

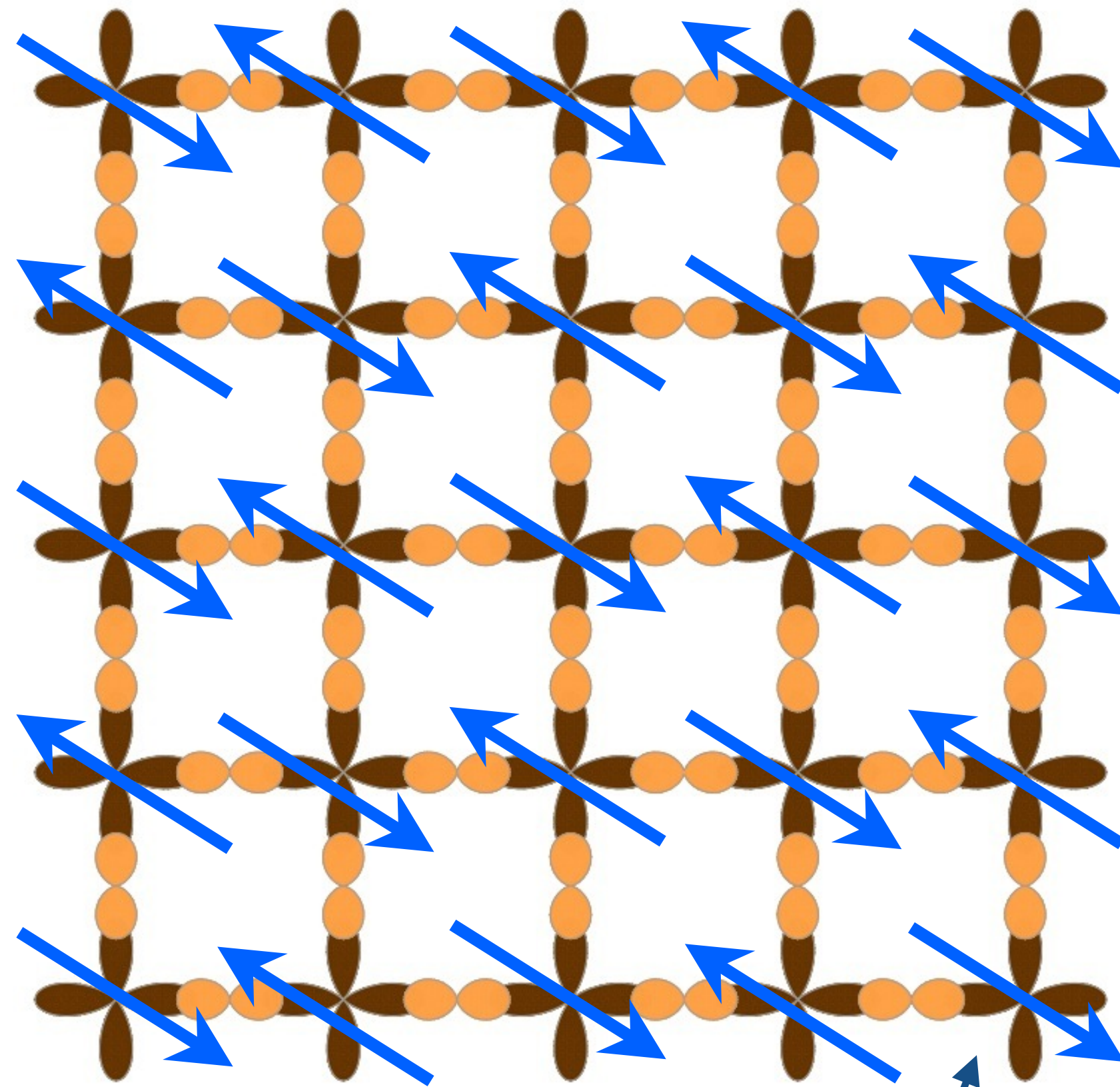
Observation of the Yamaji effect in a cuprate and FL^* theory of the pseudogap

Quantum Spin Liquids:
Experimental Enigmas and Theoretical Challenges
HUN-REN Wigner Research Centre for Physics
Budapest
October 8, 2025

Subir Sachdev



Antiferromagnetic insulator at a density of one electron per Cu



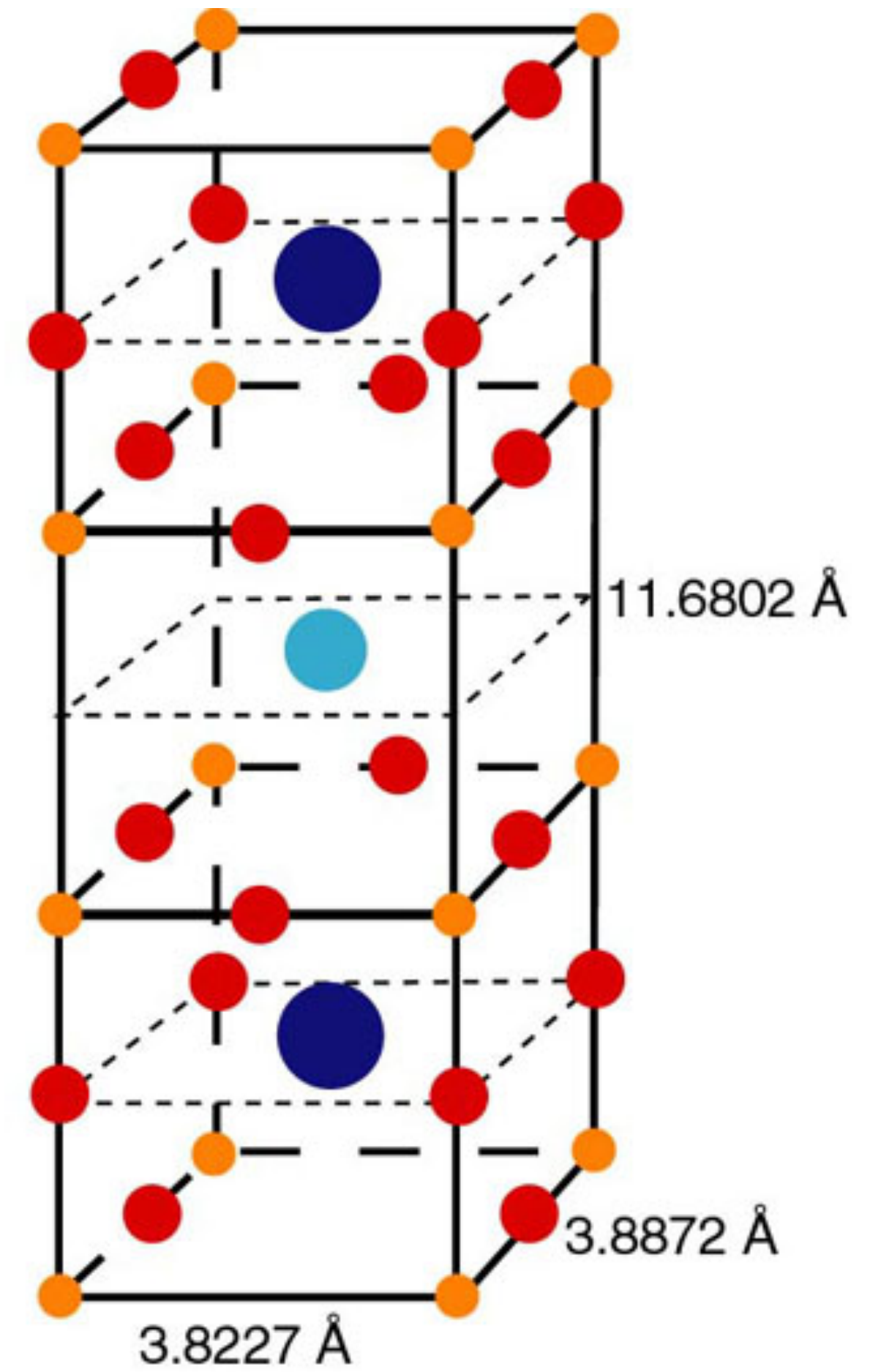
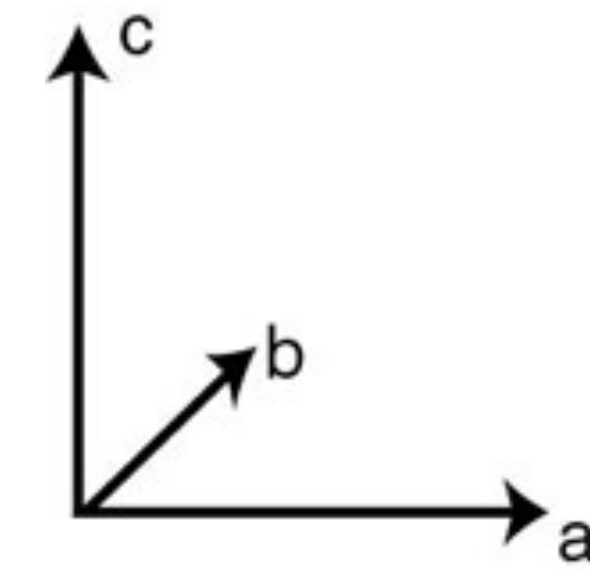
Cu

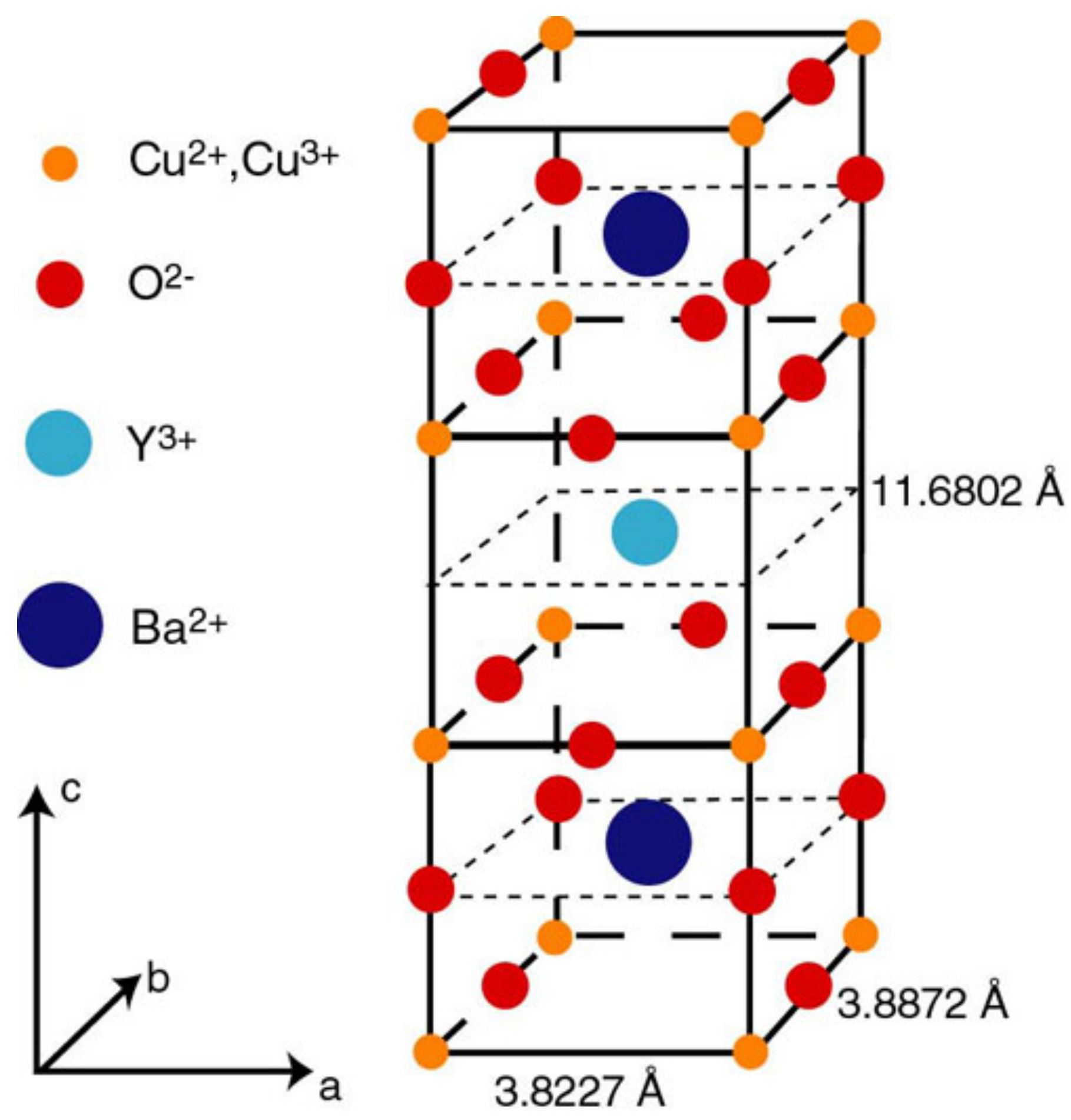
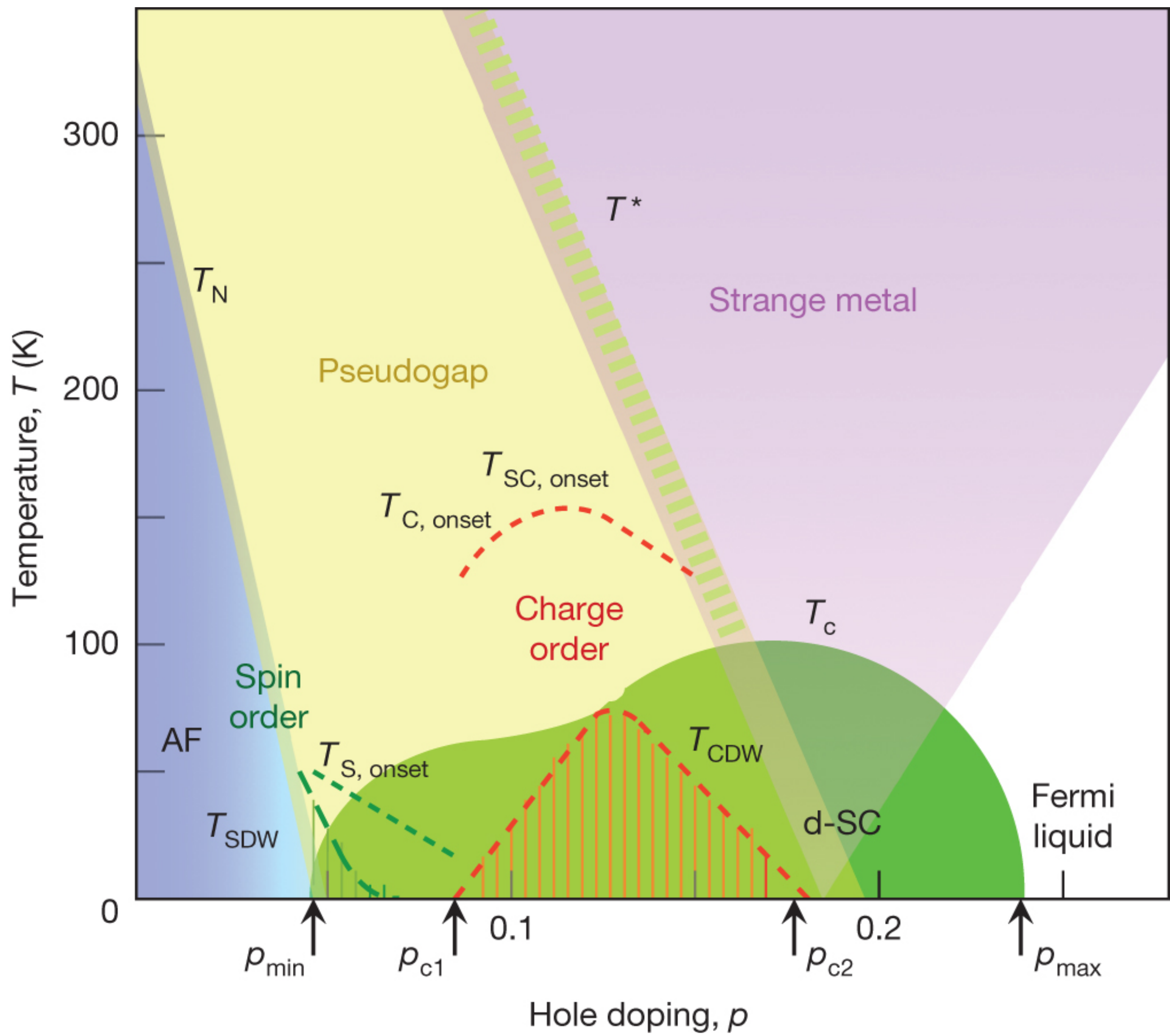
● $\text{Cu}^{2+}, \text{Cu}^{3+}$

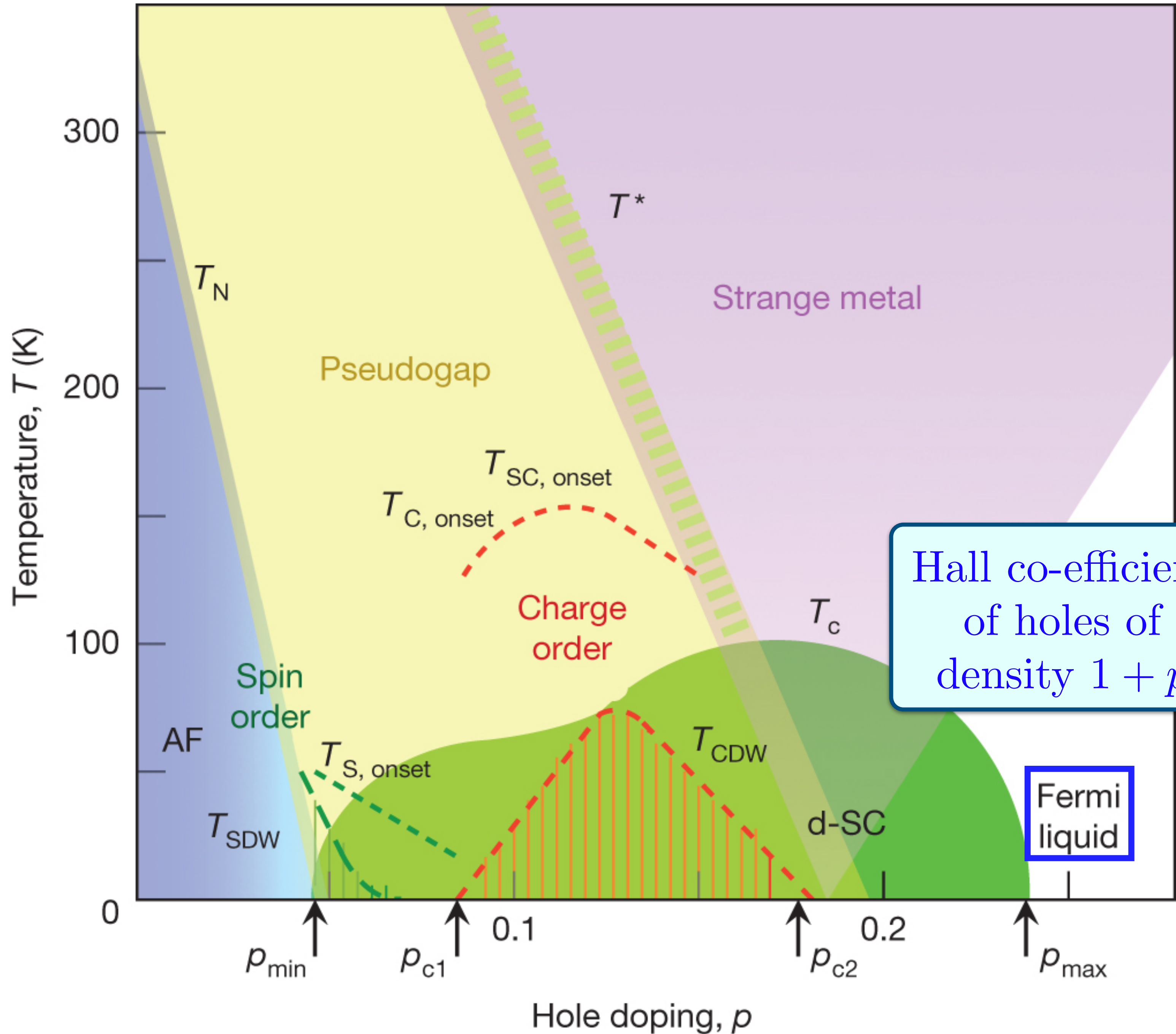
● O^{2-}

● Y^{3+}

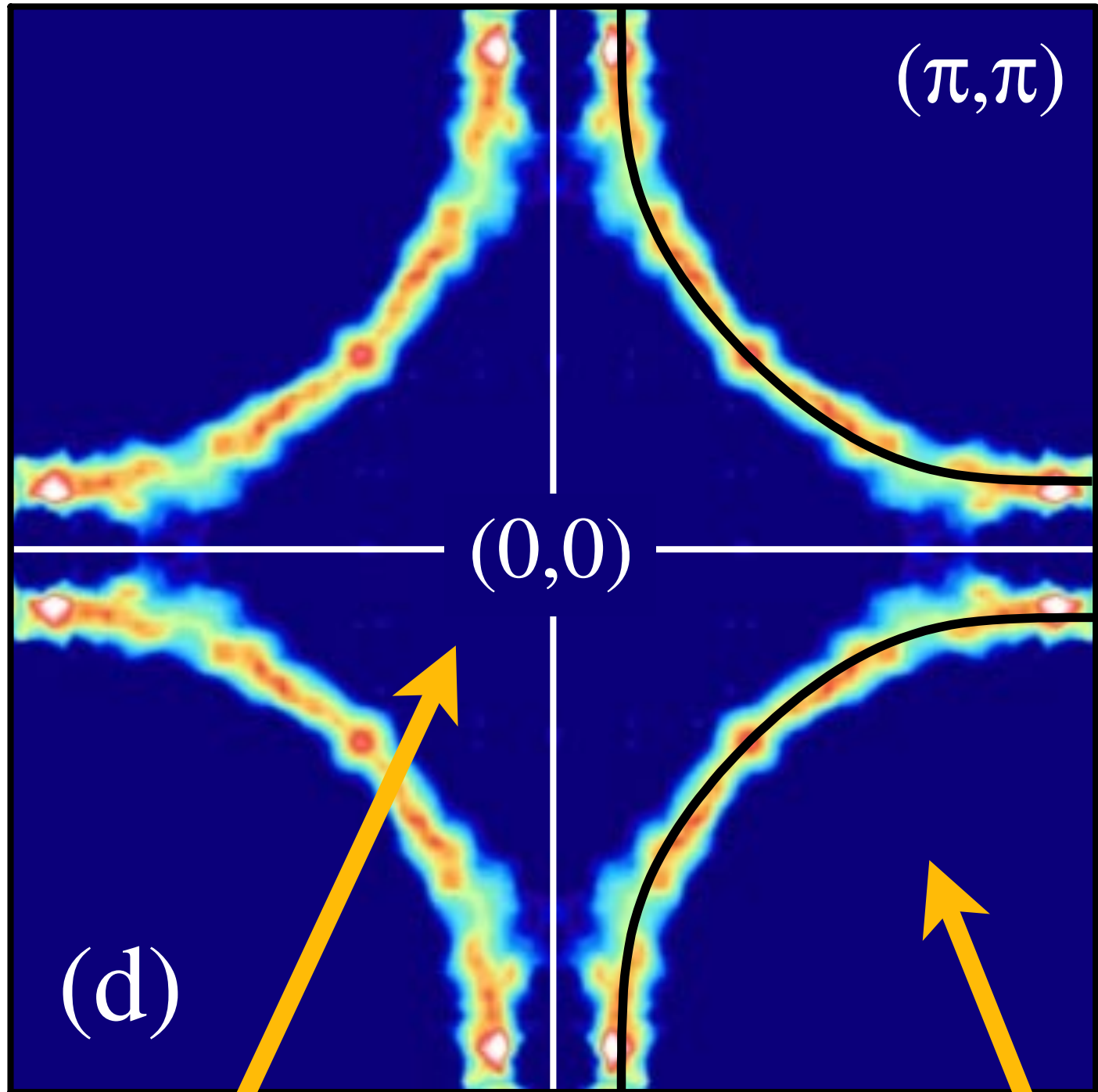
● Ba^{2+}







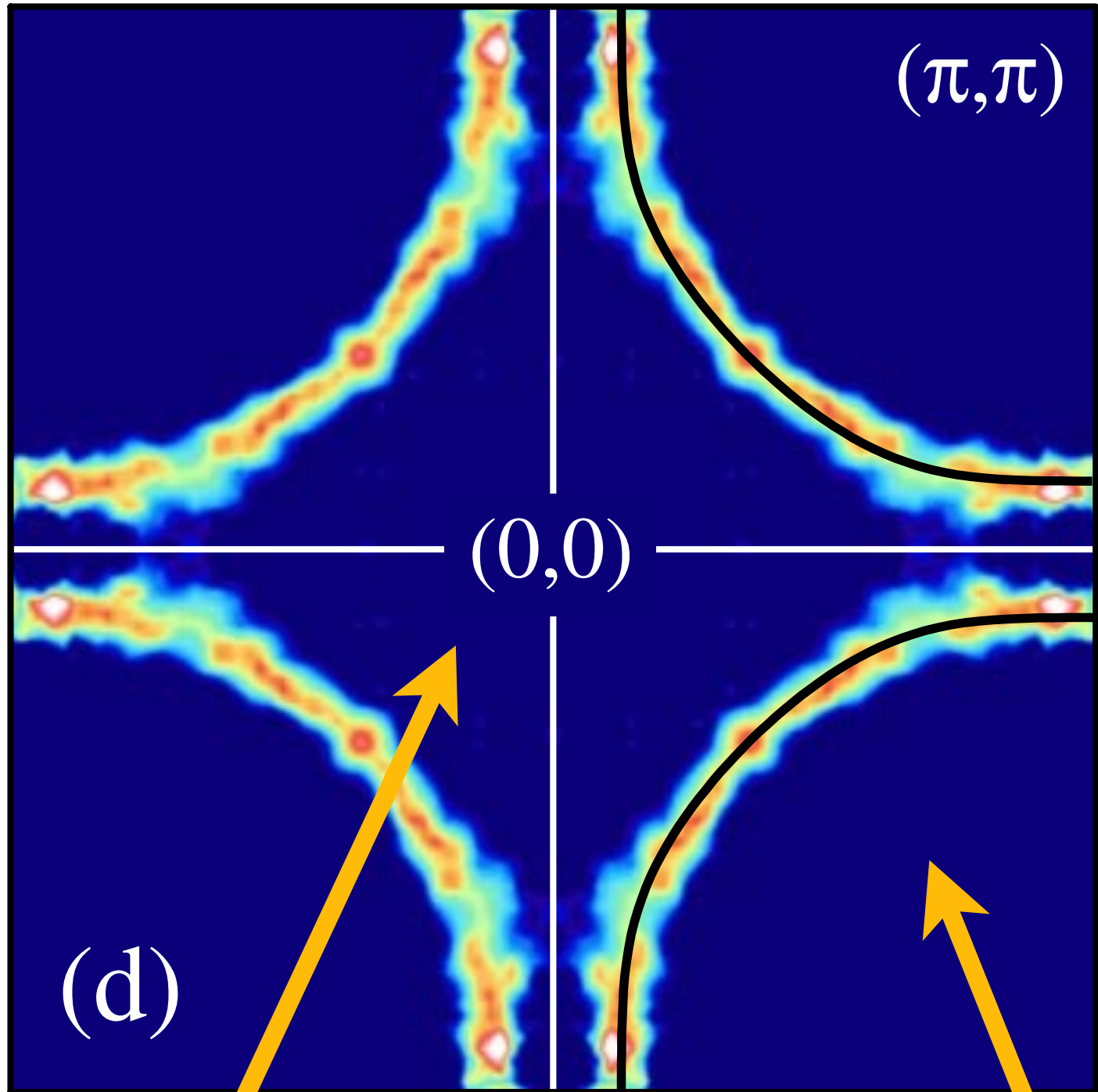
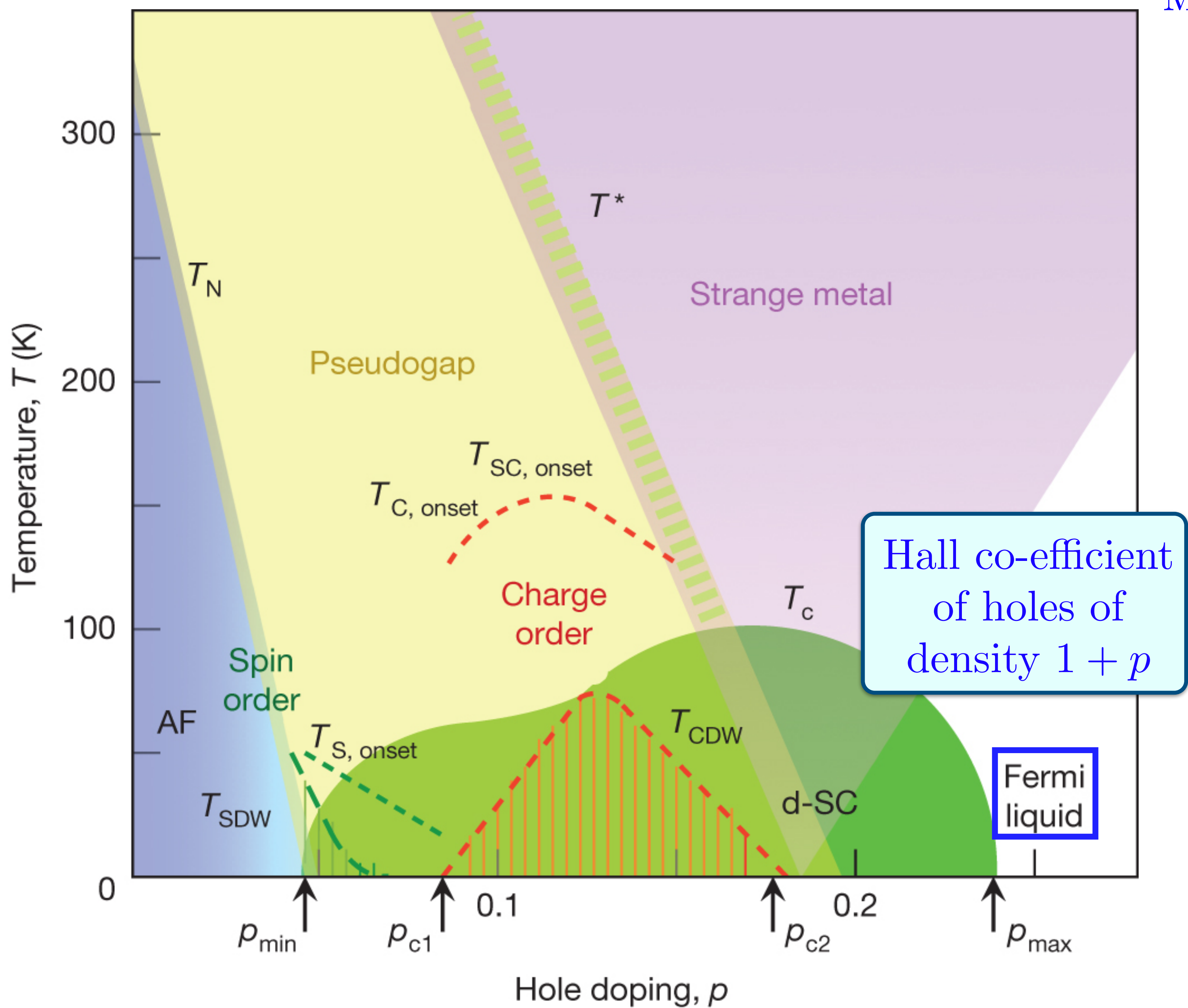
Hall co-efficient
of holes of
density $1 + p$



$1-p$ electrons

$1+p$ holes

Luttinger, 1960: Area enclosed by the Fermi surface is the same as that for free fermions *with the same symmetry*.

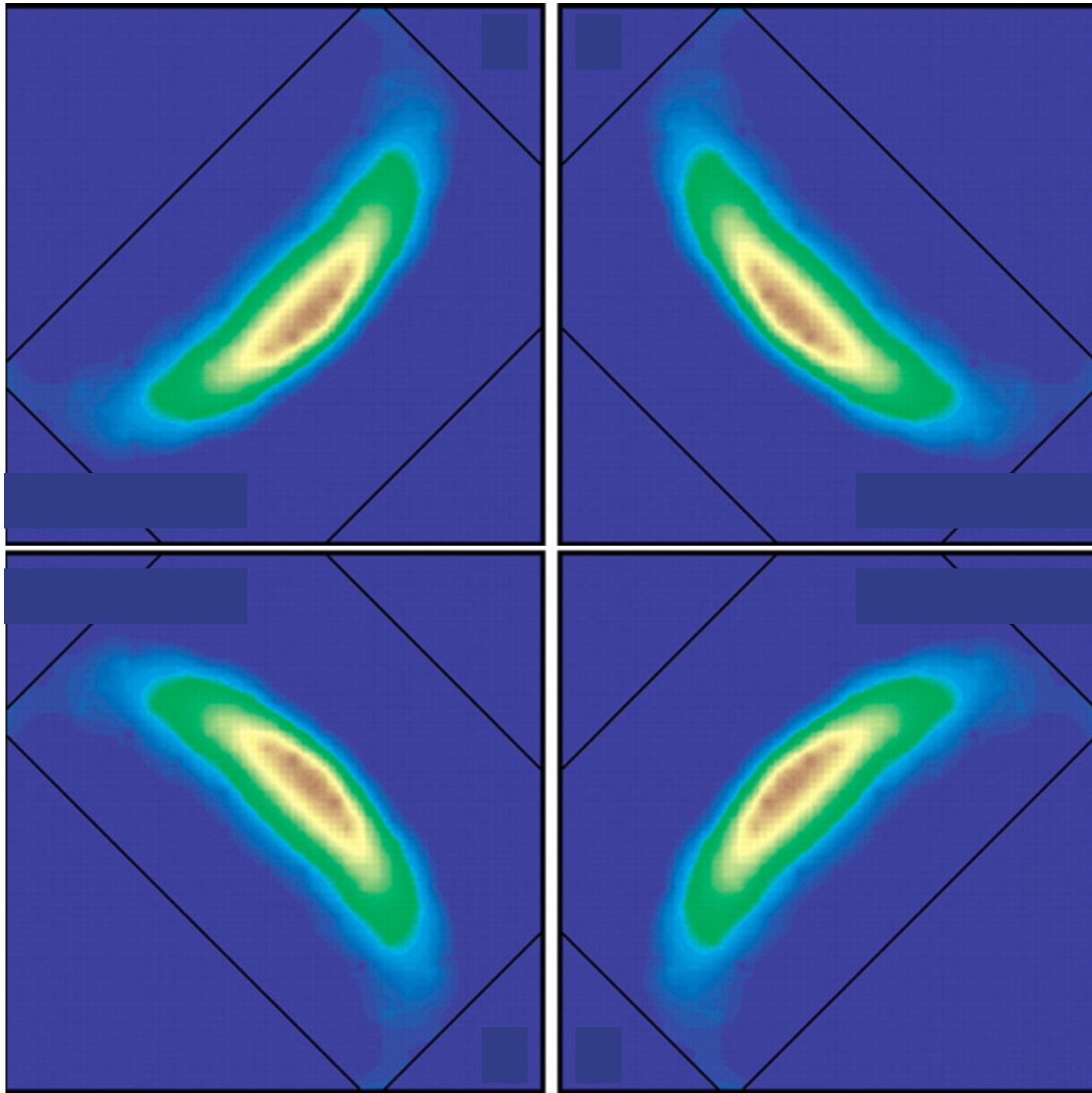
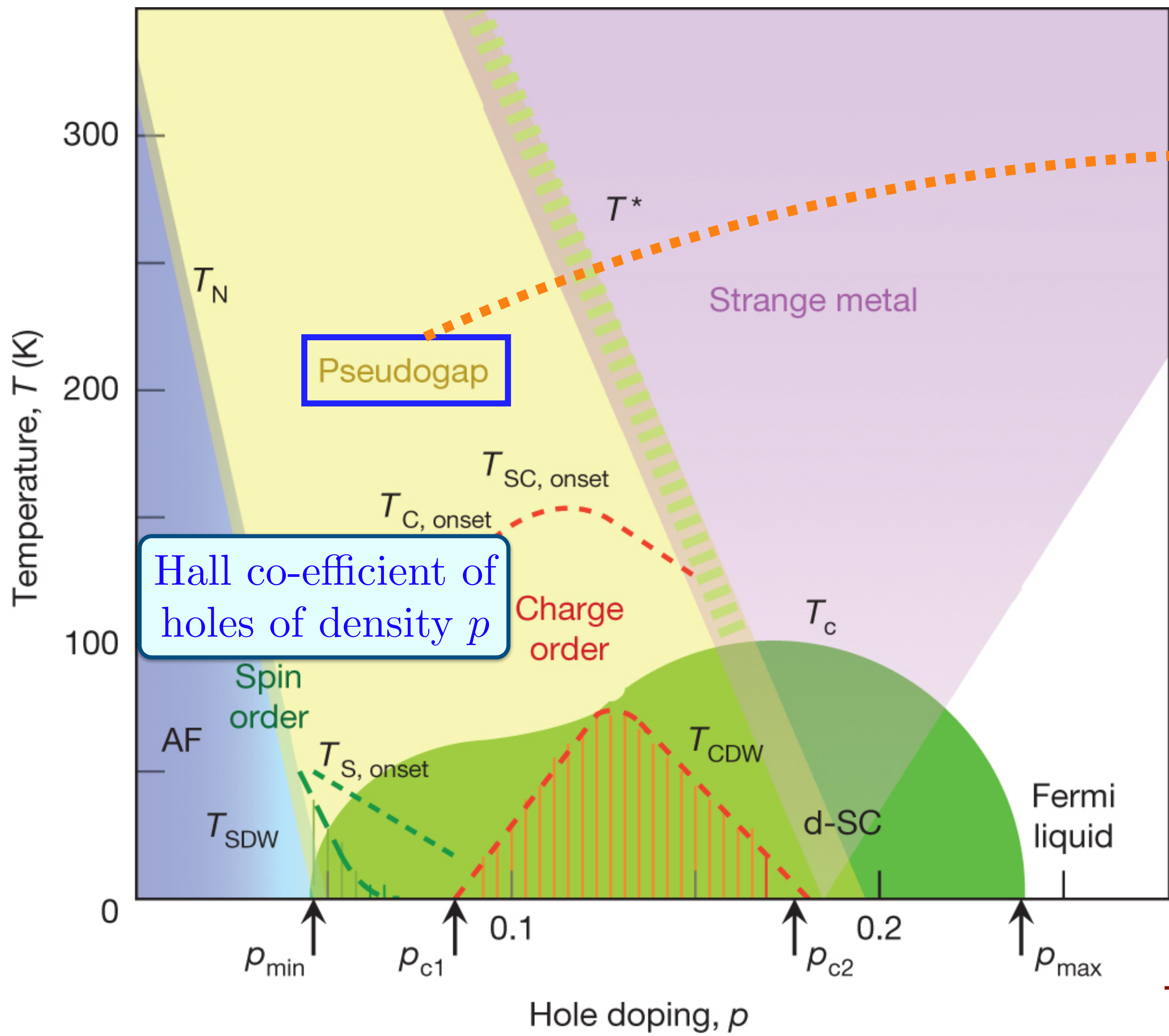


l-p electrons *l+p* holes

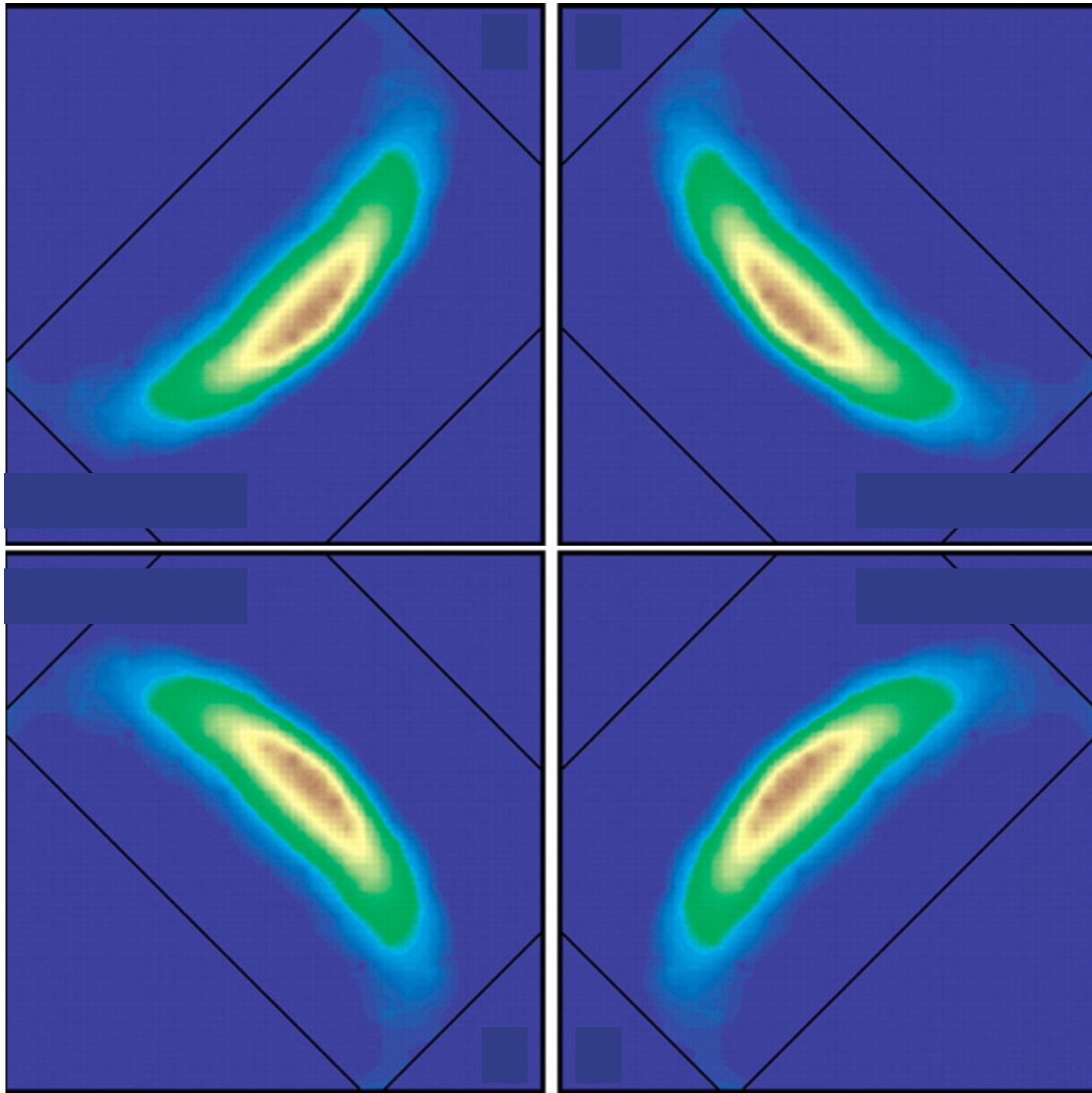
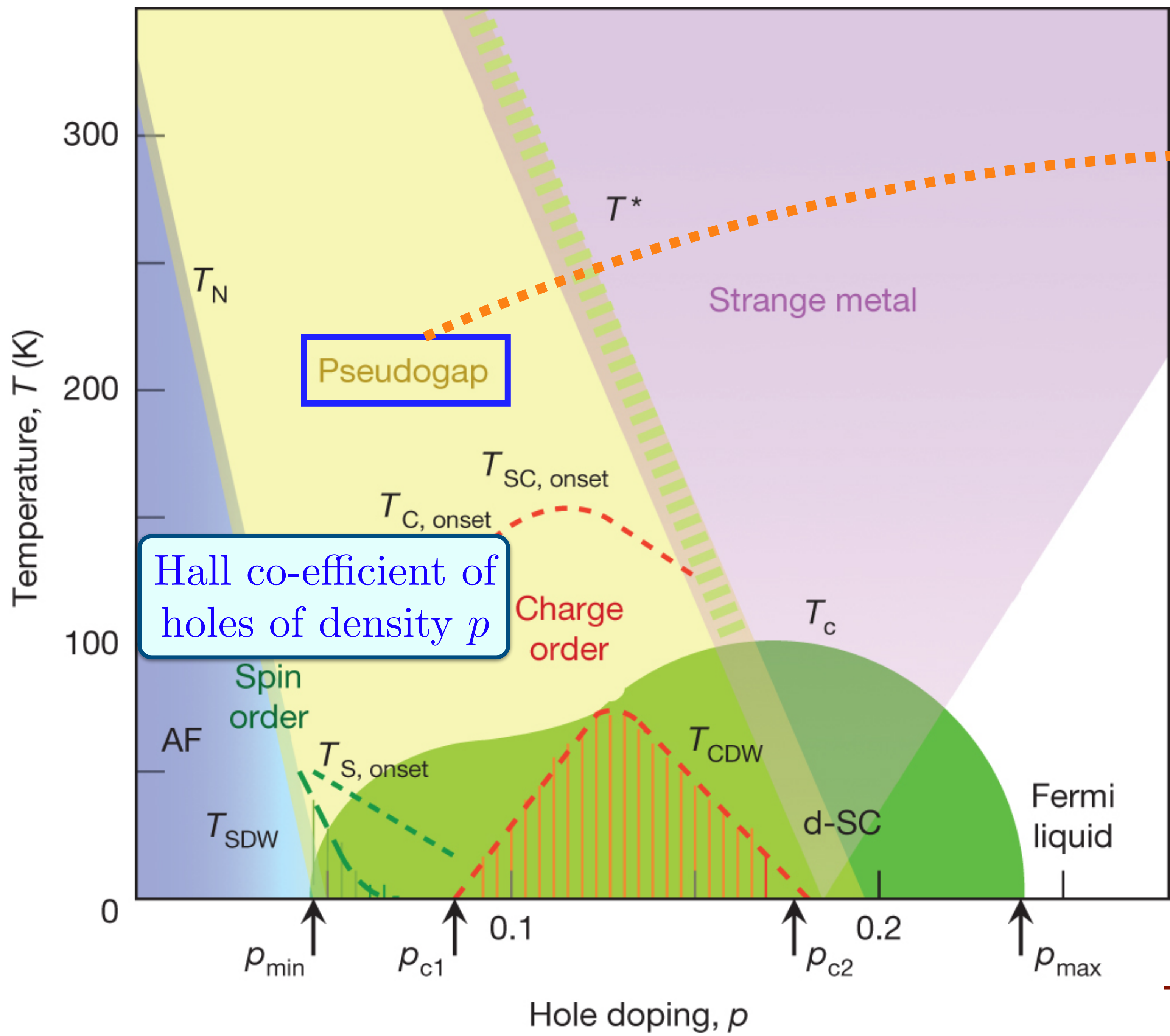
Luttinger, 1960: Area enclosed by the Fermi surface is the same as that for free fermions *with the same symmetry*.
Oshikawa, 2000: Area constrained by a 't Hooft anomaly of global U(1) and translations

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)

Kyle M. Shen *et al.*, *Science* **307**, 901 (2005)



T. Senthil, S. S., M.Vojta, PRL **90**, 216403 (2003)

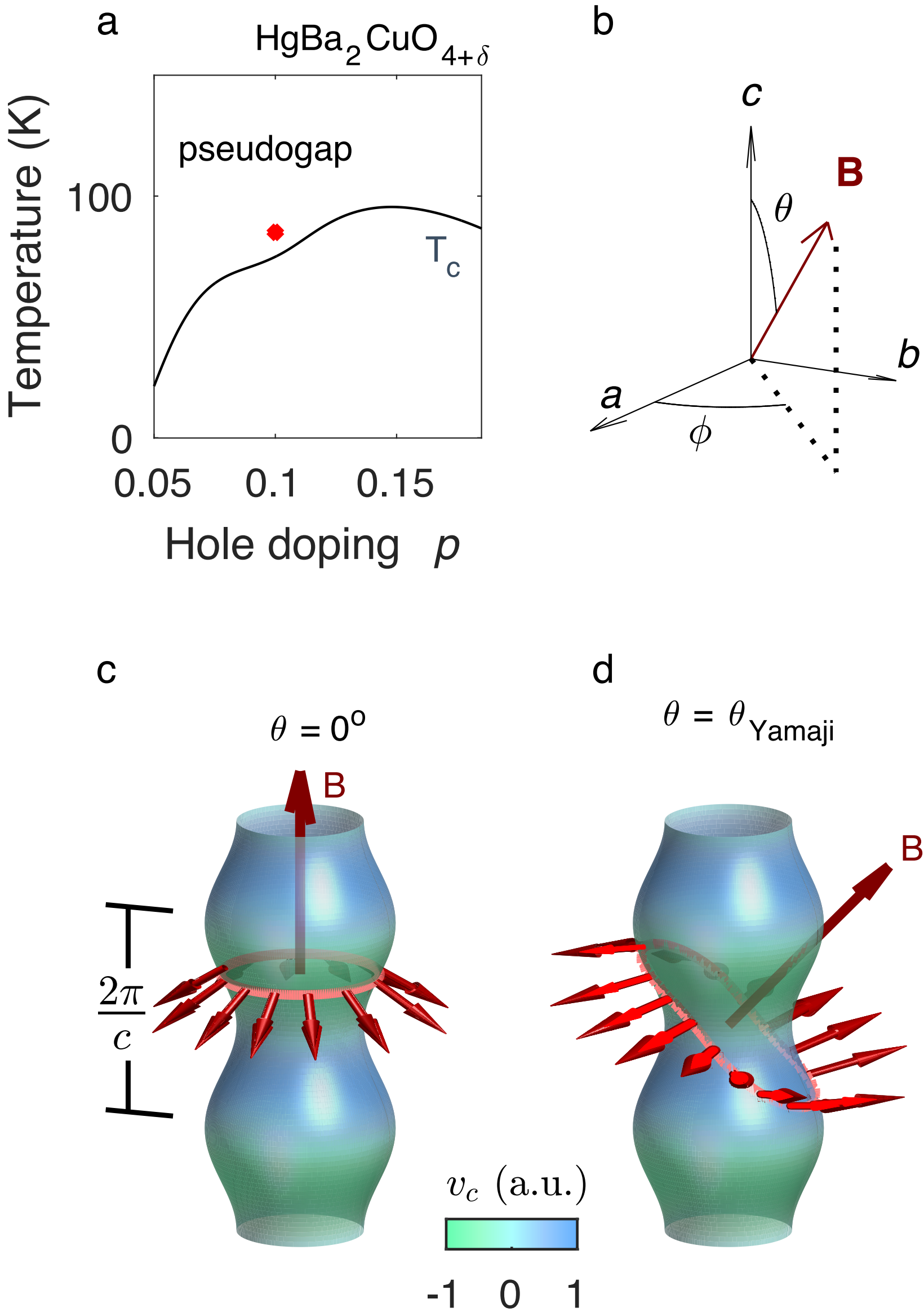


Will explain with a Fractionalized Fermi Liquid (FL*) which evades the Luttinger constraint, but satisfies the Oshikawa anomaly, by a *critical spin liquid*

Observation of the Yamaji effect in a cuprate superconductor

Mun K. Chan¹✉, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela¹,
Eric D. Bauer², Arkady Shekhter¹ & Neil Harrison¹

Published online: 16 September 2025



At the Yamaji angle, the orbits in the plane orthogonal to B have an area which is independent of momentum in the c direction, to first order in the hopping along the c direction.

K. Yamaji JPSJ **58**, 1520 (1989)

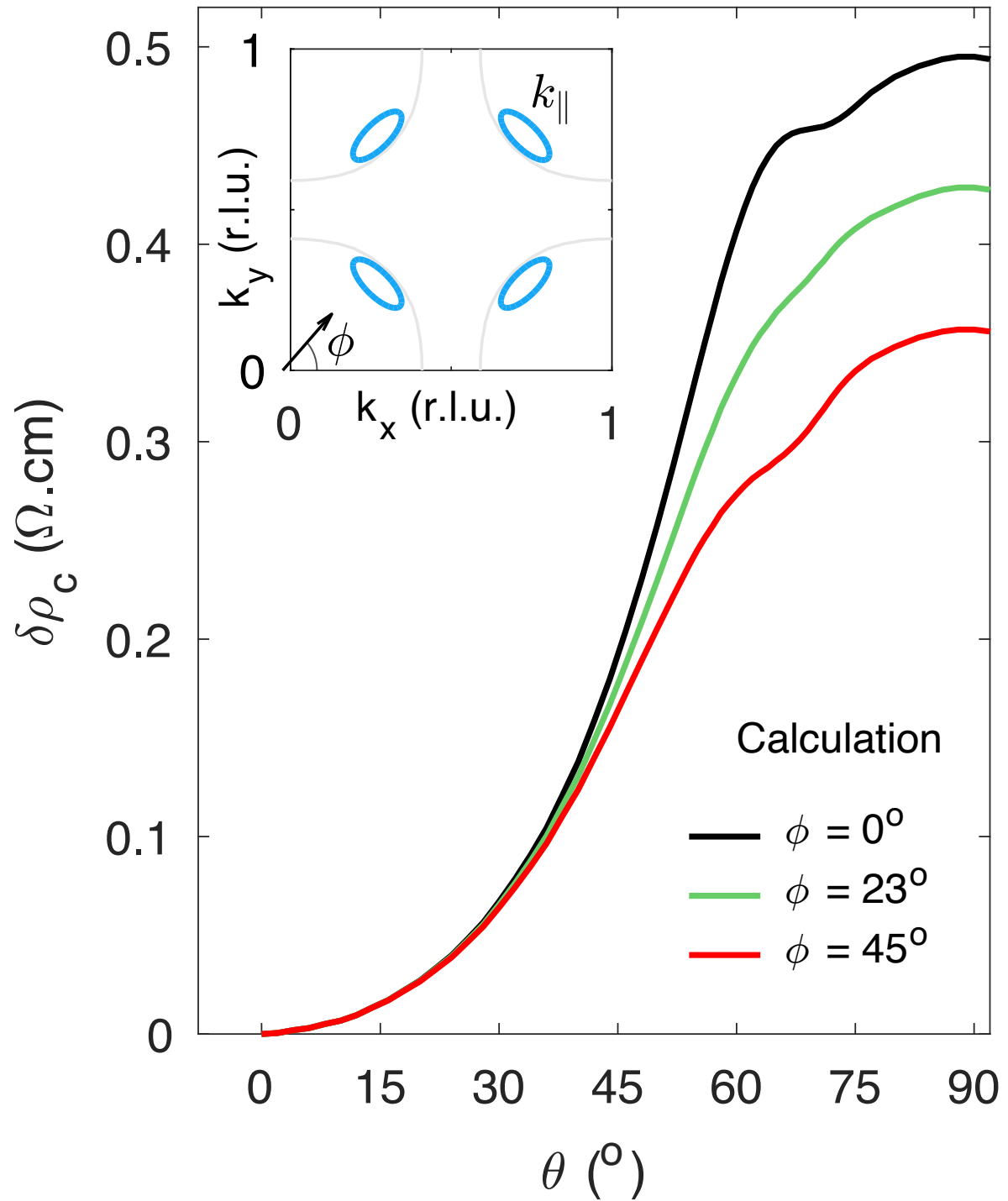
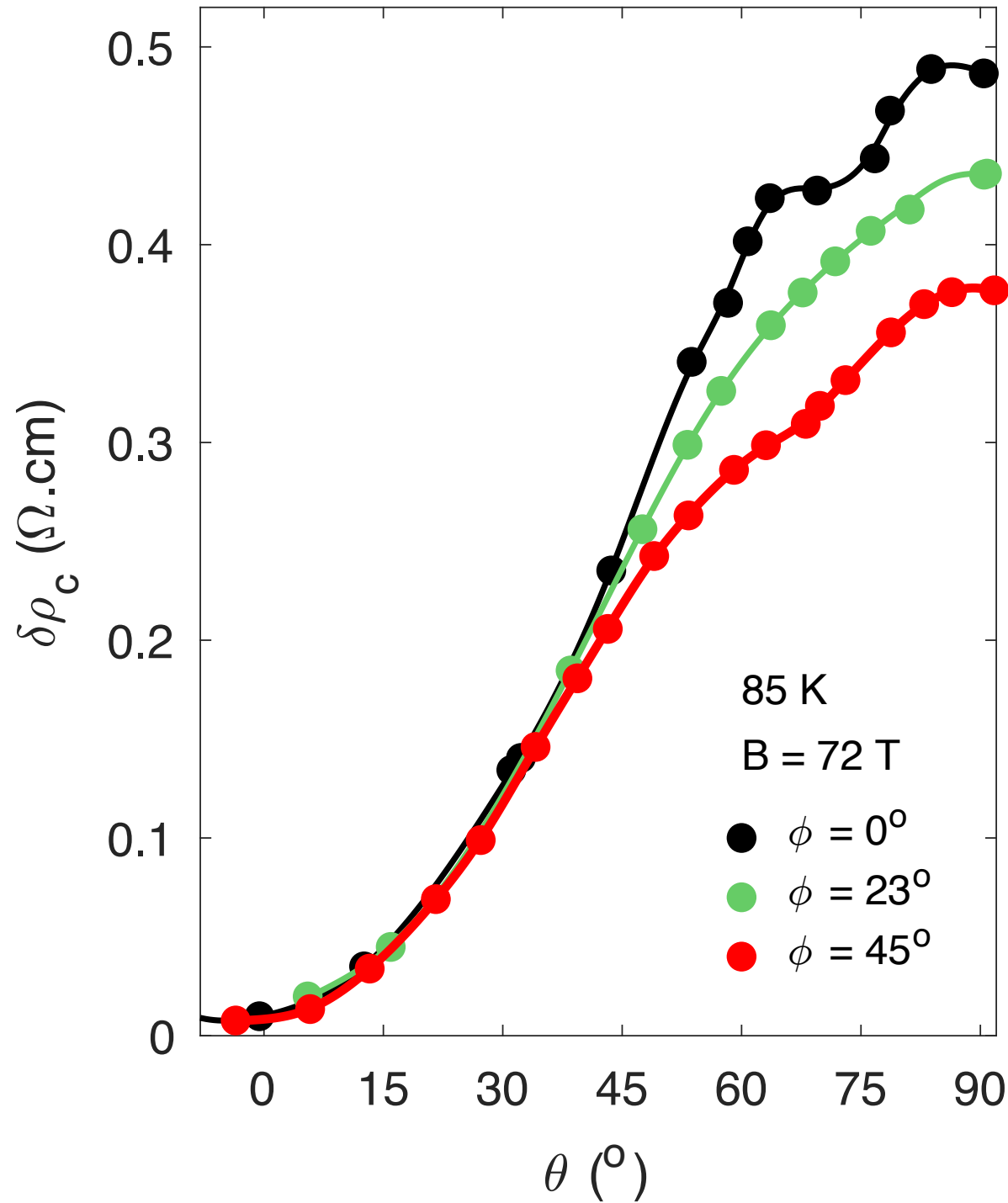
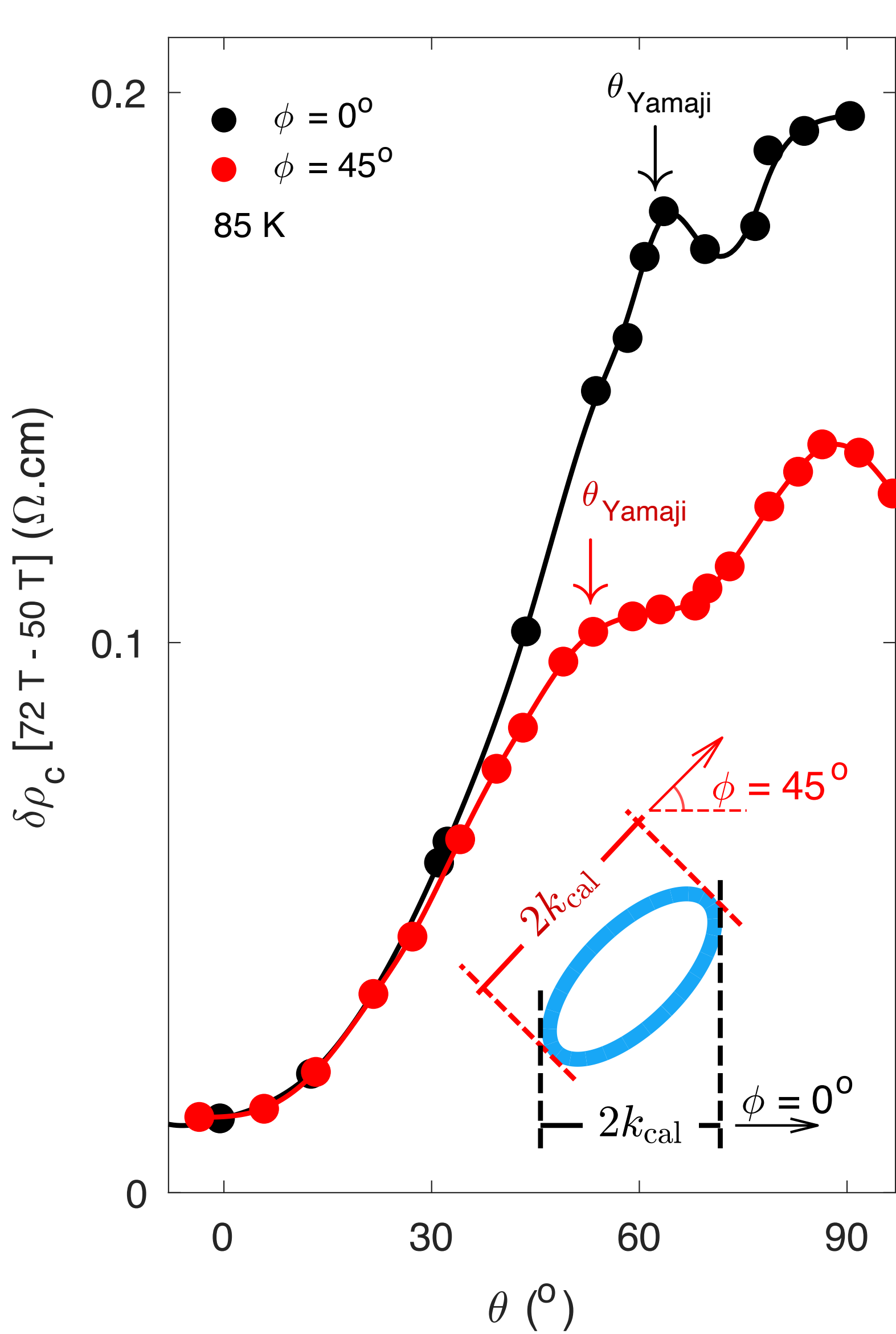
Observation of the Yamaji effect in a cuprate superconductor

nature physics

arXiv:2411.10631

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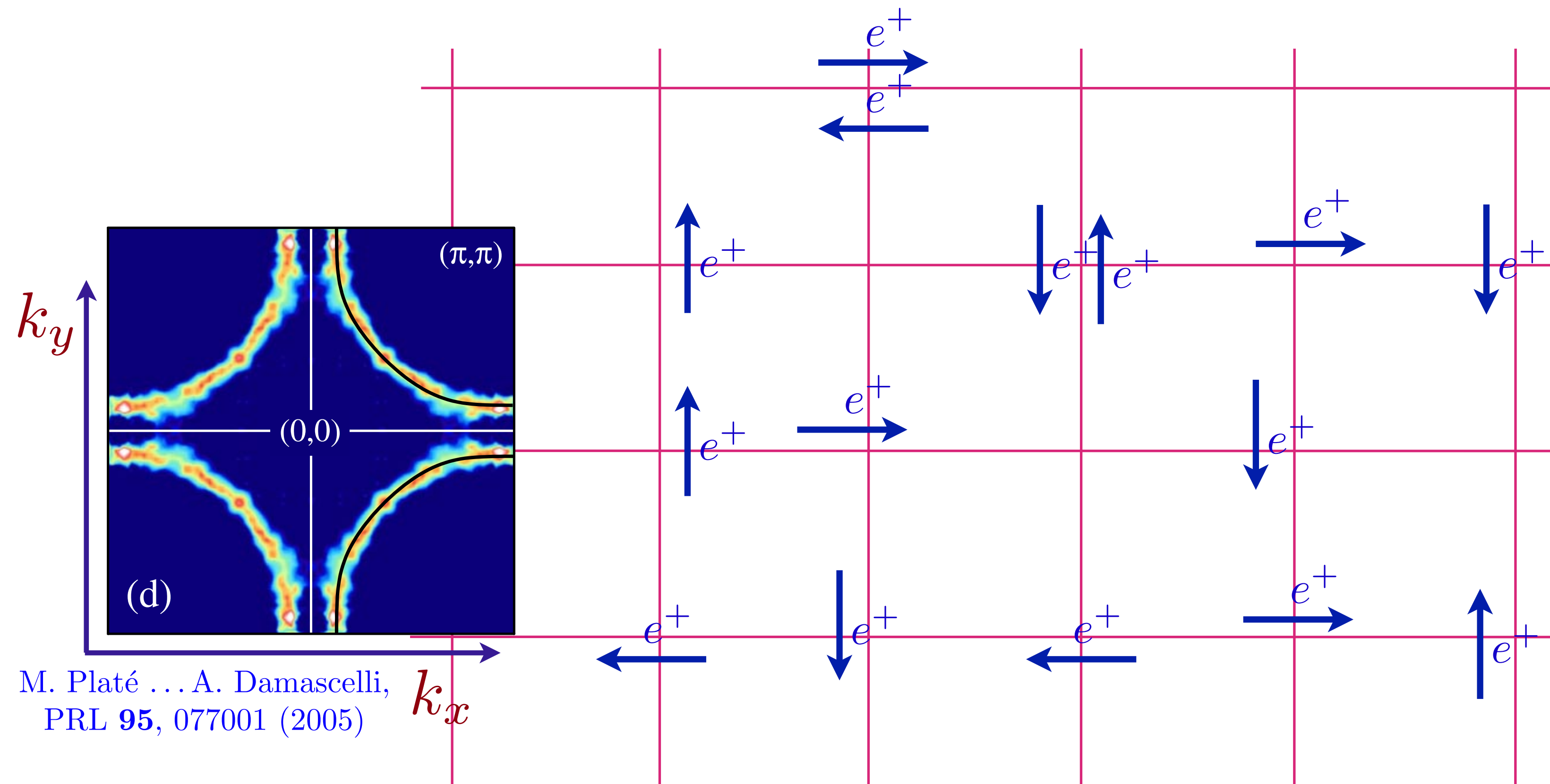


Doping
 $p = 0.1$

“The small size of the pockets determined from the Yamaji effect is ... approximately 1.3% of the Brillouin zone area”

**Metals obtained by
doping Mott insulators**

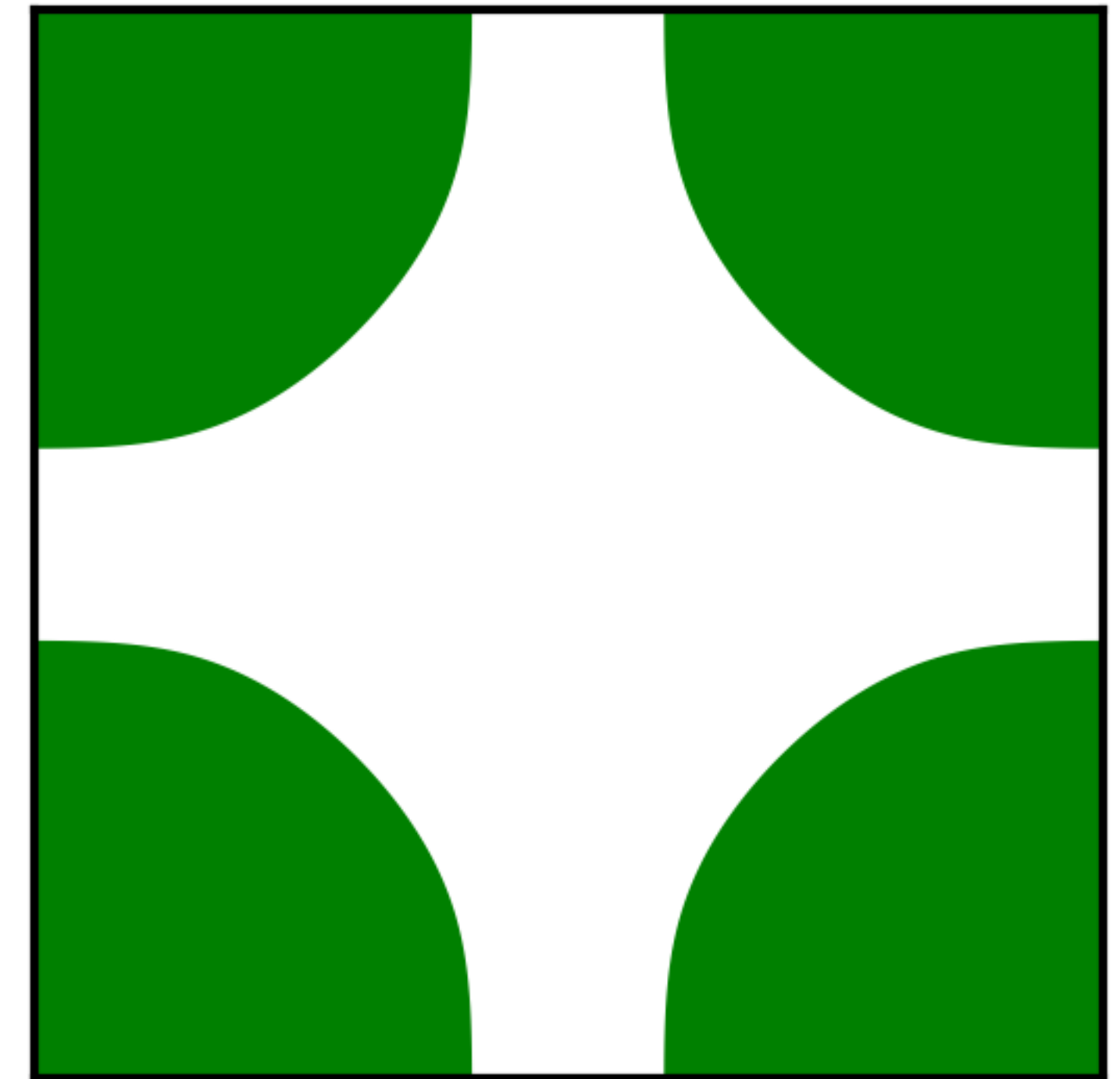
Ordinary metal



M. Platé ... A. Damascelli,
PRL **95**, 077001 (2005)

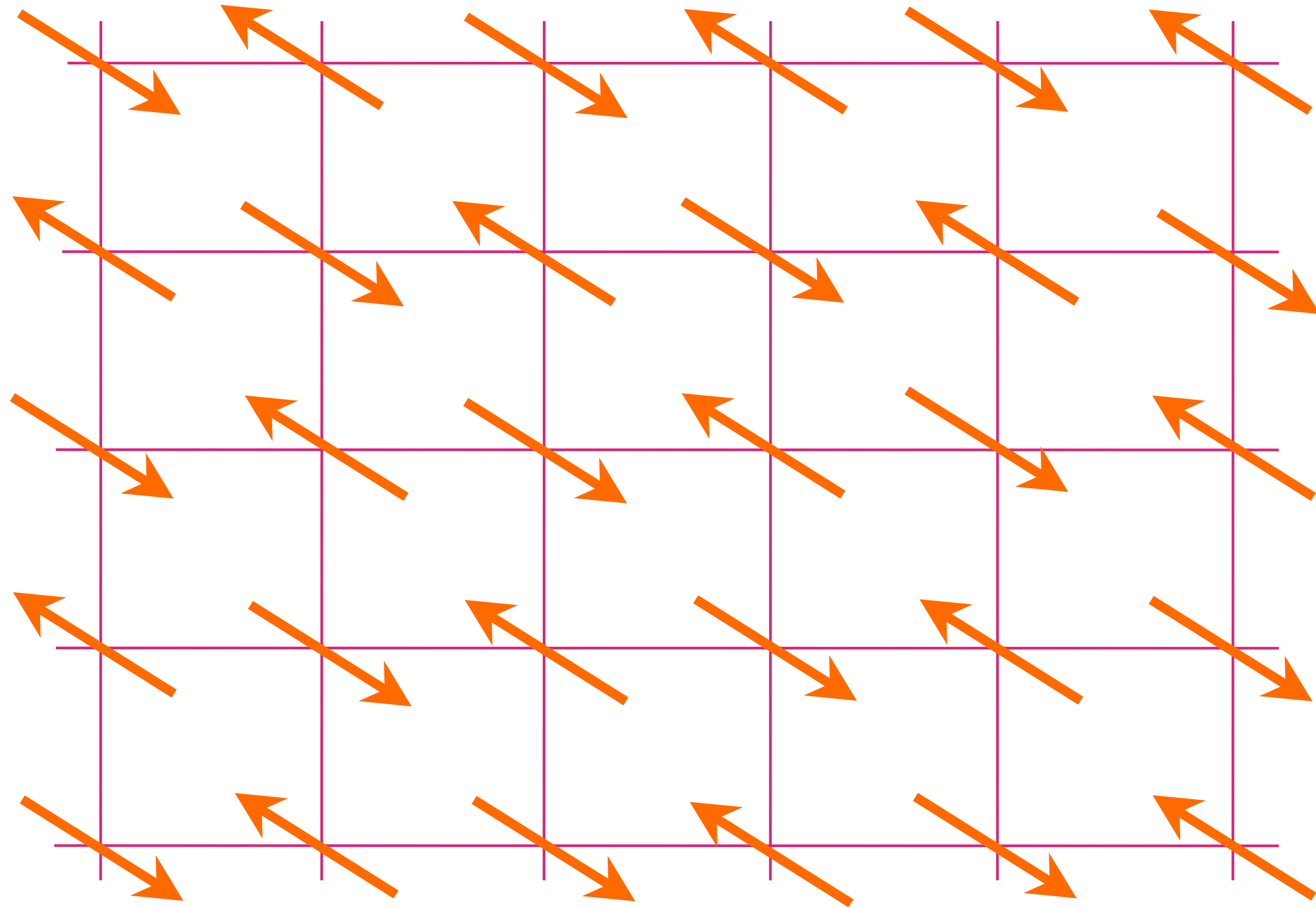
At large p , we obtain a gas of nearly free fermionic holes of density $1+p$ (relative to the filled band with 2 electrons per site)

Luttinger area.
No broken symmetry



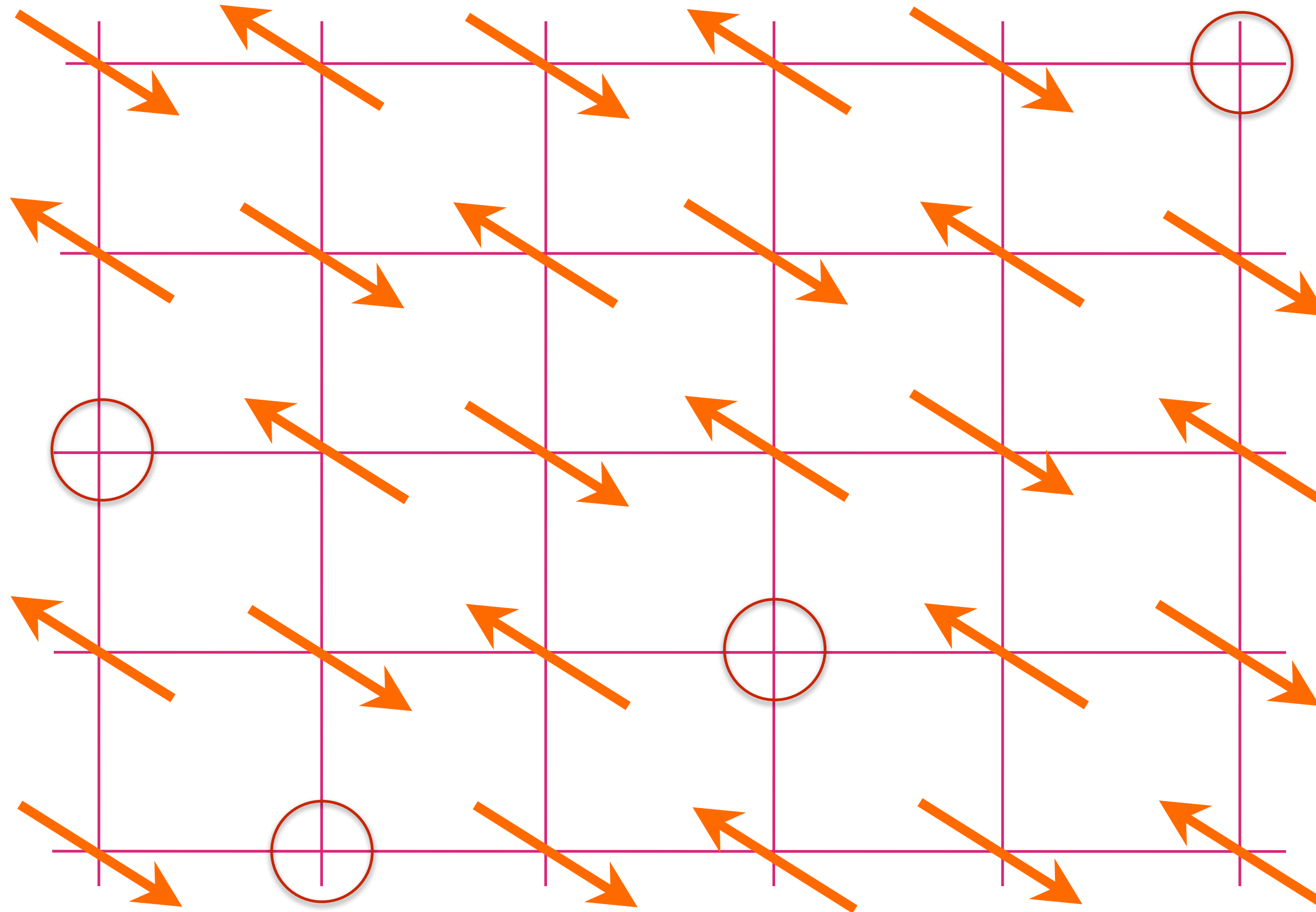
Area $(1 + p)/2$

Insulating antiferromagnet

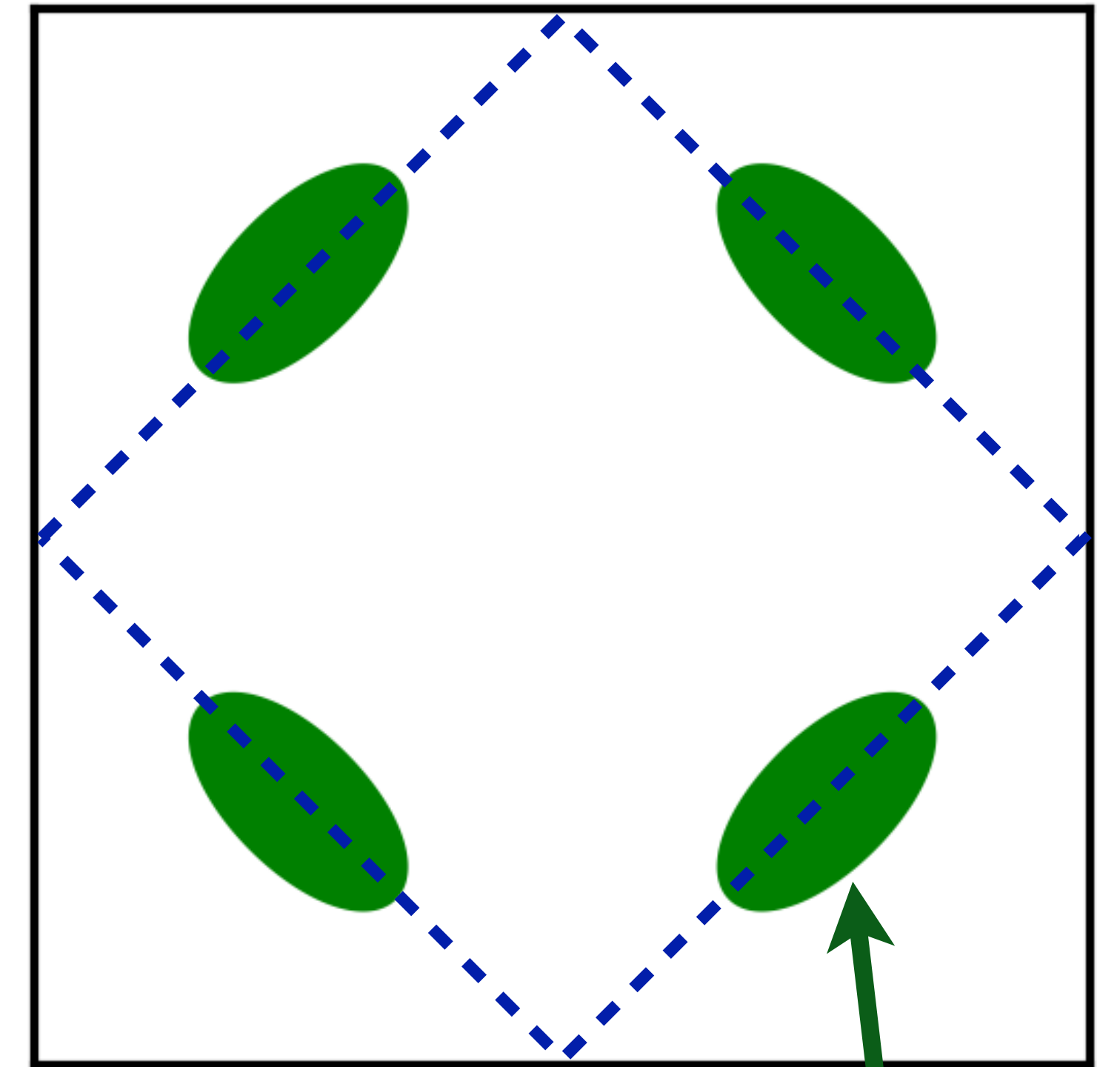


Doping an insulating antiferromagnet with holes of density p

AF metal



Luttinger area.
Broken symmetry

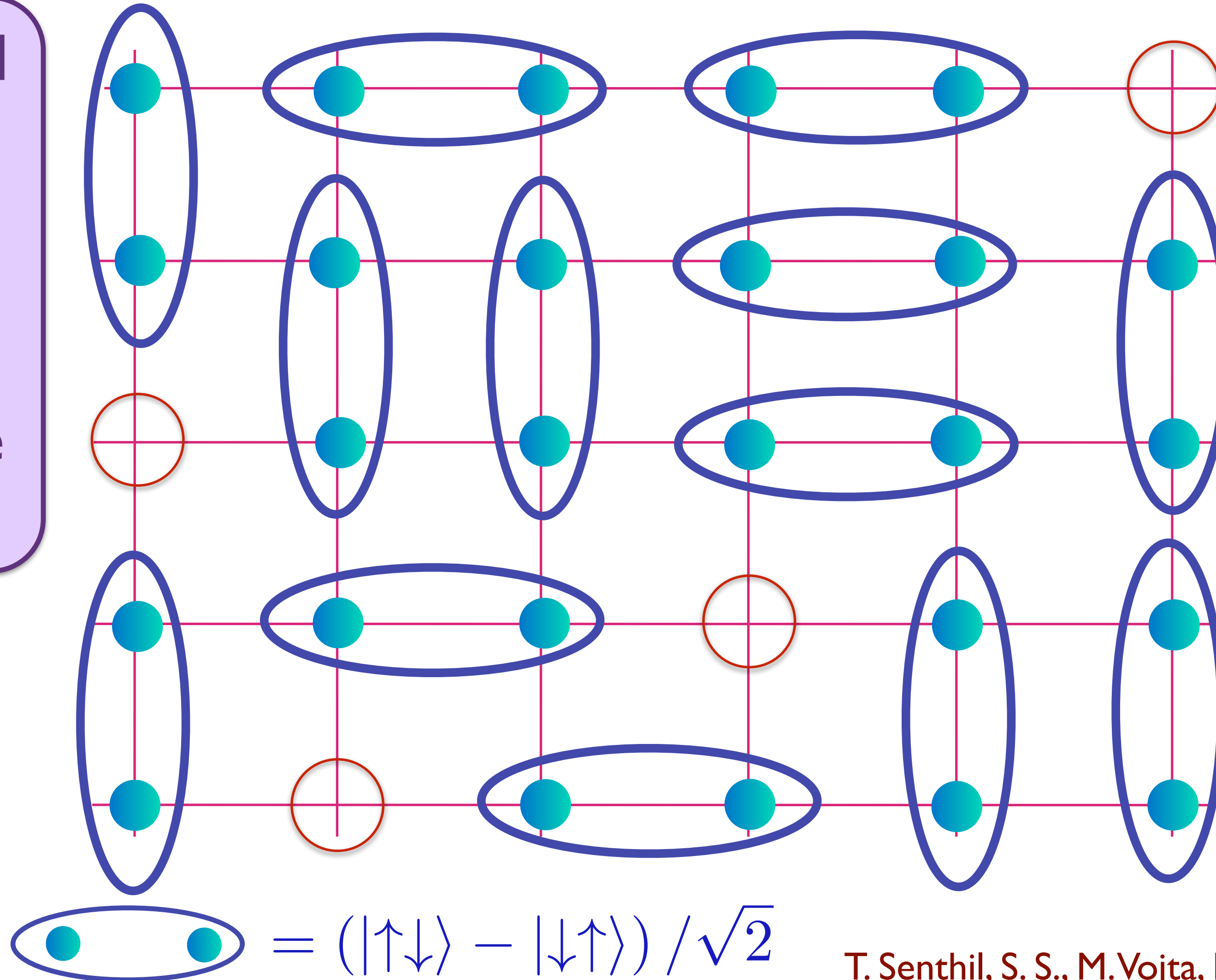


Area $p/4$

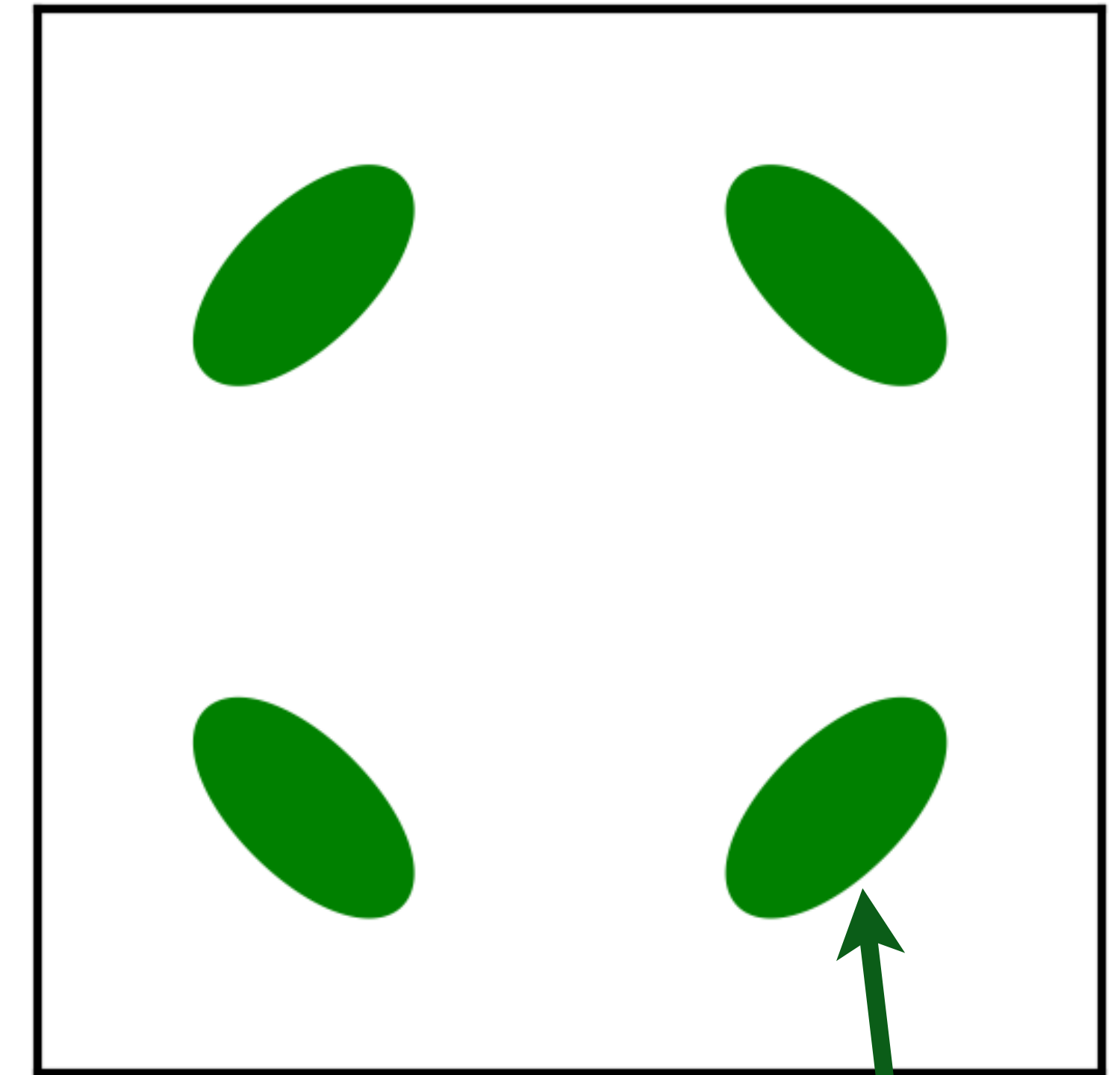
Doping an insulating antiferromagnet with holes of density p

Holon metal

Spin liquid with density p of spinless, charge $+e$ “holons”.



Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



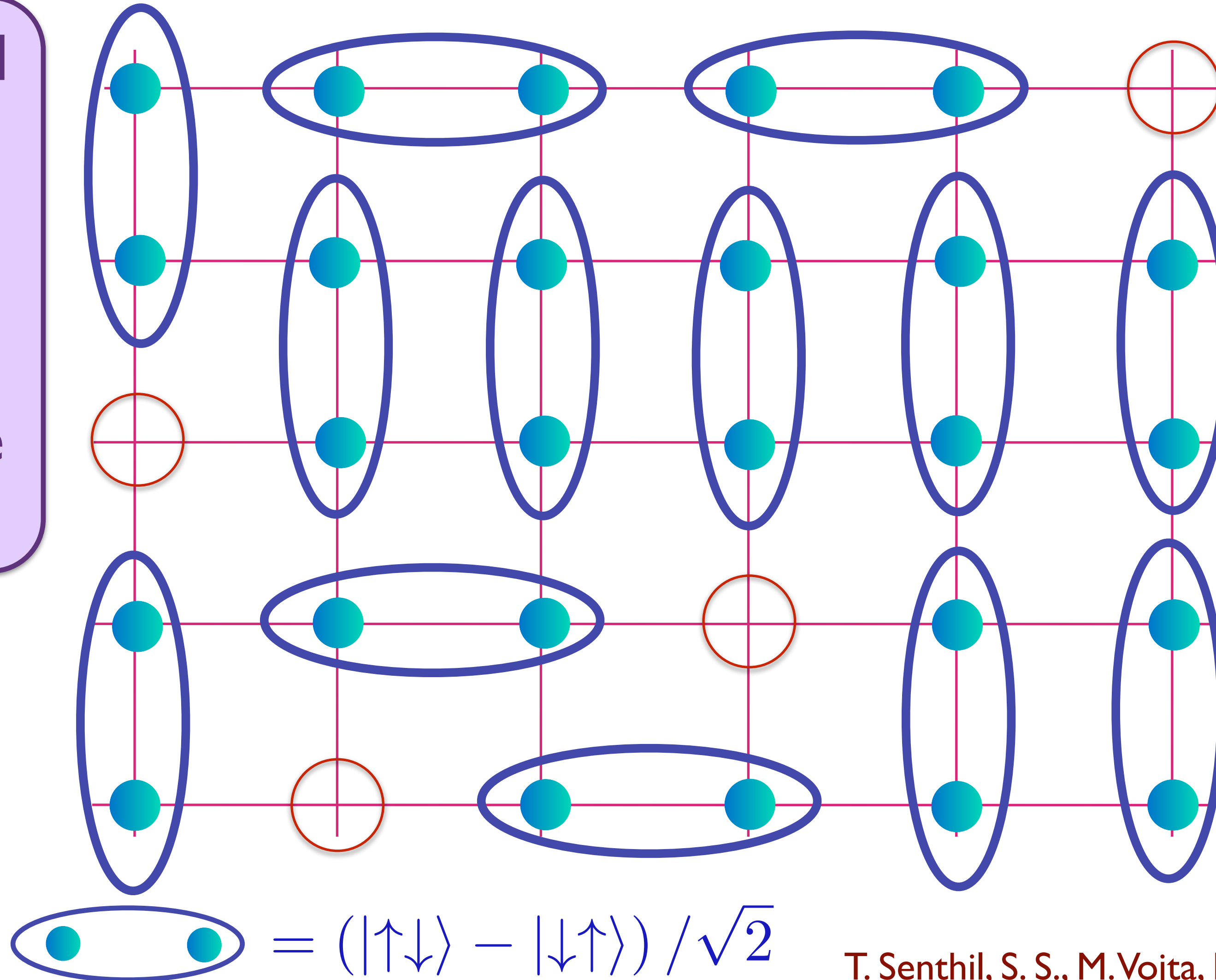
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R. K. Kaul, Y. B. Kim, S. S., T. Senthil, Nature Physics **4**, 28 (2008)

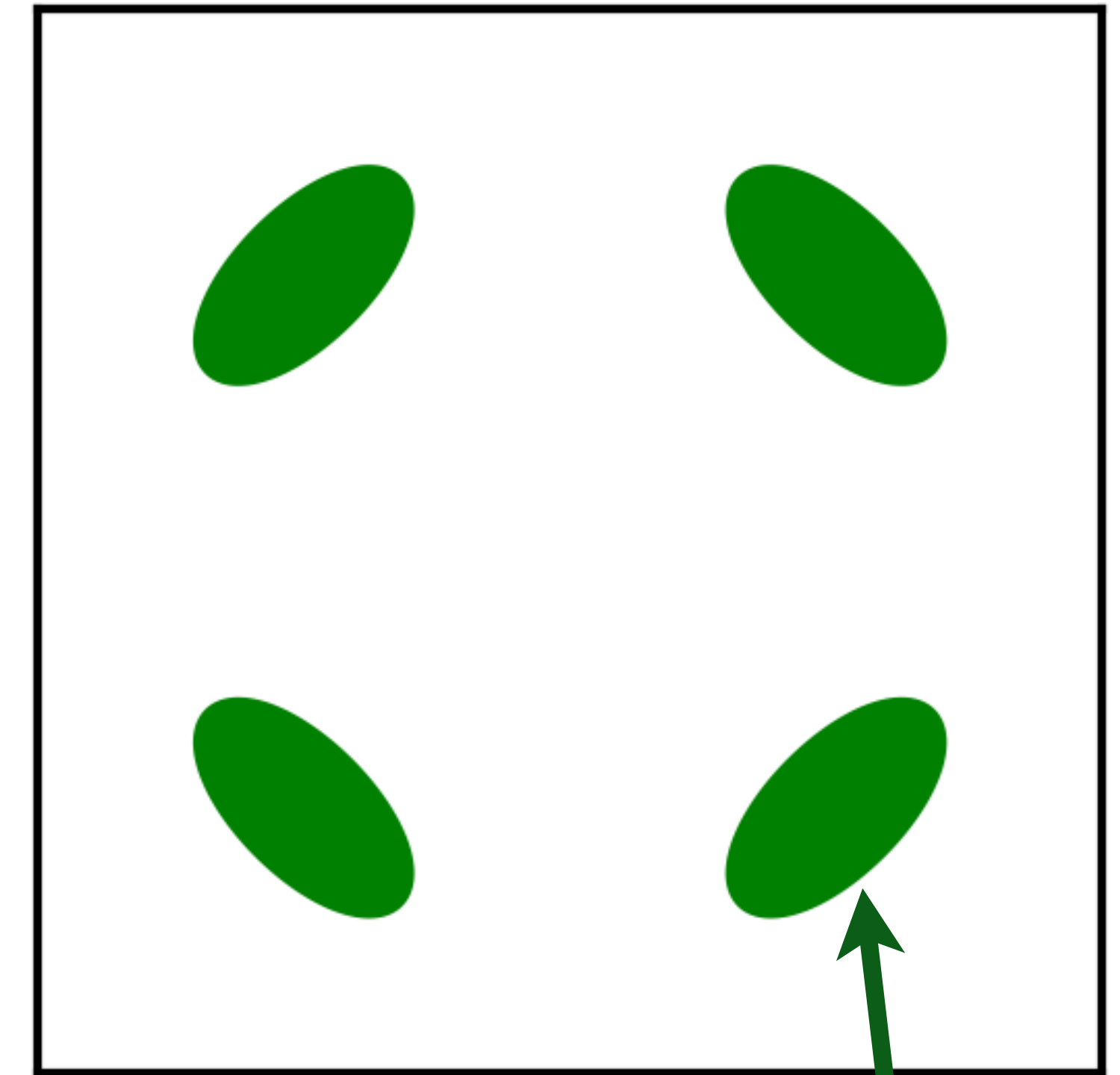
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Holon metal

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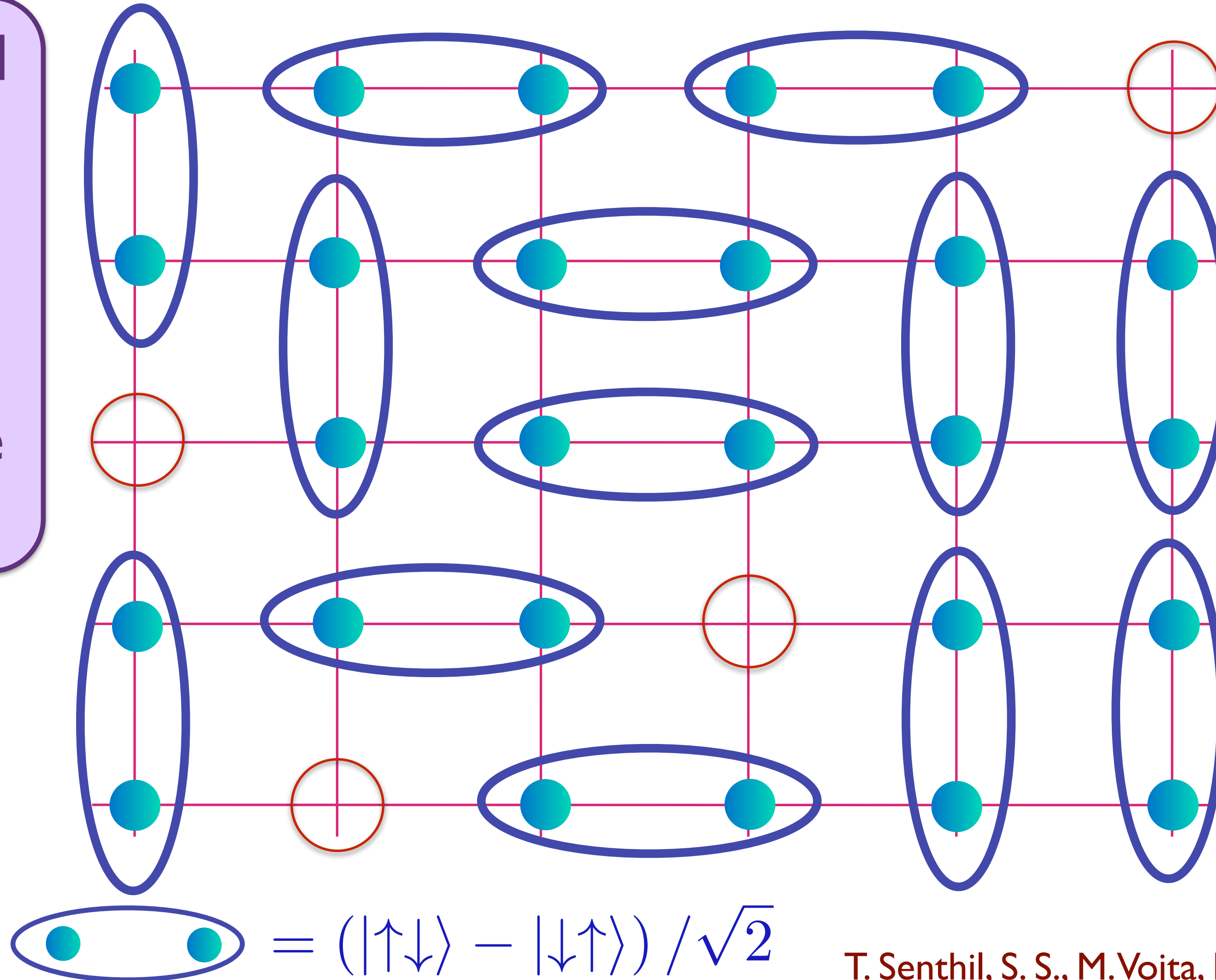
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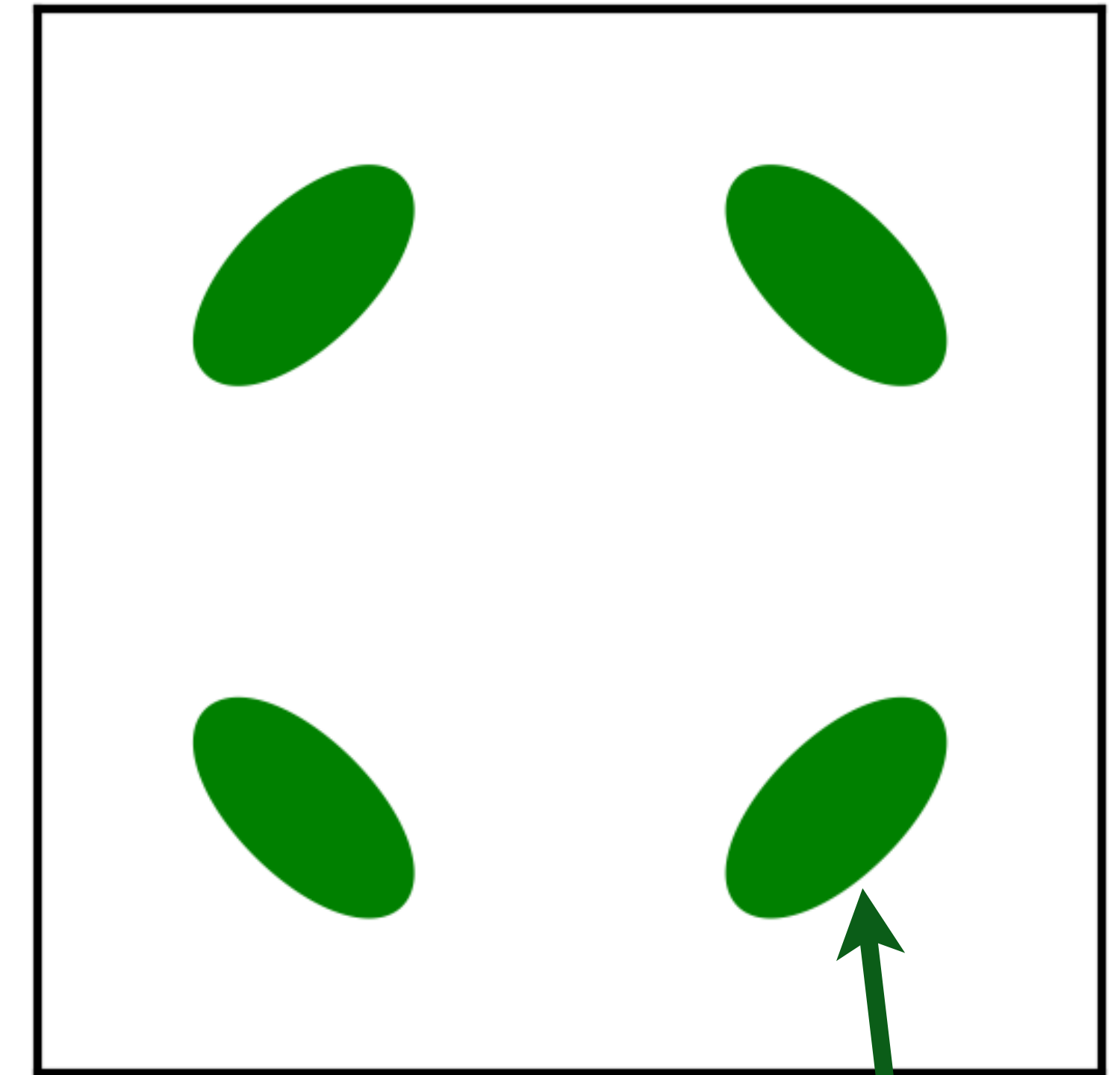
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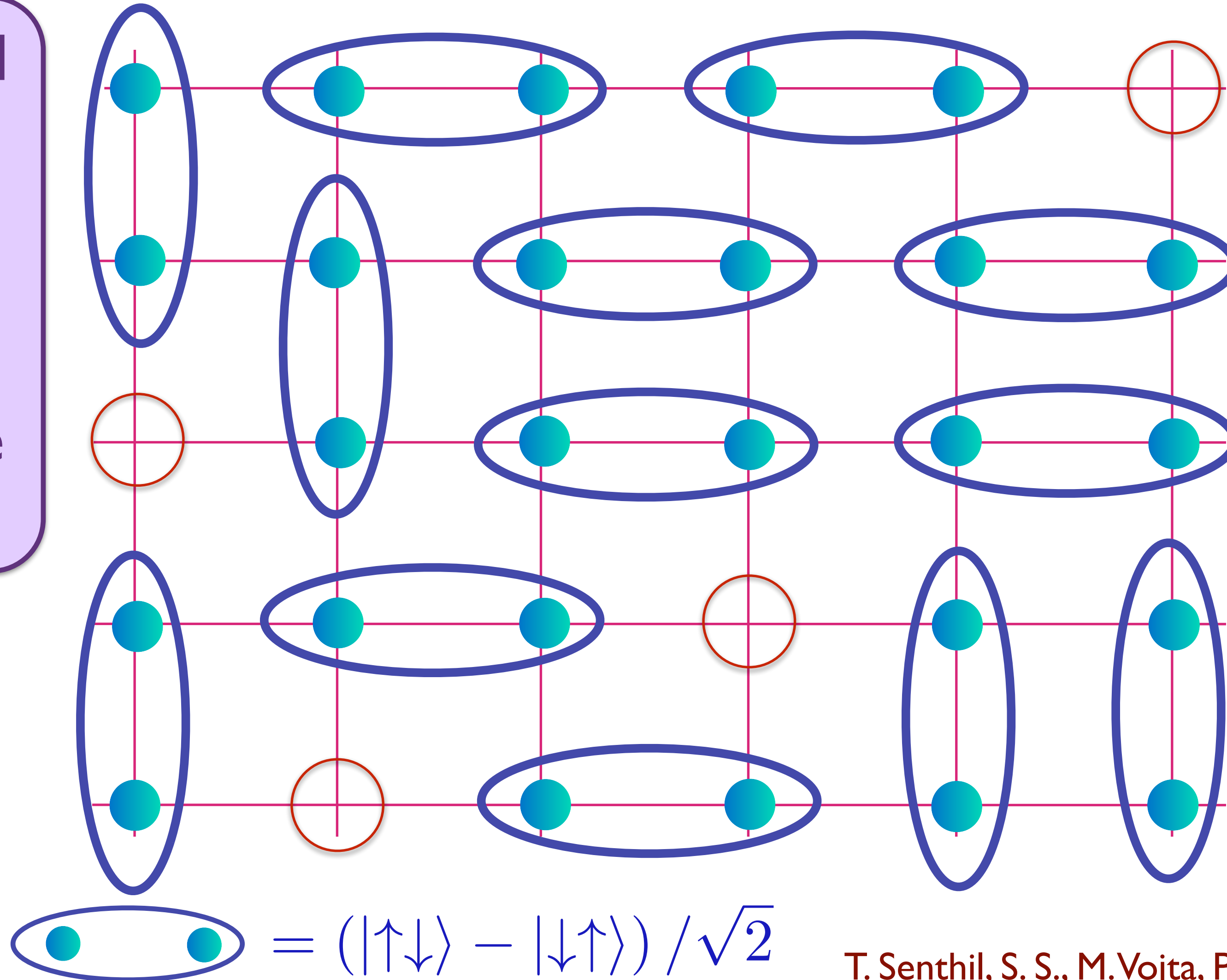
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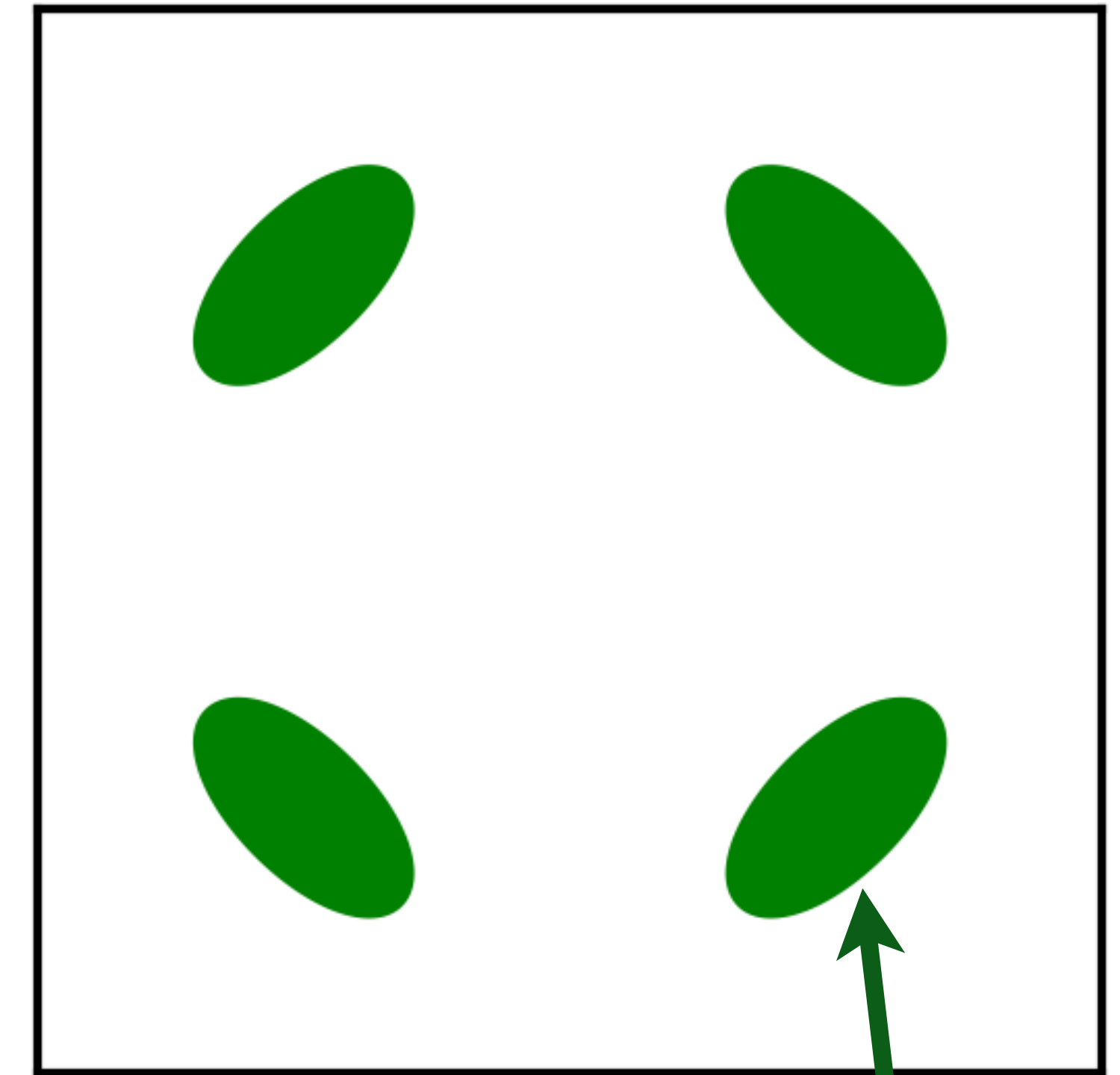
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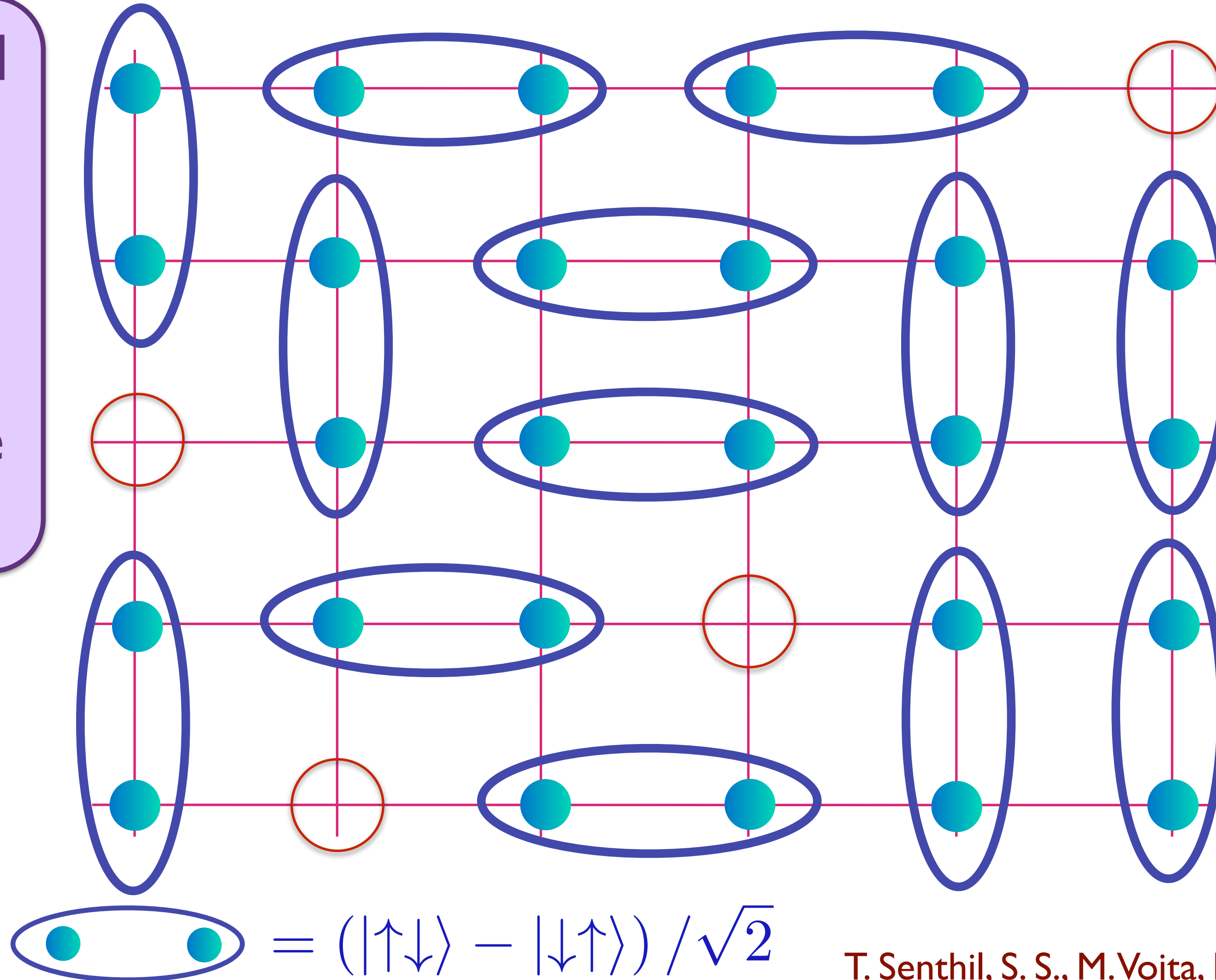
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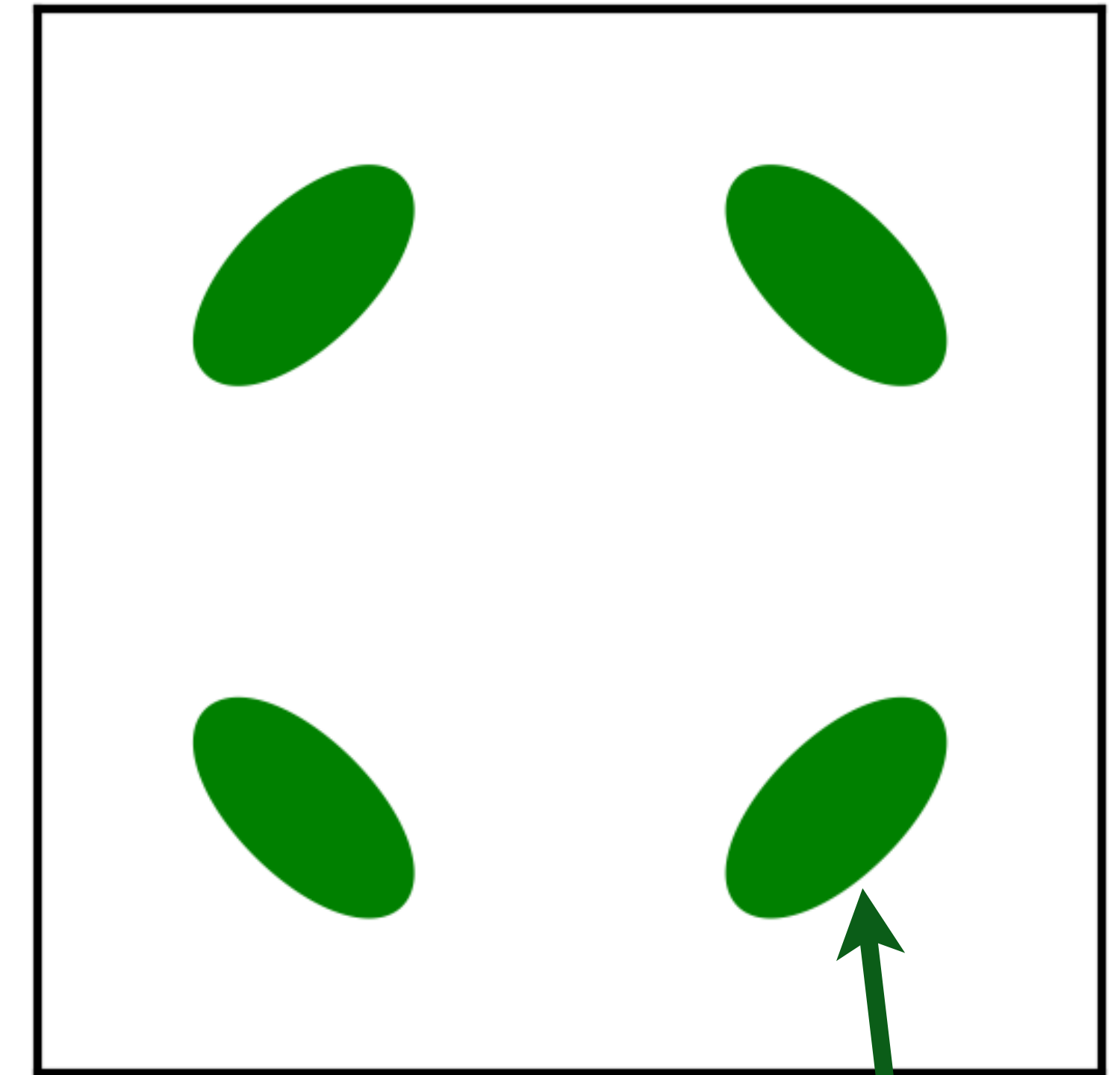
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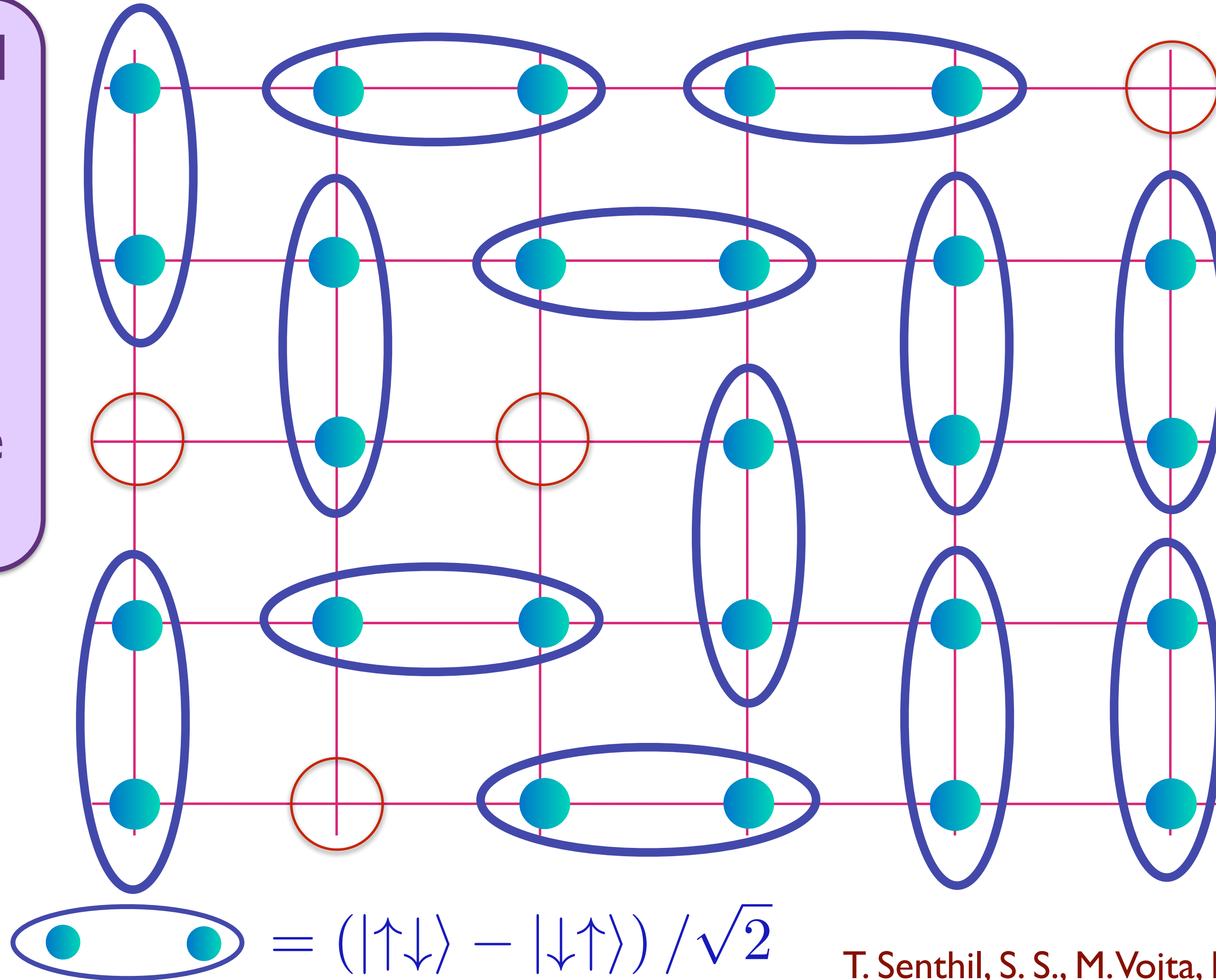
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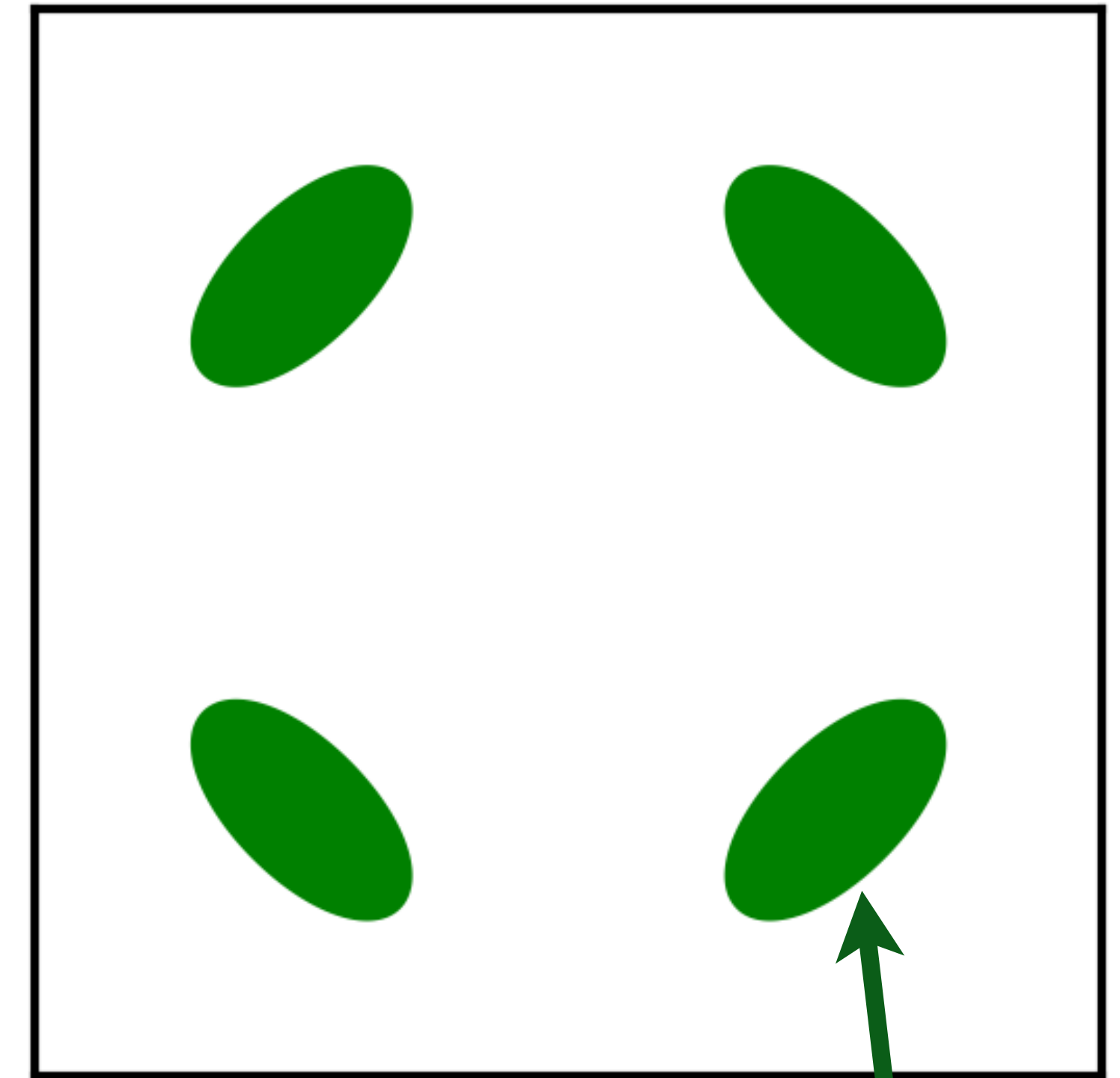
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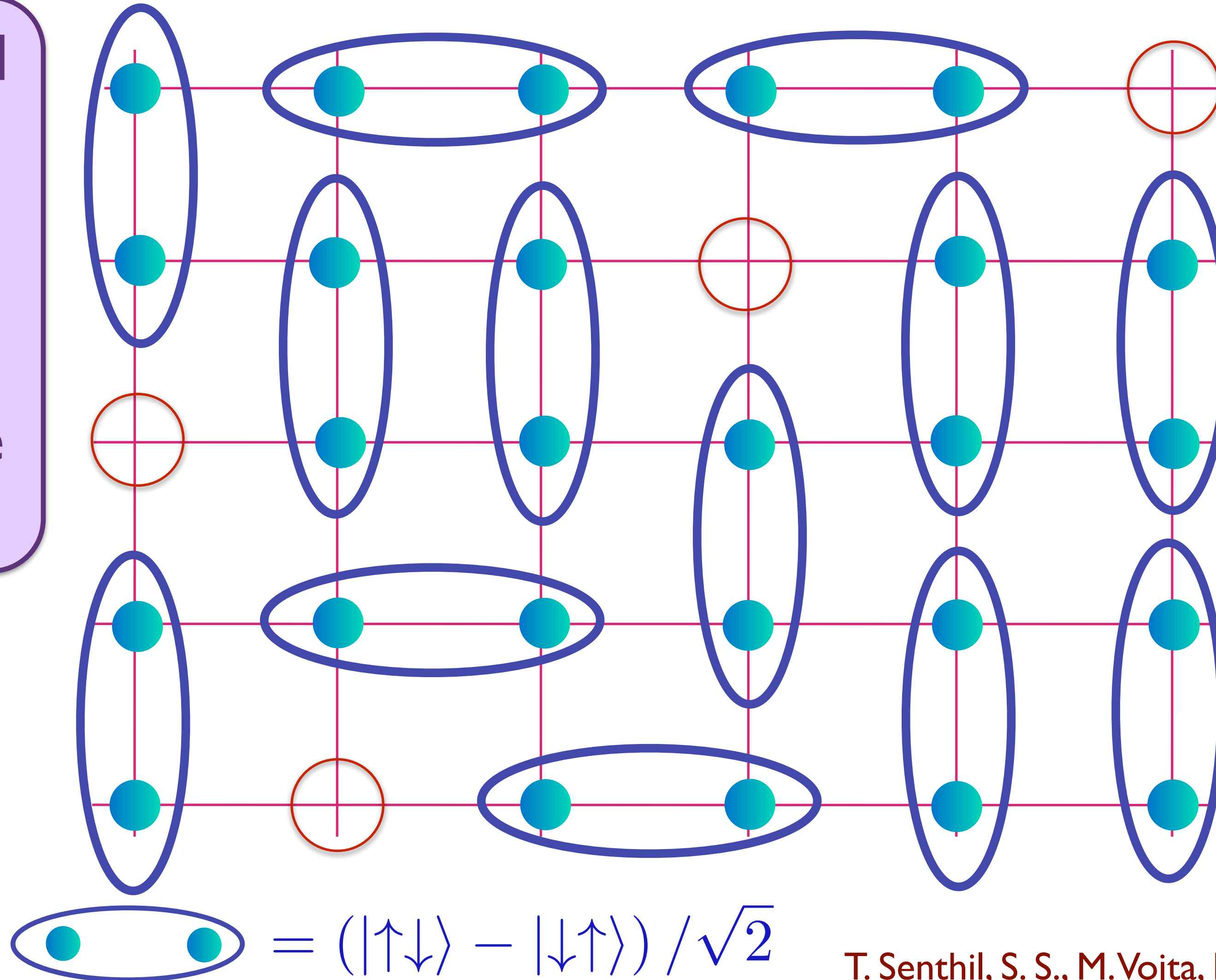
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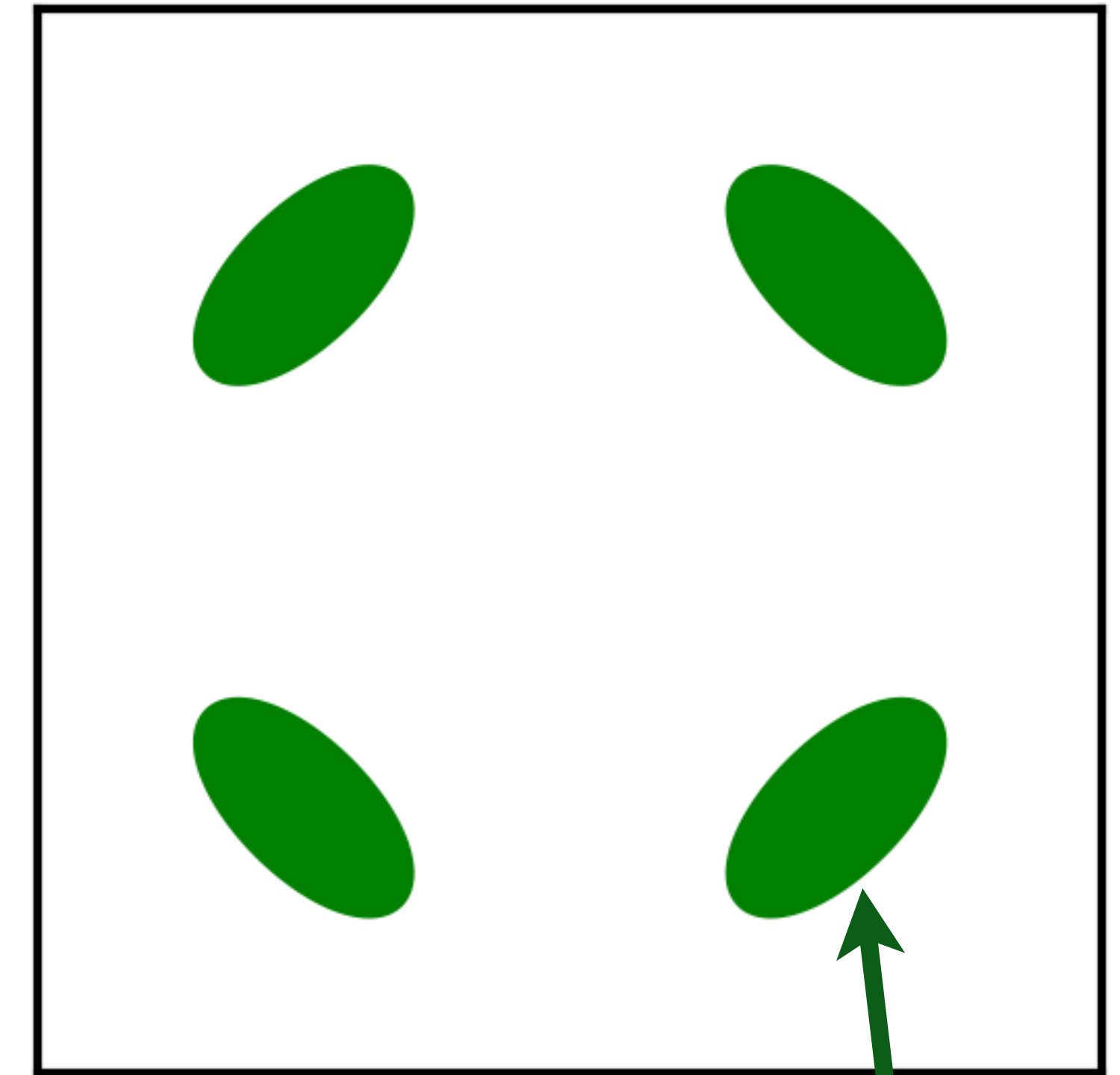
Holon metal

Spin liquid with density p of spinless, charge $+e$ “holons”.



$$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



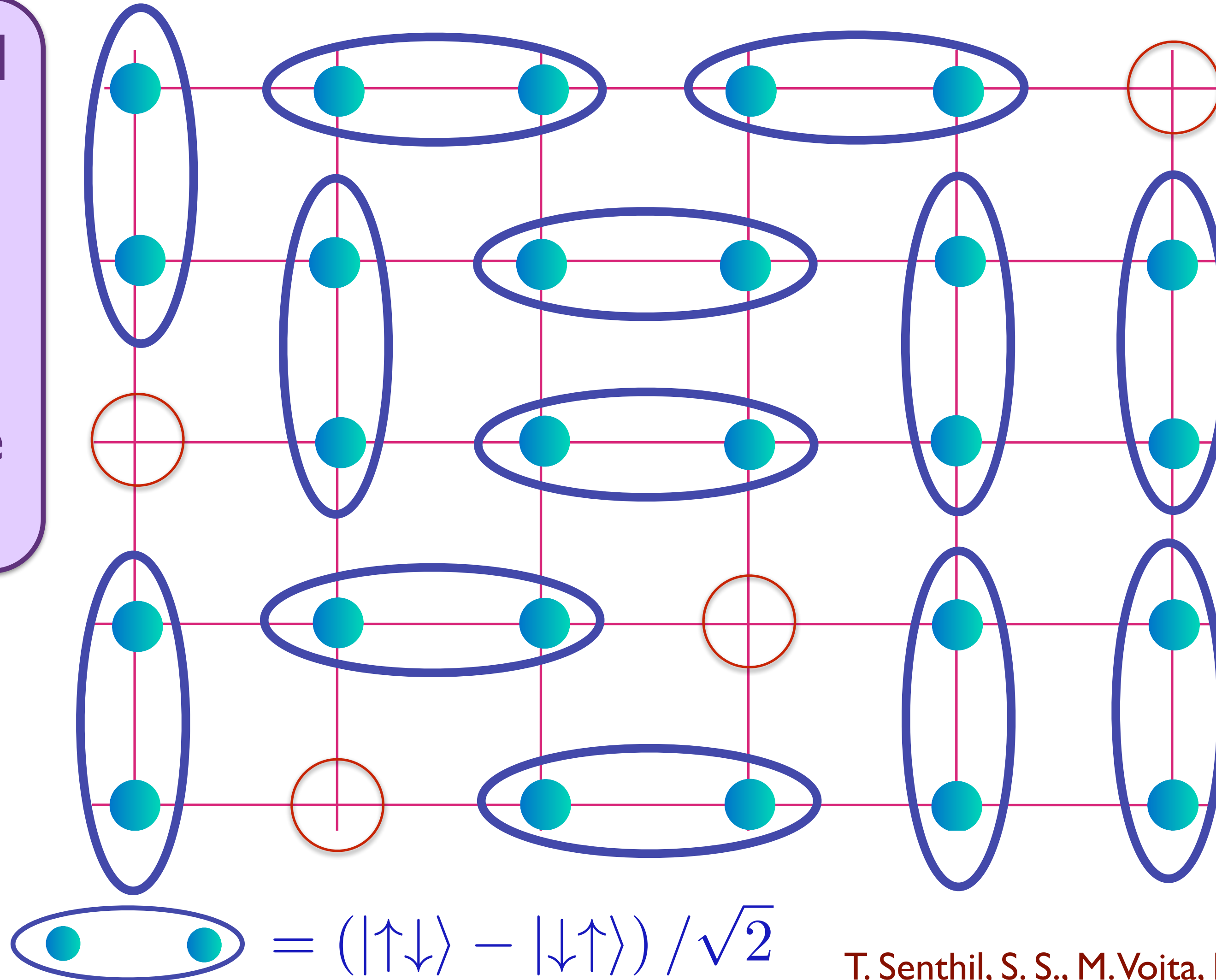
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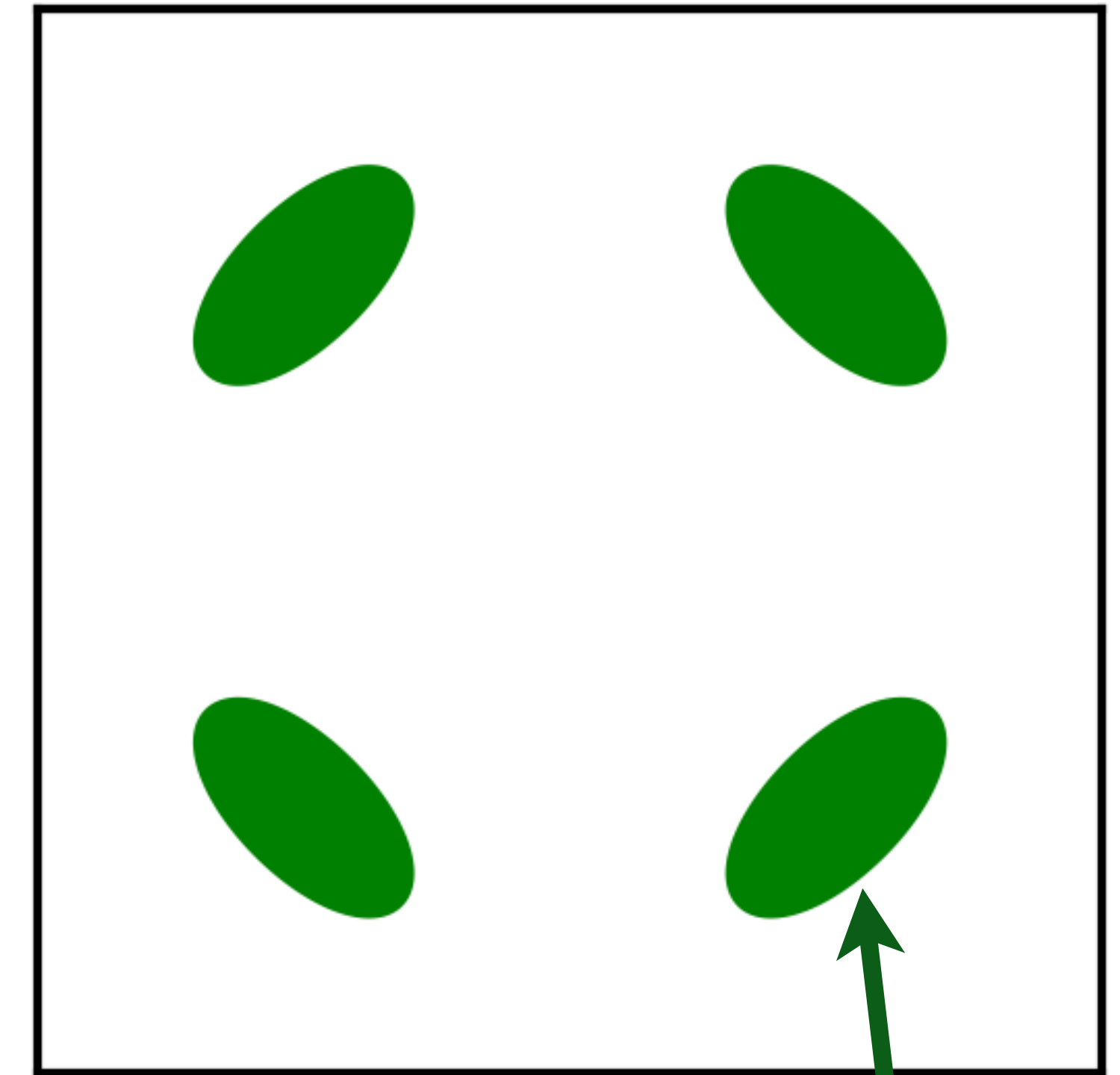
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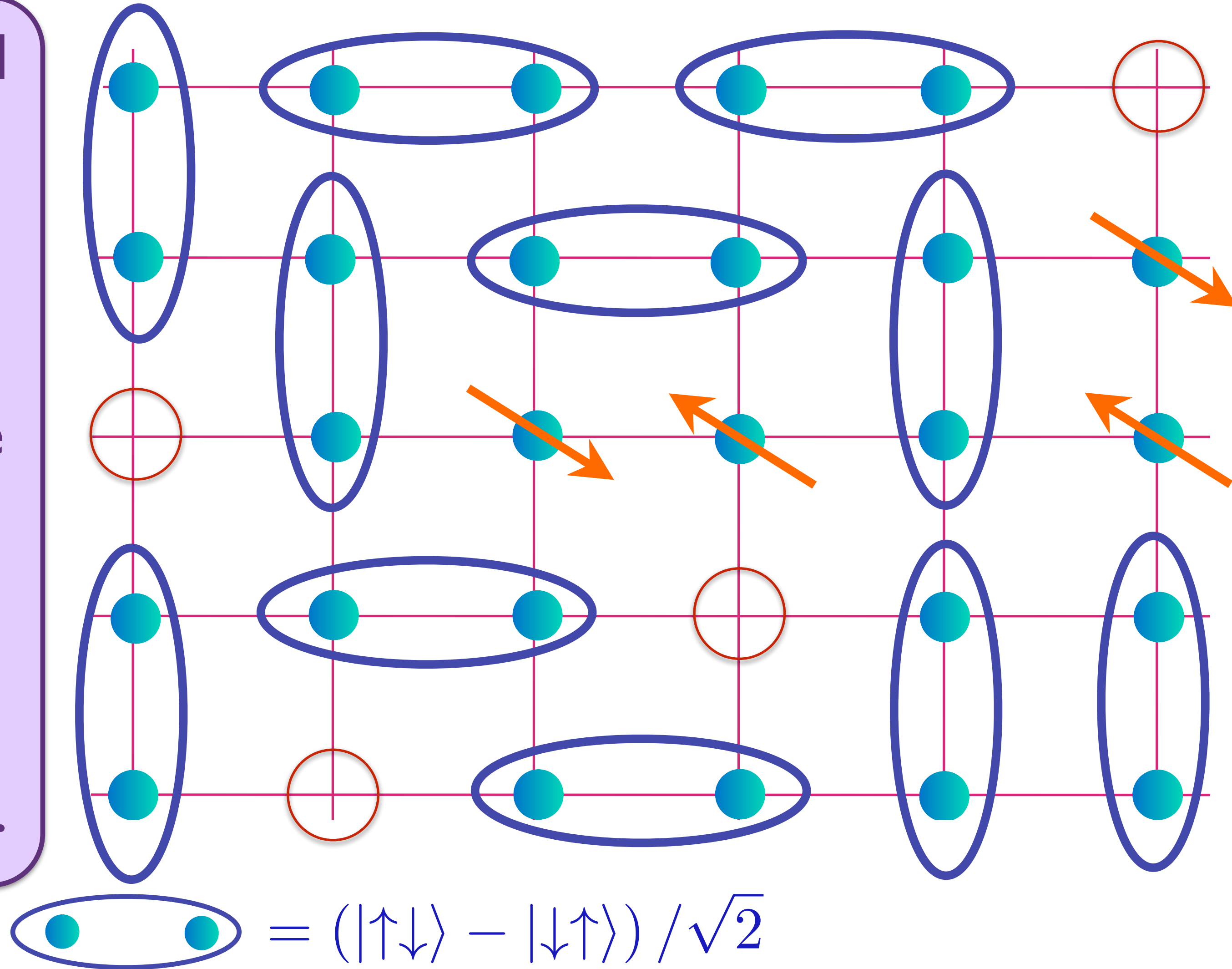
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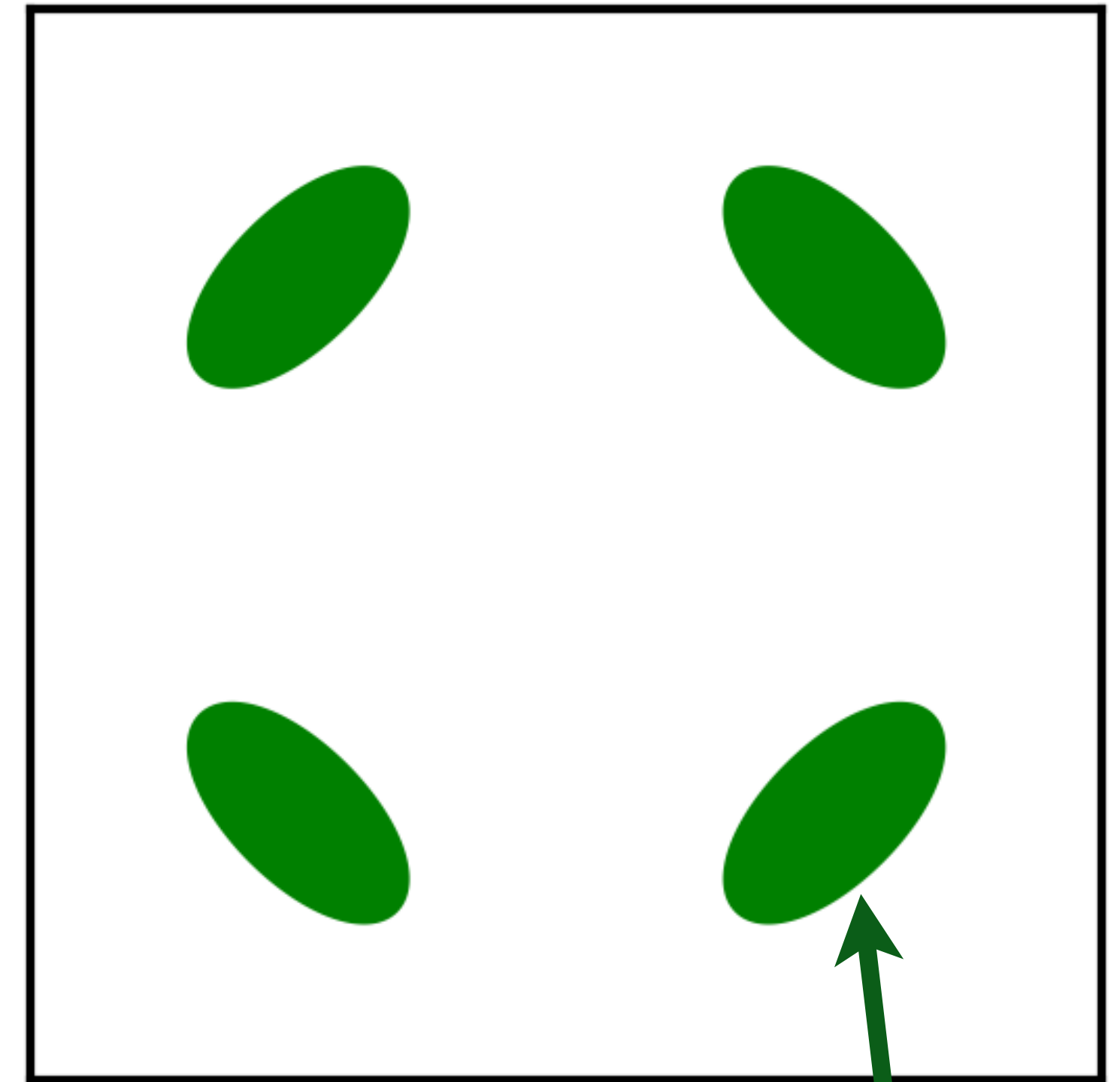
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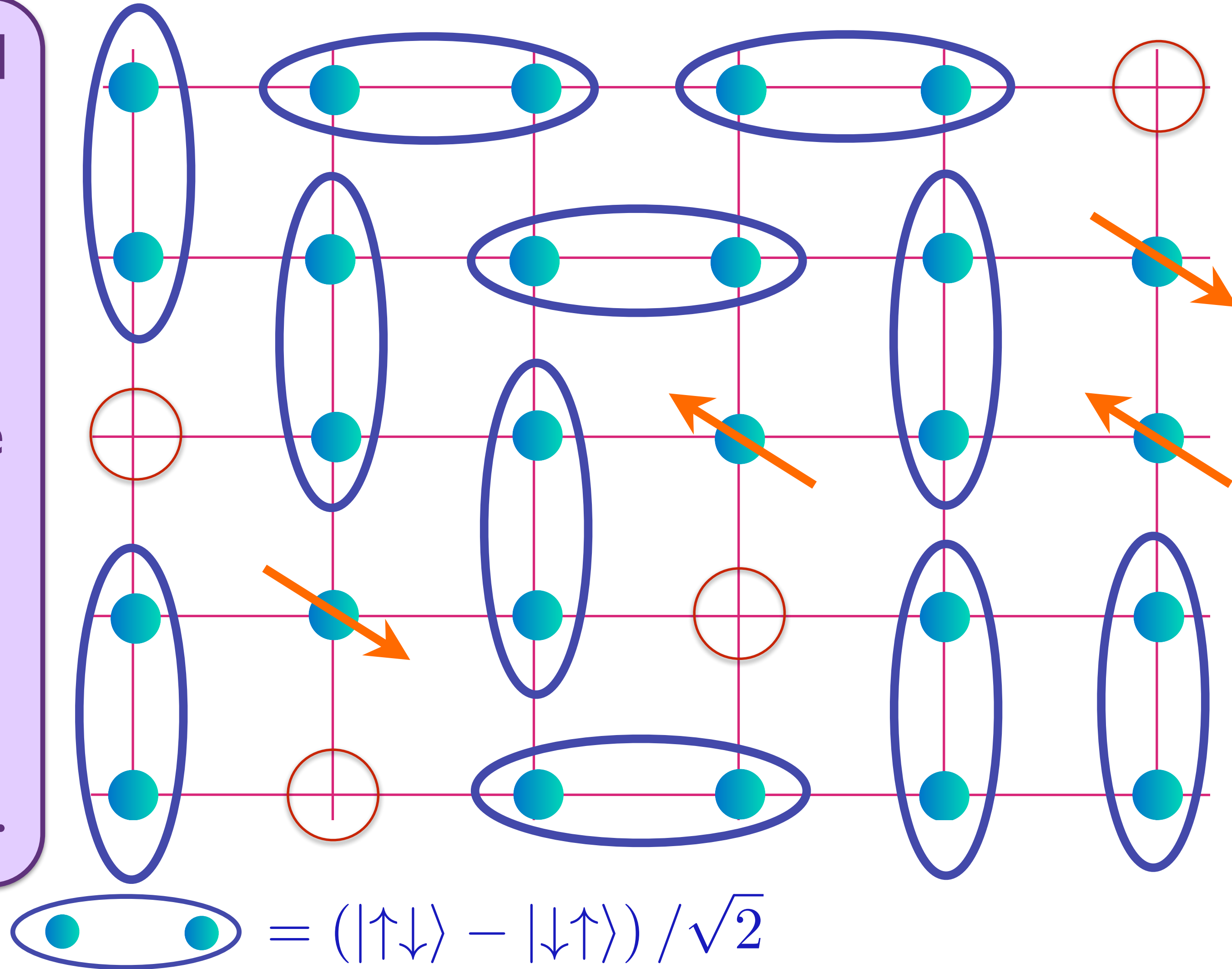


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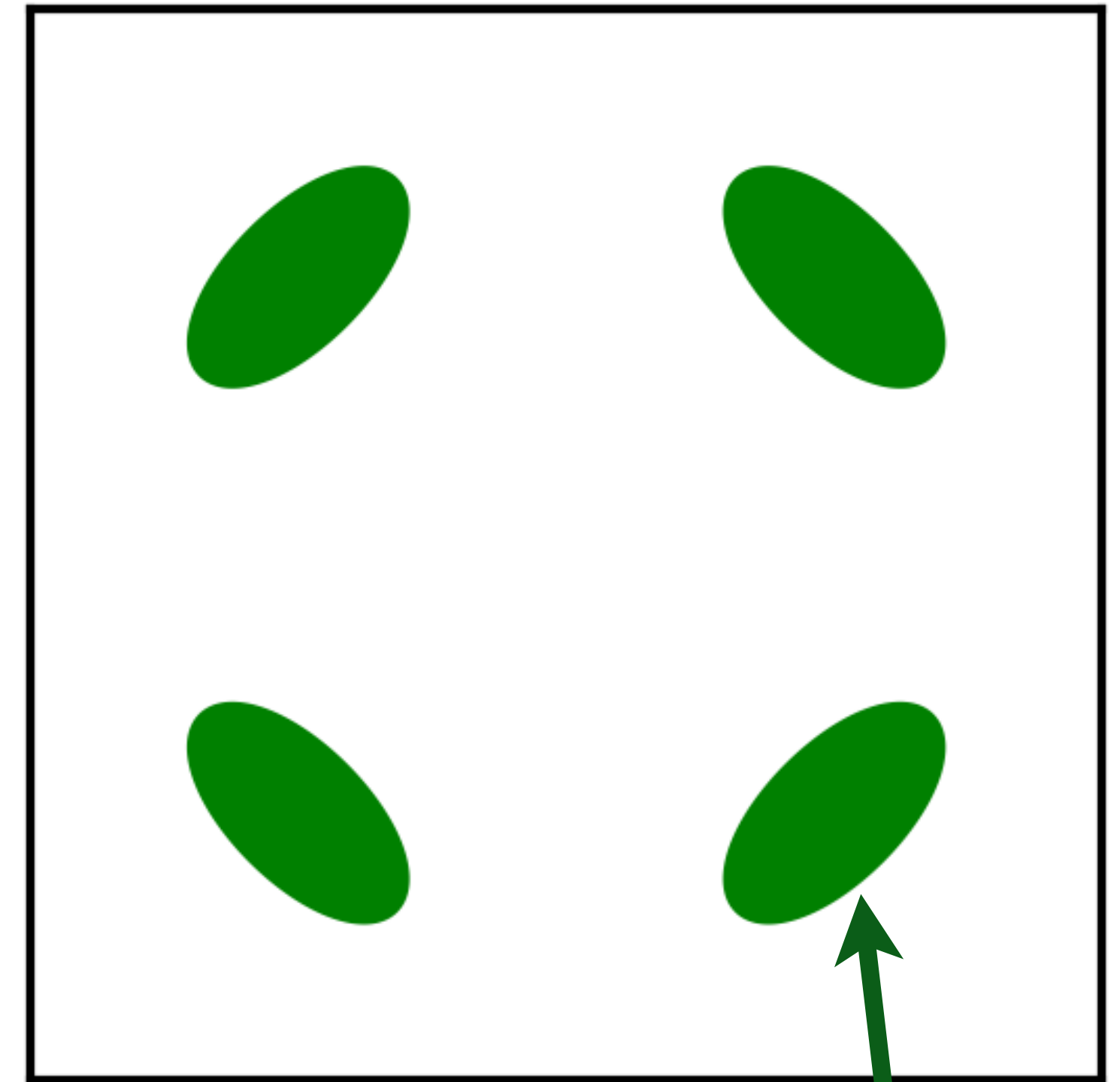
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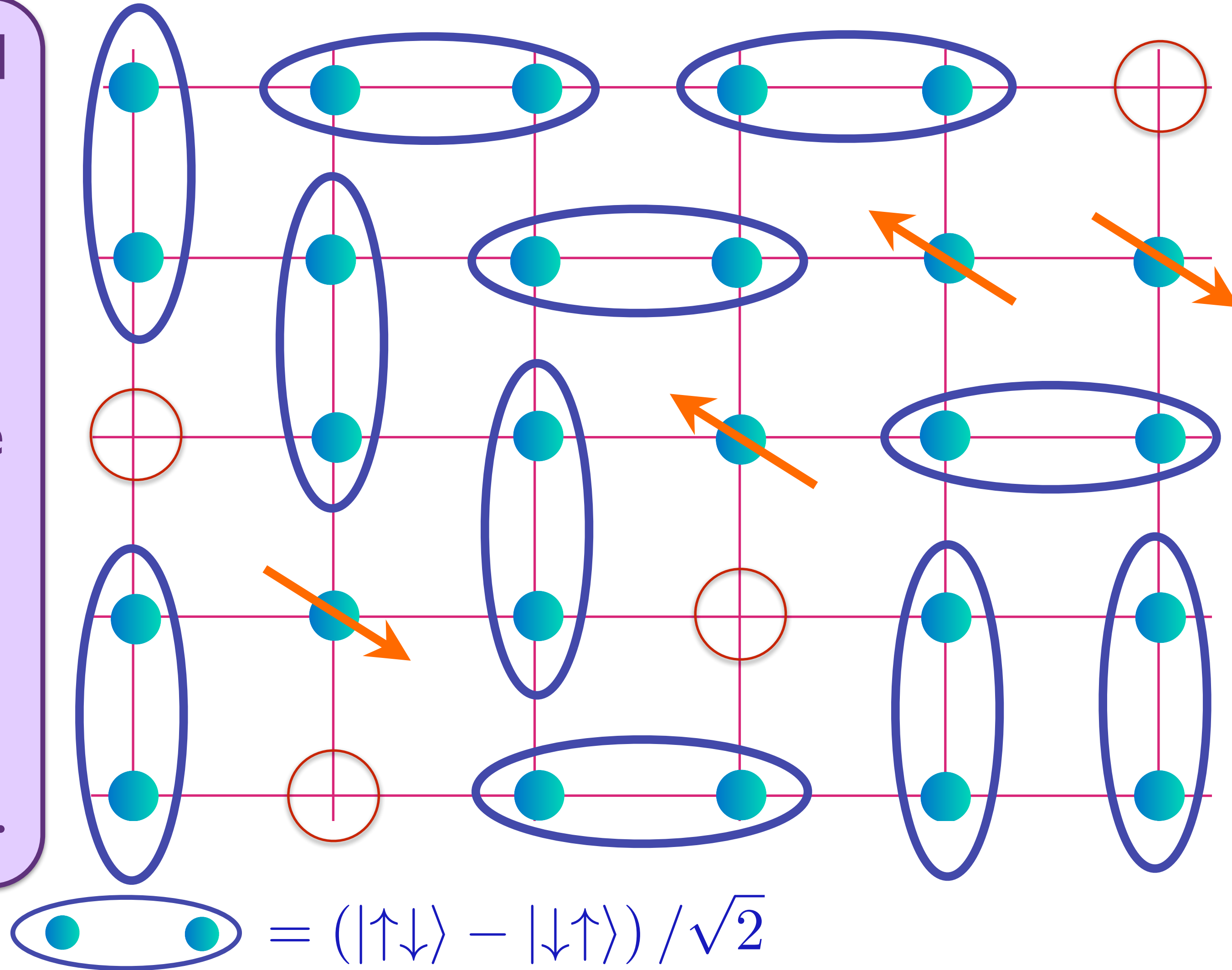


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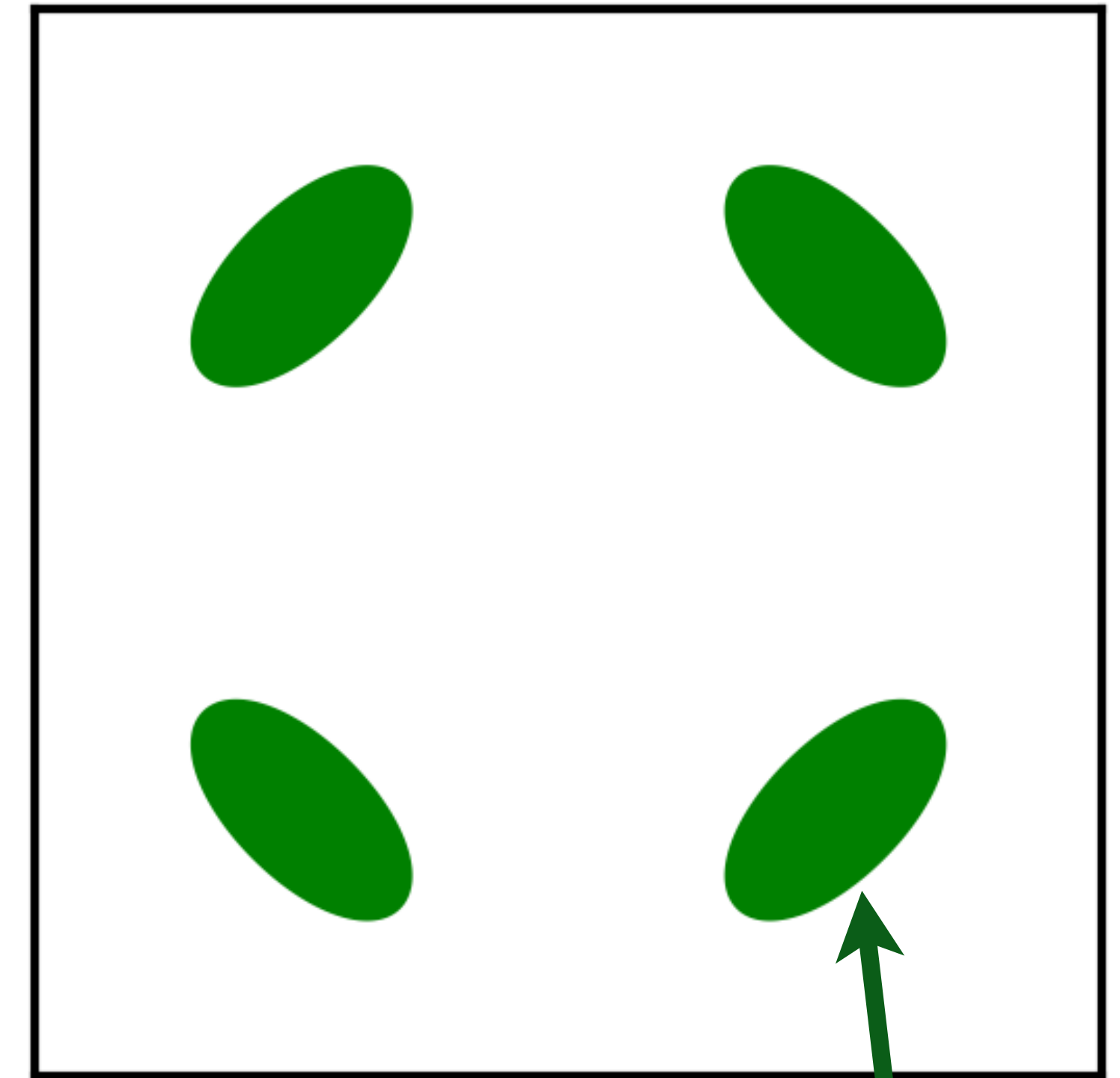
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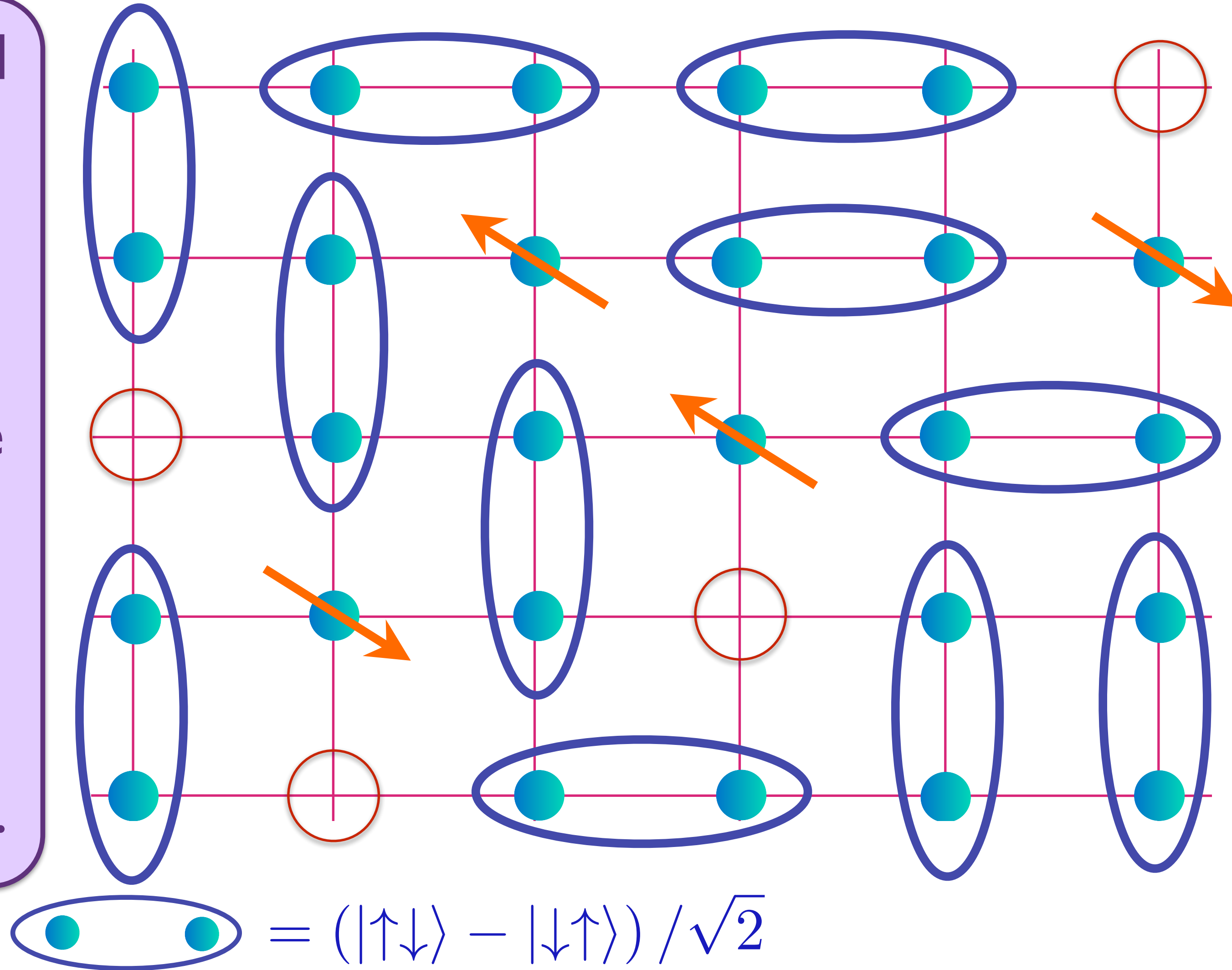


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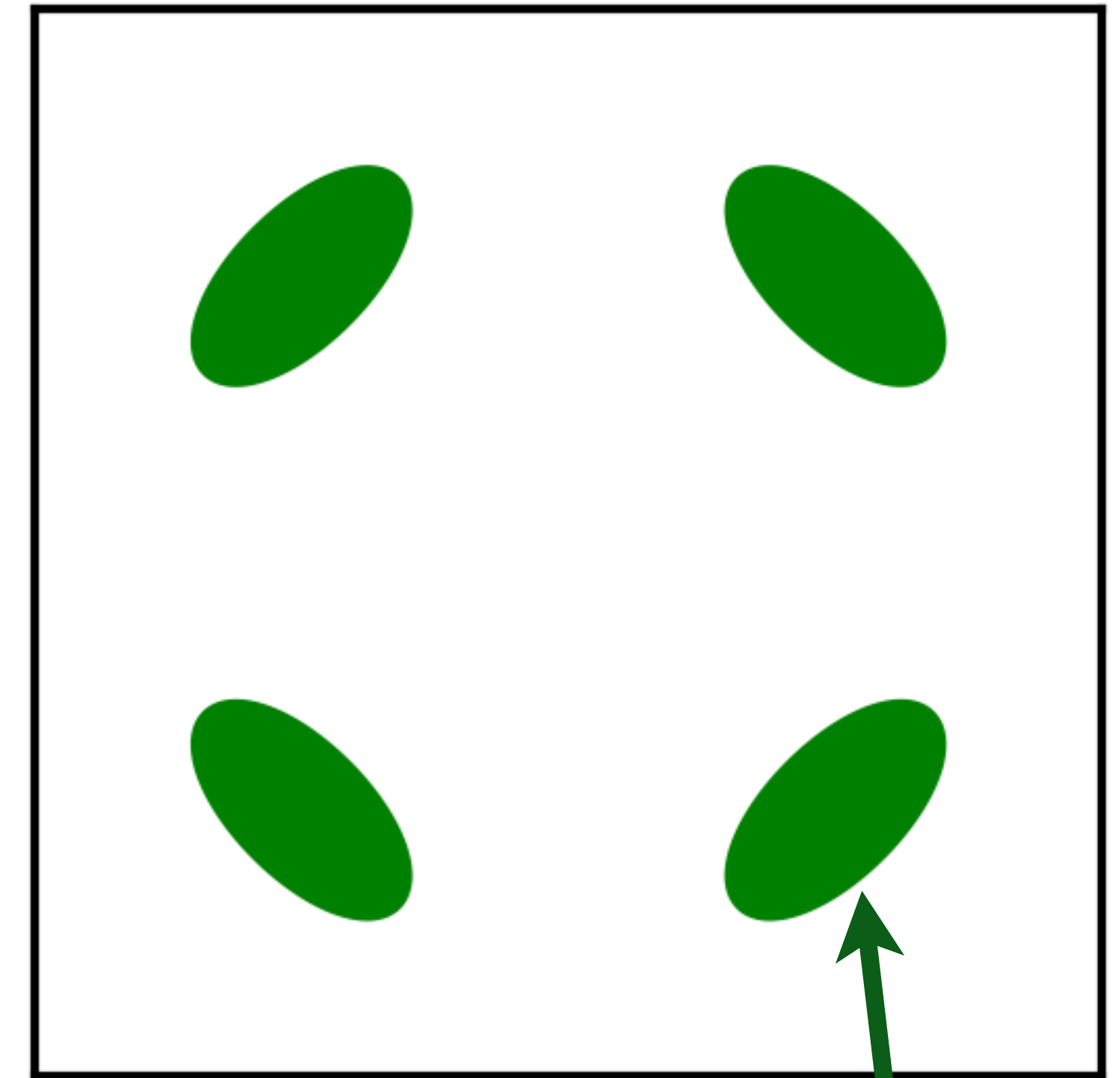
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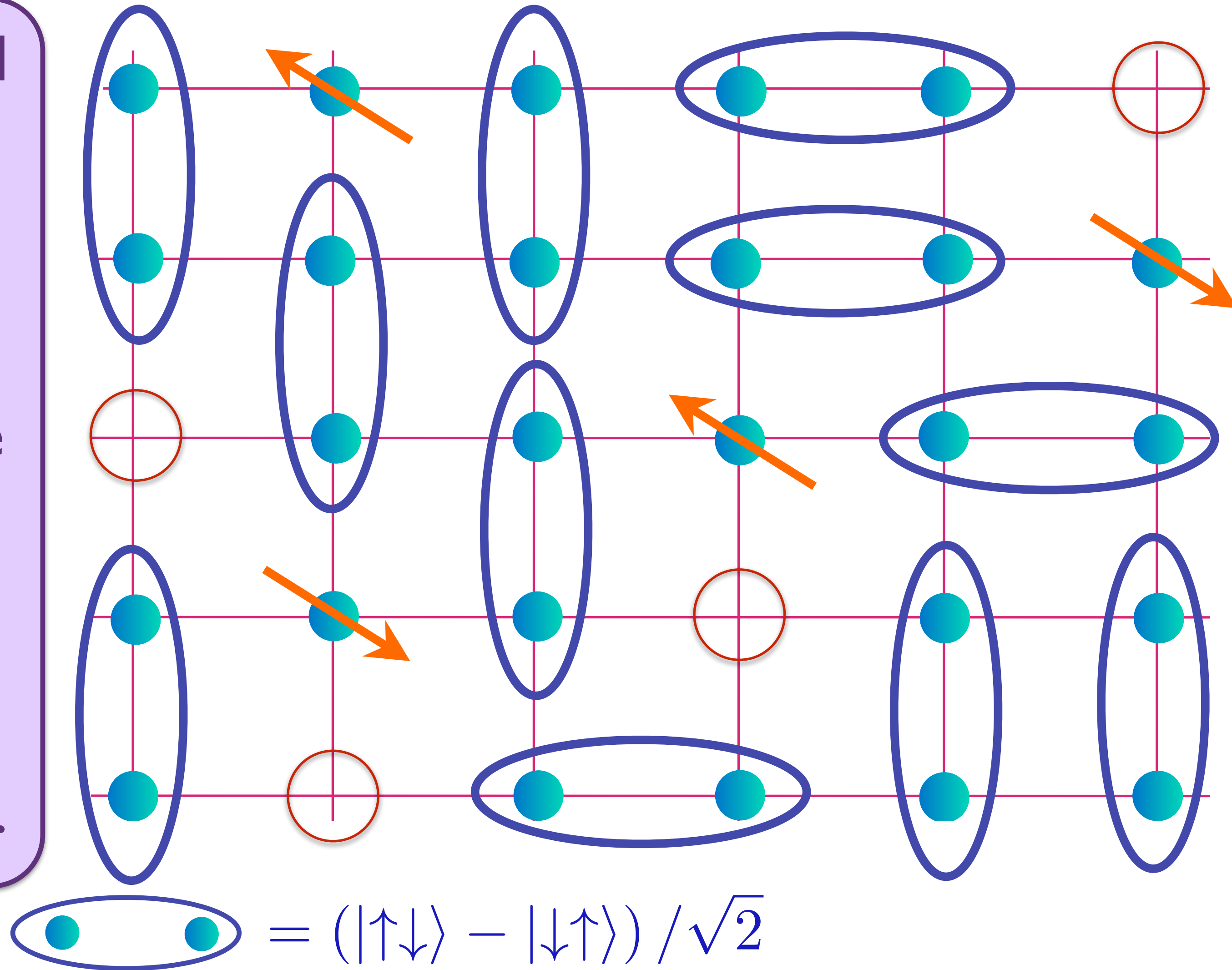


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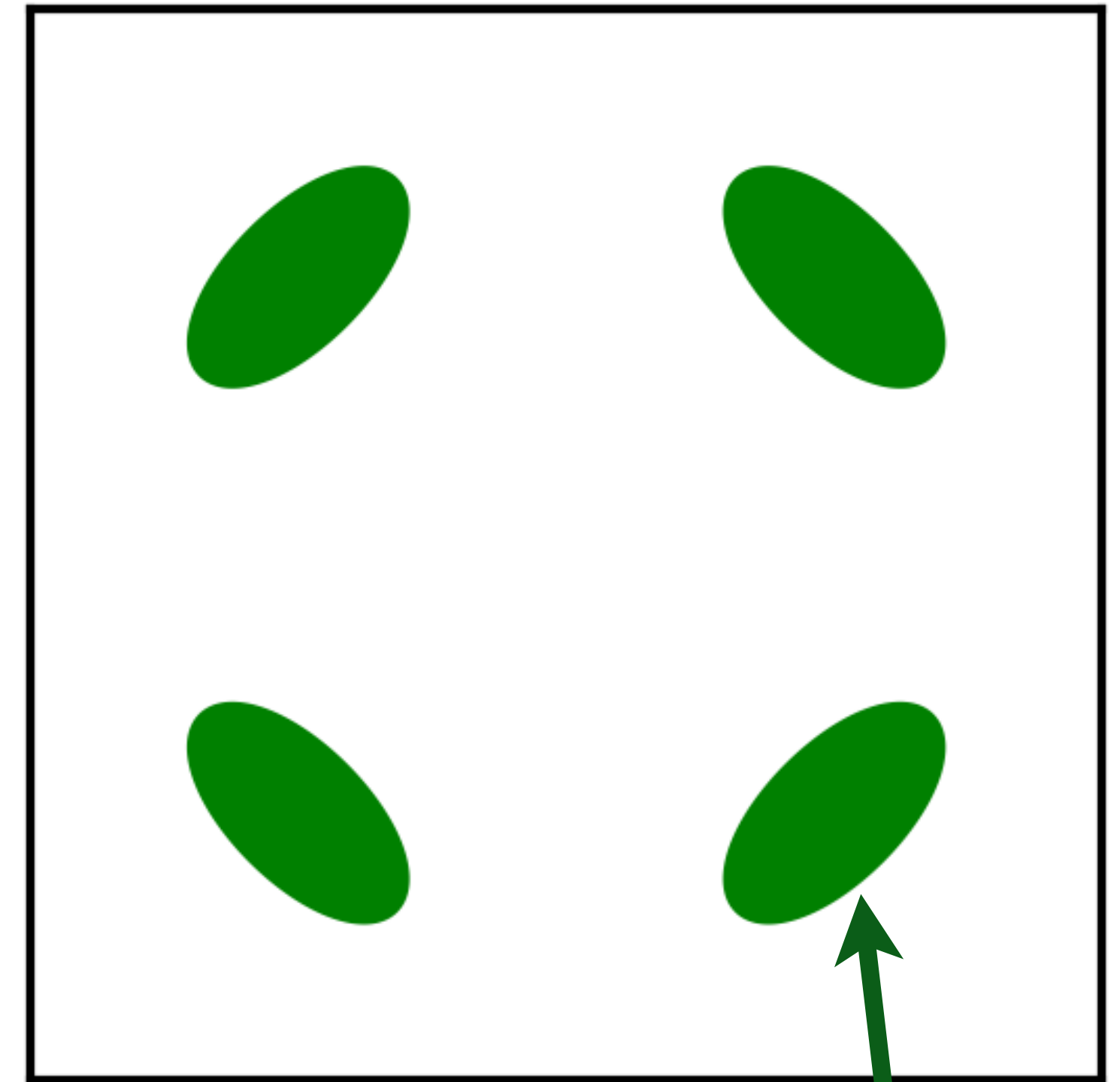
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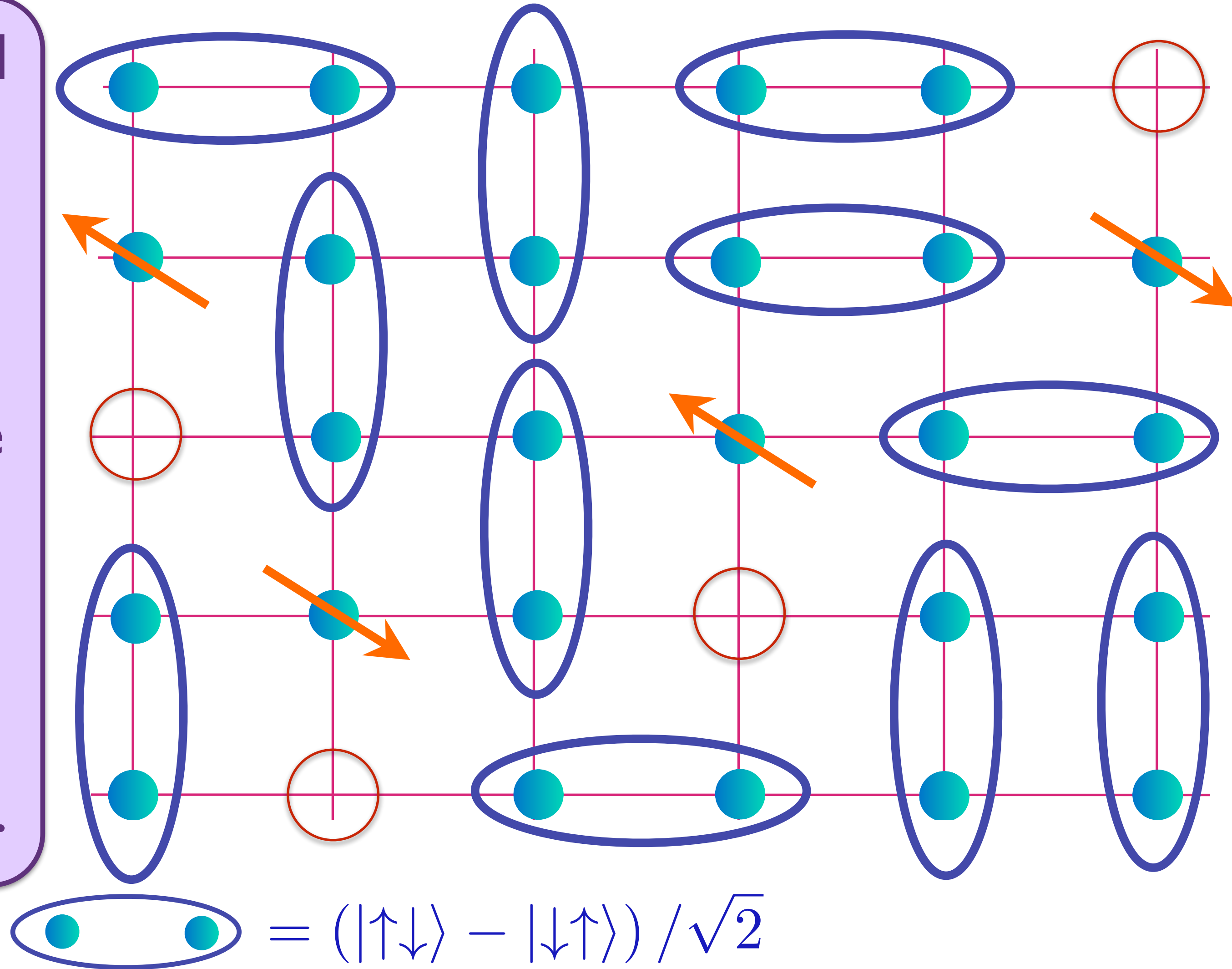


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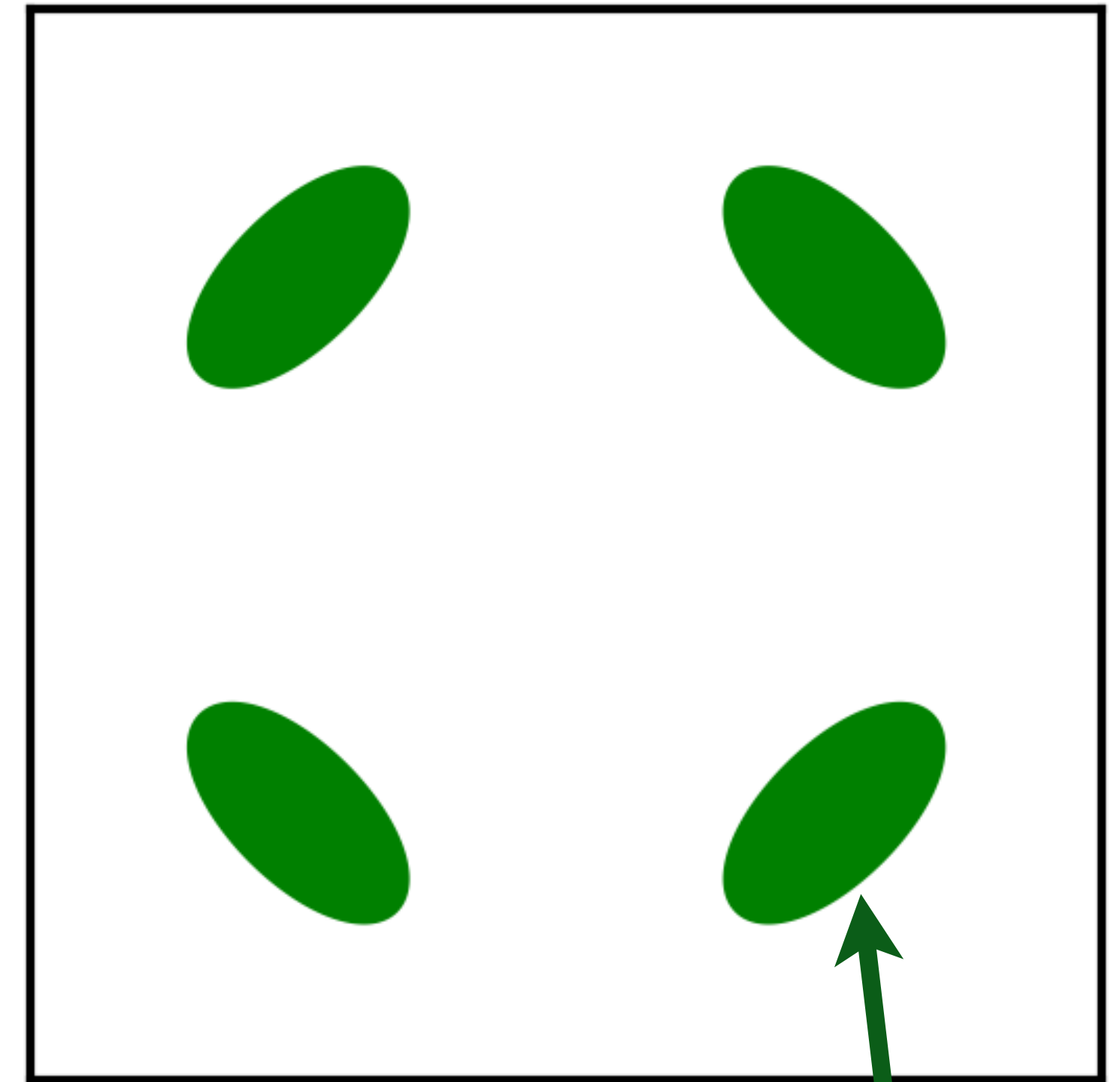
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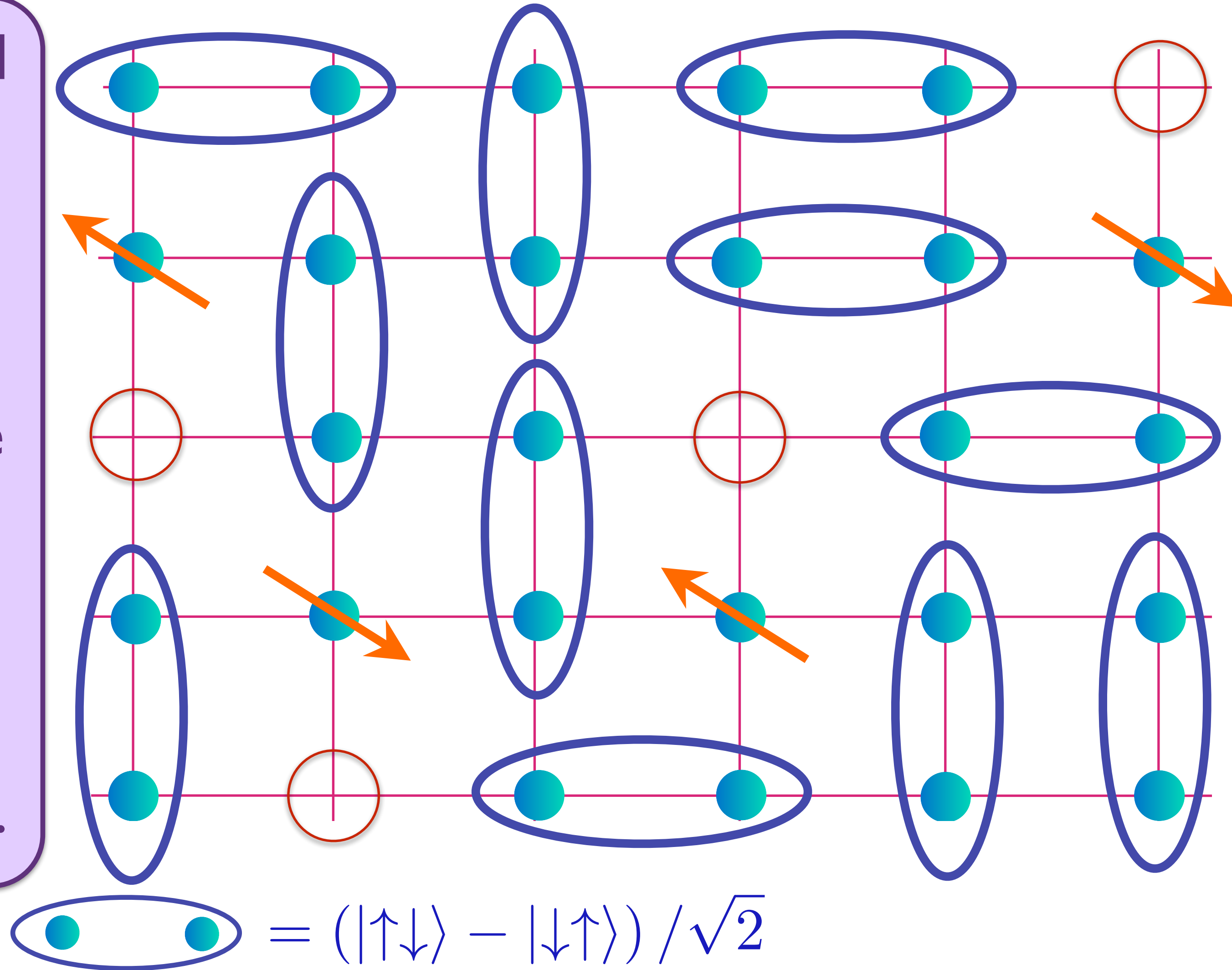


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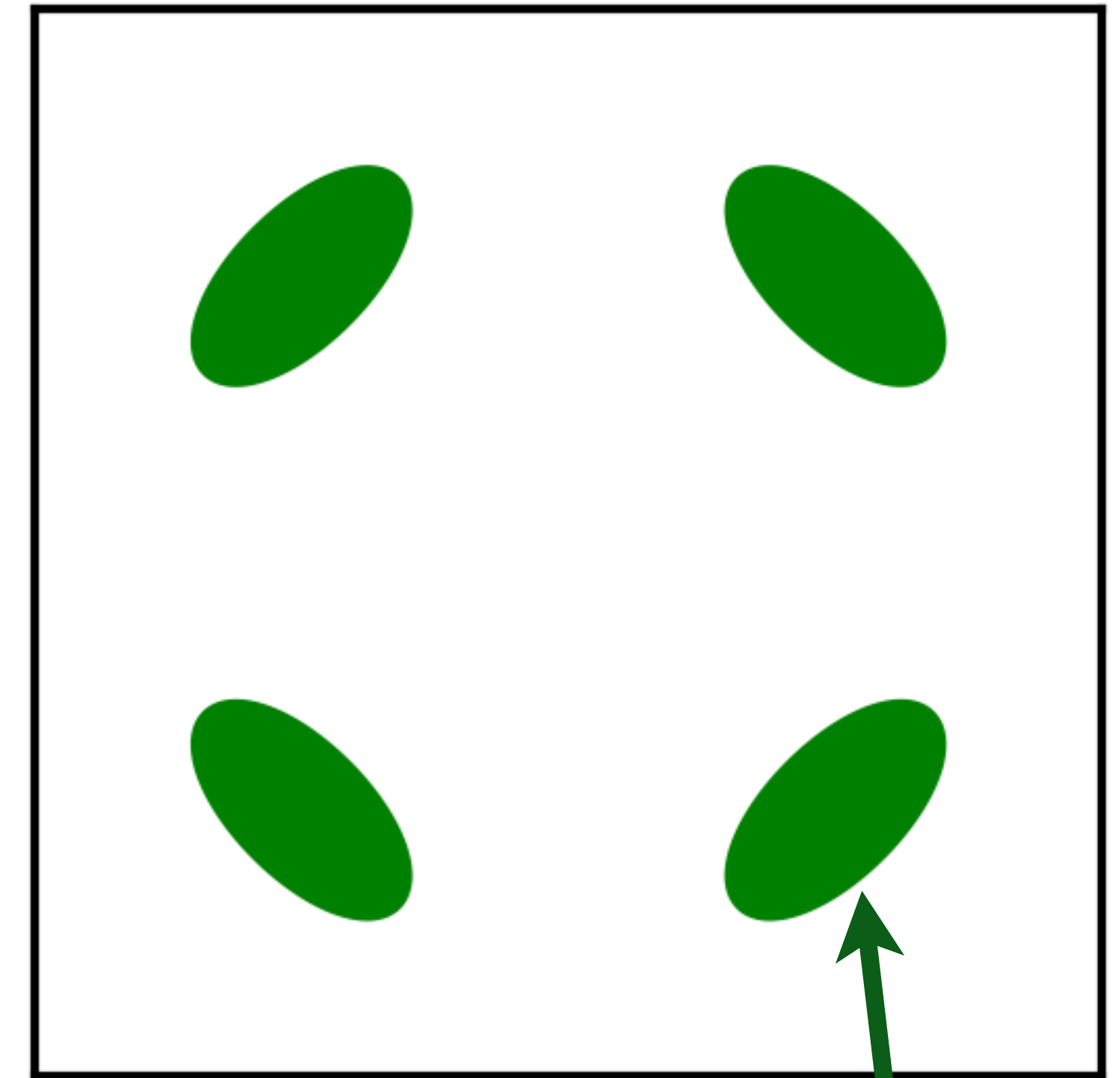
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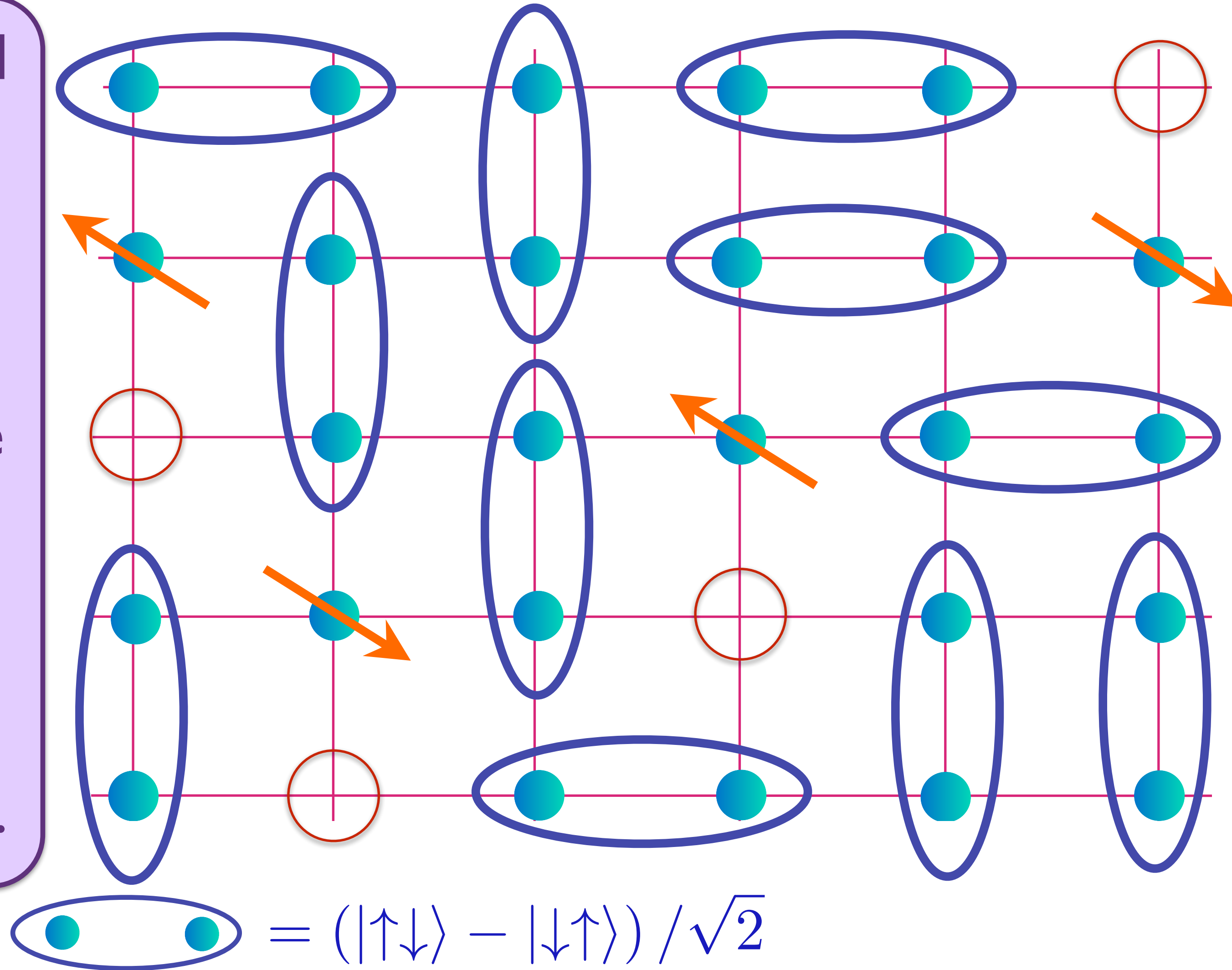


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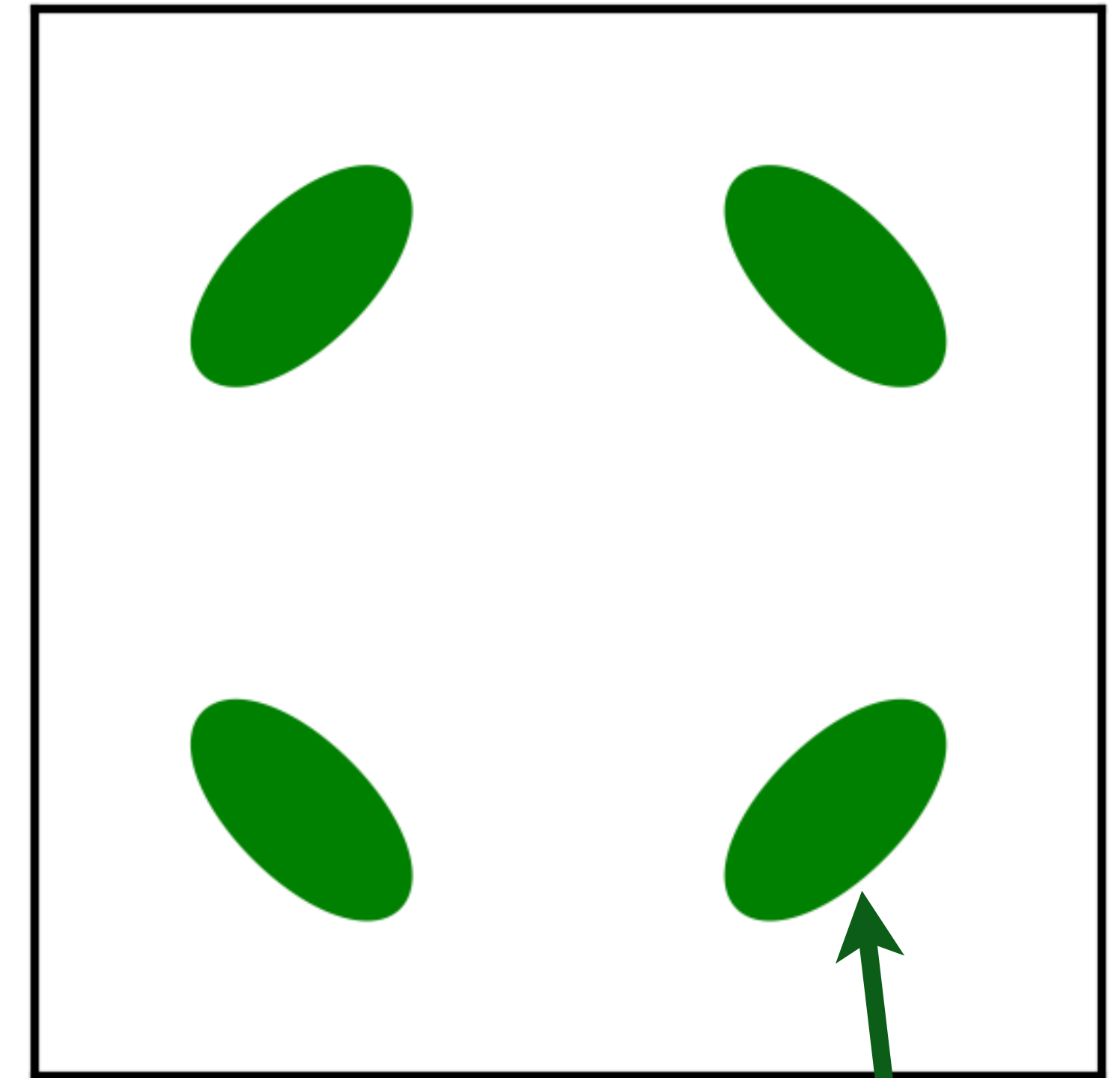
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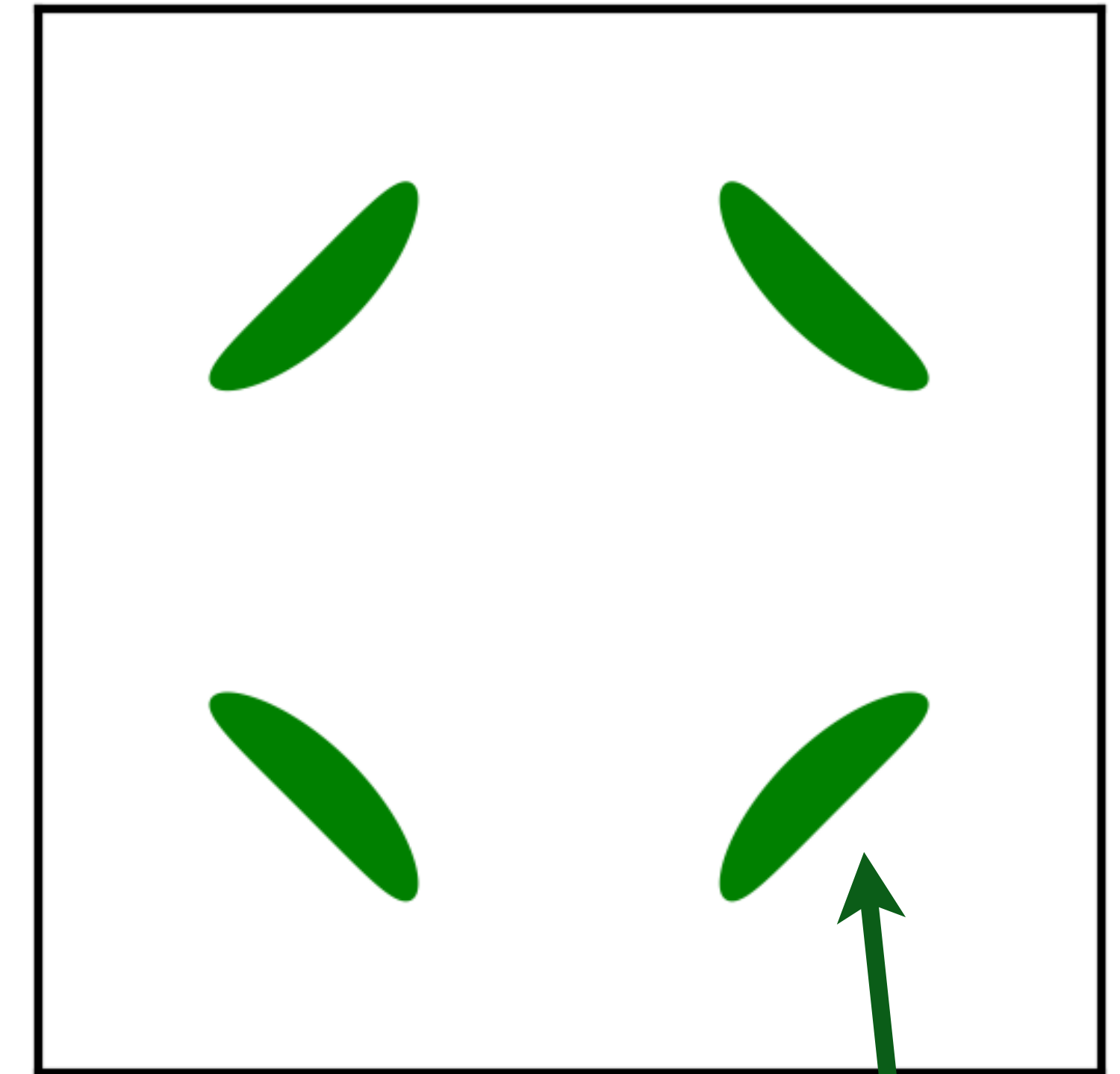
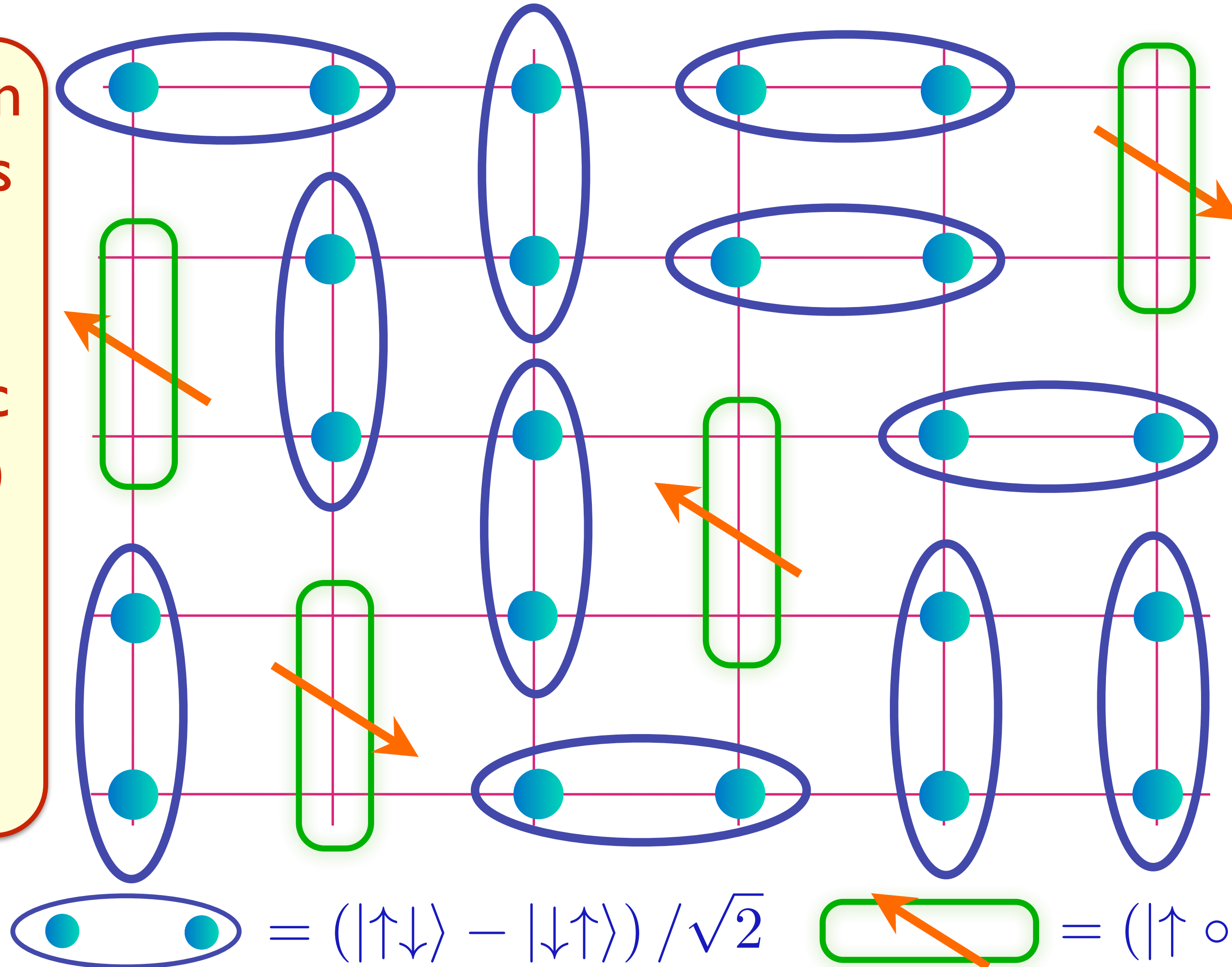
Area $p/4$

Doping an insulating antiferromagnet with holes of density p

FL*

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

Each green “dimer” is a bound state (a “magnetic polaron”) of a vacancy and a free spin



Area $p/8$

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003); R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)

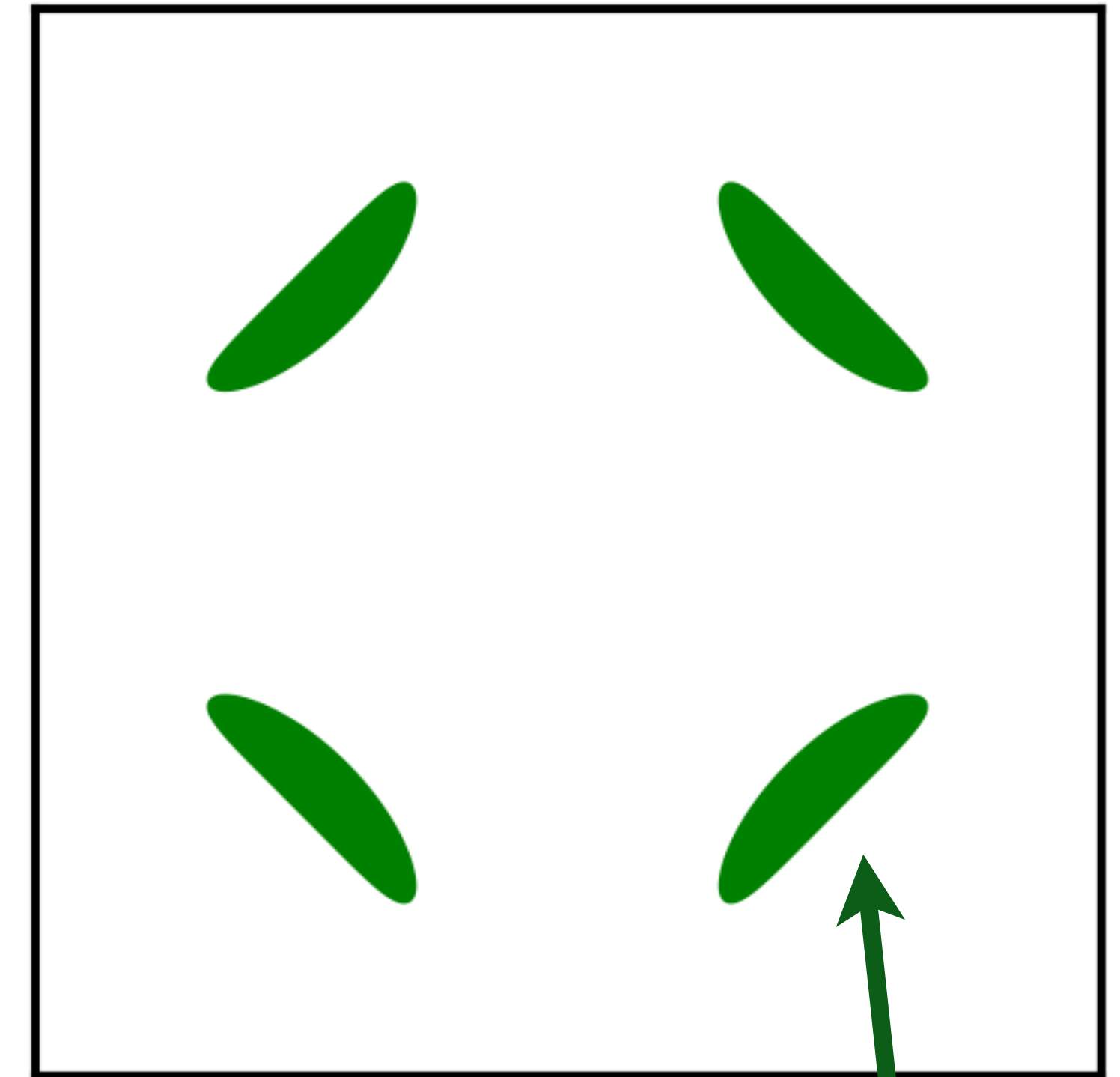
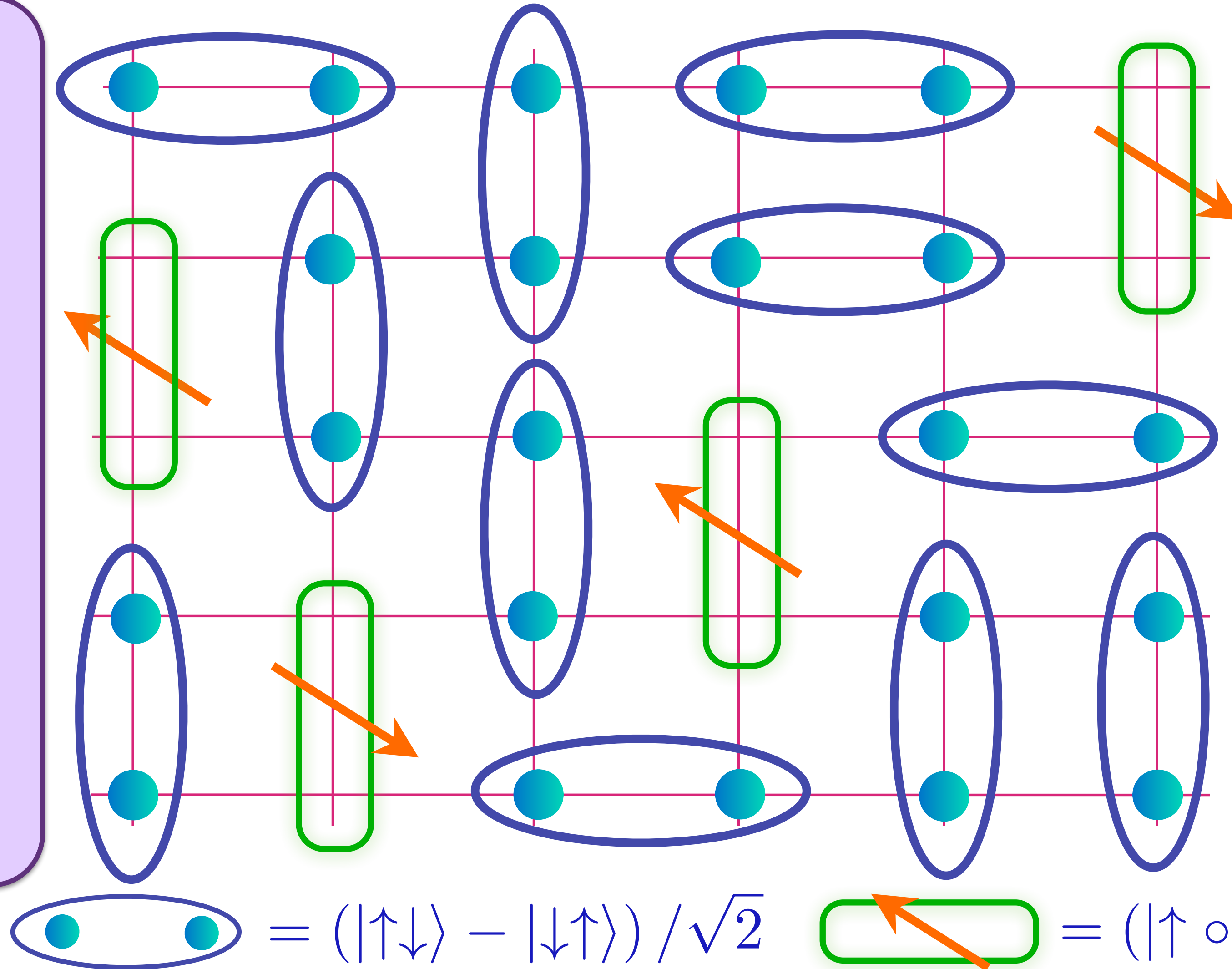
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

Doping an insulating antiferromagnet with holes of density p

FL*

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

Metal with density p of spin-1/2, charge $+e$ “holes” (or “magnetic polarons”) and charge 0 spin-1/2 “spinons”.



Area $p/8$

$$\begin{array}{|c|c|} \hline \bullet & \bullet \\ \hline \end{array} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2} \quad \begin{array}{|c|} \hline \bullet \\ \hline \end{array} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

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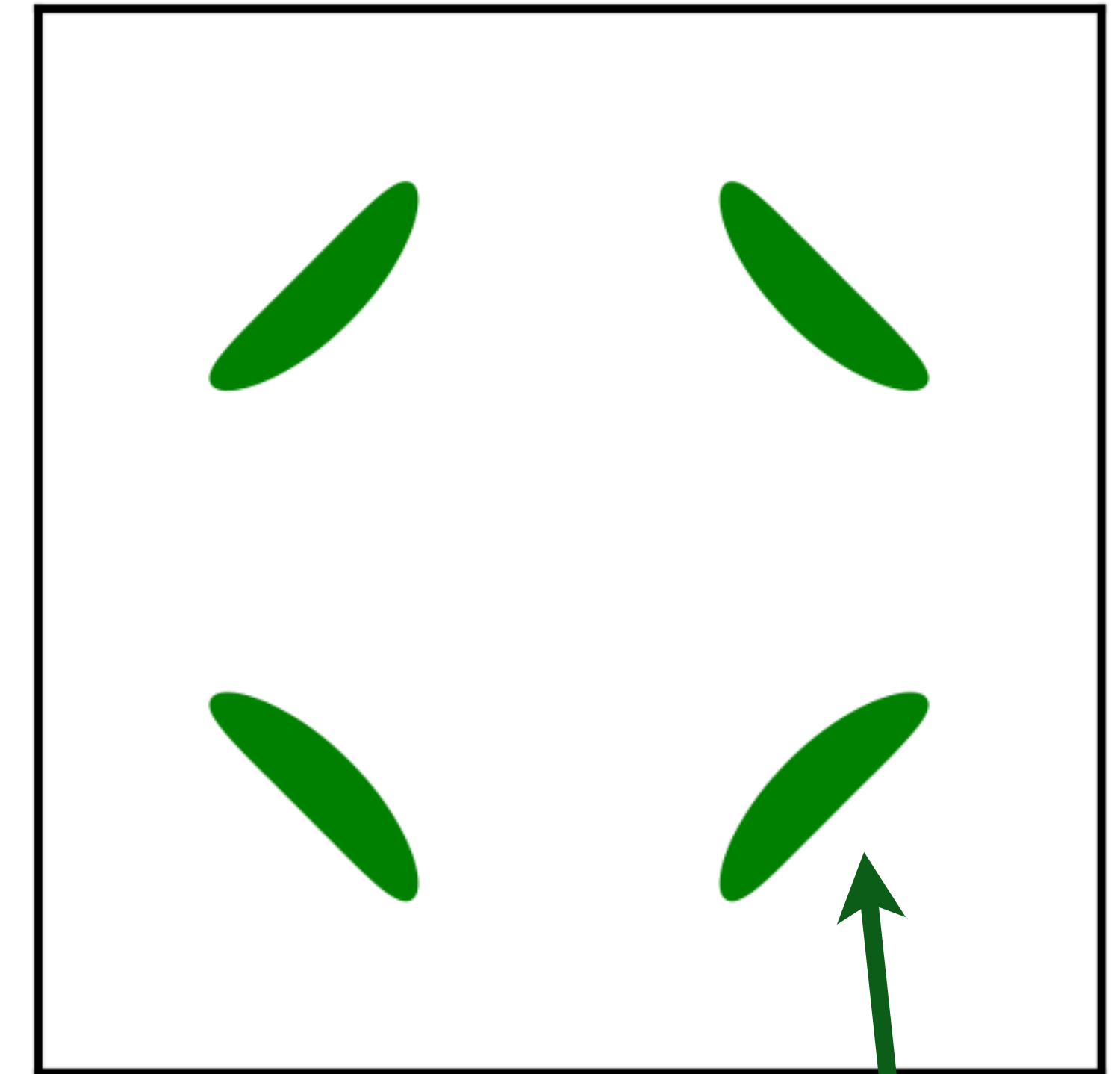
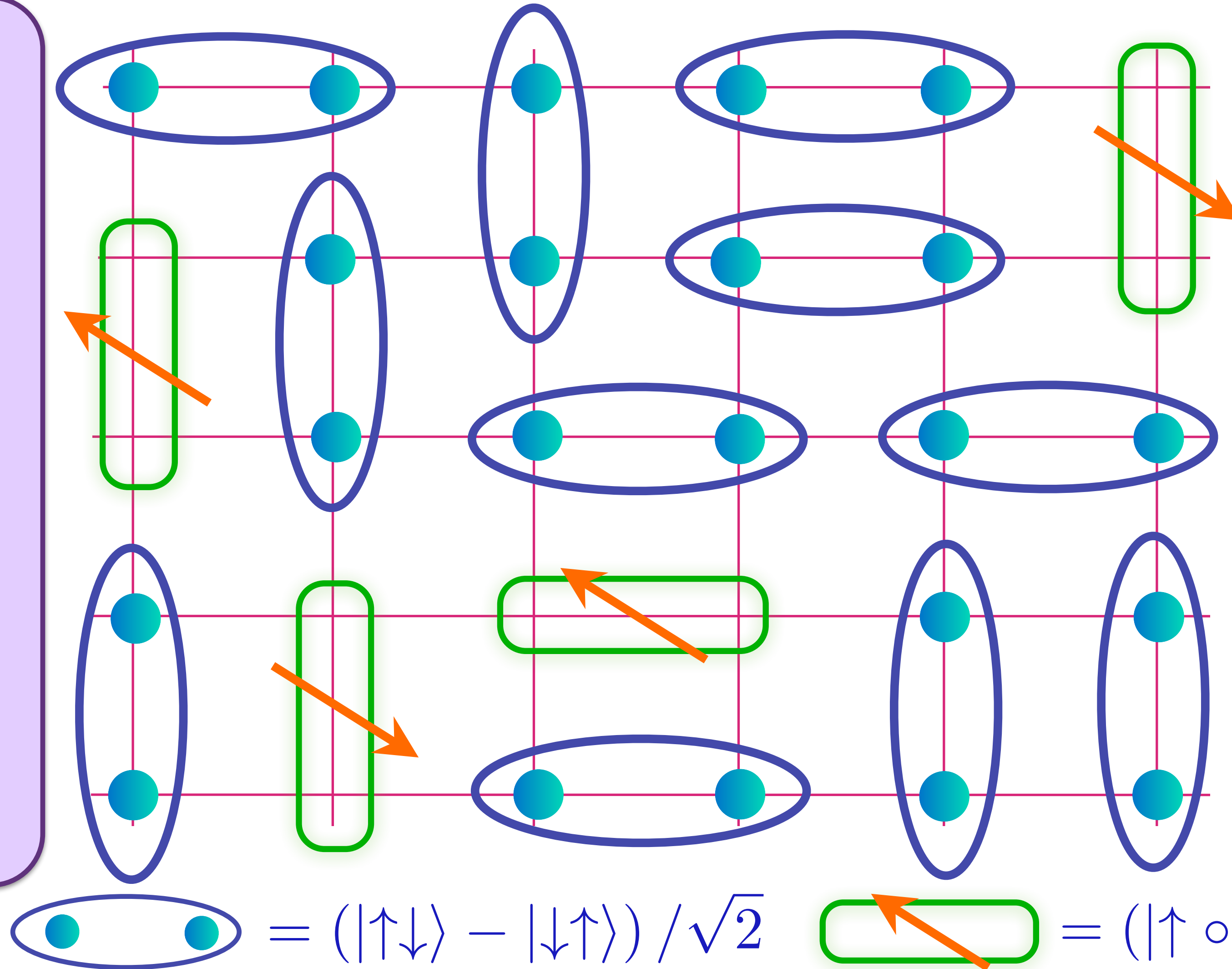
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

Doping an insulating antiferromagnet with holes of density p

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Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

Metal with density p of spin-1/2, charge $+e$ “holes” (or “magnetic polarons”) and charge 0 spin-1/2 “spinons”.



Area $p/8$

$$\begin{array}{|c|c|} \hline \bullet & \bullet \\ \hline \end{array} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2} \quad \begin{array}{|c|} \hline \bullet \\ \hline \end{array} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

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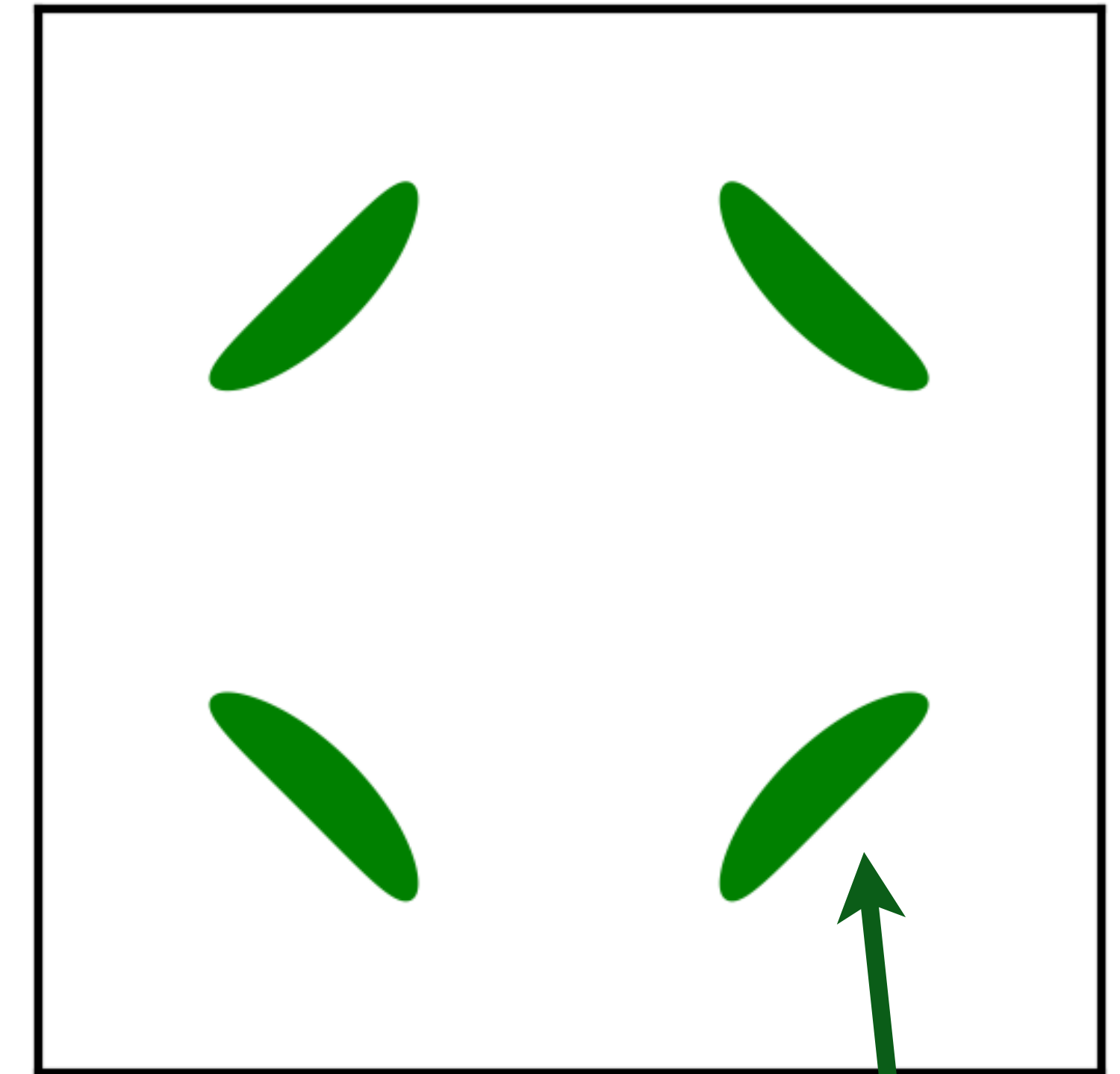
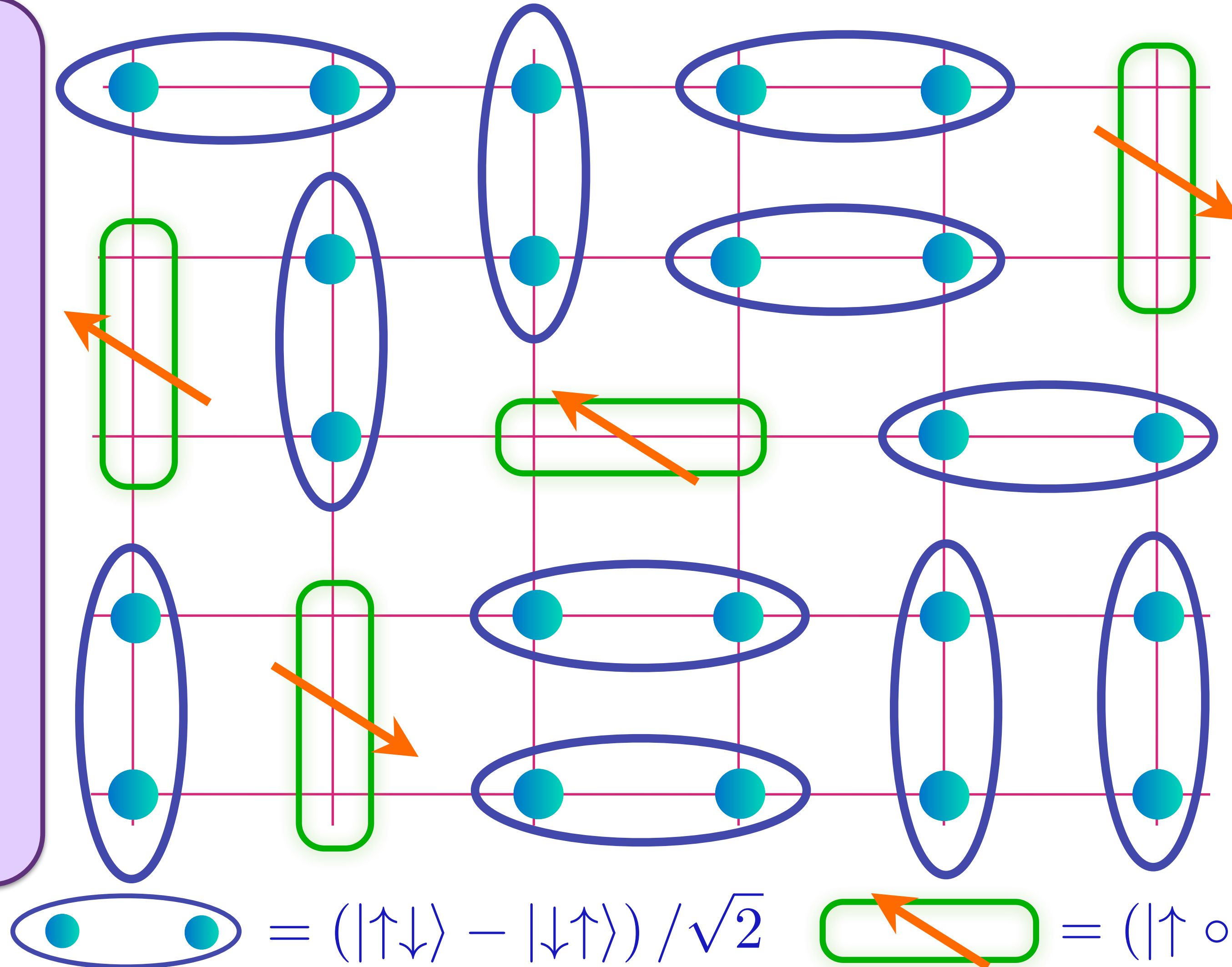
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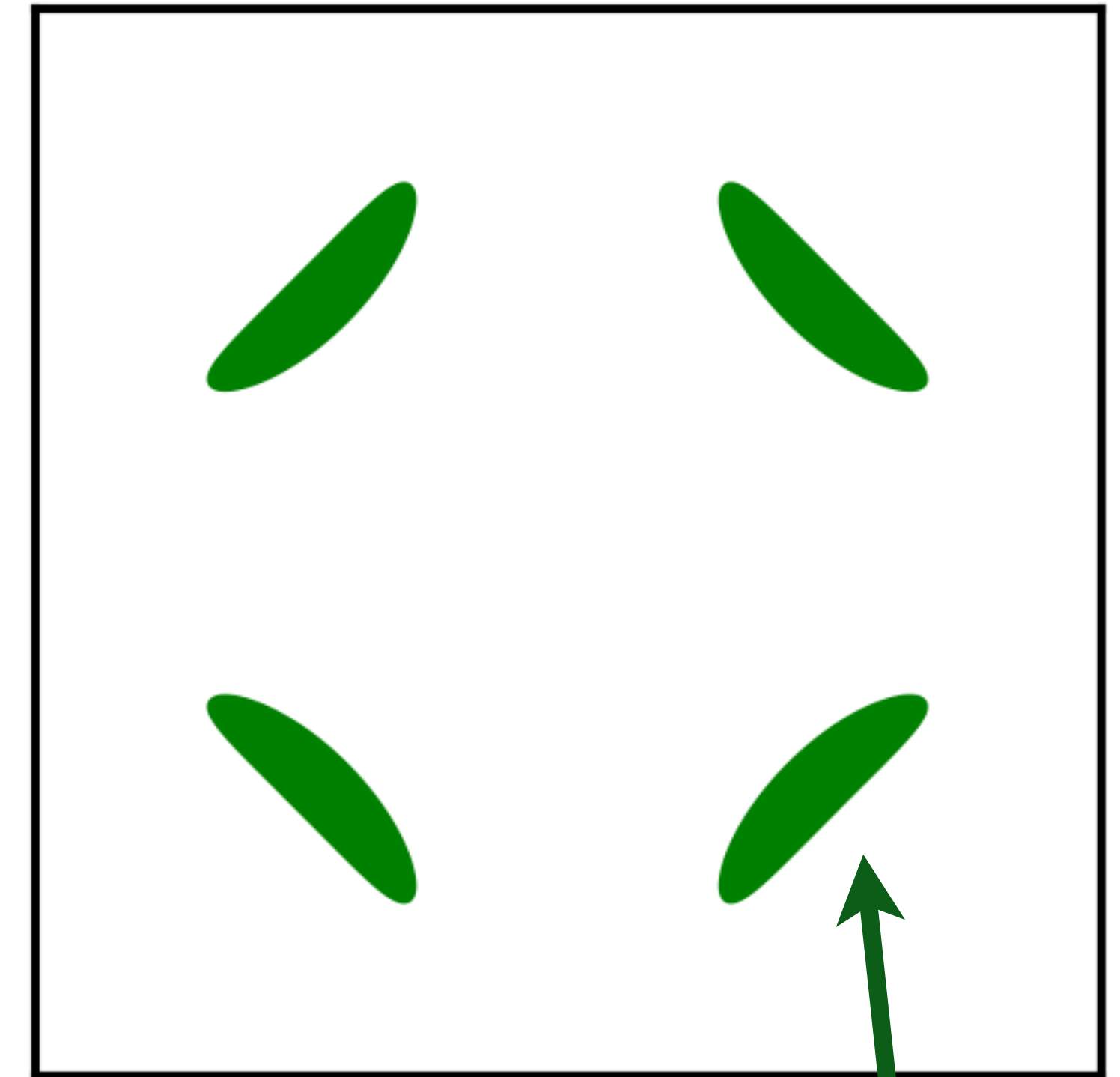
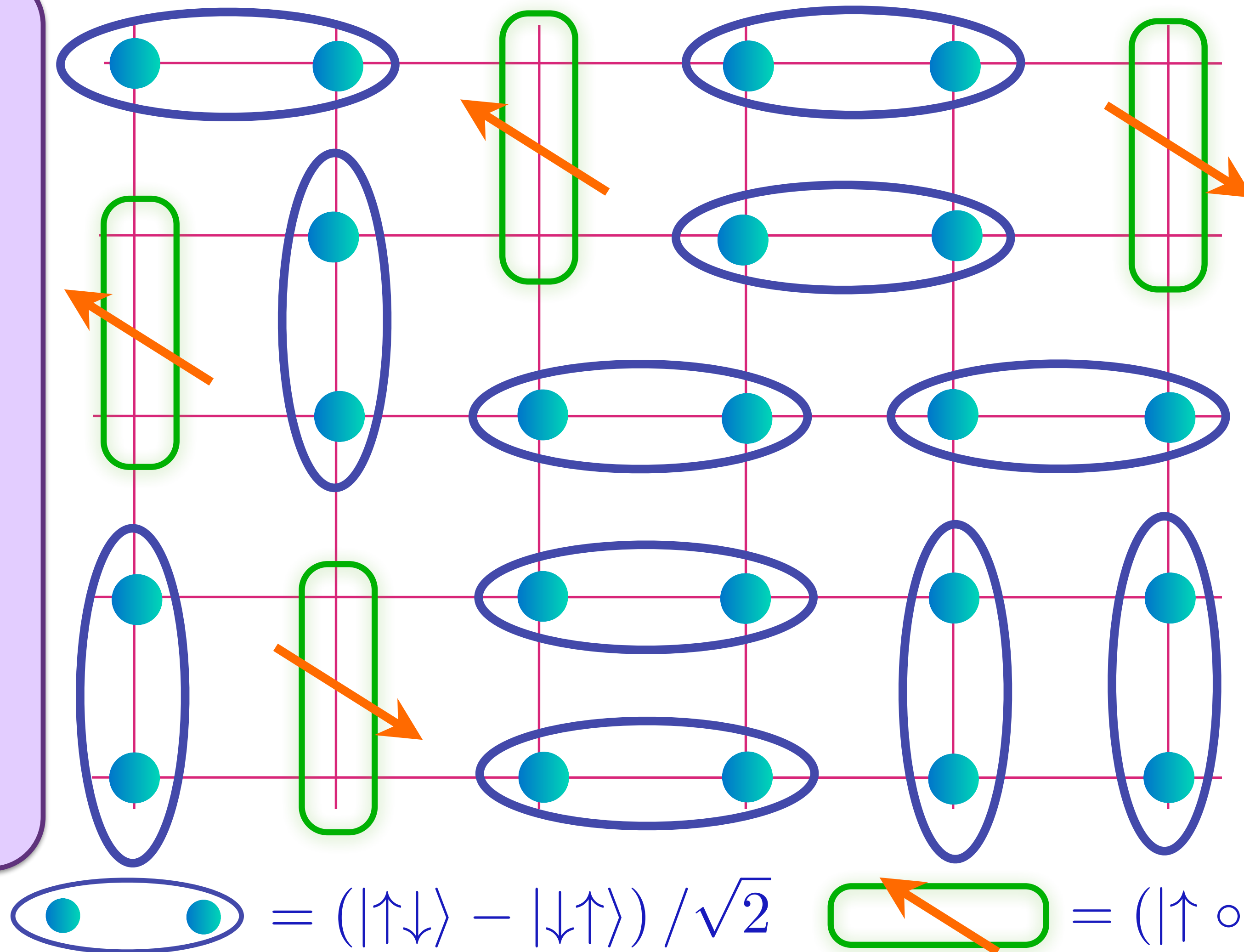
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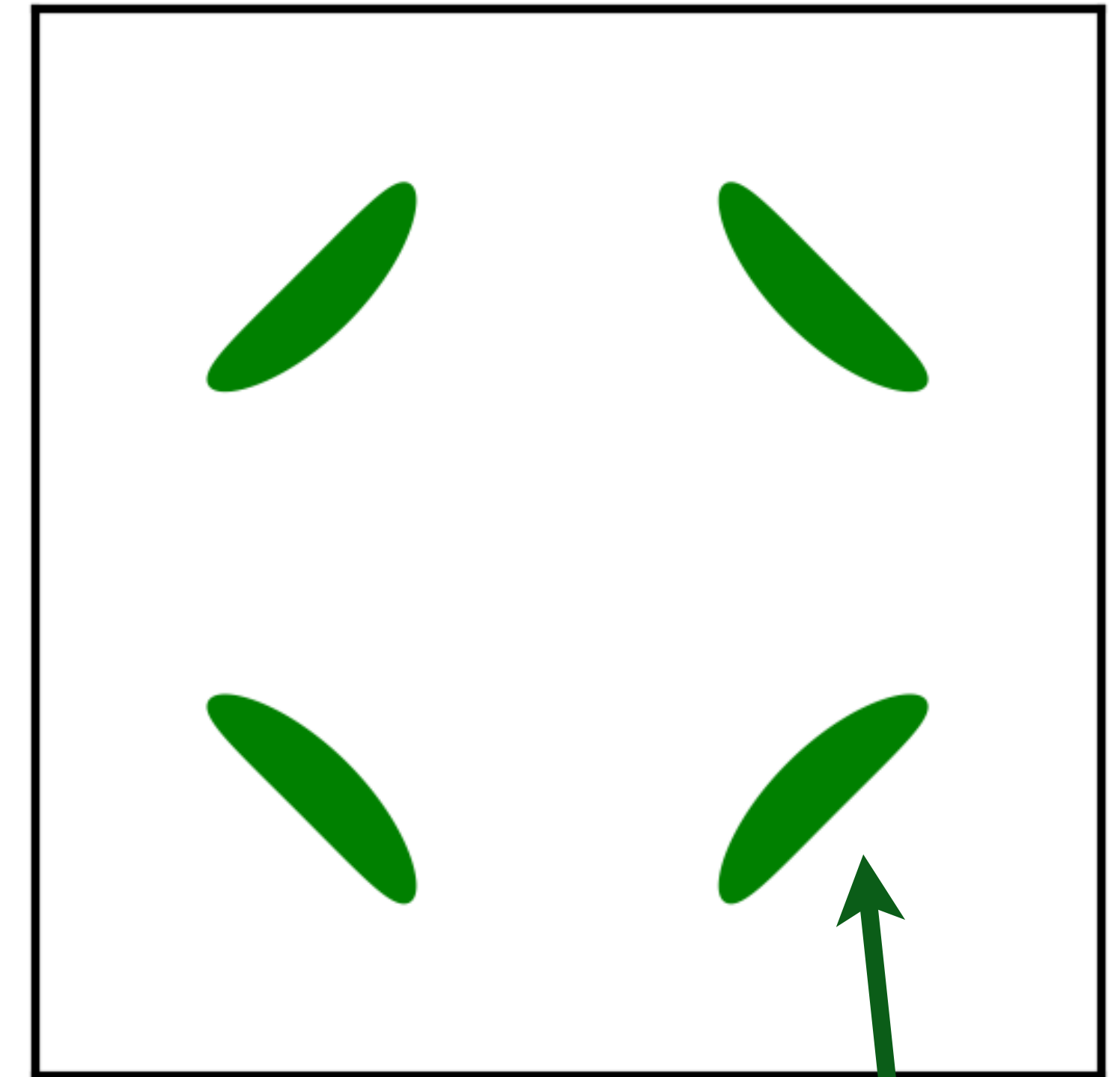
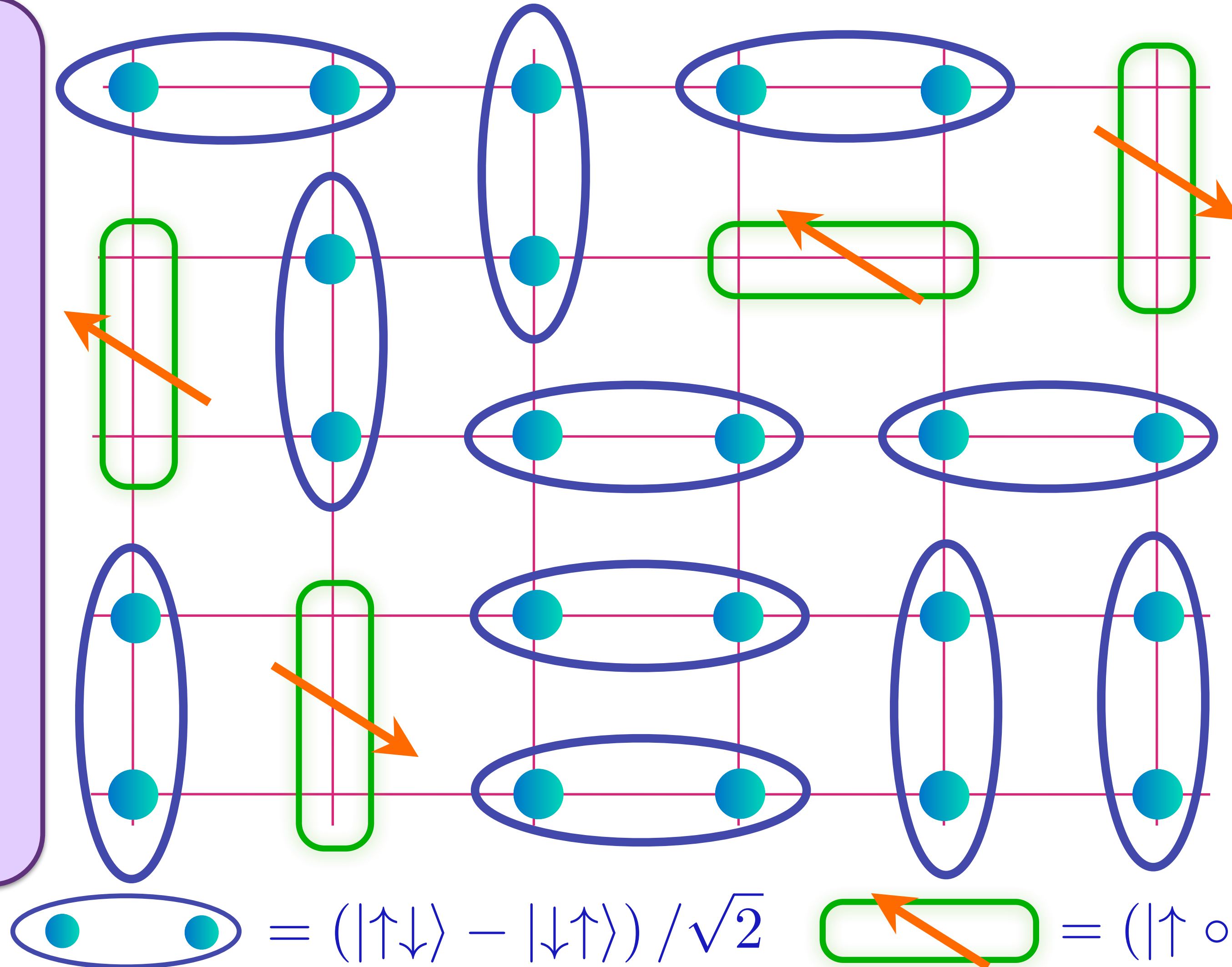
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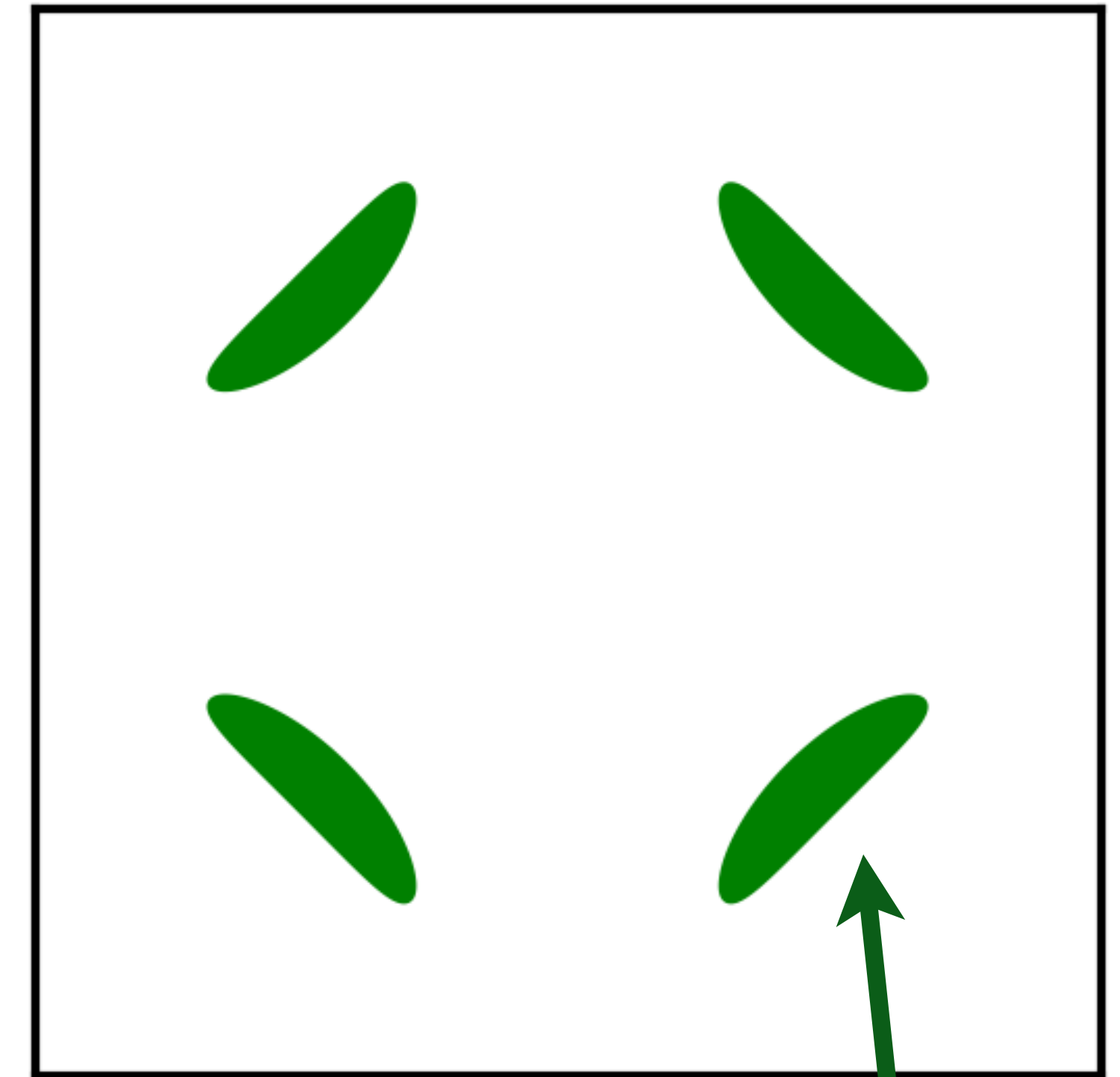
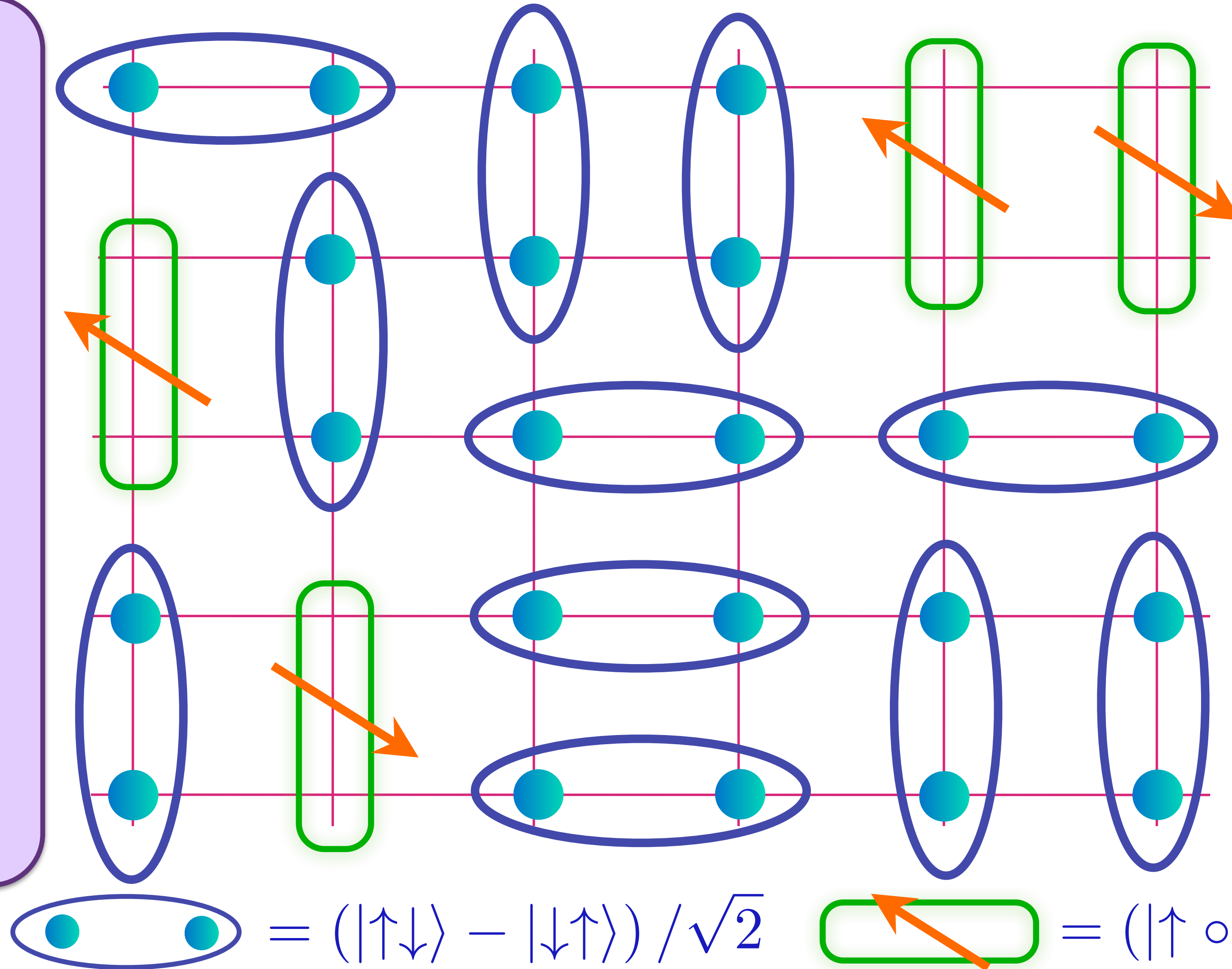
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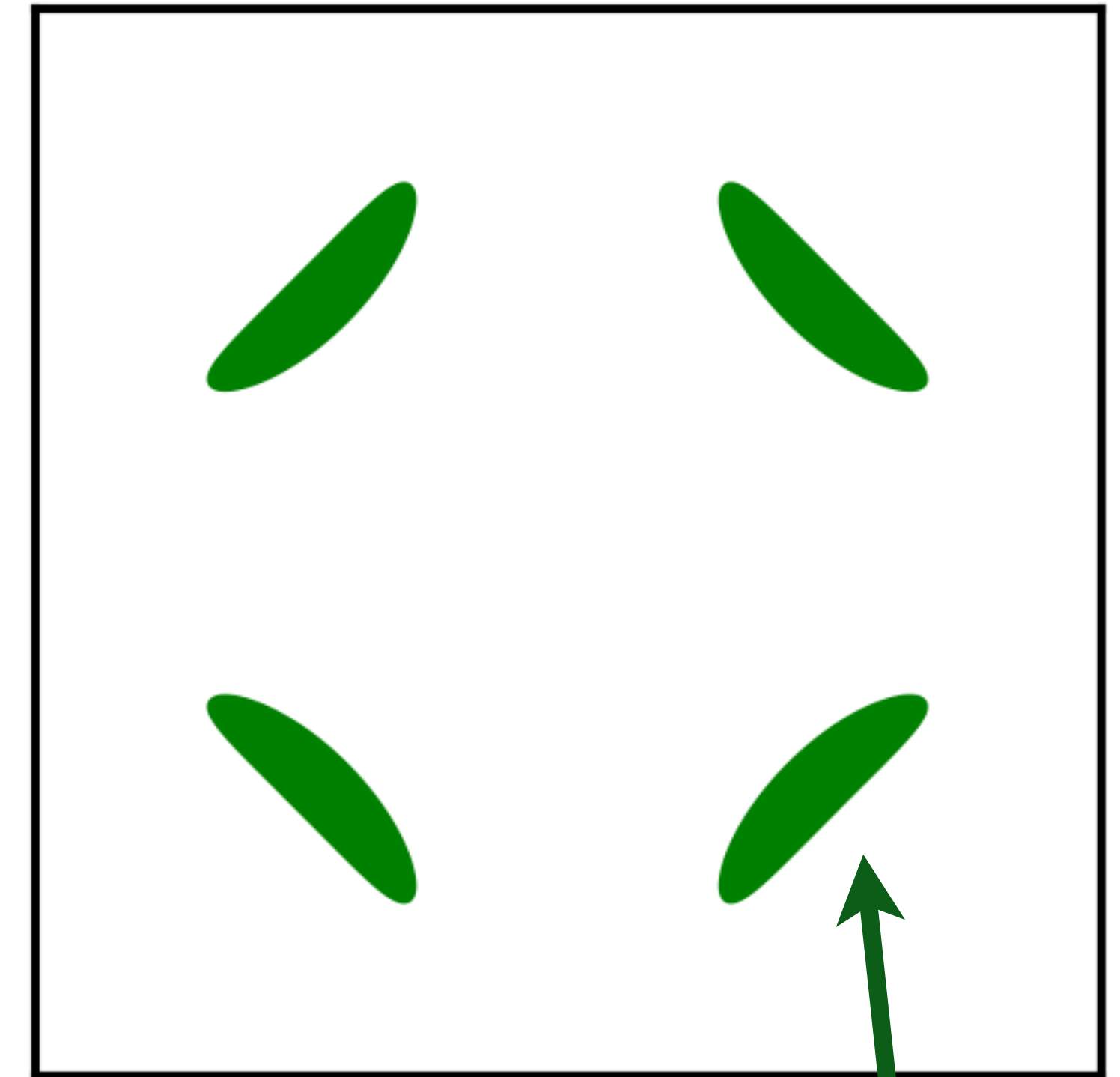
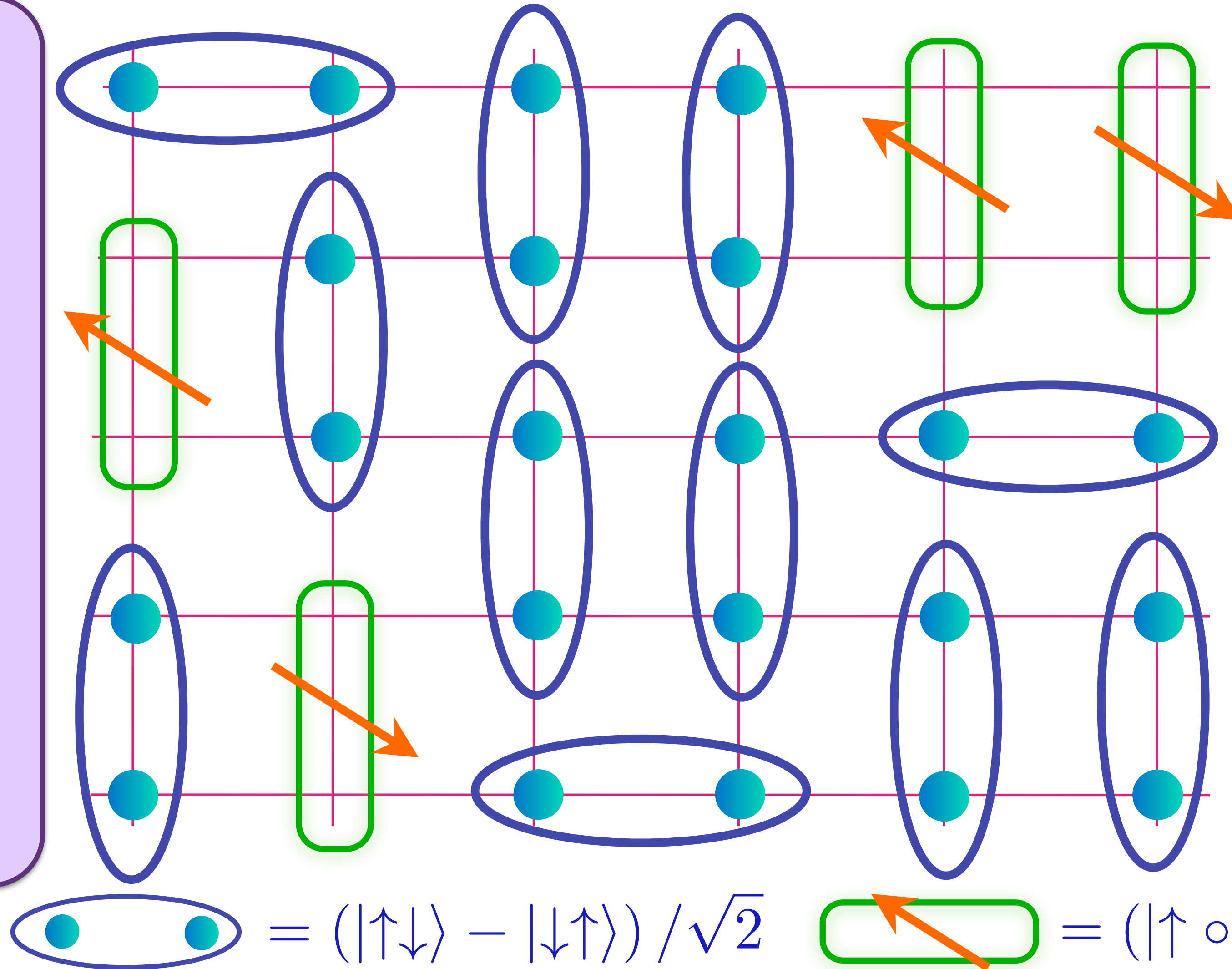
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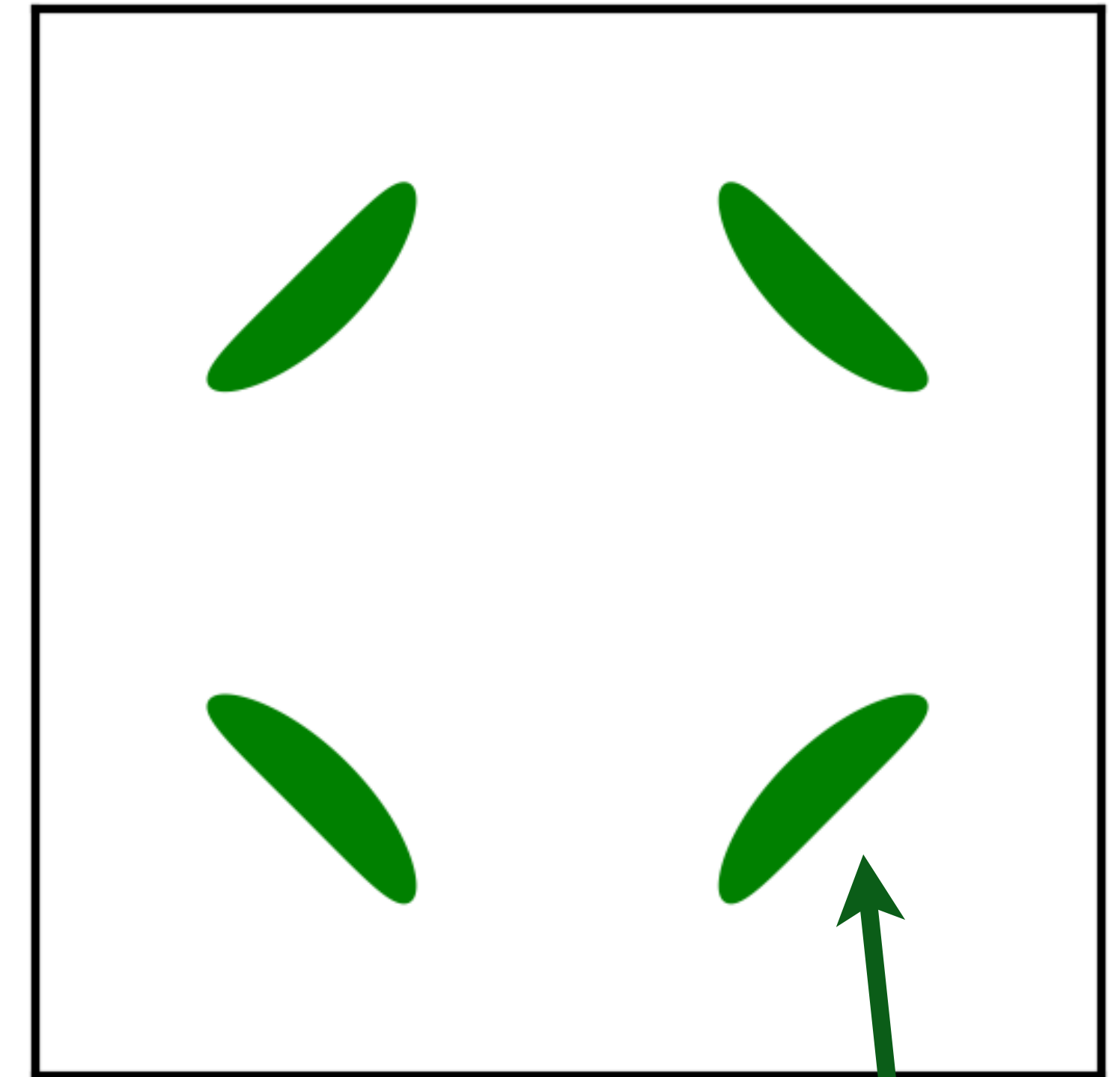
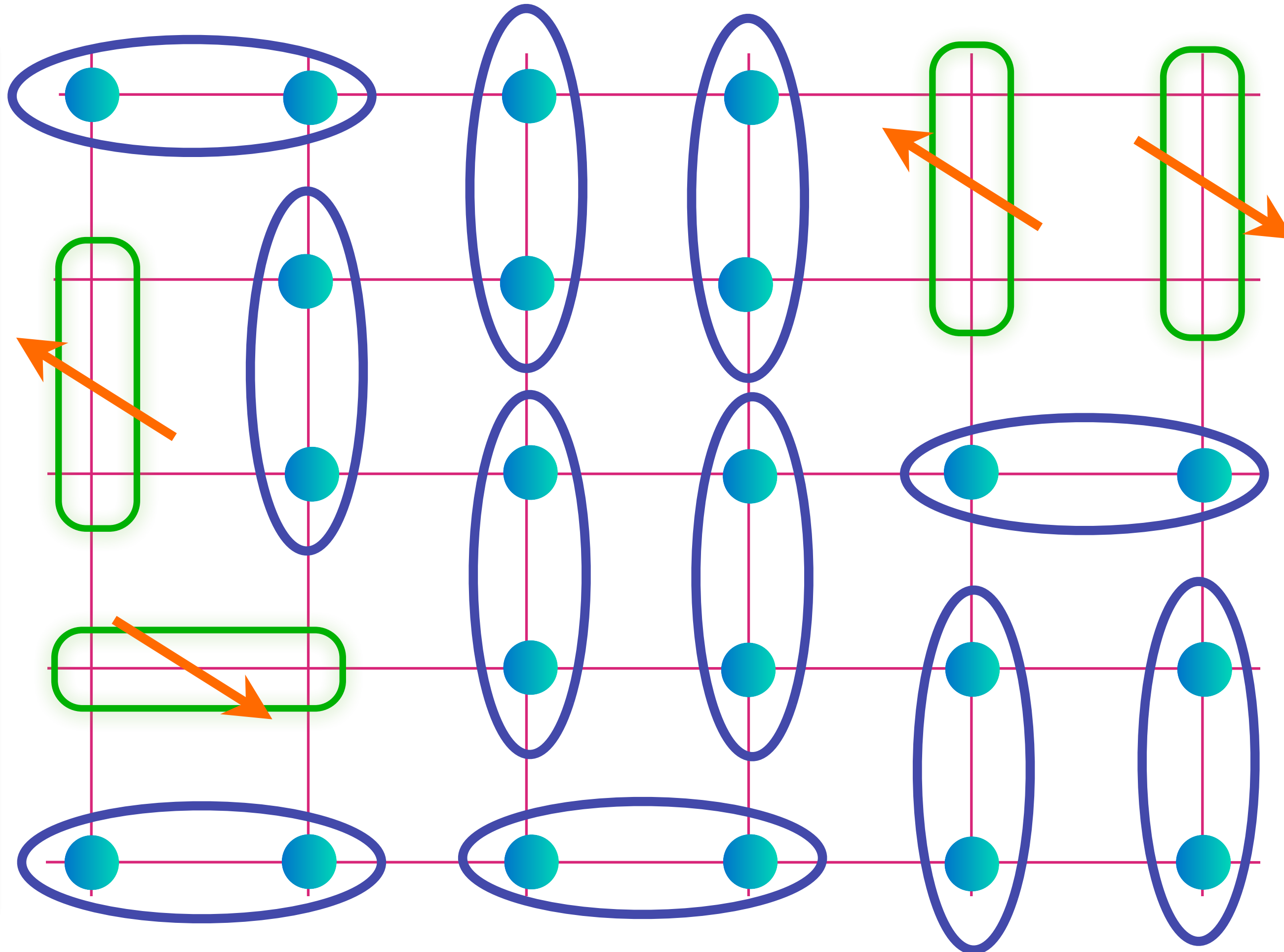
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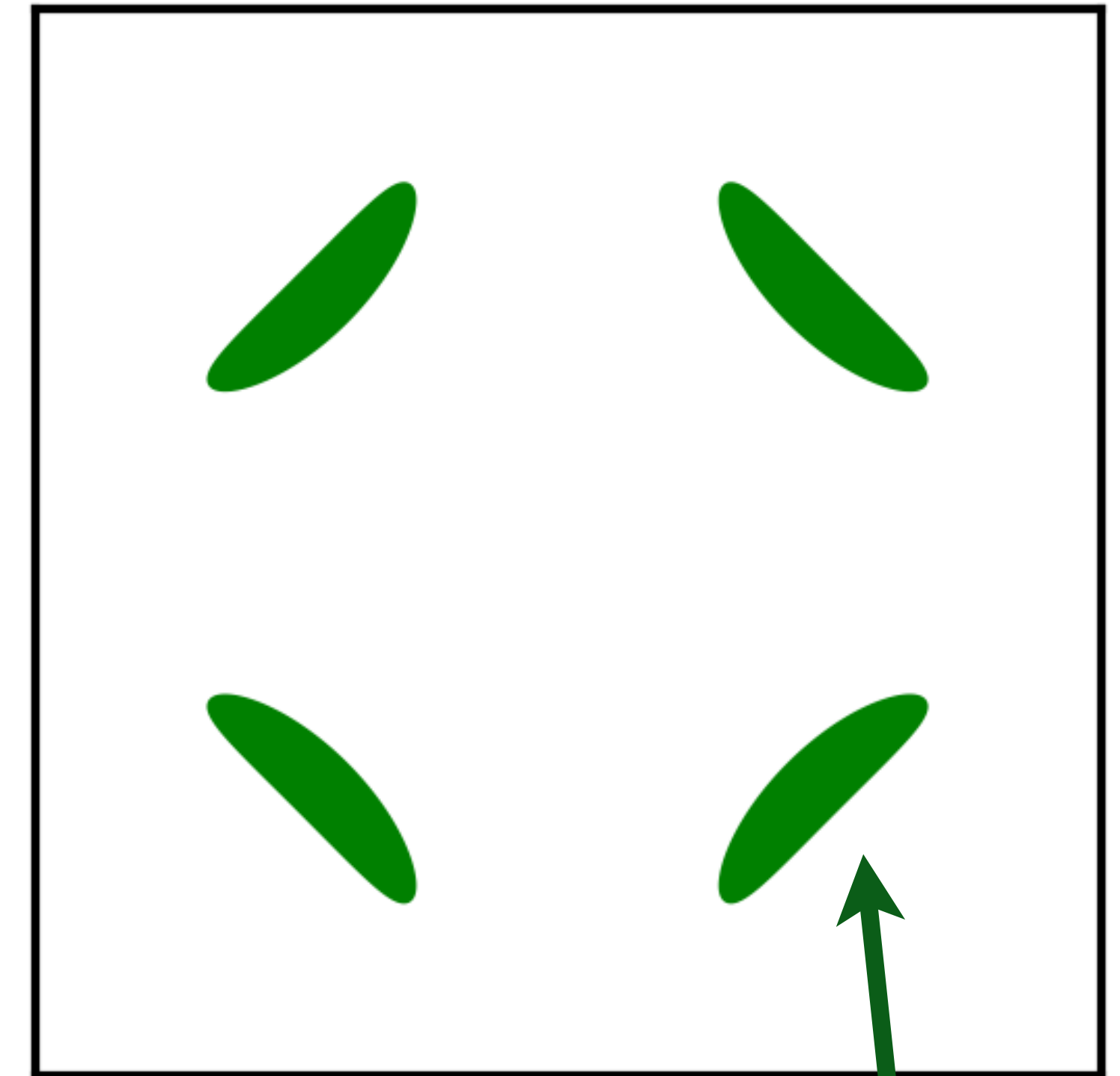
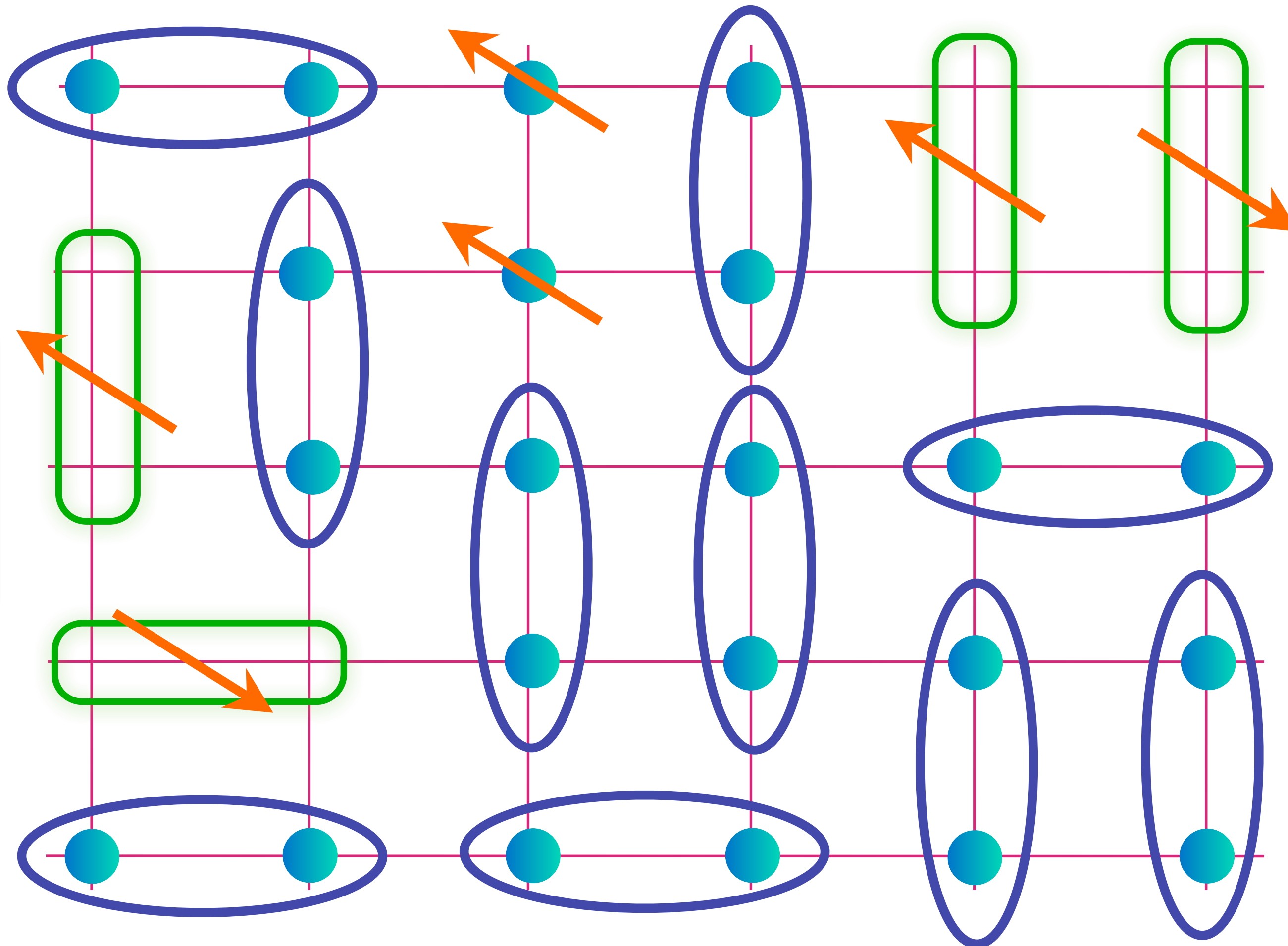
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Doping an insulating antiferromagnet with holes of density p

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The FL* state retains the spinon excitations



$$\begin{array}{|c|c|} \hline \bullet & \bullet \\ \hline \end{array} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2} \quad \begin{array}{|c|} \hline \text{orange arrow} \\ \hline \end{array} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

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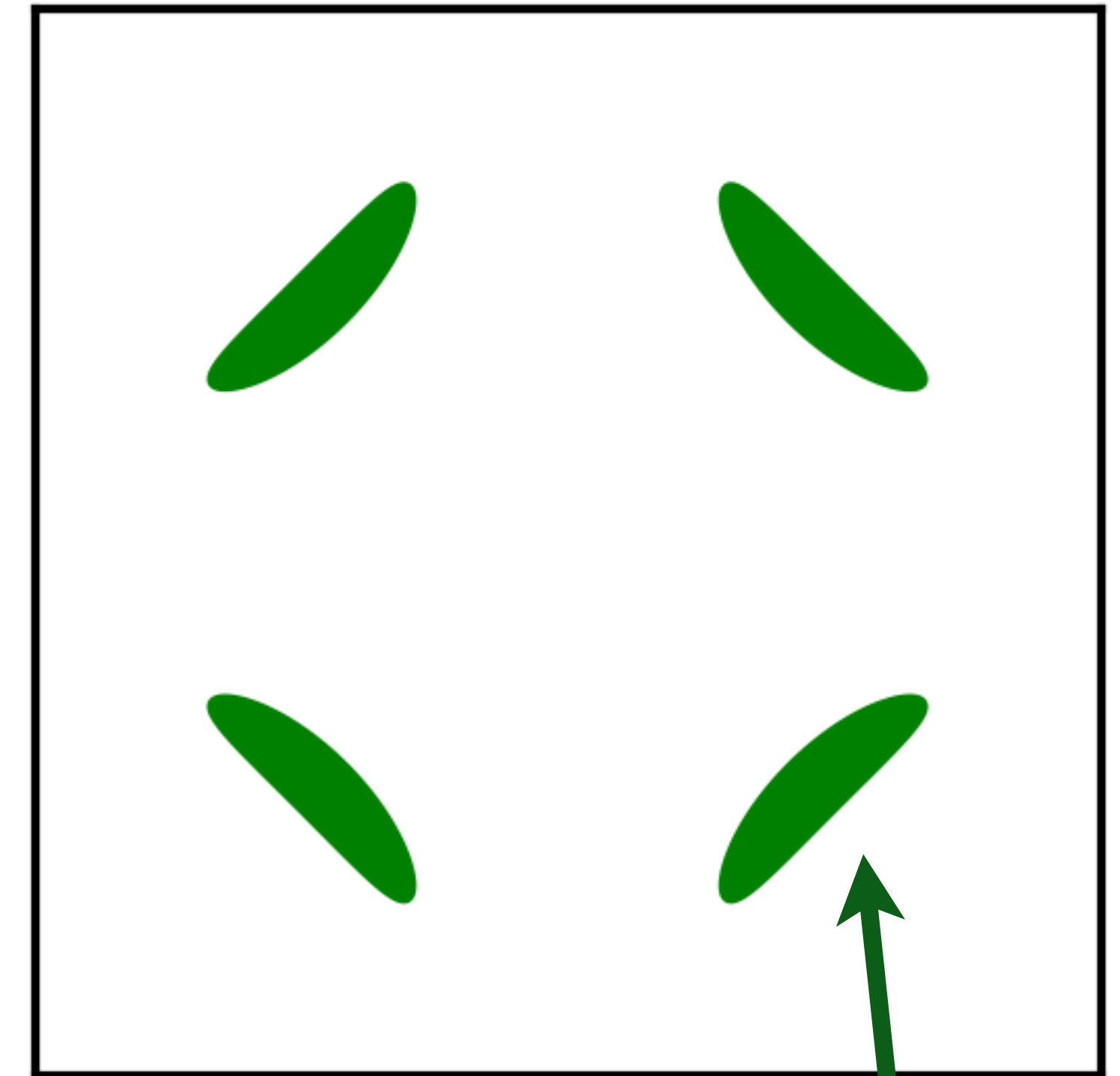
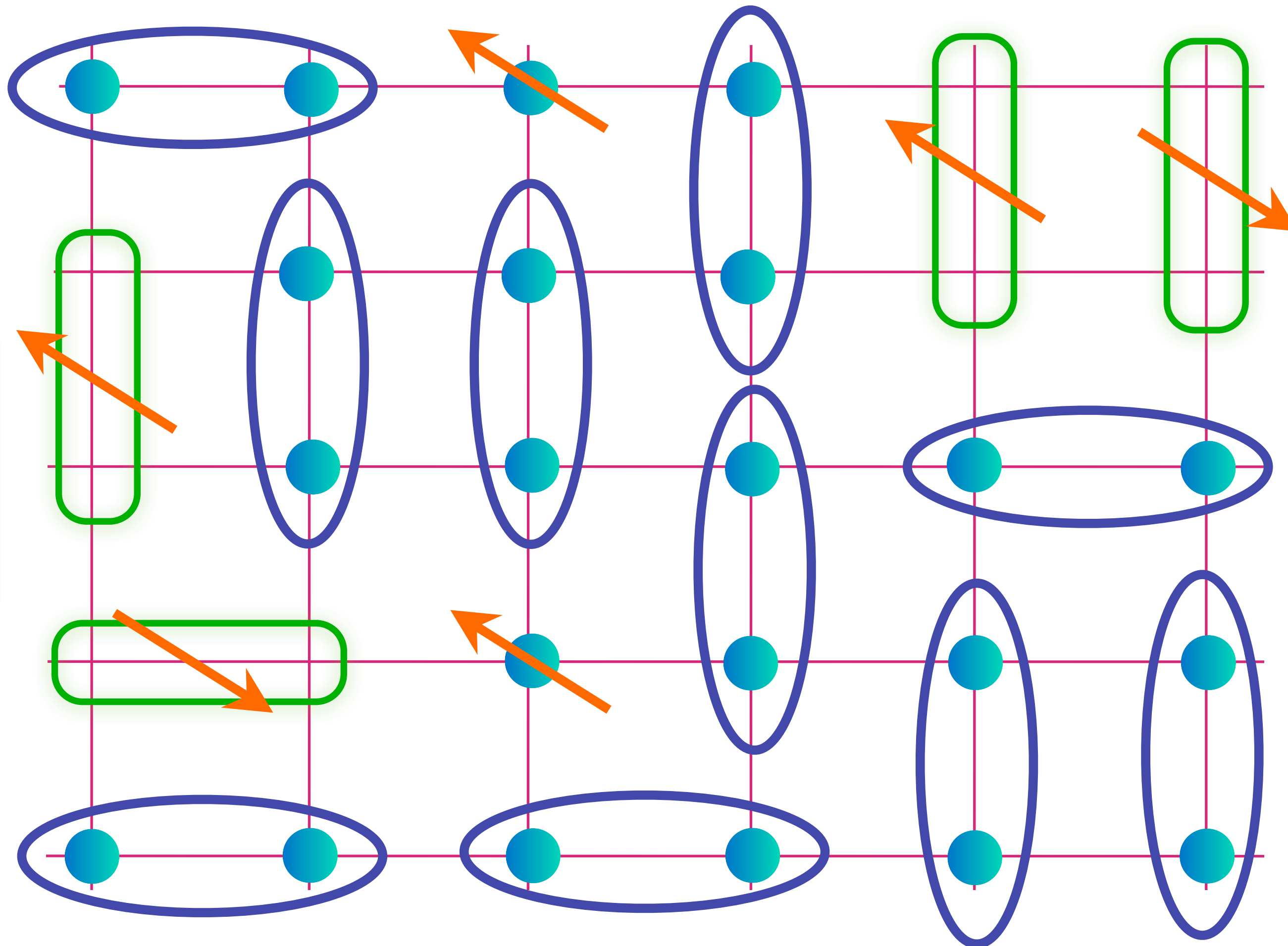
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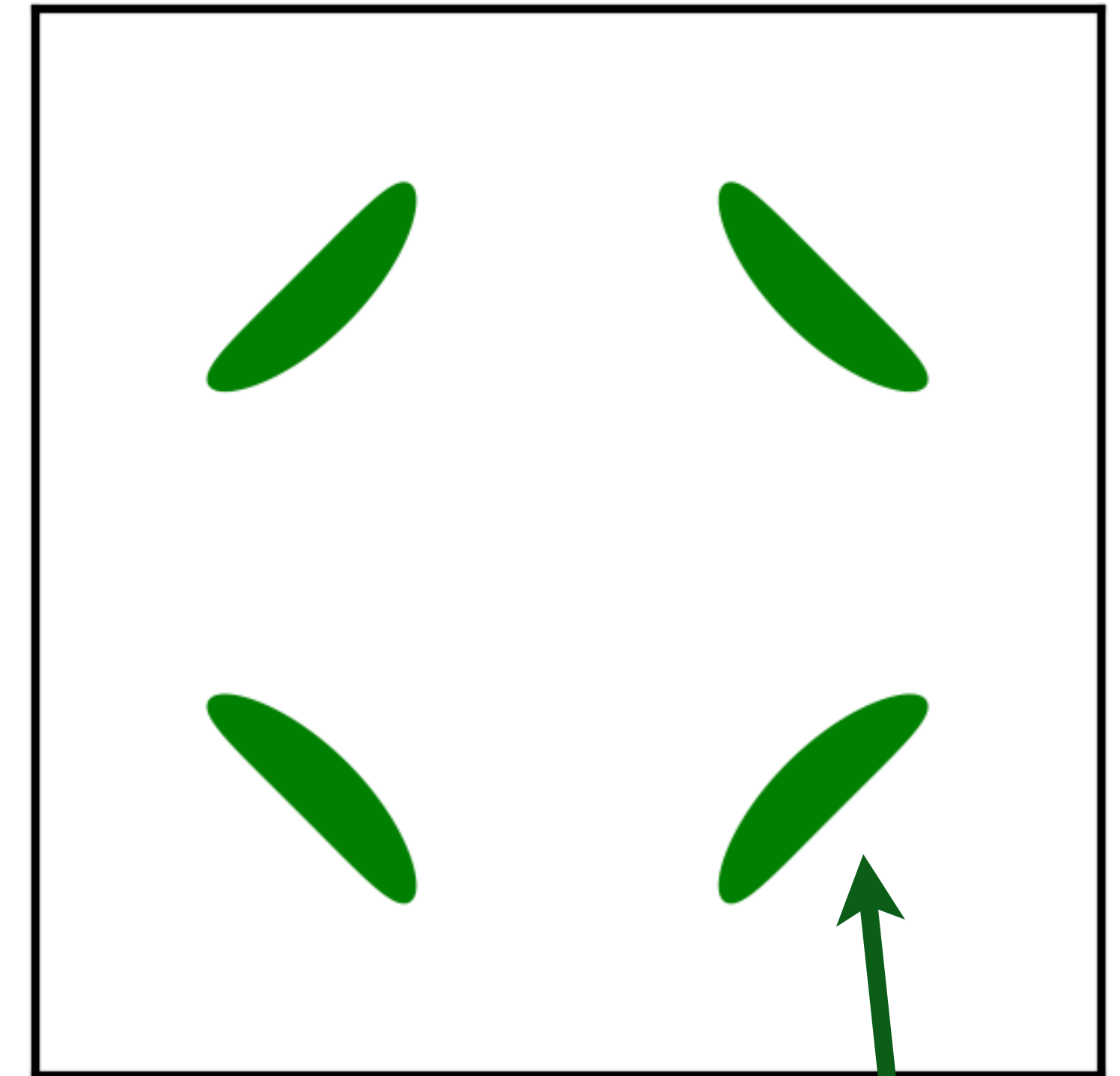
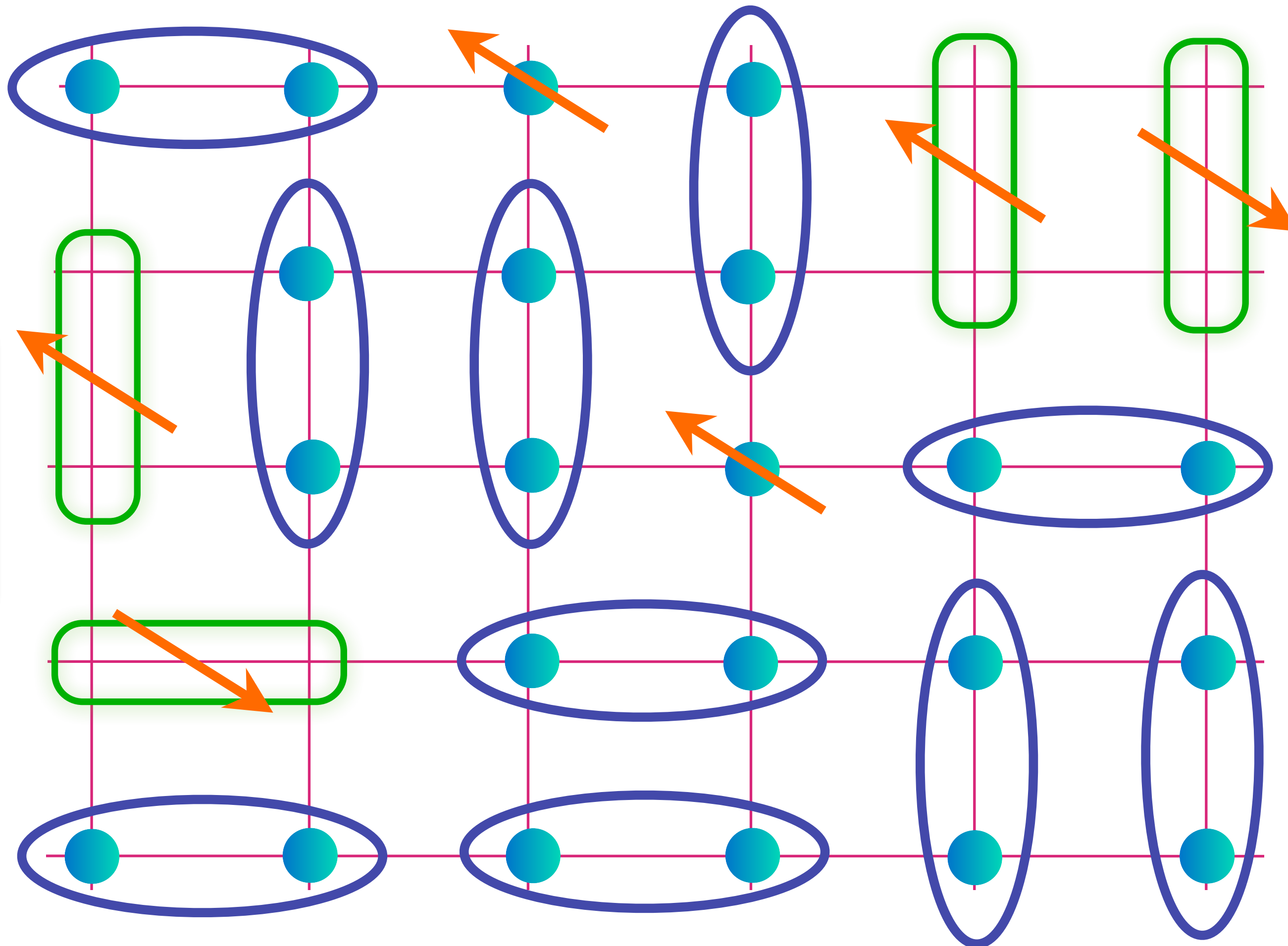
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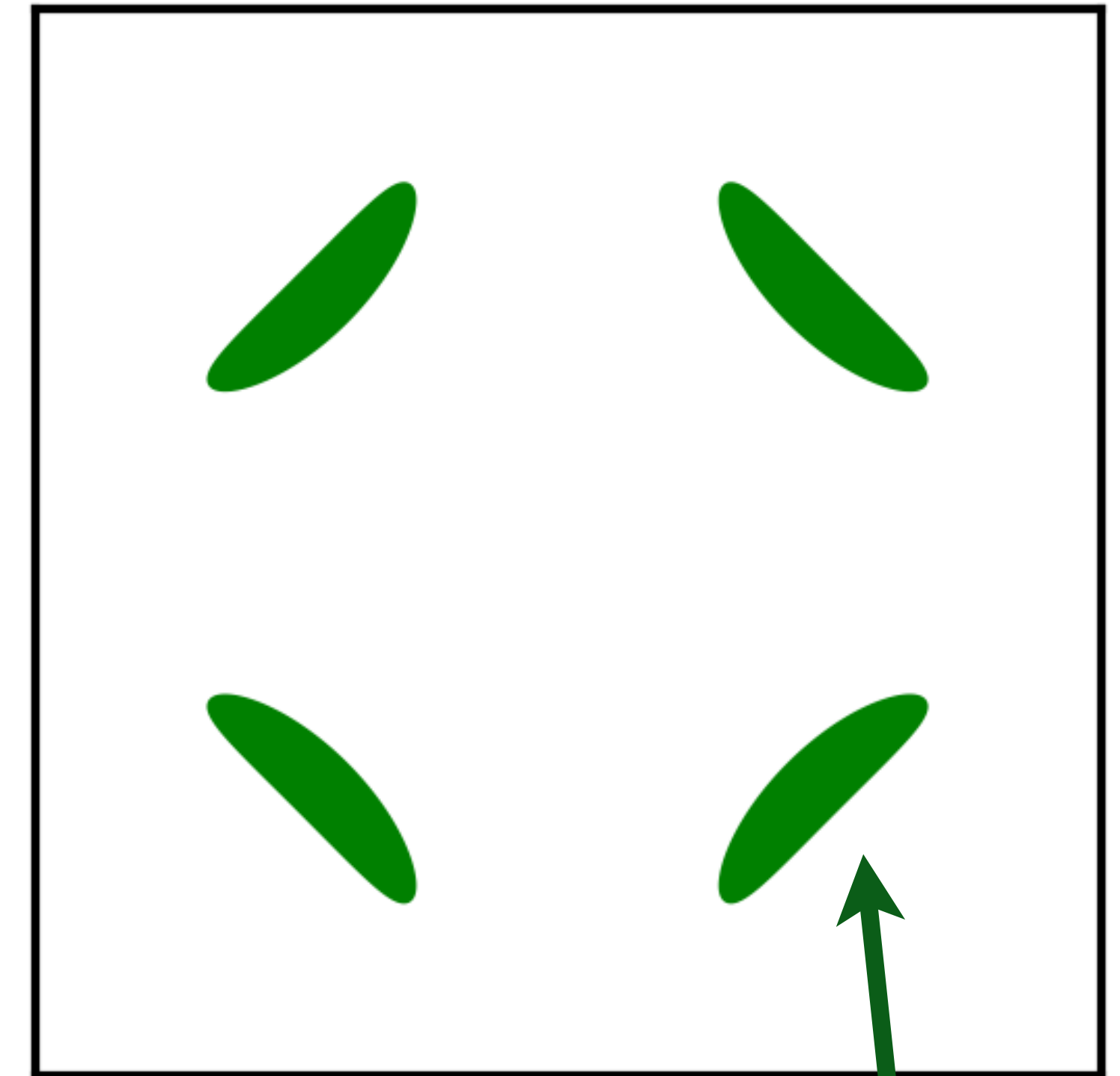
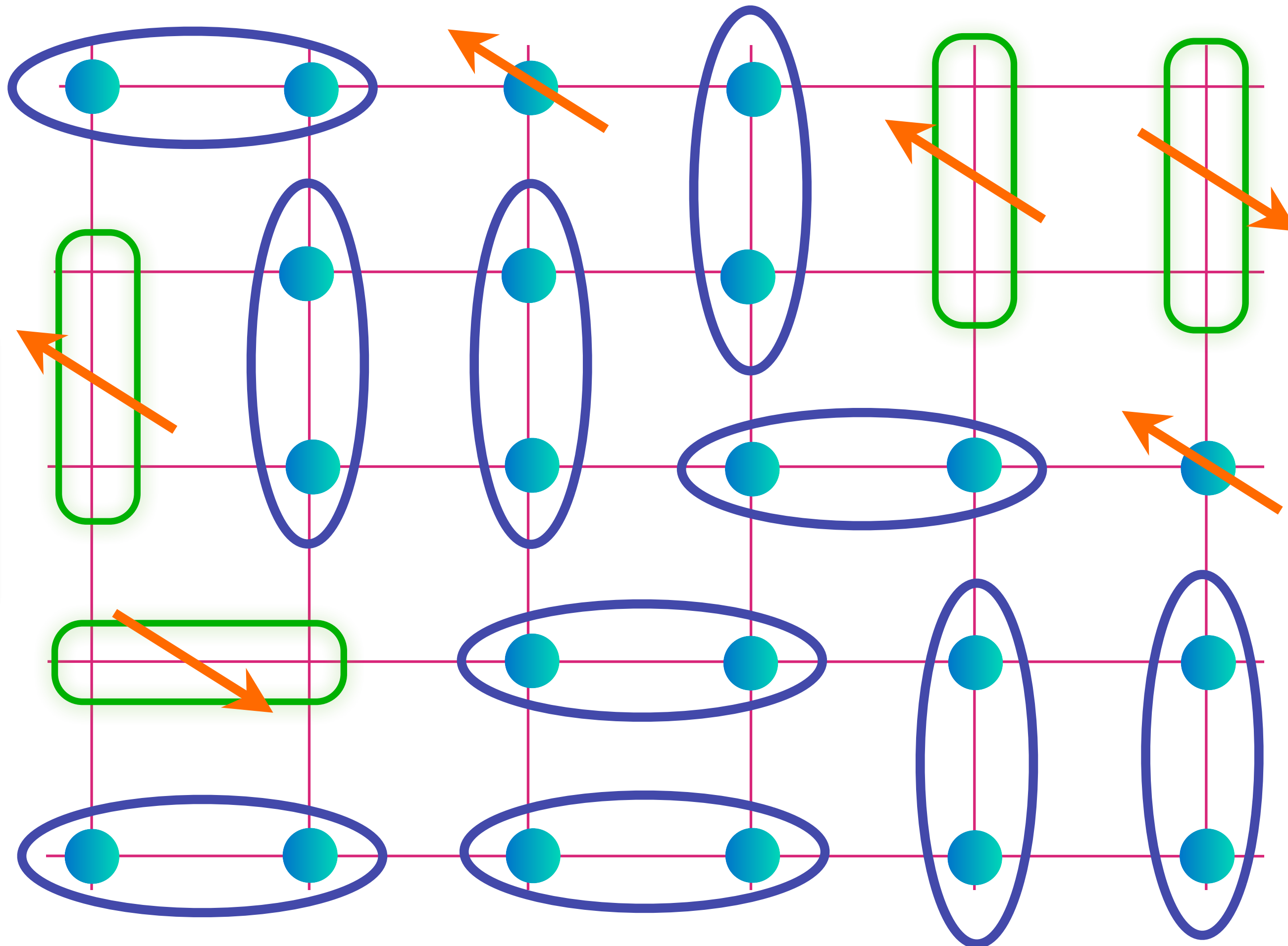
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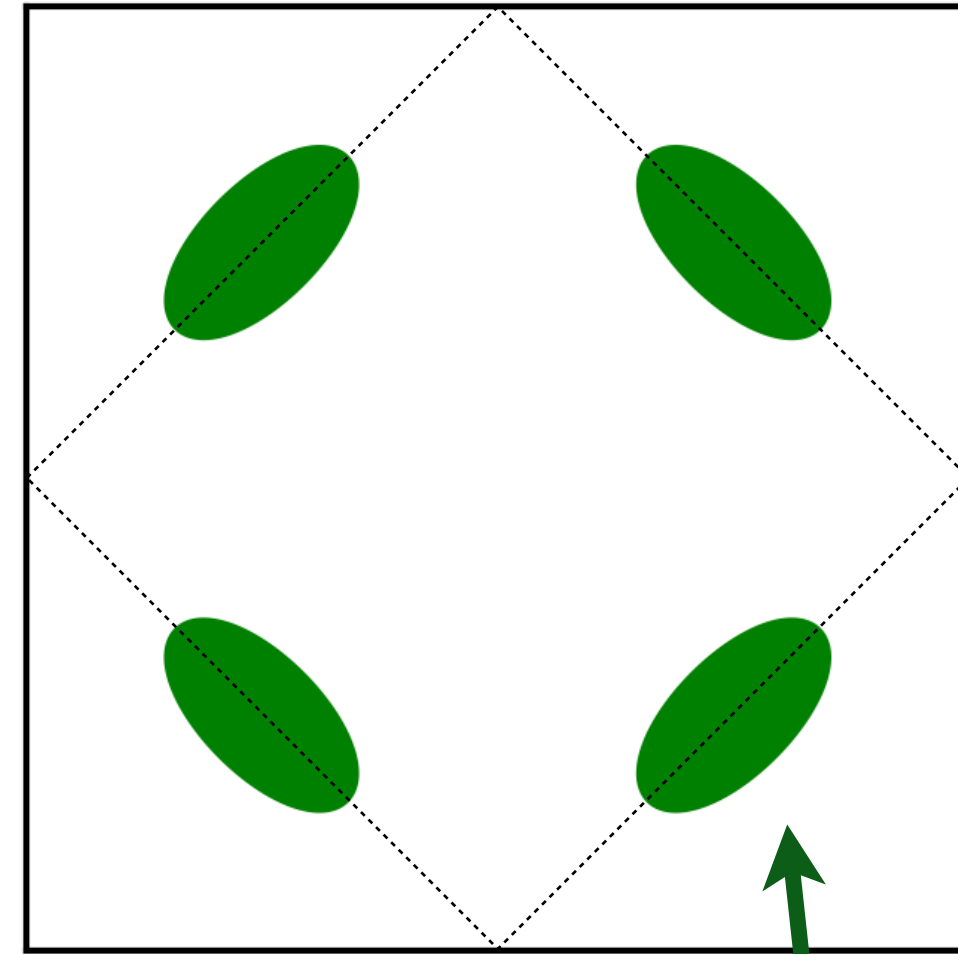
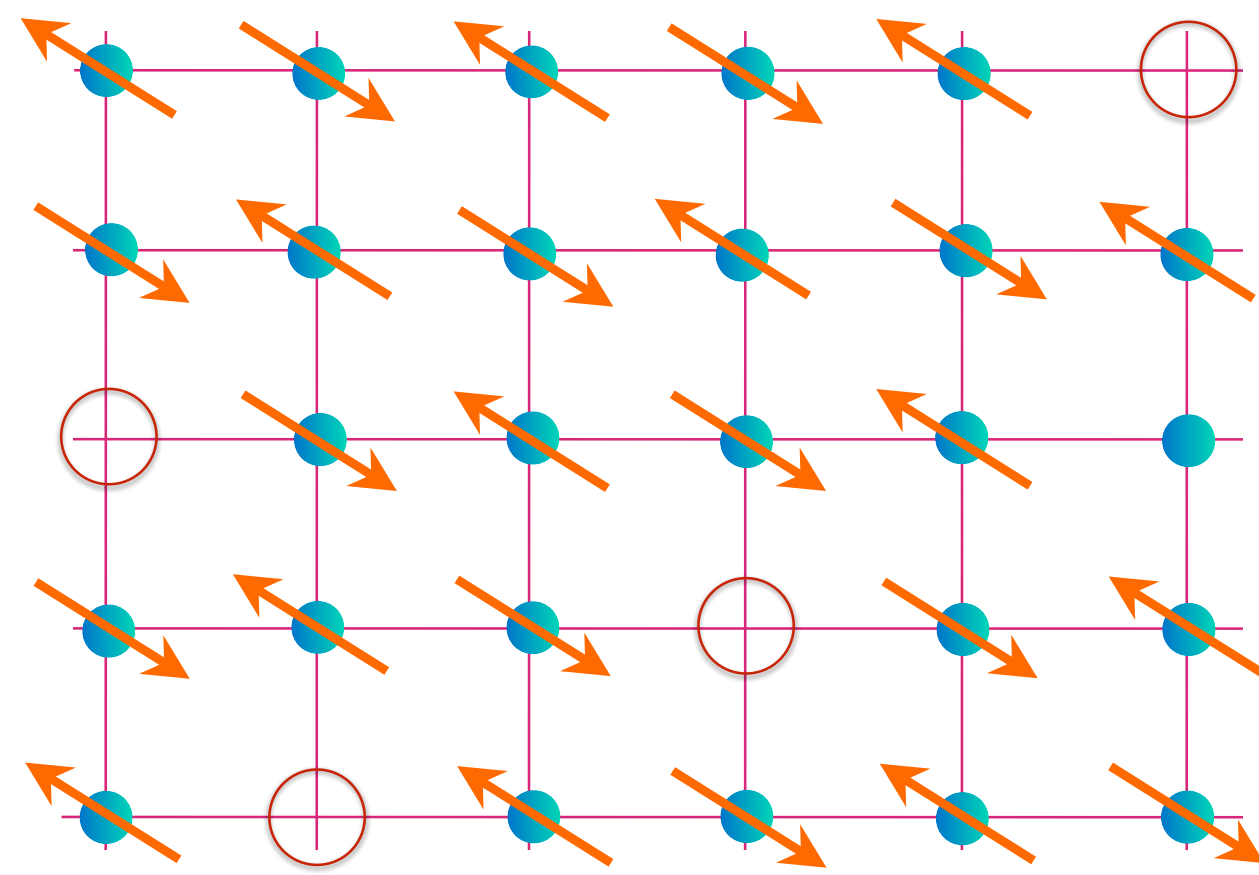
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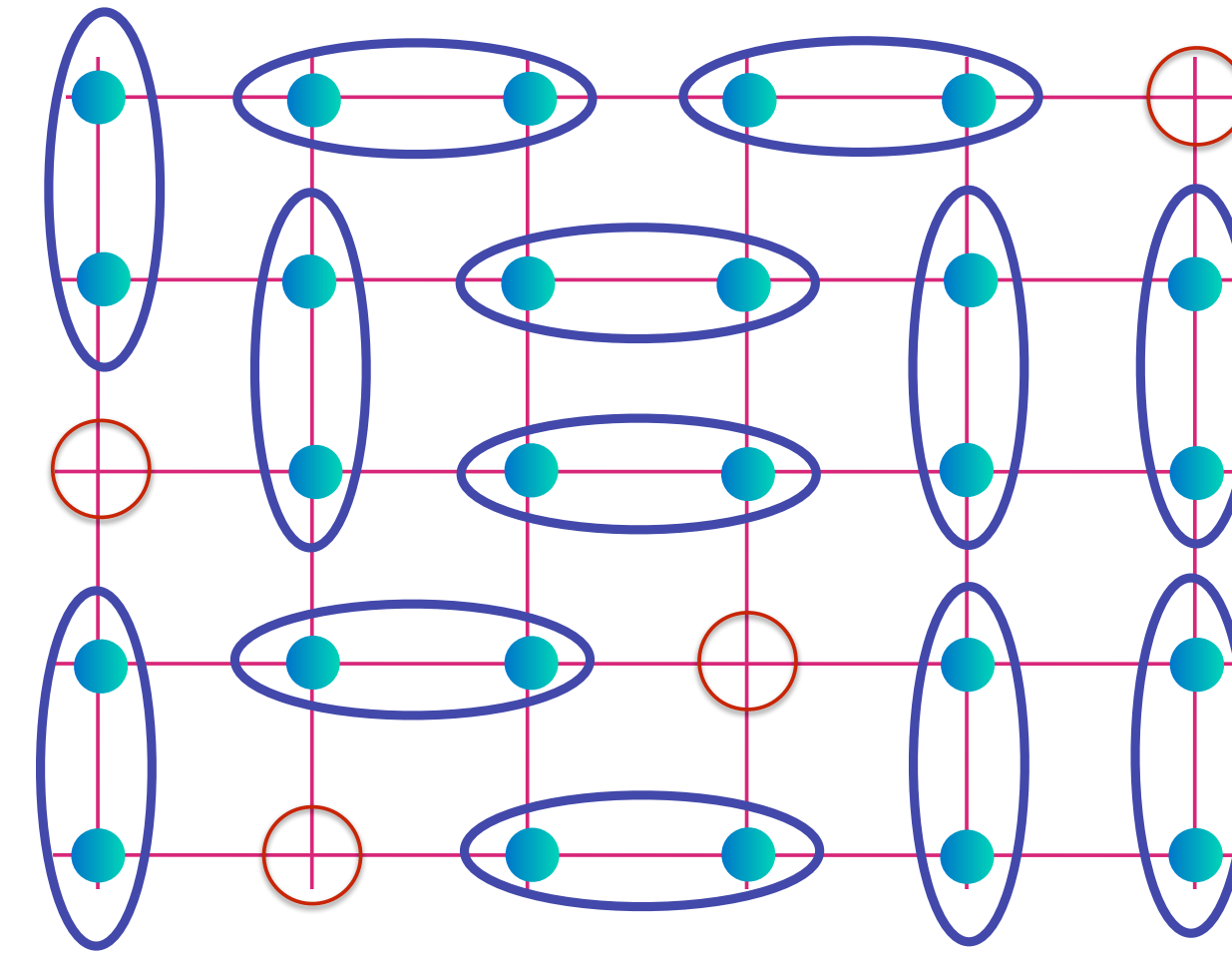
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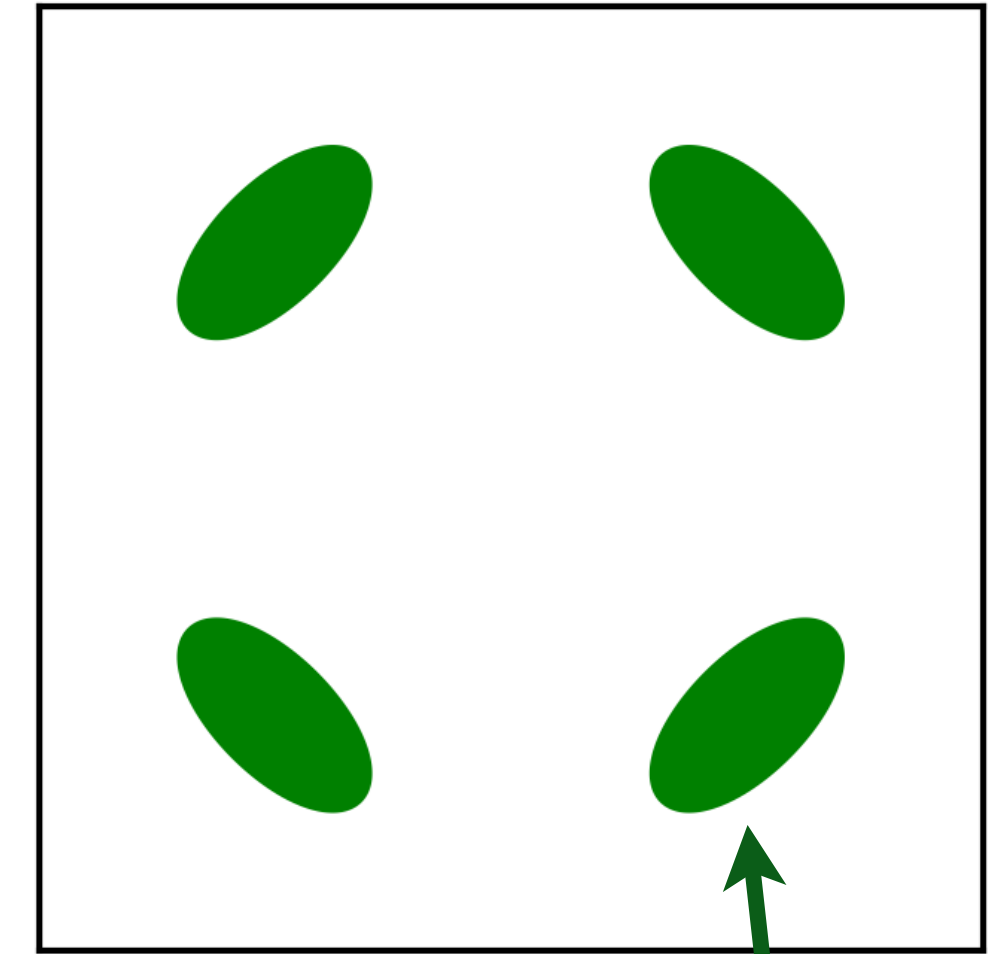
Area $p/4$

AF metal and SDW fluctuation

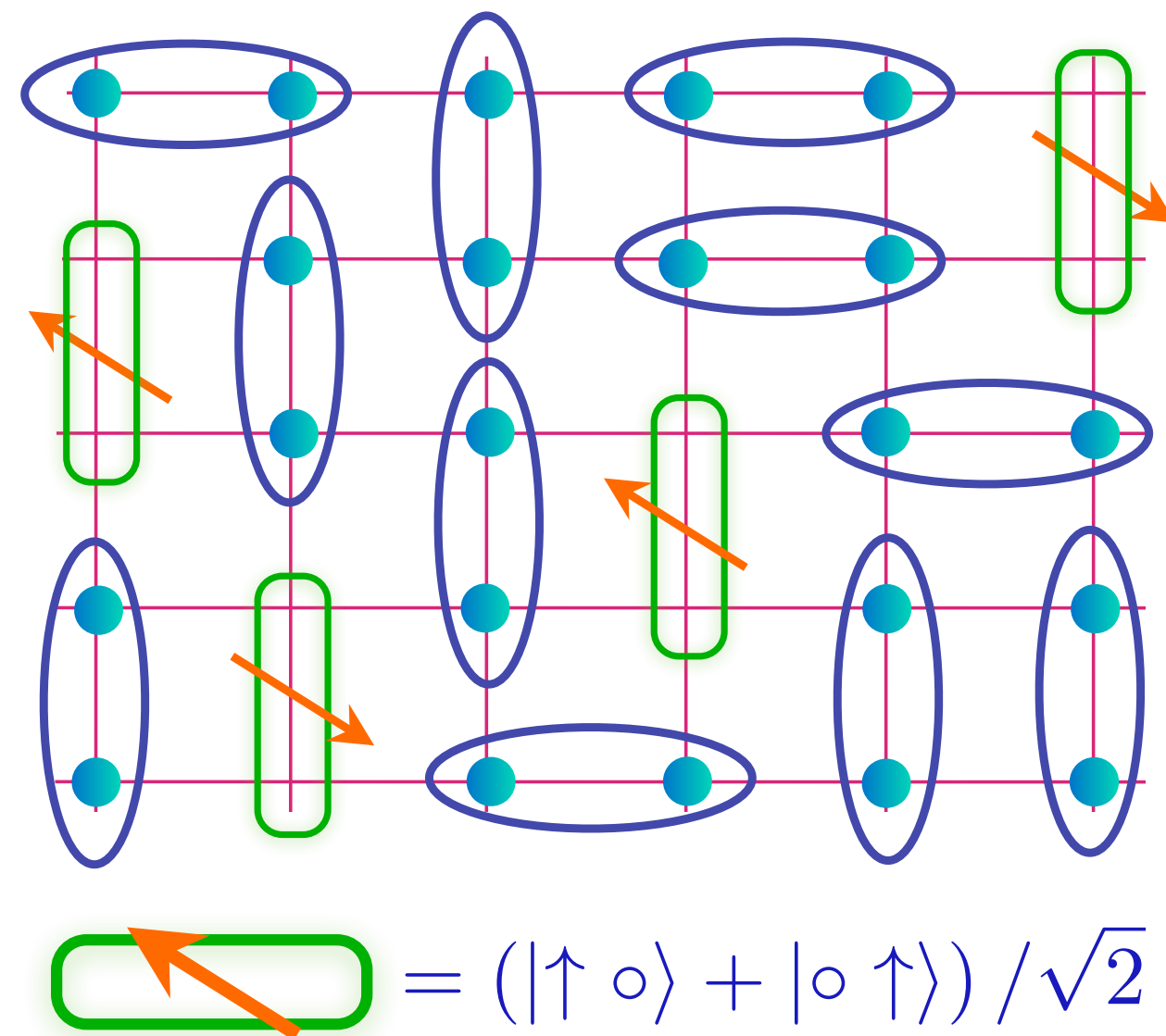


$$\text{Holon} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

Holon metal

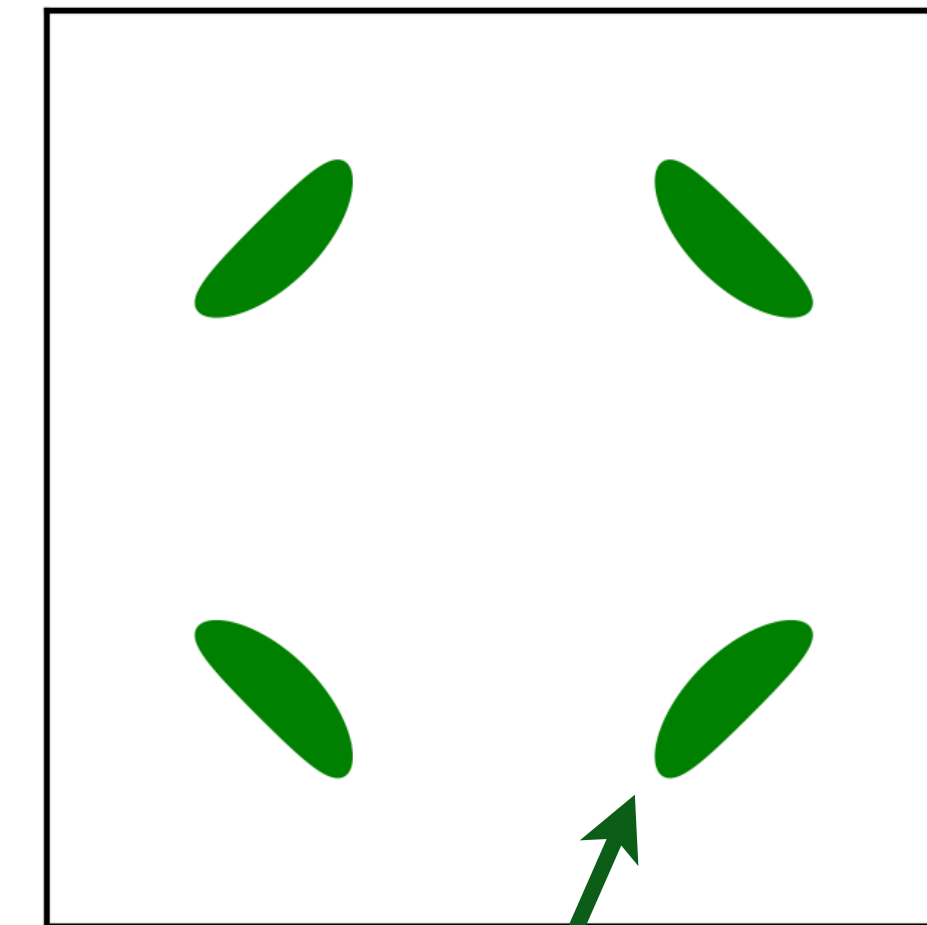


Area $p/4$



FL*

$$\text{FL}^* = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$



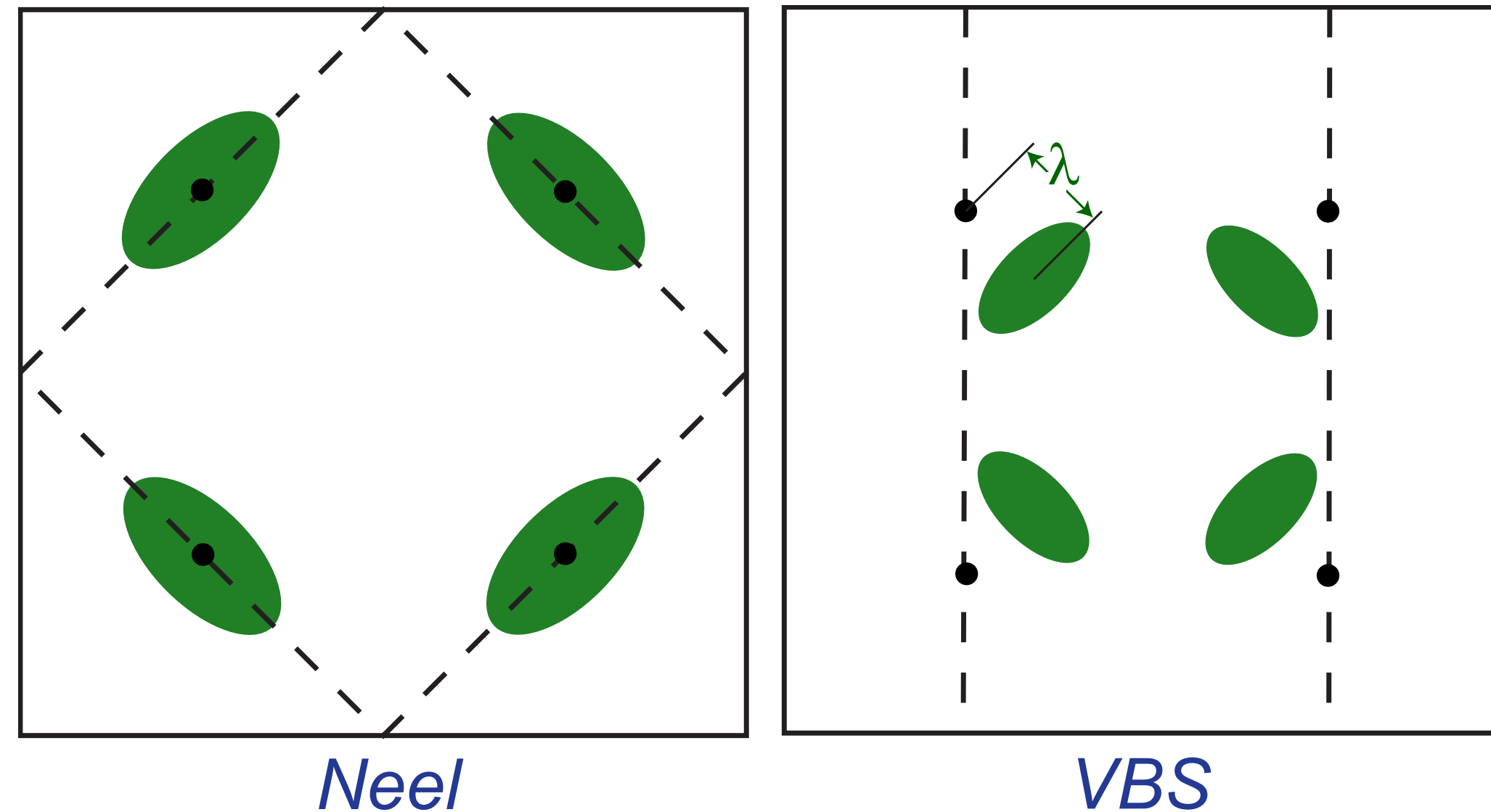
Area $p/8$

Fermi surface areas
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Factor of 2 between
SDW fluctuation
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M. Punk, A. Allais, and S. S., PNAS **112**, 9552 (2015)
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, S. S., PRB **105**, 075146 (2022)

Hole dynamics in an antiferromagnet across a deconfined quantum critical point

Ribhu K. Kaul,¹ Alexei Kolezhuk,^{1,2} Michael Levin,¹ Subir Sachdev,¹ and T. Senthil^{3,4}



The dashed line in the Néel phase indicates the boundary of the magnetic Brillouin zone. Only the Fermi surfaces within this zone contribute to the Luttinger counting, and so the area of each ellipse is $\mathcal{A}_F = (2\pi)^2 \delta/4$. In the VBS phase, all four pockets are inequivalent, and so the area of each ellipse is $\mathcal{A}_F = (2\pi)^2 \delta/8$.

Fermi surface areas are quantized and robust to all corrections!
Factor of 2 between SDW fluctuation and FL*

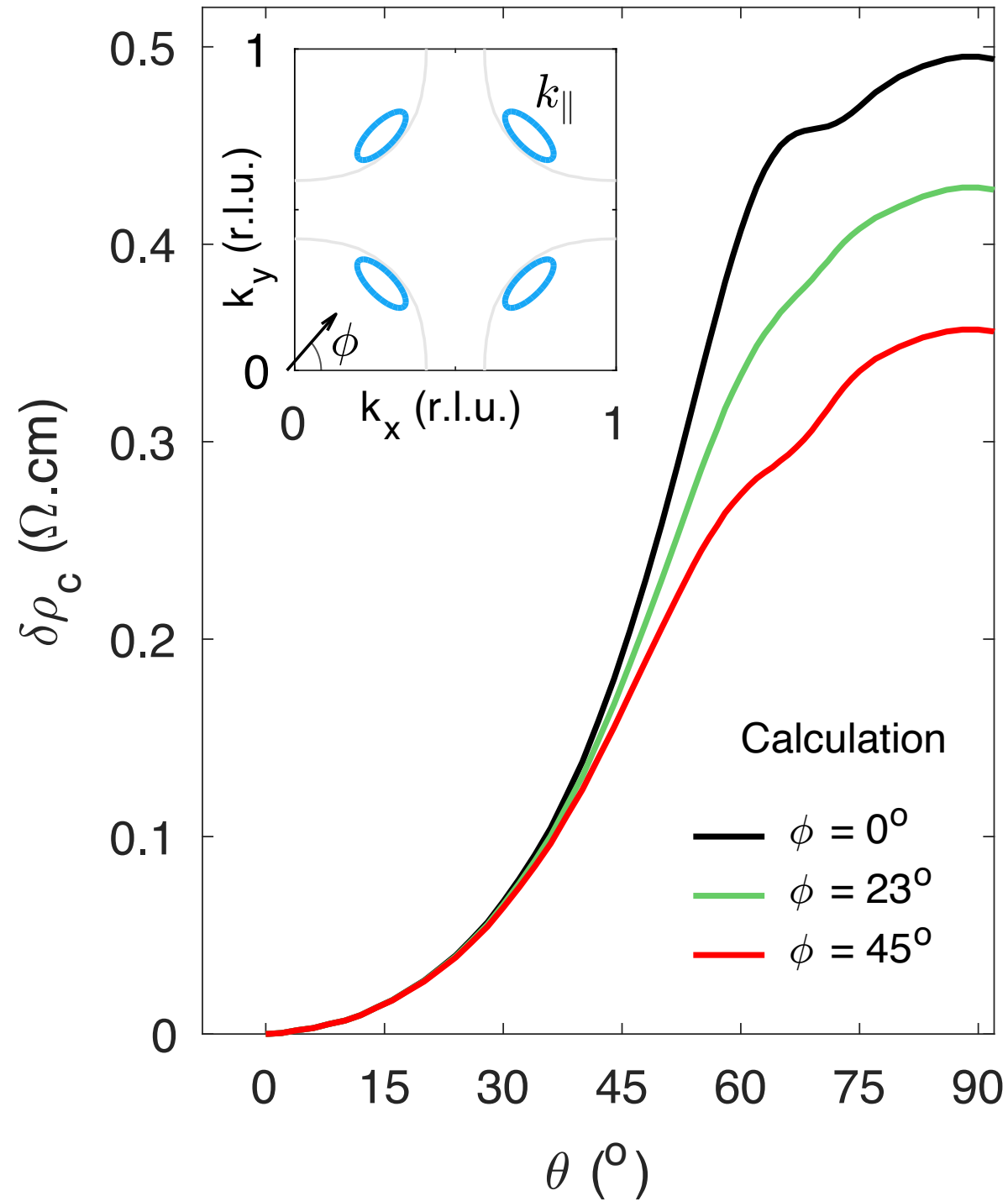
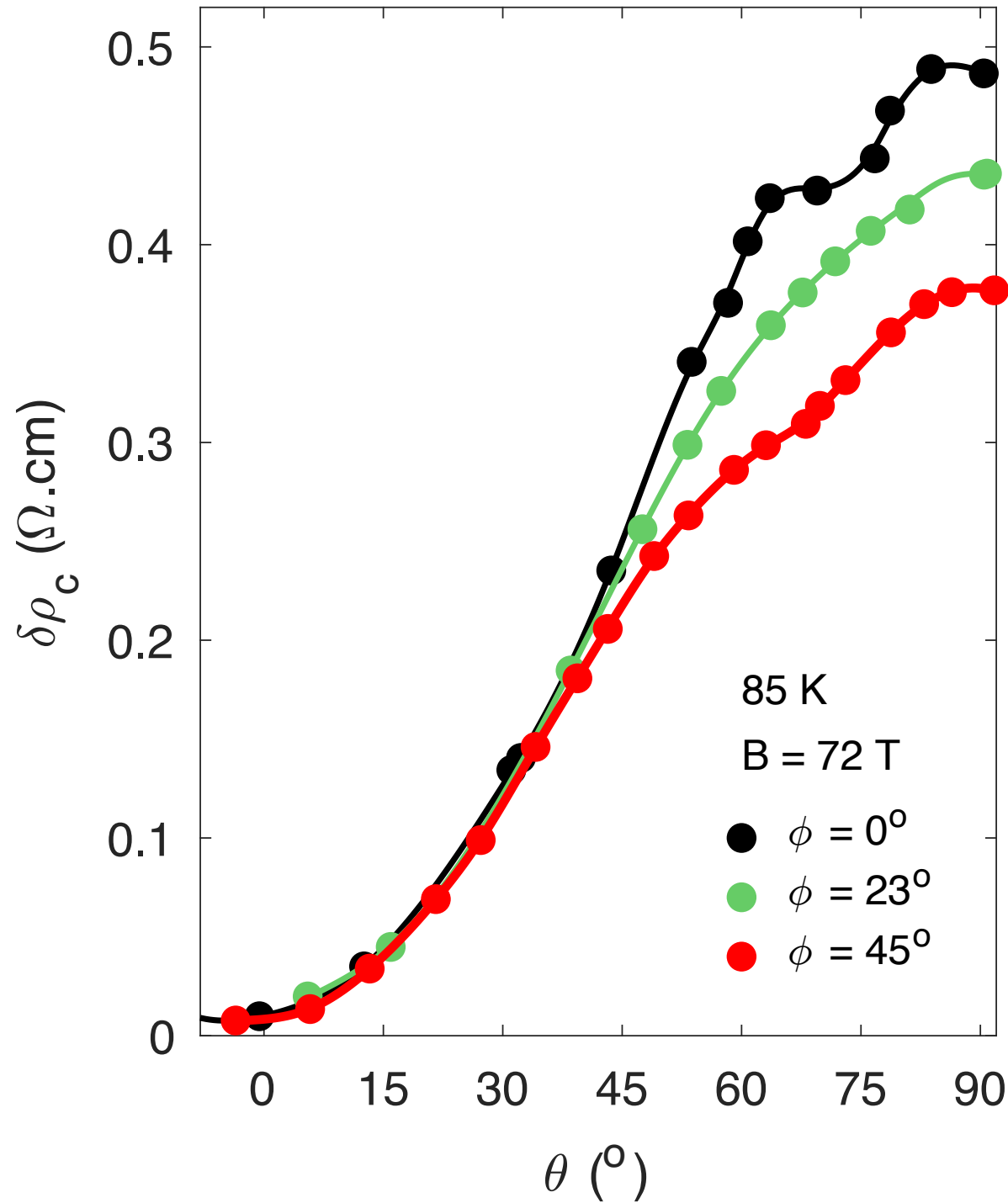
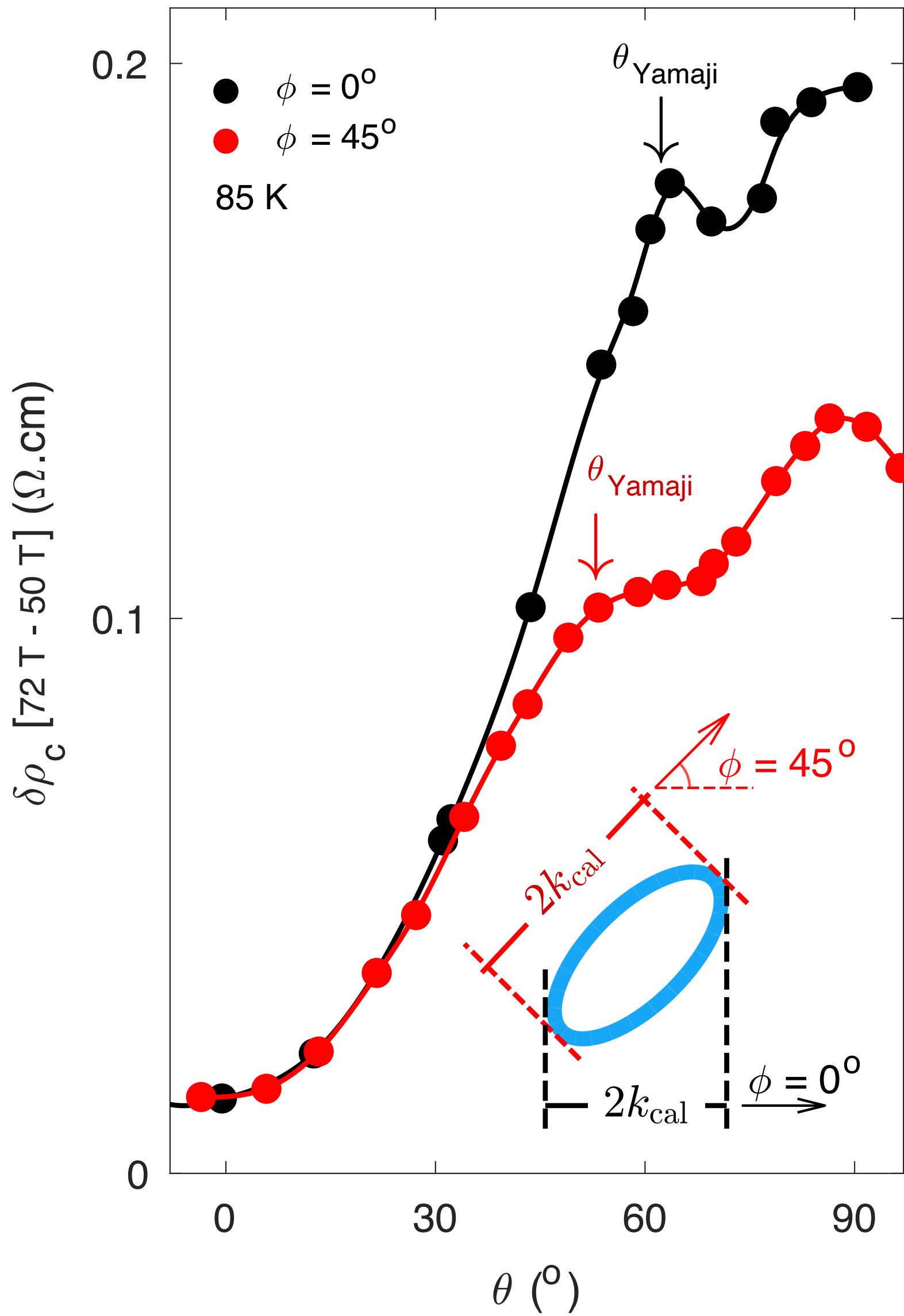
Observation of the Yamaji effect in a cuprate superconductor

nature physics

arXiv:2411.10631

Mun K. Chan¹, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela¹,
Eric D. Bauer², Arkady Shekhter¹ & Neil Harrison¹

Published online: 16 September 2025



Doping
 $p = 0.1$

“The small size of the pockets determined from the Yamaji effect is ... approximately 1.3% of the Brillouin zone area”

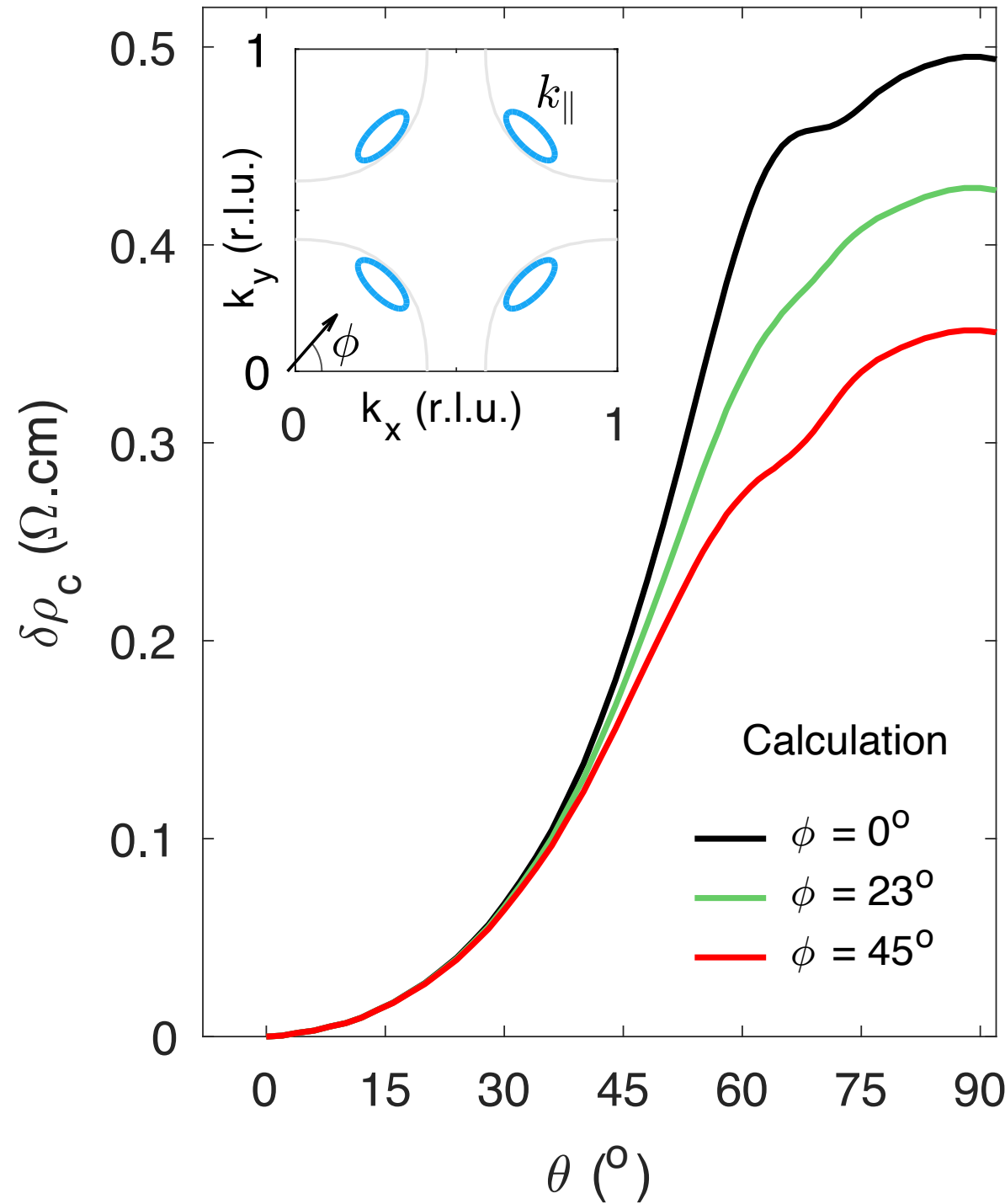
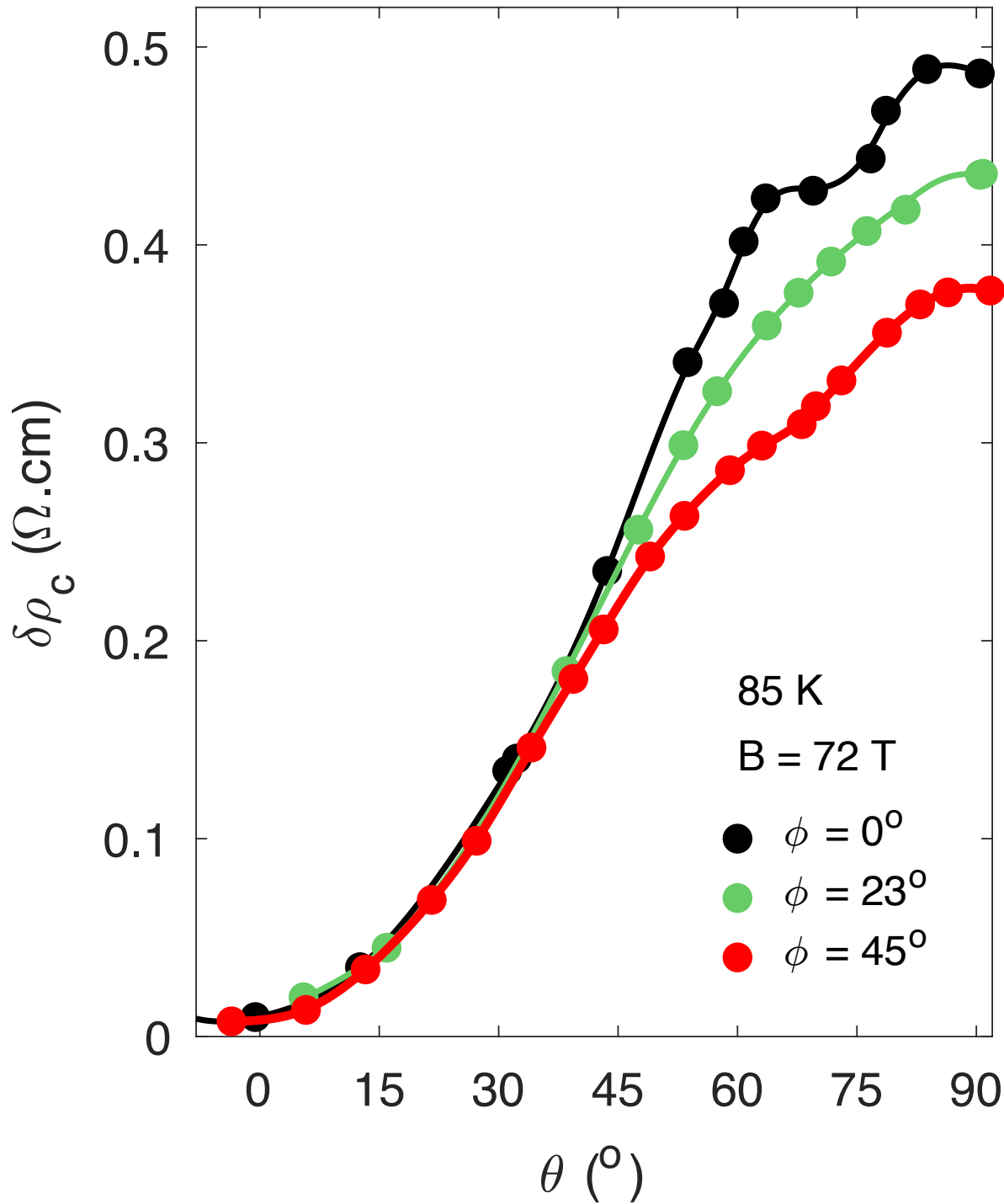
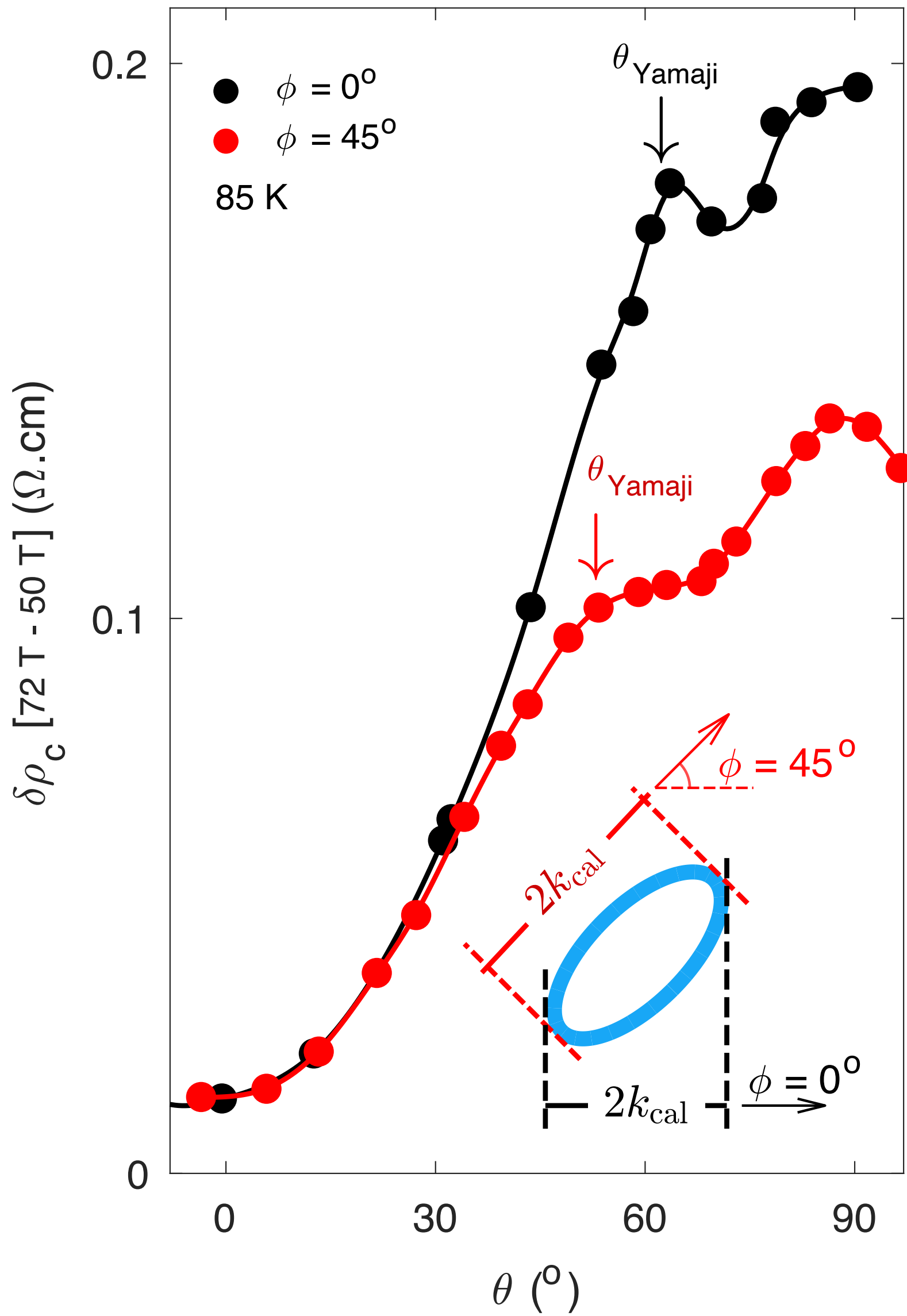
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($p/8$ also in YRZ ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar?)

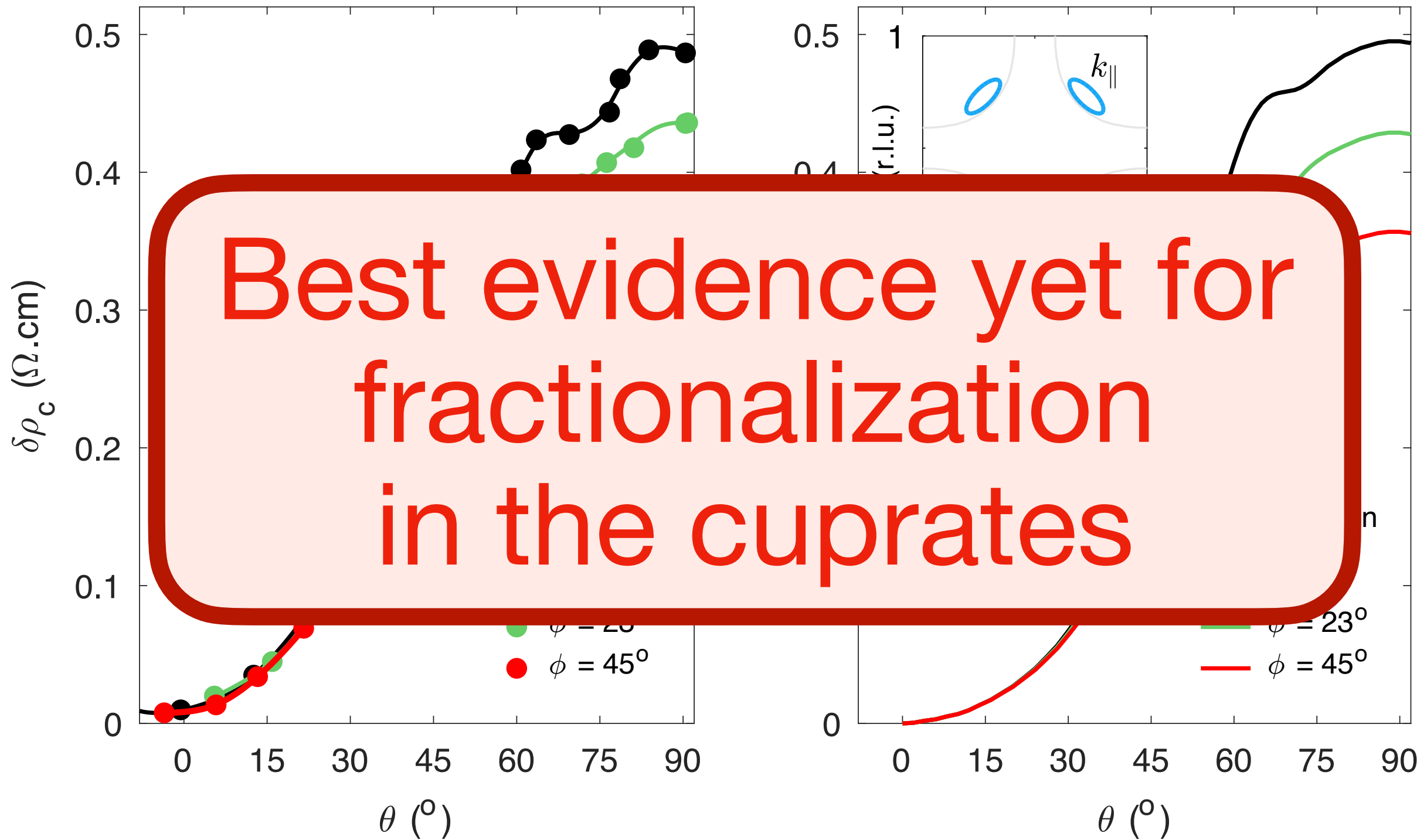
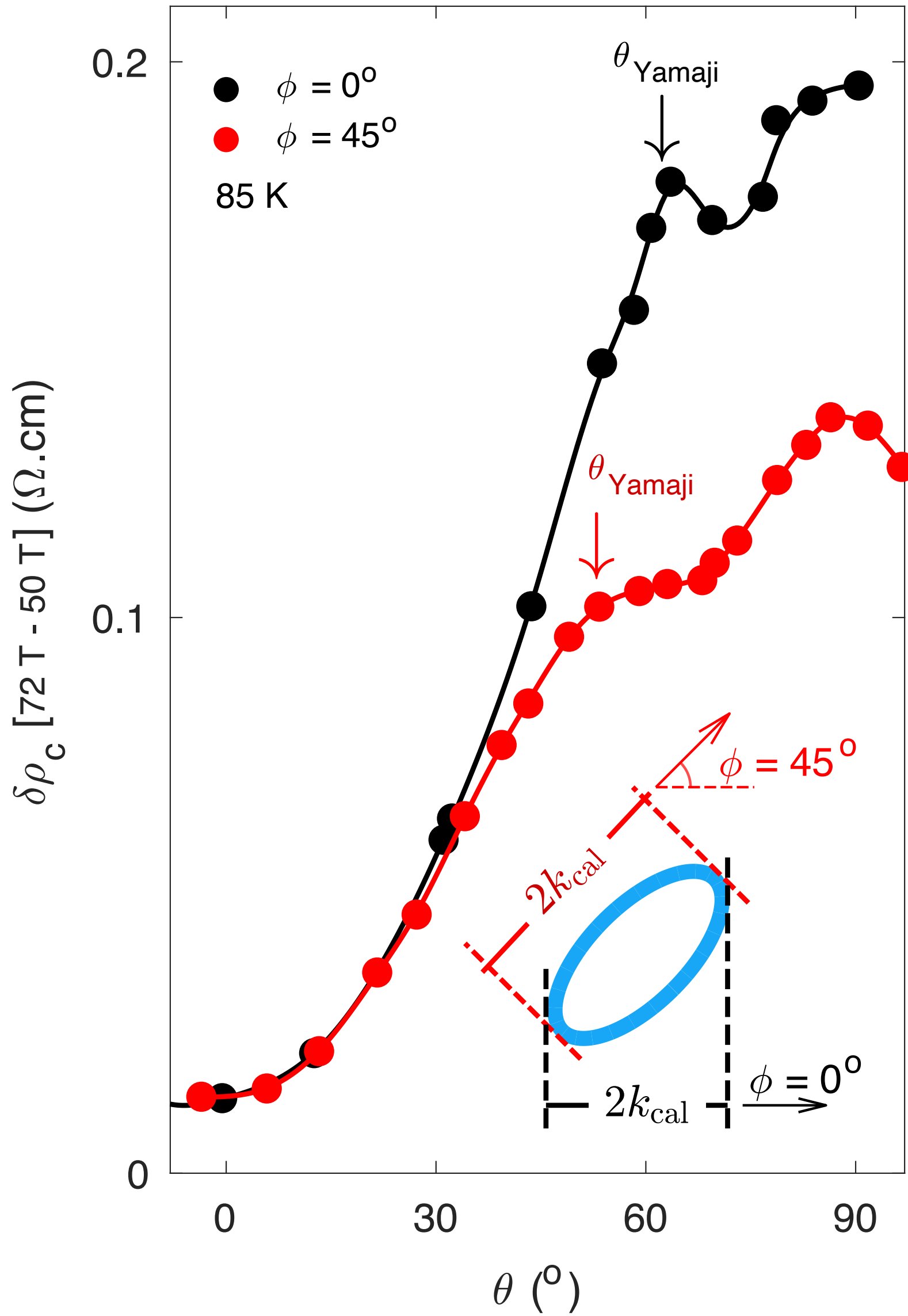
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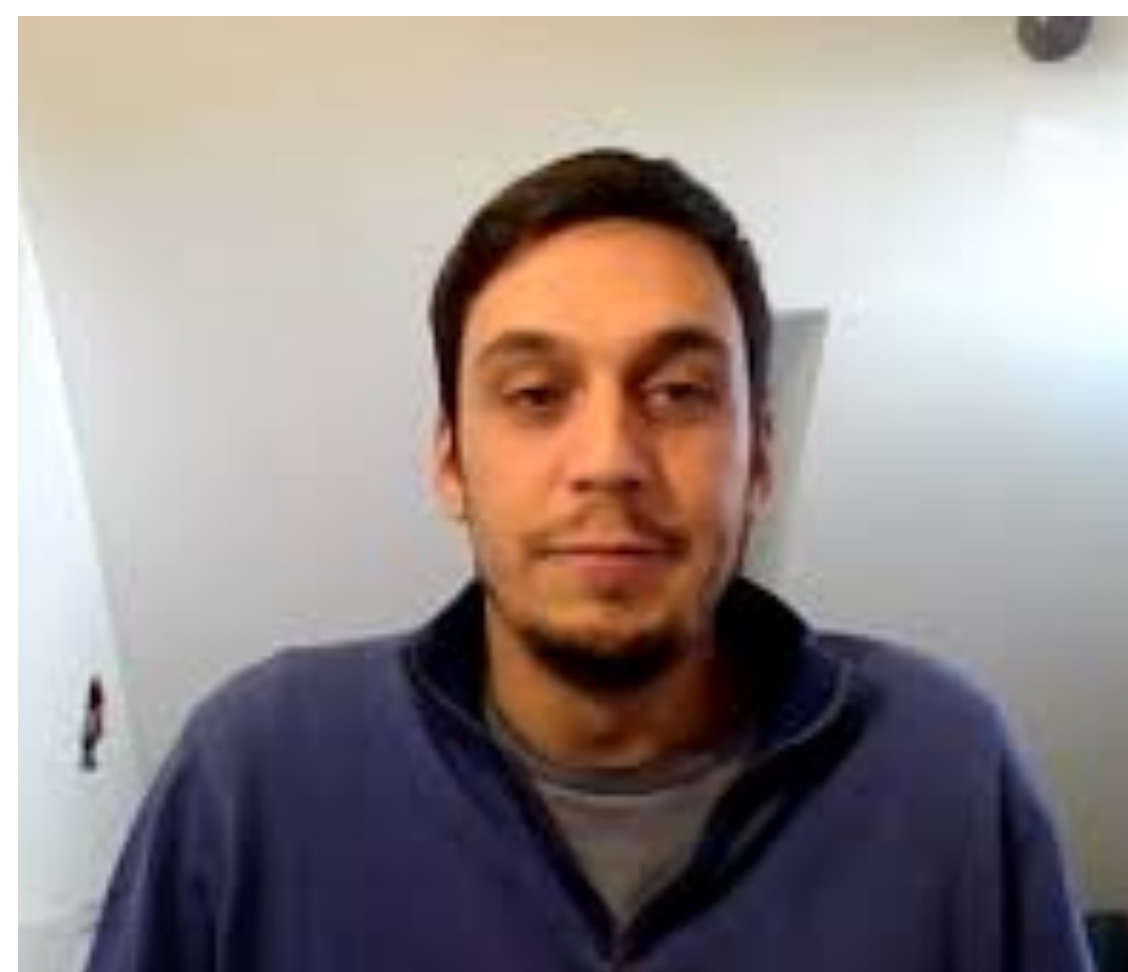
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Coupling hole pockets to spin liquid

(the spin liquid is required by
non-Luttinger area of hole pockets)



Maine Christos
Caltech



Pietro Bonetti



Alexander
Nikolaenko

Thermal $SU(2)$ lattice gauge theory of
the cuprate pseudogap: reconciling
Fermi arcs and hole pockets

H. Pandey, M. Christos, P.M. Bonetti,
R. Shanker, A. Nikolaenko, S. Sharma,
S.S., arXiv:2507.05336

The Institute of
Mathematical
Sciences,
Chennai



Harshit Pandey



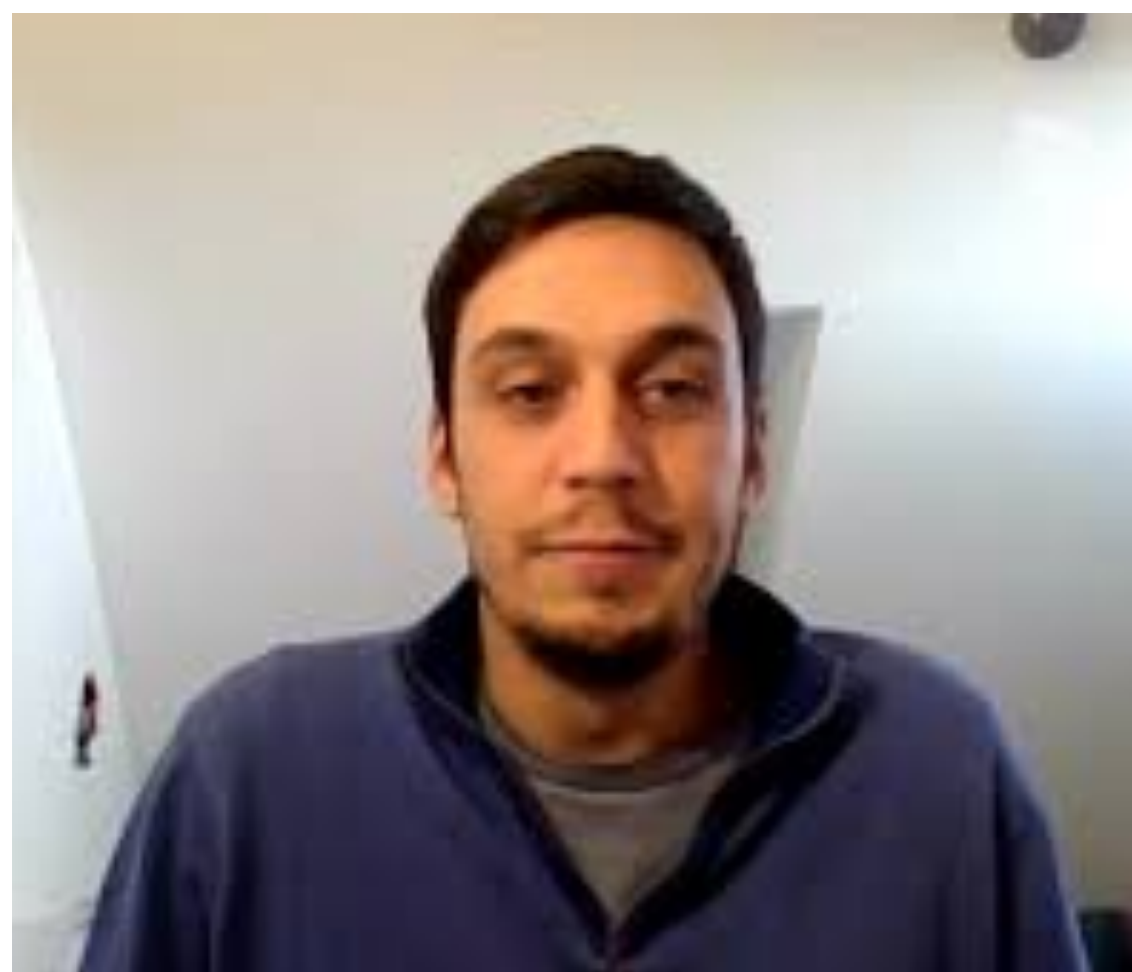
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Sayantan Sharma



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Pietro Bonetti



Alexander
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Aavishkar Patel
ICTS, Bengaluru

arXiv > cond-mat > arXiv:2508.20164

Condensed Matter > Strongly Correlated Electrons

[Submitted on 27 Aug 2025]

Critical quantum liquids and the cuprate high temperature superconductors

1. Dope spin liquid with *holes*, not holons.

The Ancilla Layer Model (ALM) enables
a theory of FL* with hole pockets and a general spin liquid.

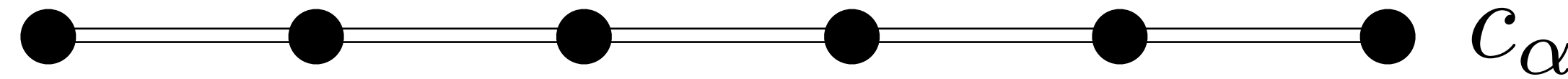
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Ancilla Layer Model of the Hubbard model

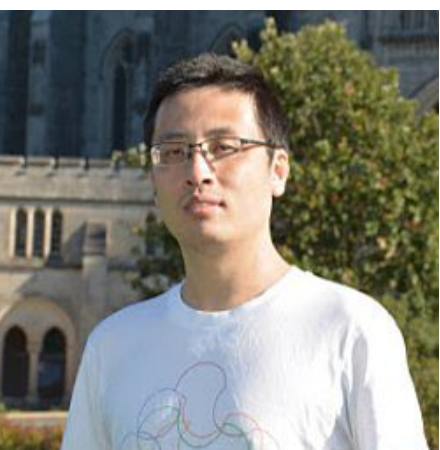
(Foolproof method to satisfy the Oshikawa anomaly)



Hubbard
model of
hole density
 $1+p$

$$\mathcal{H}_{\text{Hubbard}} = - \sum_{i,j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha} + U \sum_i (c_{i\uparrow}^\dagger c_{i\uparrow}) (c_{i\downarrow}^\dagger c_{i\downarrow})$$

Ya-Hui
Zhang

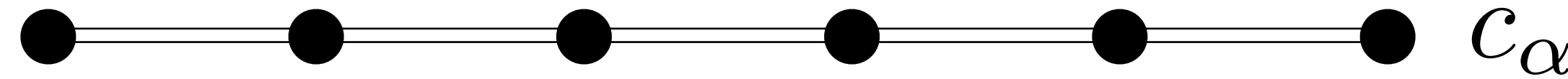


Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

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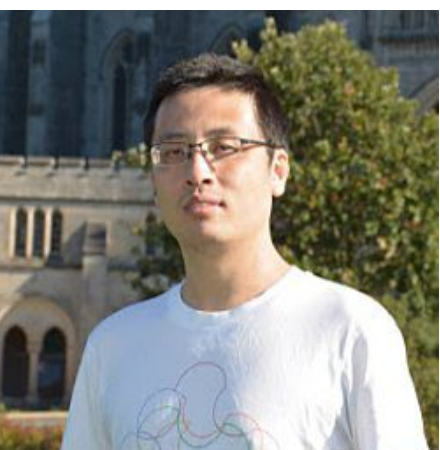


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 $1+p$

$$\mathcal{H}_{\text{Hubbard}} = - \sum_{i,j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha} + \sum_i \left[\frac{3U}{8} \mathcal{P}_i^2 + U \mathcal{P}_i \cdot c_{i\alpha}^\dagger \frac{\boldsymbol{\sigma}_{\alpha\beta}}{2} c_{i\beta} \right] .$$

$\mathcal{P}_i \Rightarrow$ Paramagnon

Ya-Hui
Zhang

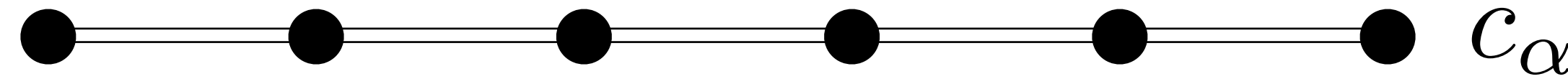


Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

Ancilla Layer Model of the Hubbard model

(Foolproof method to satisfy the Oshikawa anomaly)

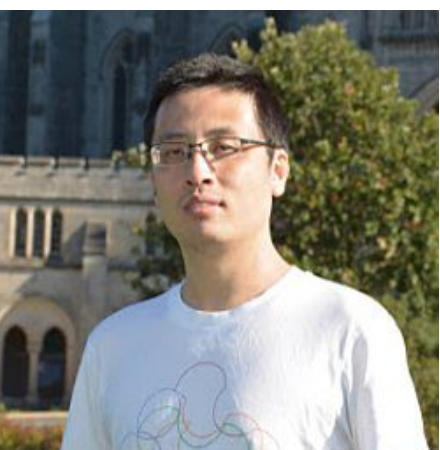


Hubbard
model of
hole density
 $1+p$

$$\mathcal{H}_{\text{Hubbard}} = - \sum_{i,j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha} + \sum_i \left[\frac{m\mathcal{P}}{2} (\partial_\tau \mathcal{P}_i)^2 + \frac{3U}{8} \mathcal{P}_i^2 + U \mathcal{P}_i \cdot c_{i\alpha}^\dagger \frac{\boldsymbol{\sigma}_{\alpha\beta}}{2} c_{i\beta} \right] .$$

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Zhang

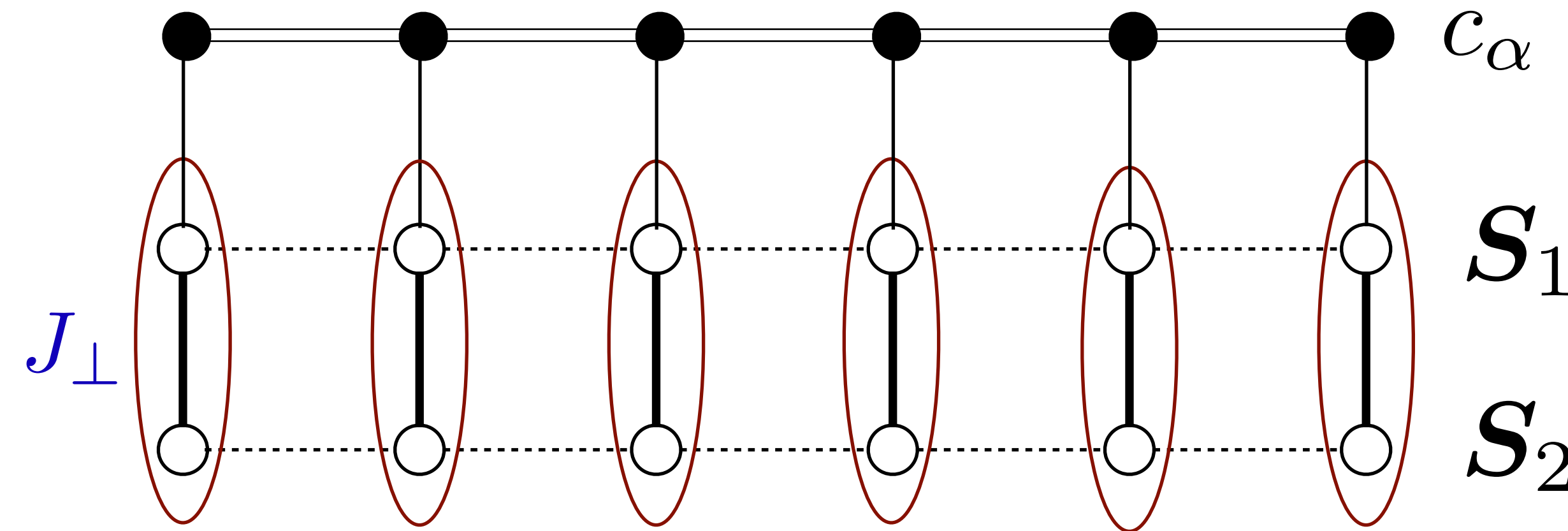


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Ancilla Layer Model of the Hubbard model

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Free holes of
density
 $1+p$

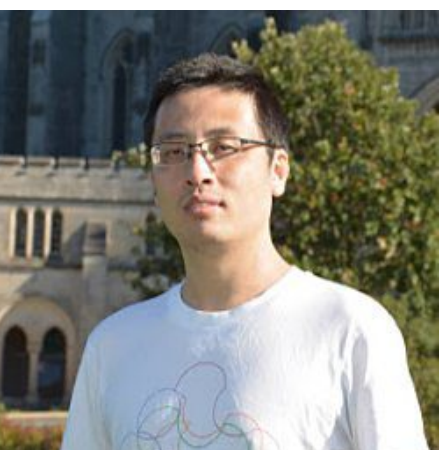
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3 $\mathcal{P}$ oscillators' states: $|0, 0, 0\rangle, |1, 0, 0\rangle, |0, 1, 0\rangle, |0, 0, 1\rangle$

$S_{1,2}$ ancilla qubits states : $(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}, |\uparrow\uparrow\rangle, (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}, |\downarrow\downarrow\rangle$

$$\mathcal{P} \sim S_1 - S_2$$

Ya-Hui
Zhang

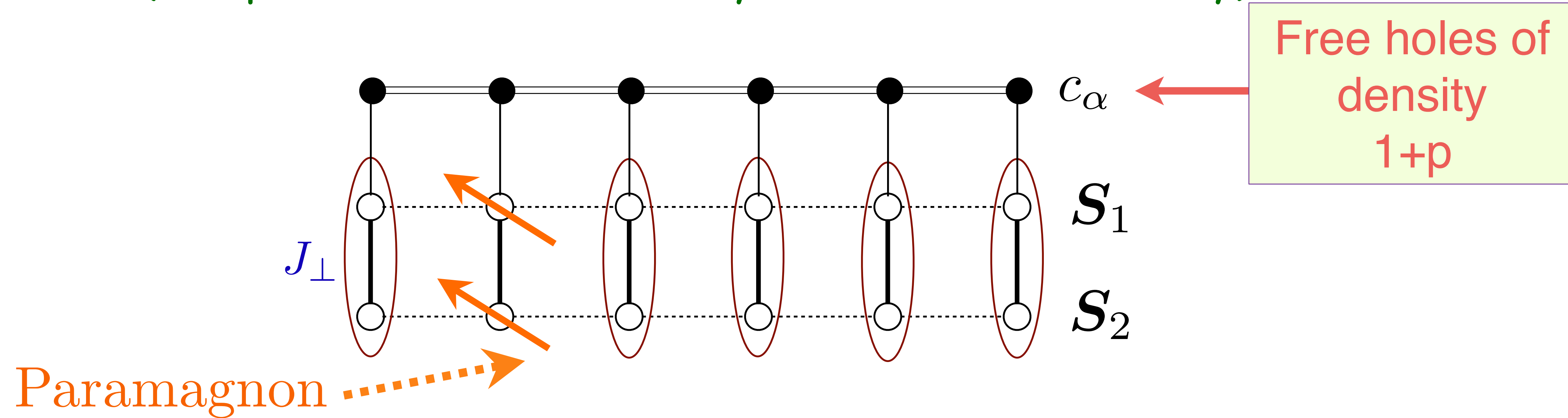


Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

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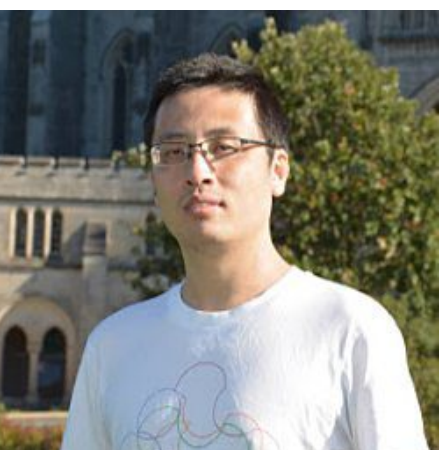
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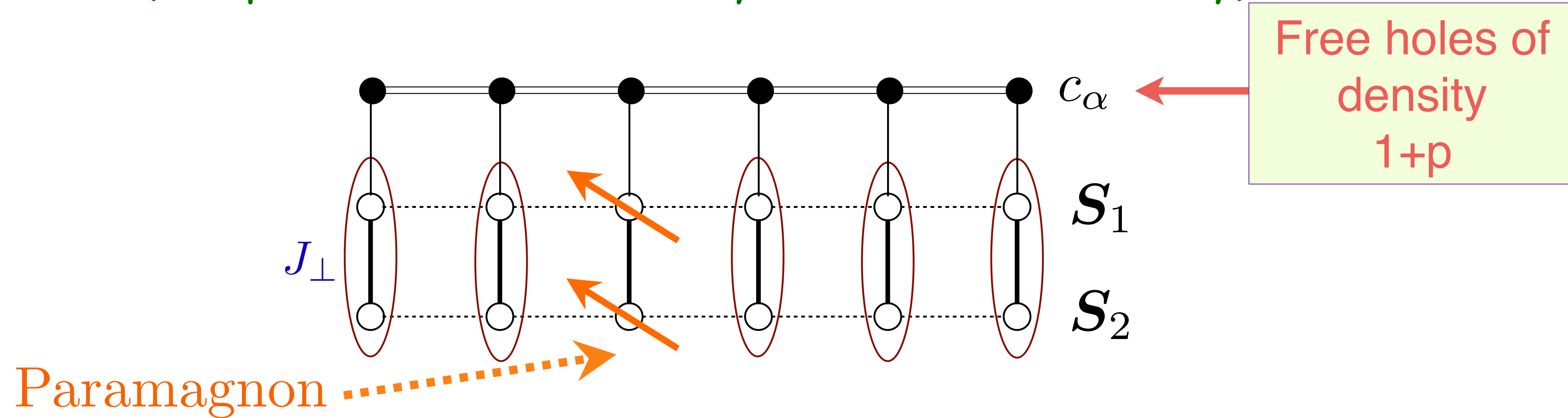


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A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

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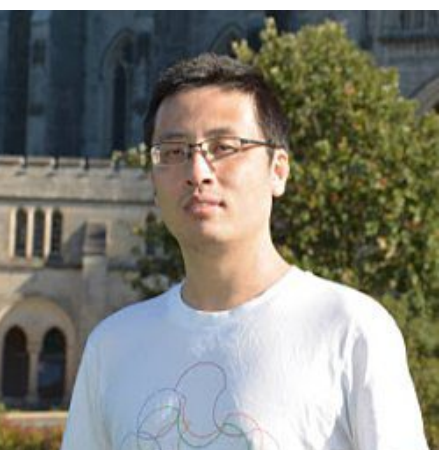
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Ya-Hui
Zhang

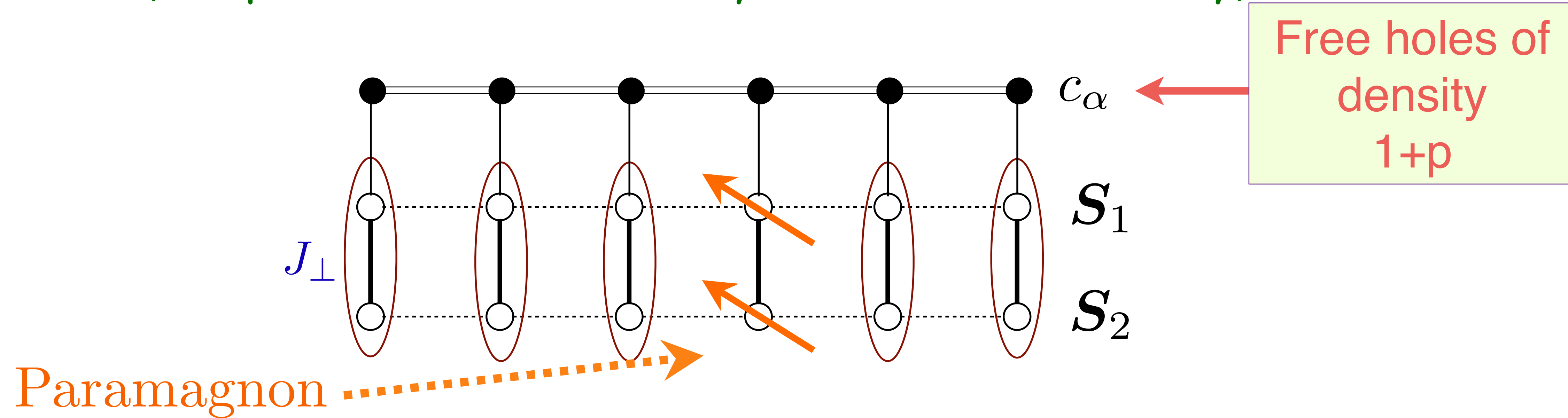


Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

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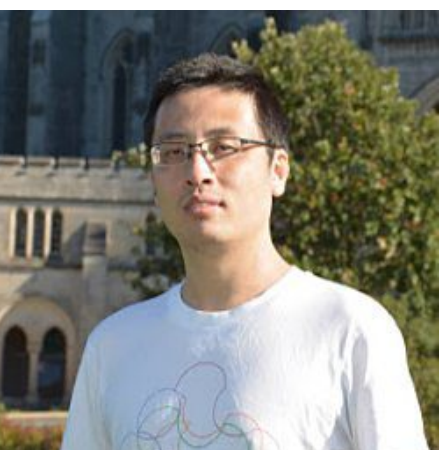
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Ya-Hui
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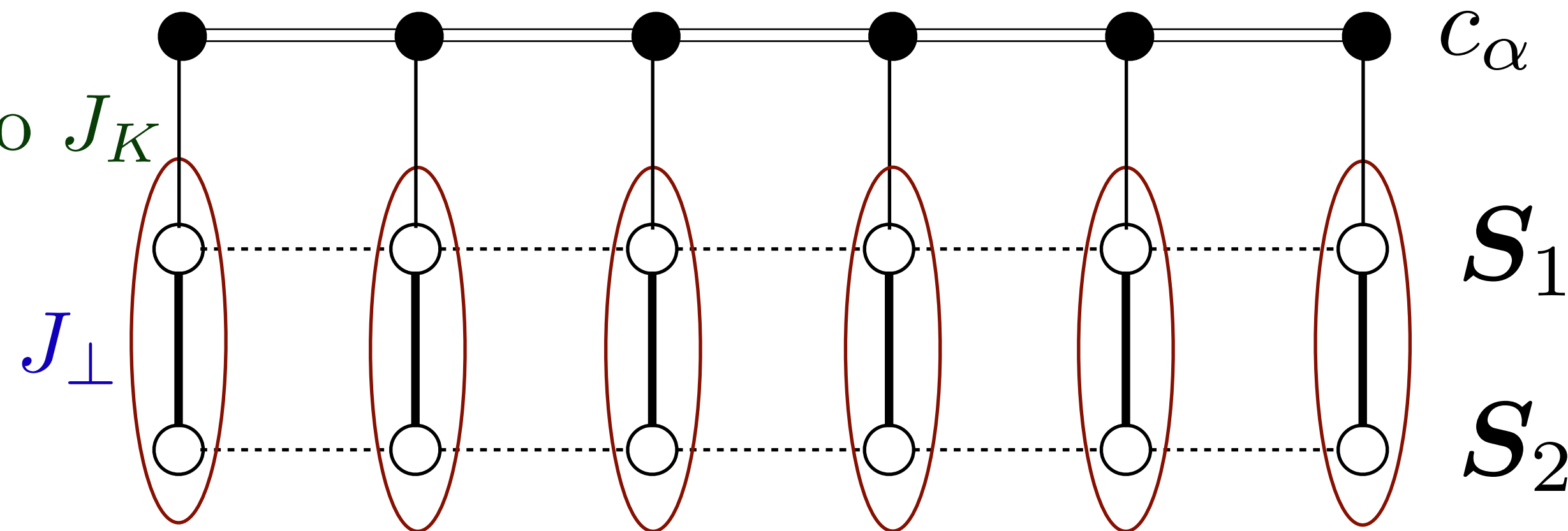
Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

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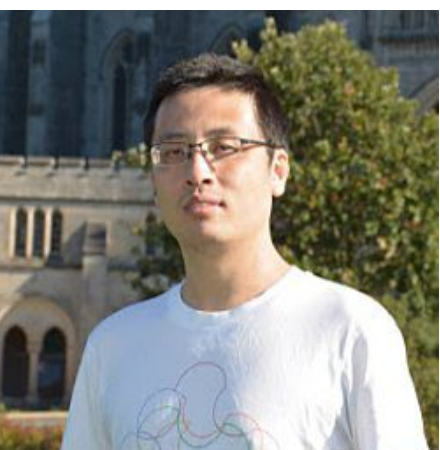
Antiferromagnetic Kondo J_K



Free holes of
density
 $1+p$

$$\mathcal{H}_{\text{ALM}} = - \sum_{i,j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha} + \sum_i \frac{J_K}{2} \mathbf{S}_{1i} \cdot c_{i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} c_{i\beta} + J_\perp \sum_i \mathbf{S}_{1i} \cdot \mathbf{S}_{2i} .$$

Ya-Hui
Zhang



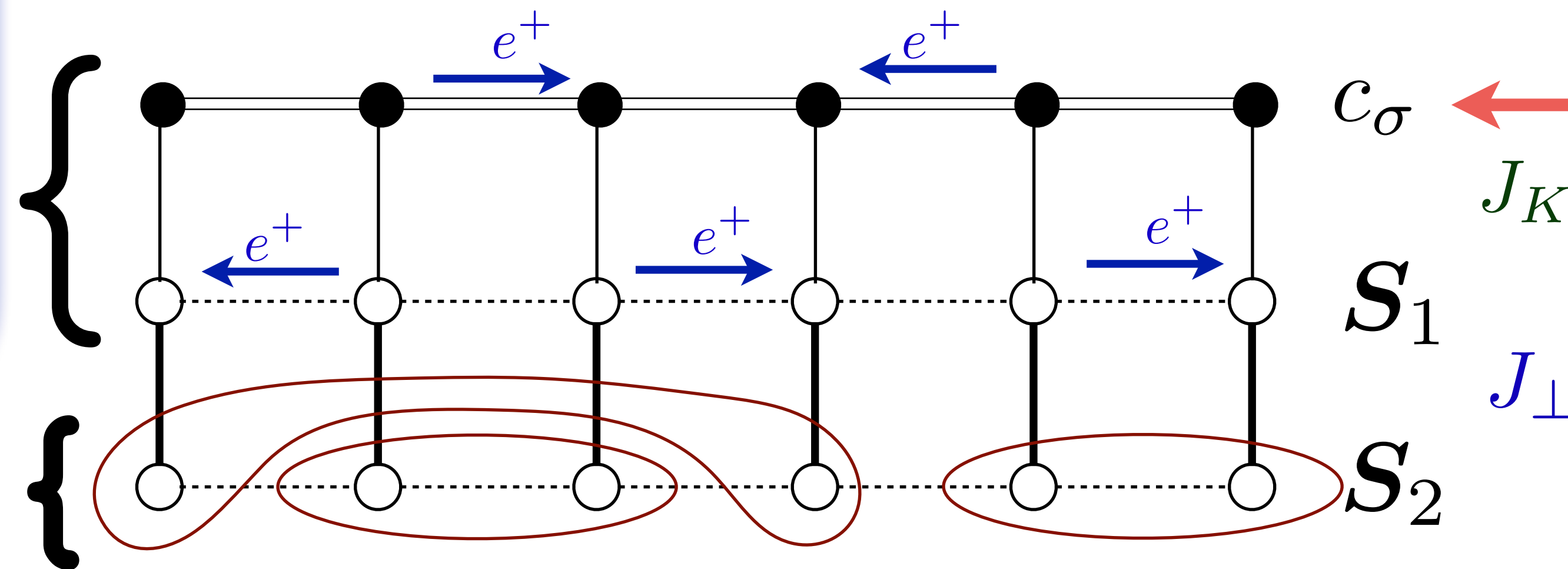
Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

ALM of FL* of Hubbard model

Kondo lattice heavy
Fermi liquid.
Area $(1 + p + 1)/2$
 $= p/2 \pmod{1}$.
Small Fermi surface!

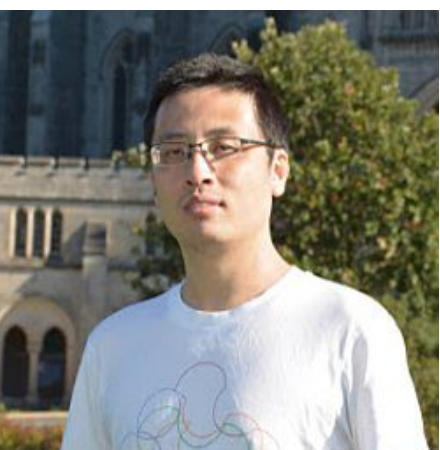
Your favorite
spin liquid



Free holes of
density
 $1+p$

Kondo Lattice FL of c_α and S_1
Pseudogap metal = $\oplus$
Spin Liquid of S_2

Ya-Hui
Zhang

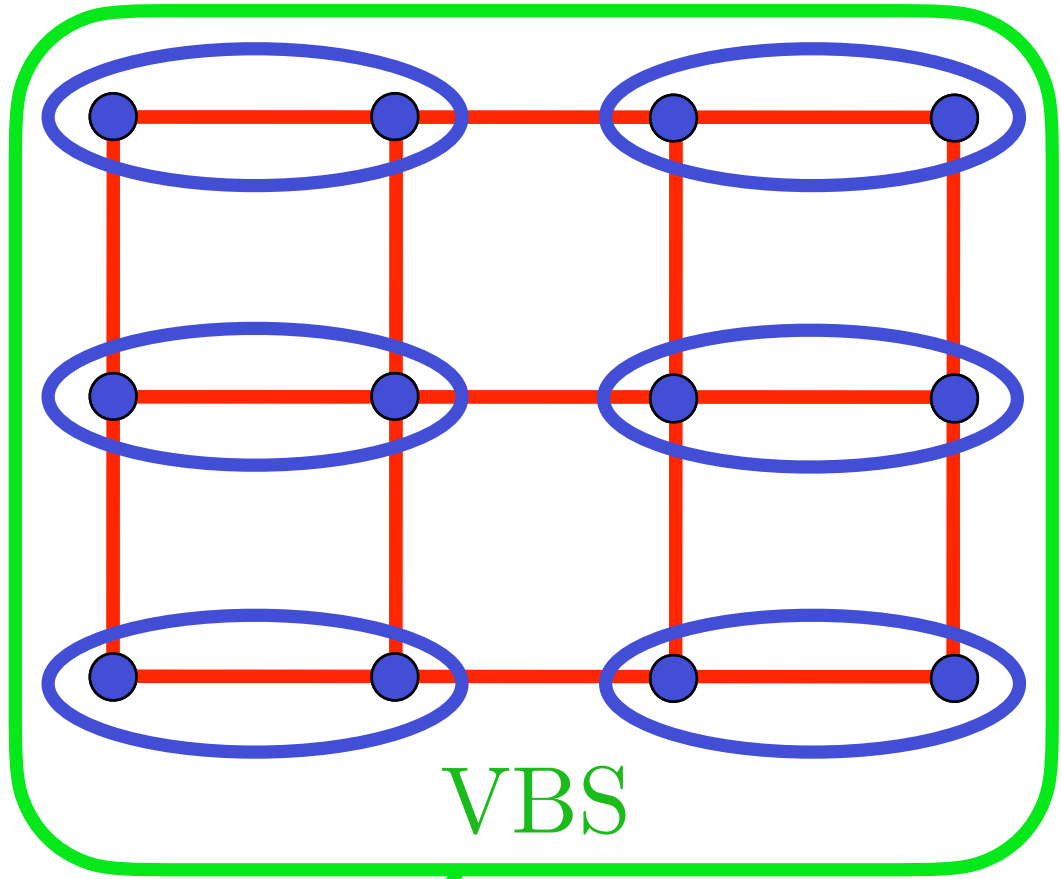
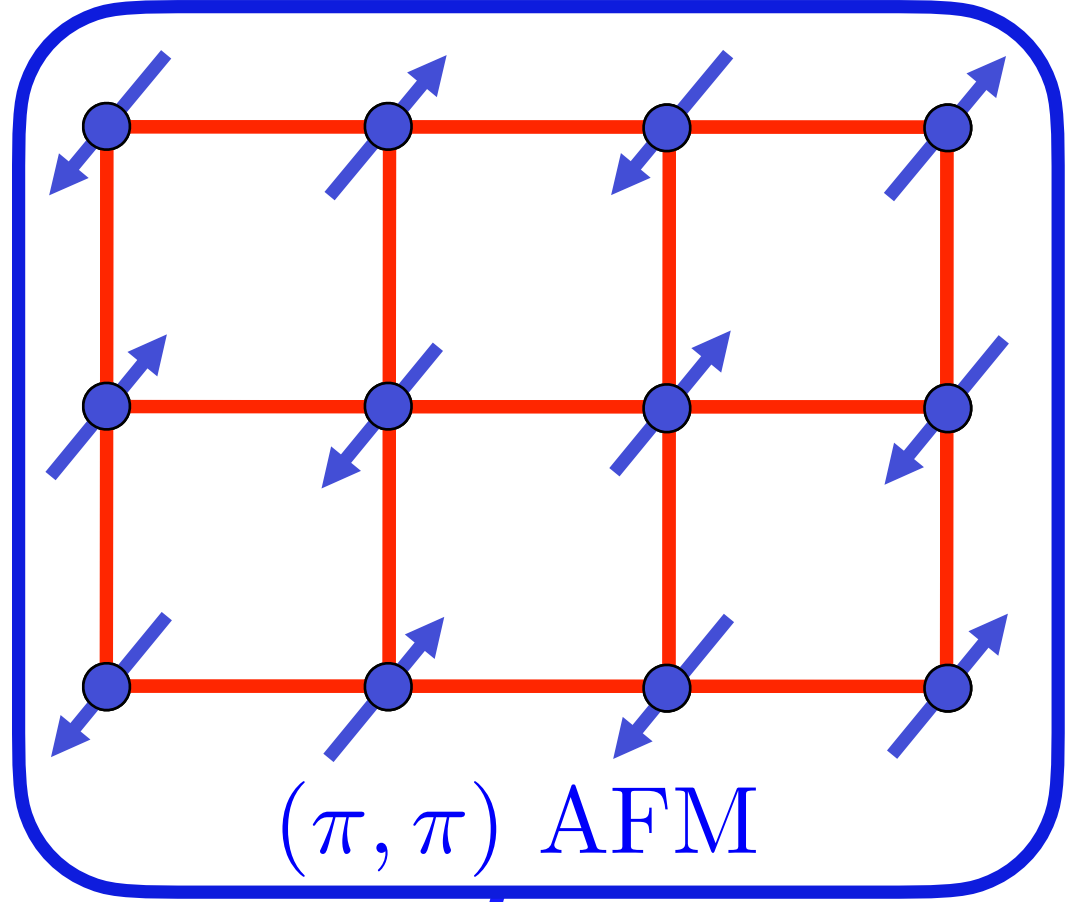
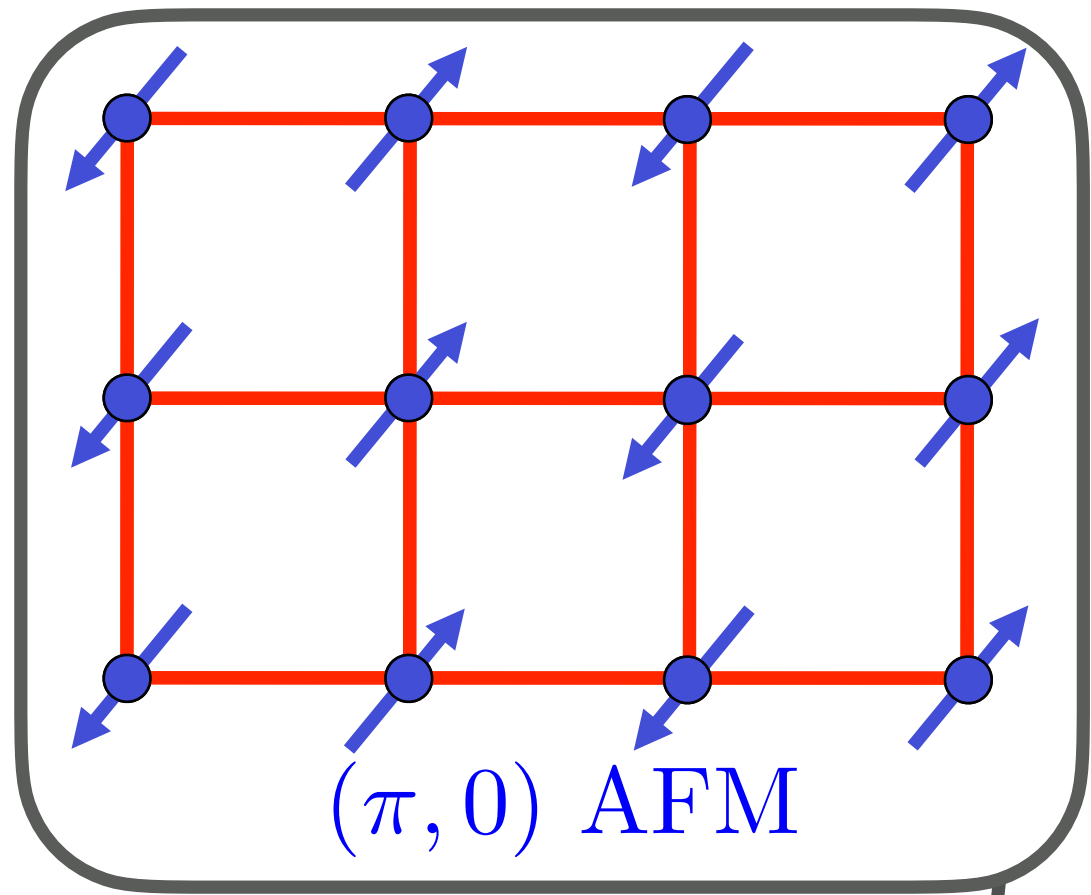


Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

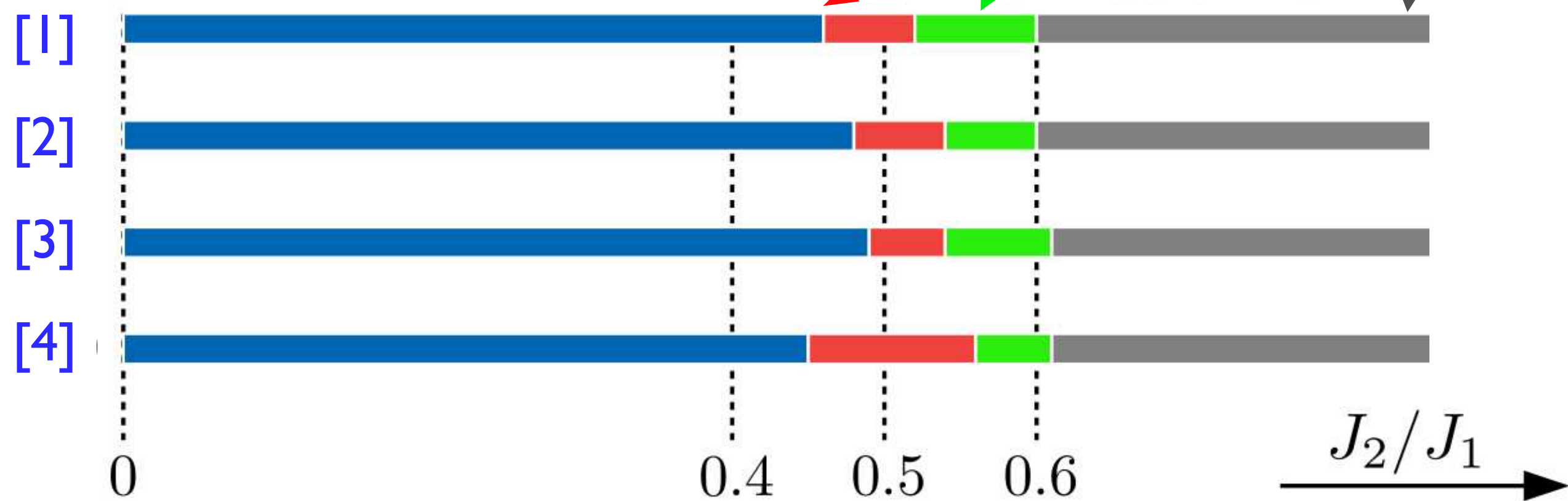
A. Nikolaenko, M. Tikhanovskaya, S. S., and Ya-Hui Zhang, PRB **103**, 235138 (2021)

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Hole pockets coupled to critical spin liquid by **thermal fluctuations** of a SU(2) gauge theory with a charge e Higgs field.

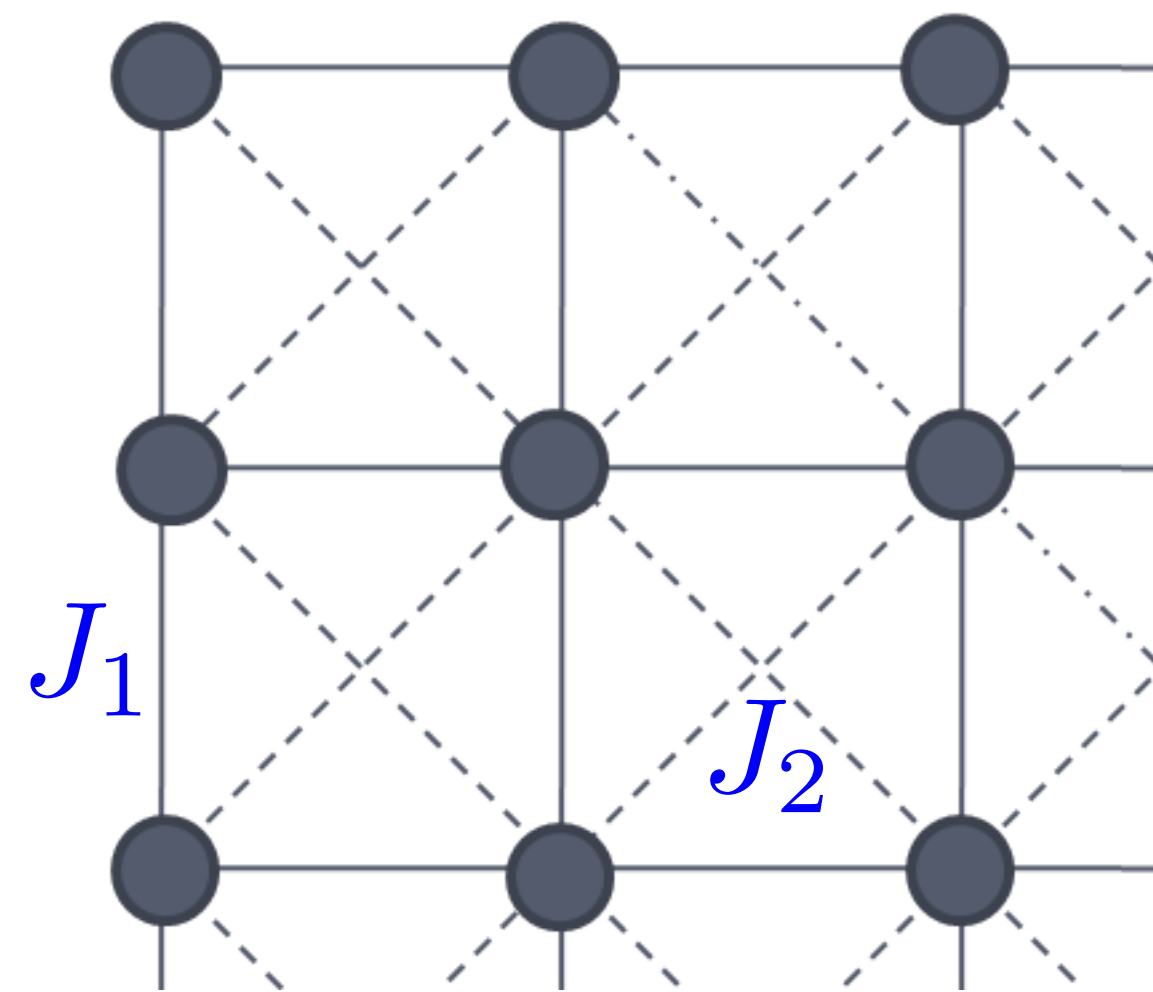
$S=1/2$ square lattice



Spin
Liquid

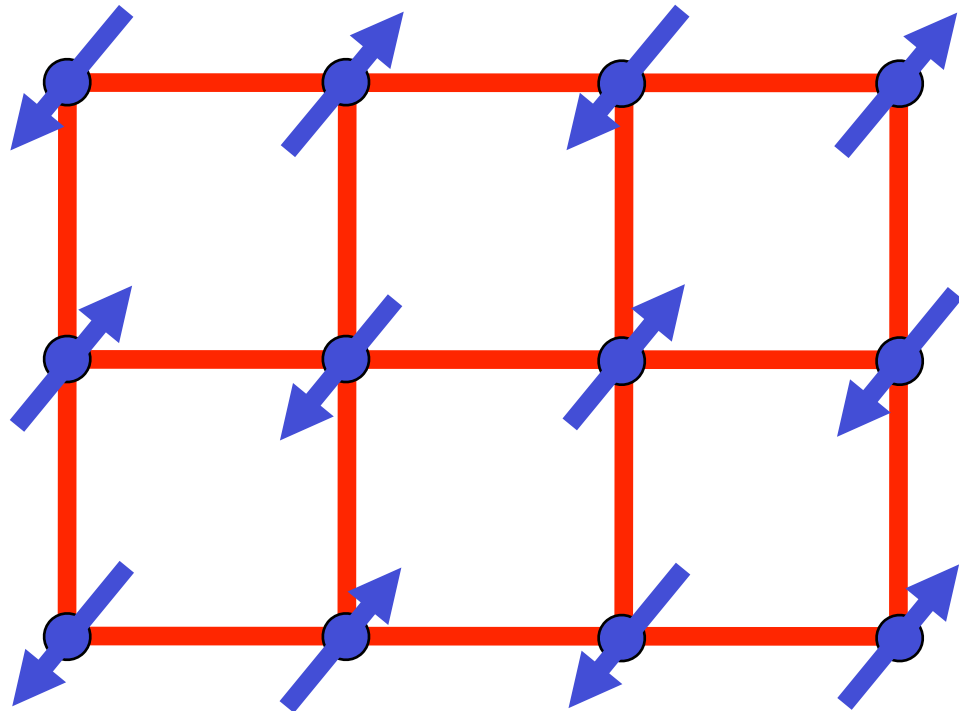


$$H = J_1 \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{\langle\langle i,j \rangle\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

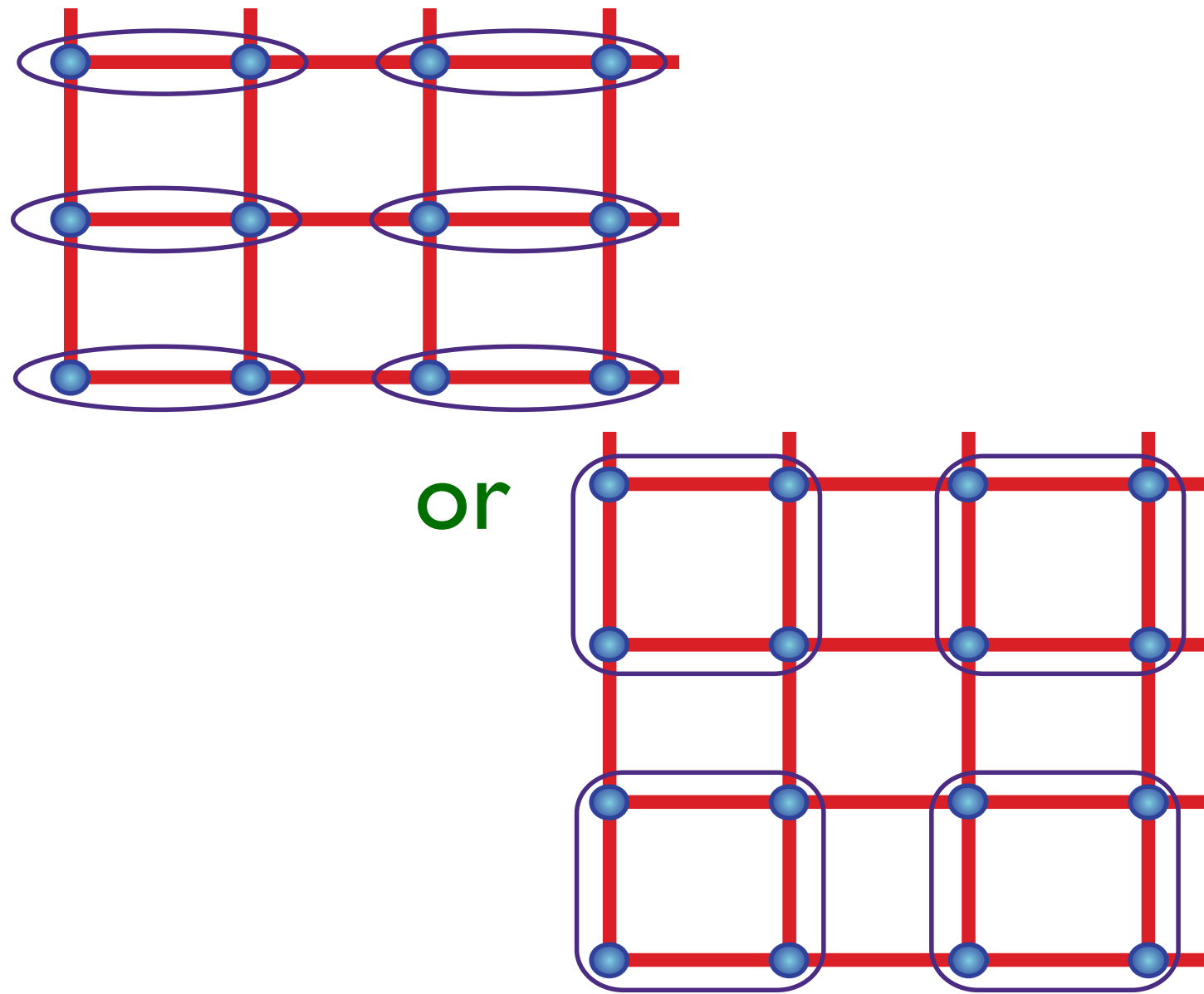


1. L.Wang and A.W. Sandvik, *Phys. Rev. Lett.* **121**, 107202 (2018)
2. F. Ferrari and F. Becca, *Phys. Rev. B* **102**, 014417 (2020)
3. Y. Nomura and M. Imada, *Phys. Rev. X* **11**, 031034 (2021)
4. W.-Y. Liu, S.-S. Gong, Y.-B. Li, D. Poilblanc, W.-Q. Chen, and Z.-C. Gu, *Science Bulletin* **67**, 1034 (2022)

$S=1/2$ square lattice



$\langle b_\alpha \rangle \neq 0$:
Néel order



$\langle b_\alpha \rangle = 0$:
Valence bond solid (VBS)

N/n_b

$$H = \sum_{i < j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

Schwinger bosons

$$\mathbf{S}_i = \frac{1}{2} b_{i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} b_{i\beta}, \quad \sum_{\alpha=1}^{N=2} b_{i\alpha}^\dagger b_{i\alpha} = n_b = 2S$$

Mean-field spin liquid
with gapped bosonic spinons.

Low energy $\mathbb{CP}^1$ U(1) gauge theory

$$z_\alpha \sim b_{A\alpha} + \varepsilon_{\alpha\beta} b_{B\beta}^\dagger$$

$$\mathcal{L} = |(\partial_\mu - i a_\mu) z_\alpha|^2 + s |z_\alpha|^2 + u |z_\alpha|^4 + \mathcal{L}_{\text{monopole}}$$

N. Read and S. Sachdev, Phys. Rev. Lett. **62**, 1694 (1989)
N. Read and S. Sachdev, Phys. Rev. B **42**, 4568 (1990)

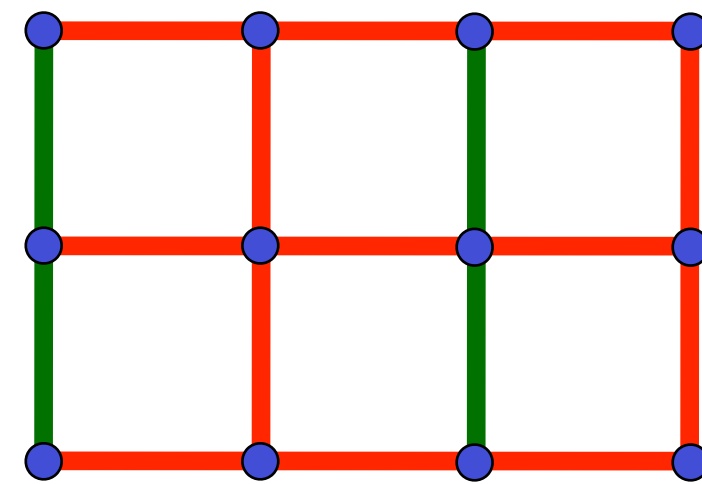
$S=1/2$ square lattice

Represent spins in terms of
 $S = 1/2$ fermionic spinons $\mathbf{S} \sim f_{\alpha}^{\dagger} \boldsymbol{\sigma}_{\alpha\beta} f_{\beta}$

I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)



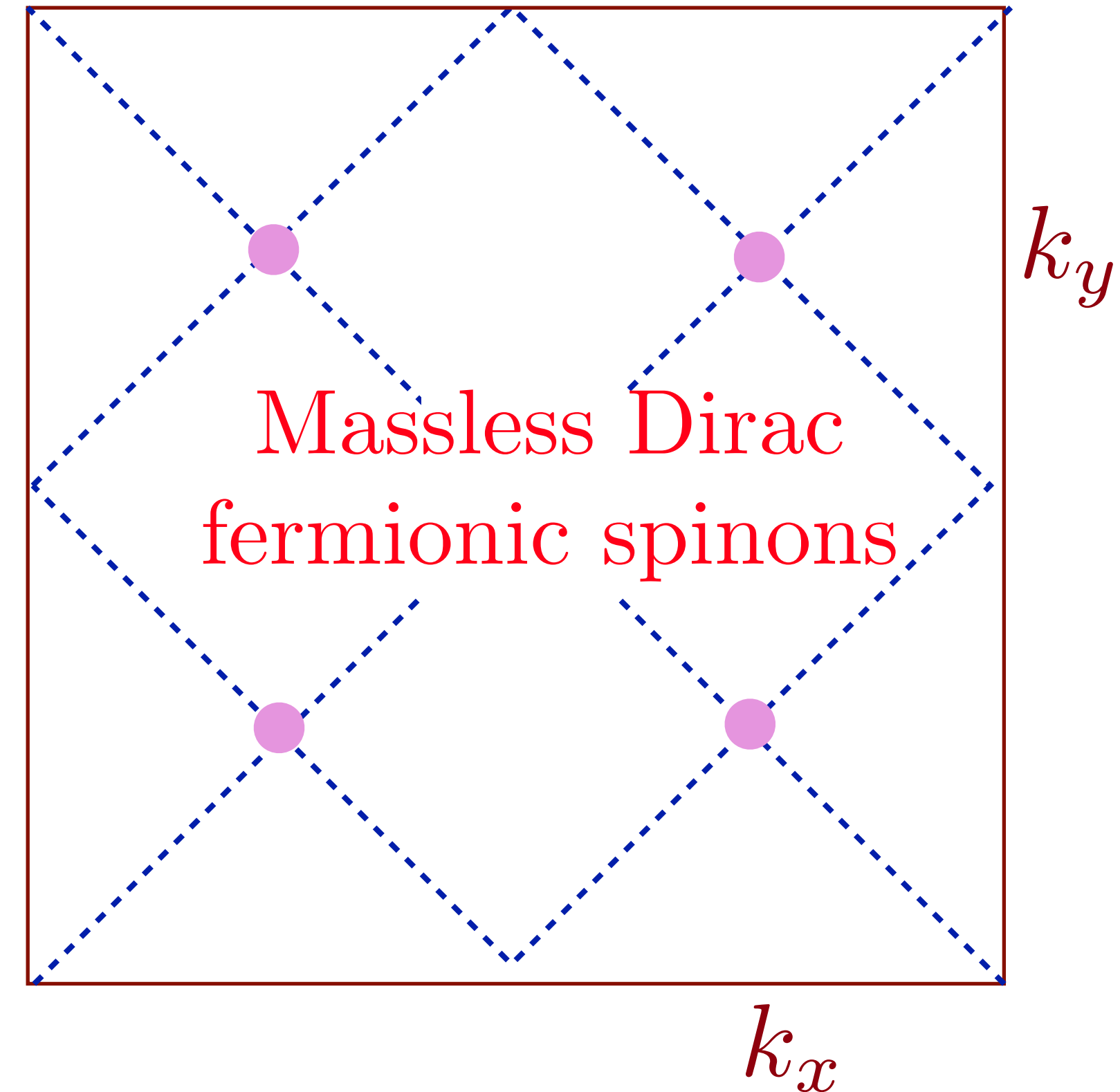
$$H_{\text{spin liquid}} = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi_i^{\dagger} U_{ij} \Psi_j - \Psi_j^{\dagger} U_{ji} \Psi_i \right); \quad \Psi_i = \begin{pmatrix} f_{i\uparrow} \\ f_{i\downarrow}^{\dagger} \end{pmatrix}$$



$$e_{ij} = 1$$

$$e_{ij} = -1$$

$$\mathcal{L} = i\bar{\psi}\gamma_{\mu}D_{\mu}\psi.$$



$N_f = 2$ SU(2) QCD

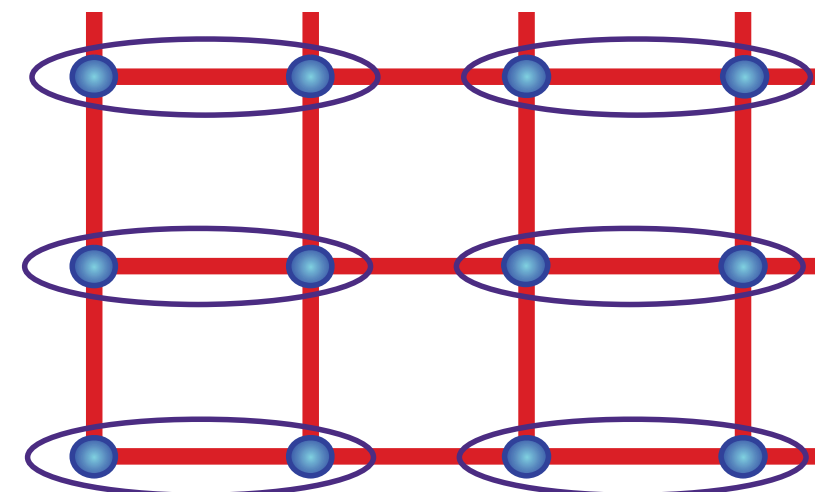
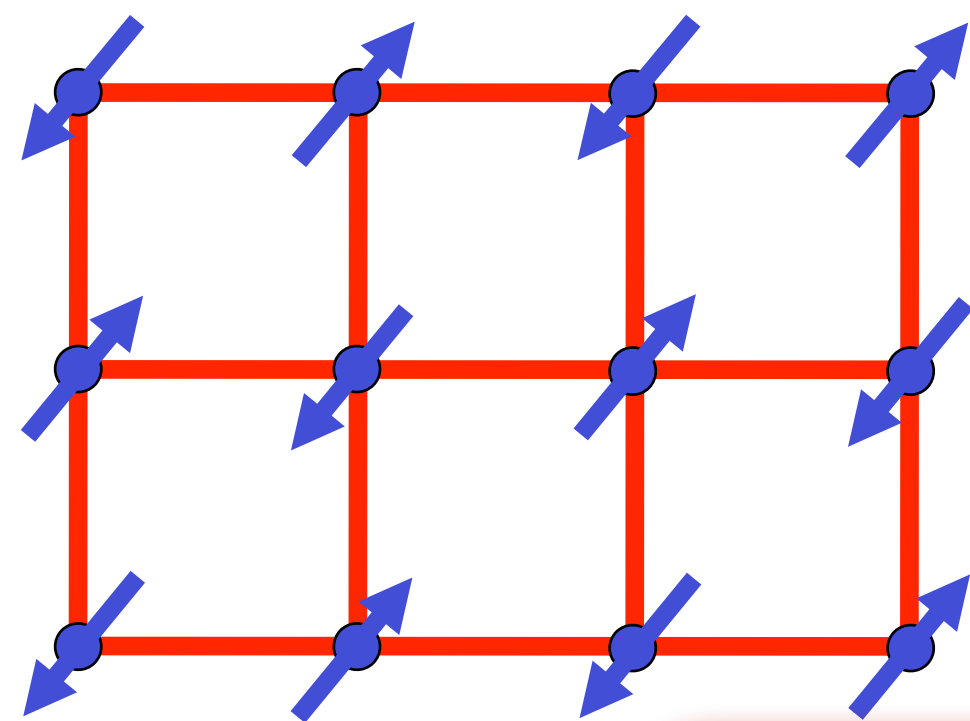
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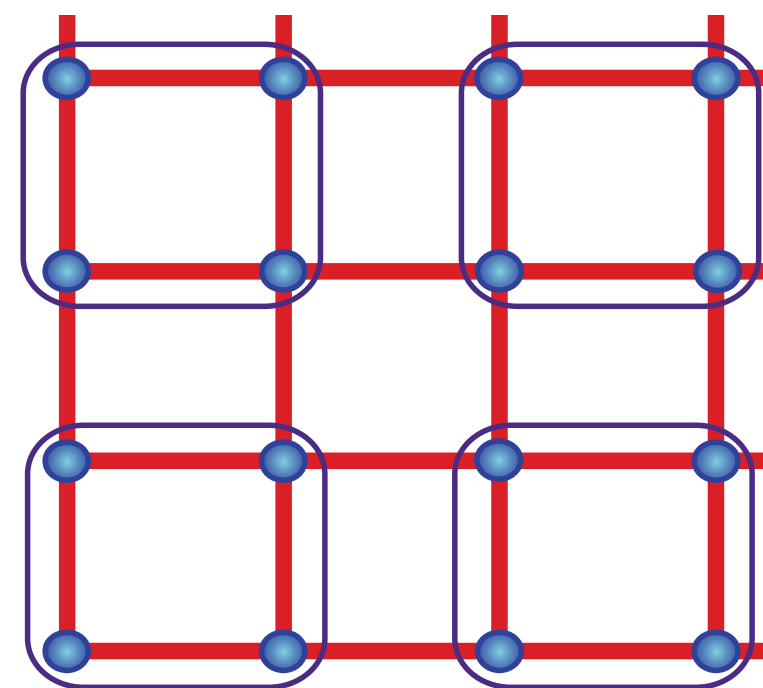
I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)

N. Read and S. Sachdev, PRL **62**, 1694 (1989)

C. Wang, A. Nahum, M. A. Metlitski, C. Xu,
 T. Senthil, *Phys. Rev. X* **7**, 031051 (2017)



or

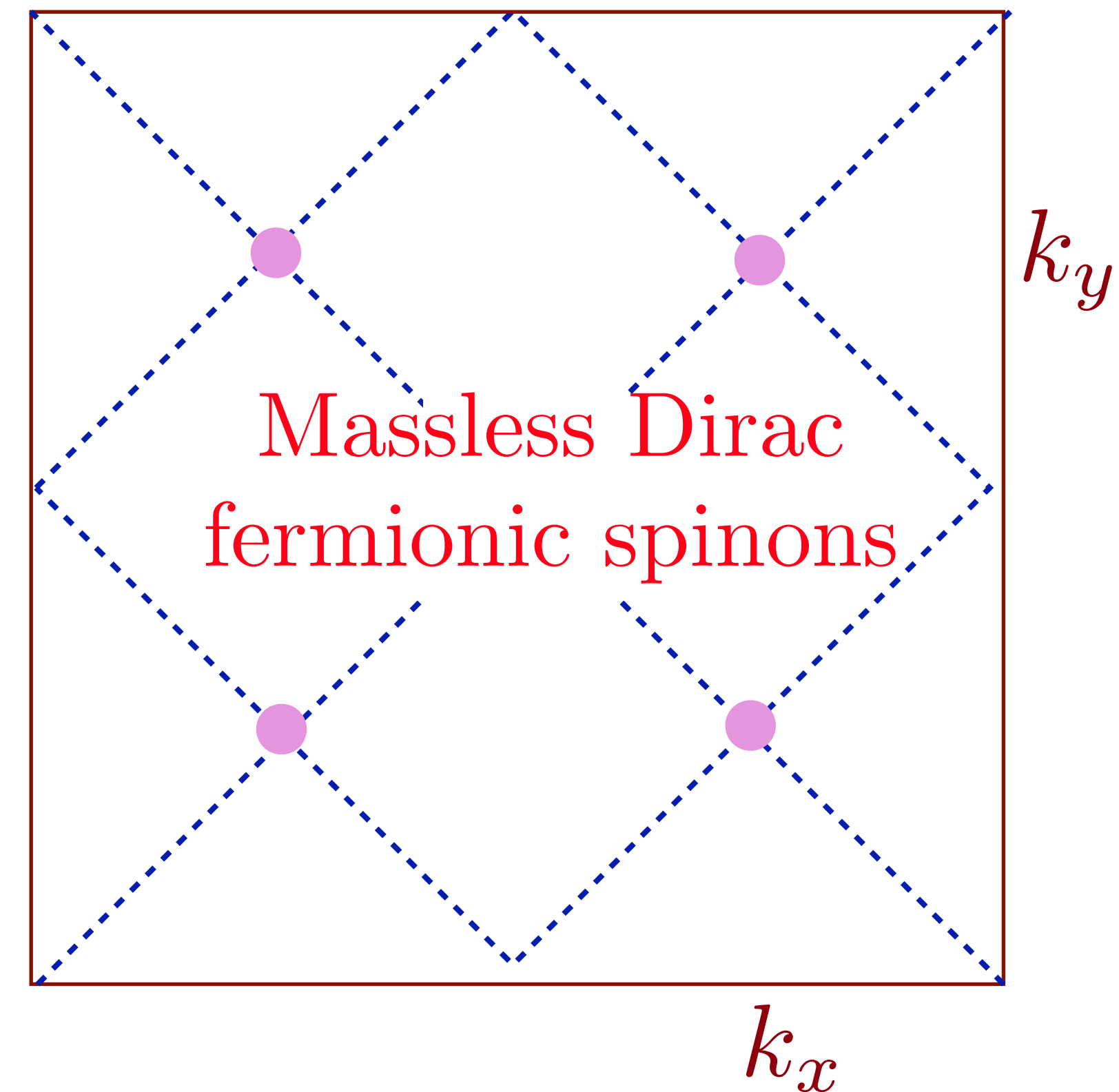


$$\mathcal{L} = i\bar{\psi}\gamma_\mu D_\mu\psi.$$

Néel order

Valence bond solid (VBS)

J_2/J_1



Critical spin liquid
 without quasiparticles?

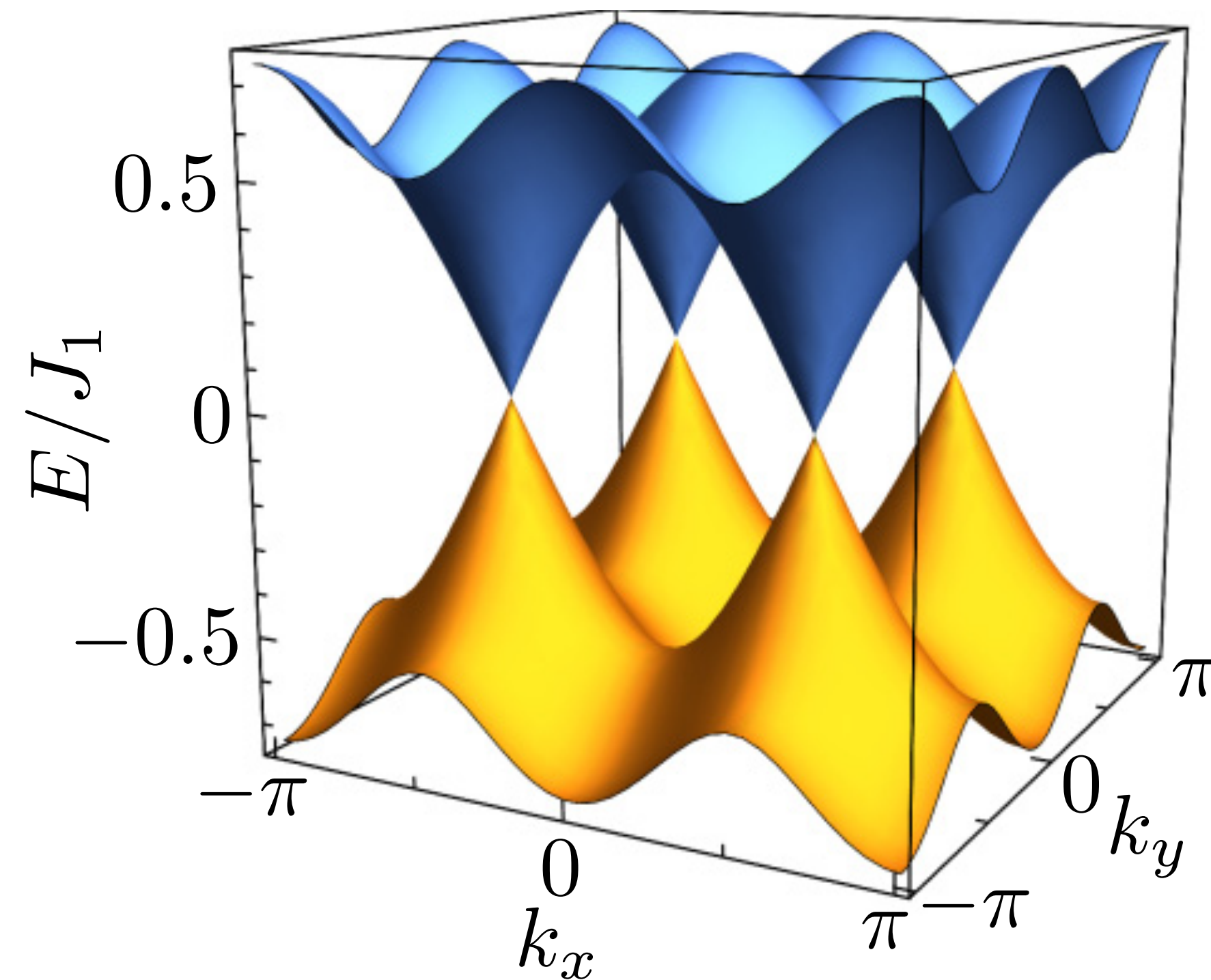
$N_f = 2$ SU(2) QCD

Confining instability
 to Néel and VBS,
 as in $\mathbb{CP}^1$ theory of Read+SS

$S=1/2$ square lattice

Characterization of quantum spin liquids and their spinon band structures via functional renormalization

We apply this approach to the antiferromagnetic J_1 - J_2 Heisenberg model on the square lattice and to the antiferromagnetic nearest-neighbor Heisenberg model on the kagome lattice. For the J_1 - J_2 model, we find that in the regime of maximal frustration a $SU(2)$ π -flux state with Dirac spinons yields the largest mean-field amplitudes.



square $J_2/J_1 = 0.55$

M. Hering, J. Sonnenschein,
Y. Iqbal and J. Reuther,
PRB **99**, 100405 (2019)



$S=1/2$ square lattice

Bosonic spinons:
 $\mathbb{CP}^1$ U(1) gauge theory

N. Read and S. Sachdev, PRL **62**, 1694 (1989)

Nearly-critical
 $S=1/2$ square
lattice
antiferromagnet
without
quasiparticles

SU(2) gauge theory of $N_f = 2$
fundamental, massless, Dirac fermions.

I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)

Obtained from a saddle-point of
fermionic spinons moving in π -flux.

SO(5) non-linear σ -model
of Néel/VBS orders
with $k = 1$ WZW term

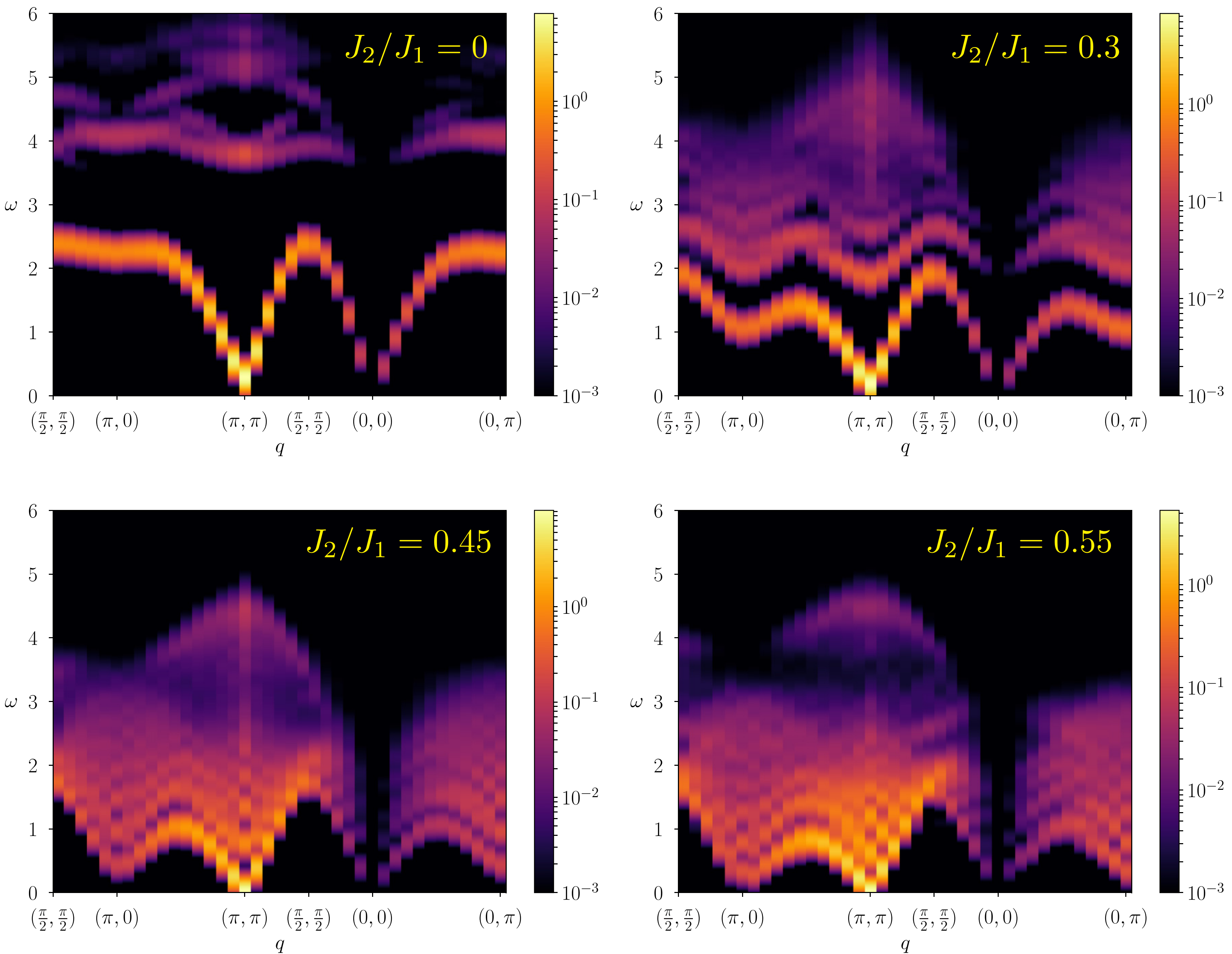
Many numerical works show that deconfined critical theory applies over a substantial length scale, but ultimately confines at the longest distances.

A. Tanaka and X. Hu, *Phys. Rev. Lett.* **95**, 036402 (2005); T. Senthil and M.P.A. Fisher *Phys. Rev. B* **74**, 064405 (2006); C. Wang, A. Nahum, M. A. Metlitski, C. Xu, T. Senthil, *Phys. Rev. X* **7**, 031051 (2017); Zheng Zhou, Liangdong Hu, Wei Zhu, Yin-Chen He, PRX **14**, 021044 (2024); S. M. Chester N. Su, PRL **132**, 111601 (2024). B.-B. Chen, X. Zhang, Y. Wang, K. Sun, Z. Y. Meng, PRL **132**, 246503 (2024); J. Takahashi, H. Shao, B. Zhao, W. Guo, A. W. Sandvik, arXiv:2405.06607.

Dynamic structure factor of the square lattice Heisenberg model with first (J_1) and second (J_2) neighbor exchange interactions.

F. Ferrari, F. Becca
PRB **98**, 100405 (2018).

Note the evolution from sharp spin-wave modes at $J_2/J_1 = 0$ to spinon continua at larger J_2/J_1 .



Anisotropic damping and wave vector dependent susceptibility of the spin fluctuations in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ studied by resonant inelastic x-ray scattering

H. C. Robarts, M. Barthélemy, K. Kummer, M. García-Fernández, J. Li, A. Nag, A. C. Walters, K. J. Zhou, and S. M. Hayden

PHYSICAL REVIEW B **100**, 214510 (2019)

- Spin waves in insulator broaden into a continuum:

Most natural interpretation is a spinon continuum, likely from the π -flux spin liquid

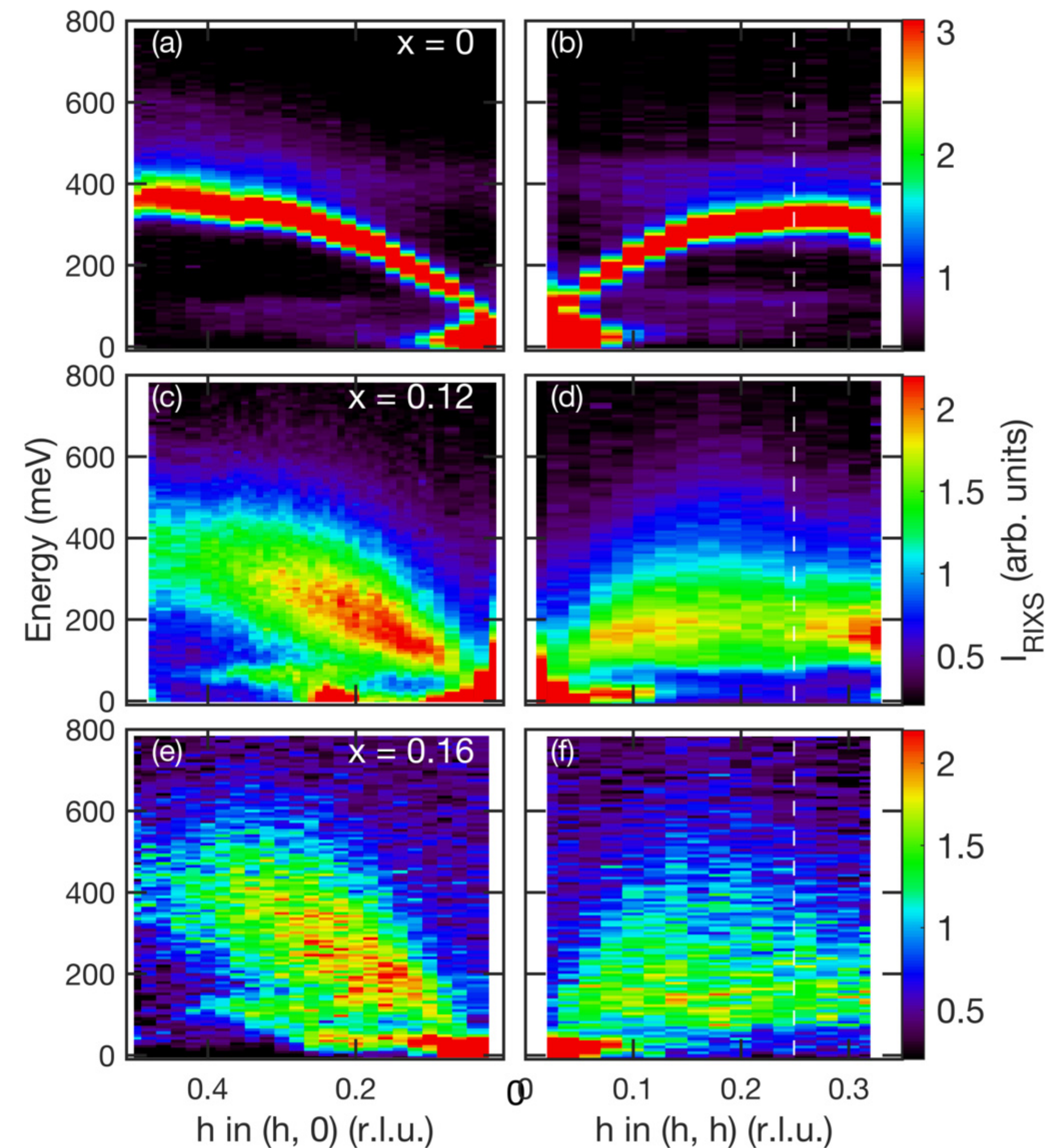
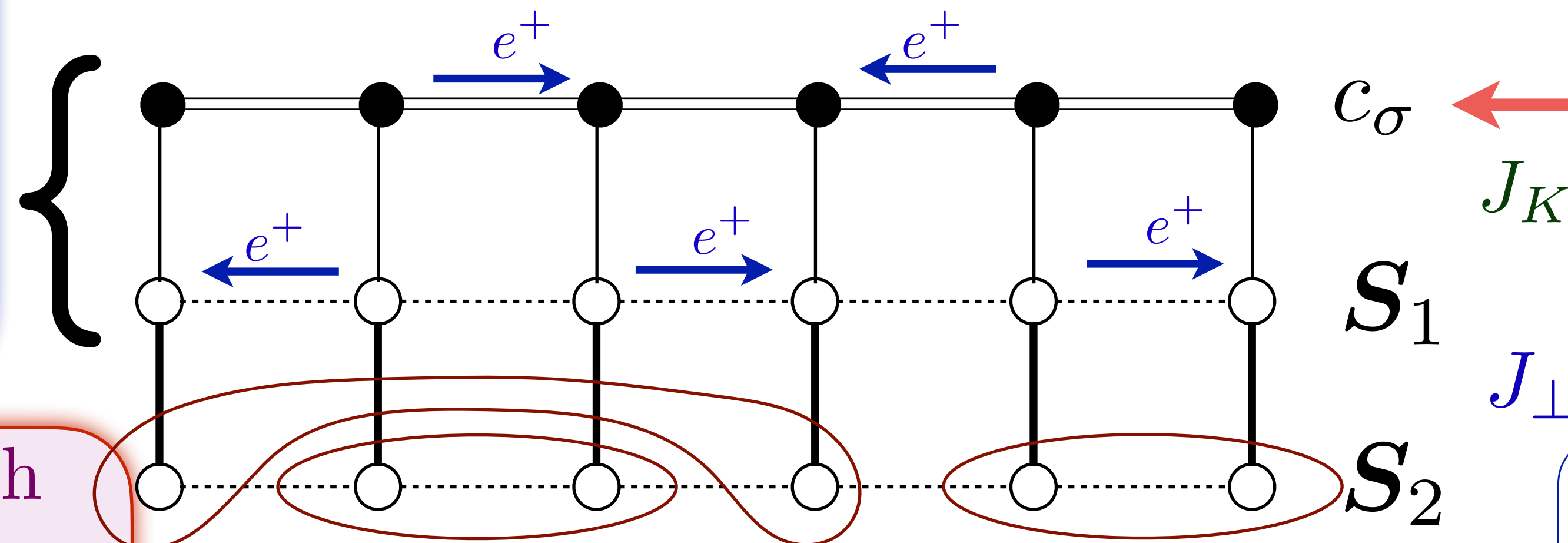


FIG. 2. I_{RIXS} intensity maps as a function of $\mathbf{Q}$ in LSCO $x = 0$ ($T \approx 20$ K), 0.12, and 0.16 ($T \approx 30$ K).

Trial wavefunction for FL* of Hubbard model

Kondo lattice heavy Fermi liquid.
Area $(1 + p + 1)/2 = p/2 \pmod{1}$.
Small Fermi surface!



Free holes of density $1+p$

π -flux spin liquid with SU(2) gauge field and massless Dirac spinons

$$\mathbf{S}_{1i} = \frac{1}{2} f_{1i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} f_{1i\beta}$$

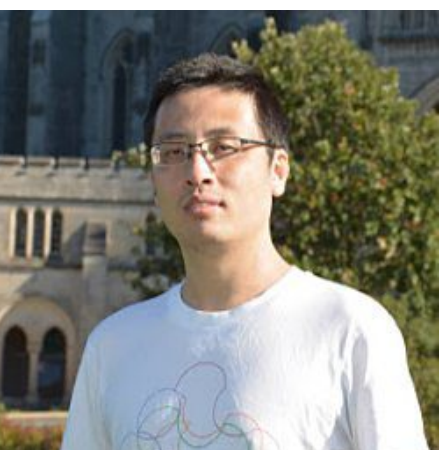
$$\mathbf{S}_{2i} = \frac{1}{2} f_{i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} f_{i\beta}$$

Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

Pseudogap metal =
Kondo Lattice Heavy Fermi Liquid
 $\oplus$
Spin Liquid

$$|\text{FL}^*\rangle = [\text{Projection onto rung singlets of } \mathbf{S}_1, \mathbf{S}_2] \\ \bowtie |\text{Slater determinant of } (c, f_1)\rangle \\ \otimes |\text{Slater determinant of } f\rangle$$

Ya-Hui Zhang



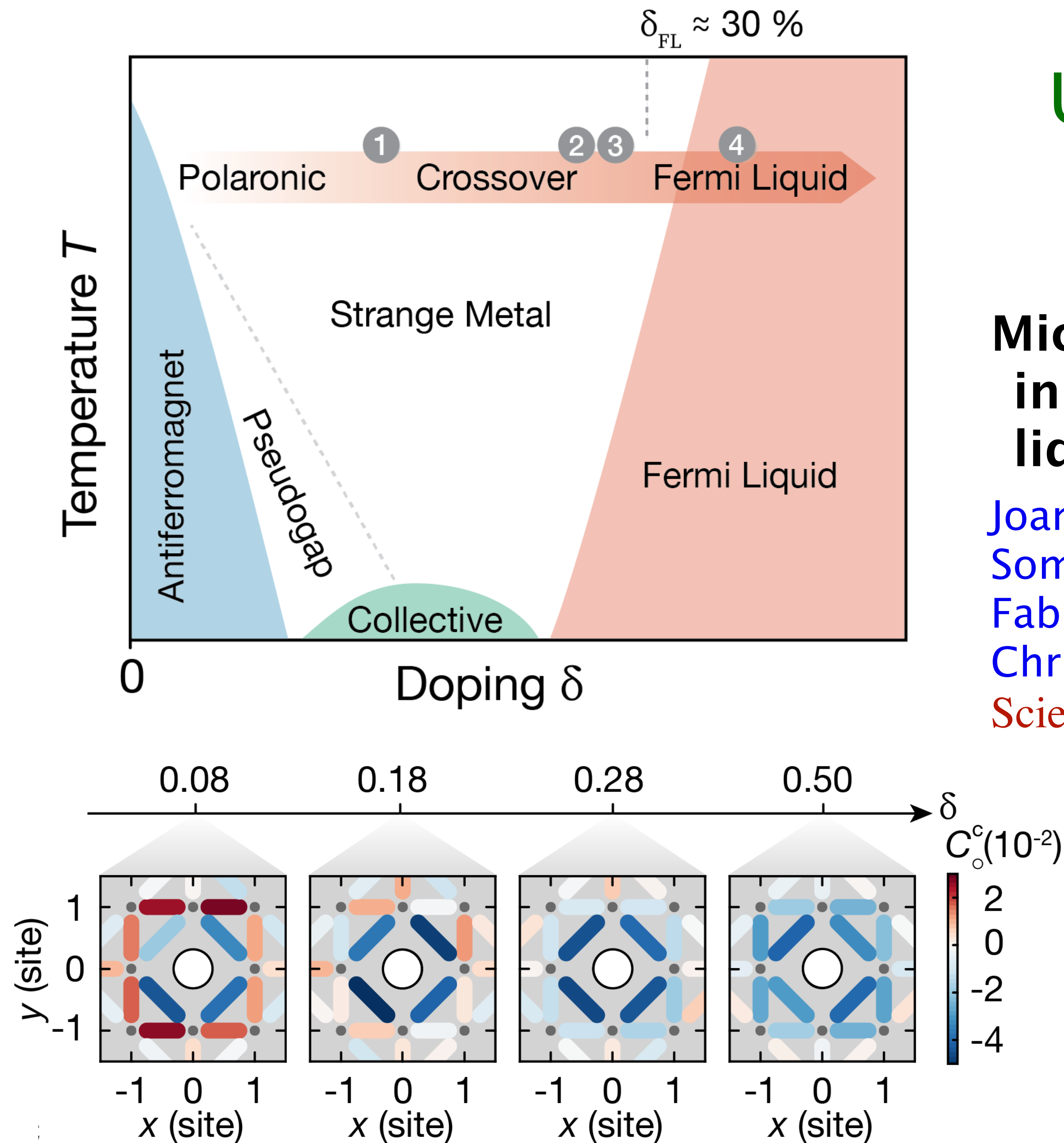
Replacement for “vanilla” Gutzwiller-projected Fermi liquid in the underdoped regime

Ultracold fermionic atoms in optical lattices

Microscopic evolution of doped Mott insulators from polaronic metal to Fermi liquid

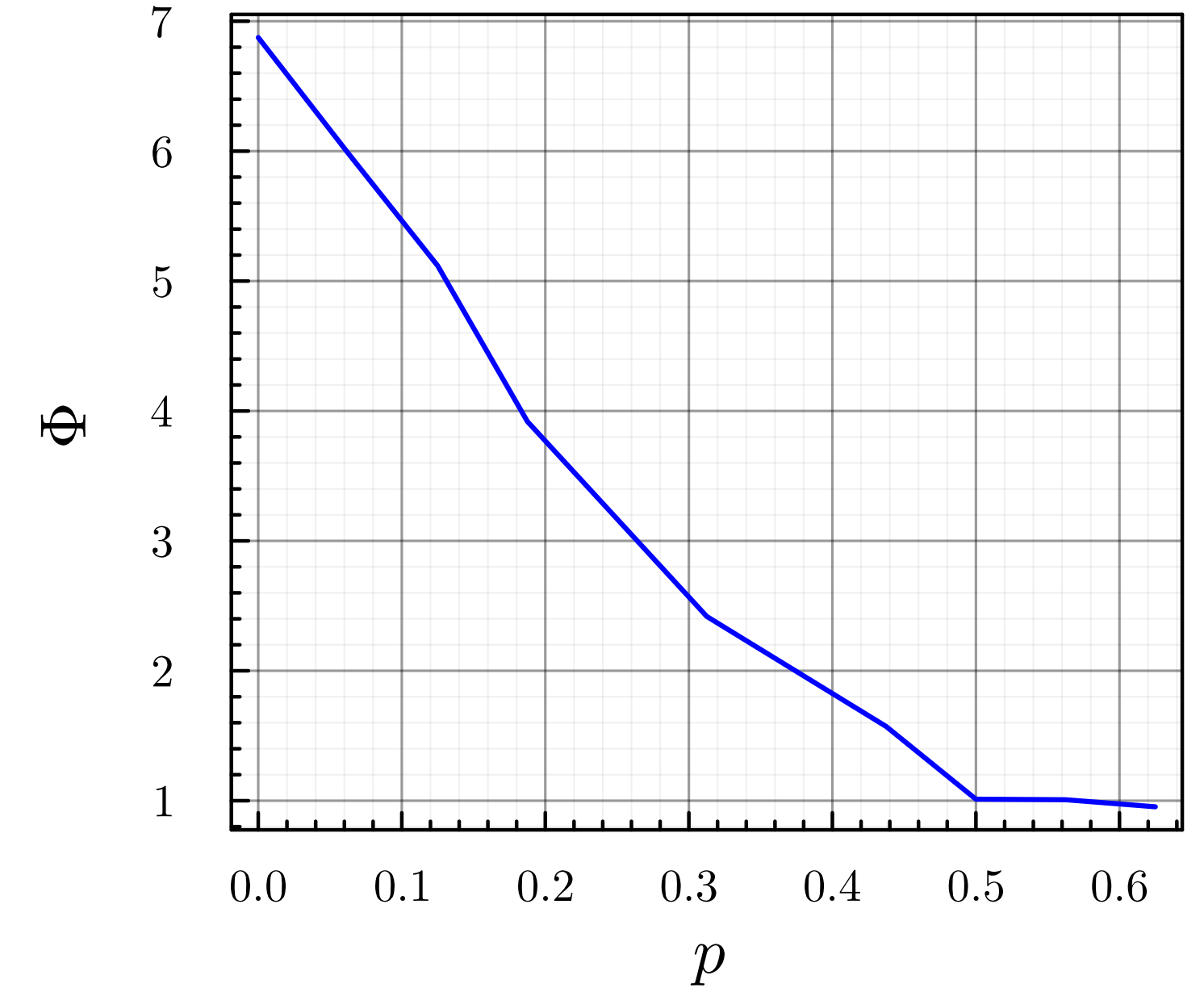
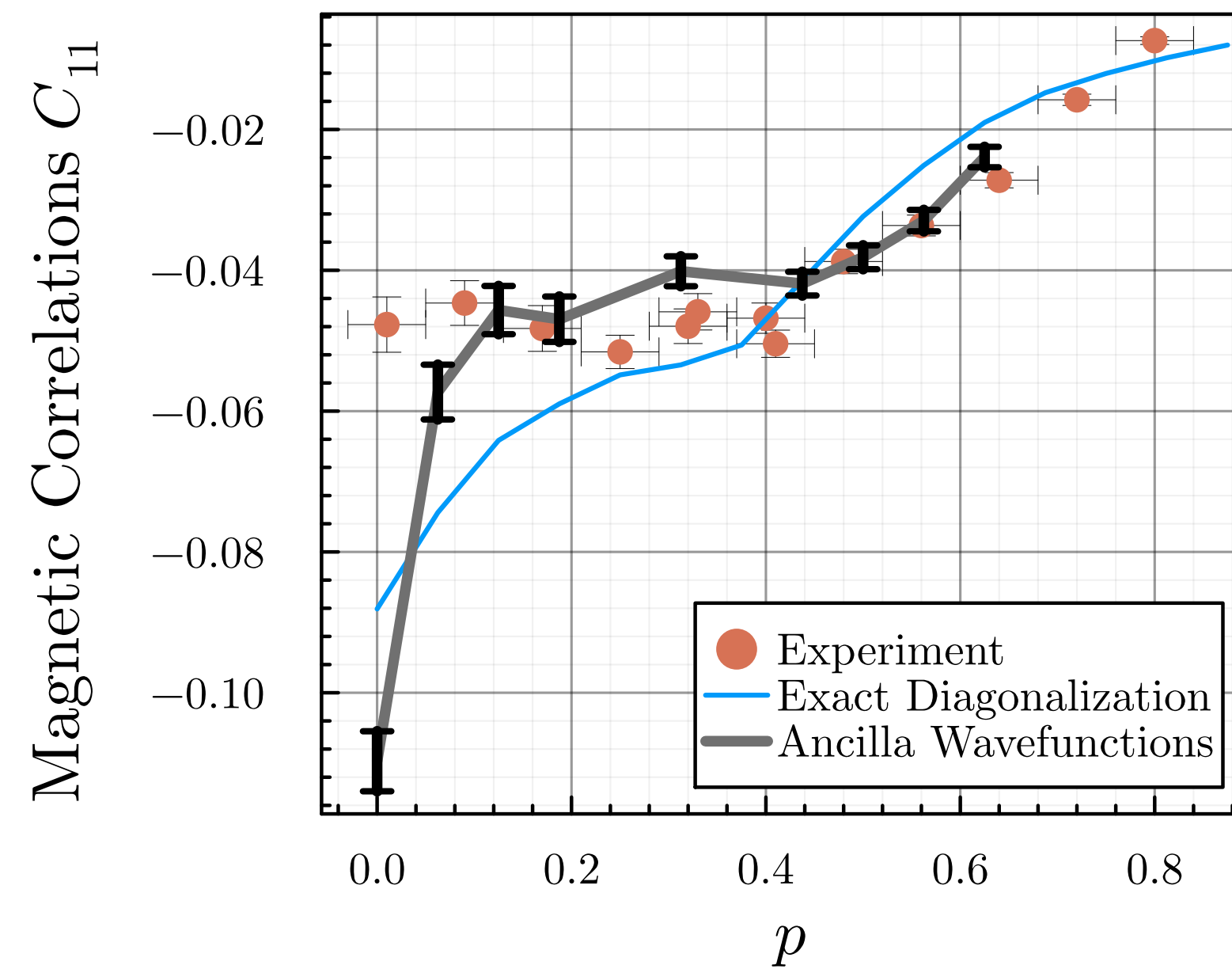
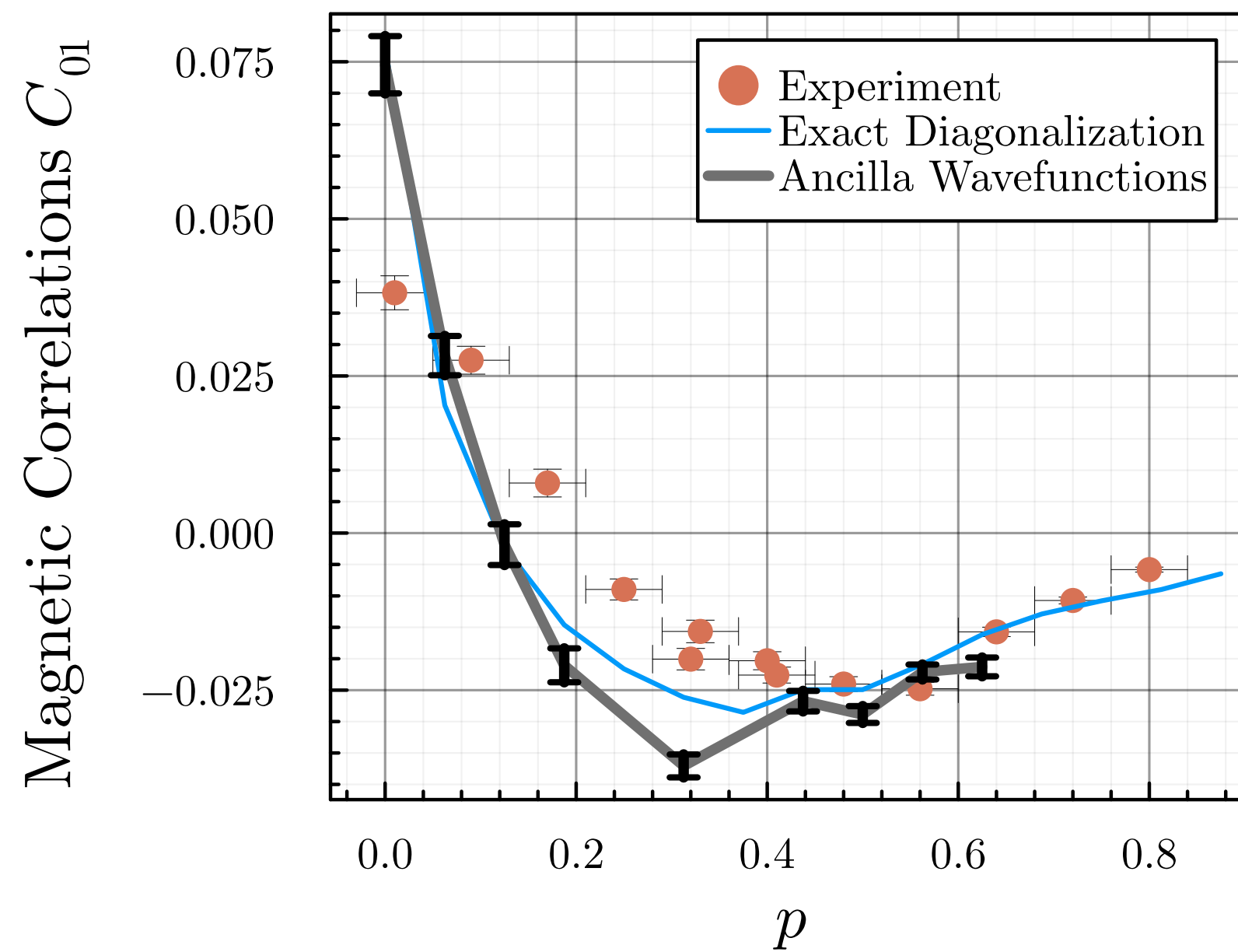
Joannis Koepsell, Dominik Bourgund, Pimonpan Sompet, Sarah Hirthe, Annabelle Bohrdt, Yao Wang, Fabian Grusdt, Eugene Demler, Guillaume Salomon, Christian Gross, Immanuel Bloch

Science **374** (2021) 82

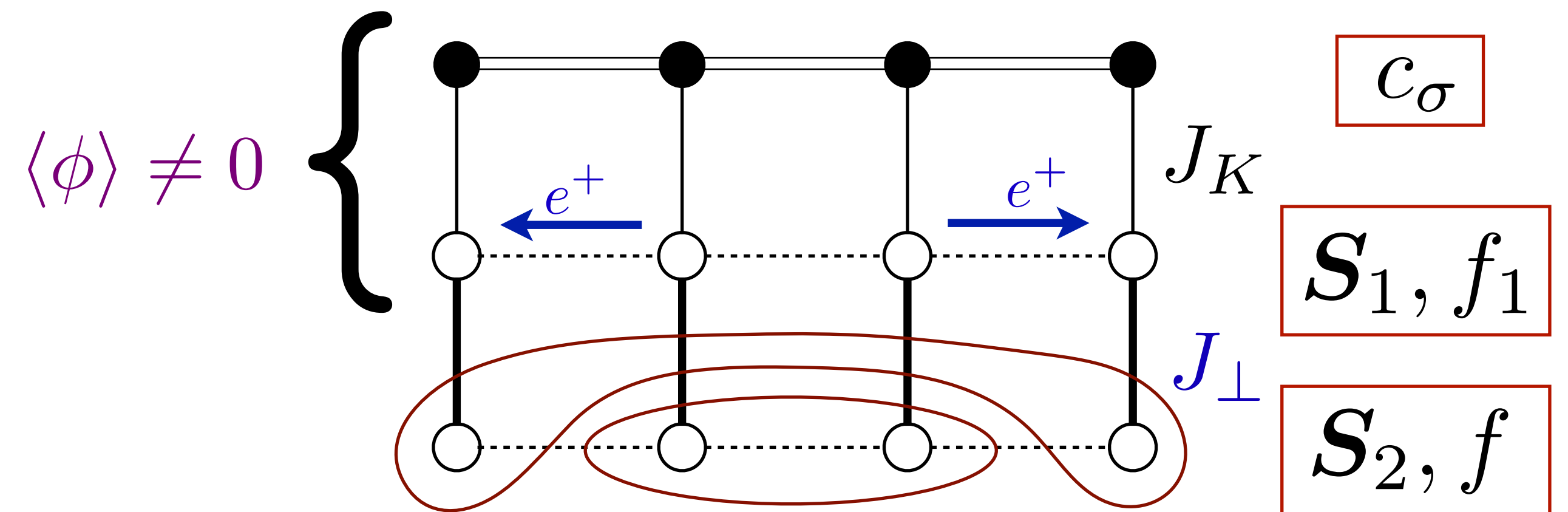


Max Planck Institute of
Quantum Optics,
Garching

Trial wavefunction for FL* of Hubbard model



Higgs boson $\phi \sim f_{1\sigma}^\dagger c_\sigma$.

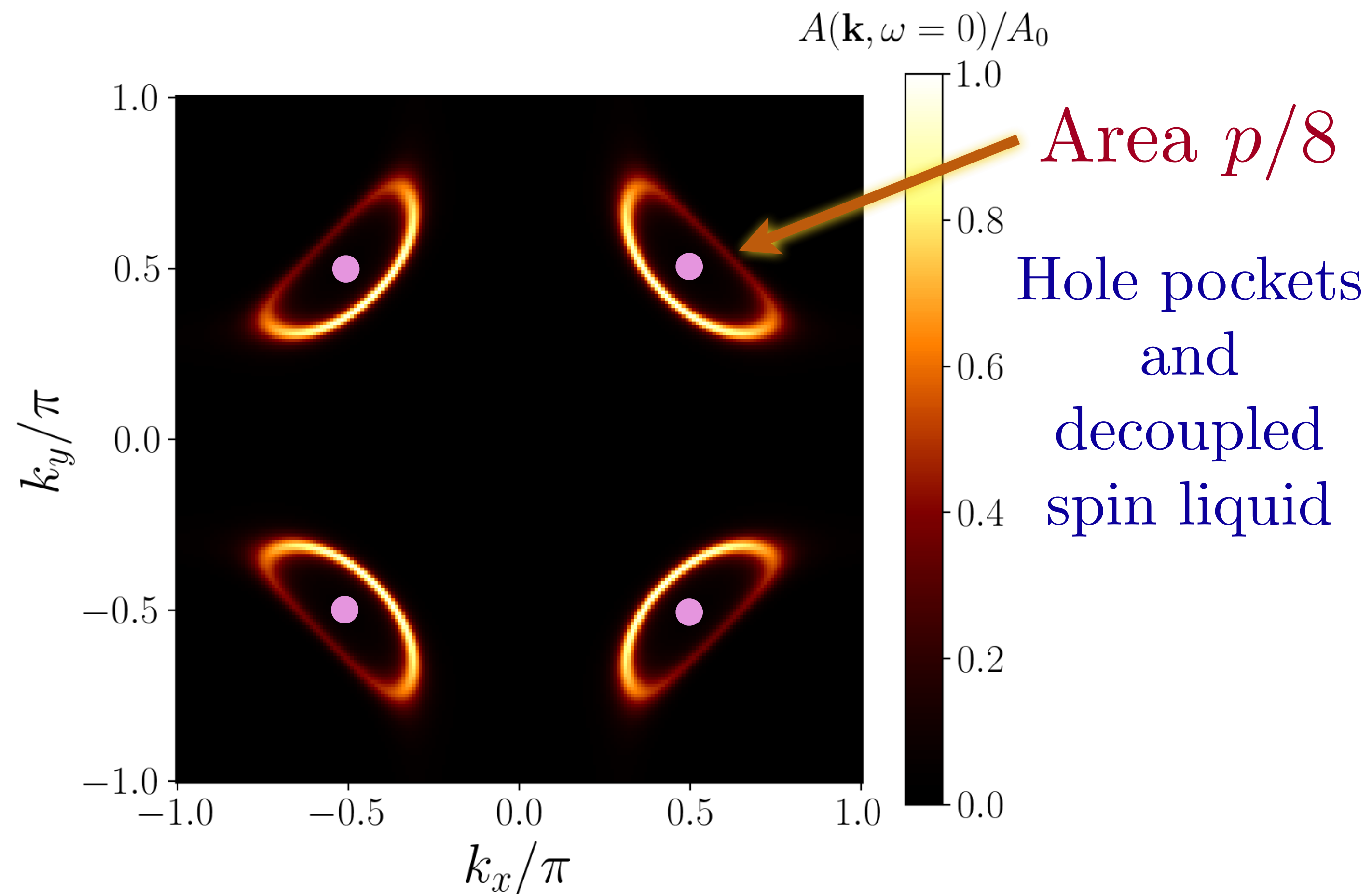


L. Shackleton and Shiwei Zhang, arXiv:2408.02190

Tobias Müller, Yasir Iqbal, S.S., Ronny Thomale, PNAS **122**, e2504261122 (2025)

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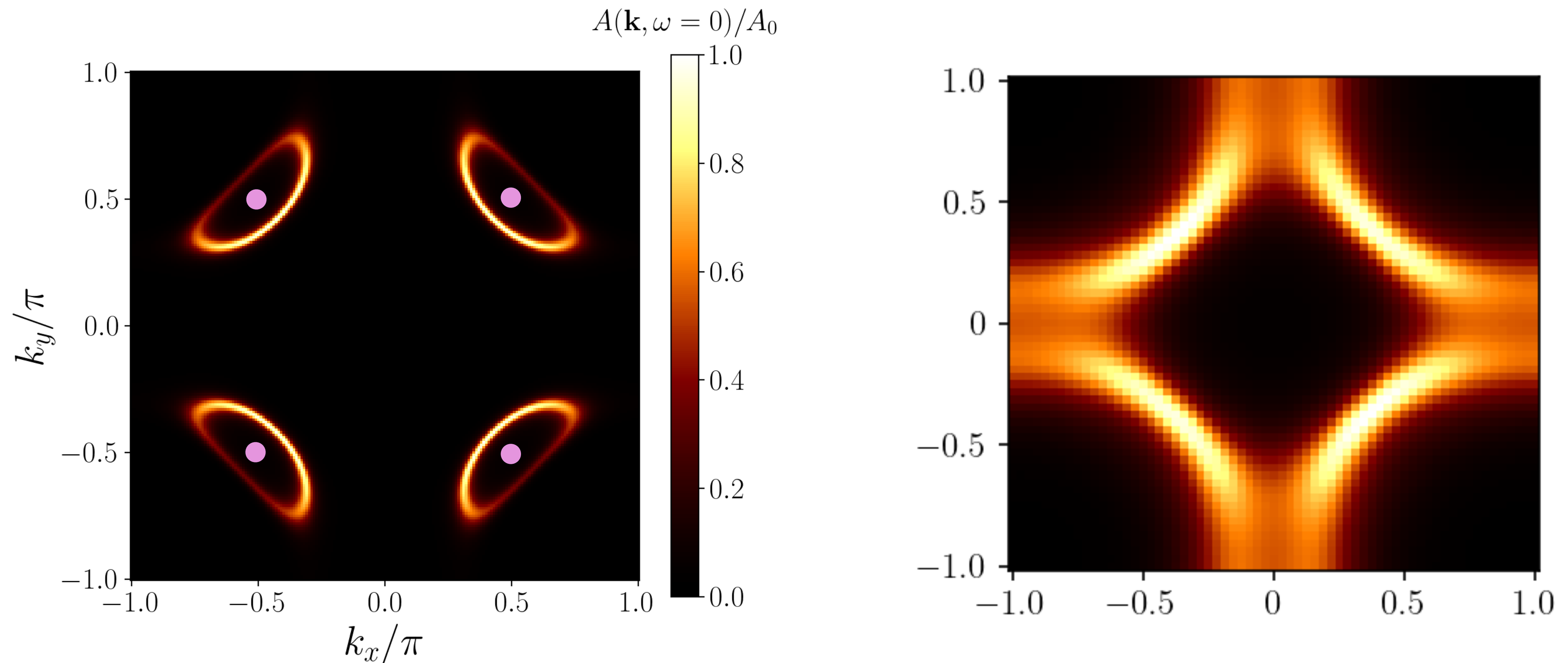
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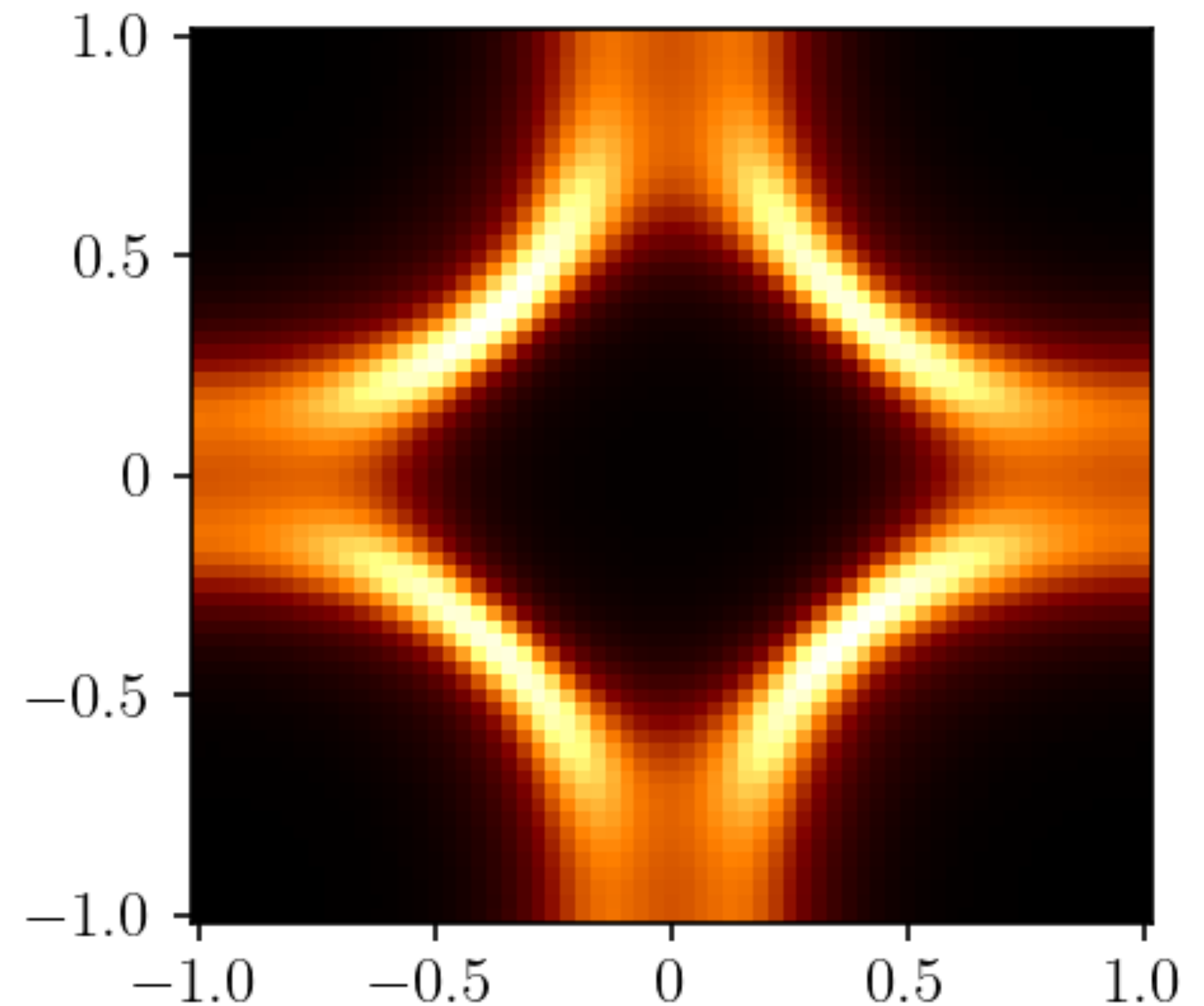
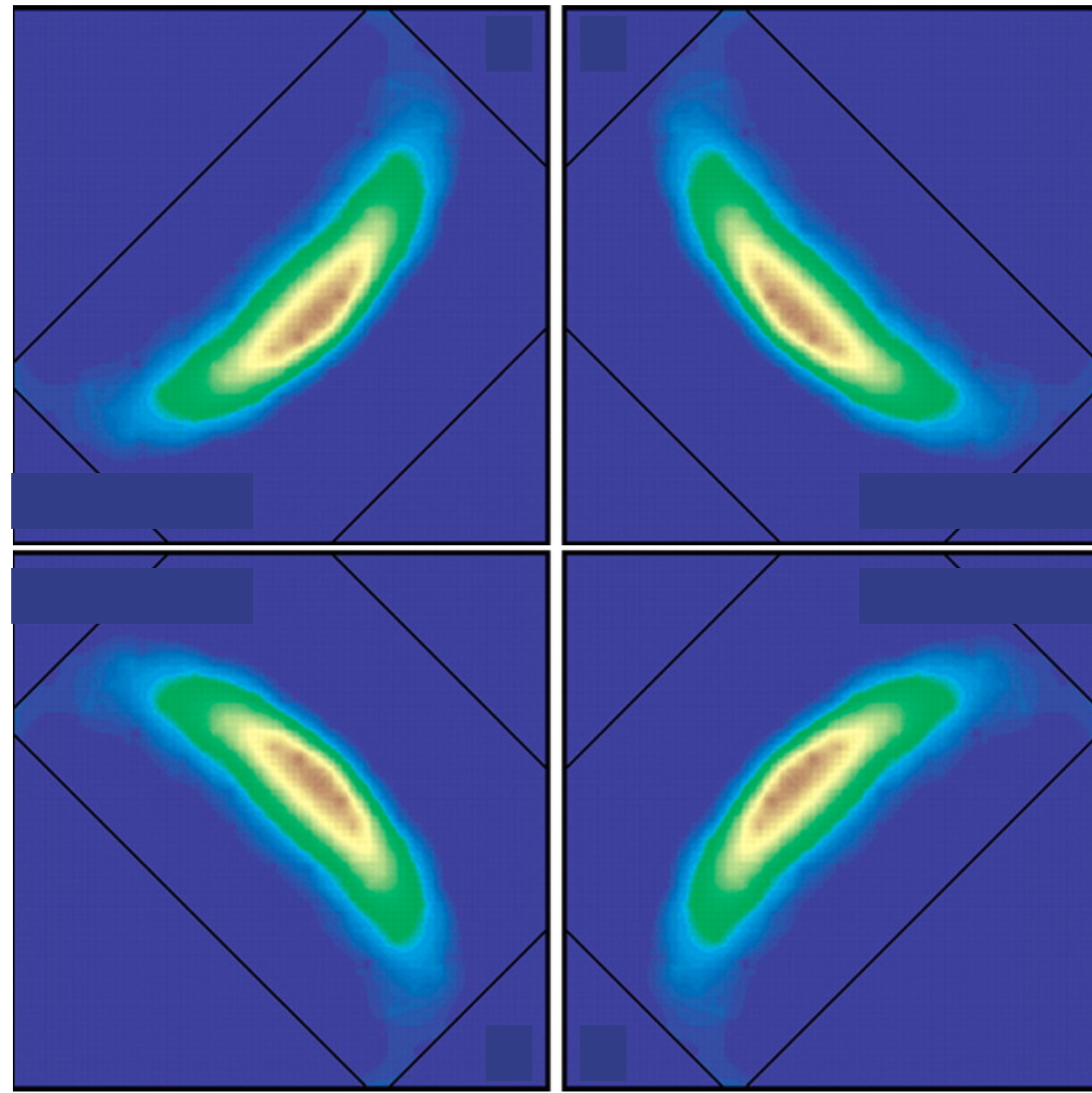
Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, S. S., PRB **105**, 075146 (2022)

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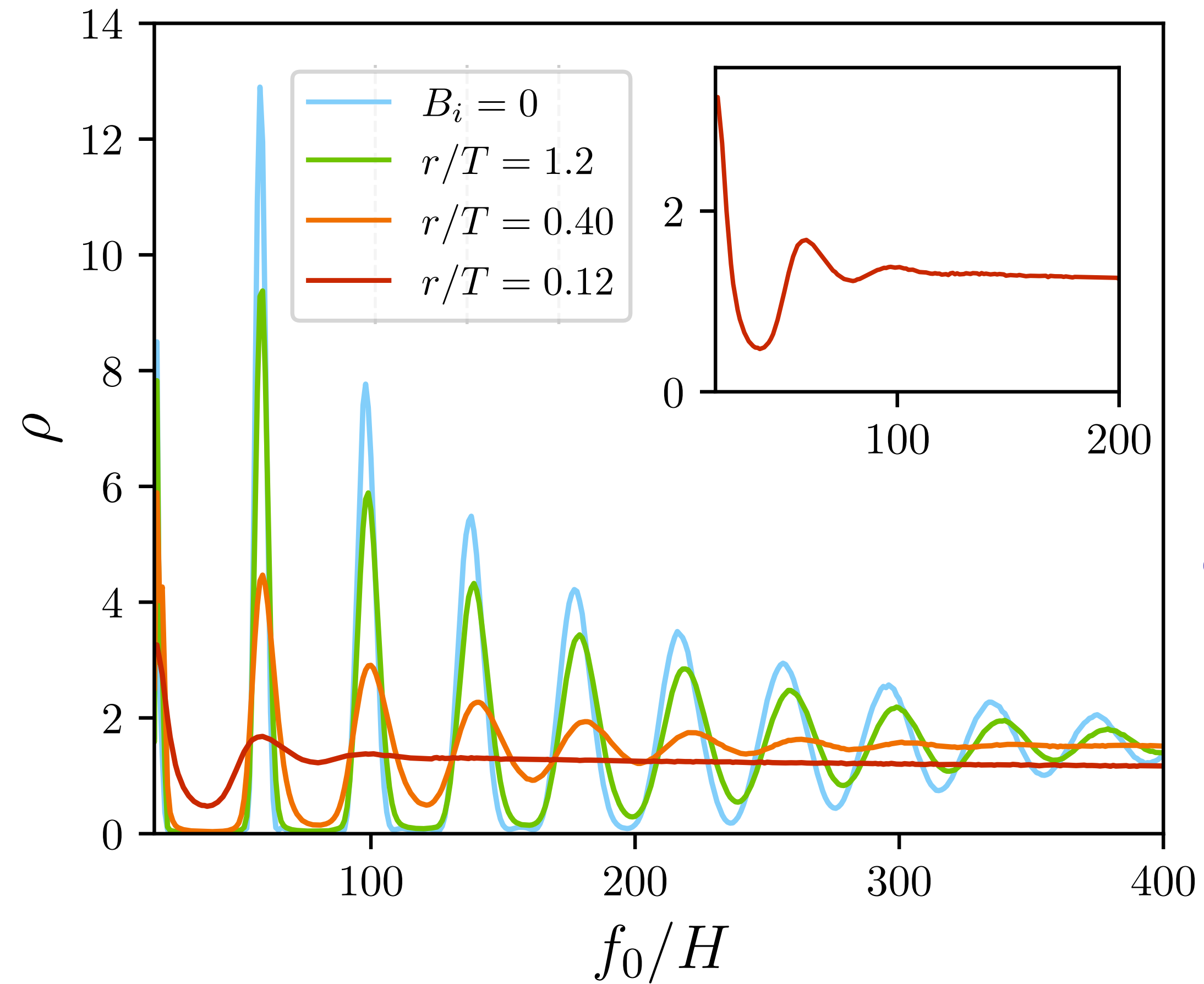
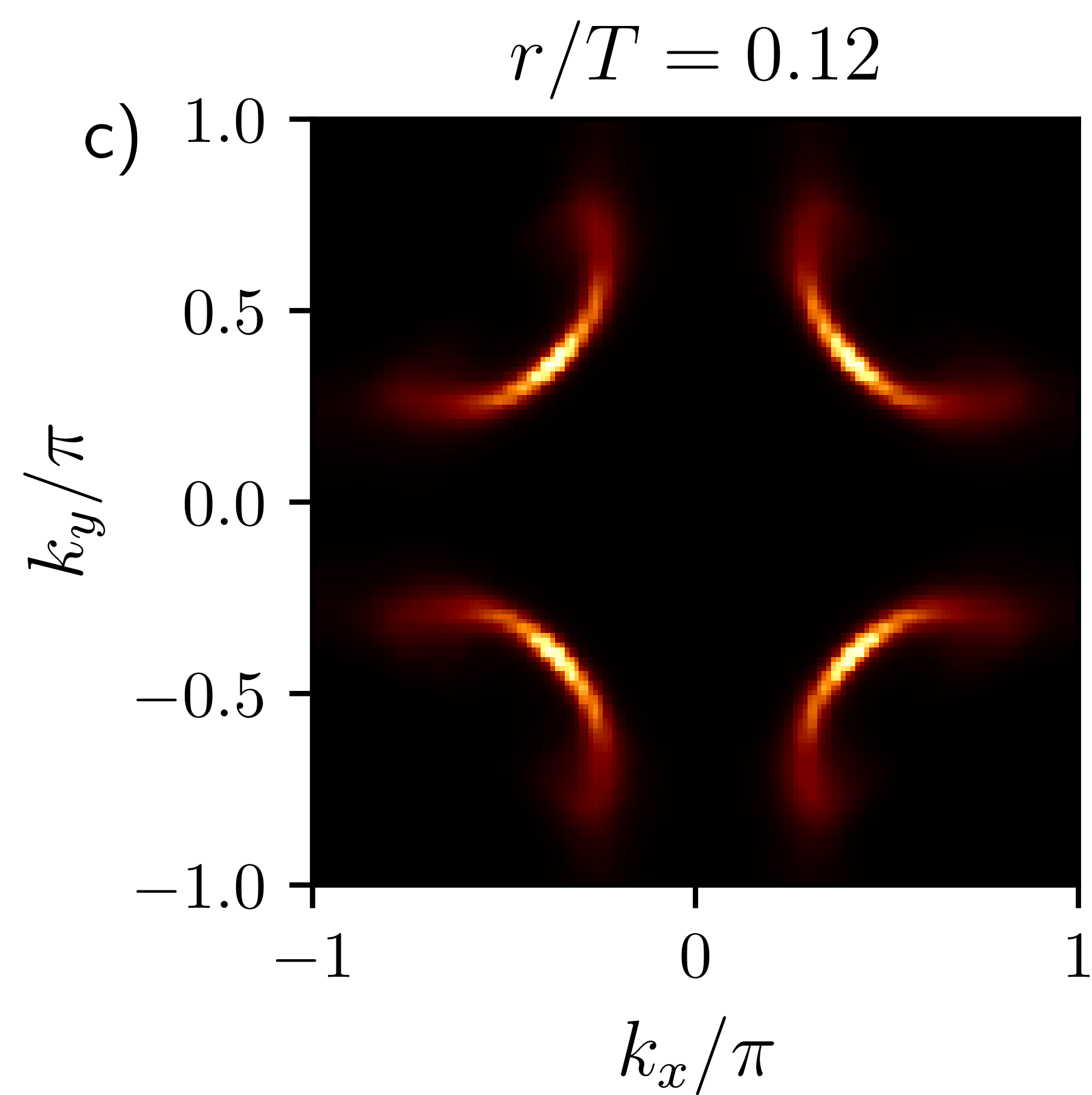
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Hole pockets coupled to critical spin liquid by **thermal fluctuations** of a $SU(2)$ gauge theory with a charge e Higgs field.



Kyle M. Shen, ... Z.-X. Shen, Science **307**, 901 (2005)

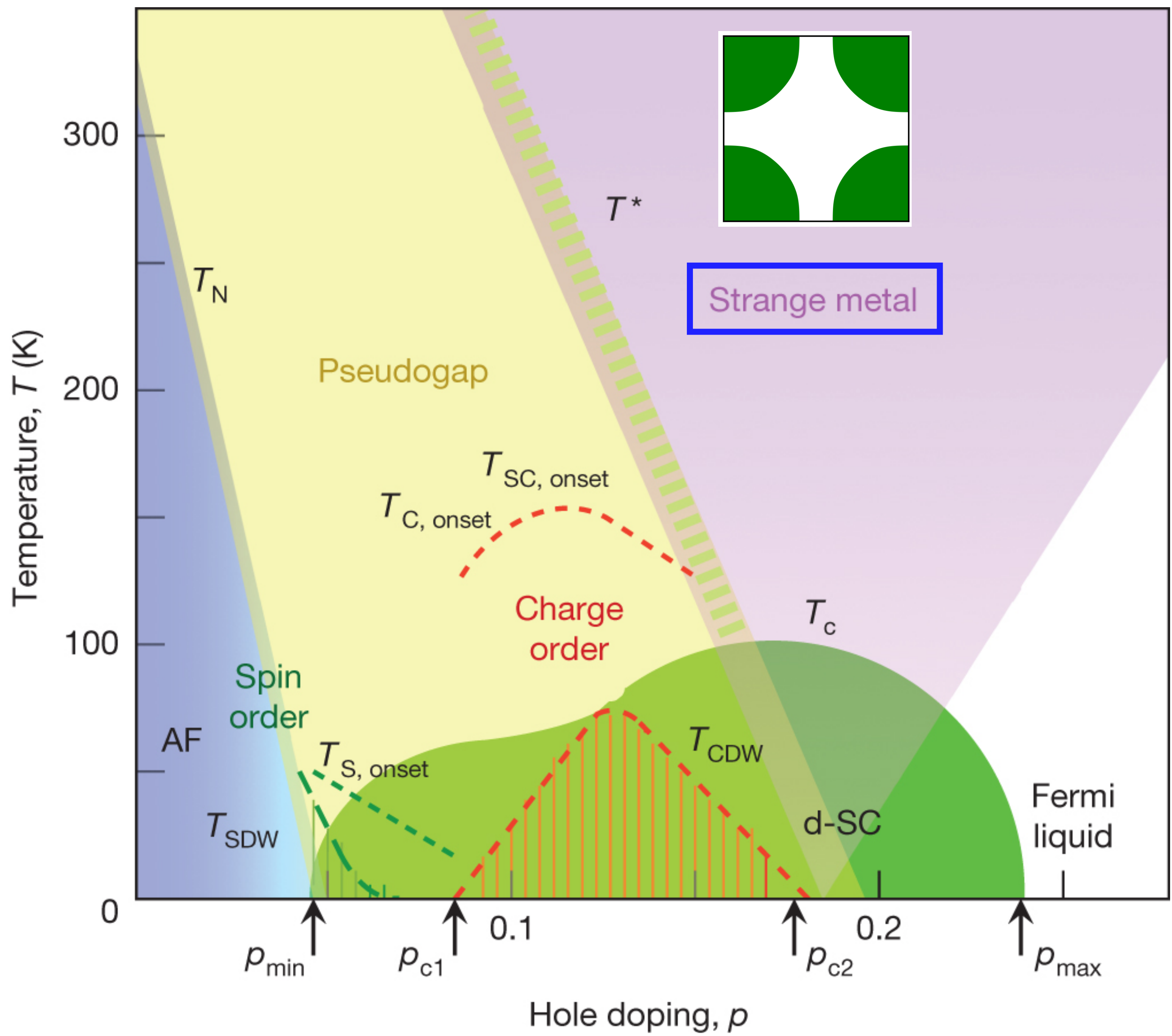
H. Pandey, M. Christos, P.M. Bonetti, R. Shanker, A. Nikolaenko, S. Sharma, S.S., arXiv:2507.05336

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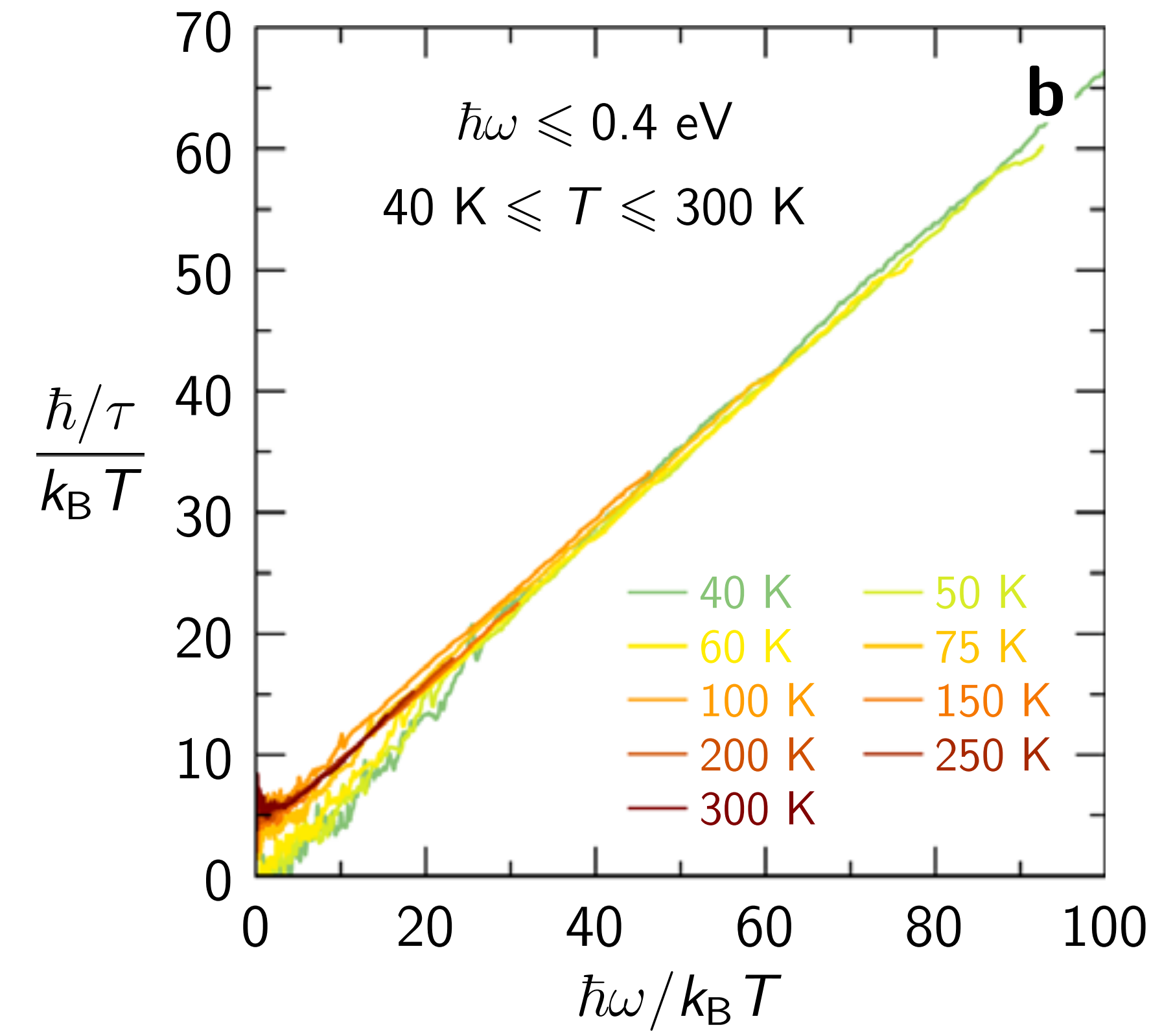


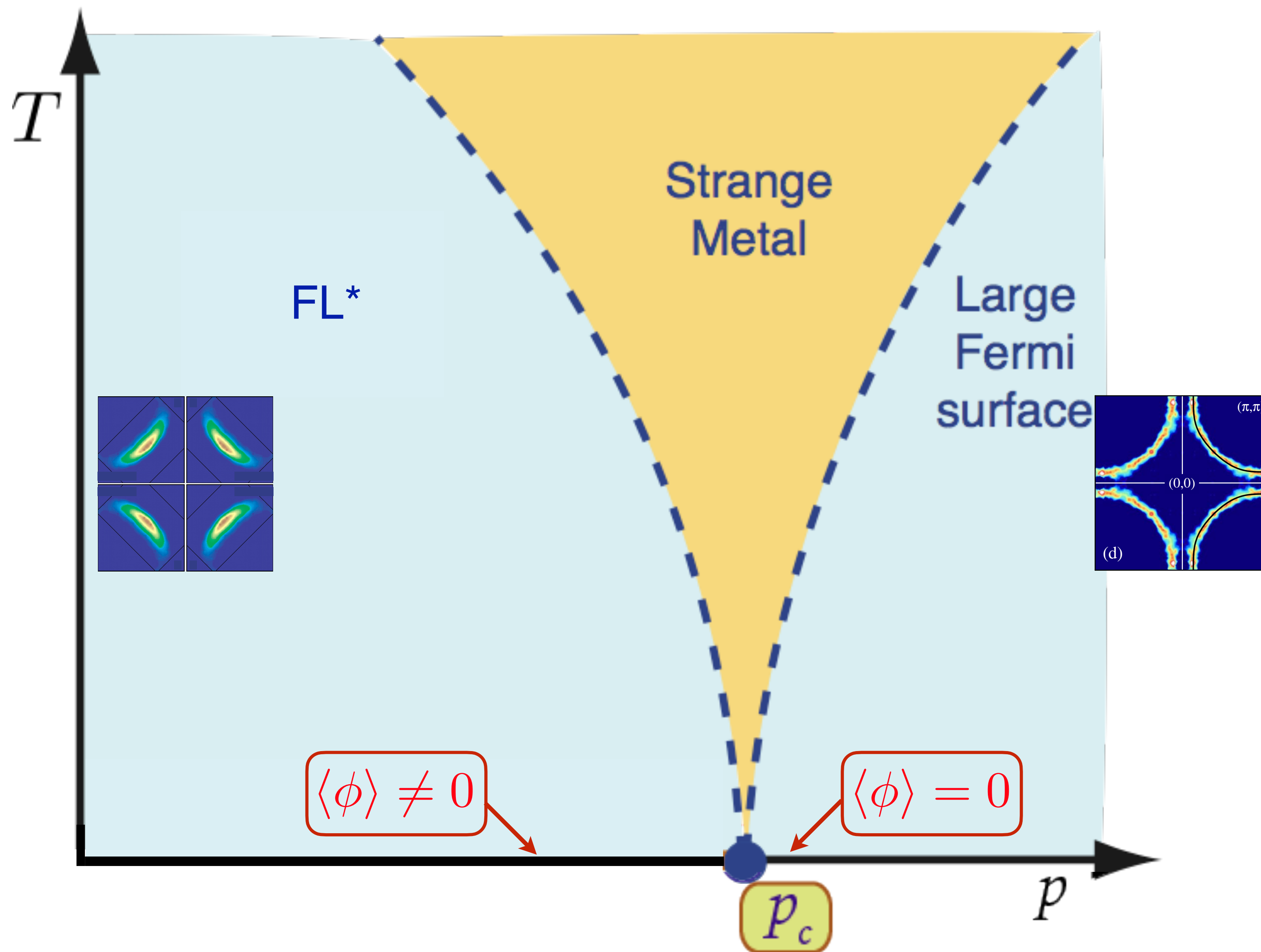
Fermi arcs
co-exist with
quantum
oscillations
of hole pockets
of area $p/8$.

Phase diagram and strange metal

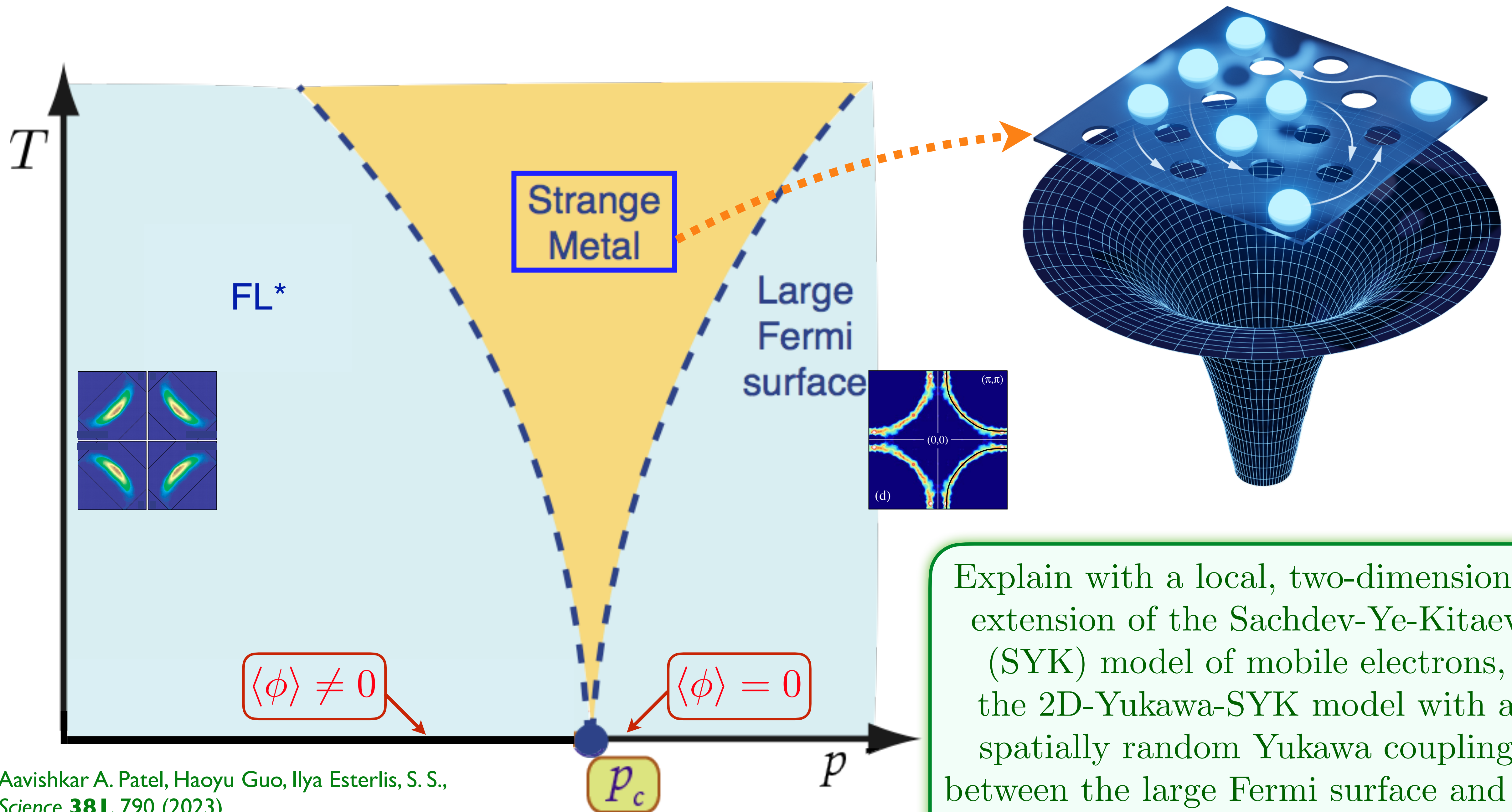


Planckian dynamics !
of large Fermi surface
Electron scattering time τ
from optical conductivity

$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$


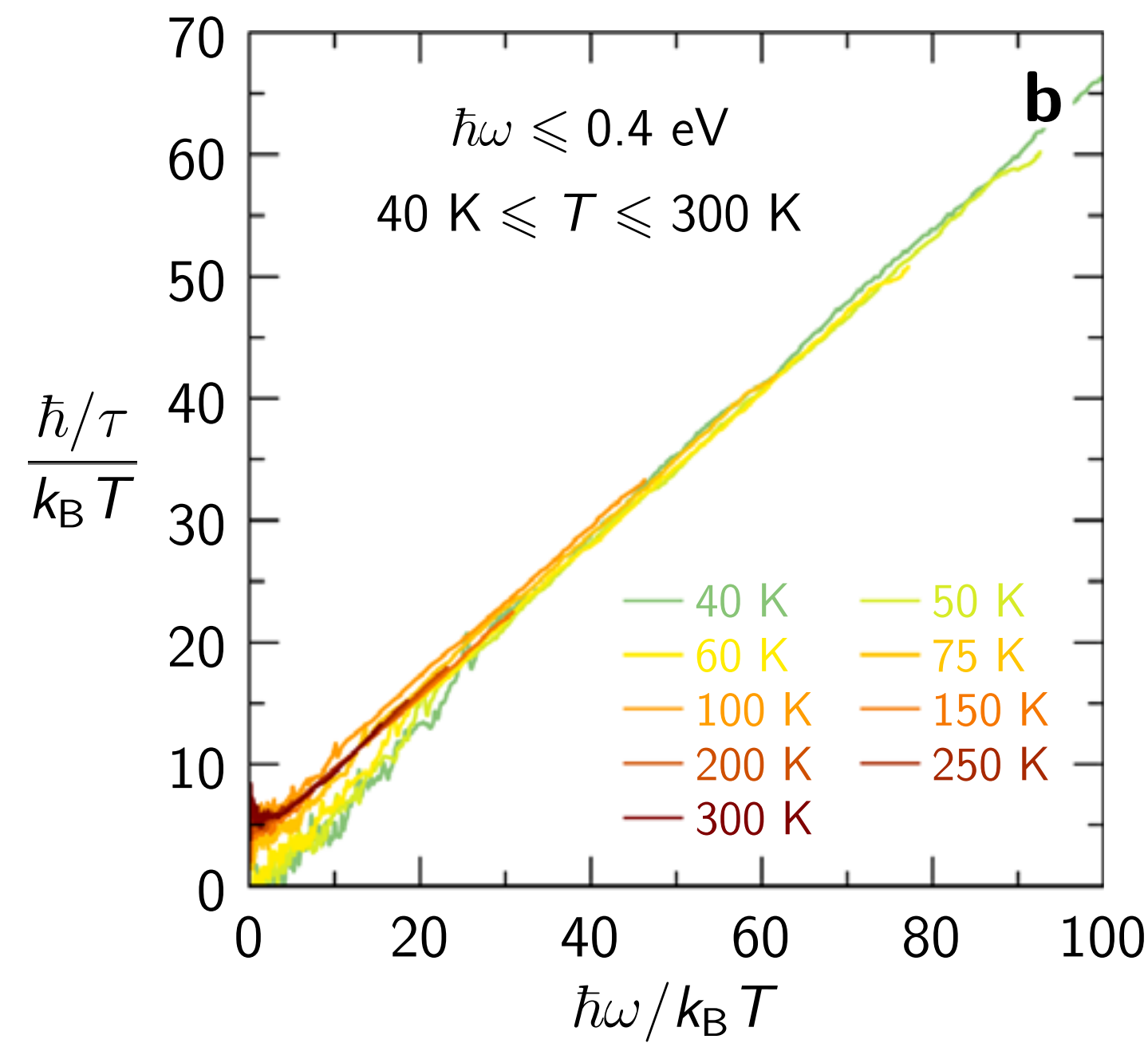
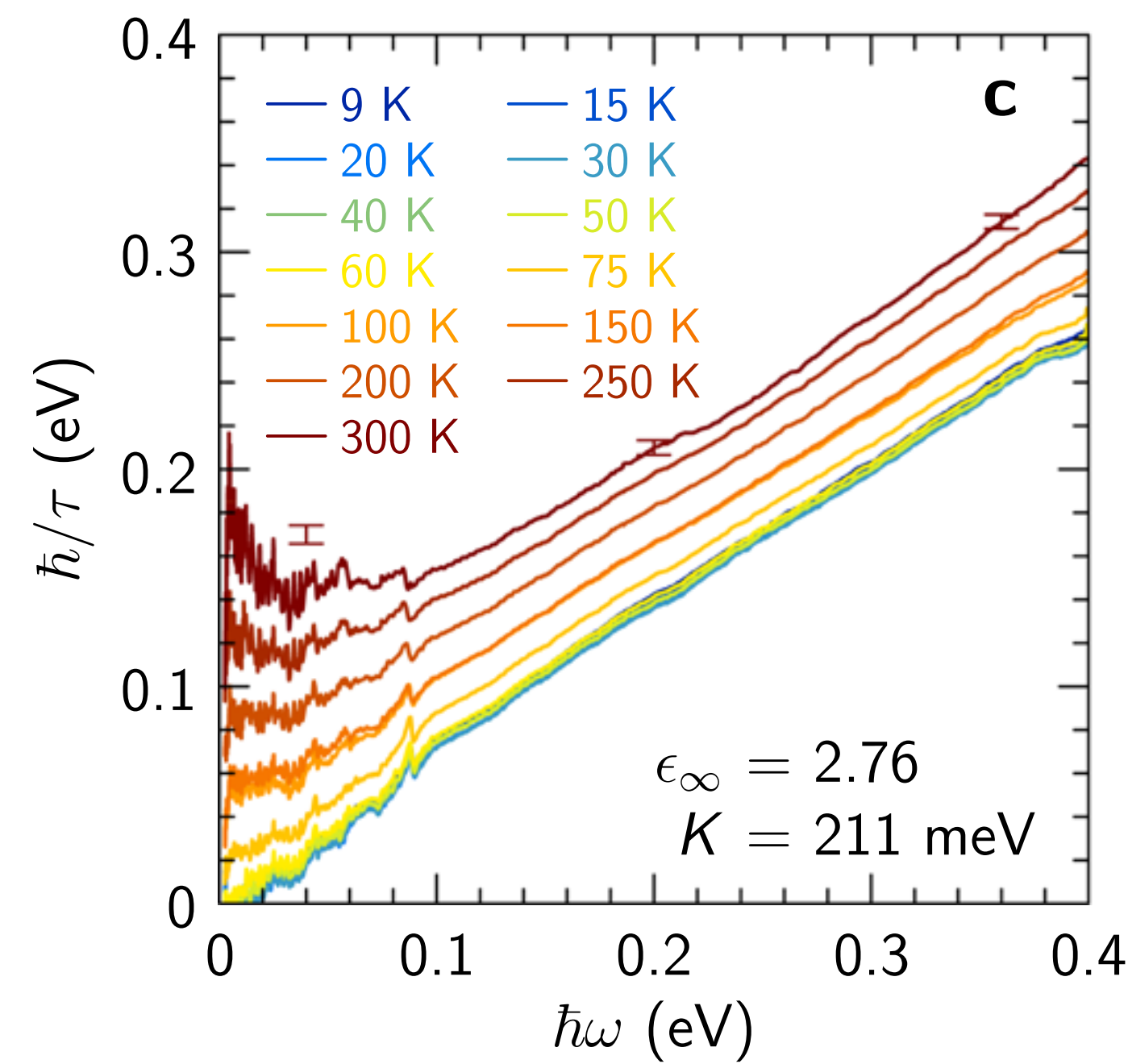


Quantum-criticality
of a
quantum phase transition
between two metals
(FL^* and FL)
at $p = p_c$,
with no symmetry breaking.
 ϕ is a Higgs field with
emergent gauge charge.



Explain with a local, two-dimensional extension of the Sachdev-Ye-Kitaev (SYK) model of mobile electrons, the 2D-Yukawa-SYK model with a spatially random Yukawa coupling between the large Fermi surface and ϕ : a critical charge liquid

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. S.,
Science **381**, 790 (2023)
 Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentini,
 Jorg Schmalian, S.S., Ilya Esterlis, *PRL* **133**, 186502 (2024)



$$\sigma(\omega) = i \frac{e^2 K / (\hbar d_c)}{\hbar\omega \frac{m^*(\omega)}{m} + i \frac{\hbar}{\tau(\omega)}}$$

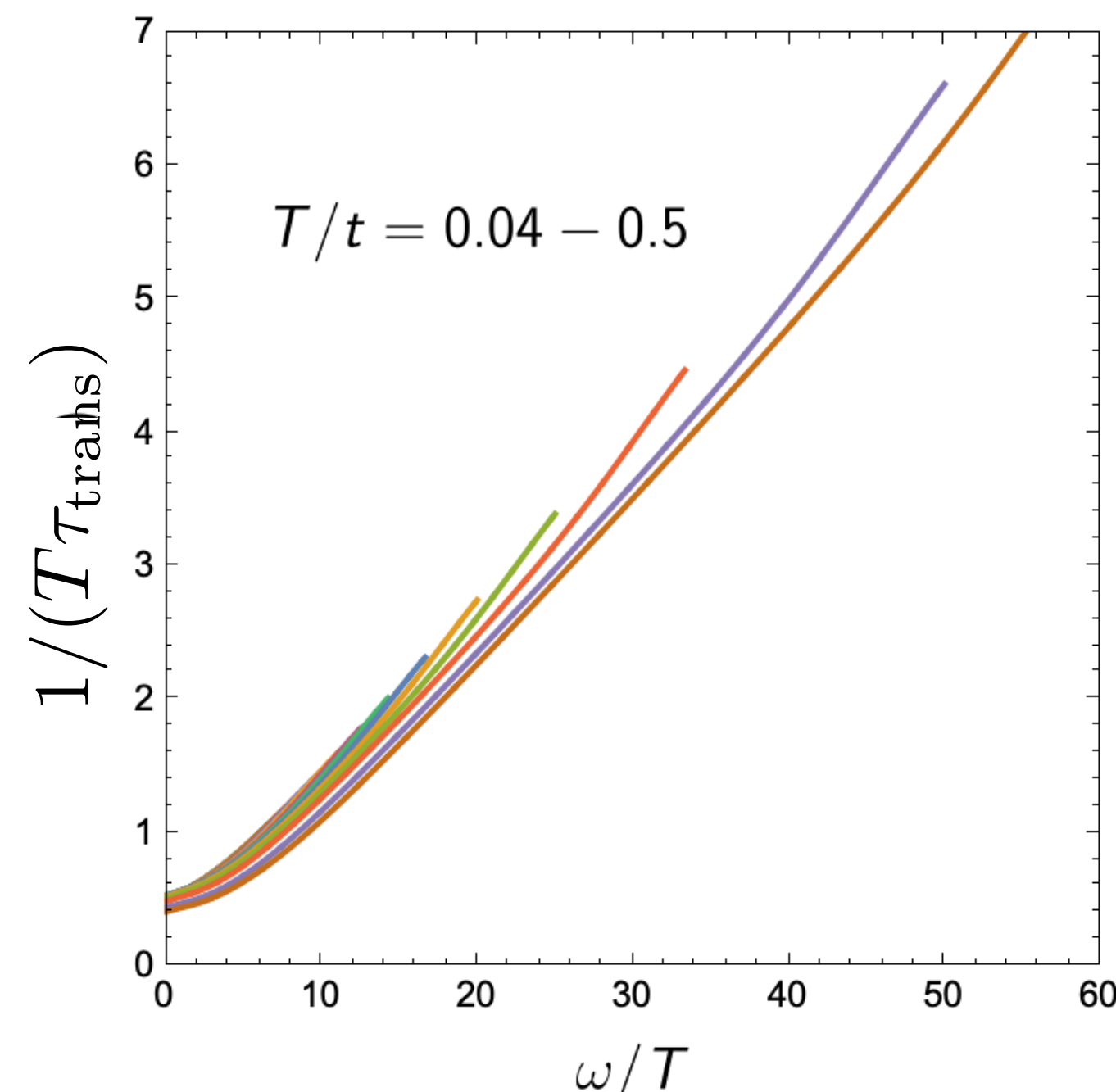
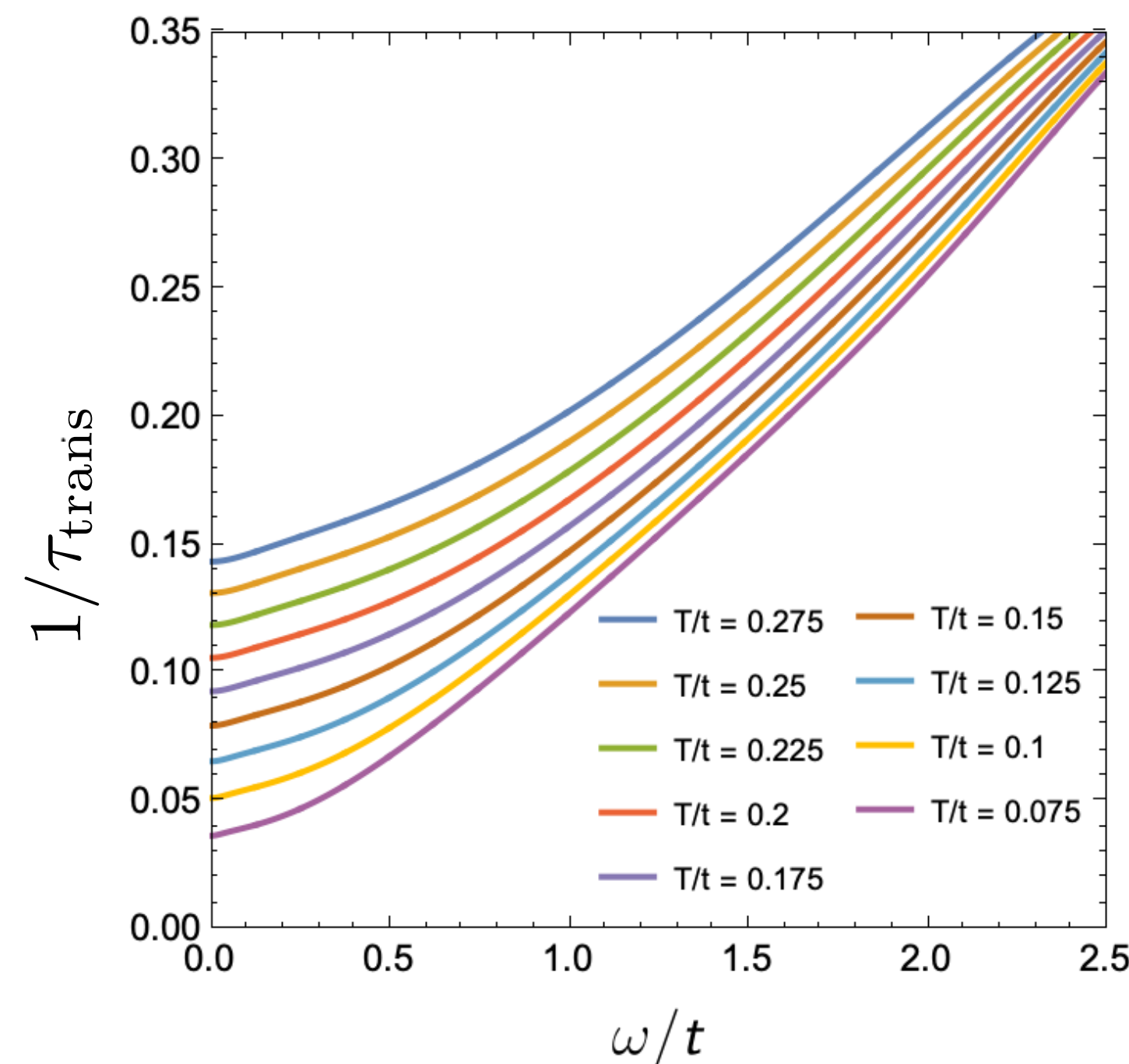
B. Michon, C. Berthod, C.W. Rischau, A. Ataei, L. Chen, S. Komiya, S. Ono, L. Taillefer, D. van der Marel, A. Georges, Nature Comm. **14**, 3033 (2023)

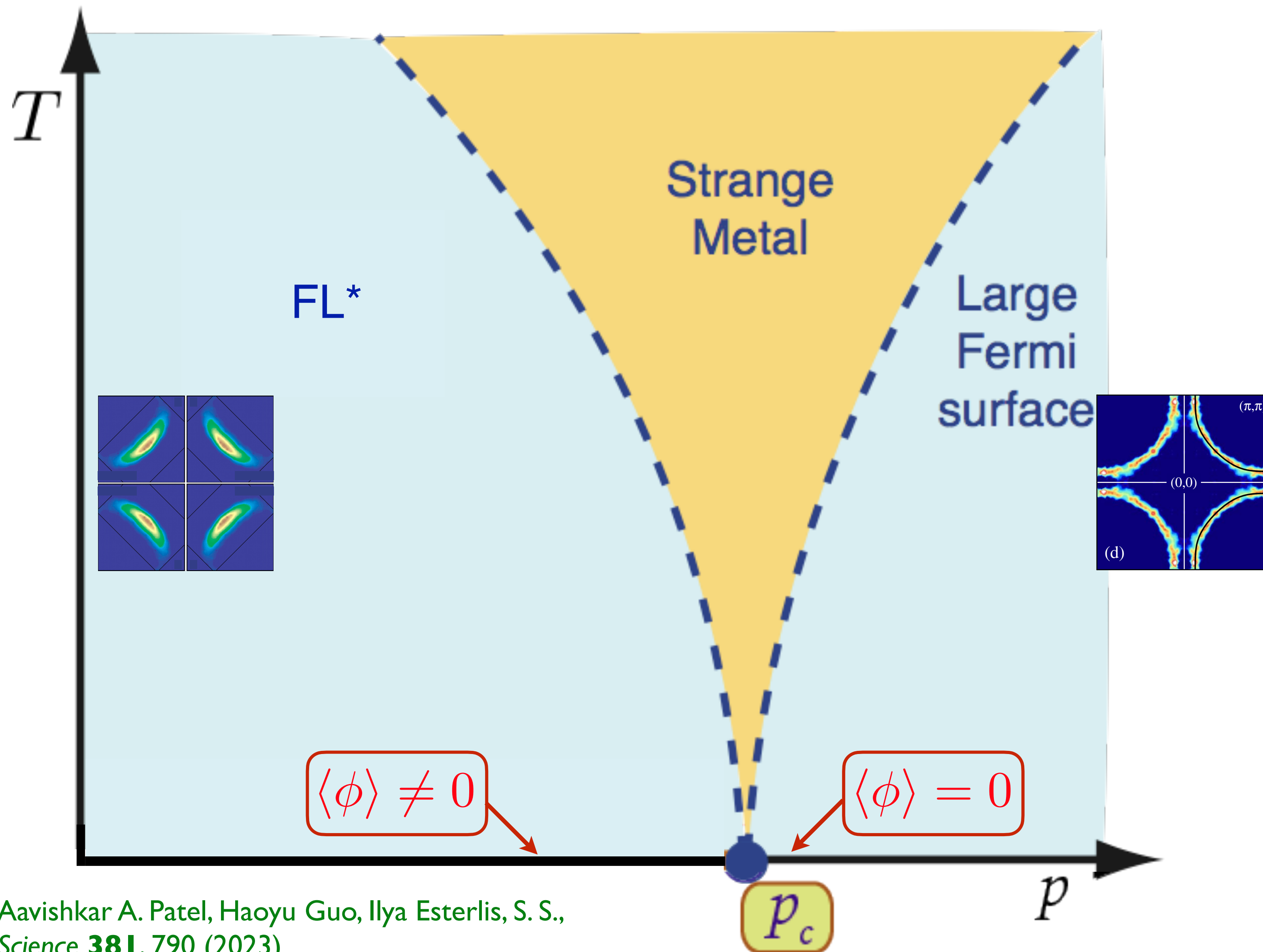
Planckian dynamics!

$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$

and entropy

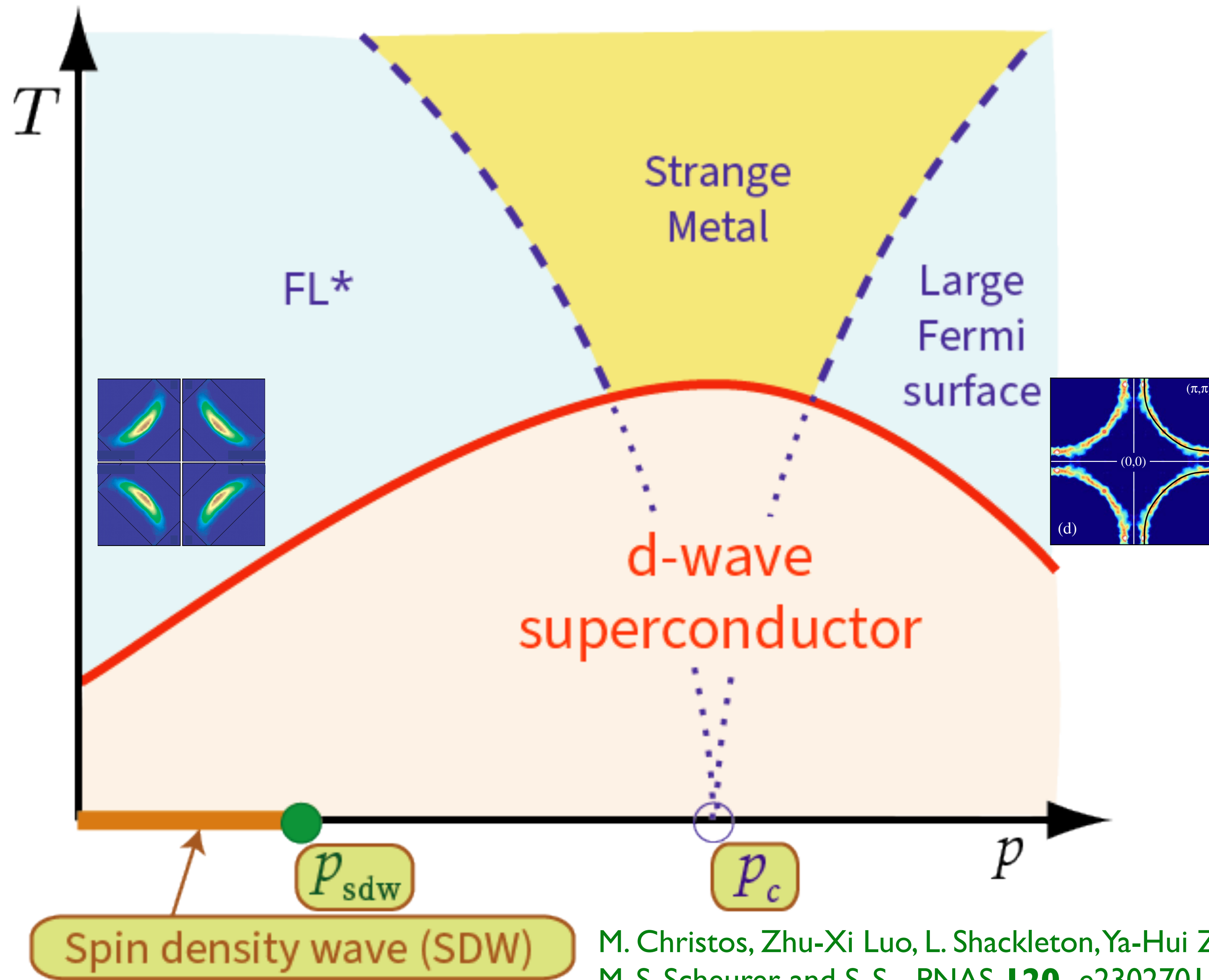
$S(T \rightarrow 0) \sim T \ln(1/T)$
in 2d-YSYK model
(unlike zero temperature entropy in SYK model).





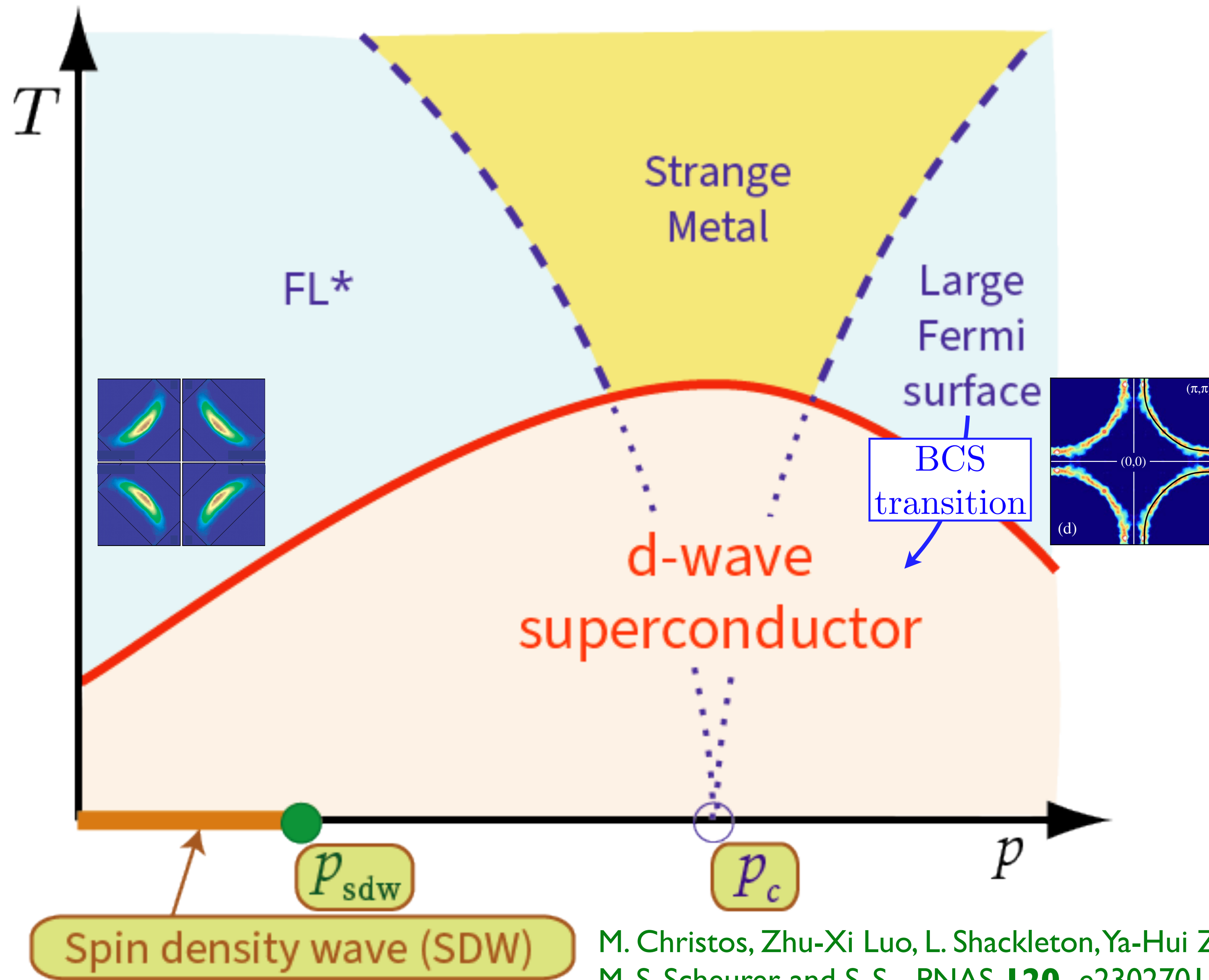
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Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. S.,
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Jorg Schmalian, S.S., Ilya Esterlis, *PRL* **133**, 186502 (2024)



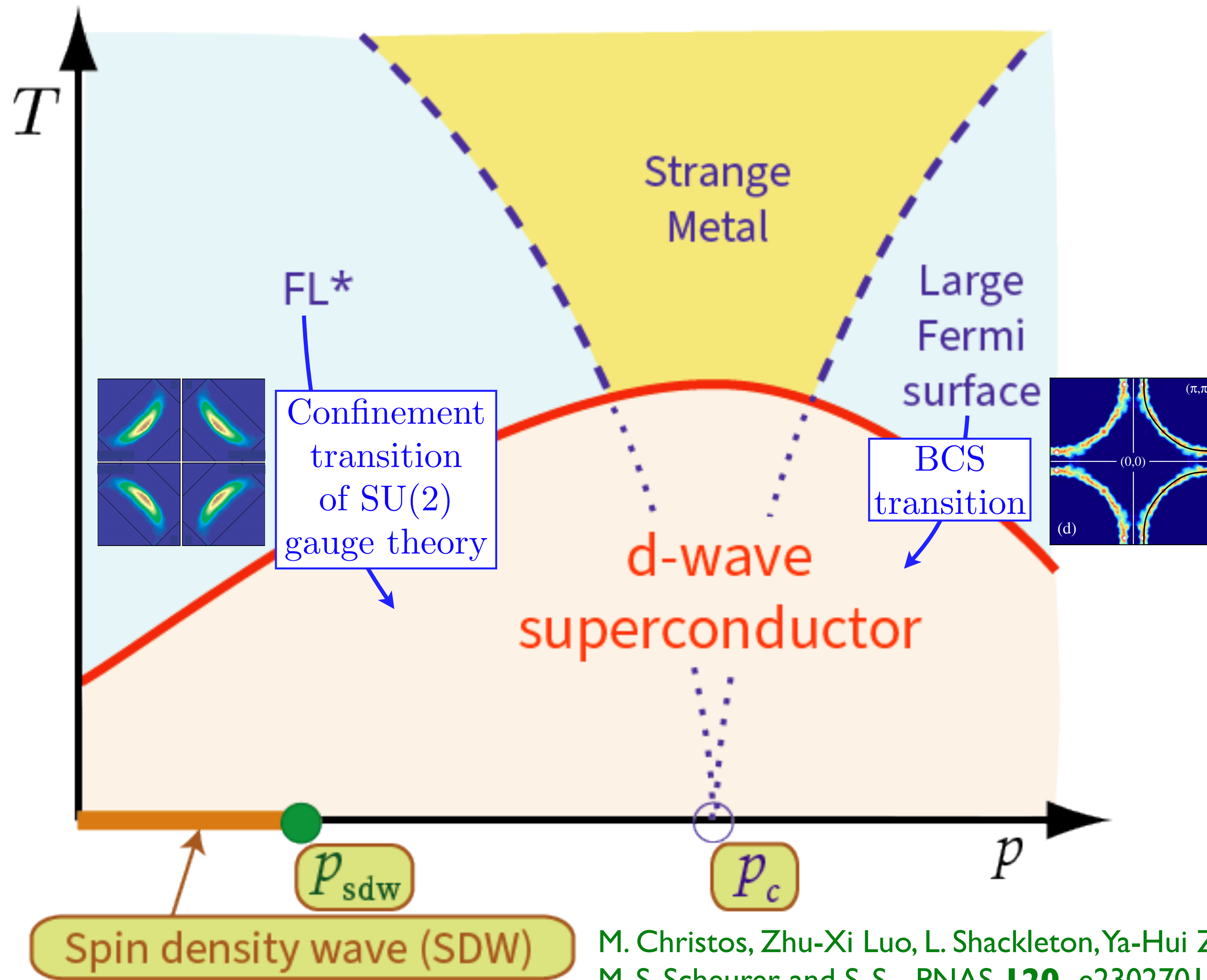
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Both metals lead to the
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at lower temperatures, and
so there is transition at
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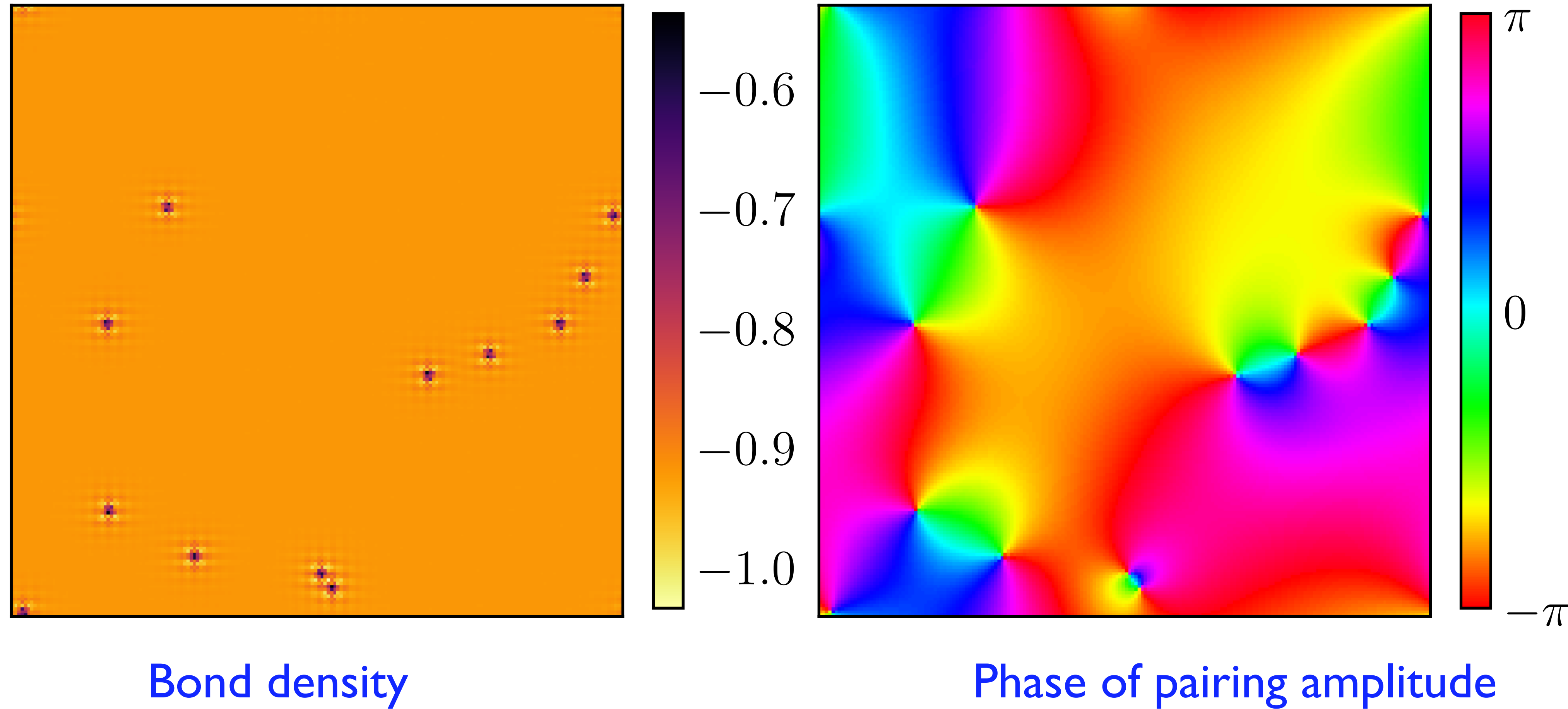
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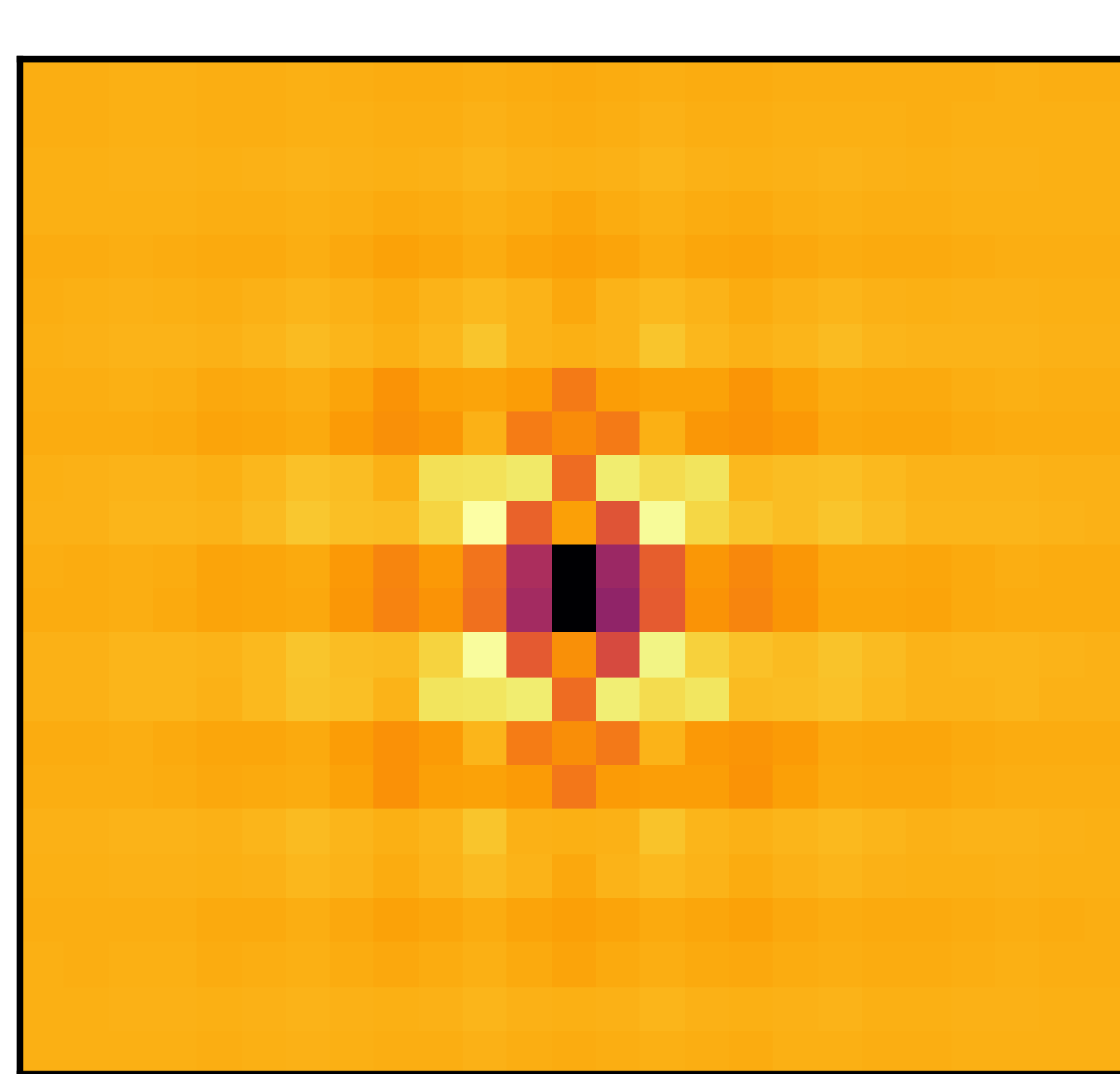
Born-Oppenheimer theory of FL* pseudogap



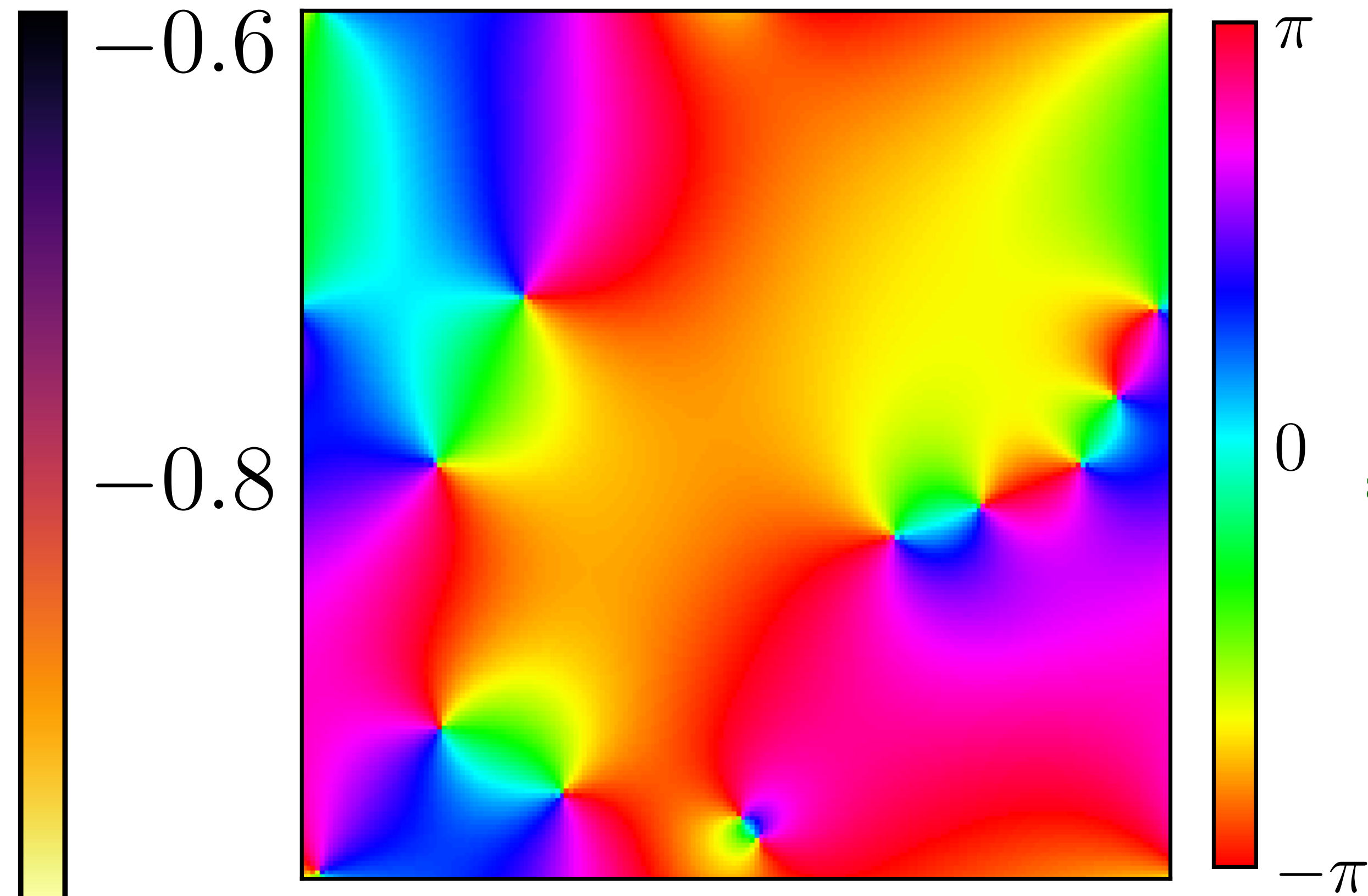
H. Pandey,
M. Christos,
P.M. Bonetti,
R. Shanker,
A. Nikolaenko,
S. Sharma,
S.S.,
arXiv:2507.05336

See also
Jia-Xin Zhang
and S. S.,
PRB **110**,
235120
(2024)

Born-Oppenheimer theory of FL* pseudogap



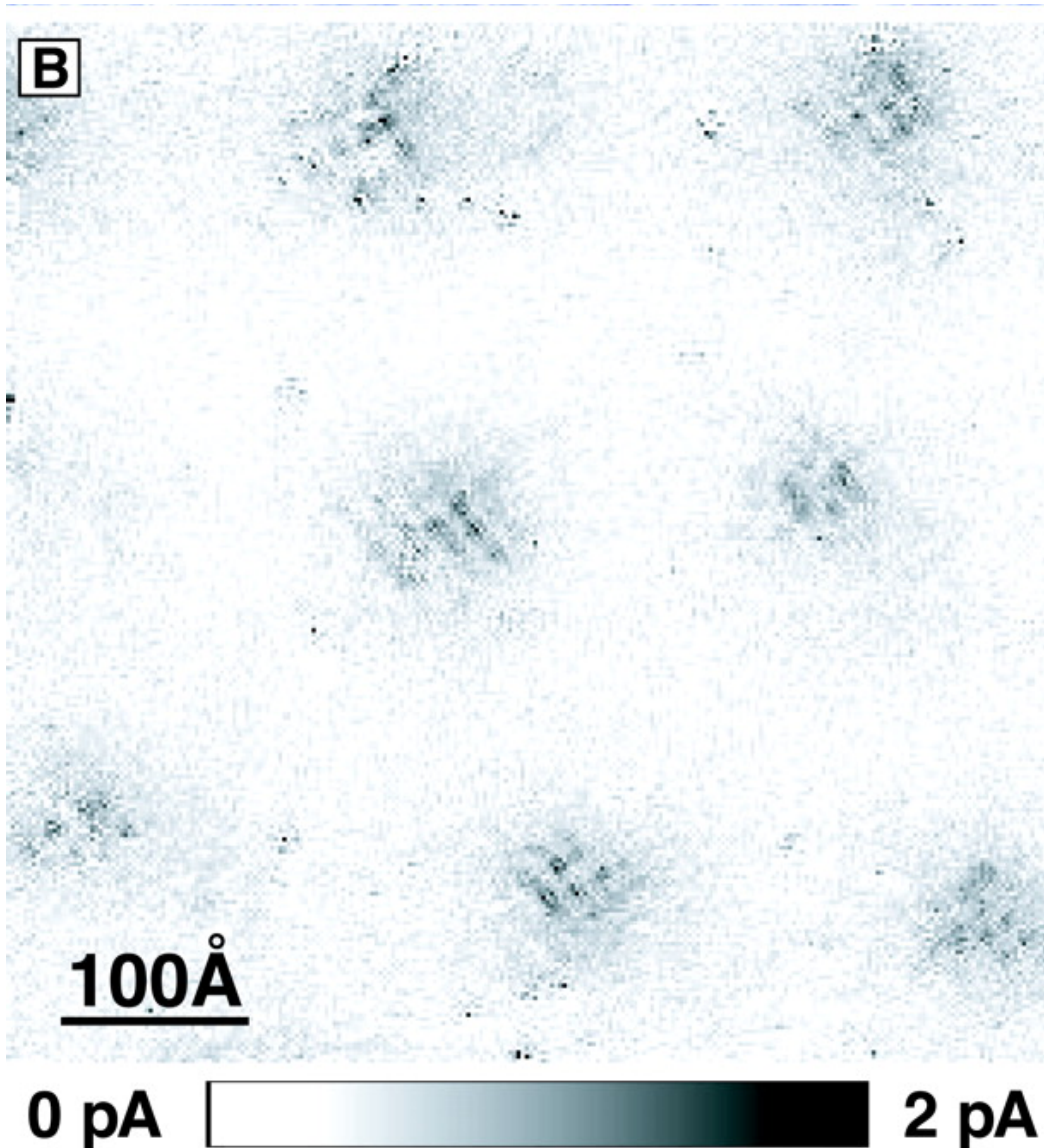
Bond density



Phase of pairing amplitude

H. Pandey,
M. Christos,
P.M. Bonetti,
R. Shanker,
A. Nikolaenko,
S. Sharma,
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arXiv:2507.05336

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Jia-Xin Zhang
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A Four Unit Cell Periodic Pattern of Quasi-Particle States Surrounding Vortex Cores in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

J. E. Hoffman, E. W. Hudson,
K. M. Lang, V. Madhavan,
H. Eisaki, S. Uchida, J.C. Davis
Science **295**, 466 (2002)



Critical quantum liquids and the
cuprate high temperature superconductors,
P. M. Bonetti, M. Christos,
A. Nikolaenko, A. A. Patel,
and S. Sachdev, arXiv:2508.20164

A **critical spin liquid**
(SU(2) gauge theory with massless
Dirac and Higgs matter)
for the FL* pseudogap

and a **critical charge liquid**
(the 2d-Yukawa-SYK model)
for the strange metal.

Gapless and strongly interacting,
many-body systems with
no particle-like excitations