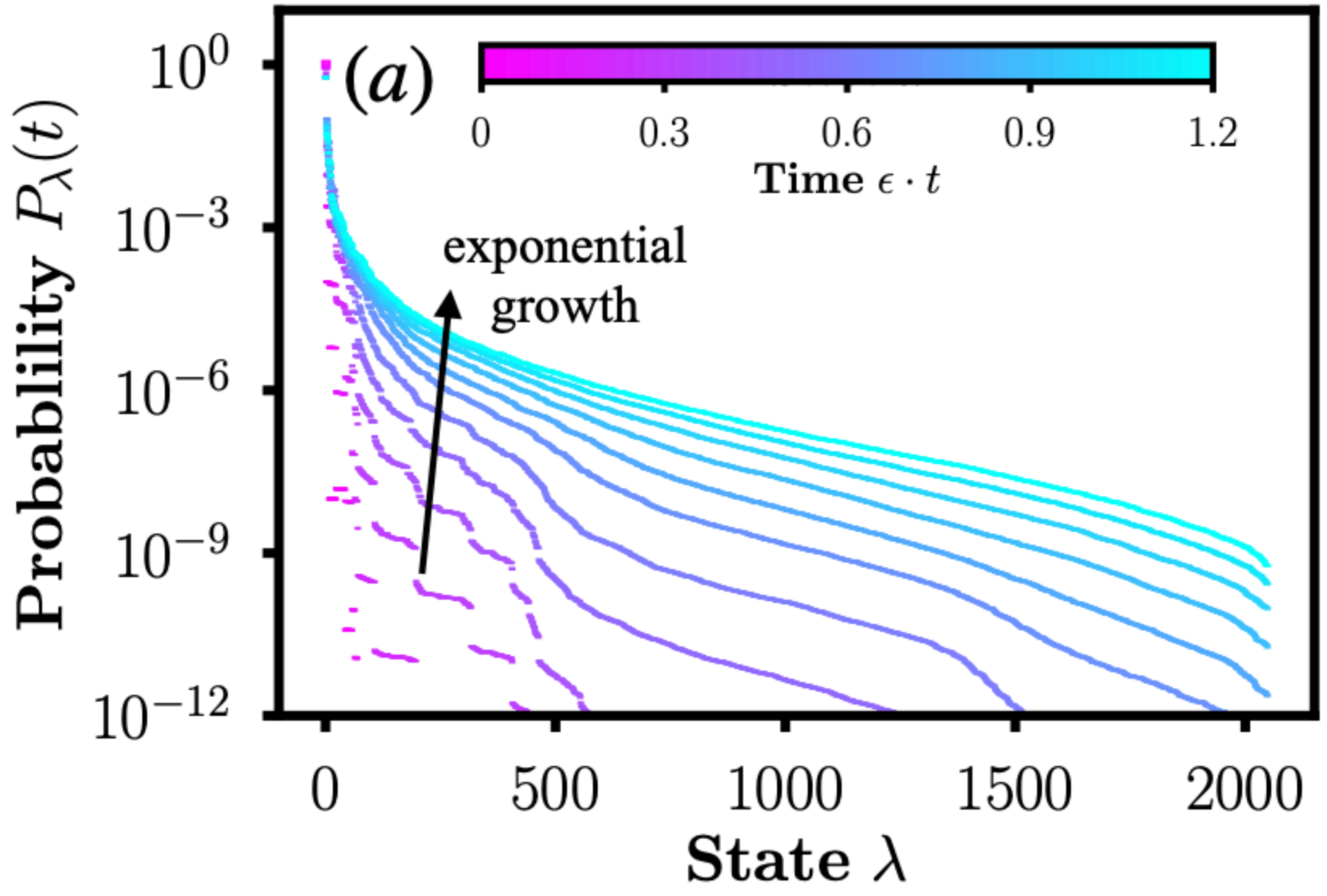

NM, Zache, Ott, PRL 129, 011601 2022)

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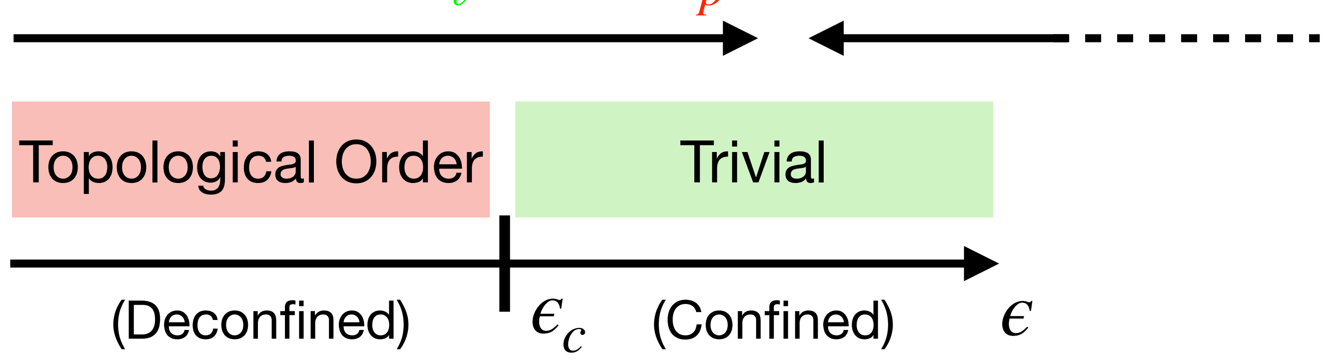

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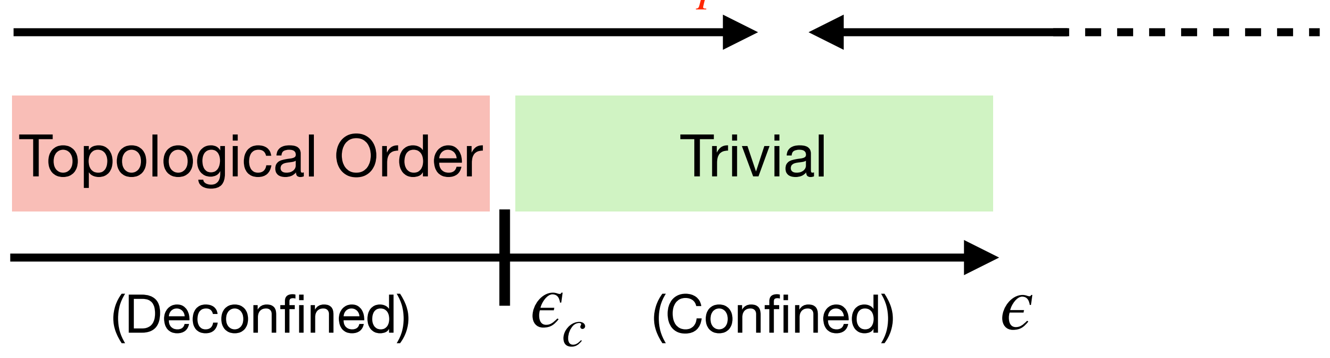

Quantum Quench

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$$r_\lambda \equiv \frac{\min(\delta_\lambda, \delta_{\lambda-1})}{\max(\delta_\lambda, \delta_{\lambda-1})} \qquad \delta_\lambda = \xi_\lambda - \xi_{\lambda-1}$$

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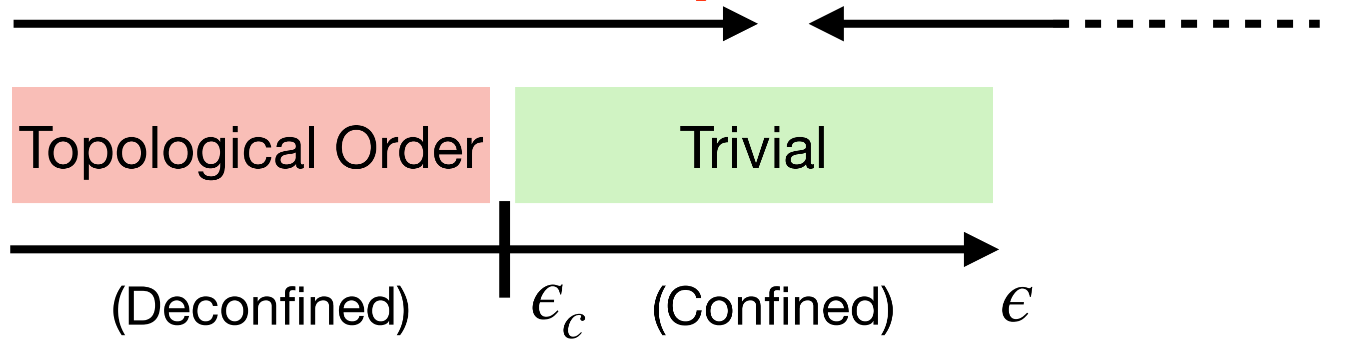

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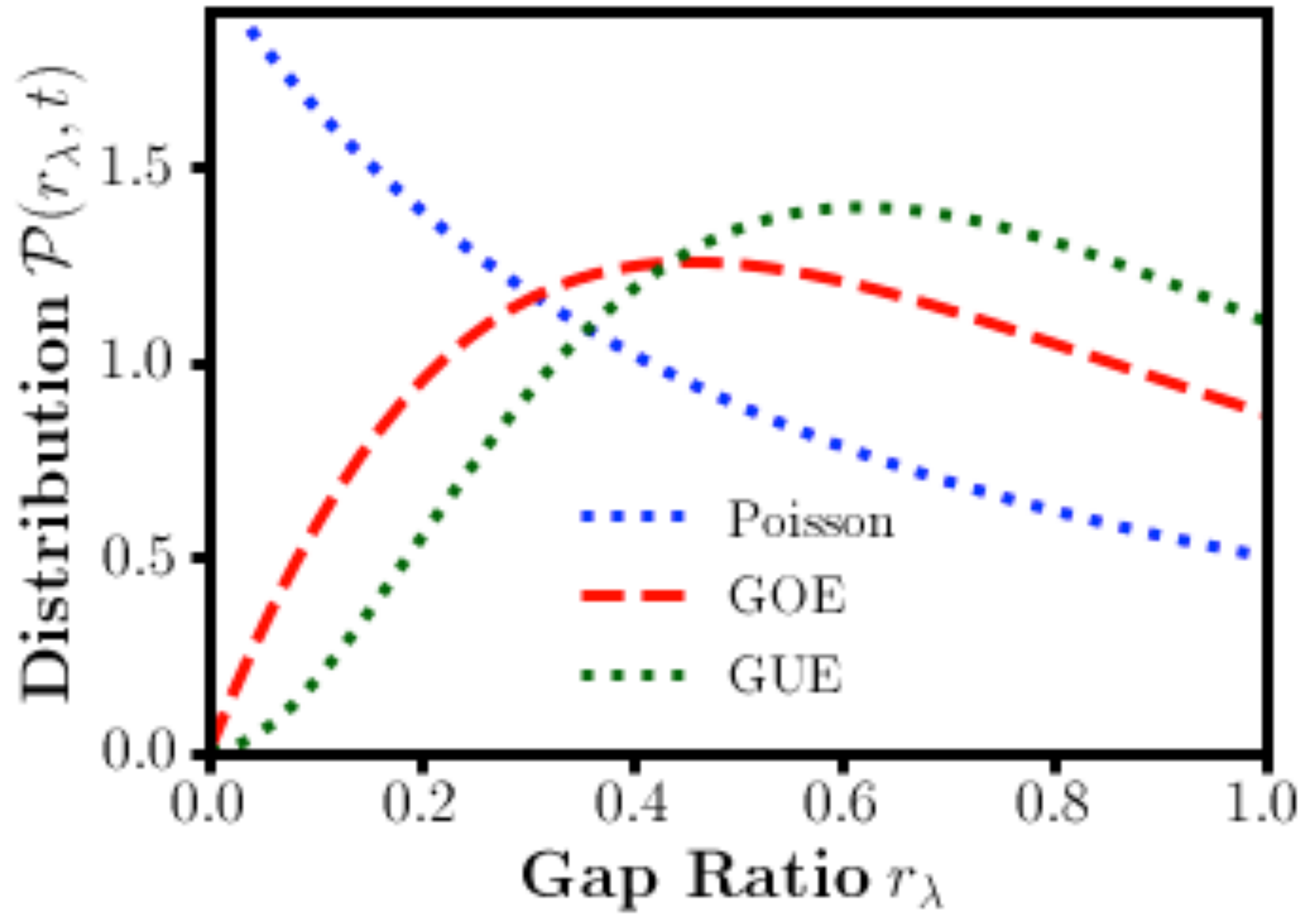

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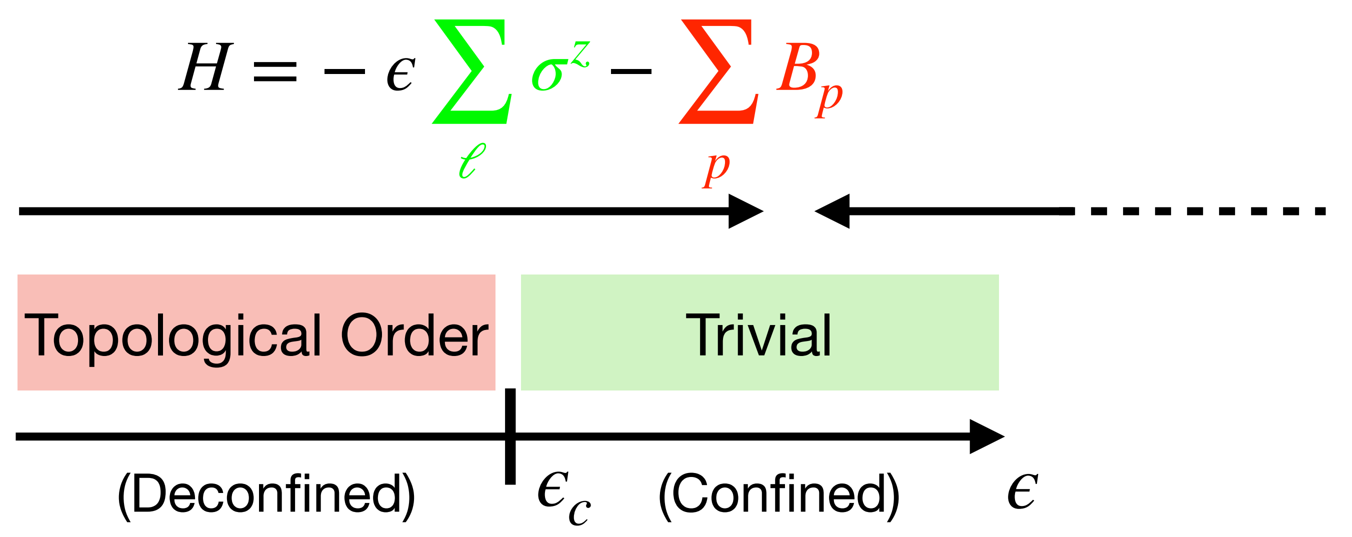

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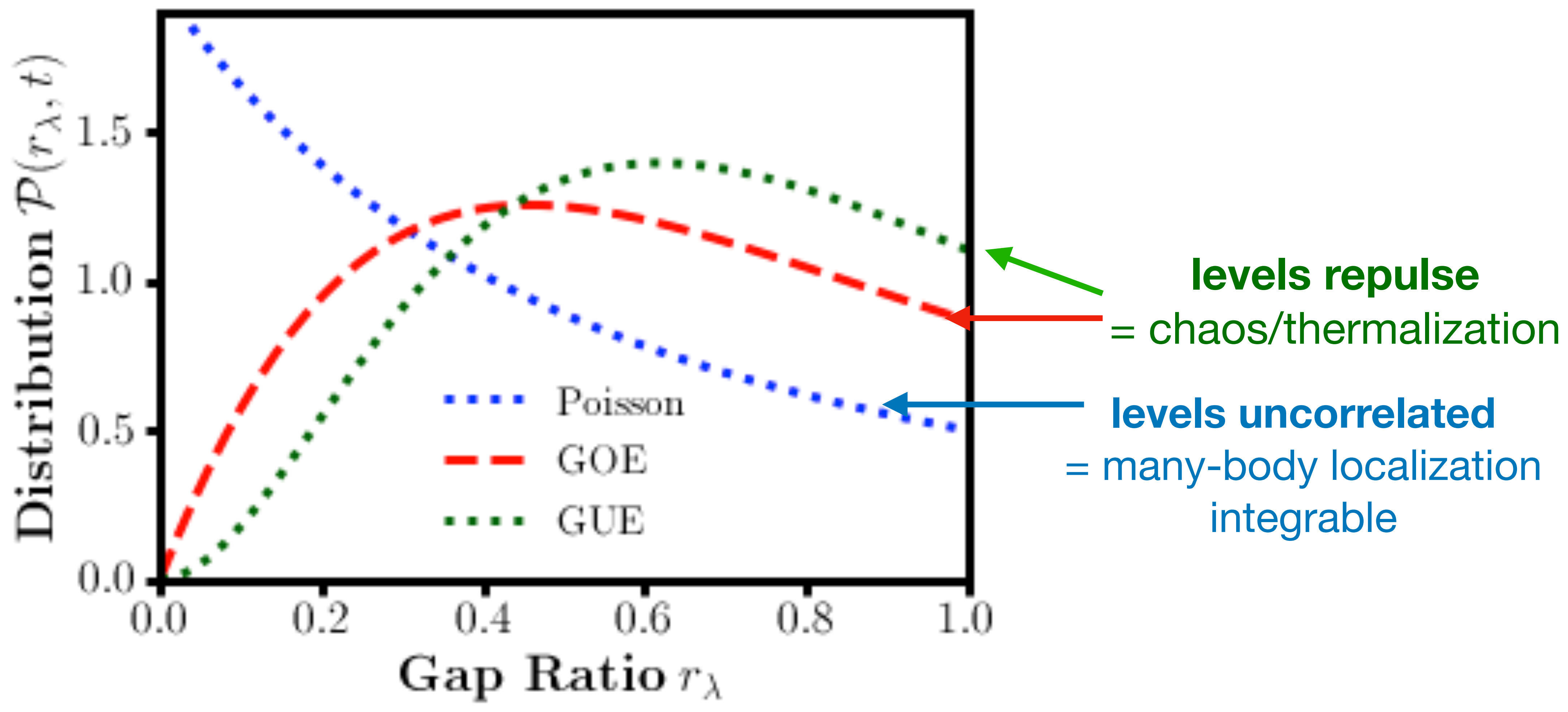

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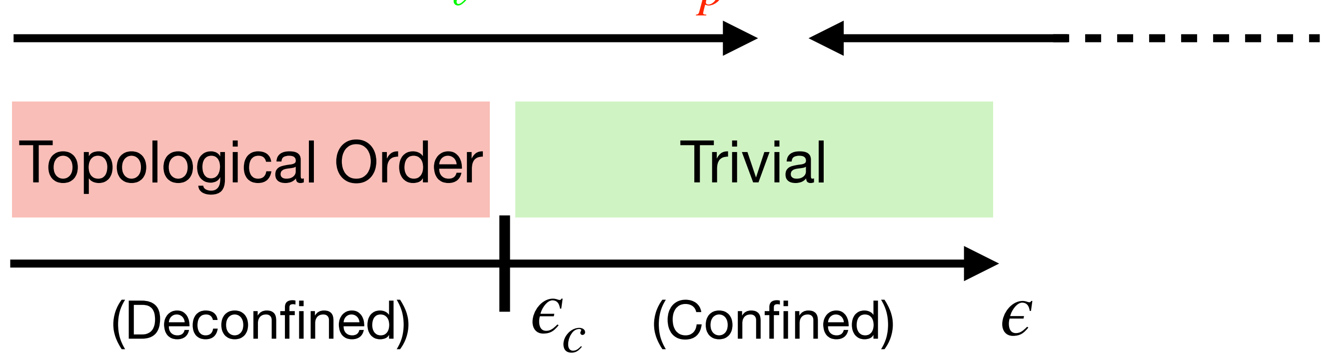

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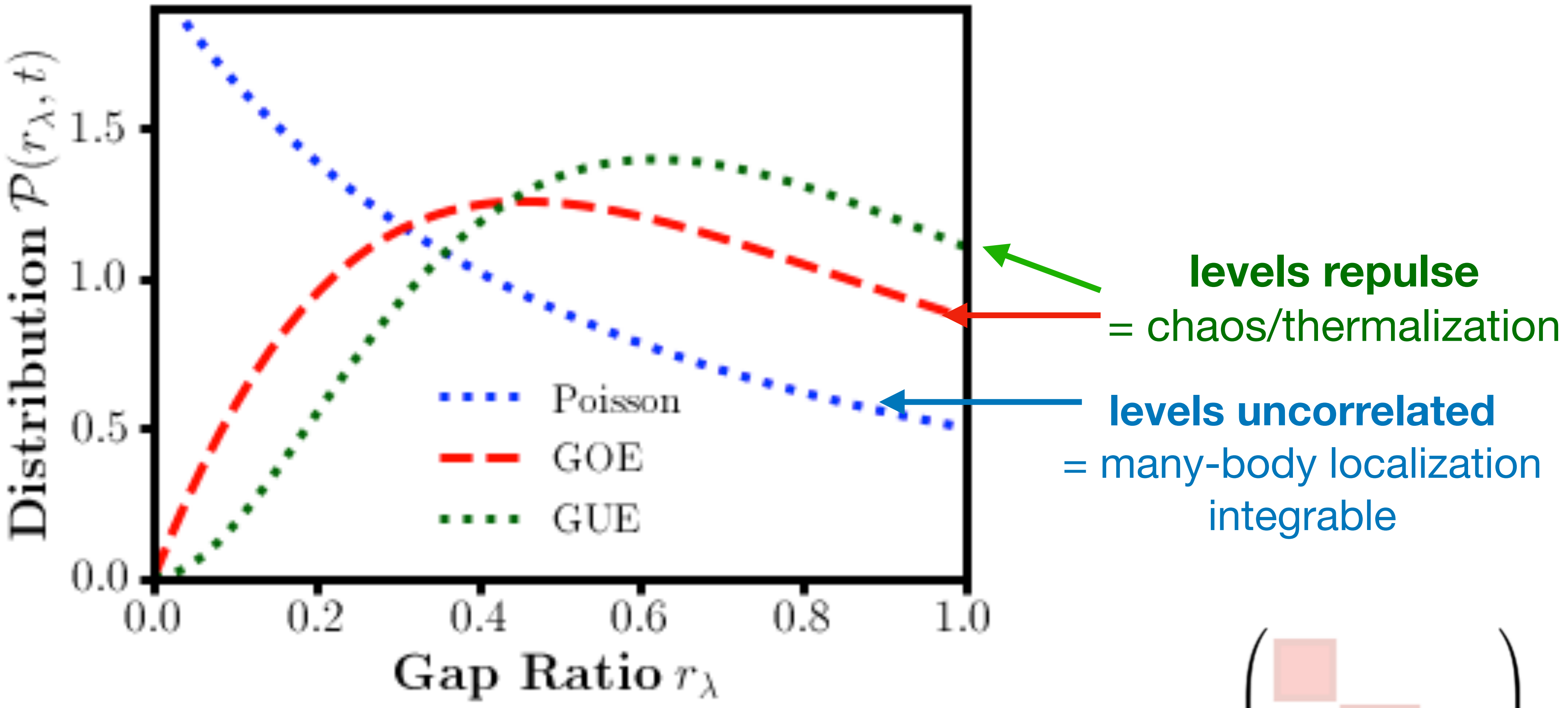
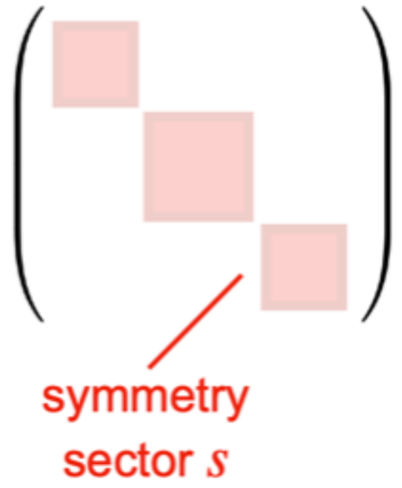


symmetries obscure level distribution



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NM, Zache, Ott, PRL 129, 011601 2022)

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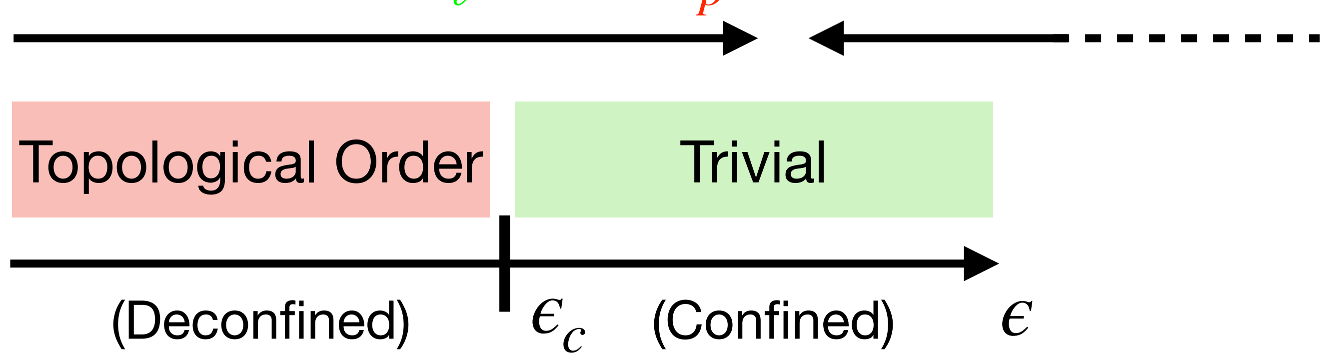

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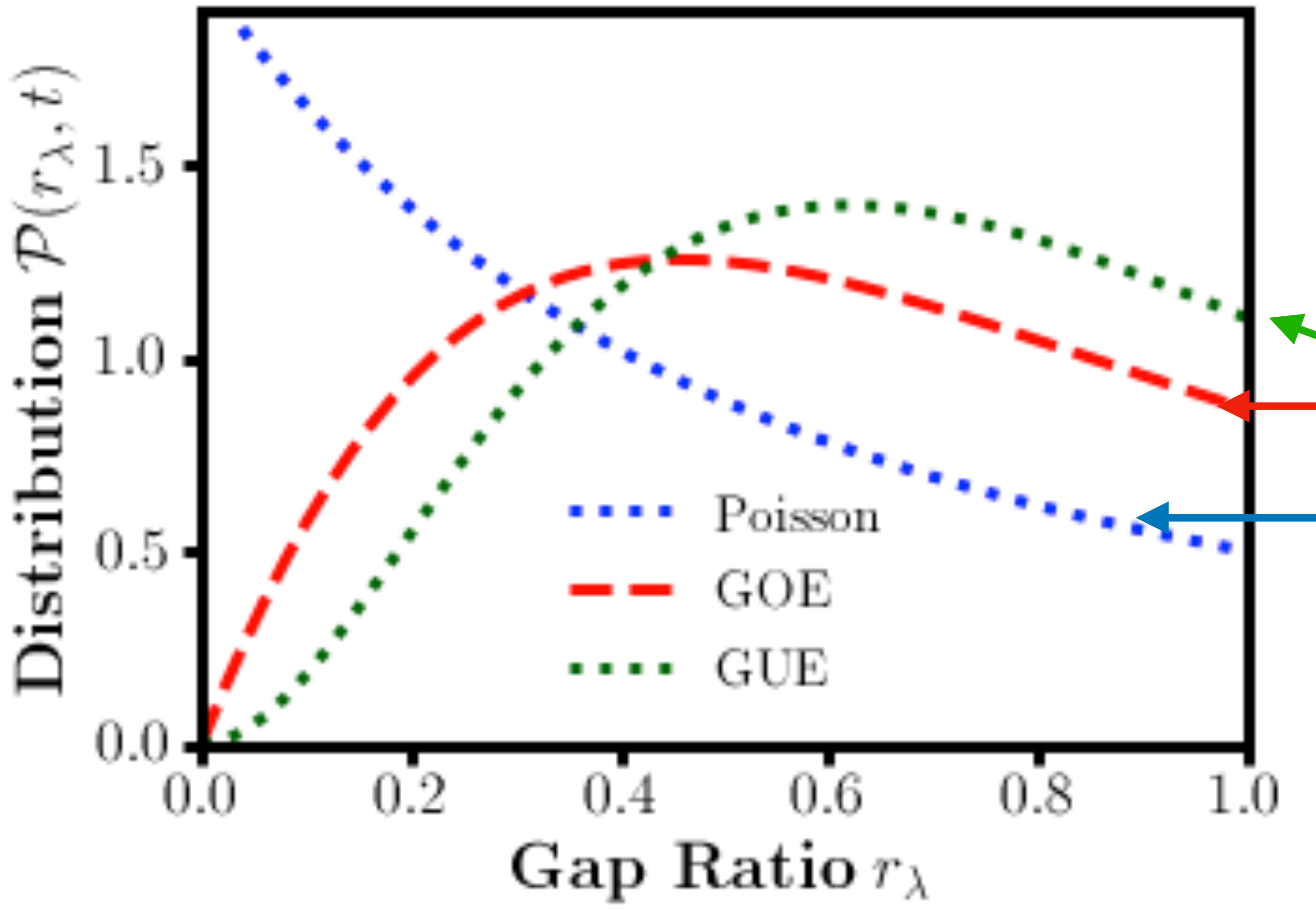
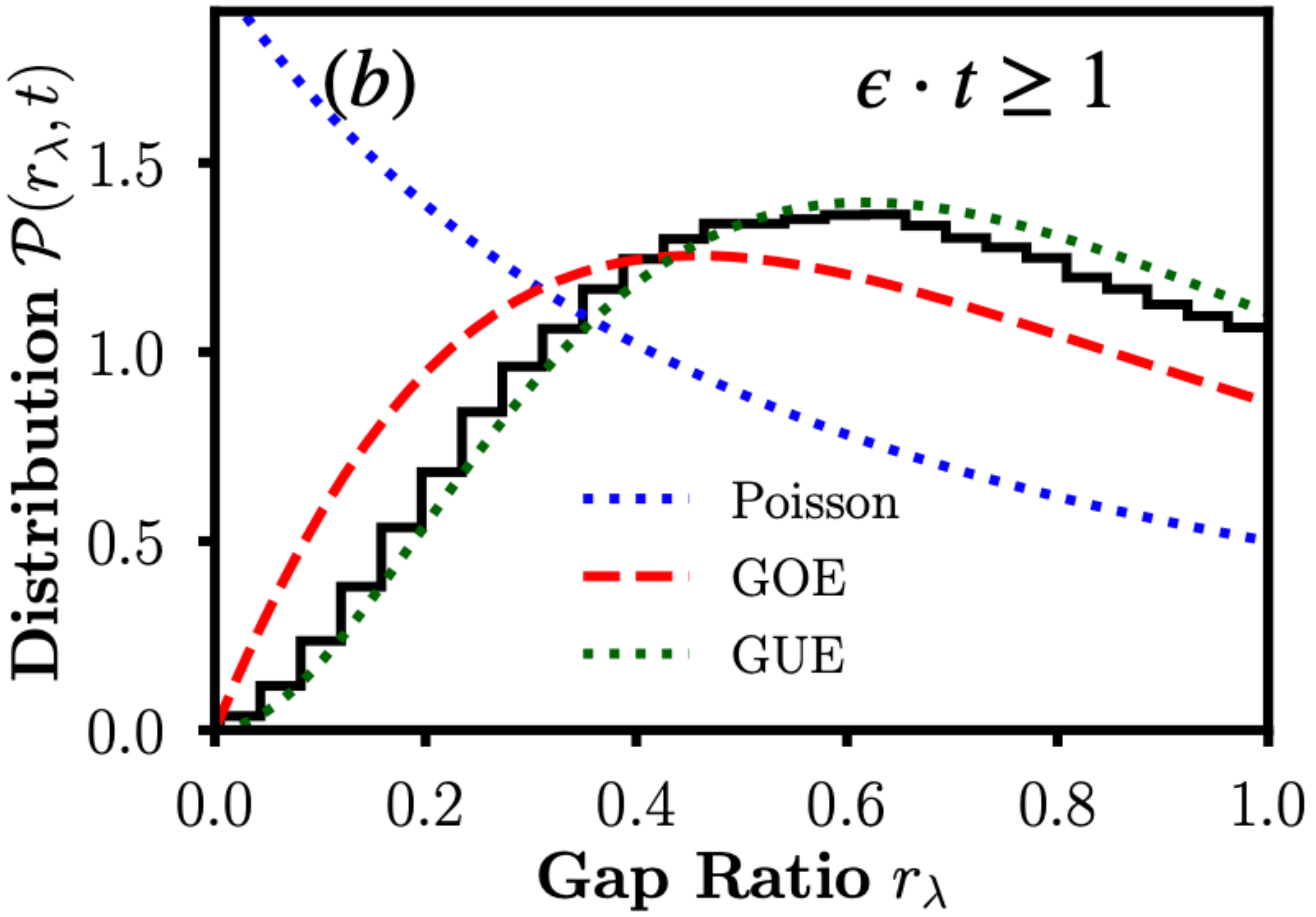


levels repulse
= chaos/thermalization

levels uncorrelated
= many-body localization
integrable



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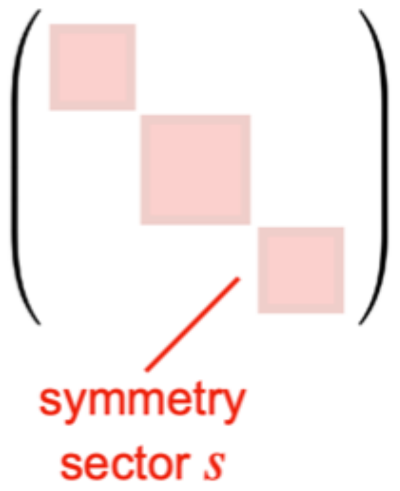

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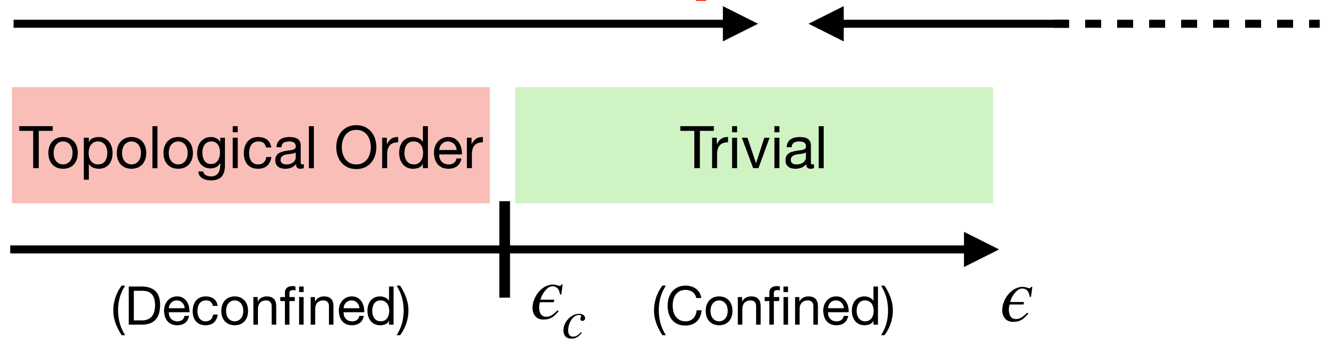

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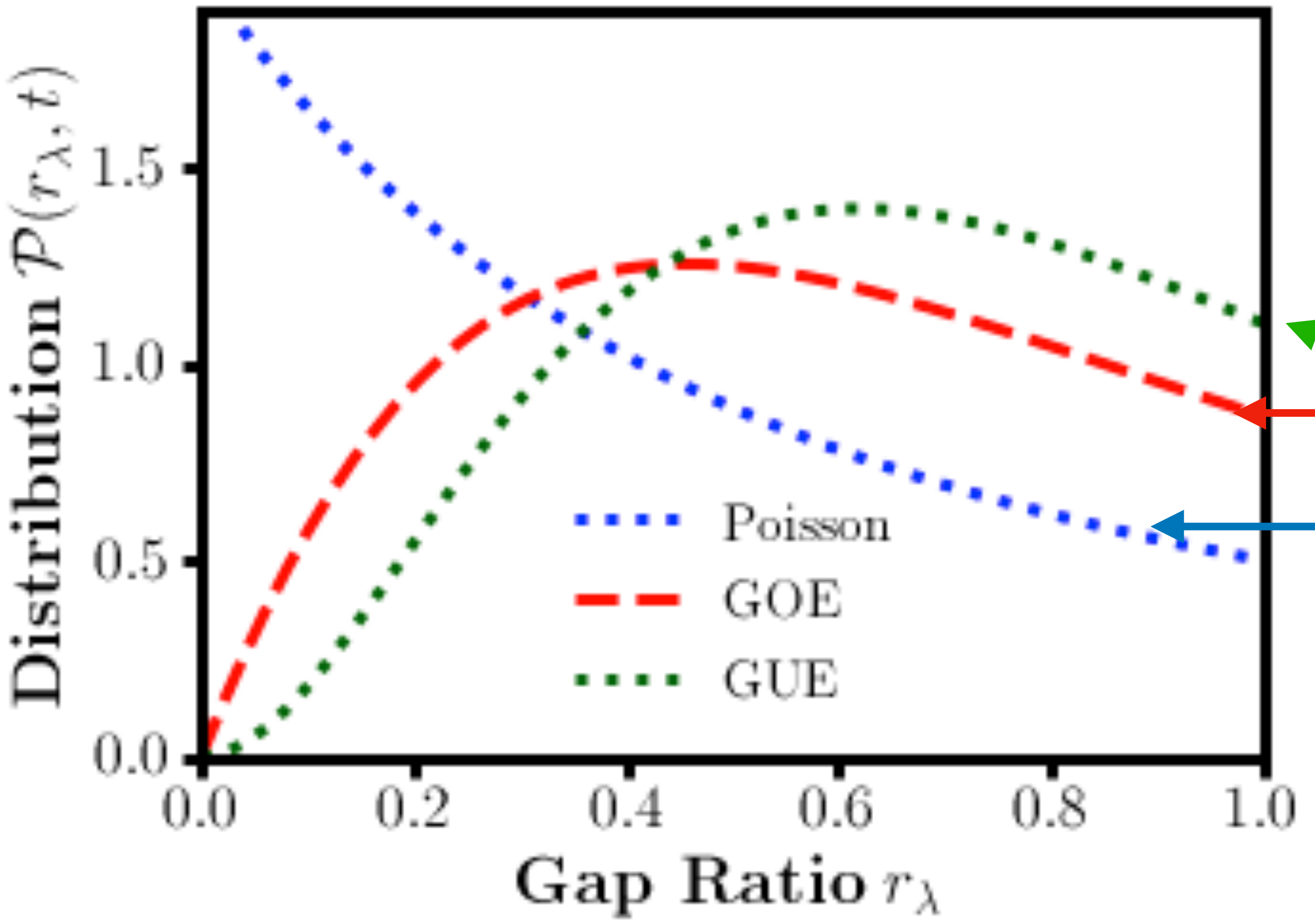

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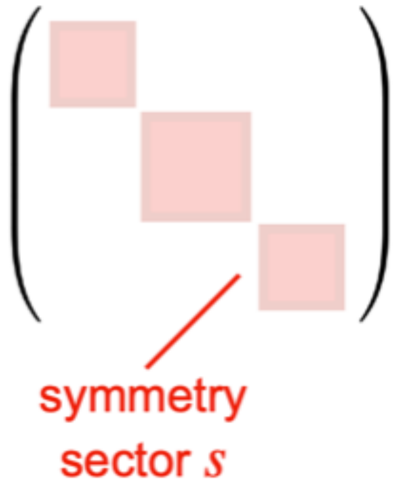

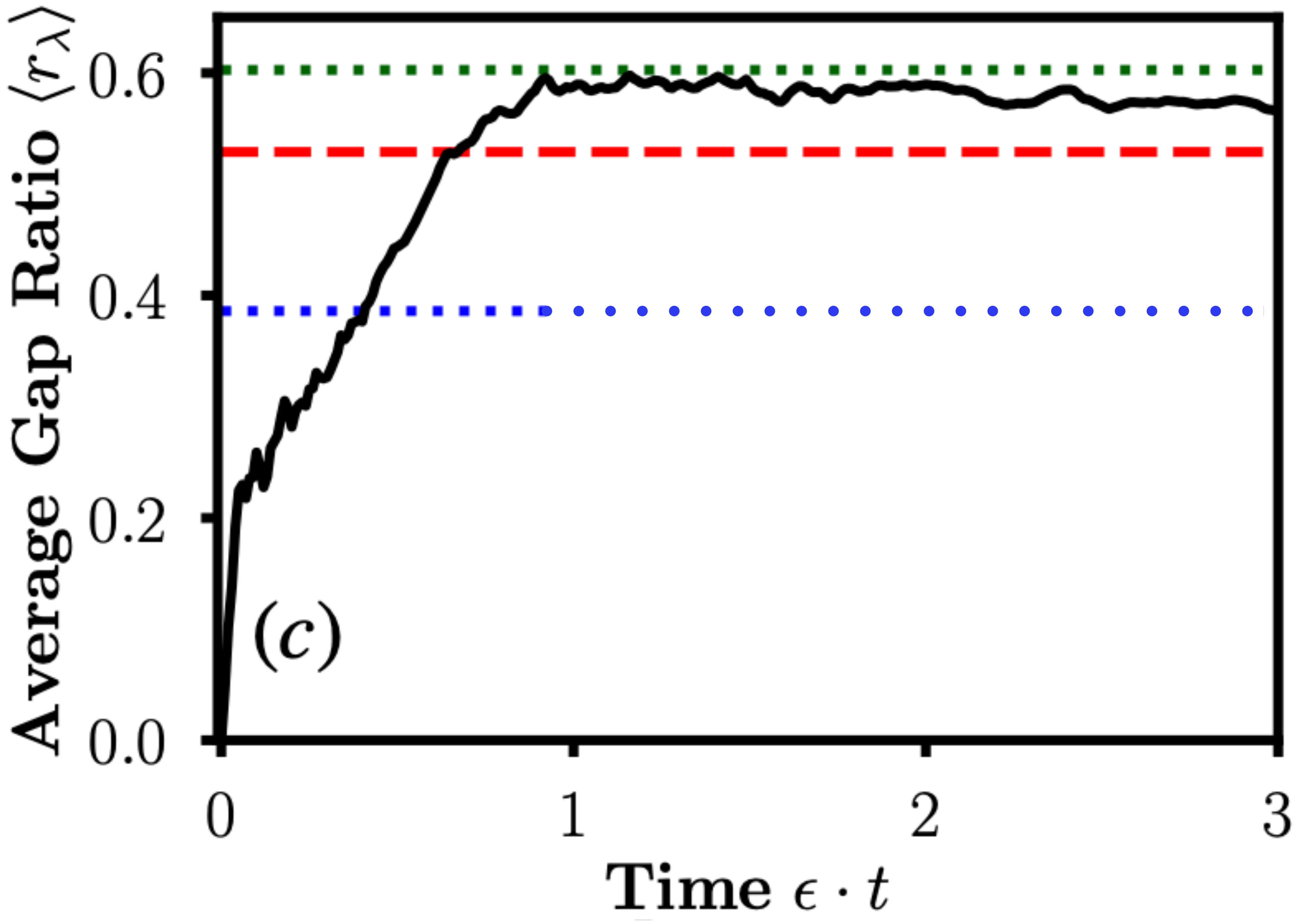

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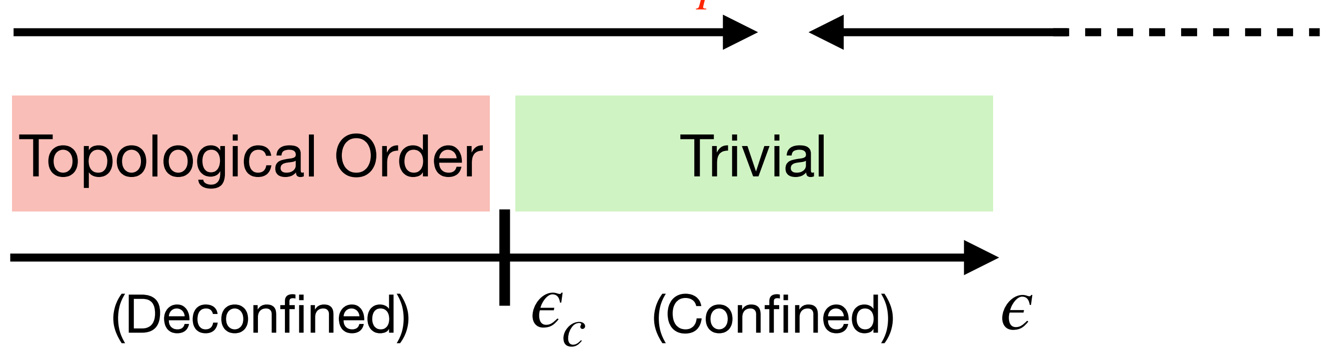

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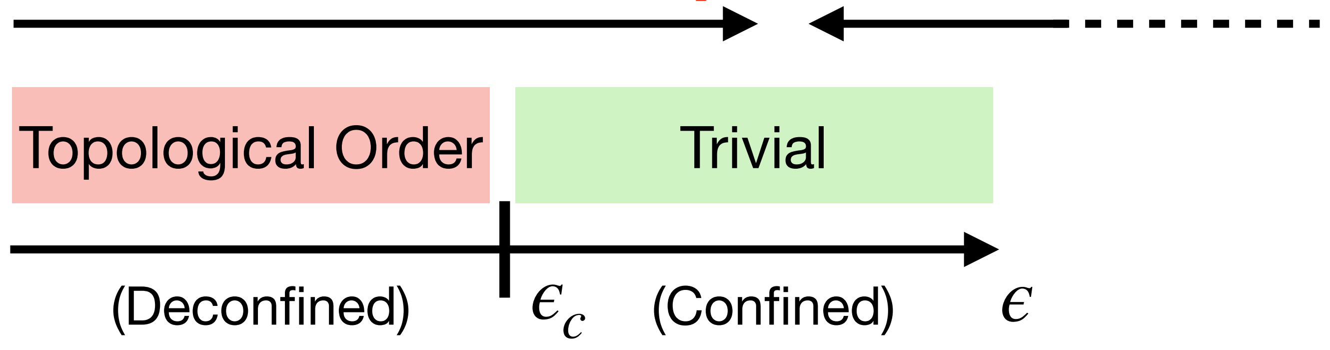

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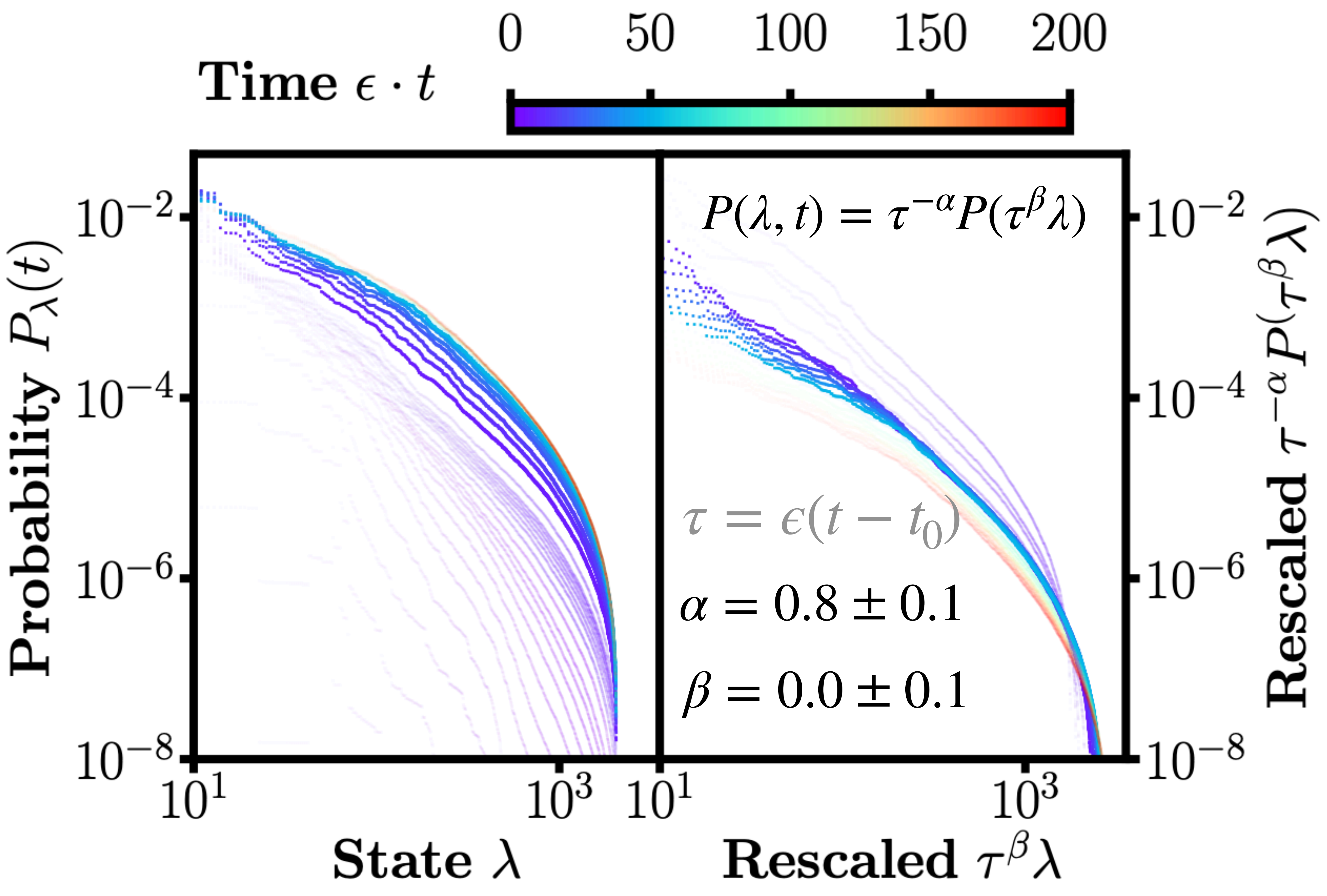

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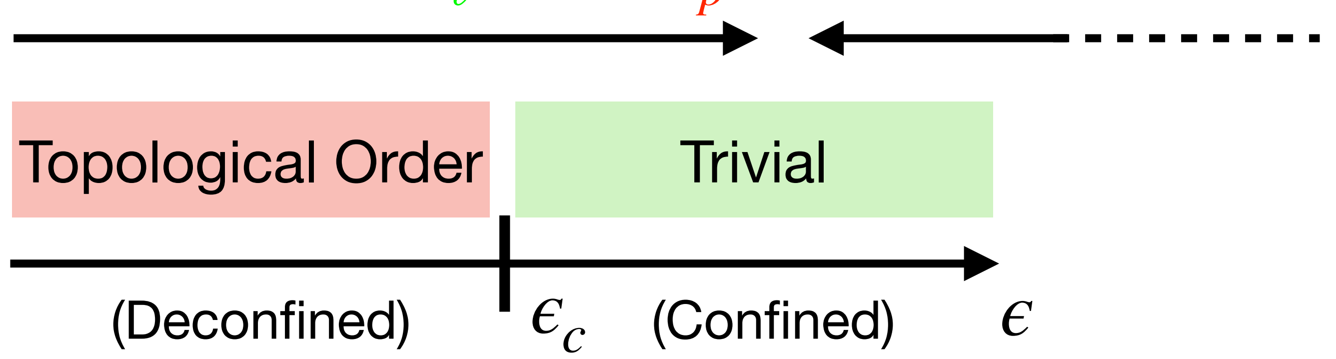

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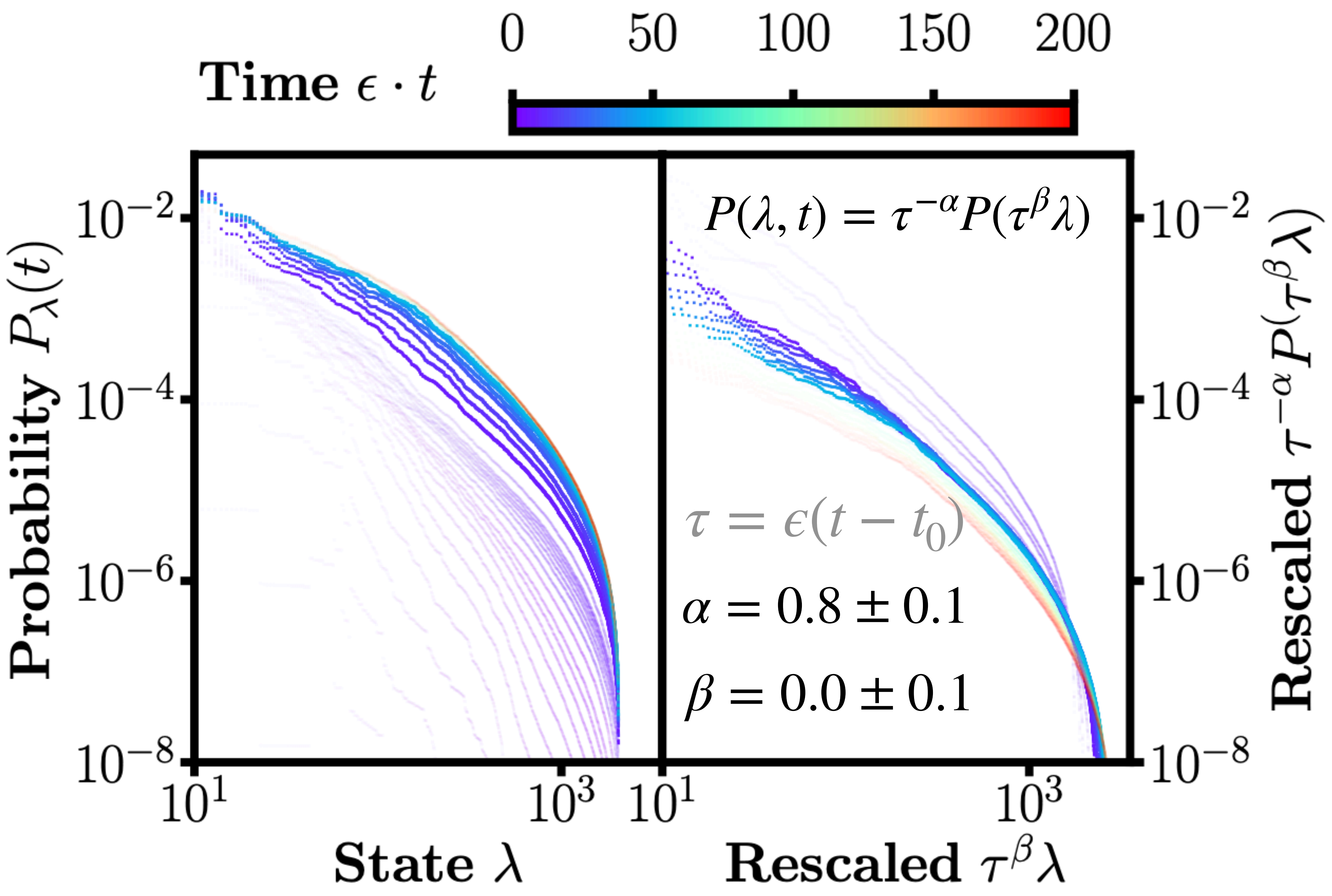

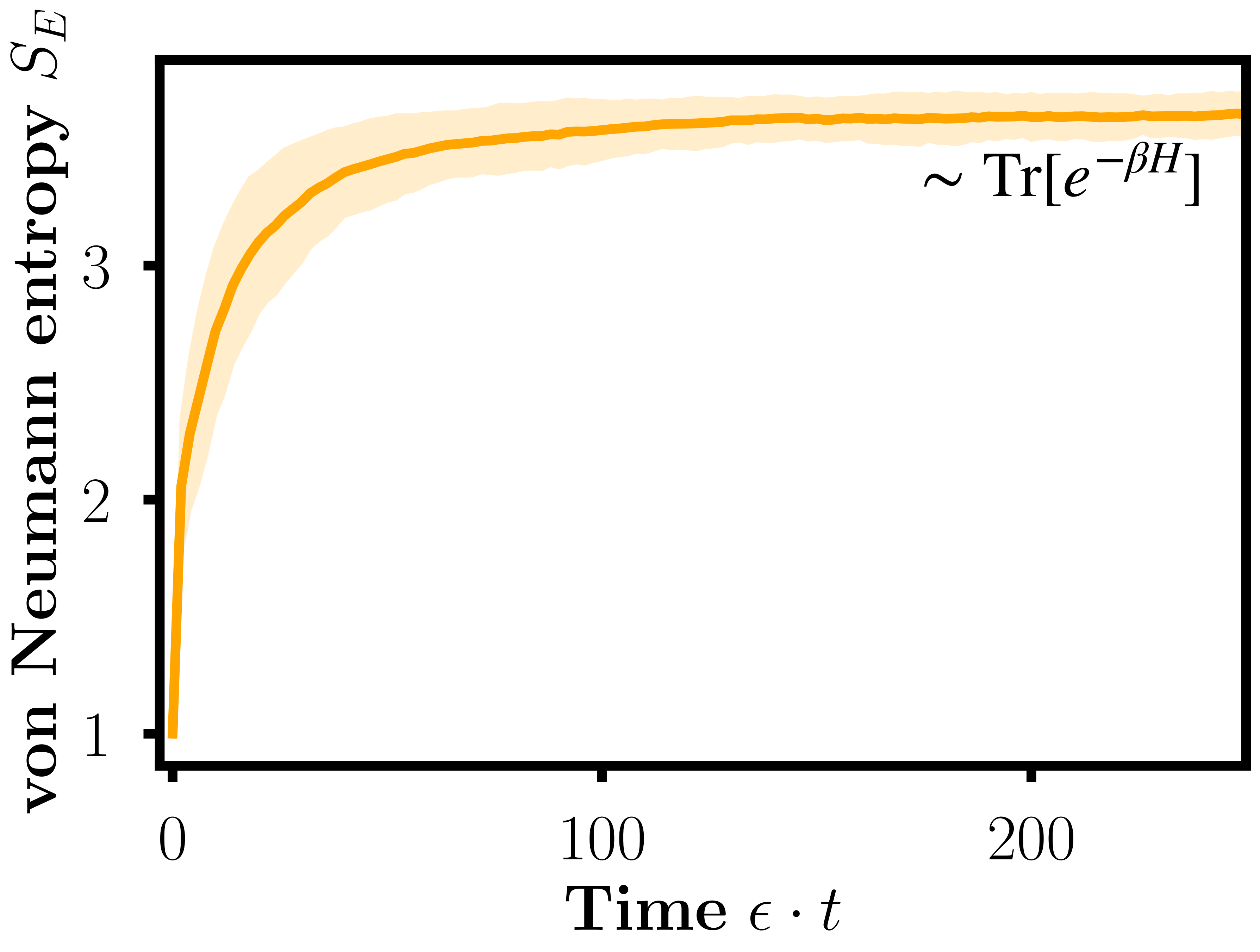

Conclusions

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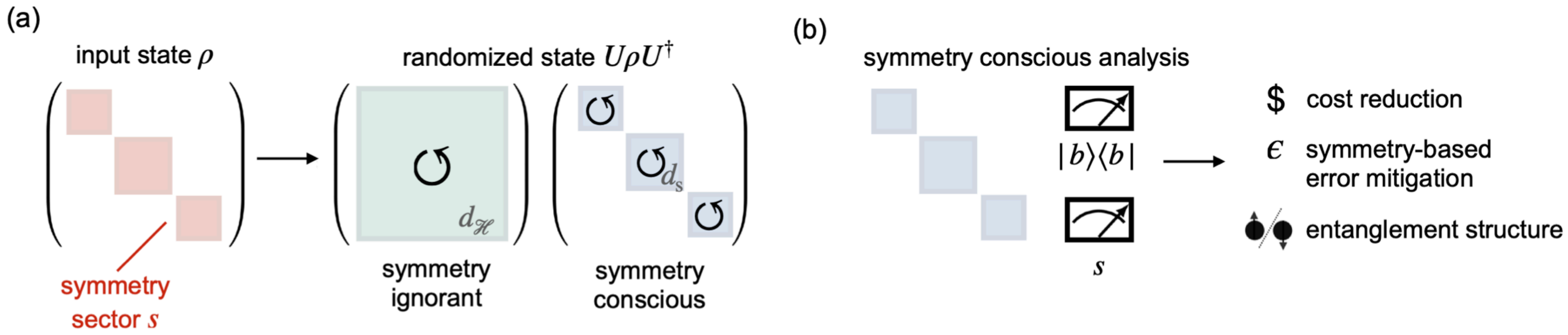

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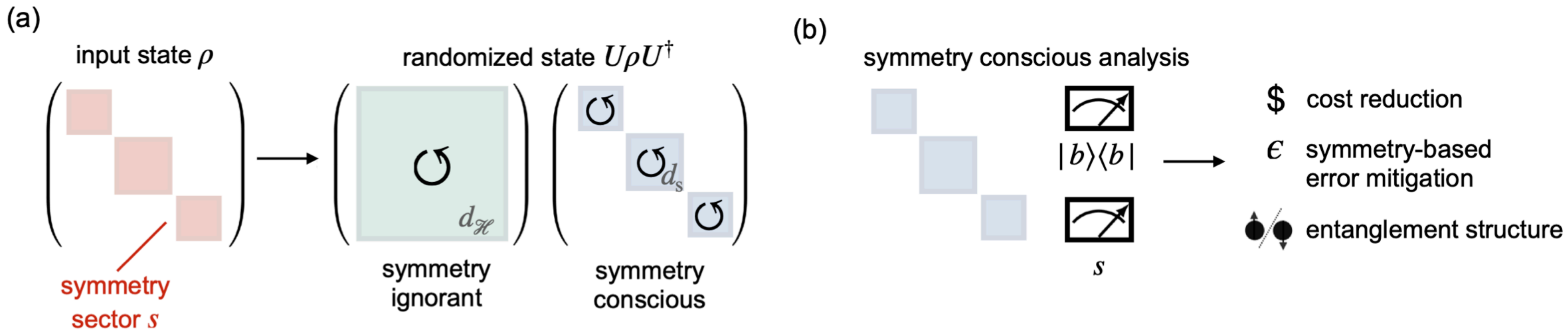

If you can implement time evolution, you can implement symmetry-conscious randomization!

Elben, Vermersch, Dalmonte, Cirac, Zoller, PRL 120, 050406 (2018)
Vermersch, Elben, Dalmonte, Cirac, Zoller, PRA 97, 023604 (2018)

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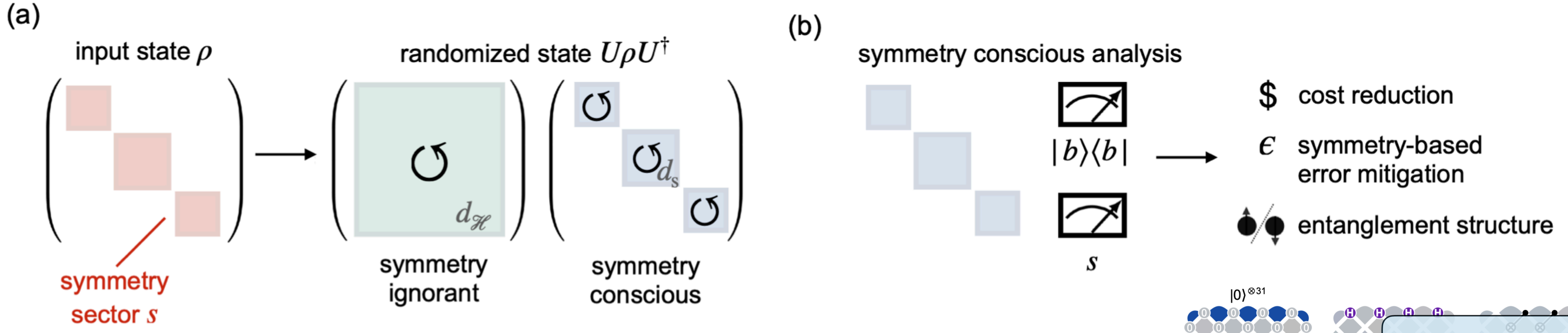

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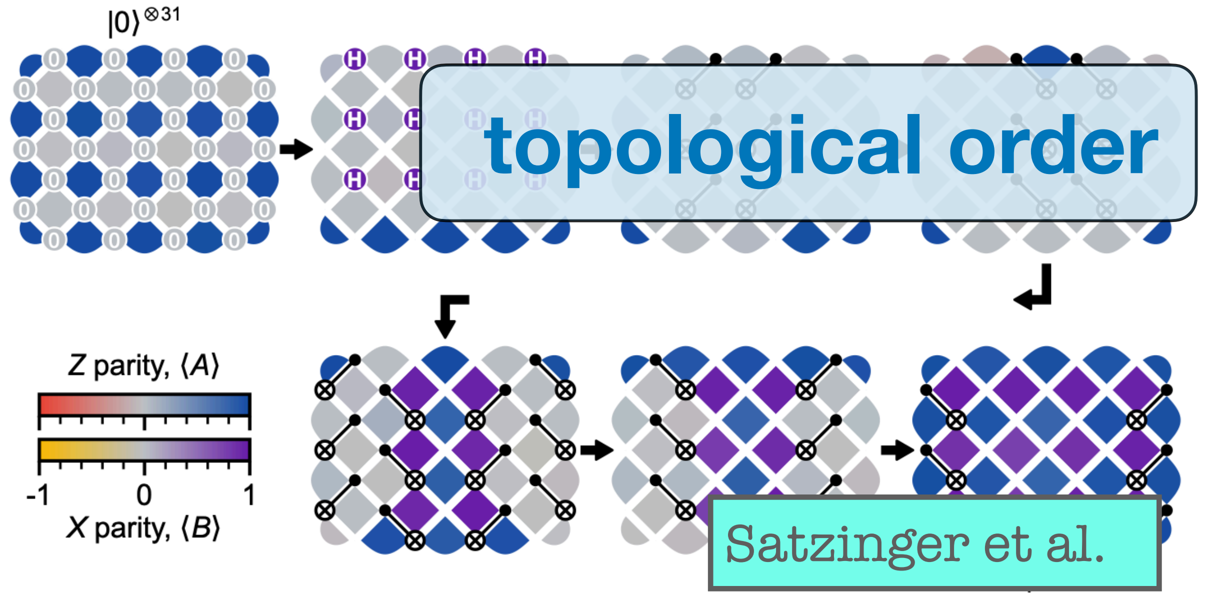

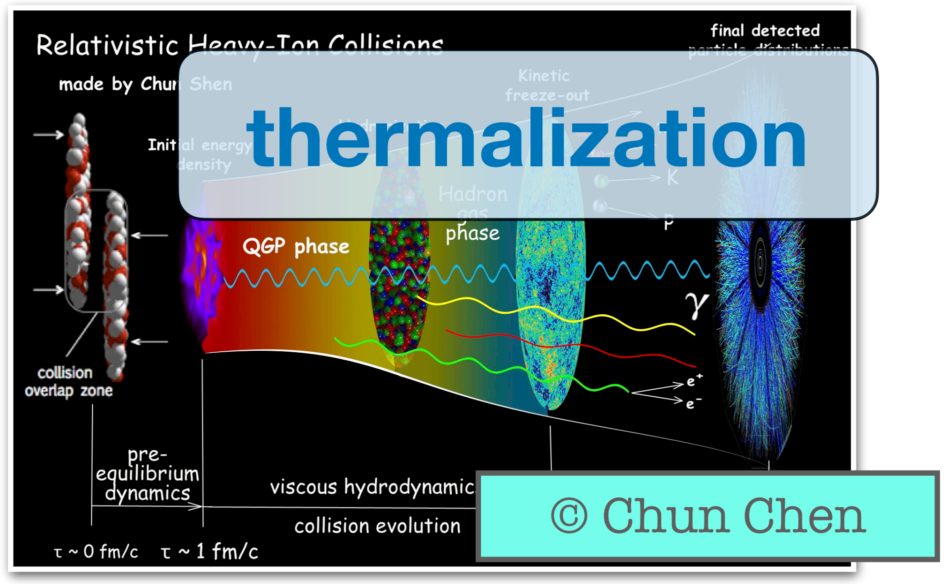

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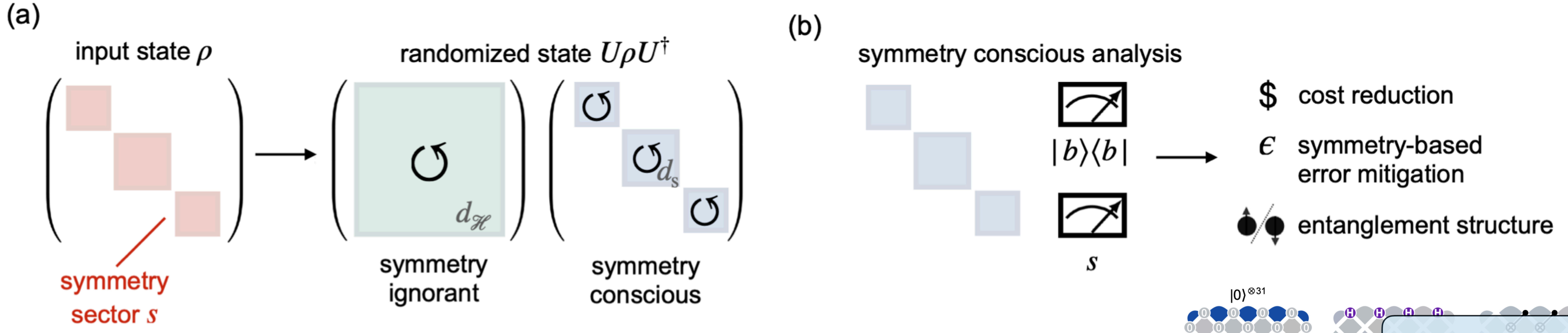

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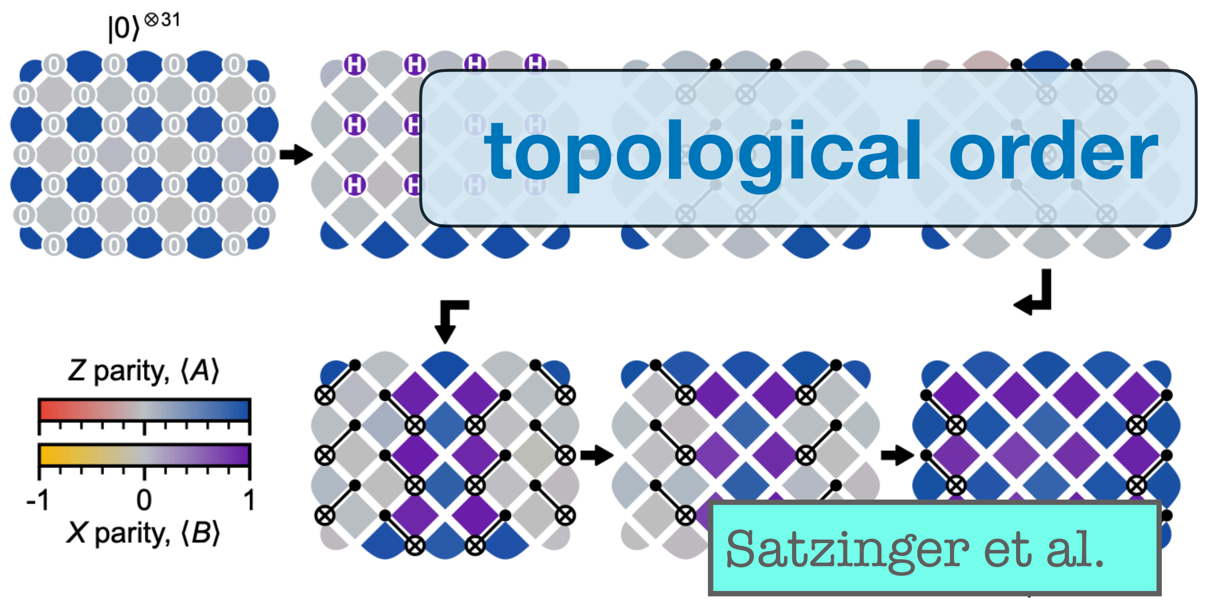

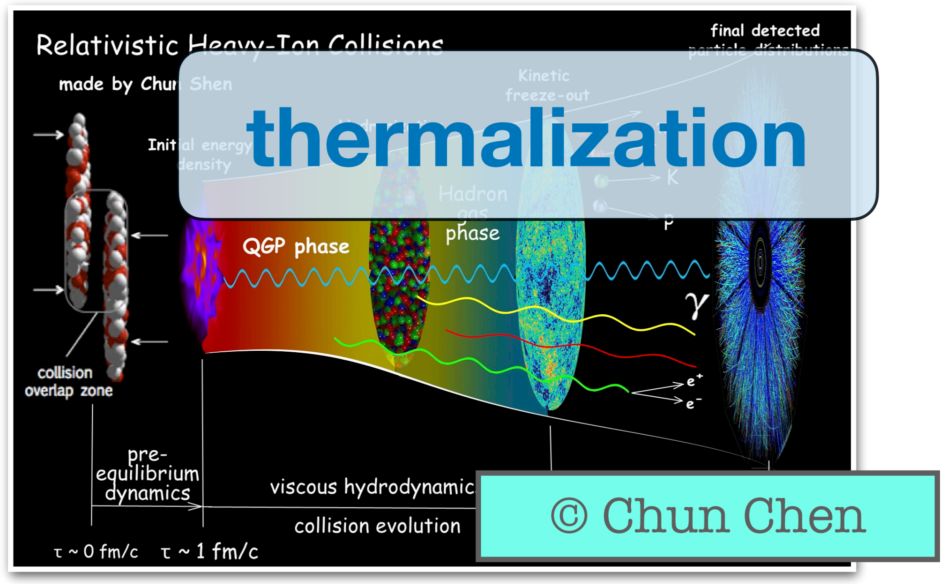

- Deep scrambling algorithms soon feasible. A lot more work. Robustness? Performance guarantees?

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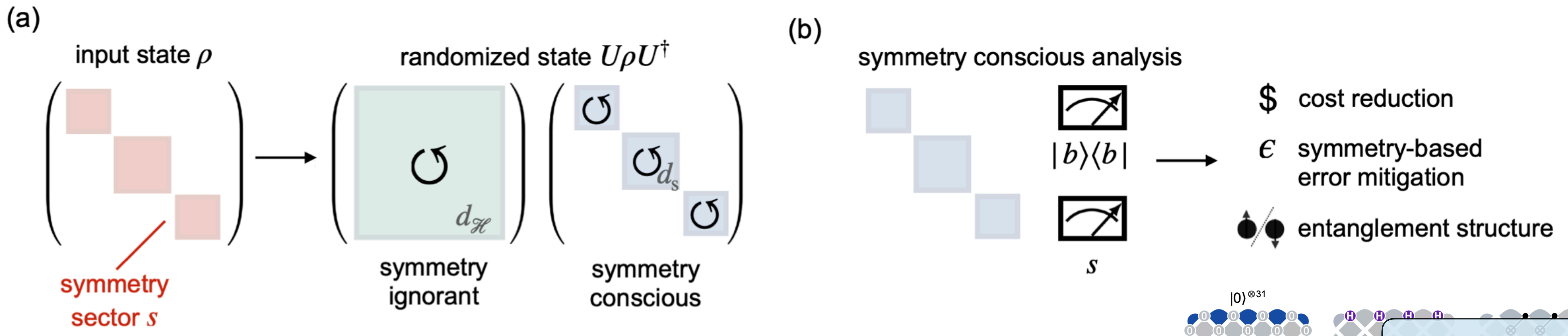

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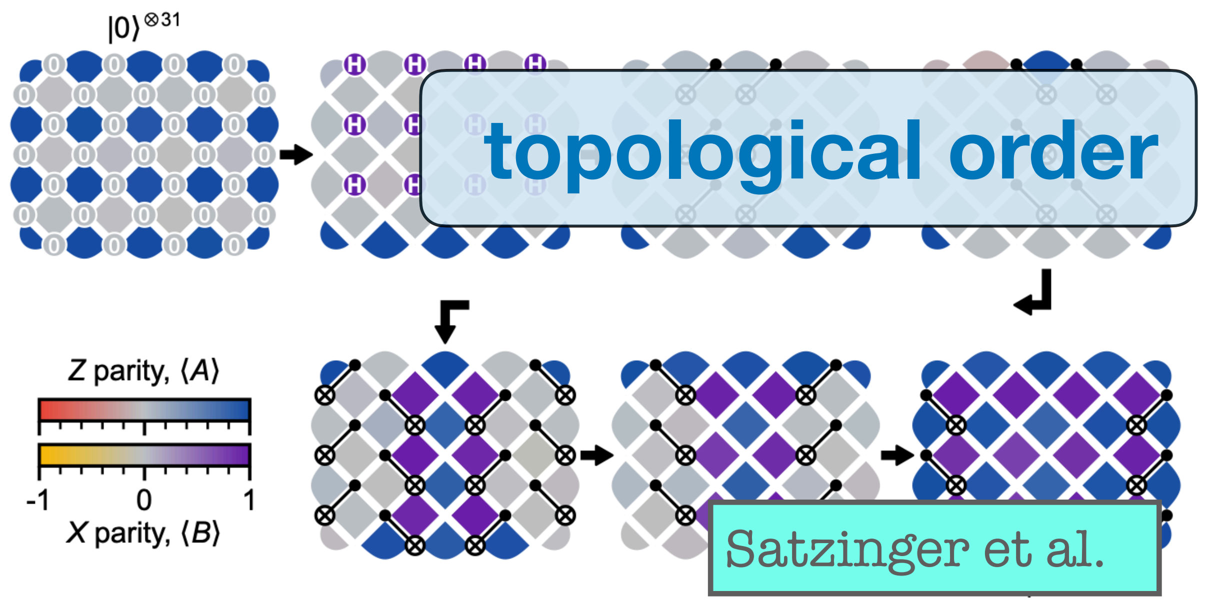
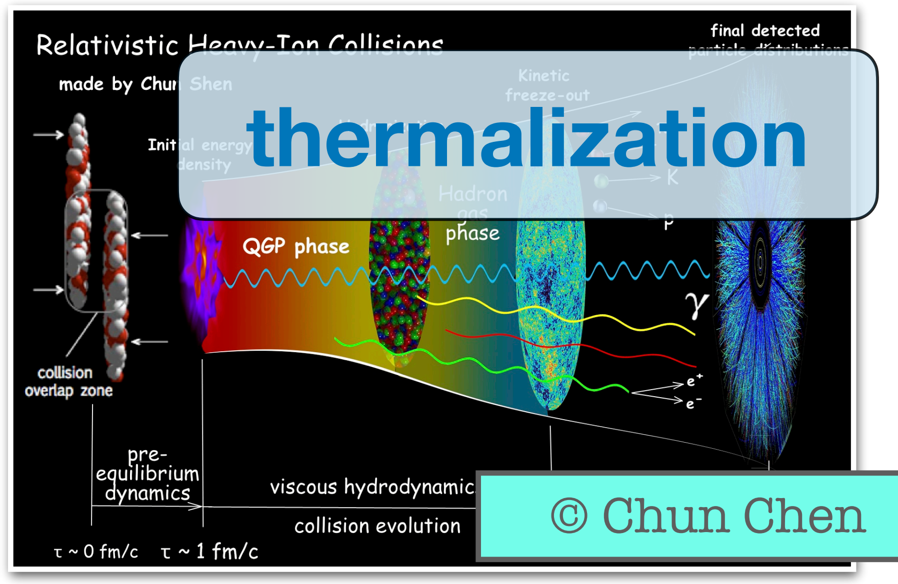


Satzinger et al.



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- Deep scrambling algorithms soon feasible. A lot more work. Robustness? Performance guarantees?
- Explore and combine with smart ideas: quantum variational & machine learning

Kokail, et al, Phys. Rev. Lett. 127, 170501 (2021)
Huang et al., Science 376 1182 (2022)
Huang, Nat. Rev. 4 (2022)

Thanks to a lot of smart collaborators

Maryland


Ron Belyansky


Elizabeth Bennewitz


Jake Bringewatt

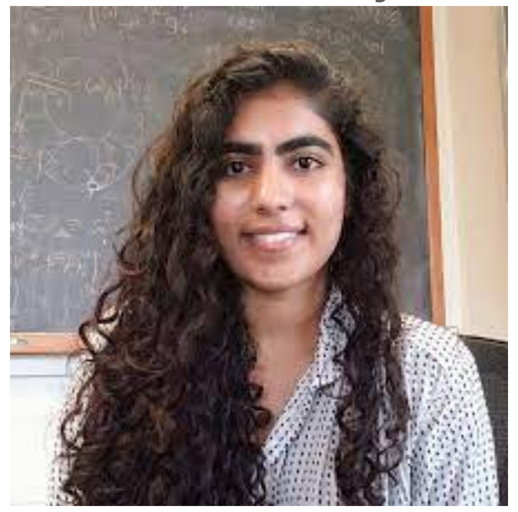

Zohreh Davoudi


Alexey Gorshkov


Chris Jarzynski


Jon Kunjummen


Connor Powers


Greeshma Oruganti


Alex Schuckert


Seth Whitsitt


Nicole Yunger Halpern


Kübra Yeter-Aydeniz
(MITRE corp.)


Drew Connelly
(NCSU)


Joe Carolan
(UIUC —> UMD)


Eugene Dumitrescu
(ORNL)

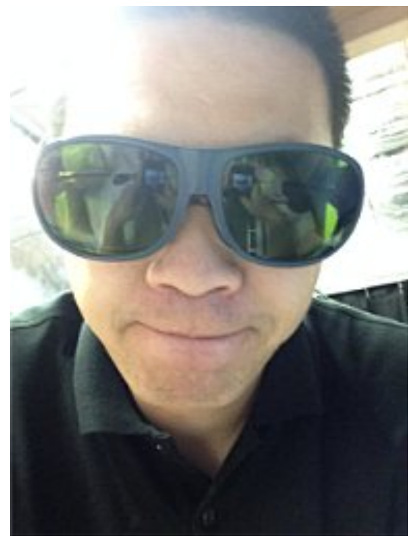
Innsbruck


Robert Ott


Torsten Zache

Duke


Marko Cetina


Lei Feng


Or Katz

Seattle


Anthony Ciavarella


Martin Savage


Henry Froland


Marc Illa Subina


Jeremy Hartse