Fermi surfaces large and small: unifying theories of the Anderson lattice and Hubbard models

Topological Aspects of Strong Correlations and Gauge Theories

International Centre for Theoretical Sciences
Tata Institute of Fundamental Research
Bengaluru, Sep 7, 2021

Talk online:
sachdev.physics.harvard.edu

Subir Sachdev

1. Anderson lattice model: the large Fermi surface, and the heavy Fermi liquid (HFL)
2. Kondo lattice model: HFL as the Higgs phase of a $\mathrm{U}(1)$ gauge theory
3. Kondo lattice model: the FL* phase — fractionalization, emergent gauge fields, and Luttinger violation
4. Hubbard model: the vanilla FL phase
5. Hubbard model: the FL* phase at small doping p, using ancilla qubits

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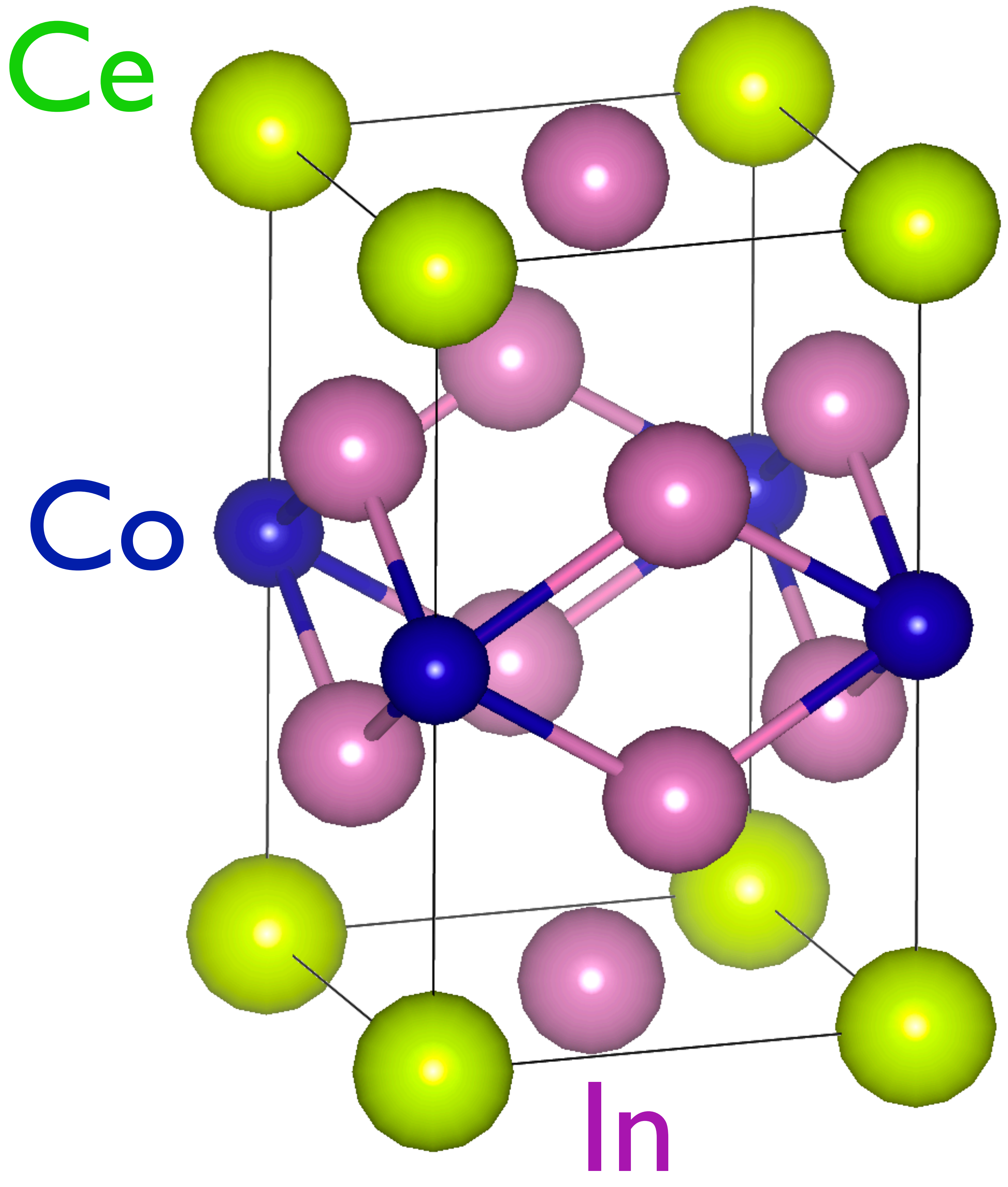

Strong on-site repulsion U only on Ce sites

$CeCoIn_5$

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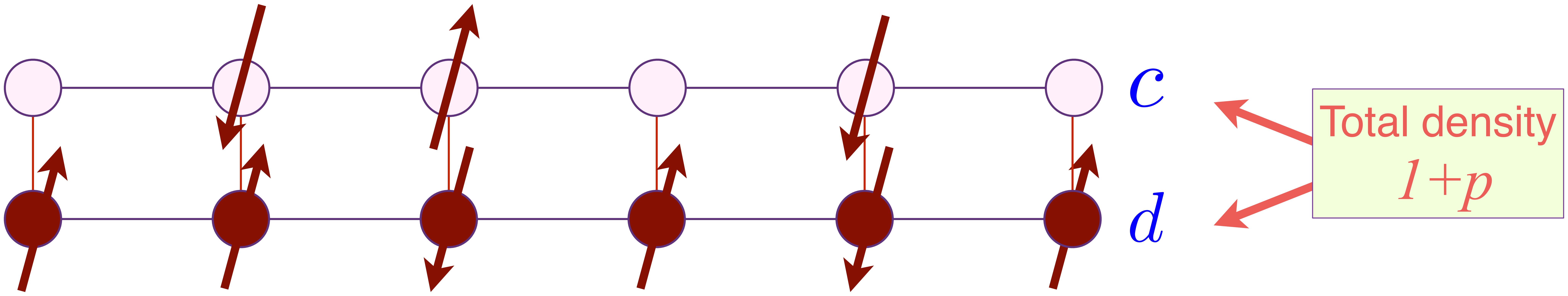

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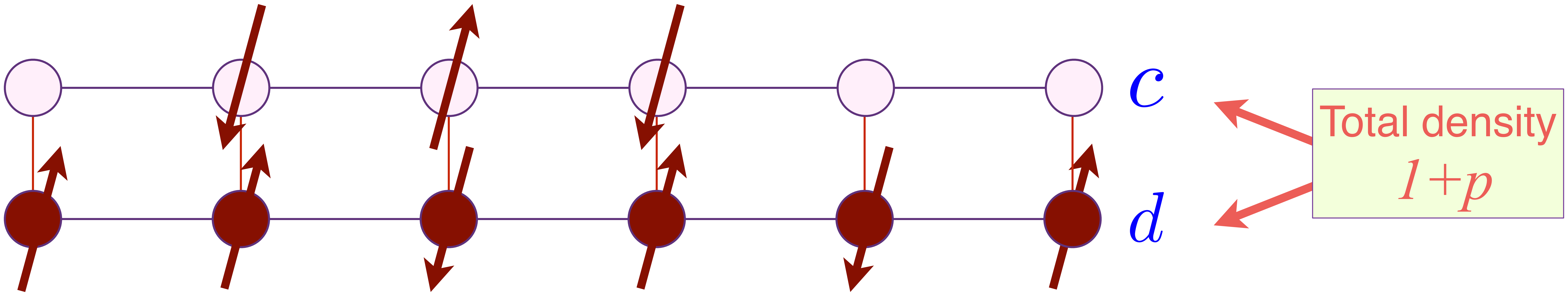

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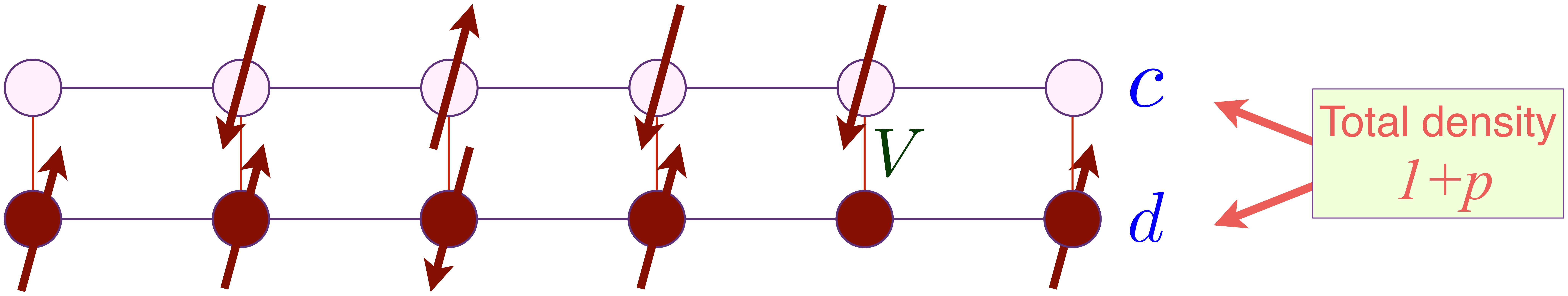

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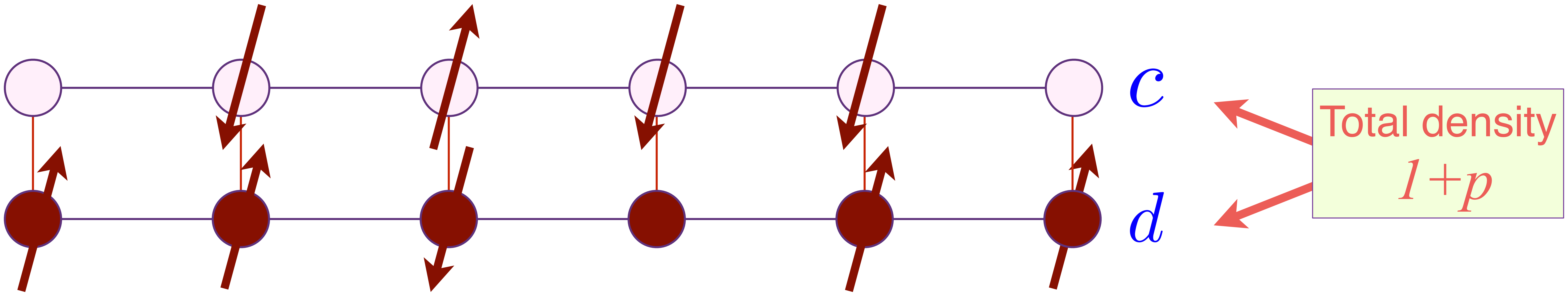

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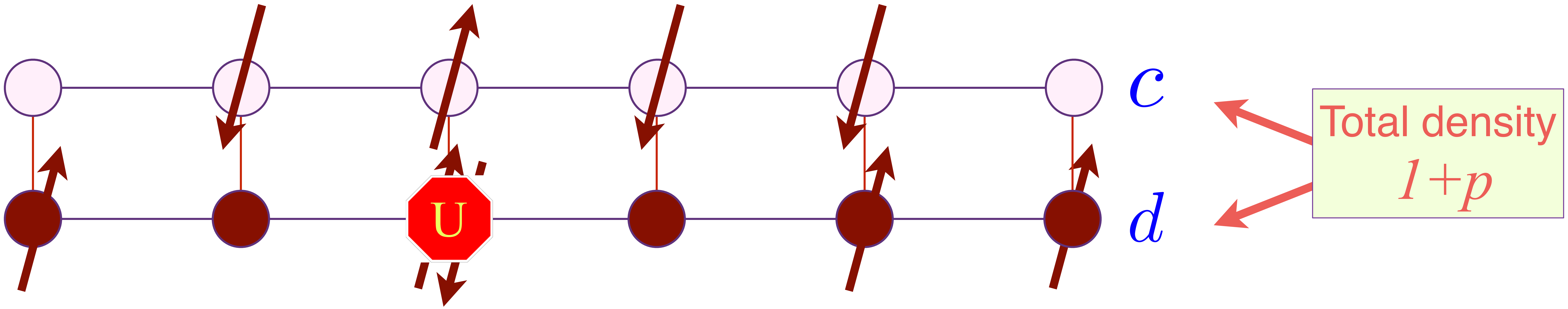

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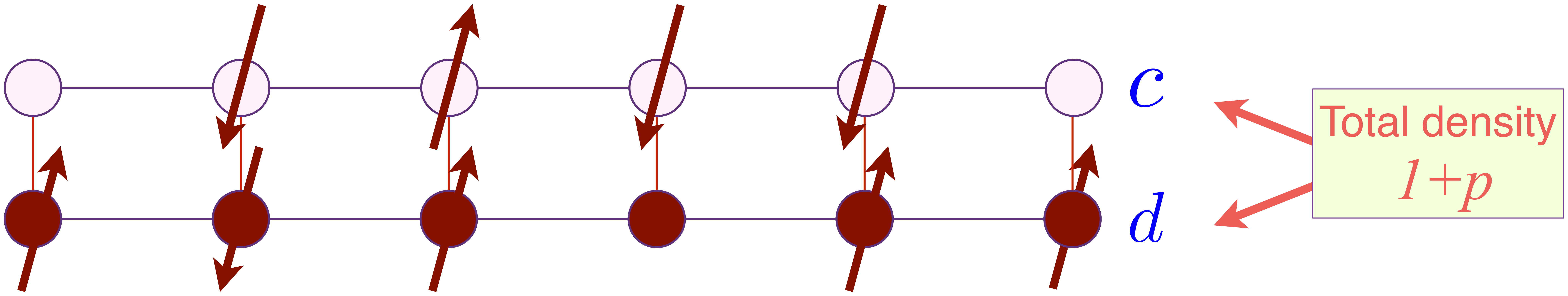

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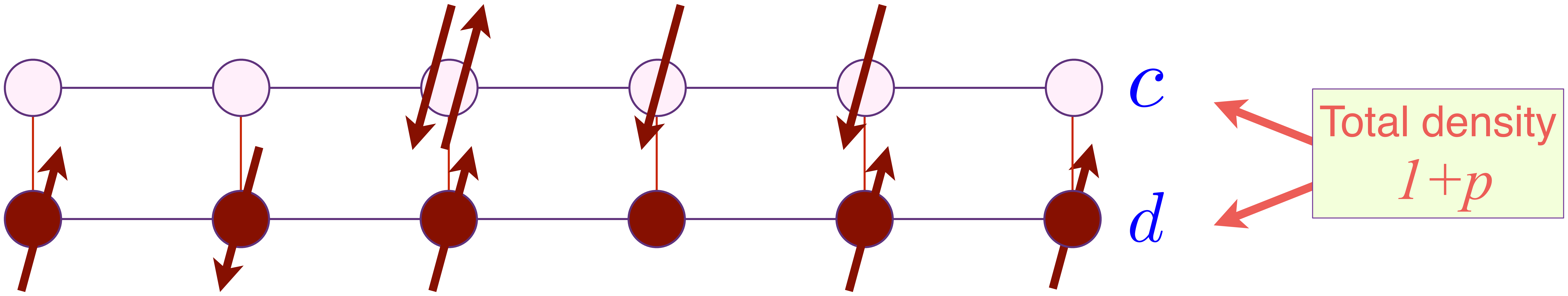

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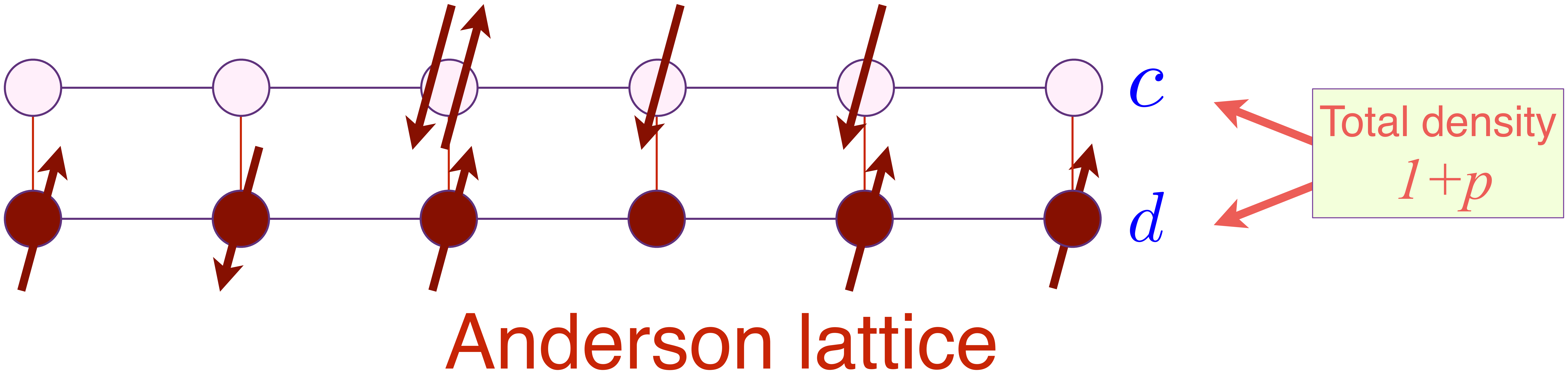

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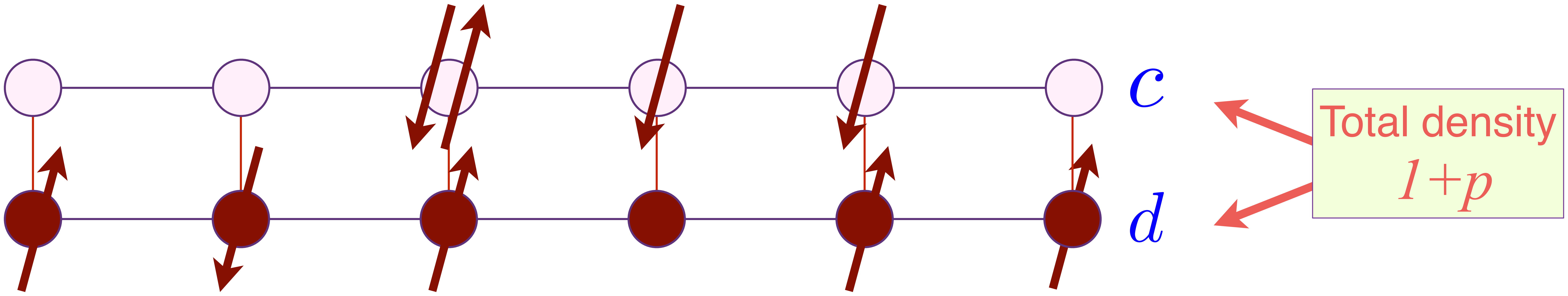

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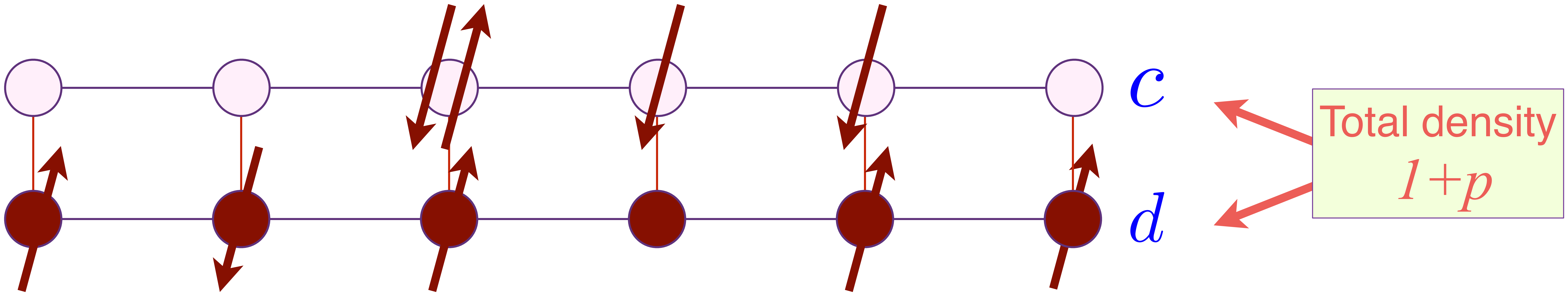
- No fundamental change in the ground state as $U \to \infty$, apart from a large effective mass renormalization of quasiparticles $m^*/m \sim \exp(c_1 U)$. This yields the theory of a heavy fermi liquid (HFL), which has been applied with success to f-electron intermetallics.

Varma, Yafet, Read, Newns, Coleman, Millis, P.A. Lee, Auerbach, Levin



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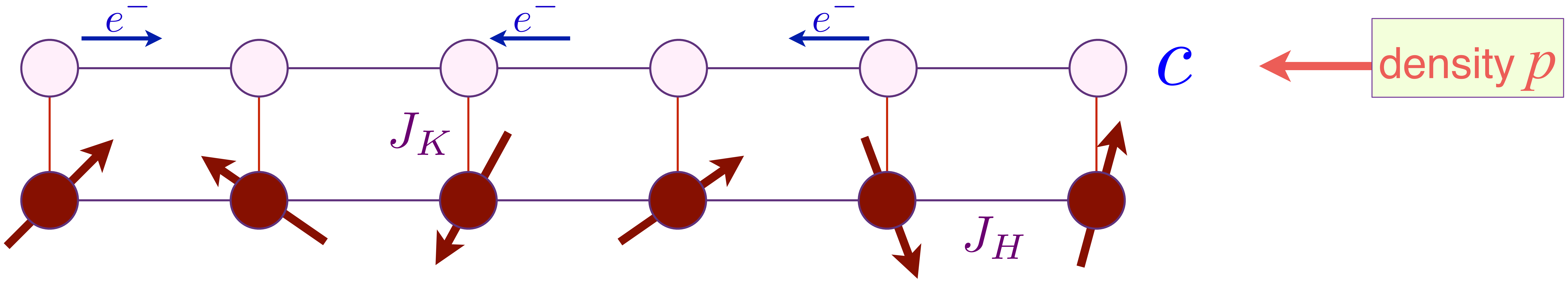
- Obtained from $\mathcal{H}_{AL}$ by a Schrieffer-Wolff canonical transformation with $J_K \sim V^2/U$ and $J_H \sim t_d^2/U$. Now the d-band consists only of spin degrees of freedom, or 'qubits'.

Kondo lattice



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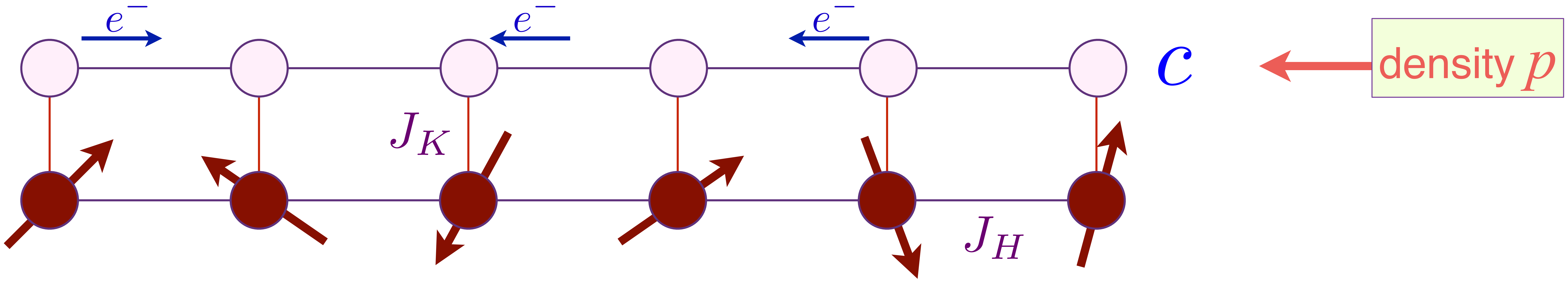

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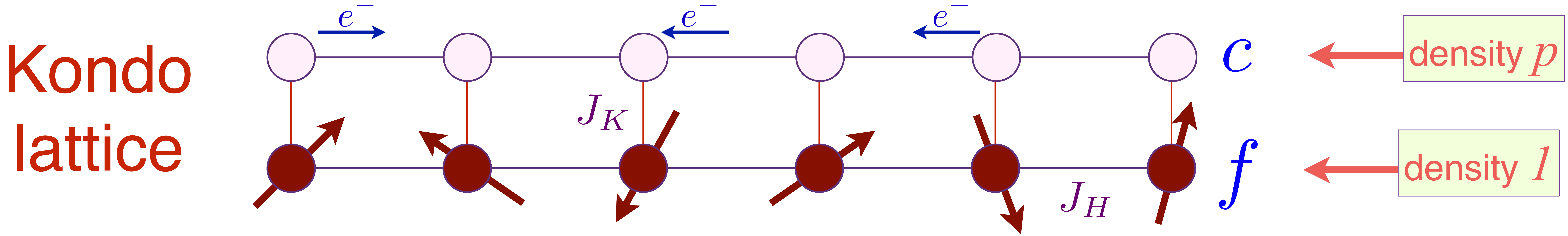

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- Variational wavefunction for HFL with 'large' Fermi surface of size $1 + p$:
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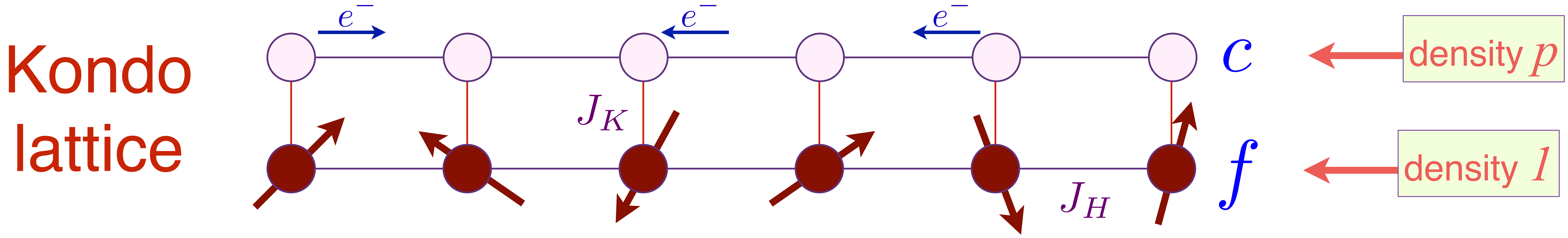

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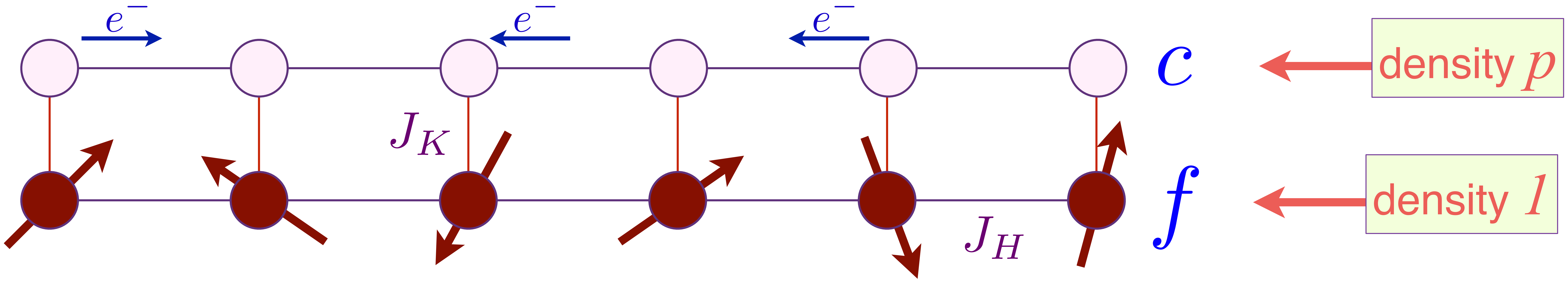

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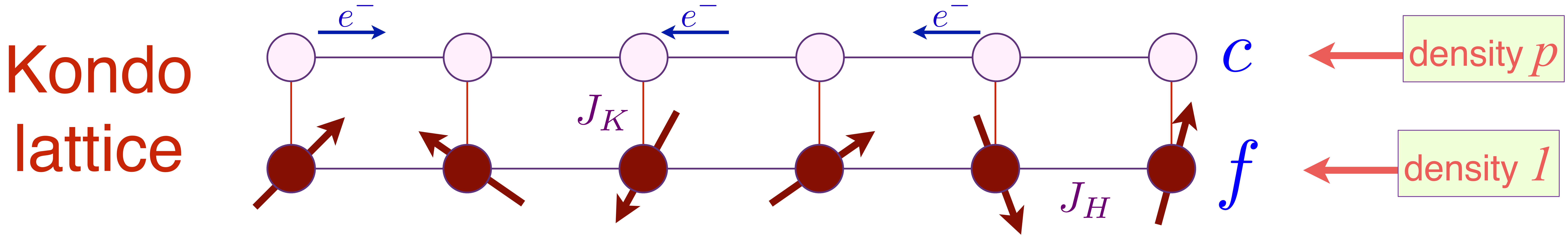
- The $\mathrm{U}(1)_{\mathrm{gauge}} \times \mathrm{U}(1)$ symmetry is 'Higgsed' by the condensation of the hybridization boson $B_i \sim f^{\dagger}_{i\sigma} c_{i\sigma}$ to a diagonal $\mathrm{U}(1)_{\mathrm{diag}}$ symmetry.



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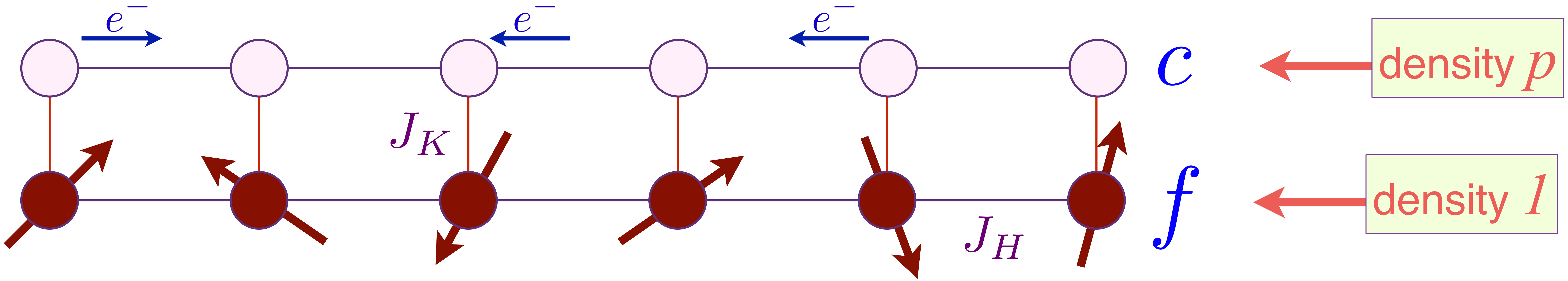

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- The Luttinger theorem arguments can only be applied to the unbroken $\mathrm{U(1)_{diag}}$ symmetry, which counts *both* c and f fermions.

- The Fermi surface is *large*, of size $1 + p$, and we obtain the HFL state.

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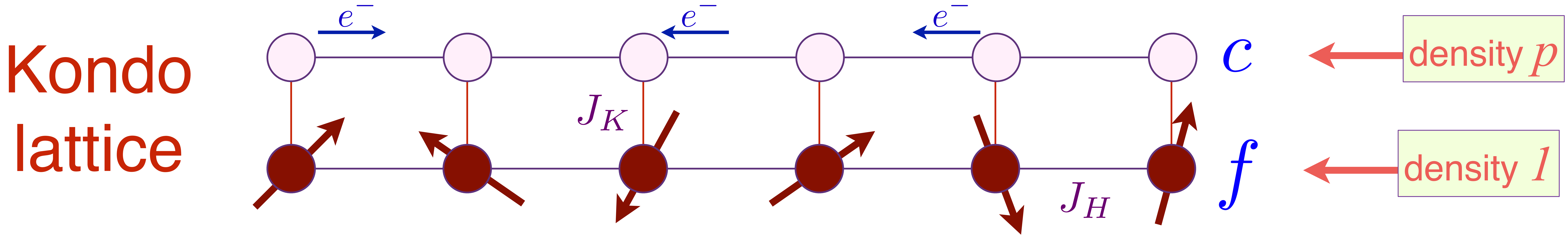

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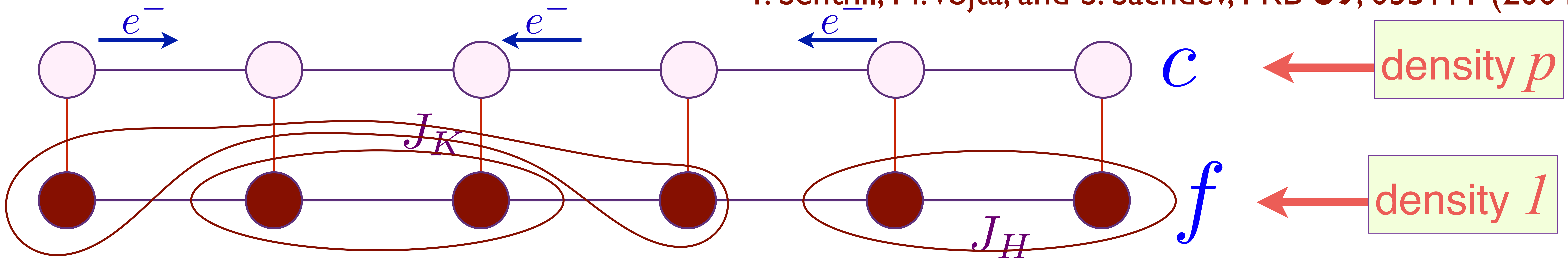
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)

Kondo lattice



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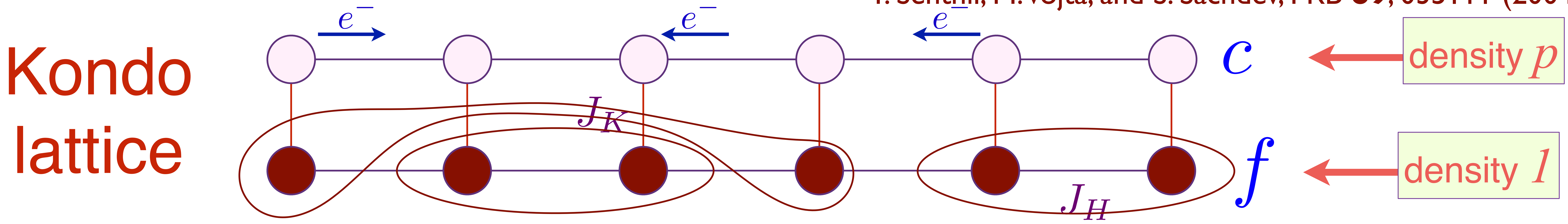

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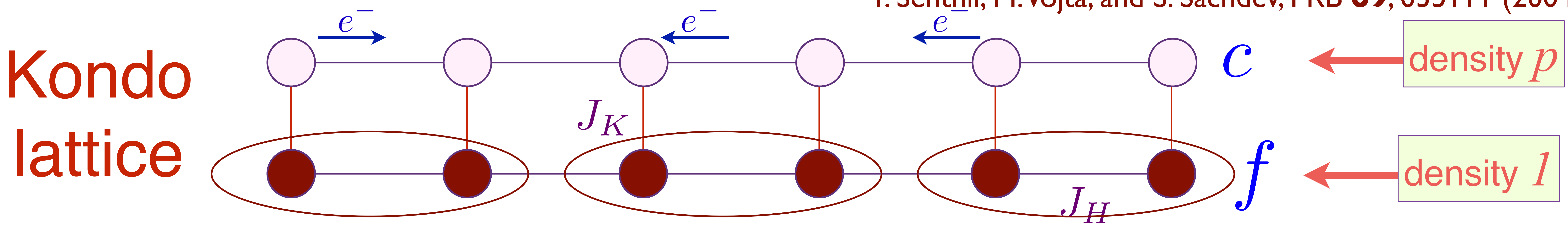

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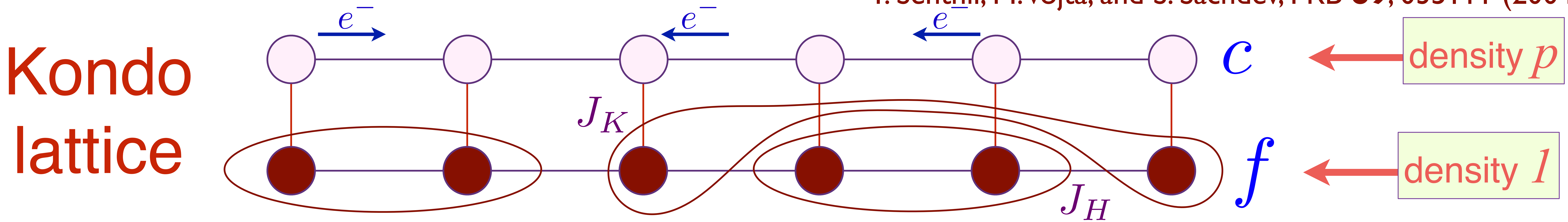

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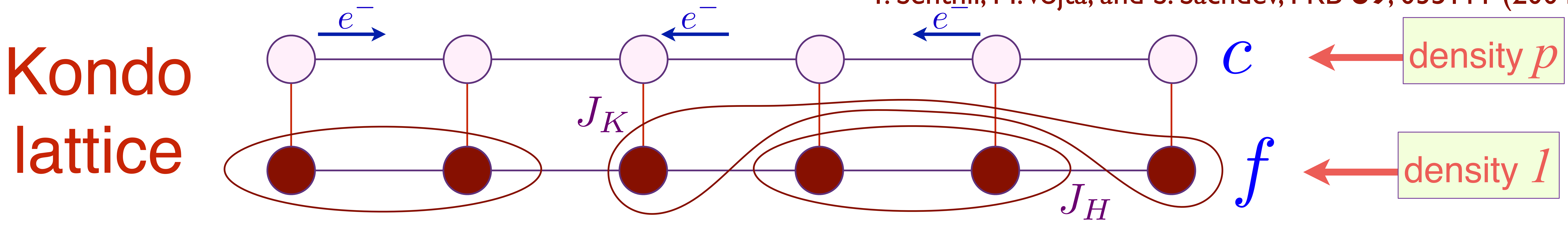

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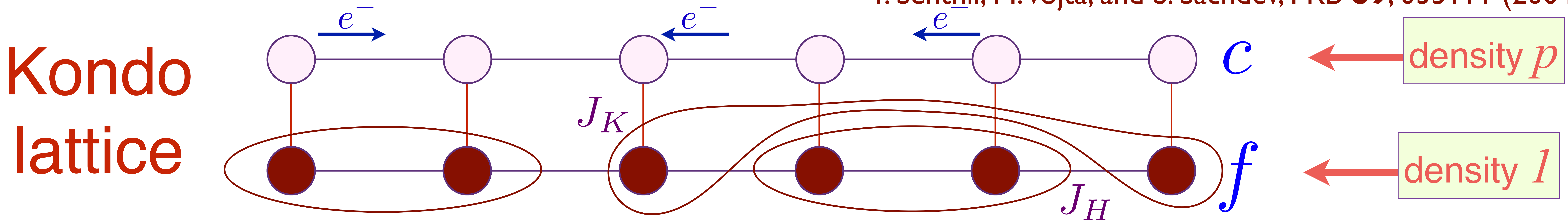
- The Luttinger arguments applied to $\mathrm{U}(1)_{\mathrm{gauge}}$ lead to 'symmetry enriched topological (SET)' or 'symmetry fractionalization' constraints on the spin liquid sector.

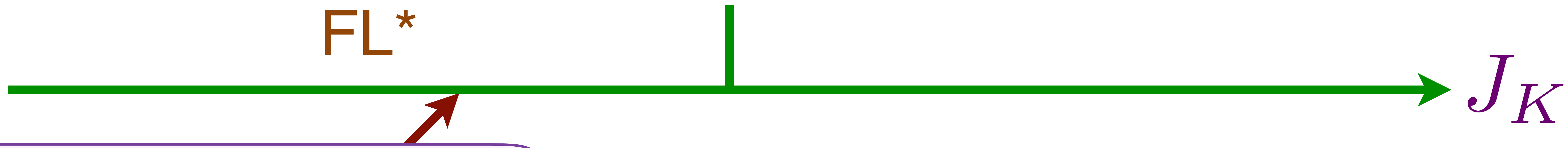
P. Bonderson, M. Cheng, K. Patel, E. Plamadeala, arXiv:1601.07902

T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)



FL* phase in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



Small Fermi surface of size p

$$|\mathrm{FL}*\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } f\rangle \otimes |\text{Slater determinant of } c\rangle$$

S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)
A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004)

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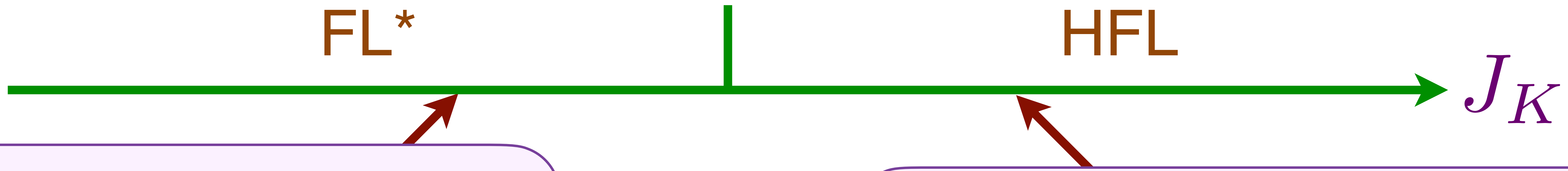

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Large Fermi surface of size $1 + p$

$$|\text{HFL}\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } (c, f)\rangle$$

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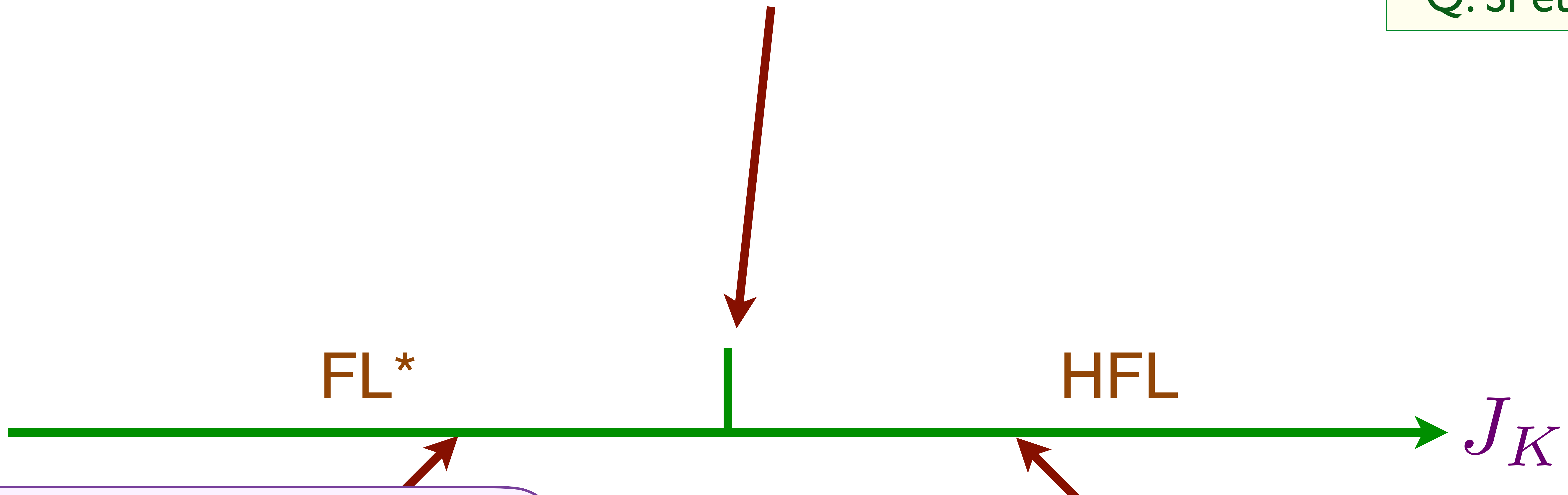
A. Sengupta (2000)
Q. Si et al. (2001)

Kondo-breakdown transition



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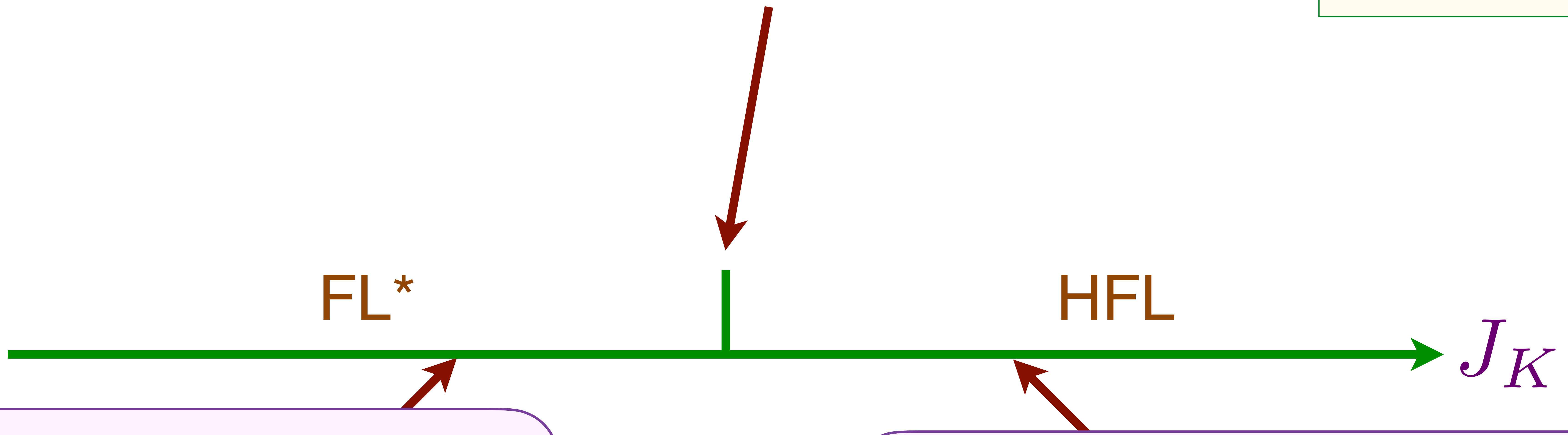
Kondo-breakdown transition
'Selective Mott' transition

V. Anisimov *et al.* (2002)
L. de' Medici *et al.* (2005)



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Kondo-breakdown transition
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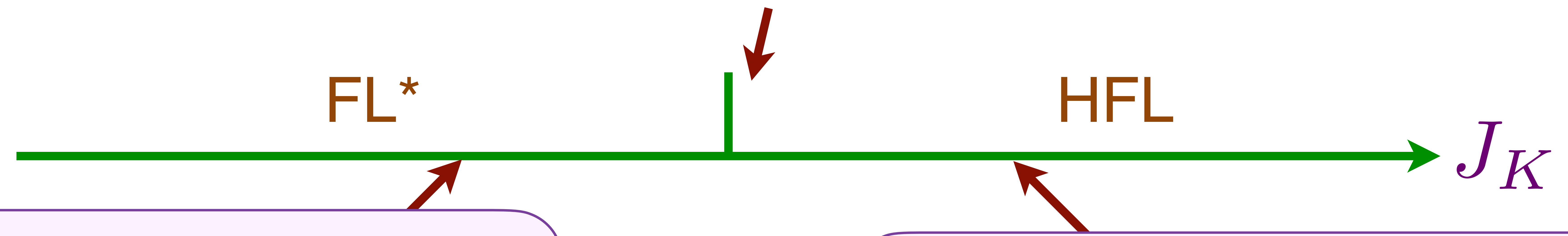
Deconfined criticality of a U(1) gauge theory with a
Higgs field, spinons, and a small Fermi surface of electrons.
(FL* can be replaced by a confining phase with AFM or VBS order).



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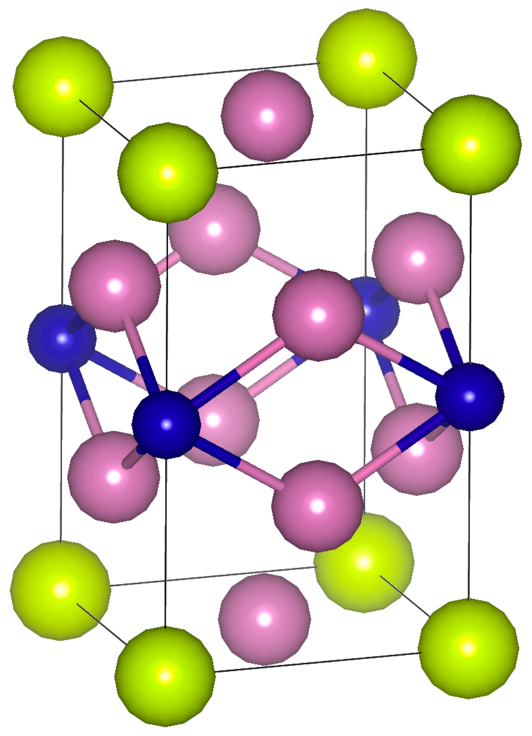
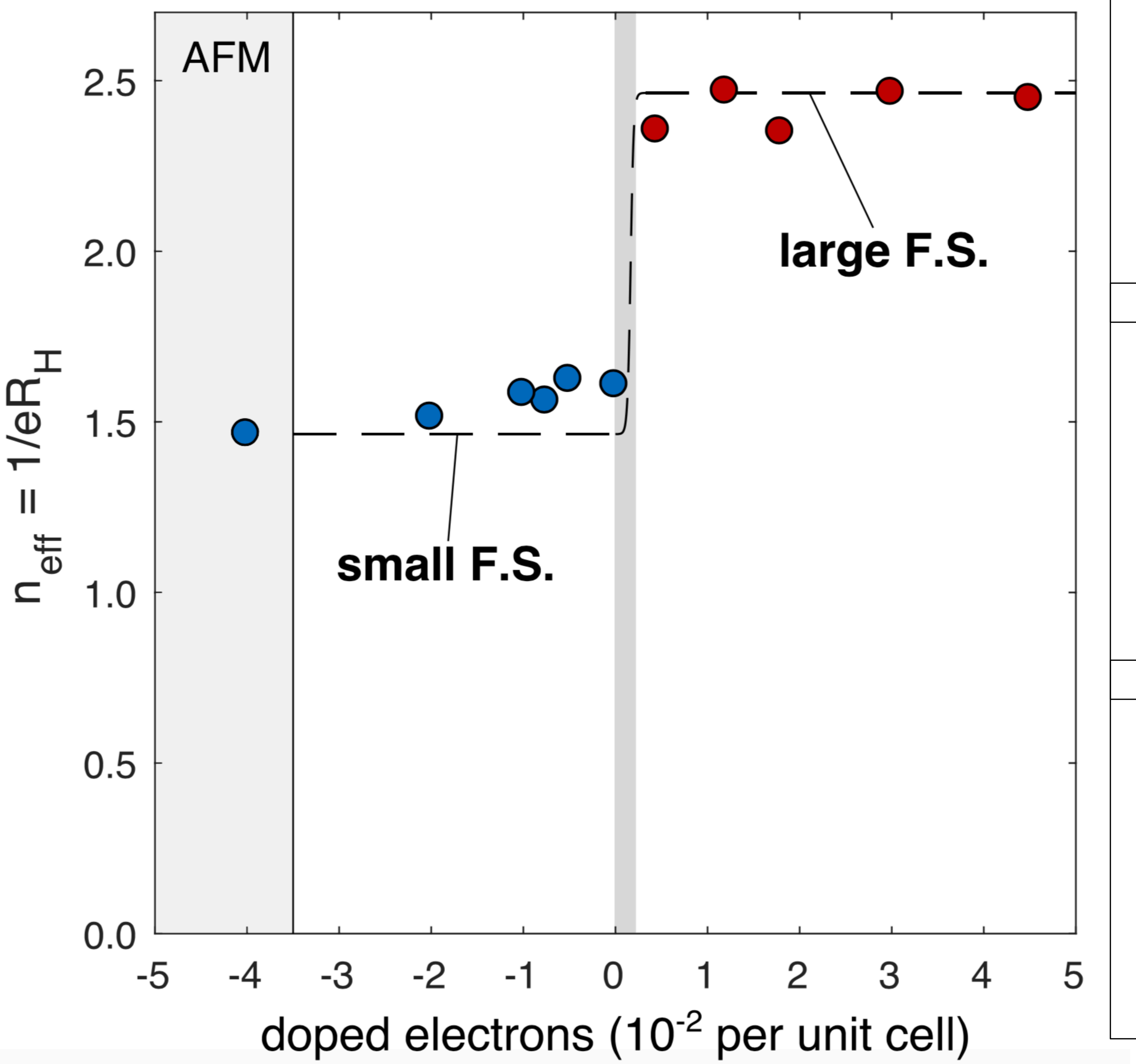
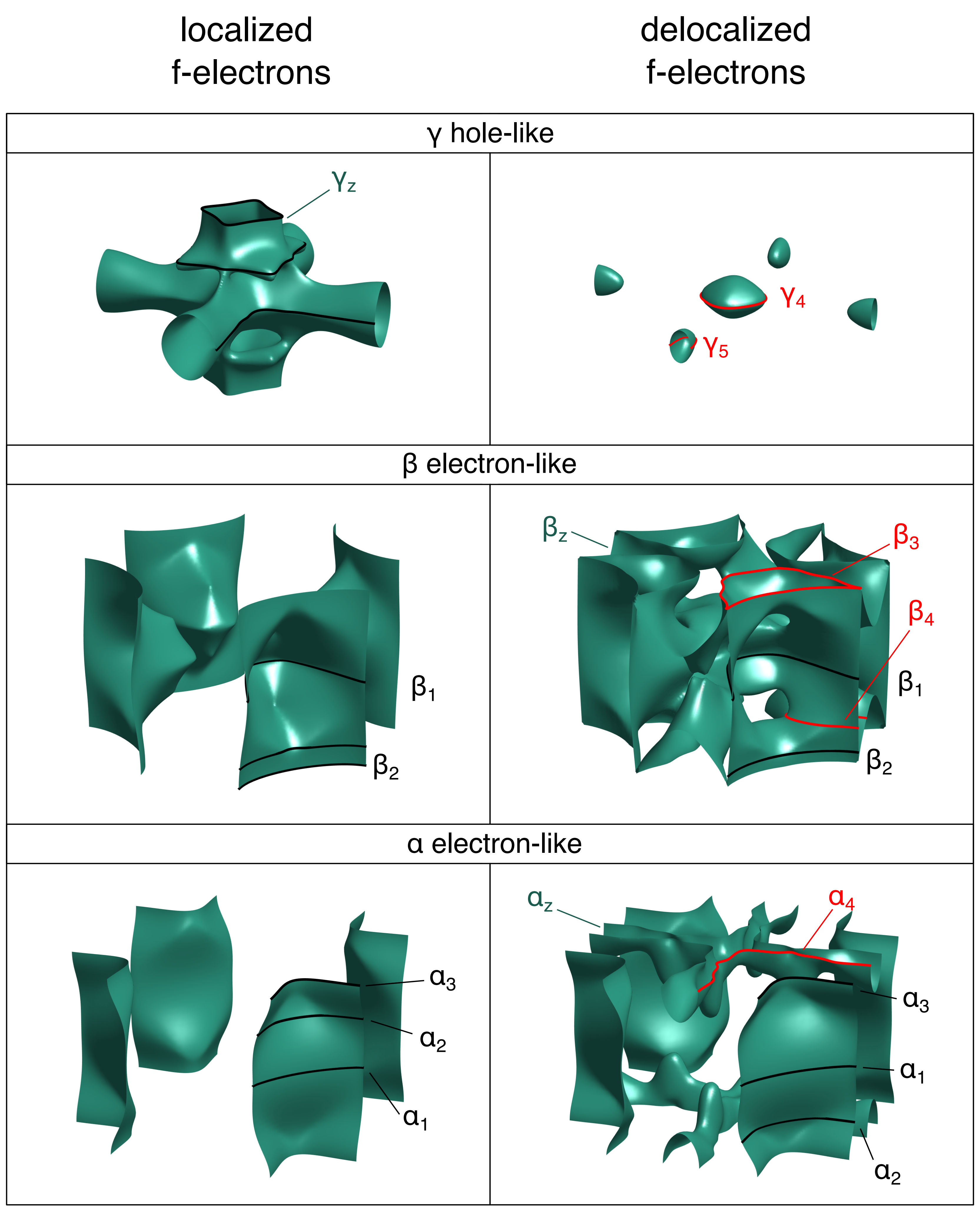
Evidence for freezing of charge degrees of freedom across a critical point in $CeCoIn_5$

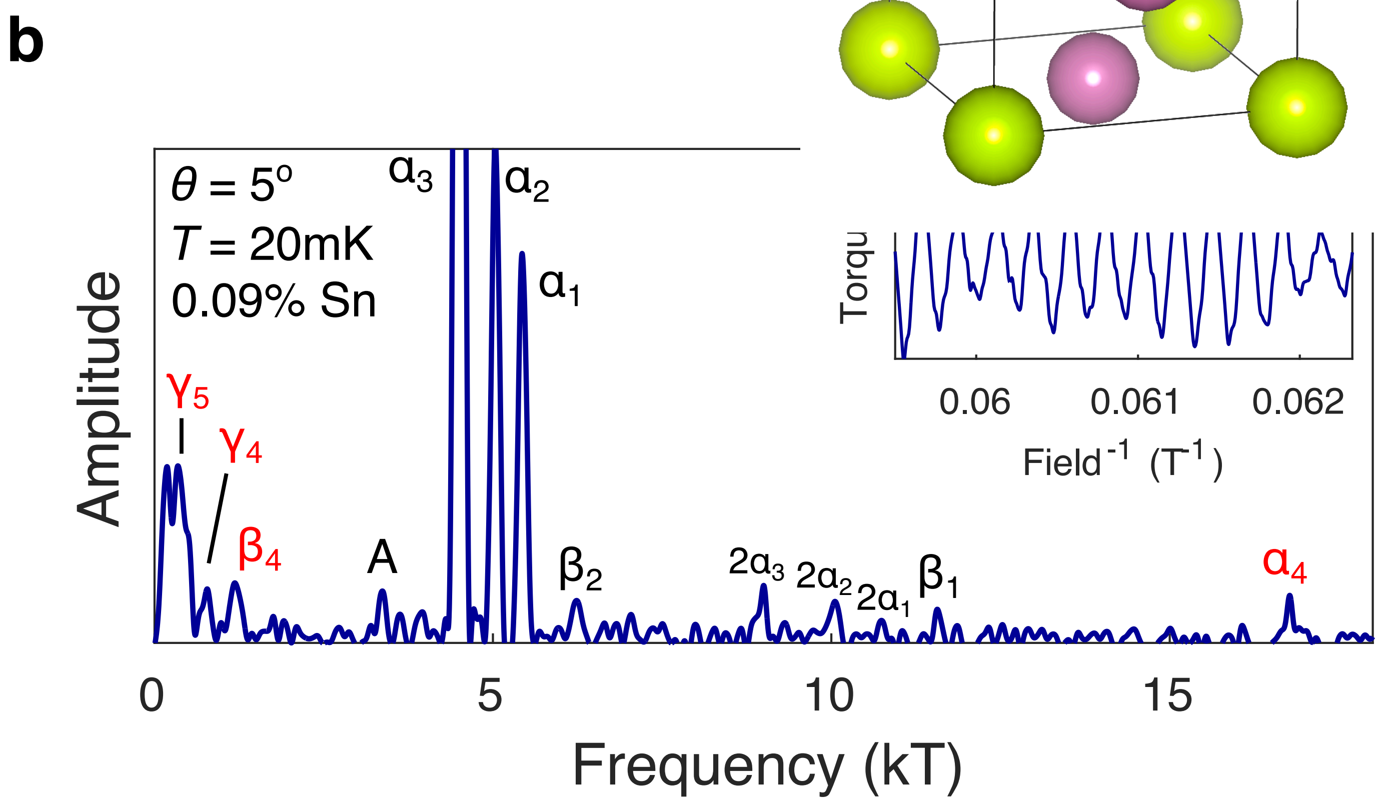
Nikola Maksimovic, Taylor Cookmeyer, Jan Rusz, Vikram Nagarajan, Amanda Gong, Fanghui Wan, Stefano Faubel, Ian M. Hayes, Sooyoung Jang, Yochai Werman, Peter M. Oppeneer, Ehud Altman, James G. Analytis

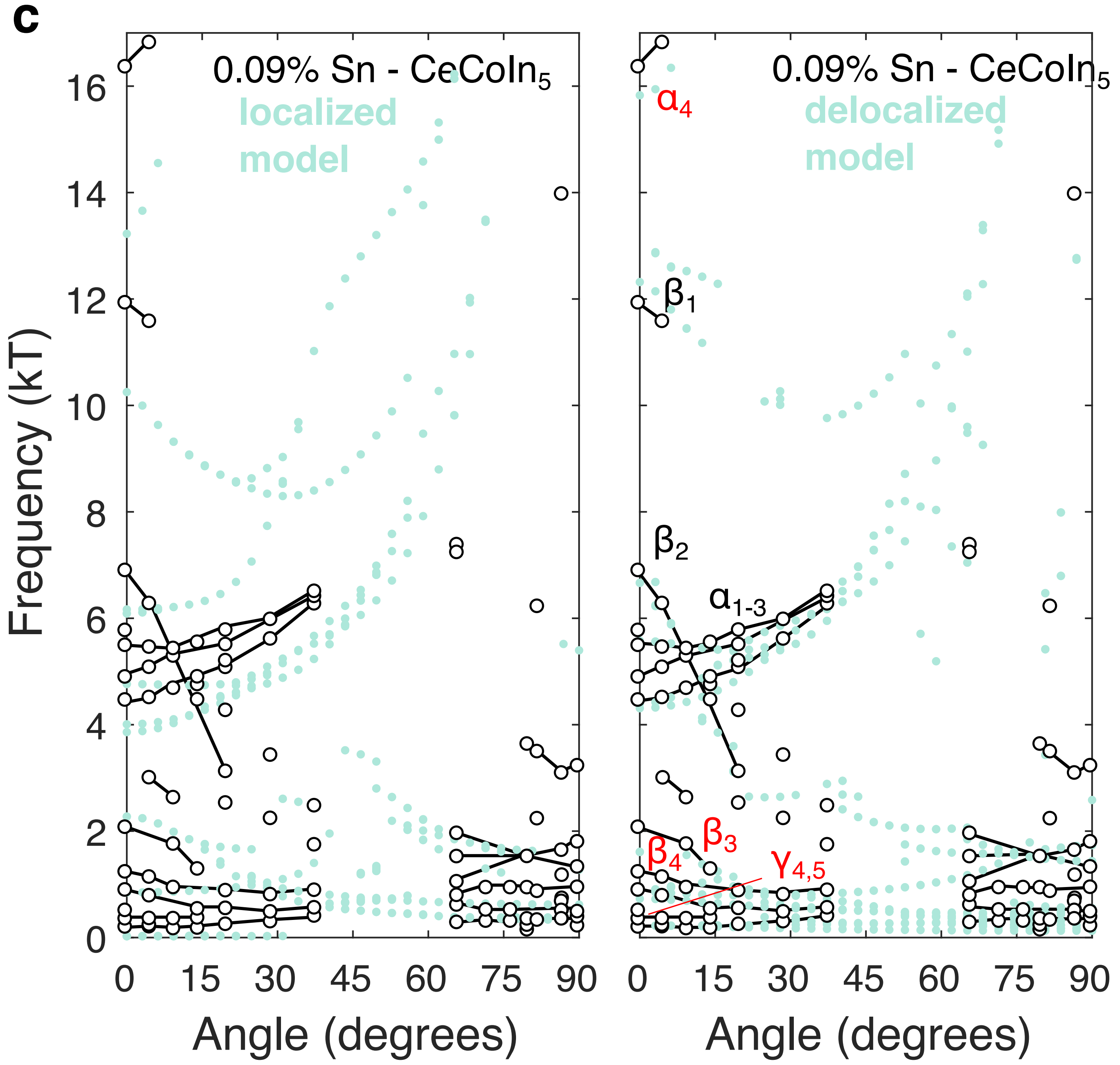


arXiv:2011.12951









See also H. Zhao, J. Zhang, M. Lyu, S. Bachus, Y. Tokiwa, P. Gegenwart, S. Zhang, J. Cheng, Y.-f. Yang, G. Chen, Y. Isikawa, Q. Si, F. Steglich, and P. Sun, Nature Physics 15, 1261 (2019) for CePdAl

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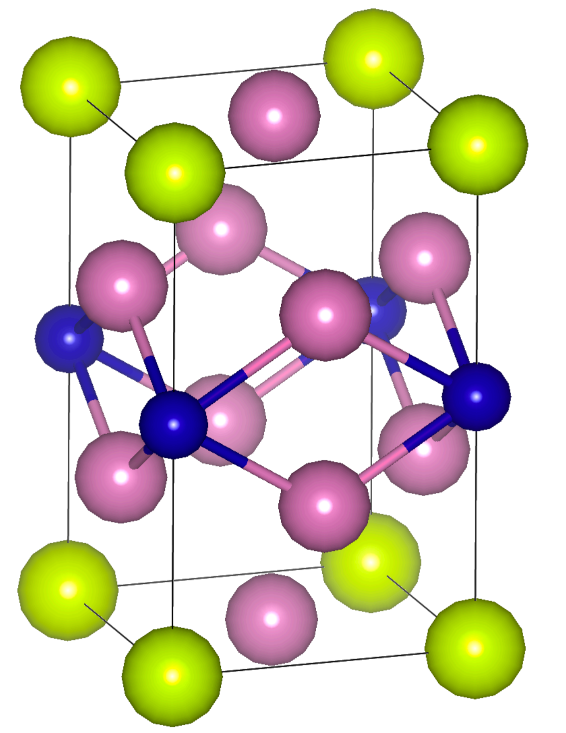

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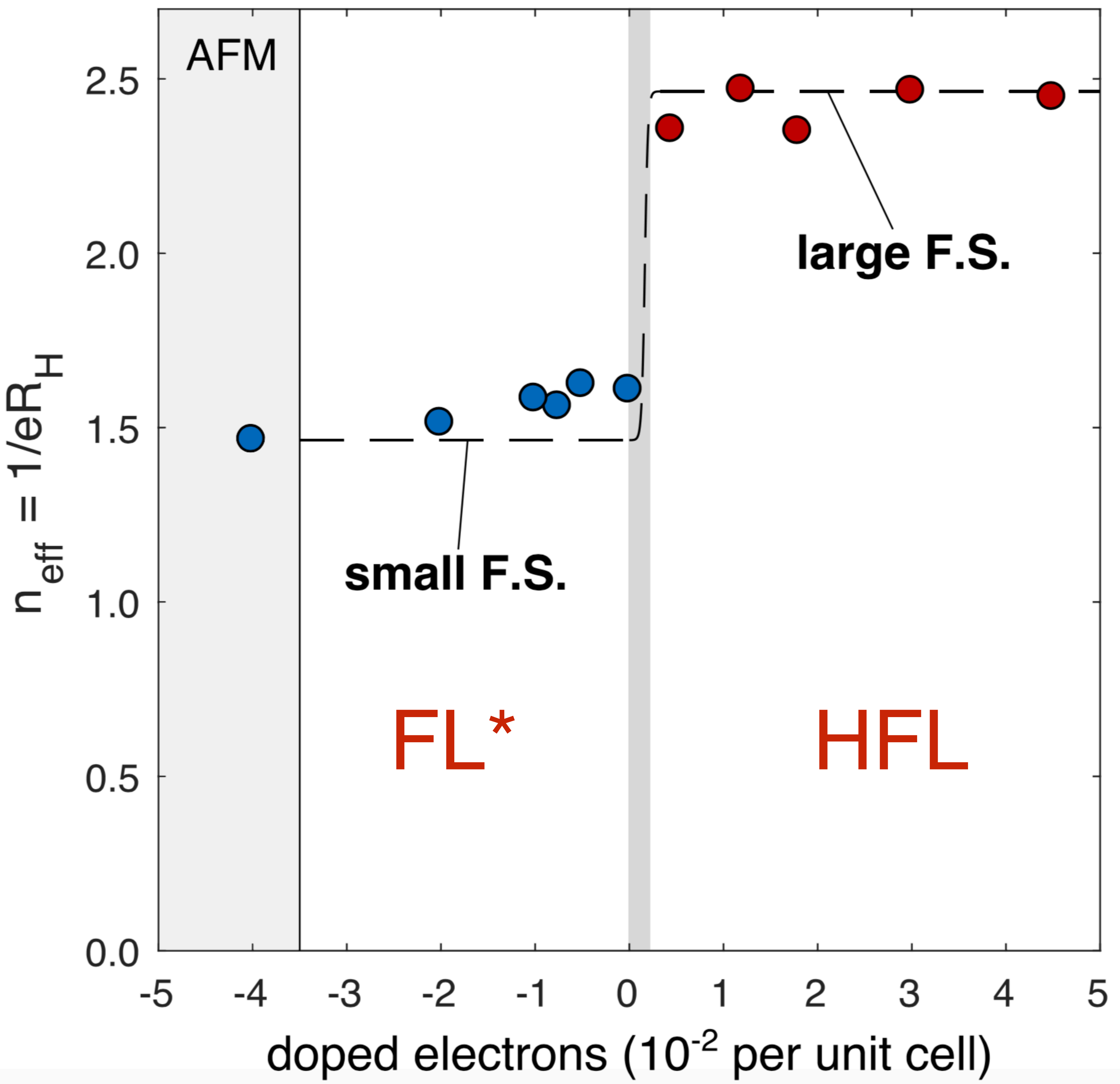

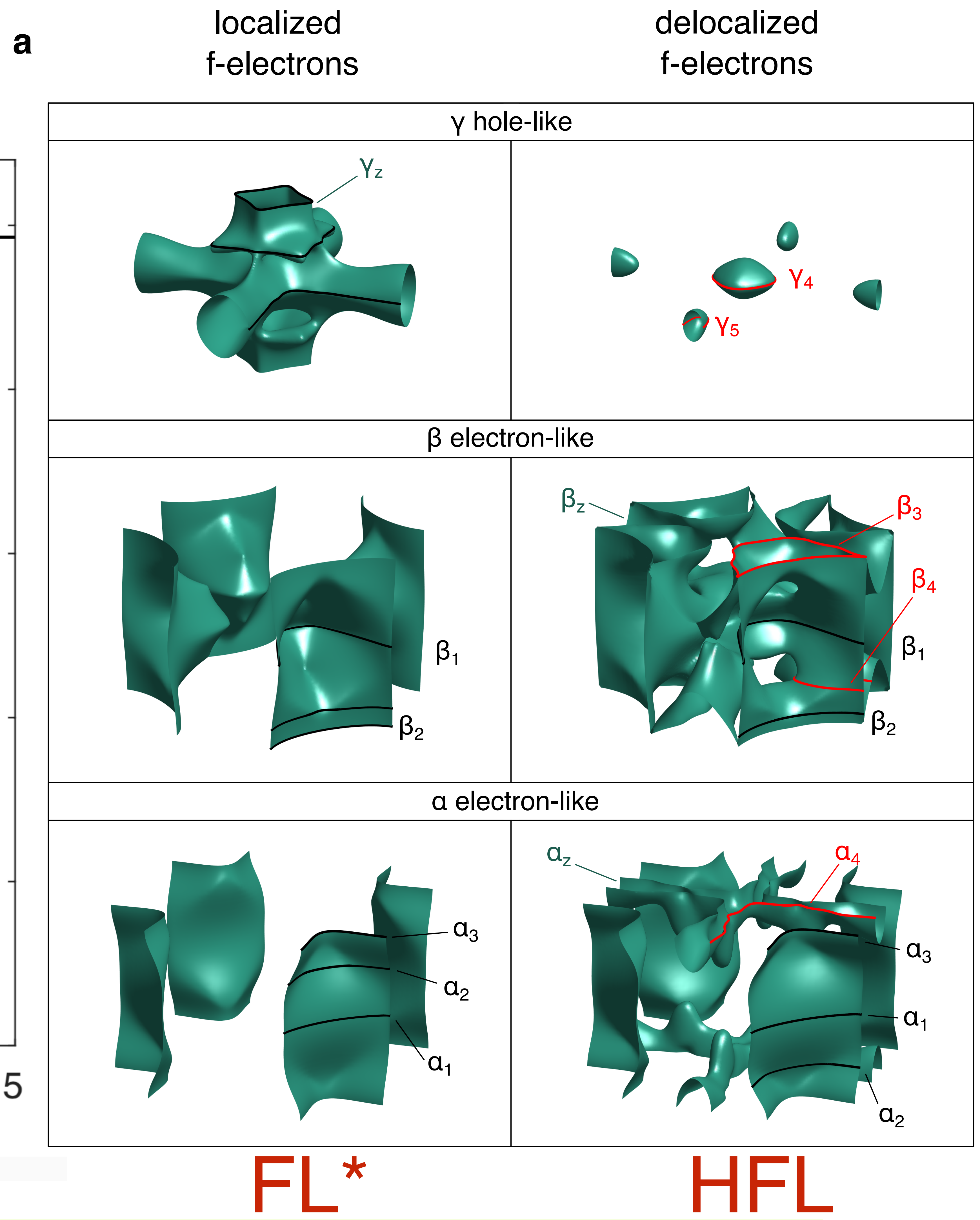

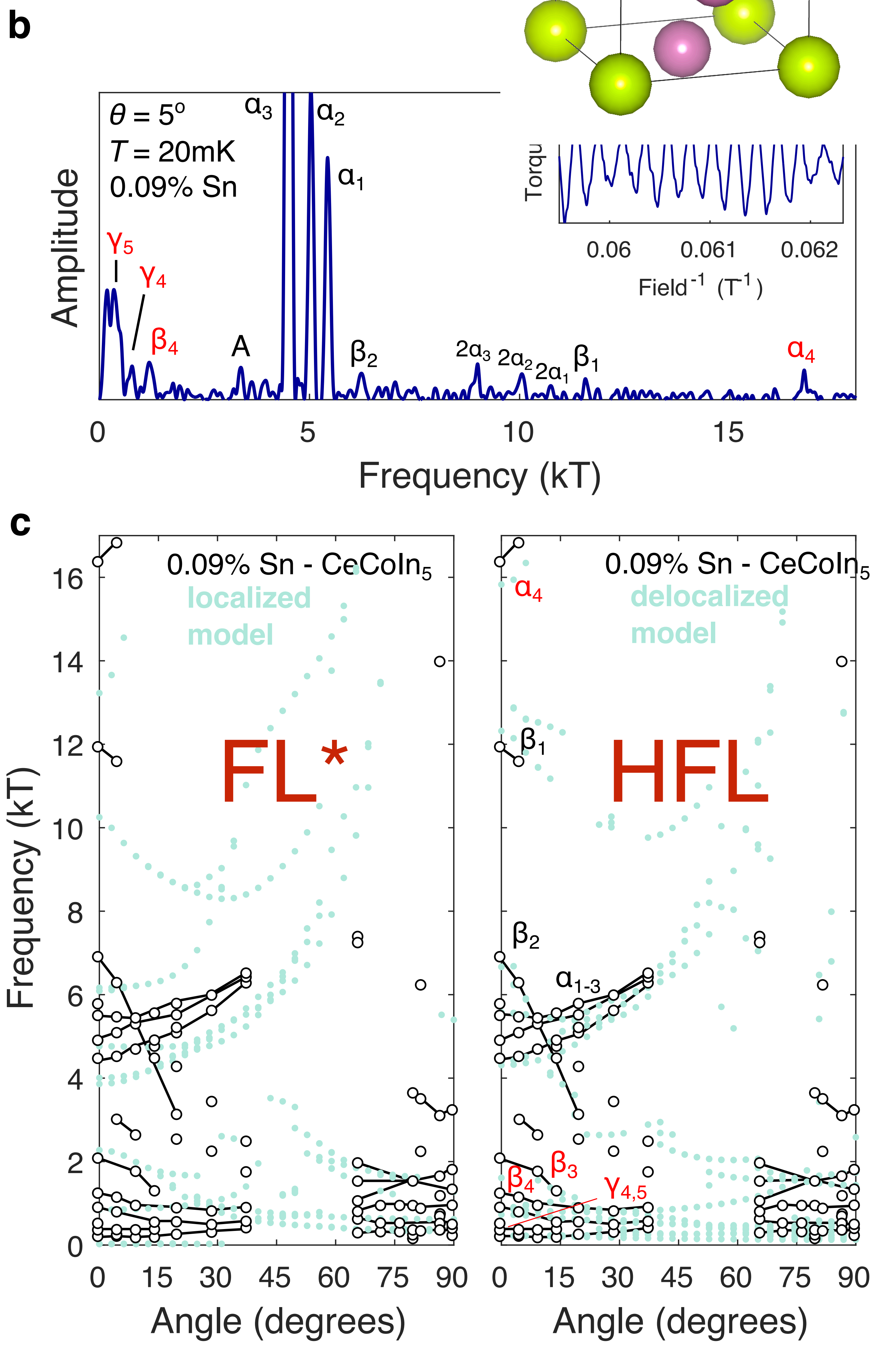

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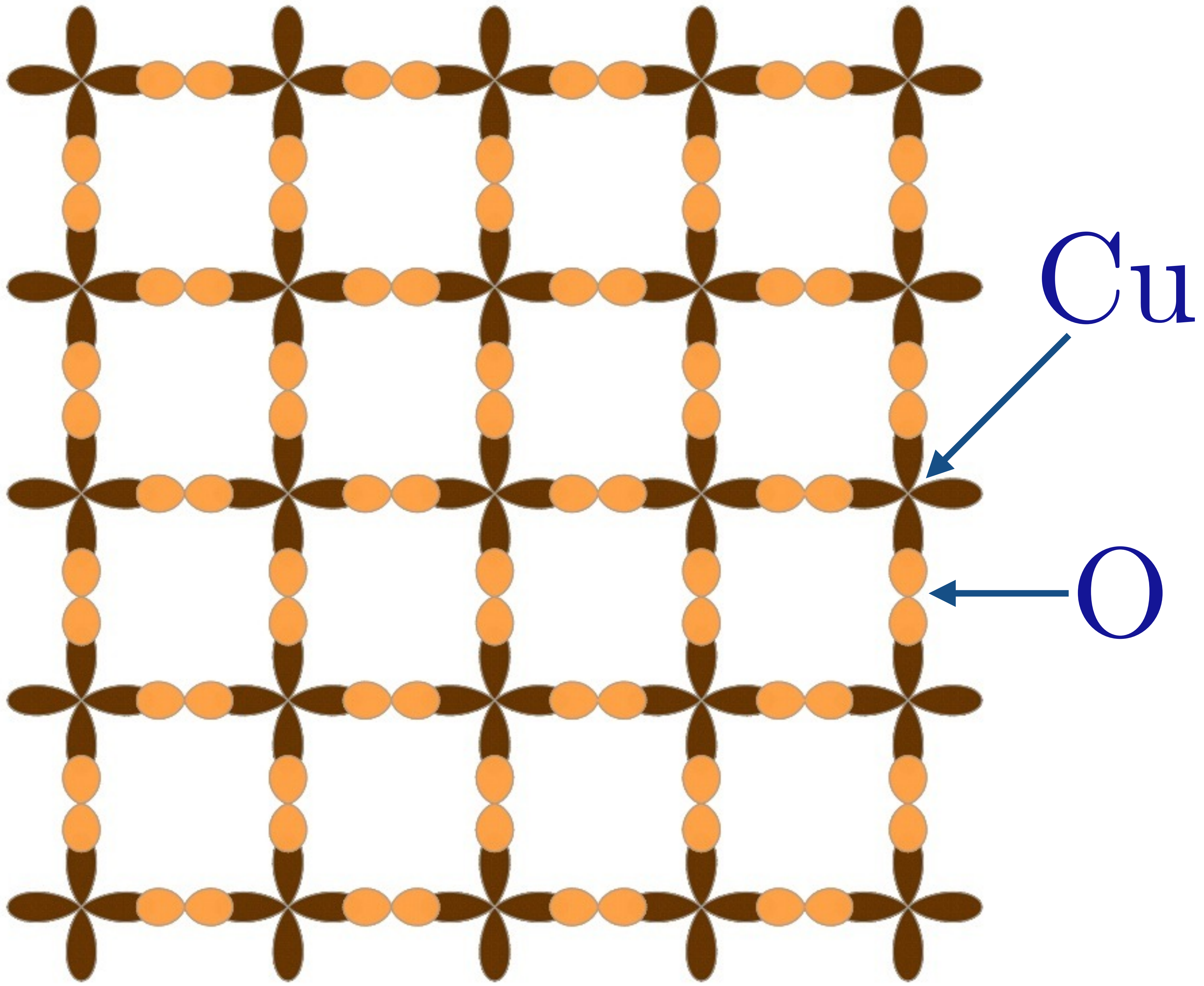
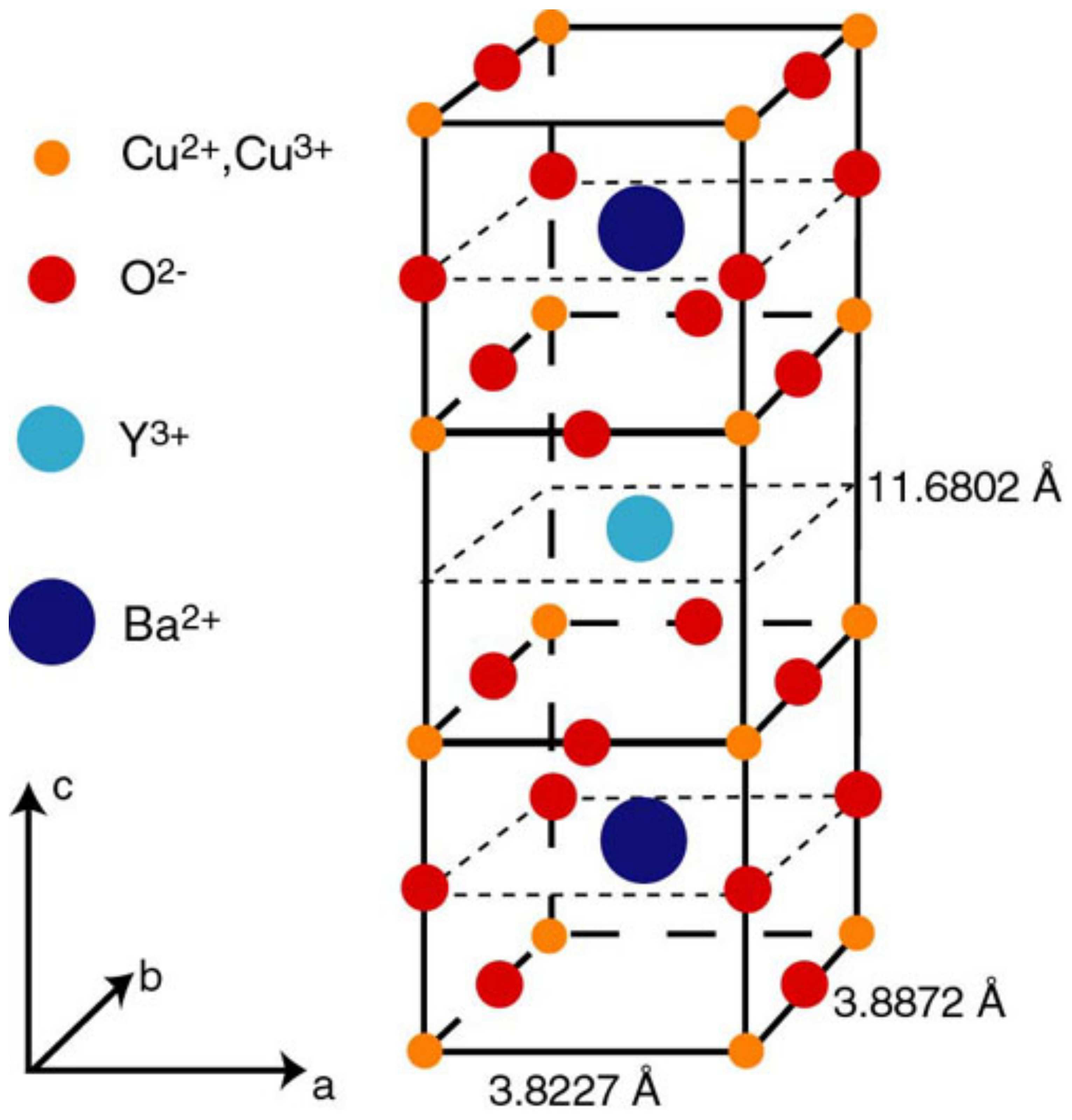
$$\mathcal{H}_H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^{\dagger}_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

High temperature superconductors



CuO_2 plane



$YBa_2Cu_3O_{6+x}$

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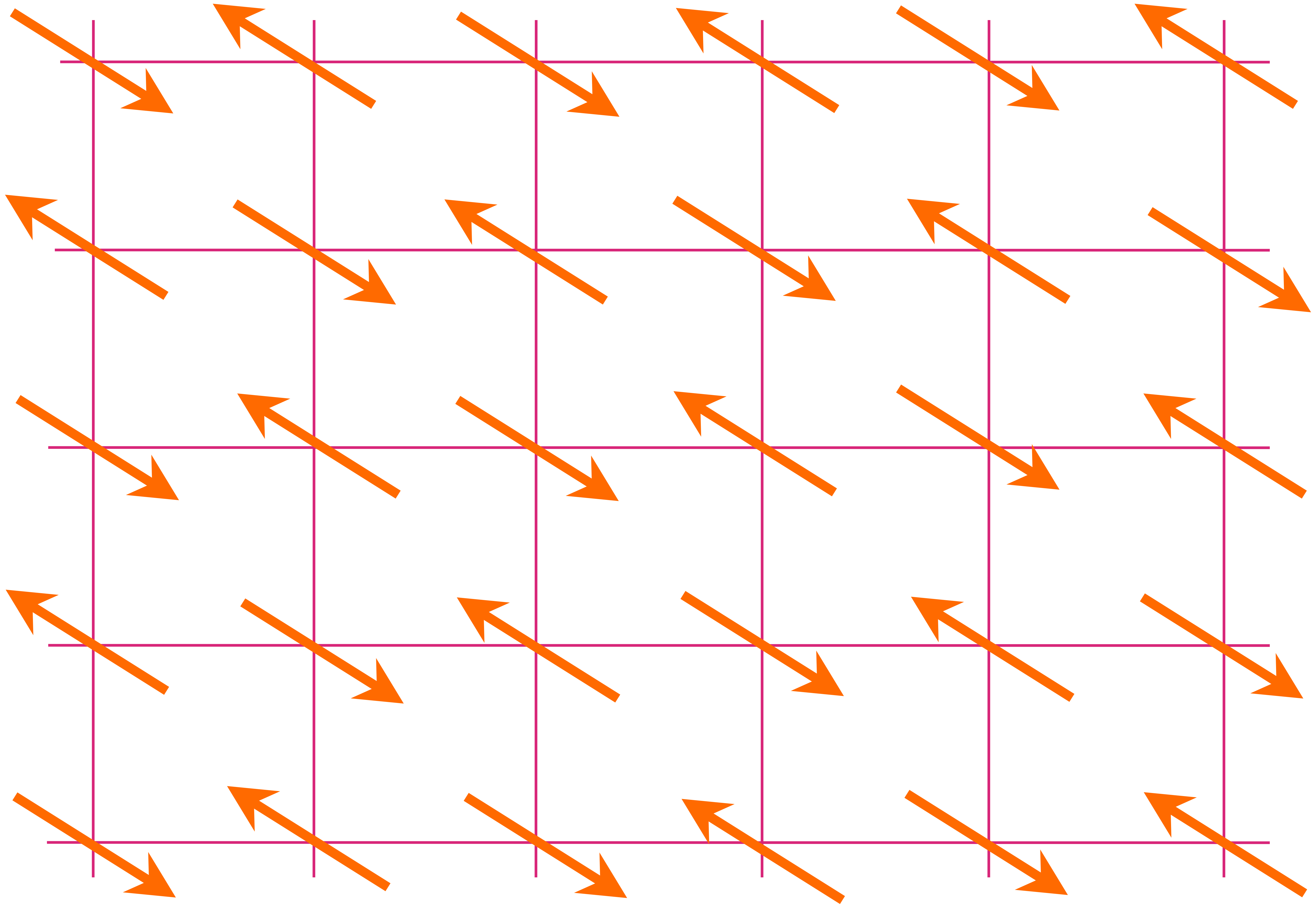

Insulating antiferromagnet

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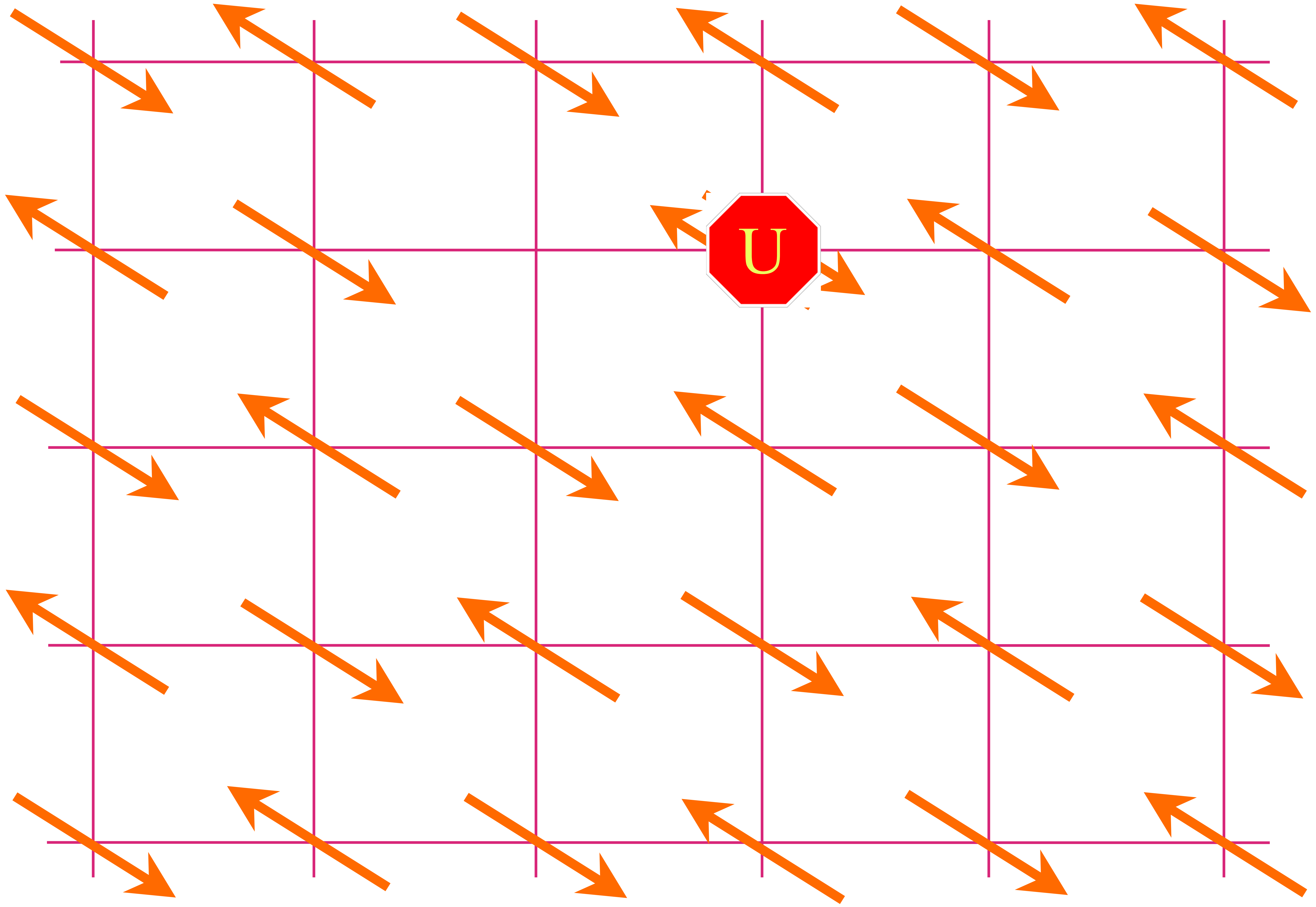

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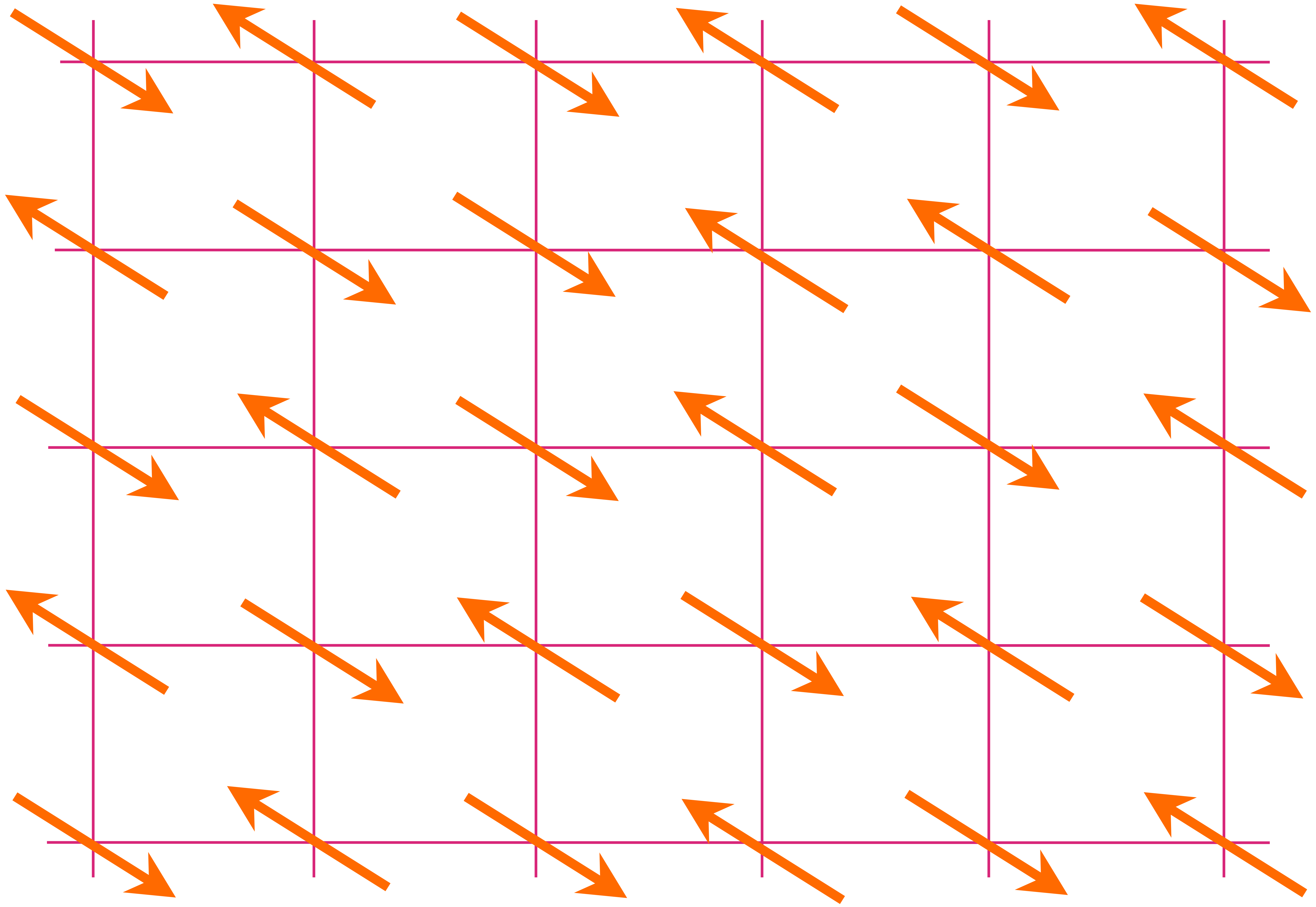

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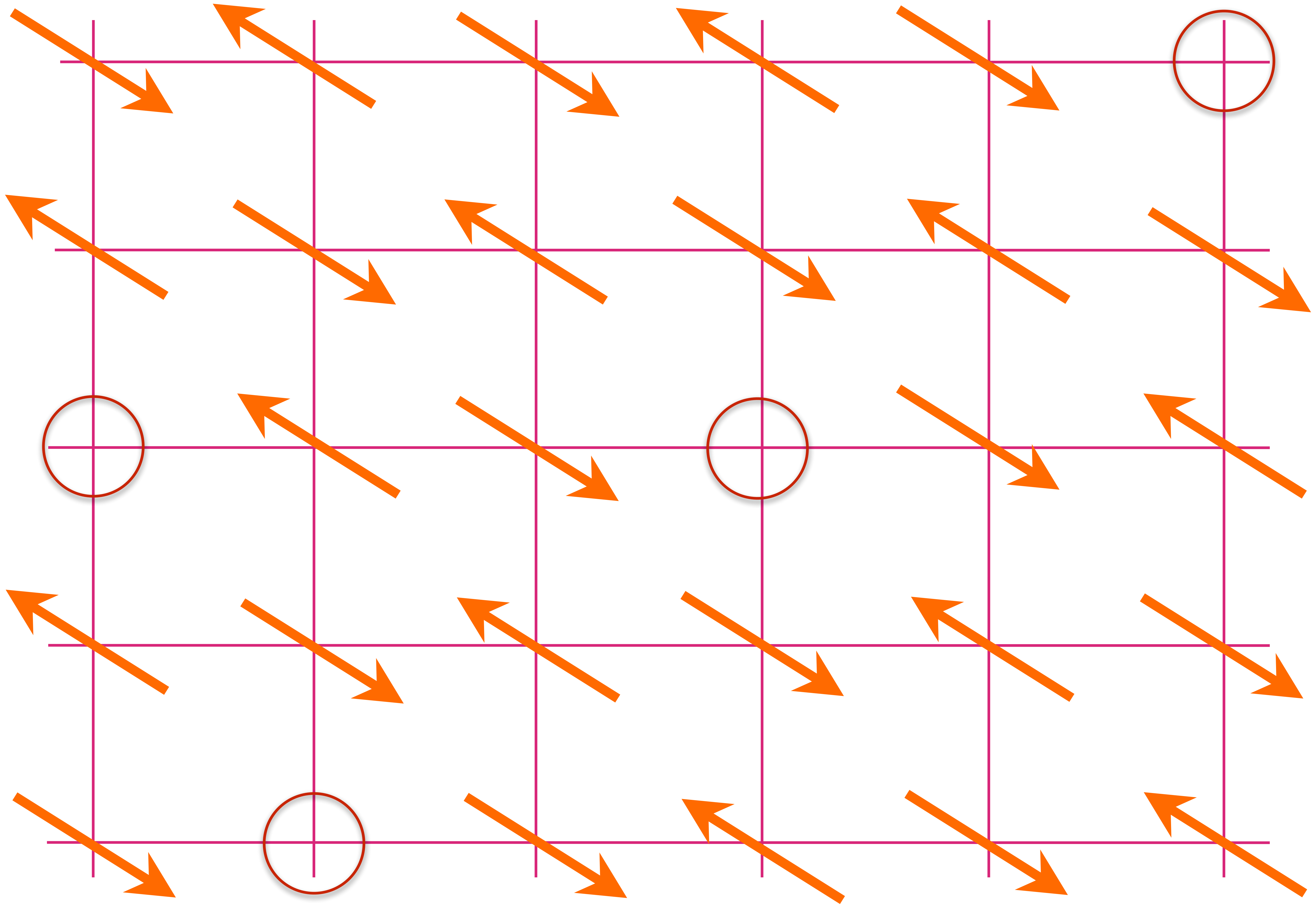
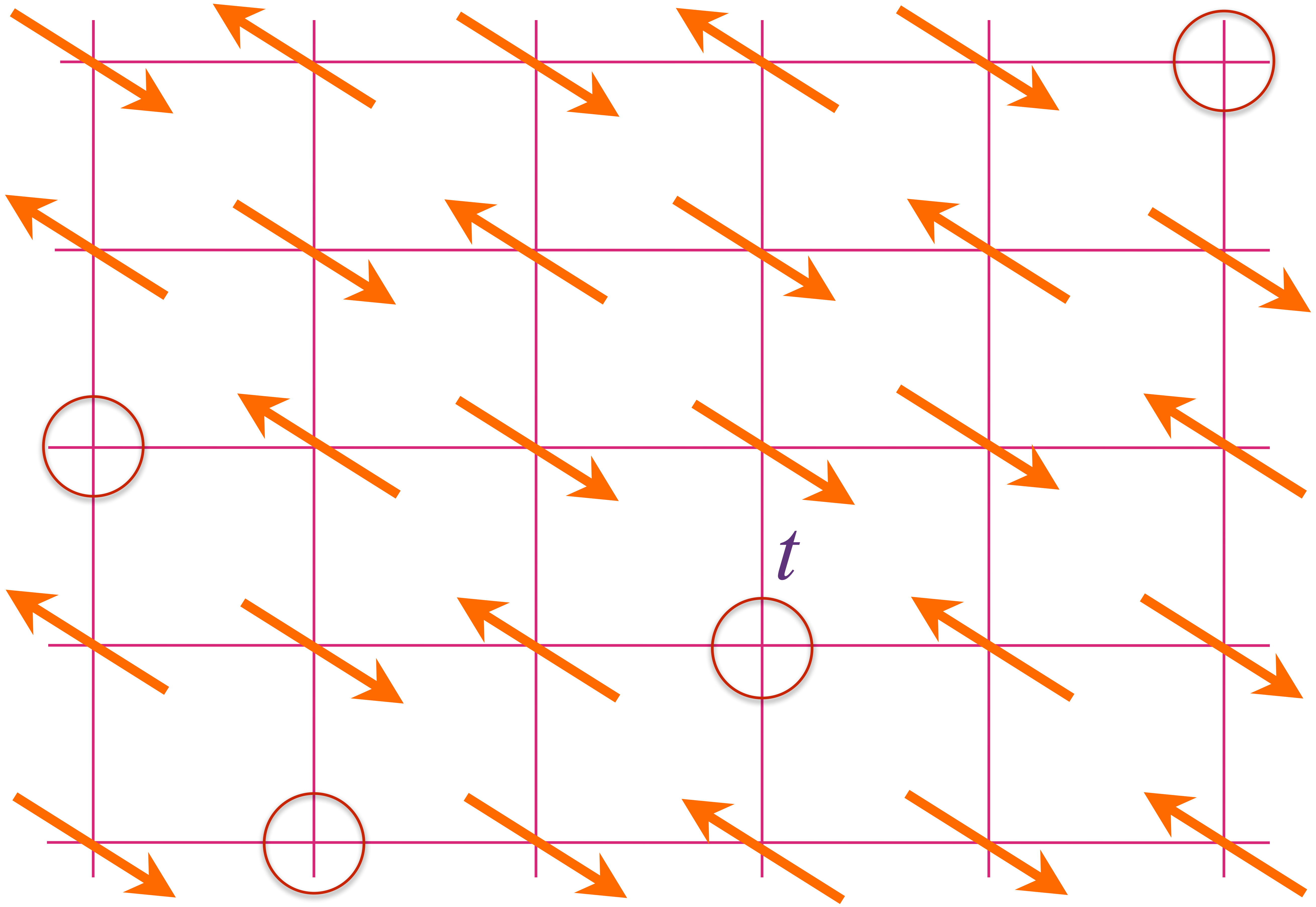


Antiferromagnet doped with hole density p

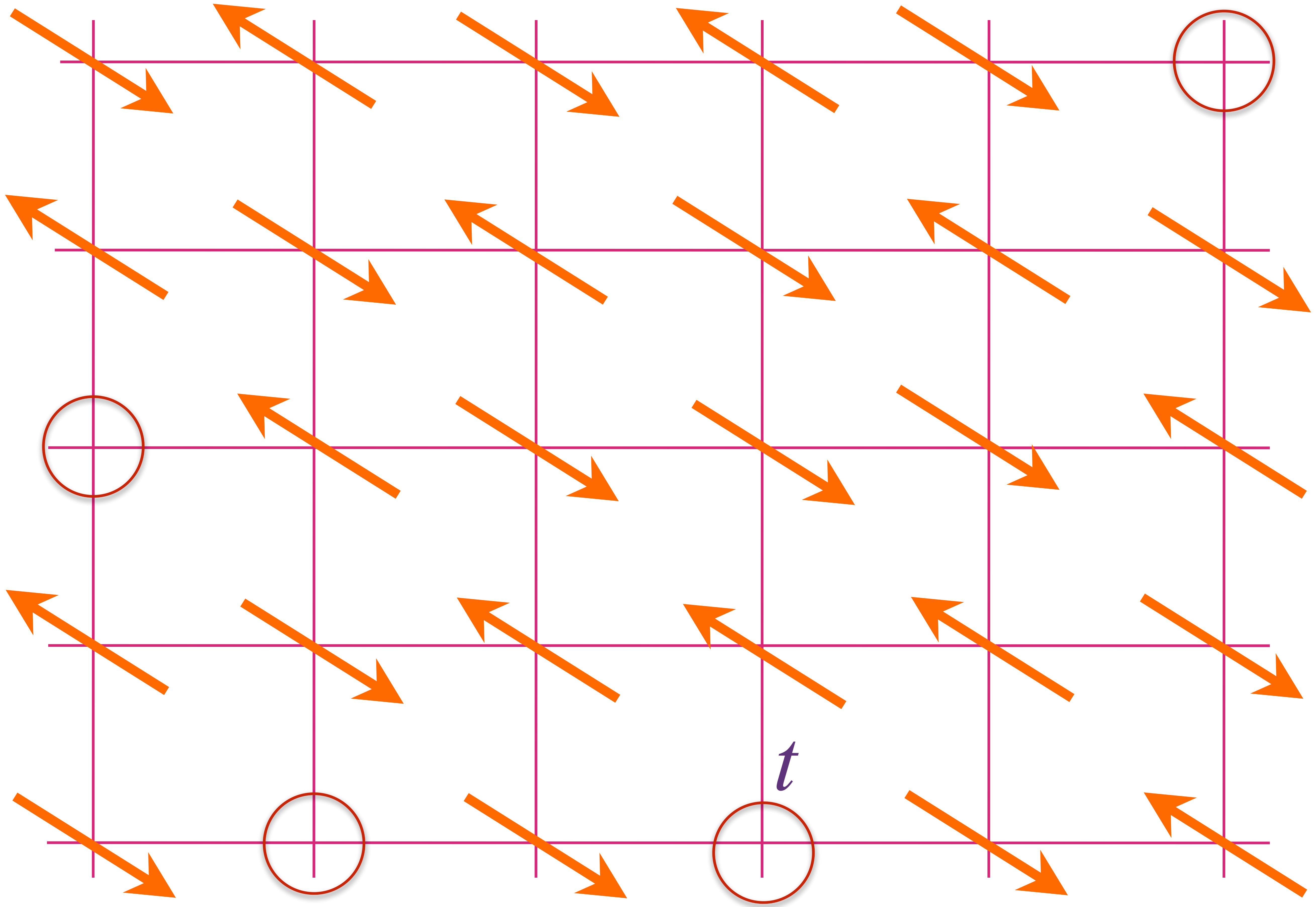
$$\mathcal{H}_H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c_{\mathbf{p}\sigma}^{\dagger} c_{\mathbf{p}\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



Antiferromagnet doped with hole density p

p mobile holes in a background of fluctuating spins

$$\mathcal{H}_H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



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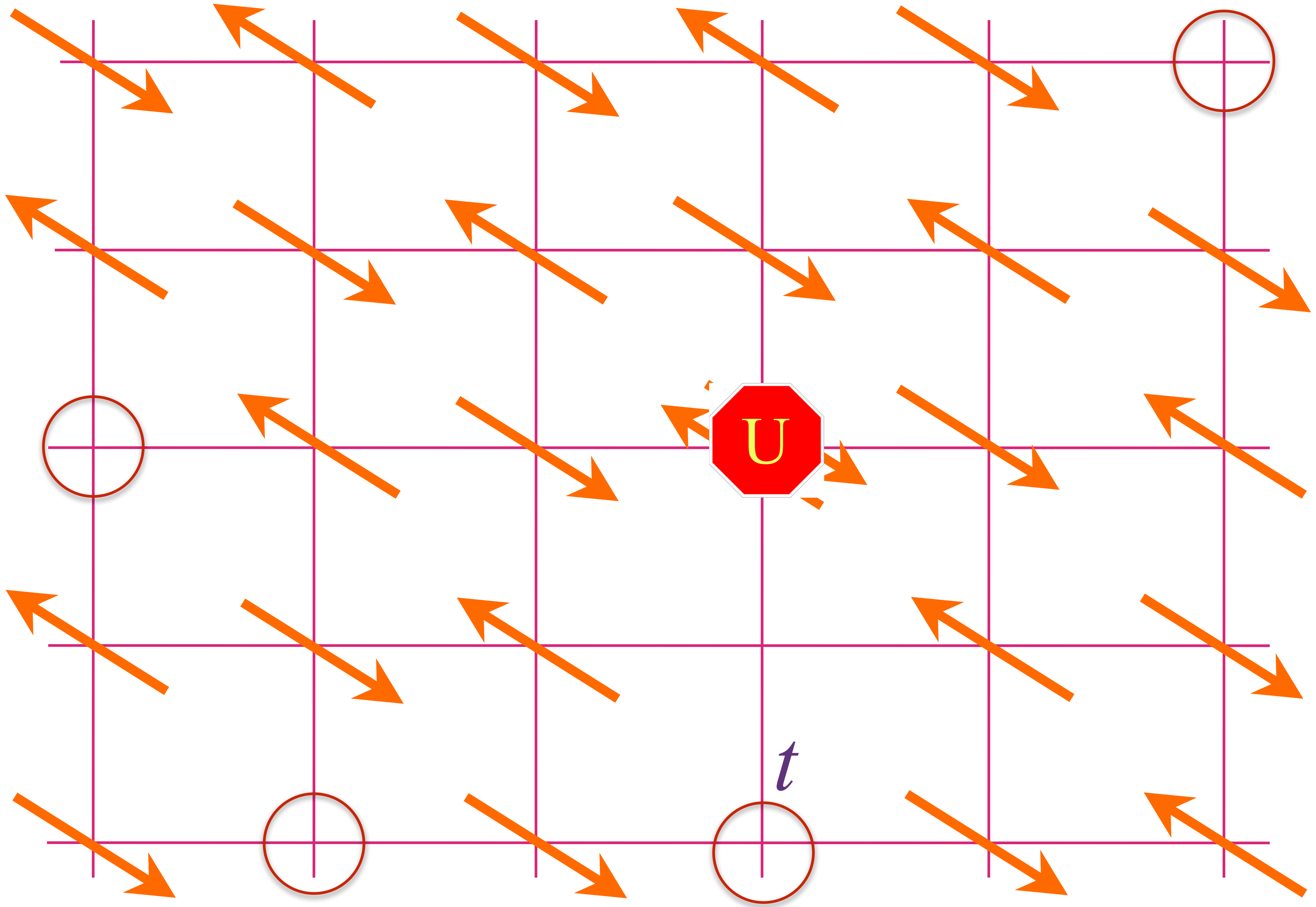

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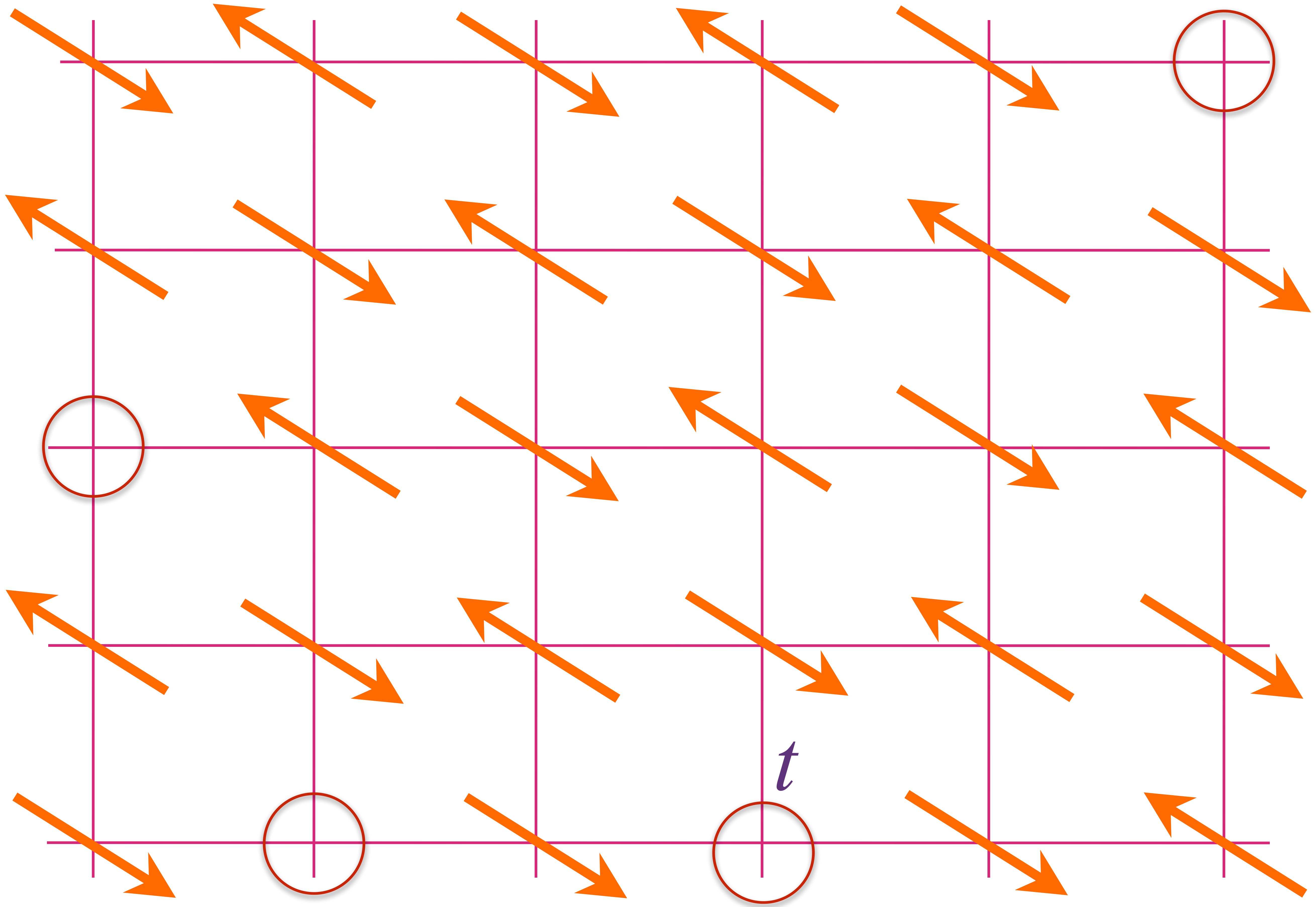

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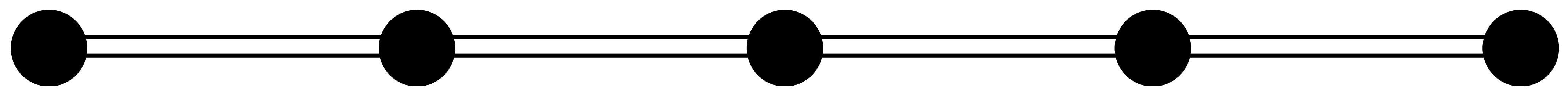
- The Luttinger theorem implies a FL phase with 'large' Fermi surface of size $1+p$ holes (or $1-p$ electrons) for all U and all p.



c_σ

density
1+p

$$\mathcal{H}_H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c_{\mathbf{p}\sigma}^{\dagger} c_{\mathbf{p}\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

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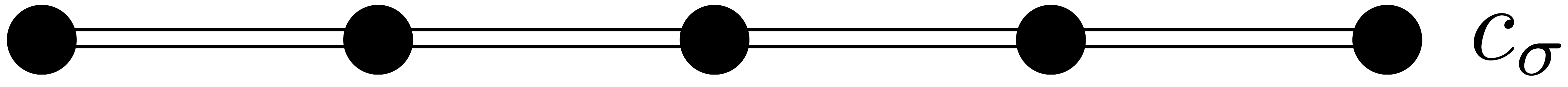

density
1+p

P. W. Anderson, P. A. Lee, M. Randeria, T. M. Rice, N. Trivedi, and F. C. Zhang, Journal of Physics Condensed Matter **16**, R755 (2004)

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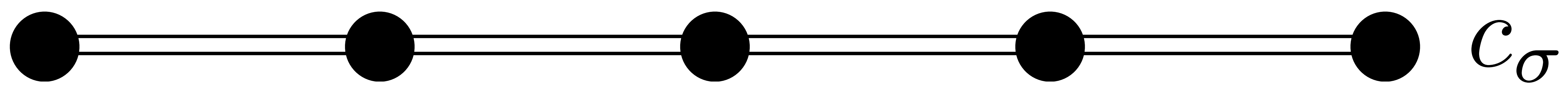
- The main effect of the projection is a 'Brinkman-Rice' enhancement of the quasiparticle mass as $p \to 0$, with $m^*/m \sim 1/p$.



density
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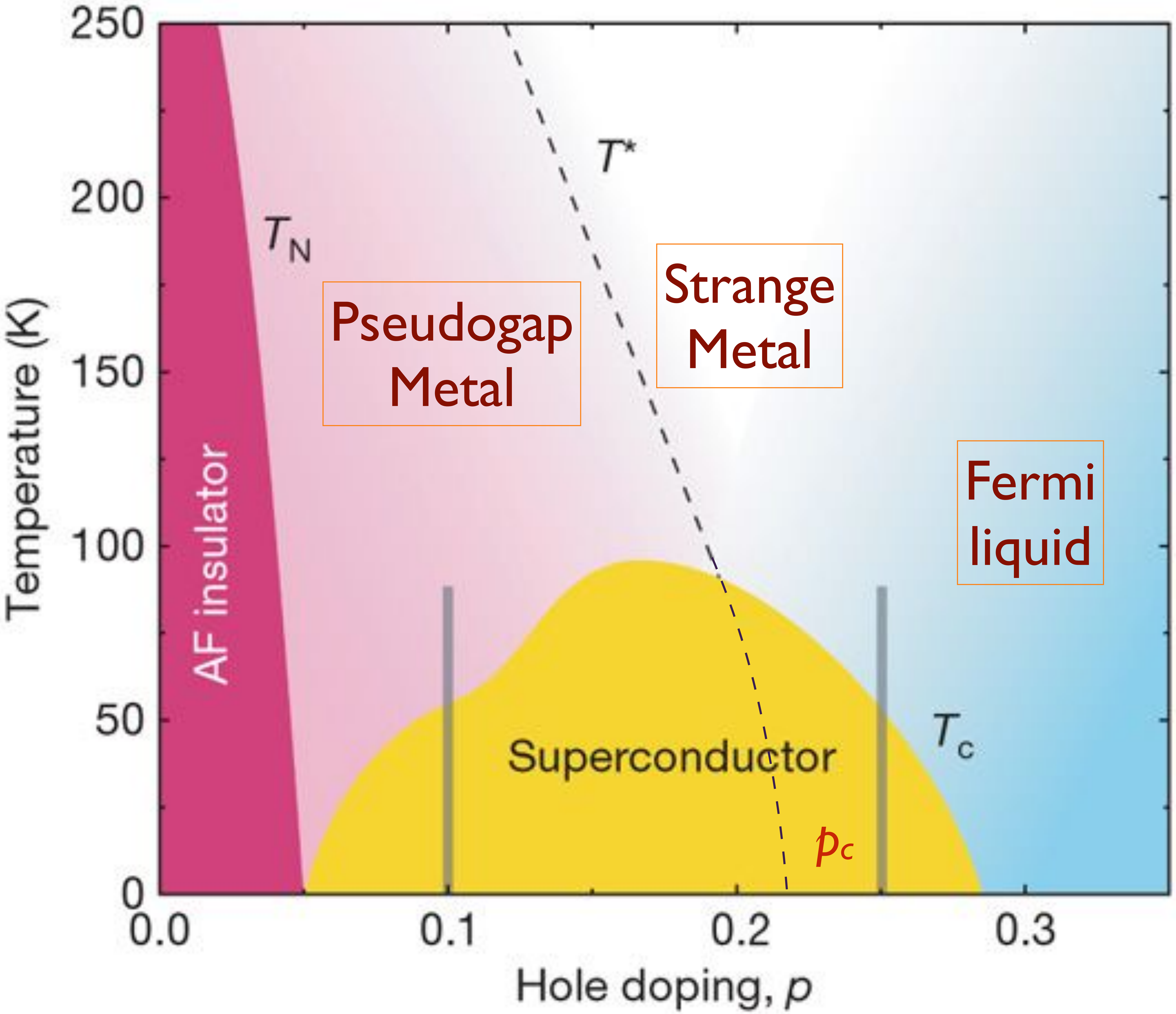
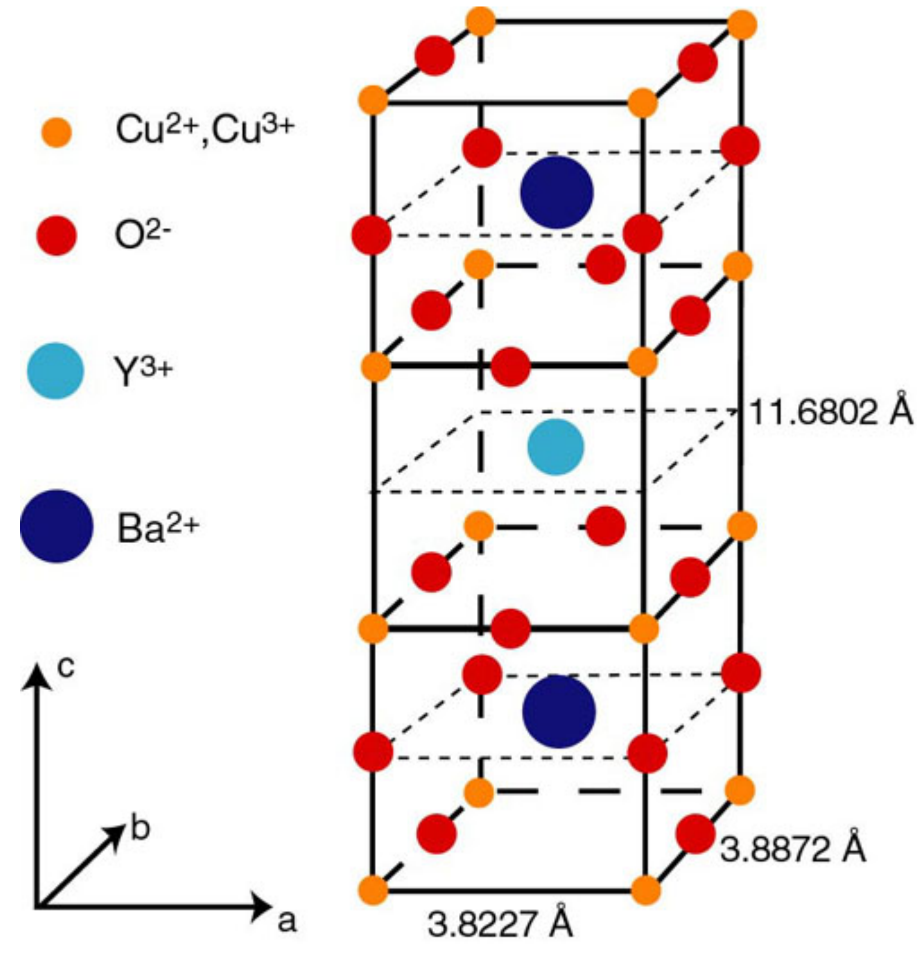
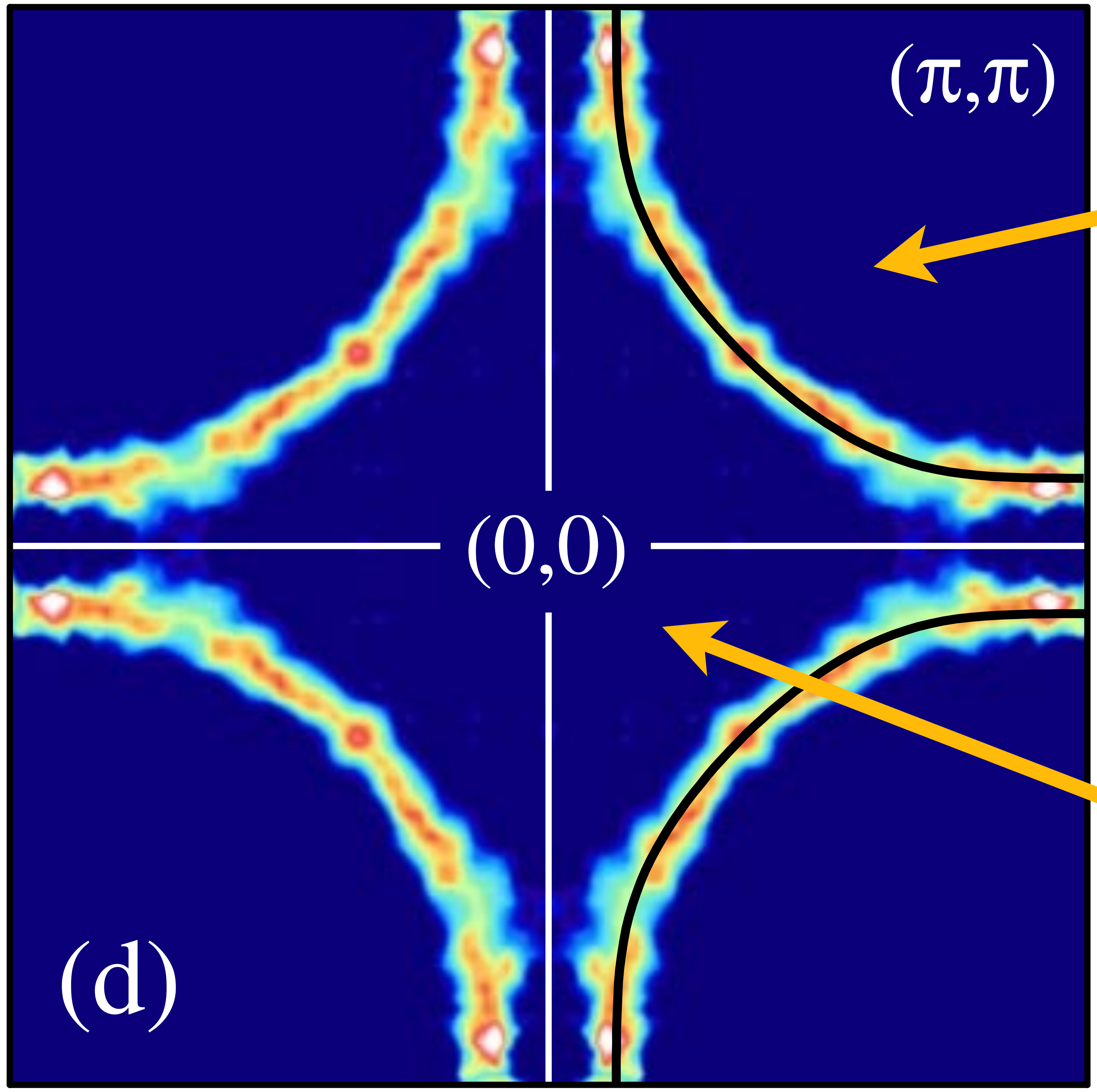

250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Pseudogap Metal
Strange Metal
Fermi liquid
Superconductor
T_c
p_c


Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å

Photoemission at large p



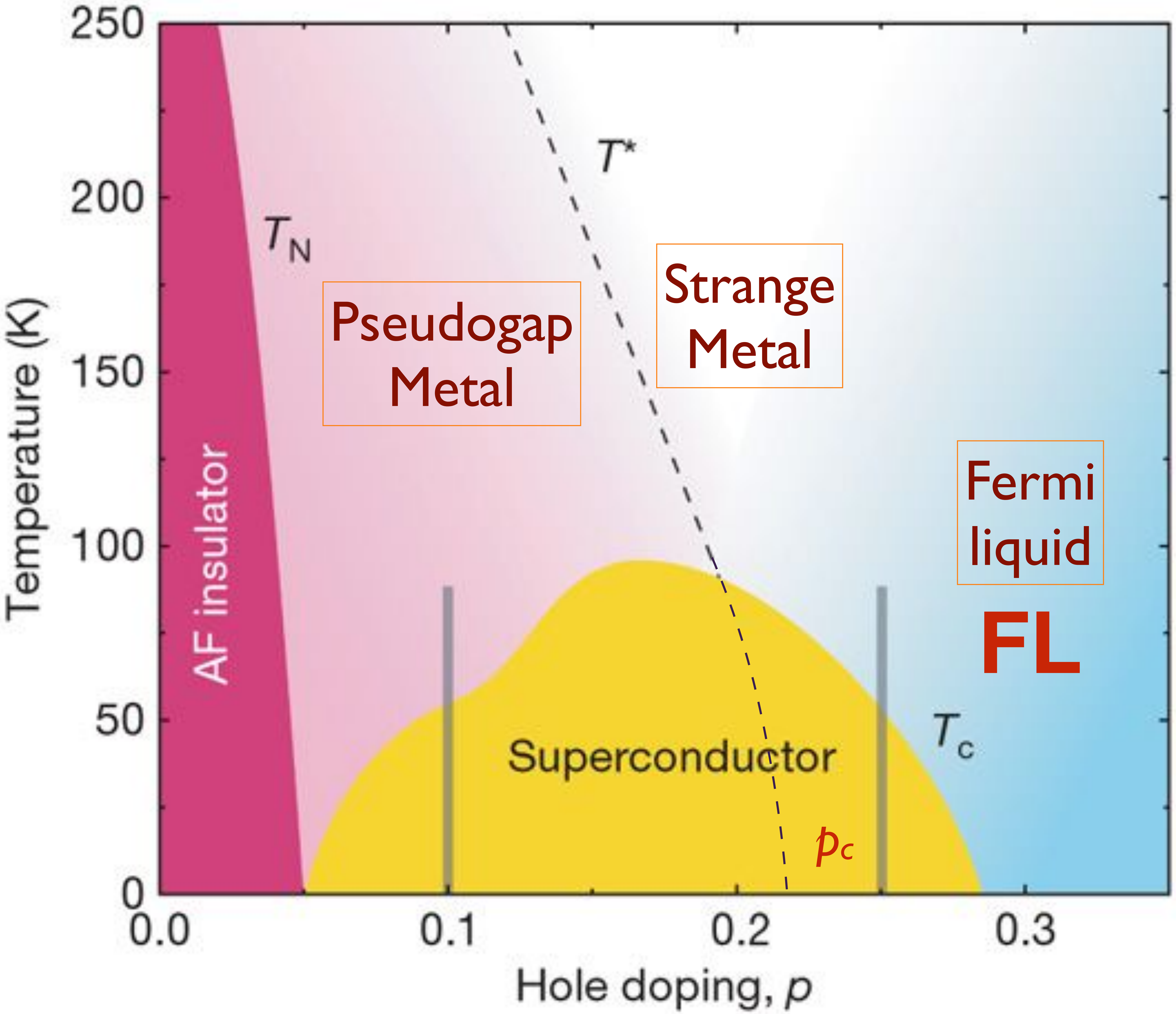
$1+p$ holes

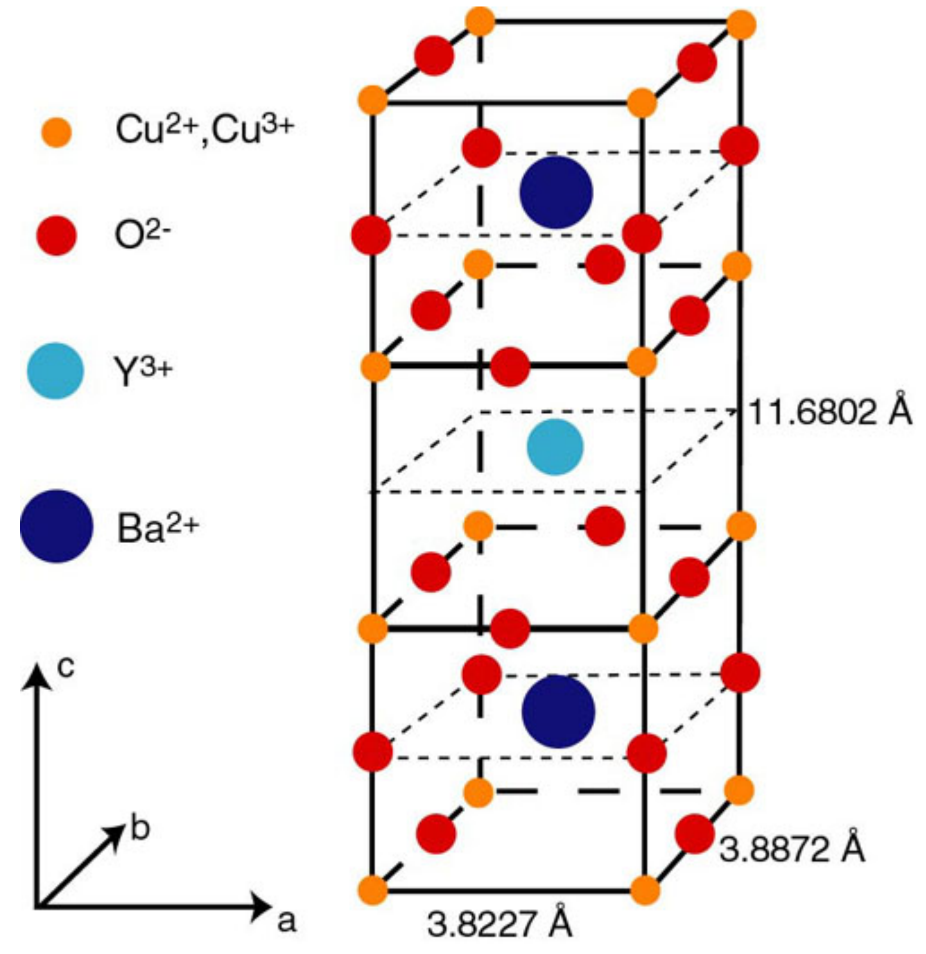
1-p electrons

Overdoped $Tl_2Ba_2CuO_{6+\delta}$
$T_c = 30$K

$1+p$ mobile holes in a filled band

M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
Pseudogap Metal
T*
Strange Metal
Fermi liquid
FL
Superconductor
T_c
p_c


Cu2+,Cu3+
O2-
Y3+
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c
b
a
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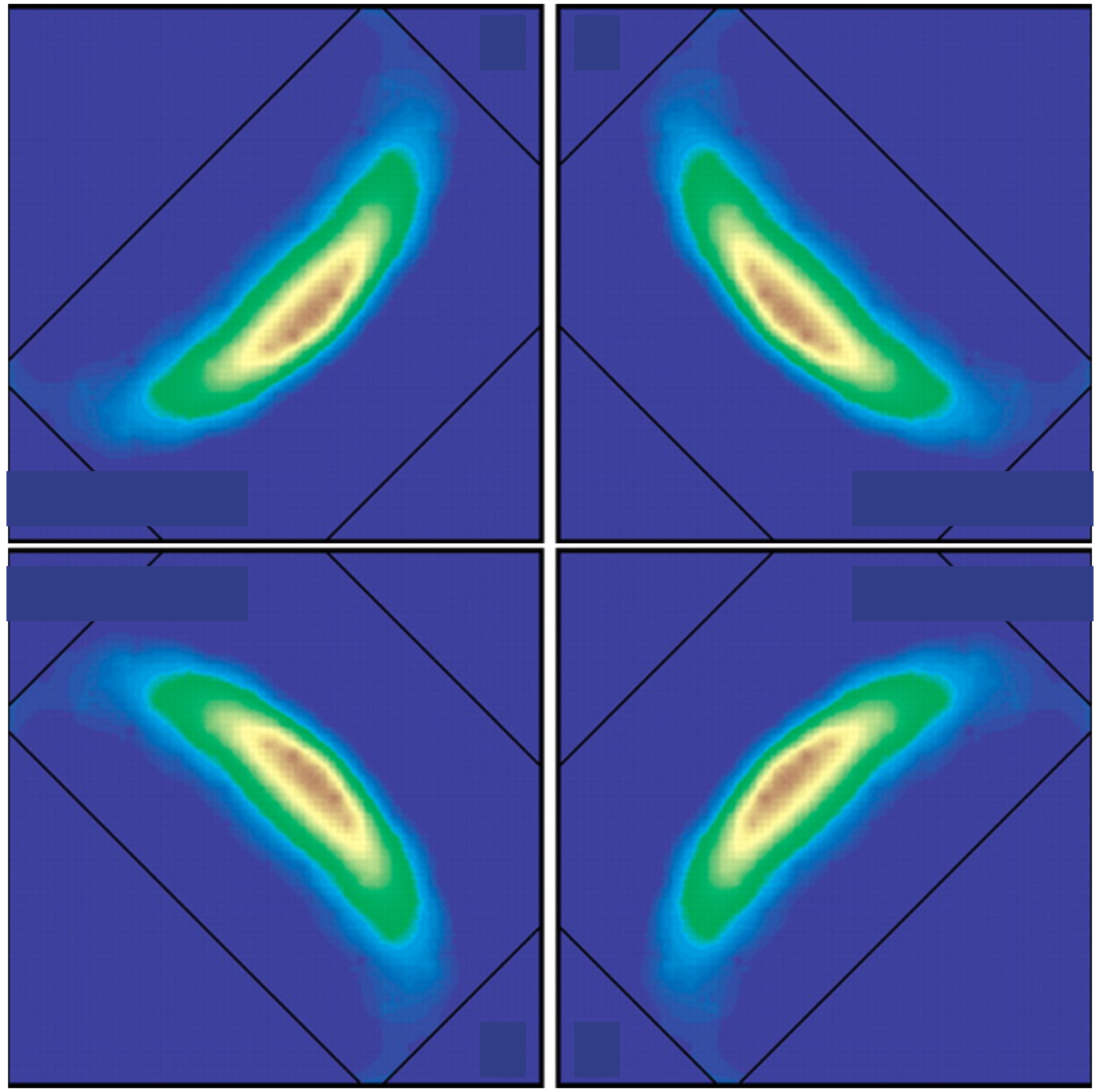
Photoemission at small p



$Ca_{2-x}Na_xCuO_2Cl_2$
at $x = 0.10$

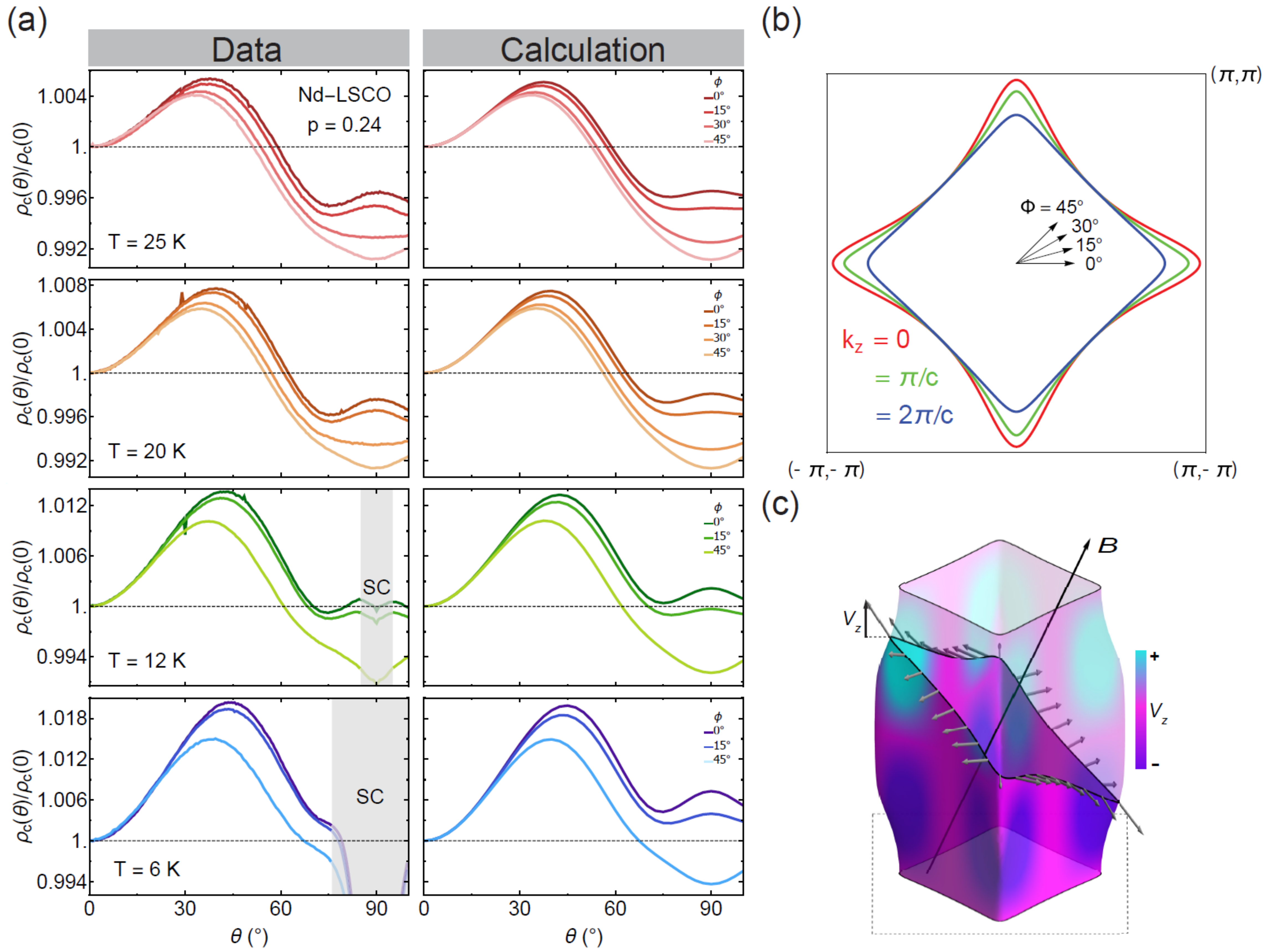
"Fermi arcs"

Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

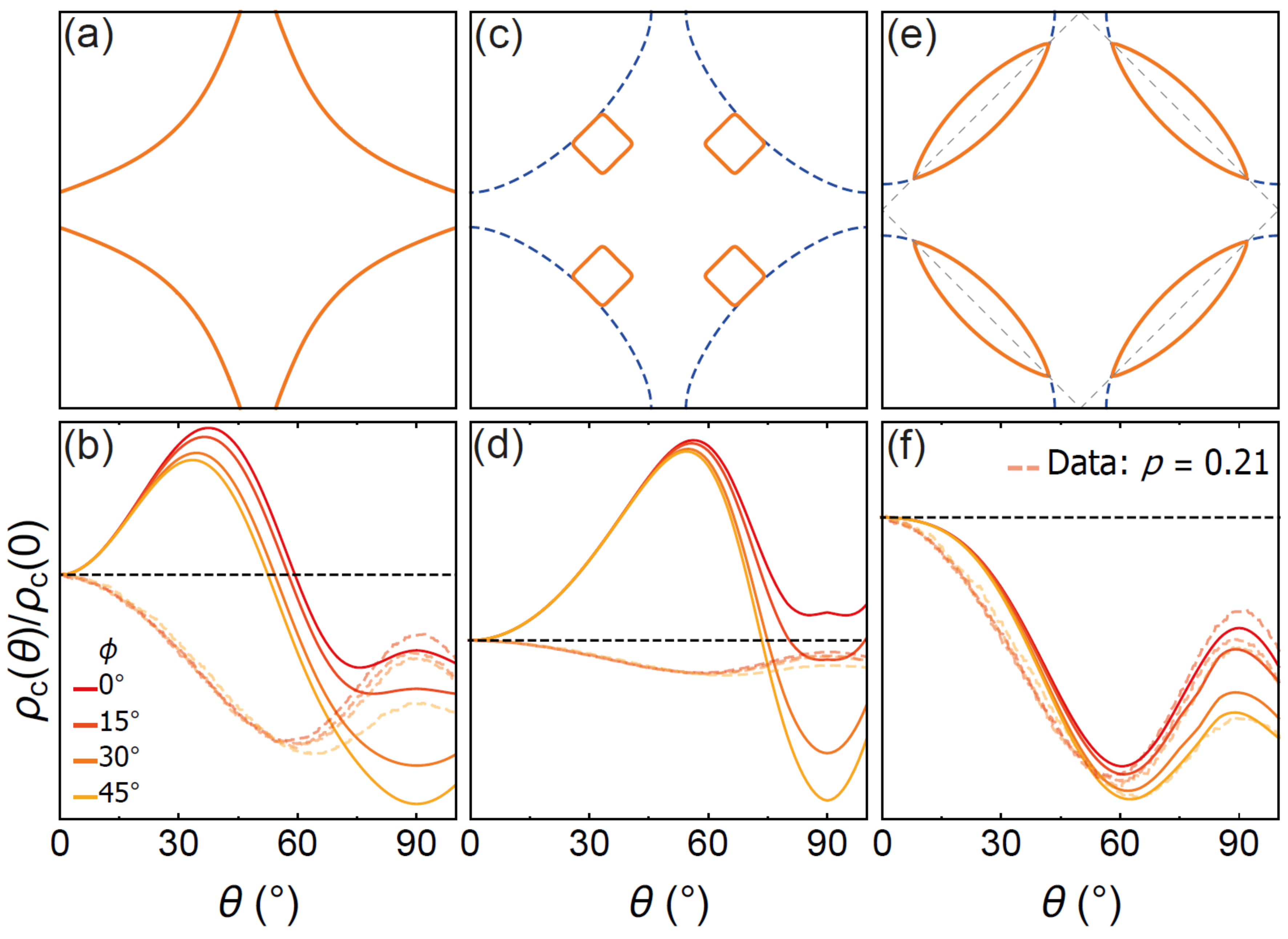
Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

Yawen Fang, Gaël Grissonnanche, Anaëlle Legros, Simon Verret, Francis Laliberté, Clément Collignon, Amirreza Ataei, Maxime Dion, Jianshi Zhou, David Graf, M. J. Lawler, Paul Goddard, Louis Taillefer, and B. J. Ramshaw, arXiv:2004.01725

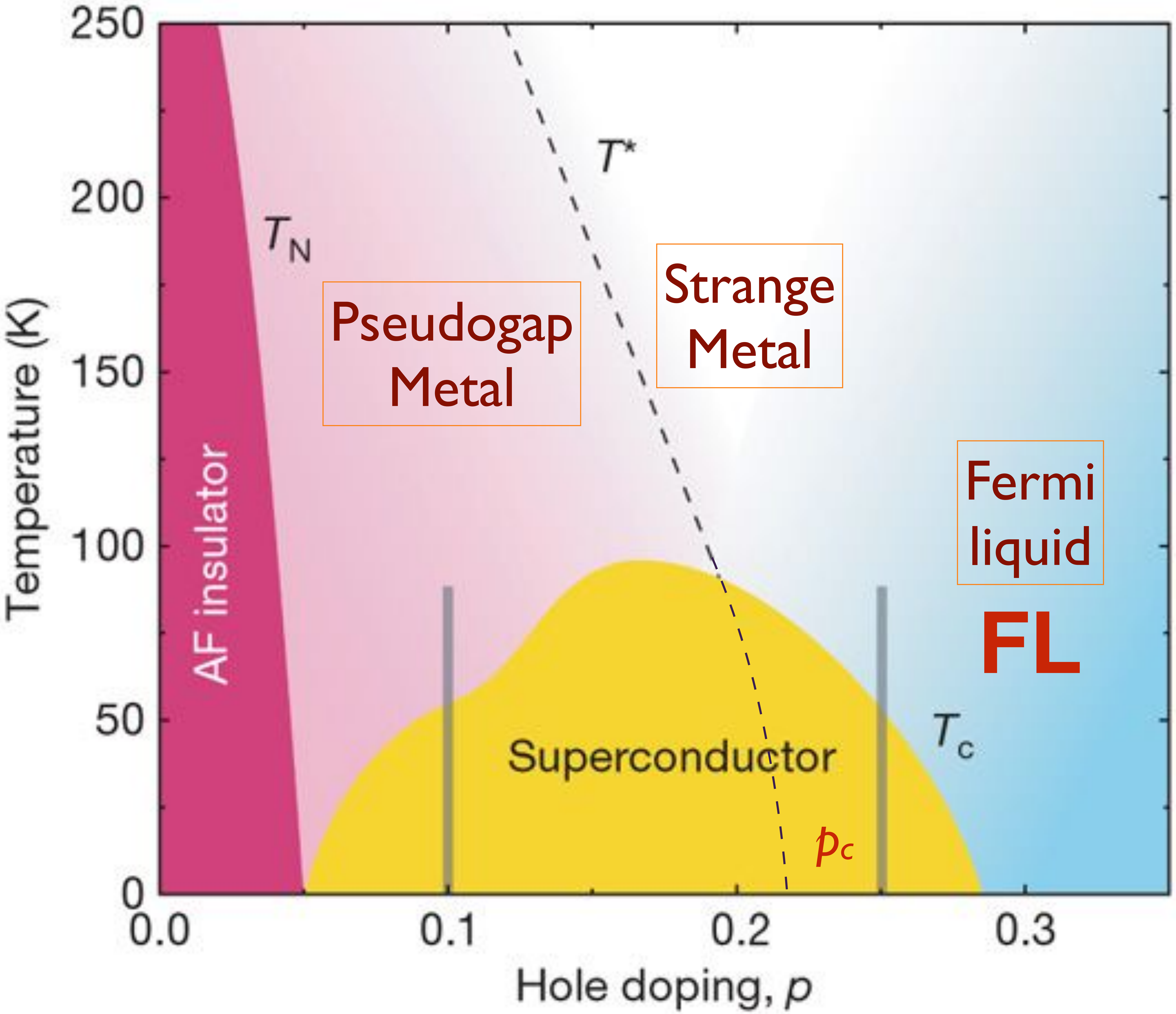
We use angle-dependent magnetoresistance (ADMR) to measure the Fermi surface of the cuprate $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$. Above the critical doping p*—outside of the pseudogap phase—we find a Fermi surface that is in quantitative agreement with angle-resolved photoemission. Below p*, however, the ADMR is qualitatively different, revealing a clear change in Fermi surface topology. We find that our data is most consistent with a Fermi surface that has been reconstructed by a Q = (π,π) wavevector. While static Q = (π,π) antiferromagnetism is not found at these dopings, our results suggest that this wavevector is a fundamental organizing principle of the pseudogap phase.



$p > p_c$ Large Fermi surface



$p < p_c$ Reconstructed Fermi surface


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
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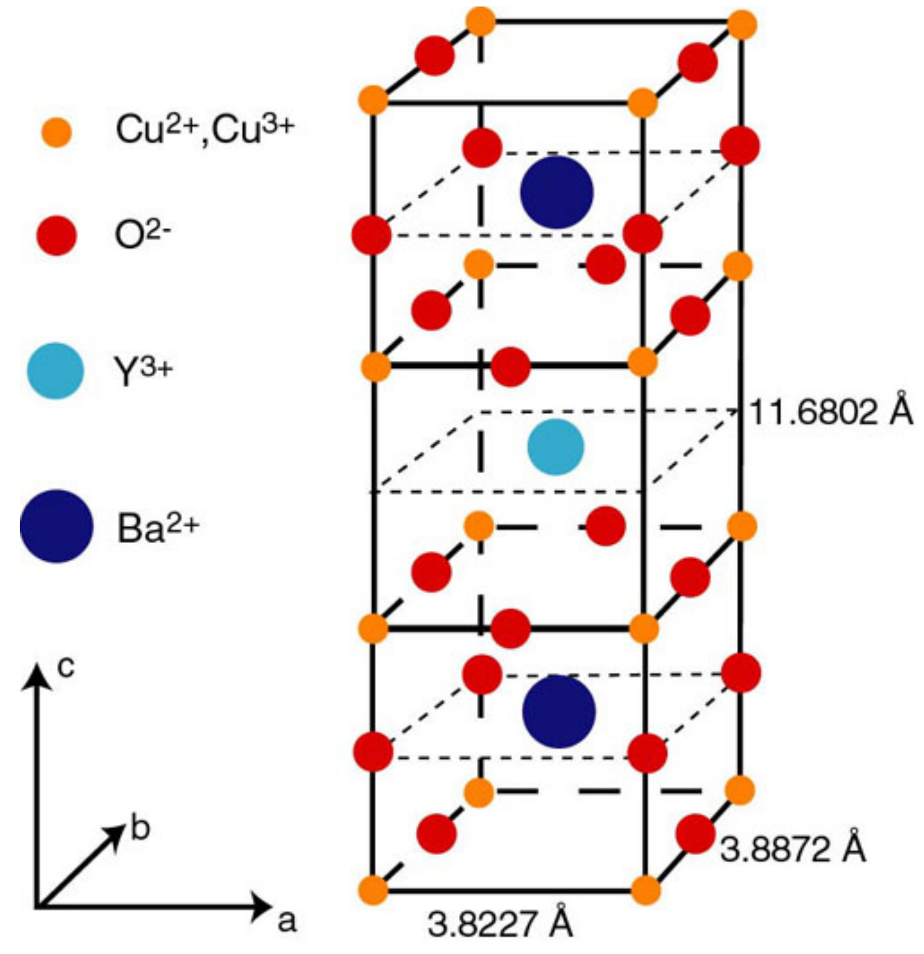
Fermi liquid
FL
Superconductor
T_c
p_c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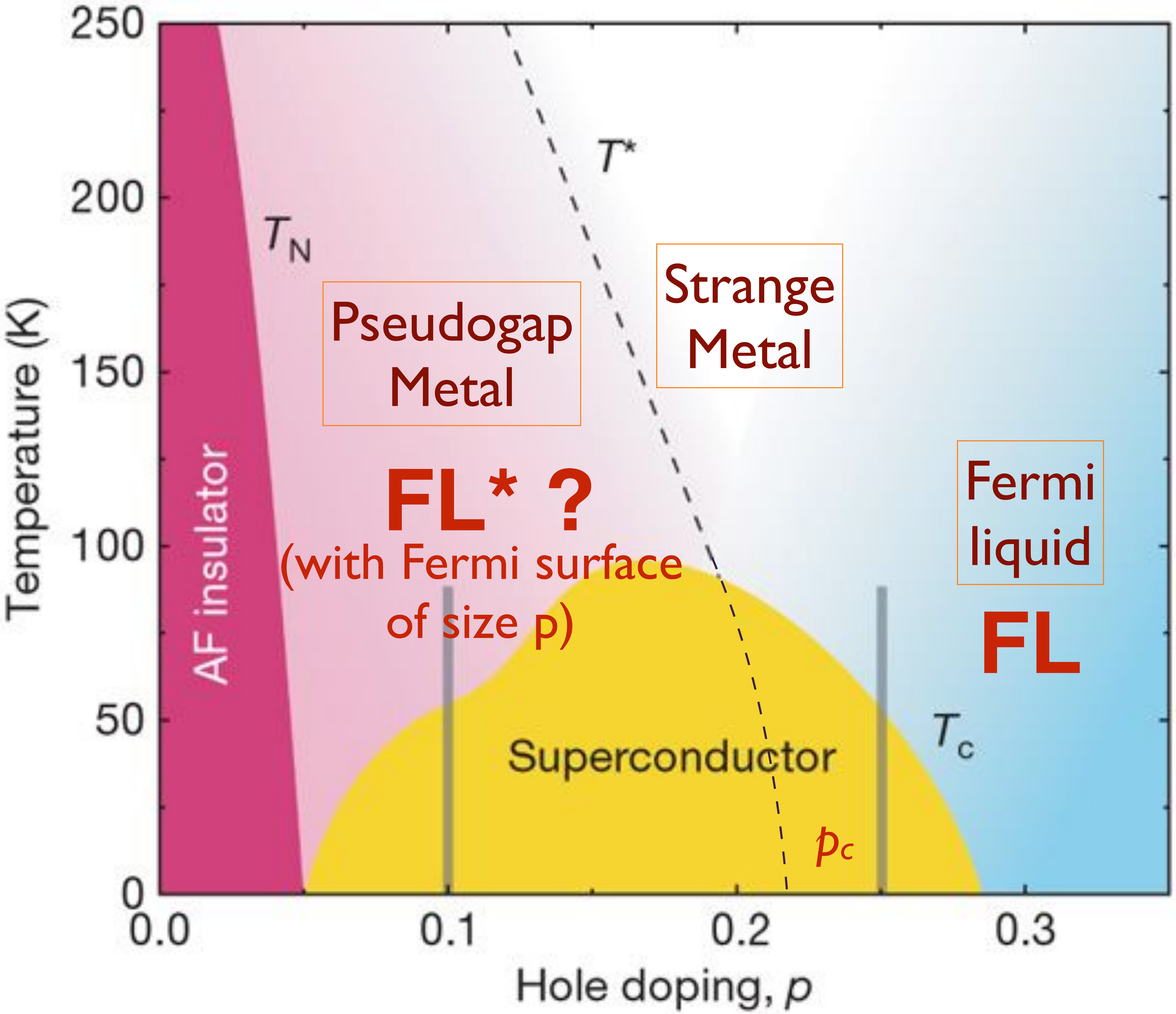

250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Pseudogap Metal
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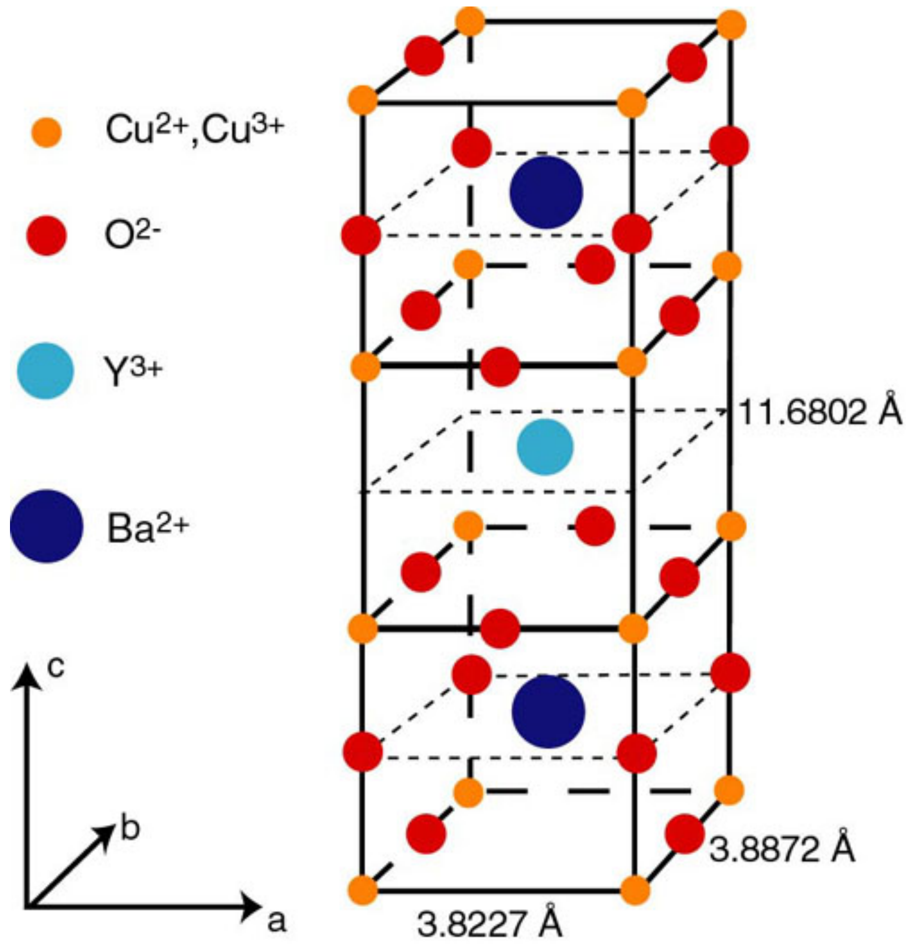
FL* ?
(with Fermi surface of size p)
Fermi liquid
FL
T_c
Superconductor
p_c



Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å

The pseudogap metal ≈ FL* (these papers fractionalize the mobile electron)

X.-G. Wen and P. A. Lee, "Theory of Underdoped Cuprates," Phys. Rev. Lett. **76**, 503 (1996), arXiv:cond-mat/9506065 [cond-mat].

J.-W. Mei, S. Kawasaki, G.-Q. Zheng, Z.-Y. Weng, and X.-G. Wen, "Luttinger-volume violating Fermi liquid in the pseudogap phase of the cuprate superconductors," Phys. Rev. B **85**, 134519 (2012), arXiv:1109.0406 [cond-mat.supr-con].

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N. J. Robinson, P. D. Johnson, T. M. Rice, and A. M. Tsvelik, "Anomalies in the pseudogap phase of the cuprates: competing ground states and the role of umklapp scattering," Reports on Progress in Physics **82**, 126501 (2019), arXiv:1906.09005 [cond-mat.supr-con].

J. Feldmeier, S. Huber, and M. Punk, "Exact solution of a two-species quantum dimer model for pseudogap metals," Phys. Rev. Lett. **120**, 187001 (2018), arXiv:1712.01854 [cond-mat.str-el].

B. Verheijden, Y. Zhao, and M. Punk, "Solvable lattice models for metals with Z_2 topological order," SciPost Physics **7**, 074 (2019), arXiv:1908.00103 [cond-mat.str-el].

J. Brunkert and M. Punk, "Slave-boson description of pseudogap metals in t-J models," Physical Review Research **2**, 043019 (2020), arXiv:2002.04041 [cond-mat.str-el].

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S. Sachdev, H. D. Scammell, M. S. Scheurer, and G. Tarnopolsky, "Gauge theory for the cuprates near optimal doping," Phys. Rev. B **99**, 054516 (2019), arXiv:1811.04930 [cond-mat.str-el].

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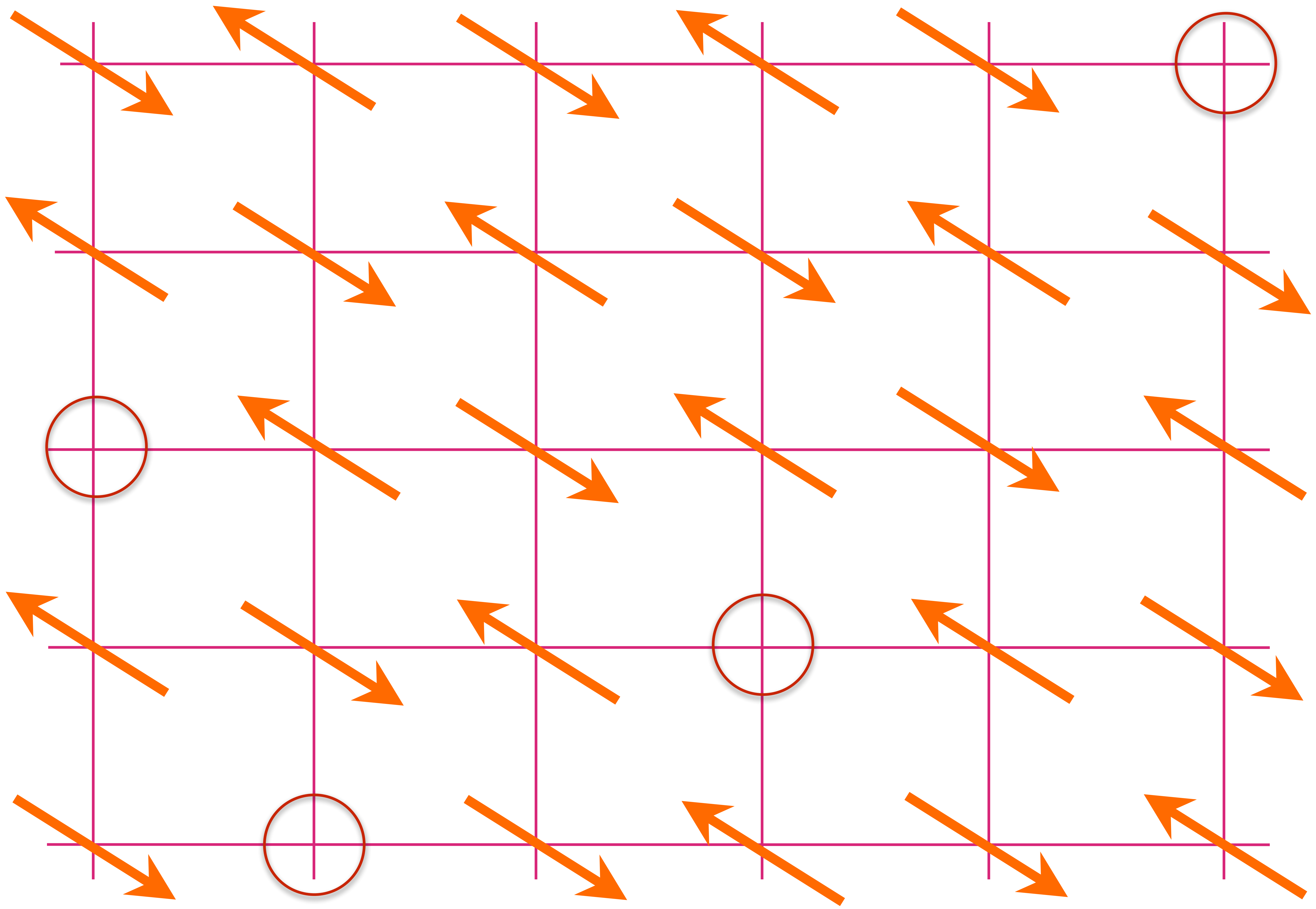
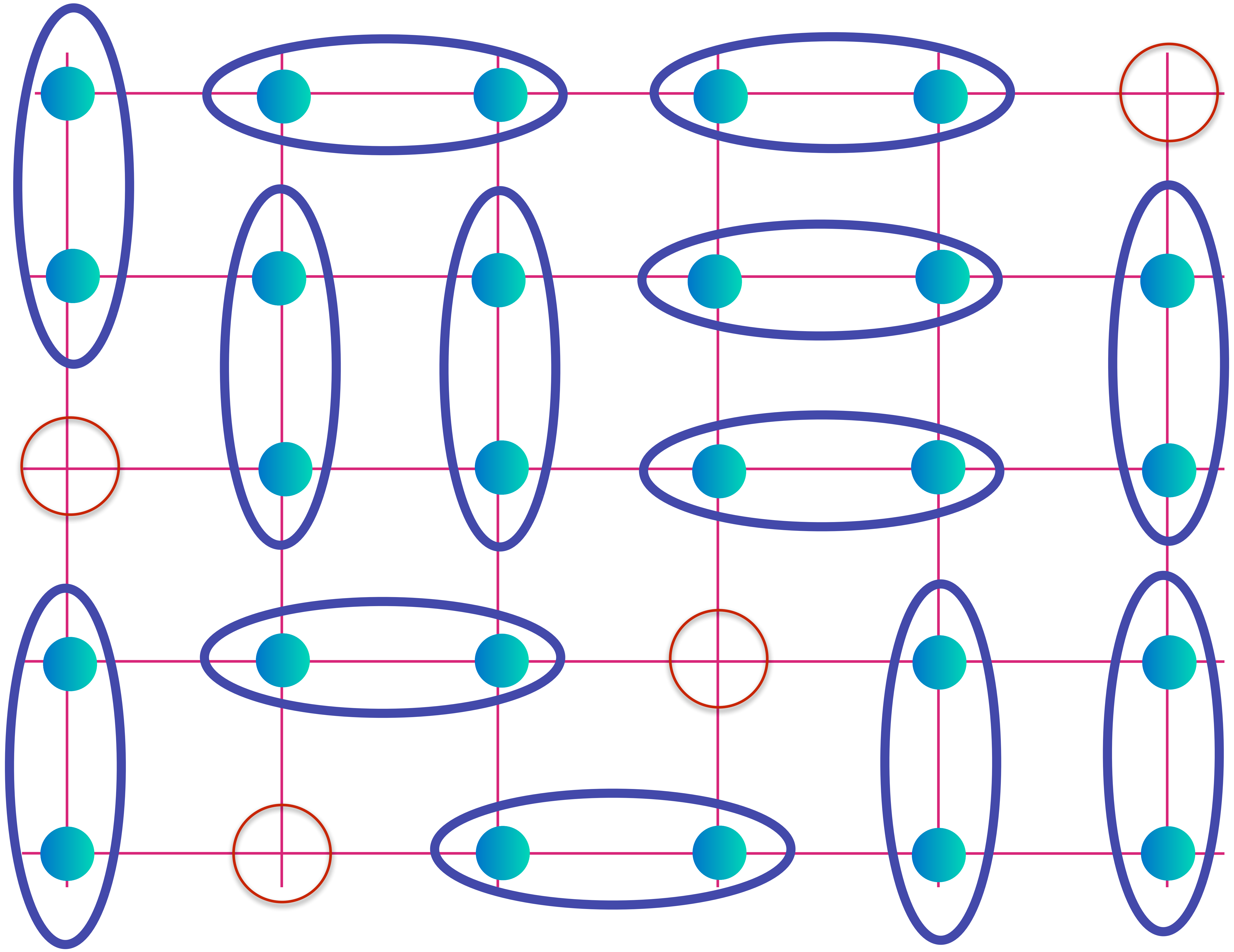


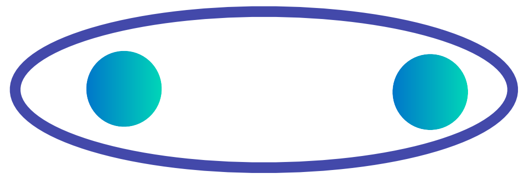
Anti-ferromagnet with p holes per square

Holon metal

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)
D. Rokhsar and S.A. Kivelson, PRL **61**, 2376 (1988)



Spin liquid with density p of spinless, charge +e "holons".



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

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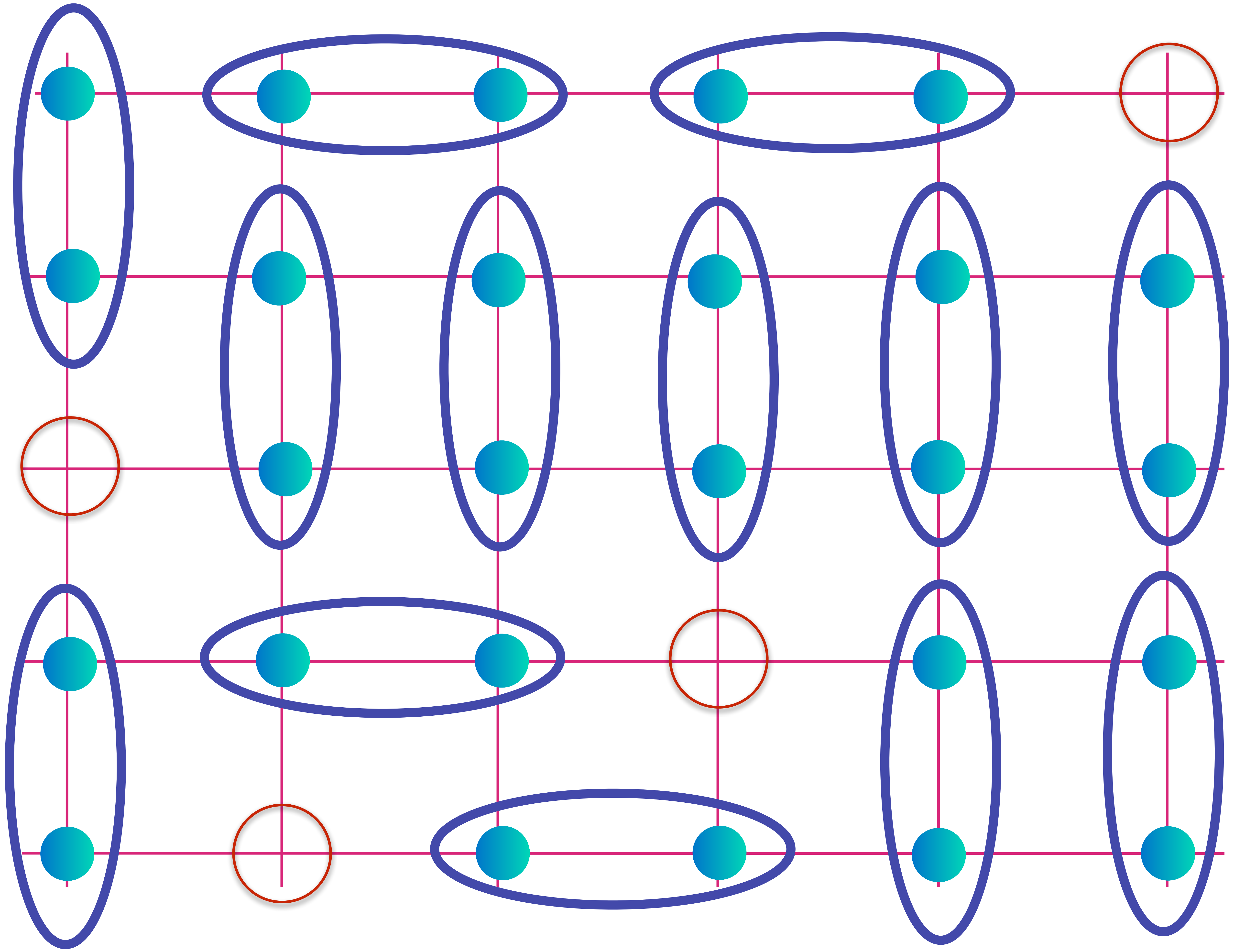

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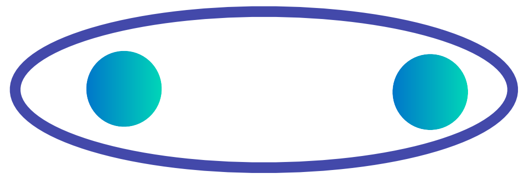

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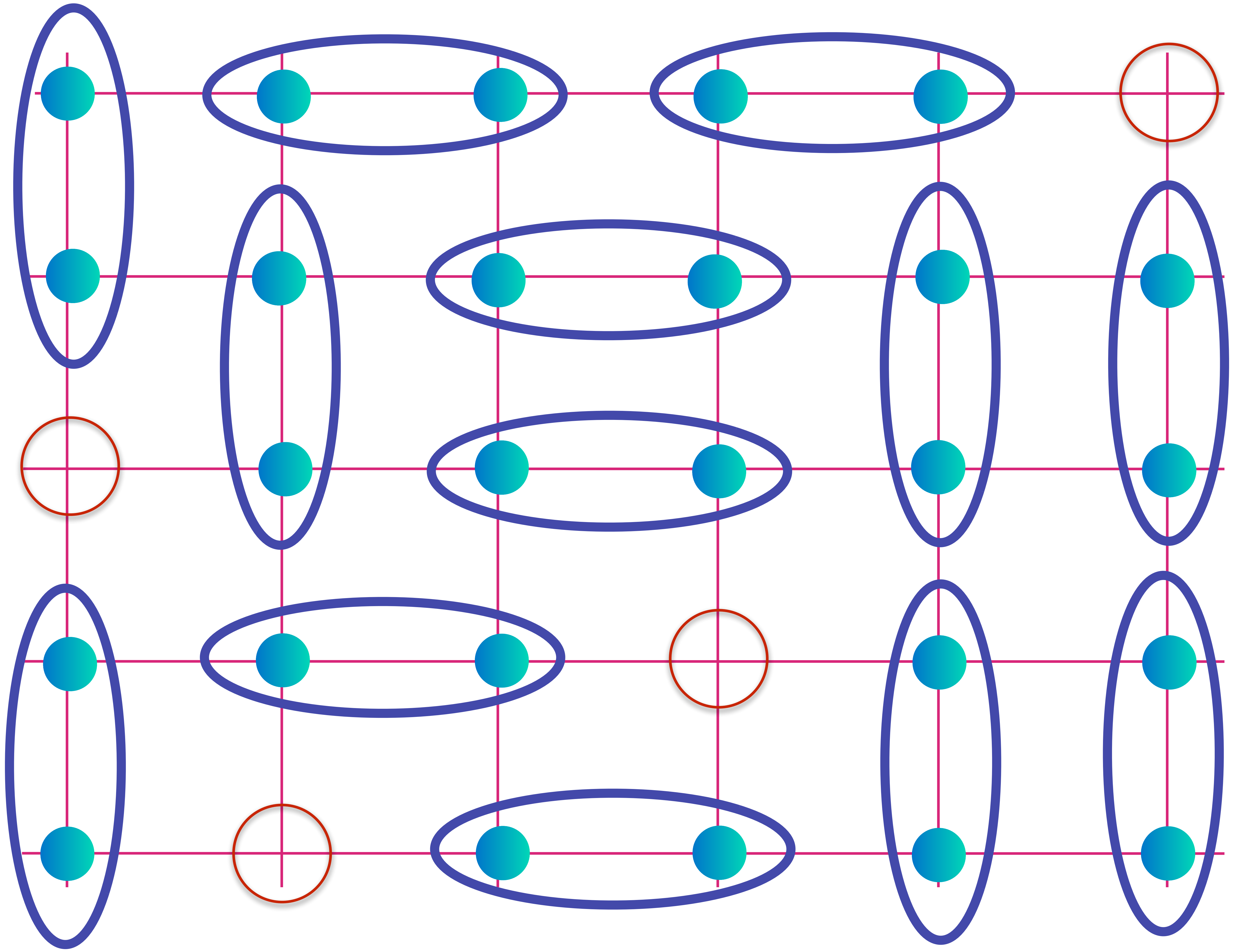

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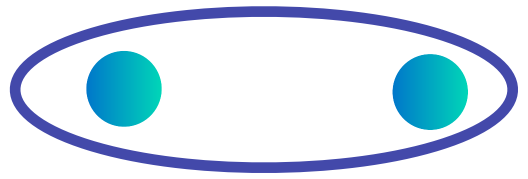 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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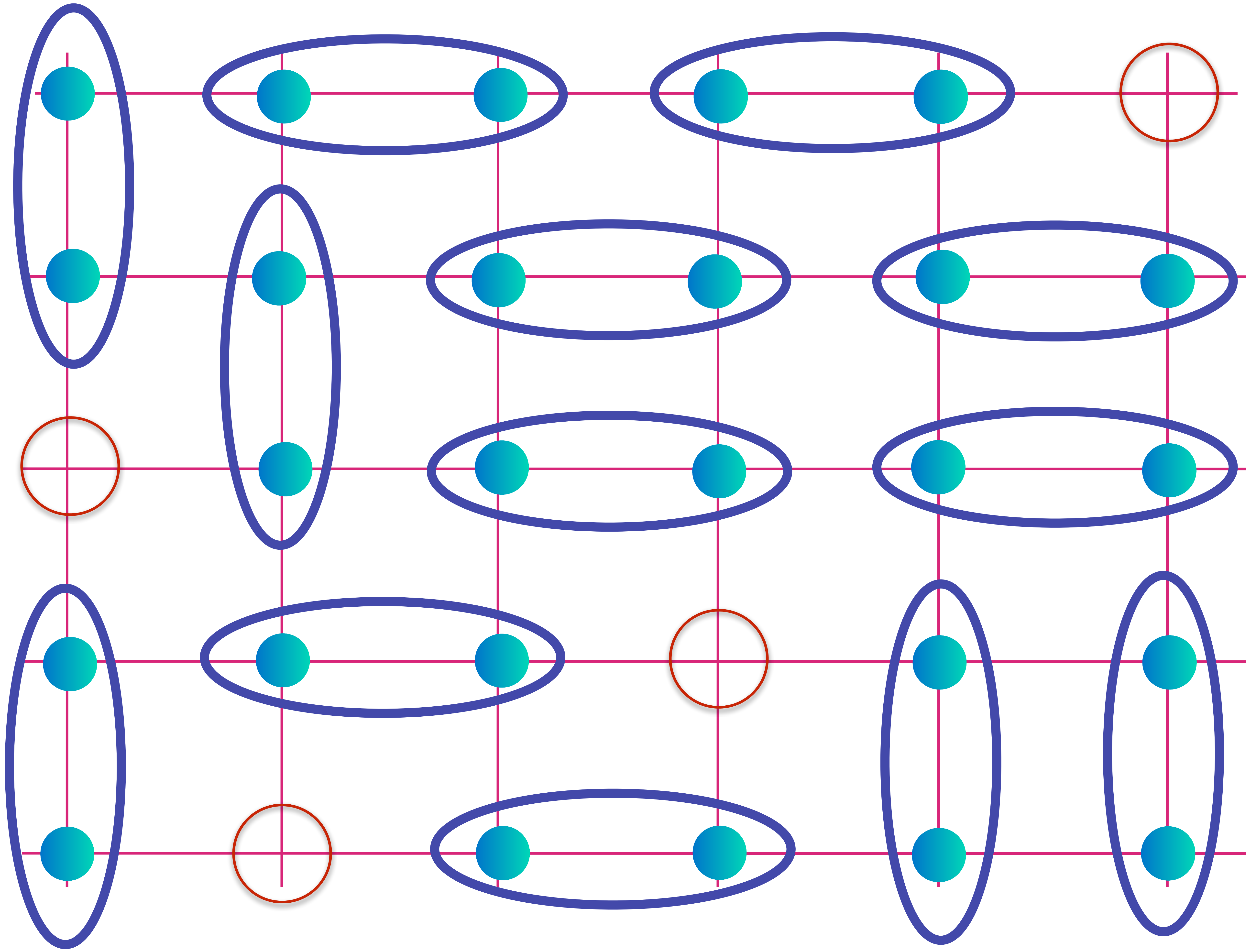

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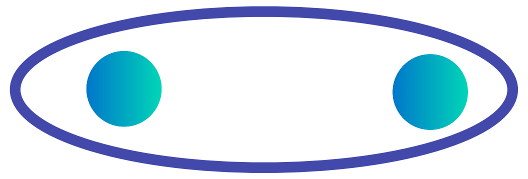

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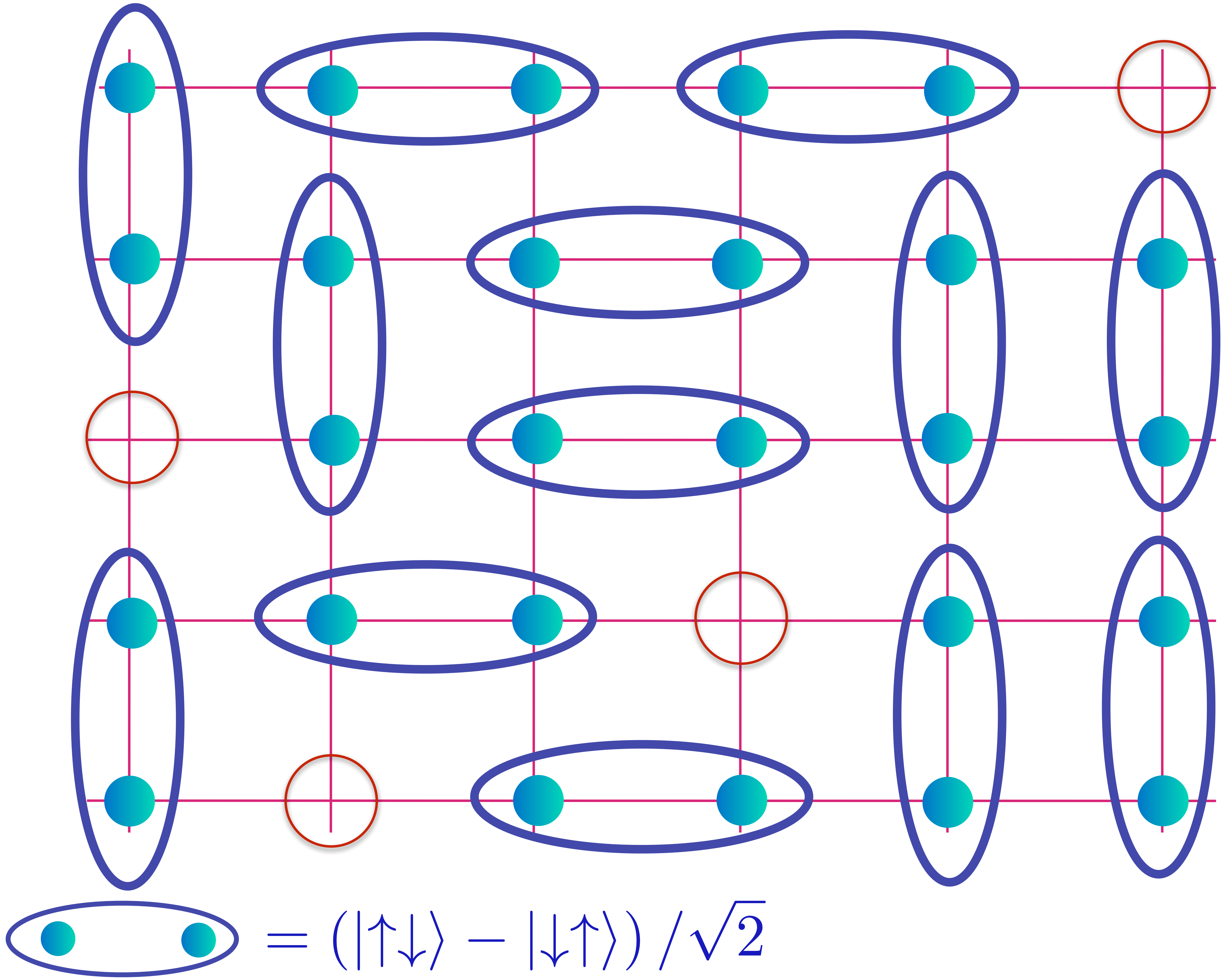

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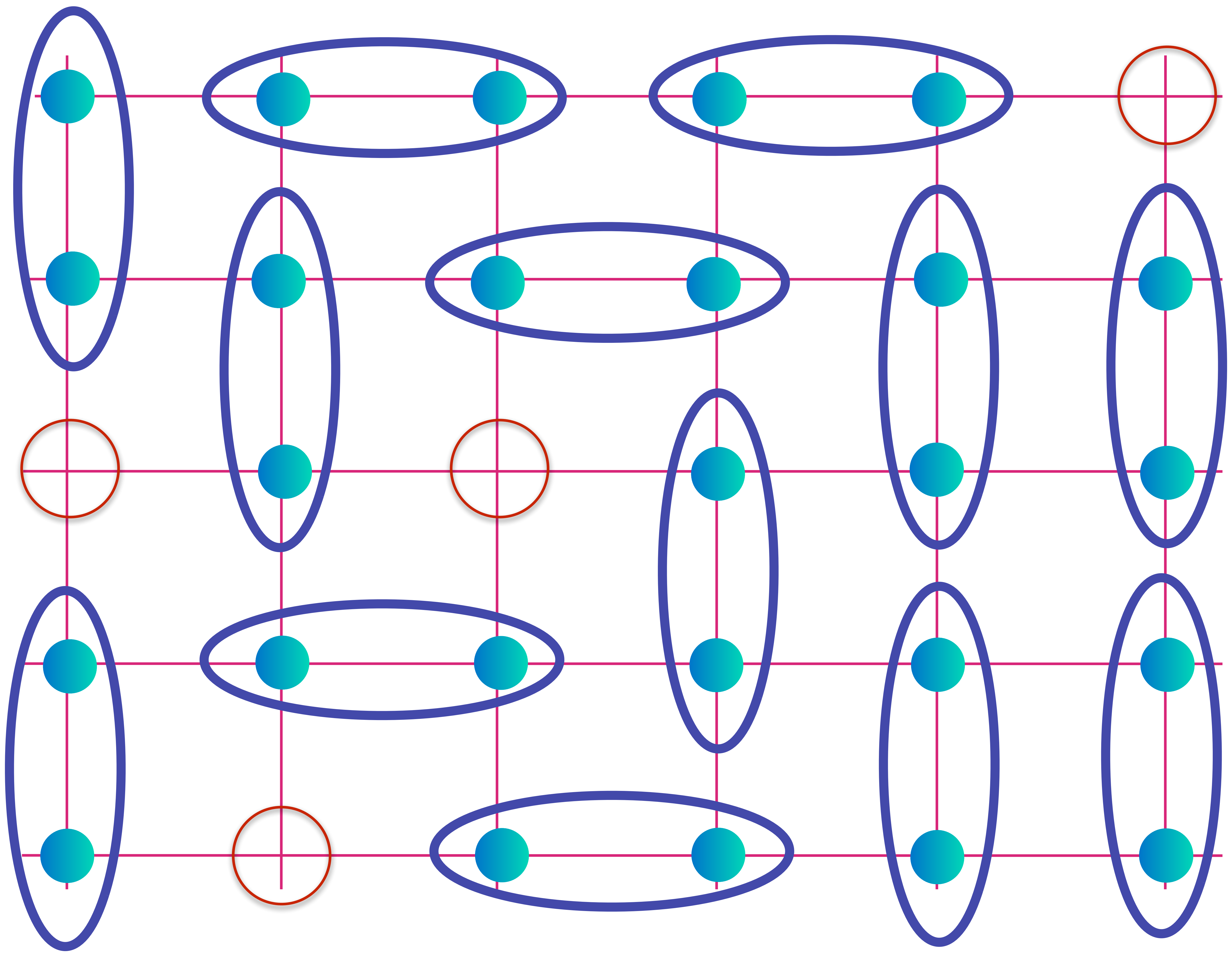

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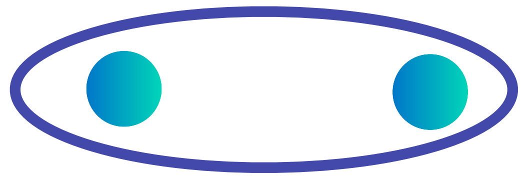
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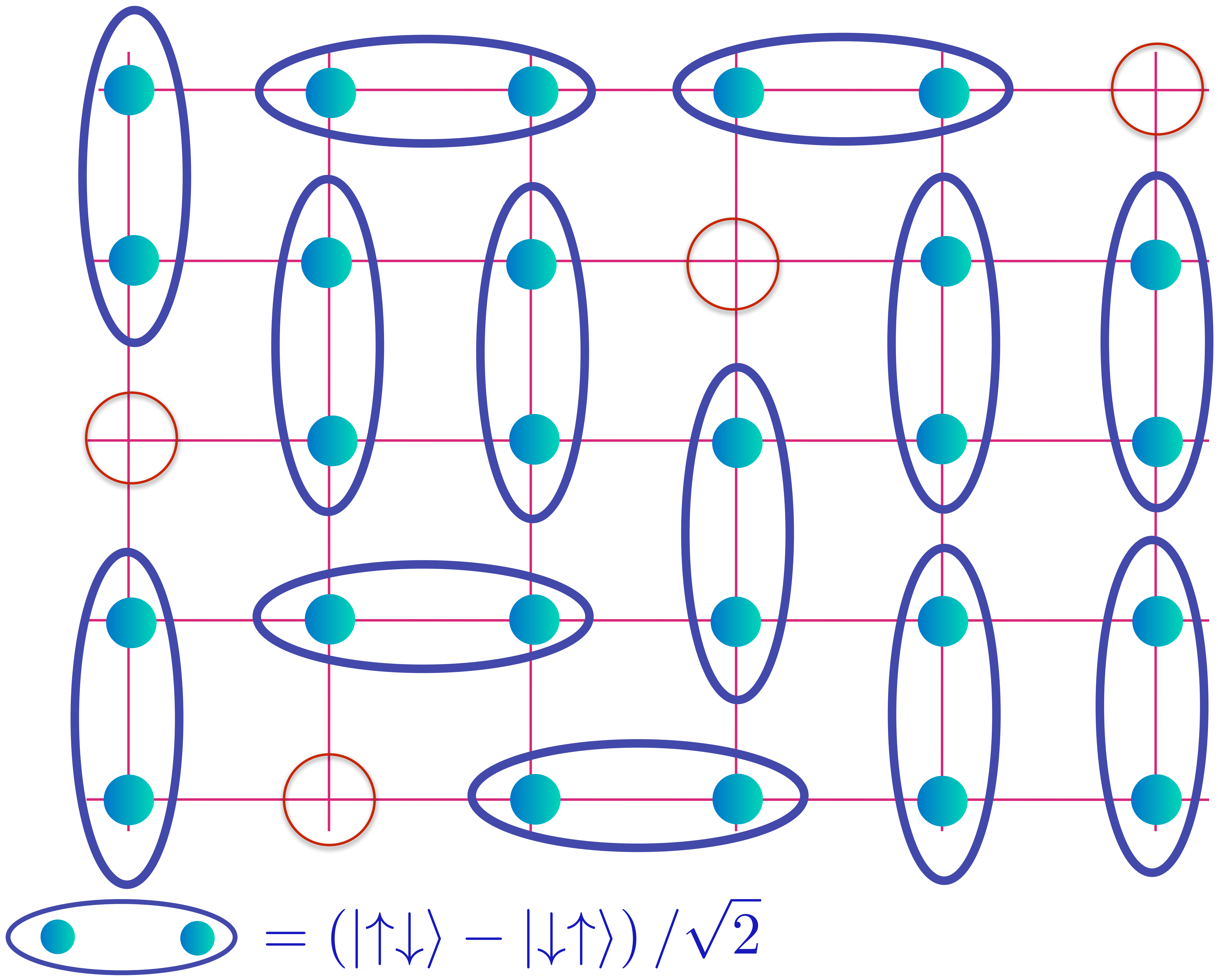

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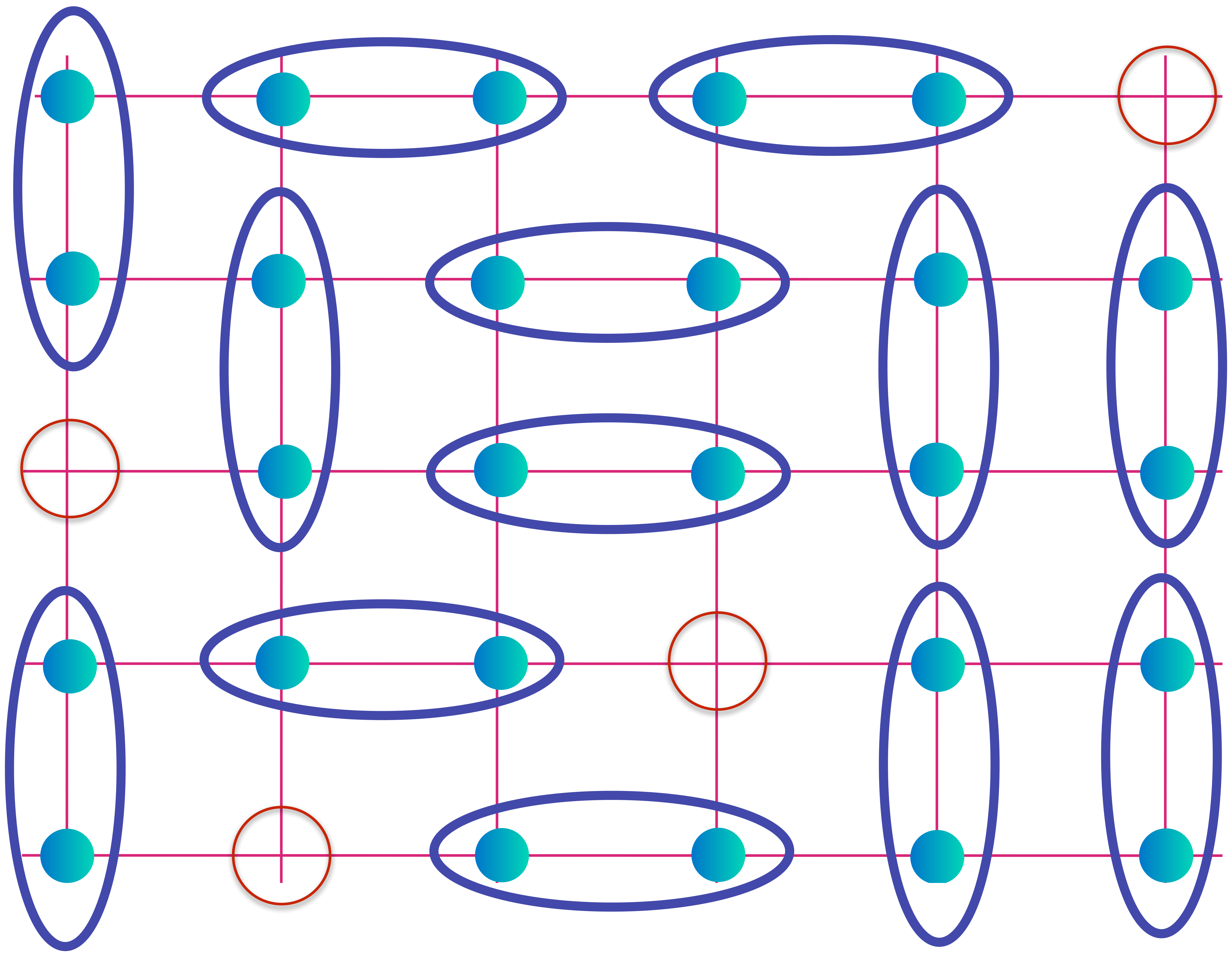

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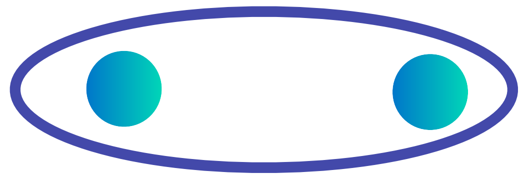
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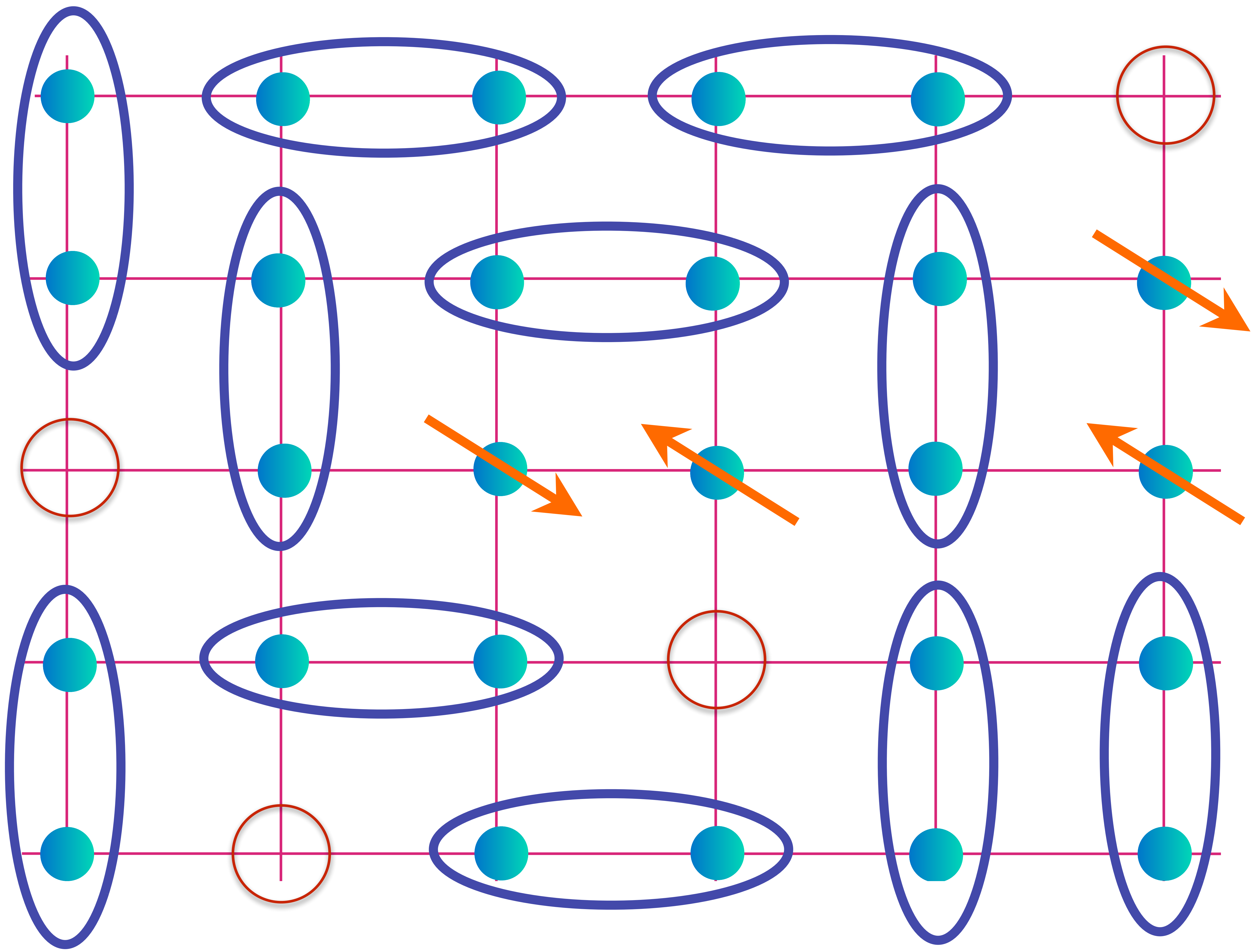

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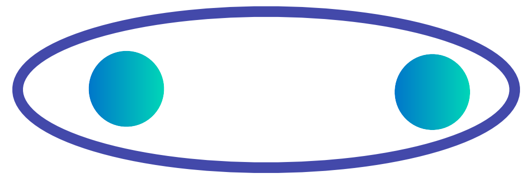

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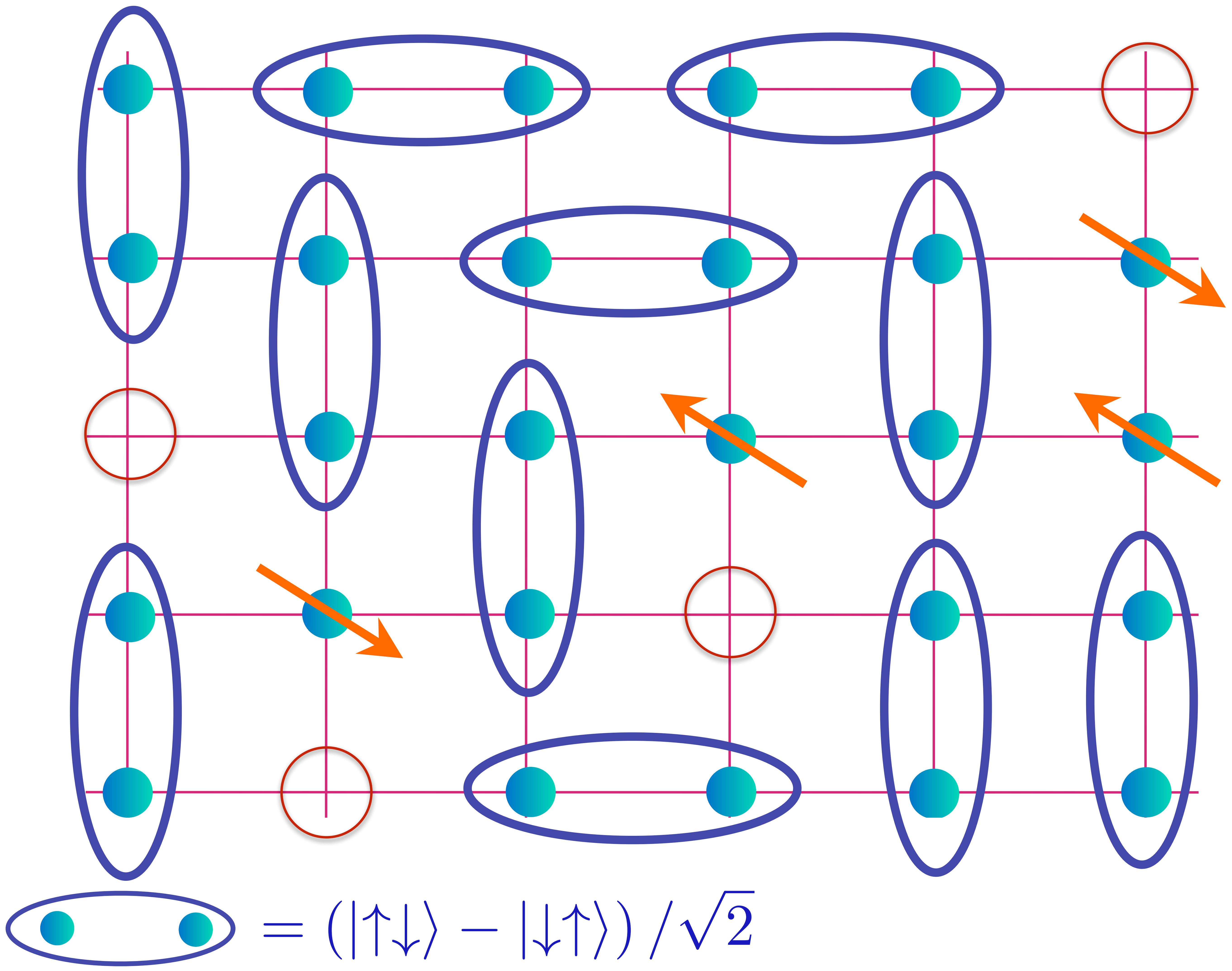

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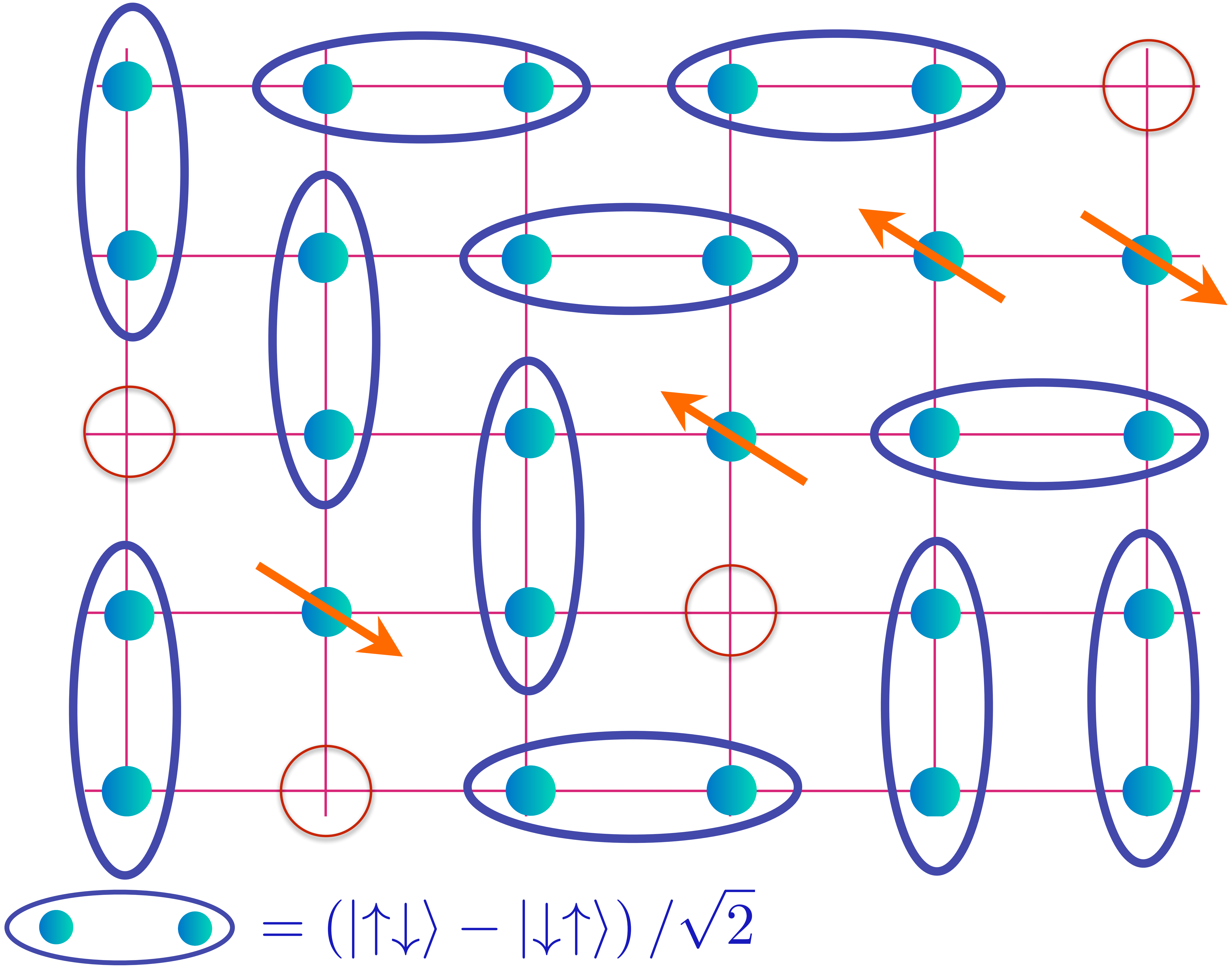

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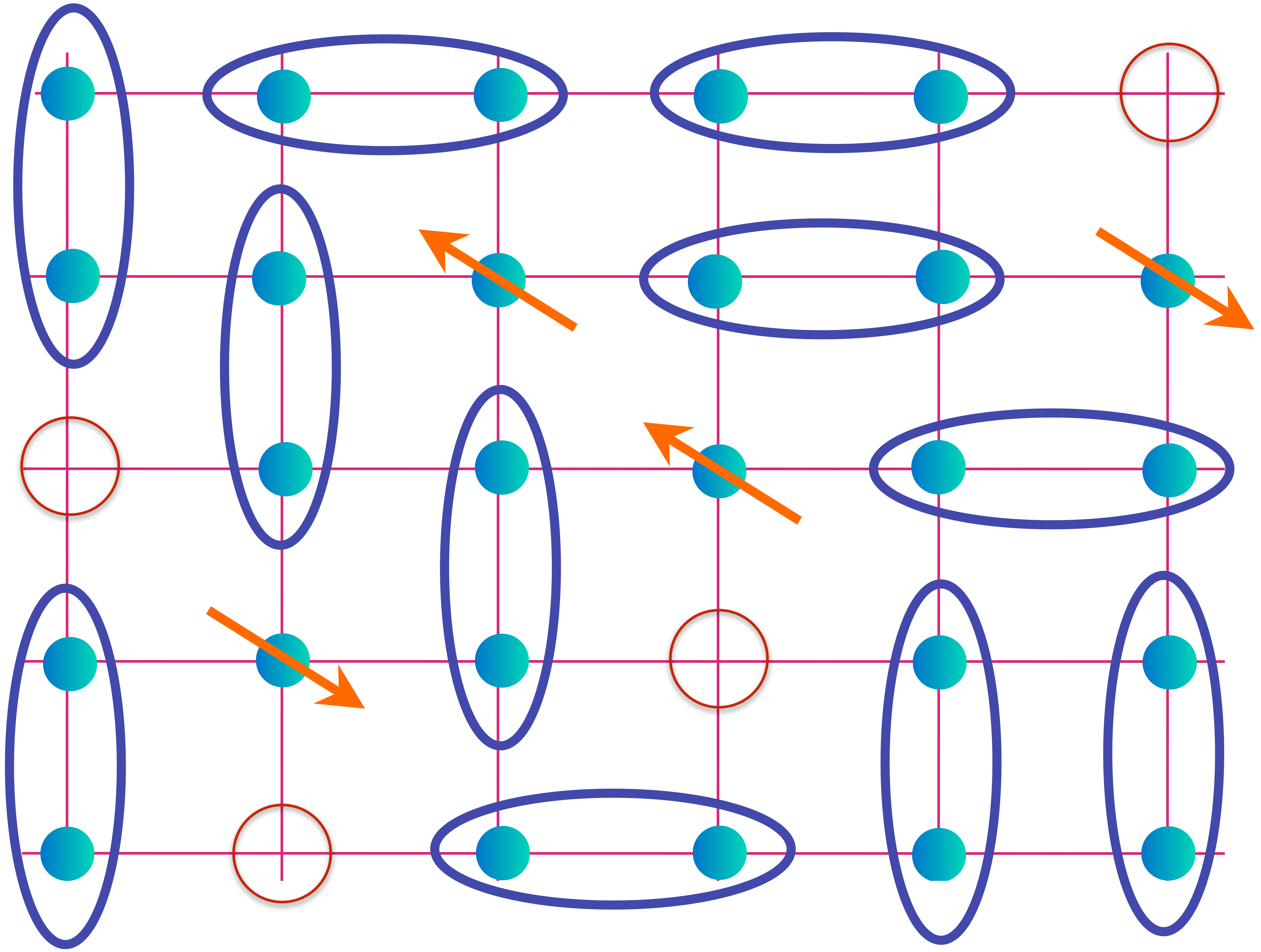

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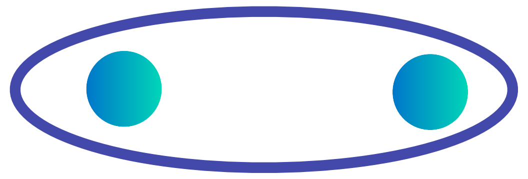 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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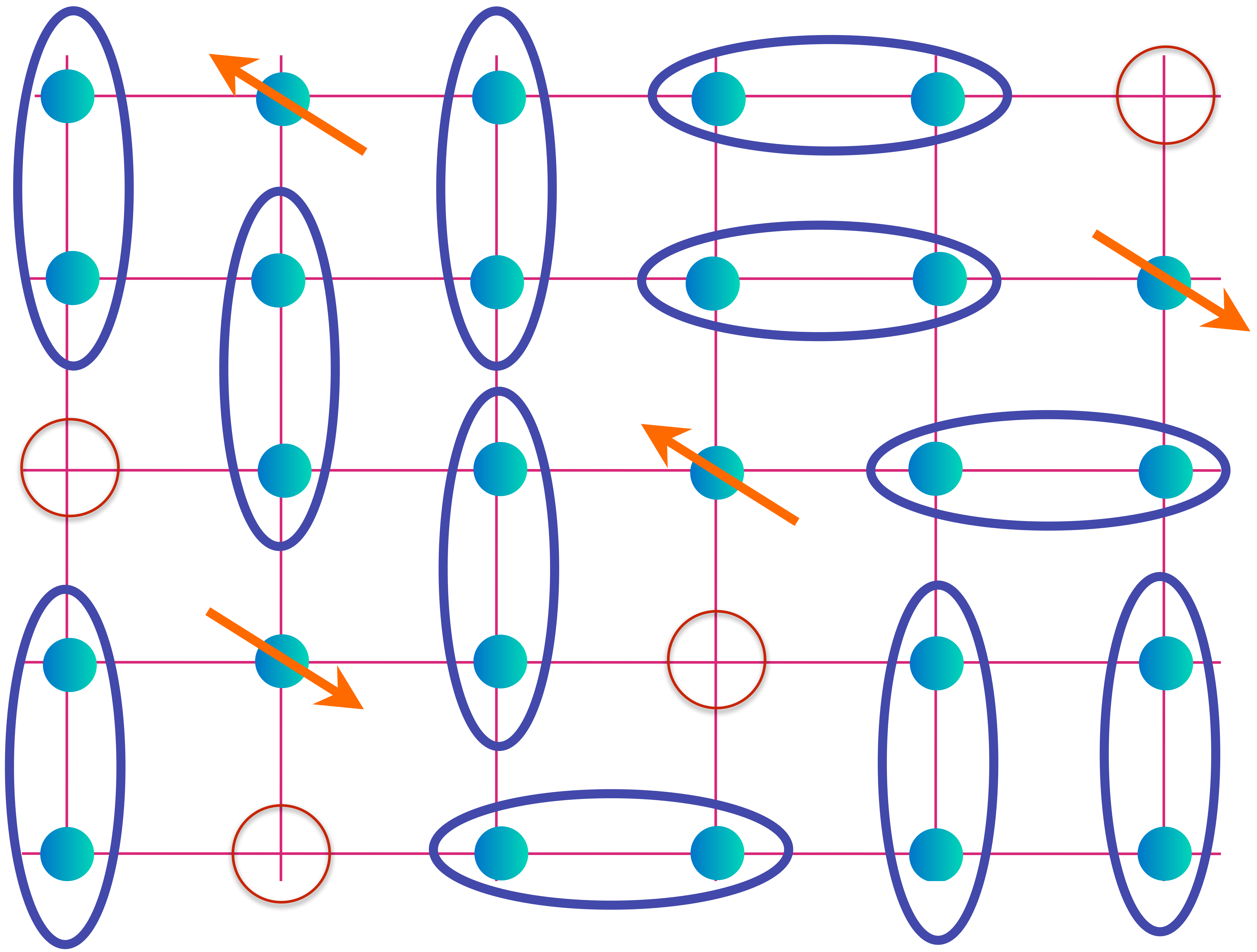

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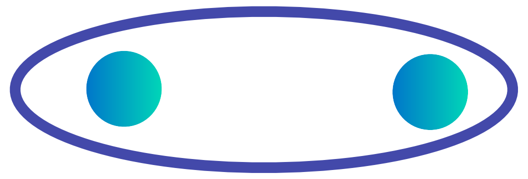

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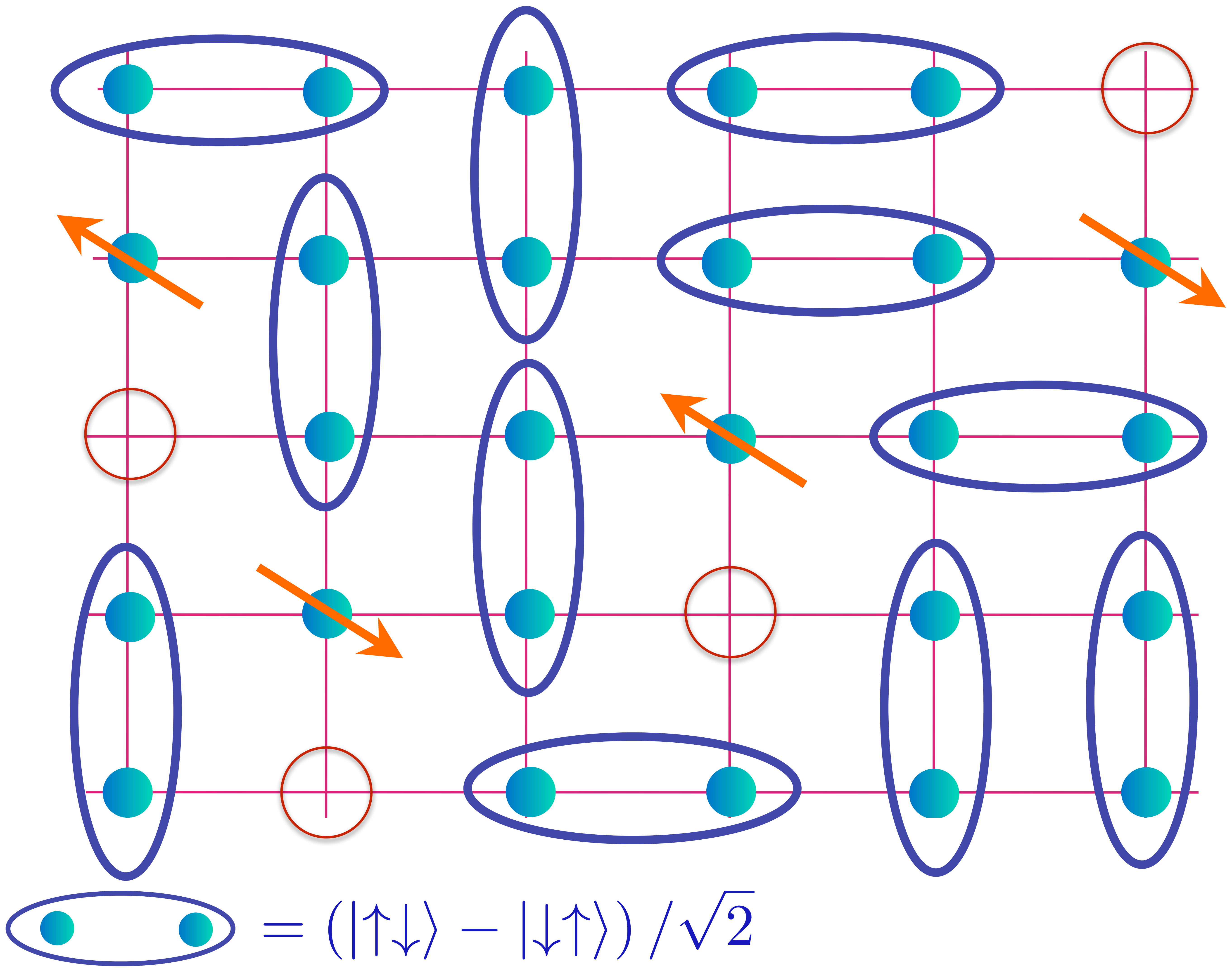

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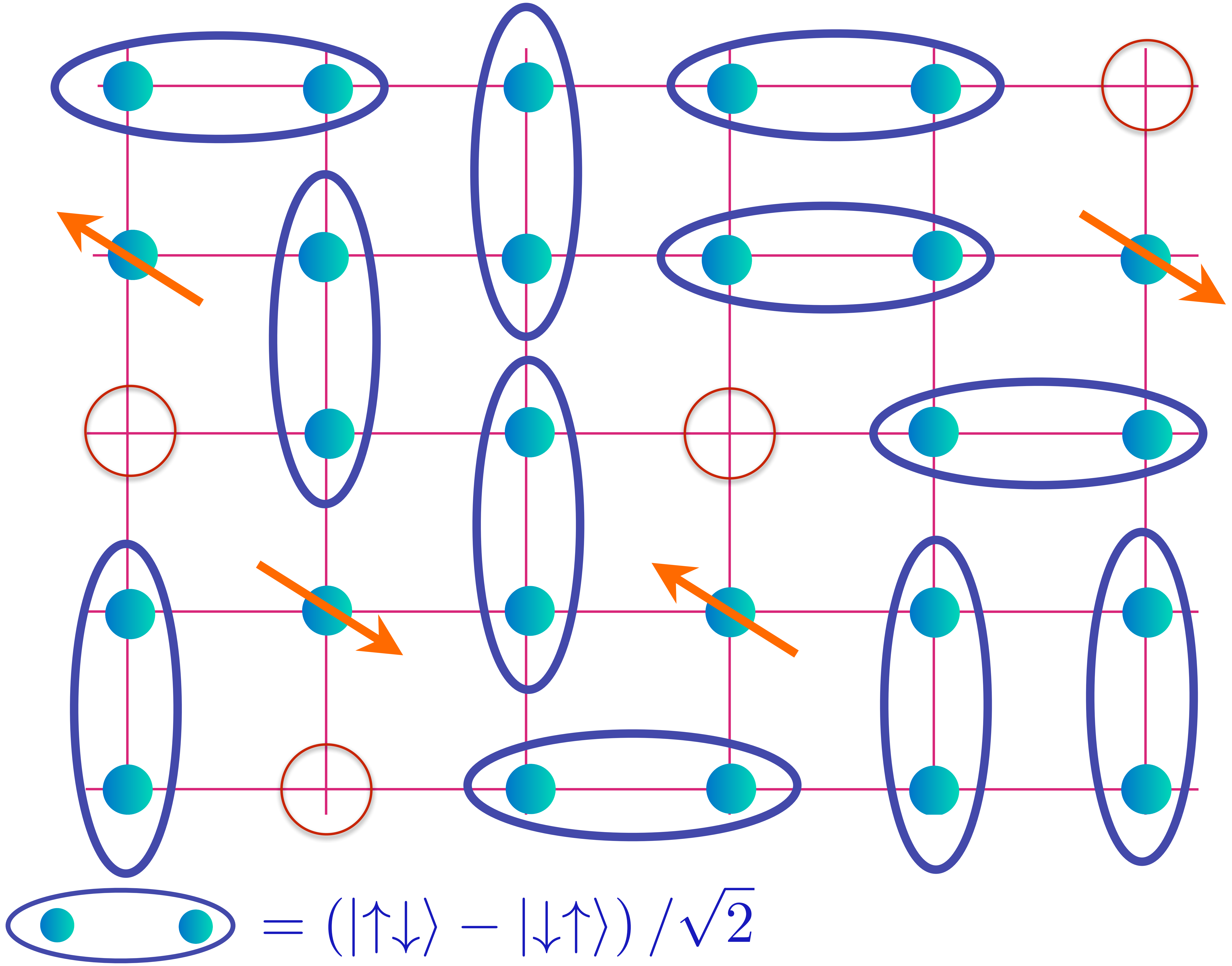

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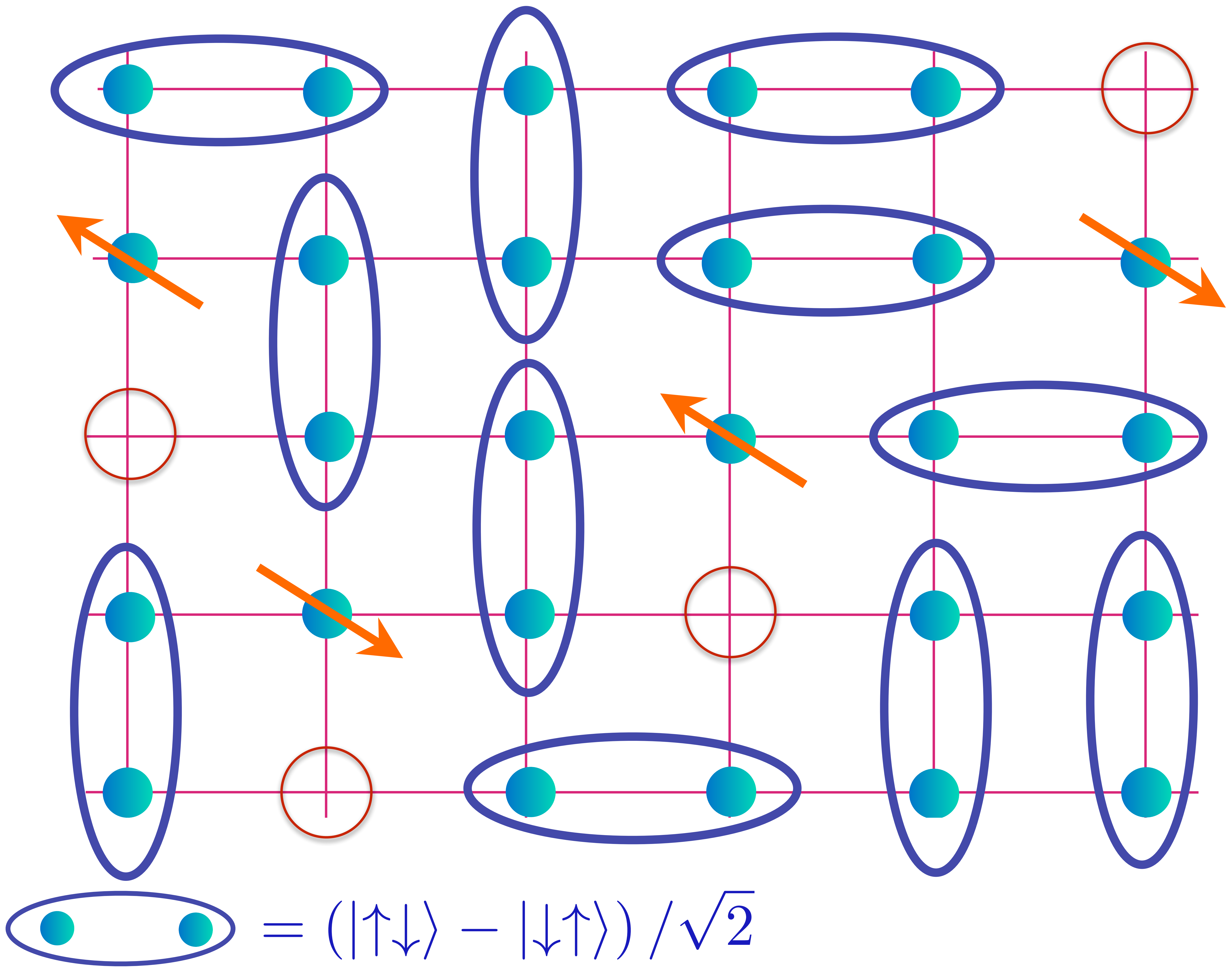

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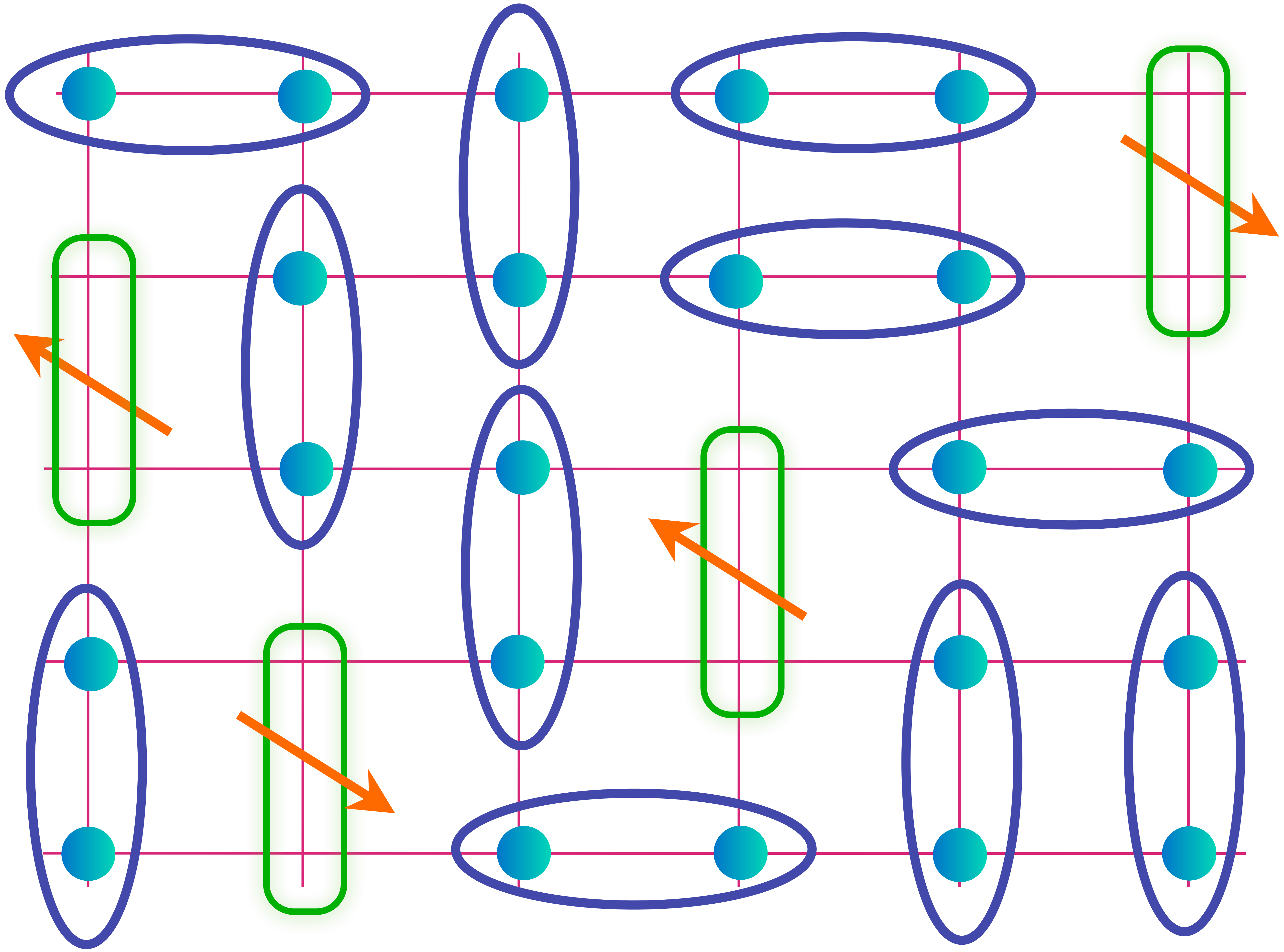

Each green "dimer" is a "bound state" of a vacancy and a free spin

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

$= (|\uparrow \circ\rangle + |\circ \uparrow\rangle) / \sqrt{2}$

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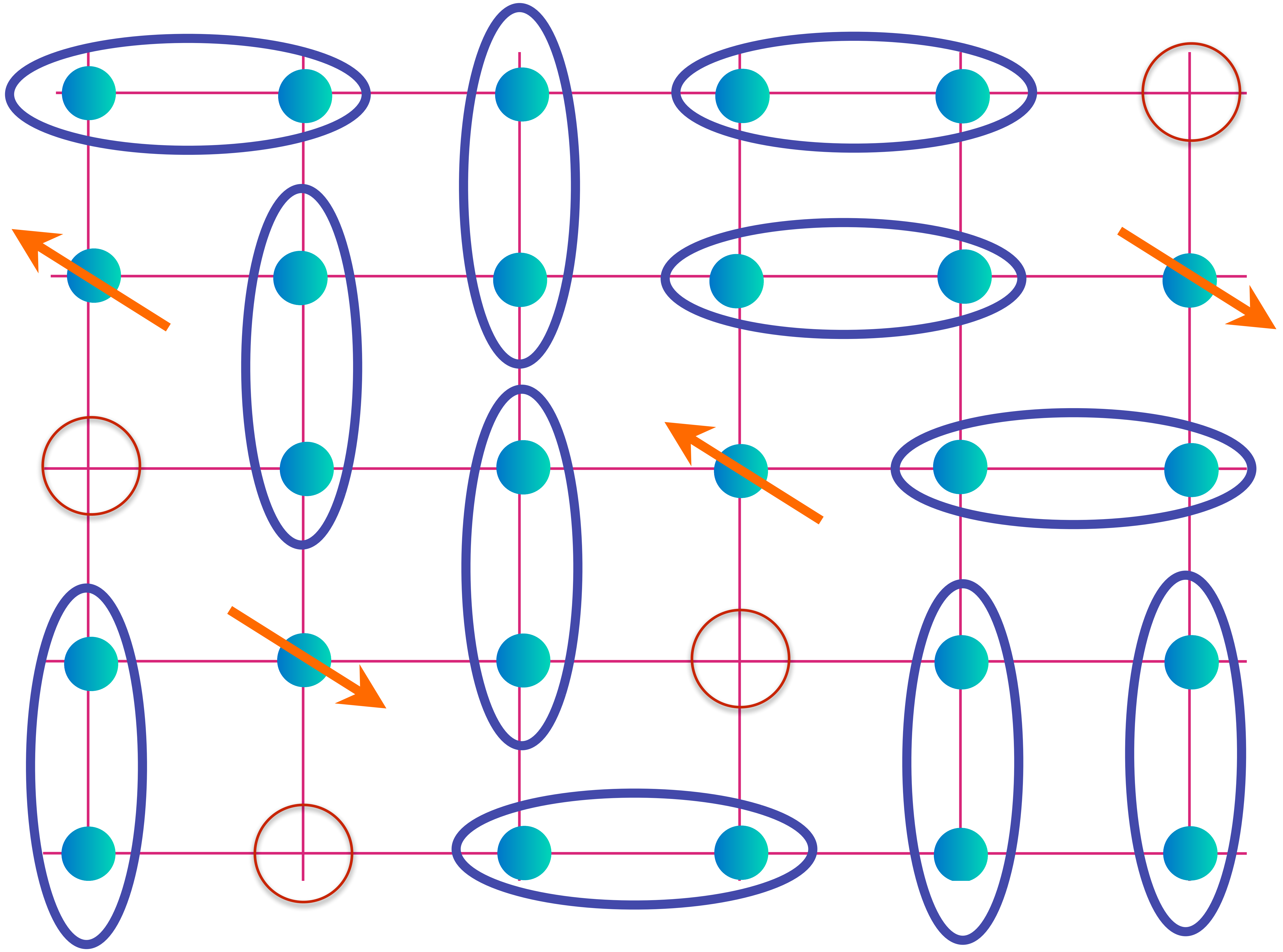

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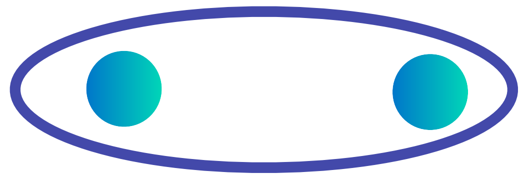
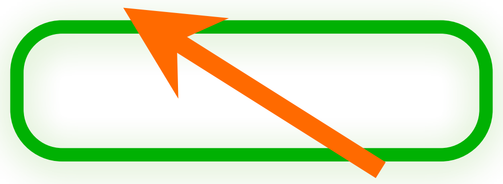
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

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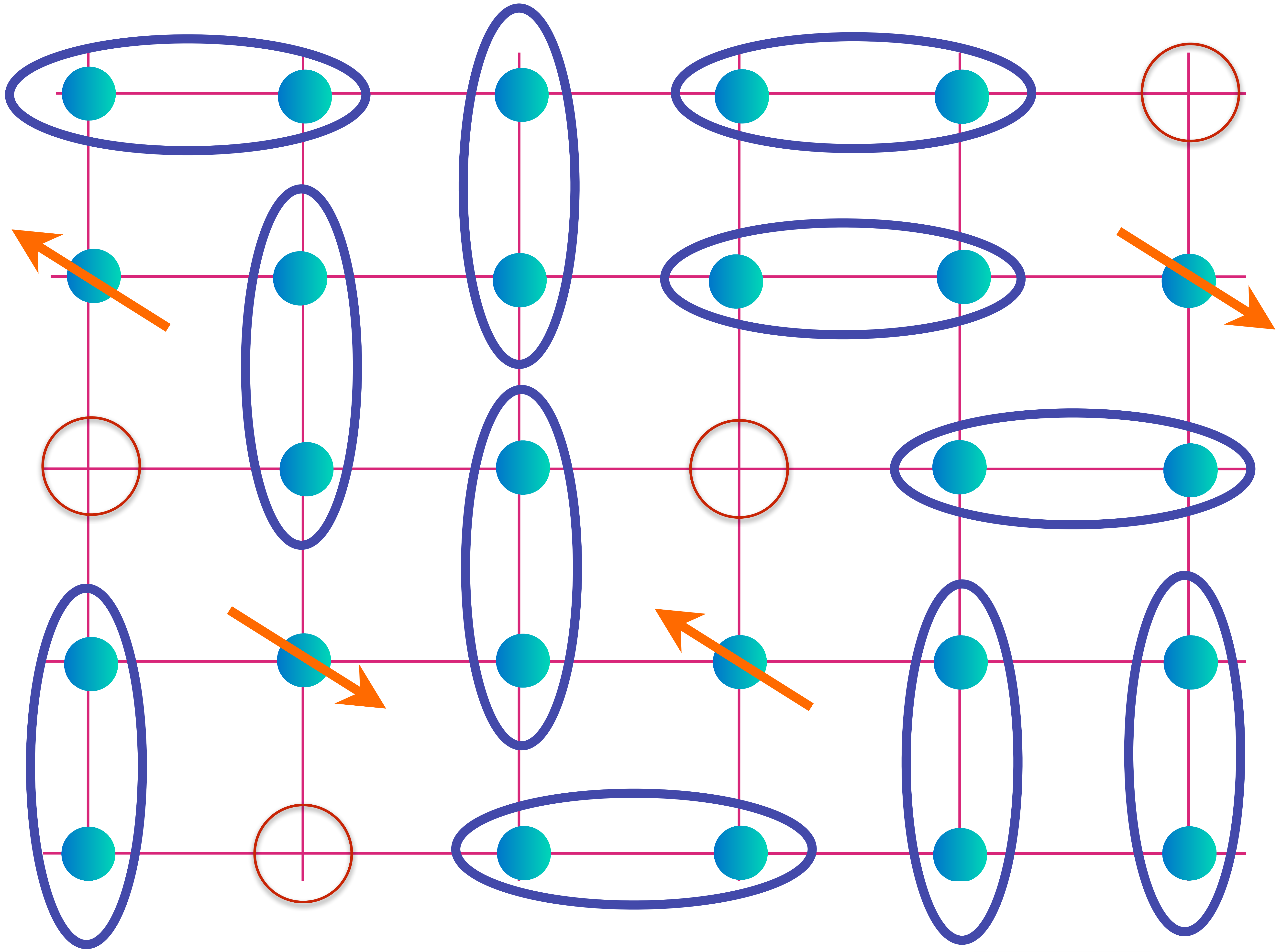

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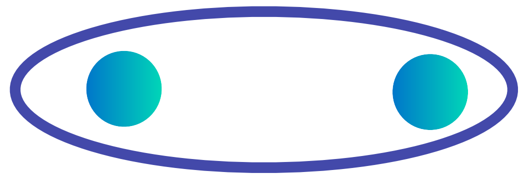
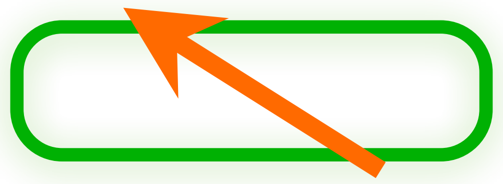
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle\right)/\sqrt{2}$

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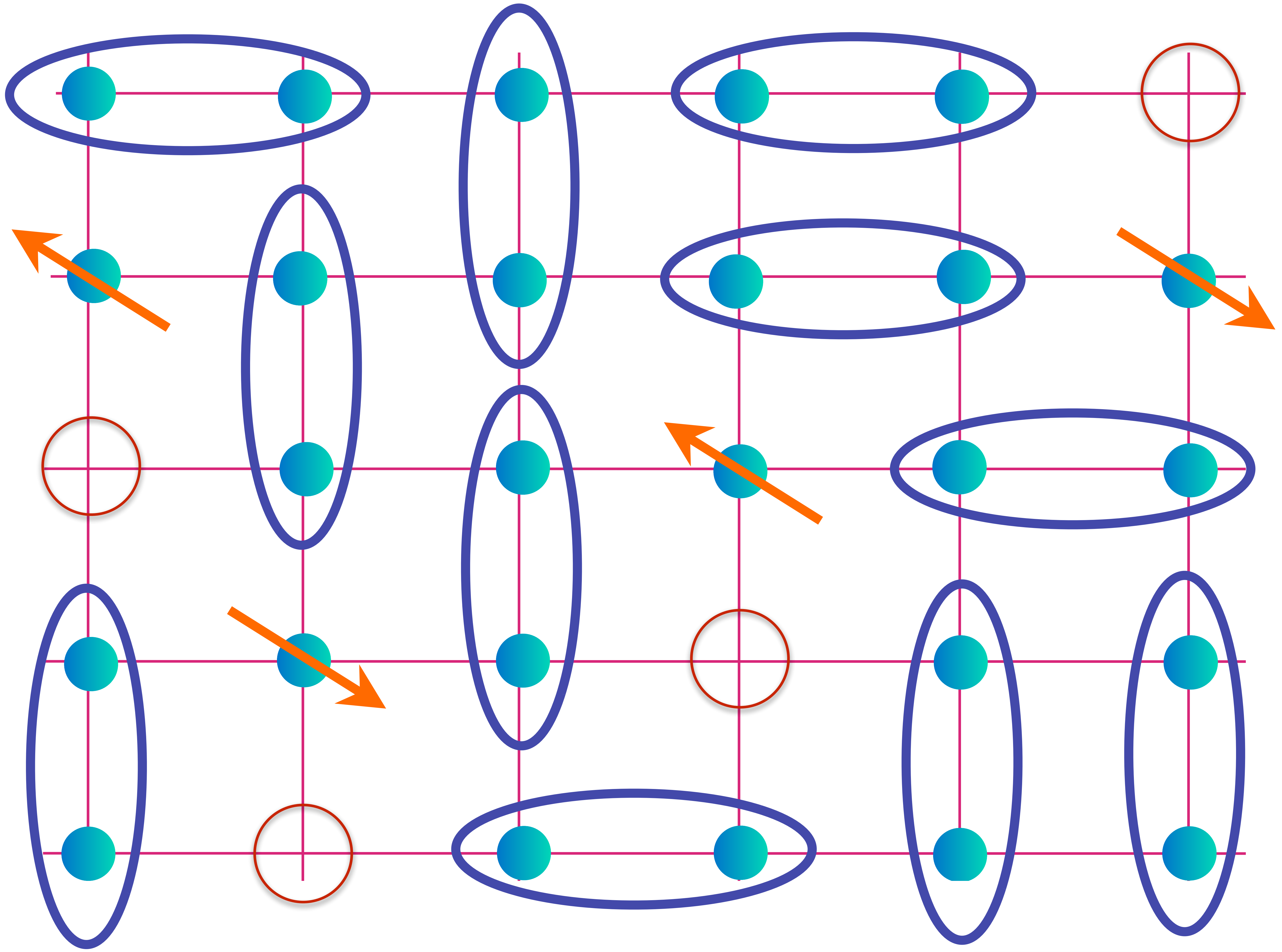

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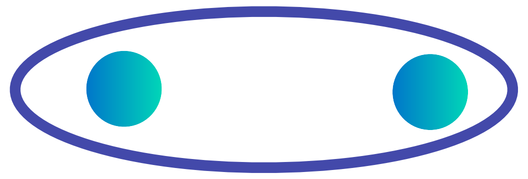
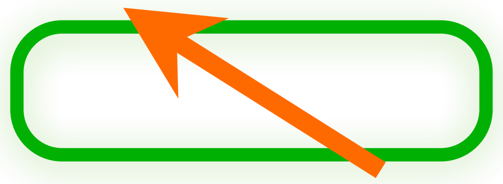
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

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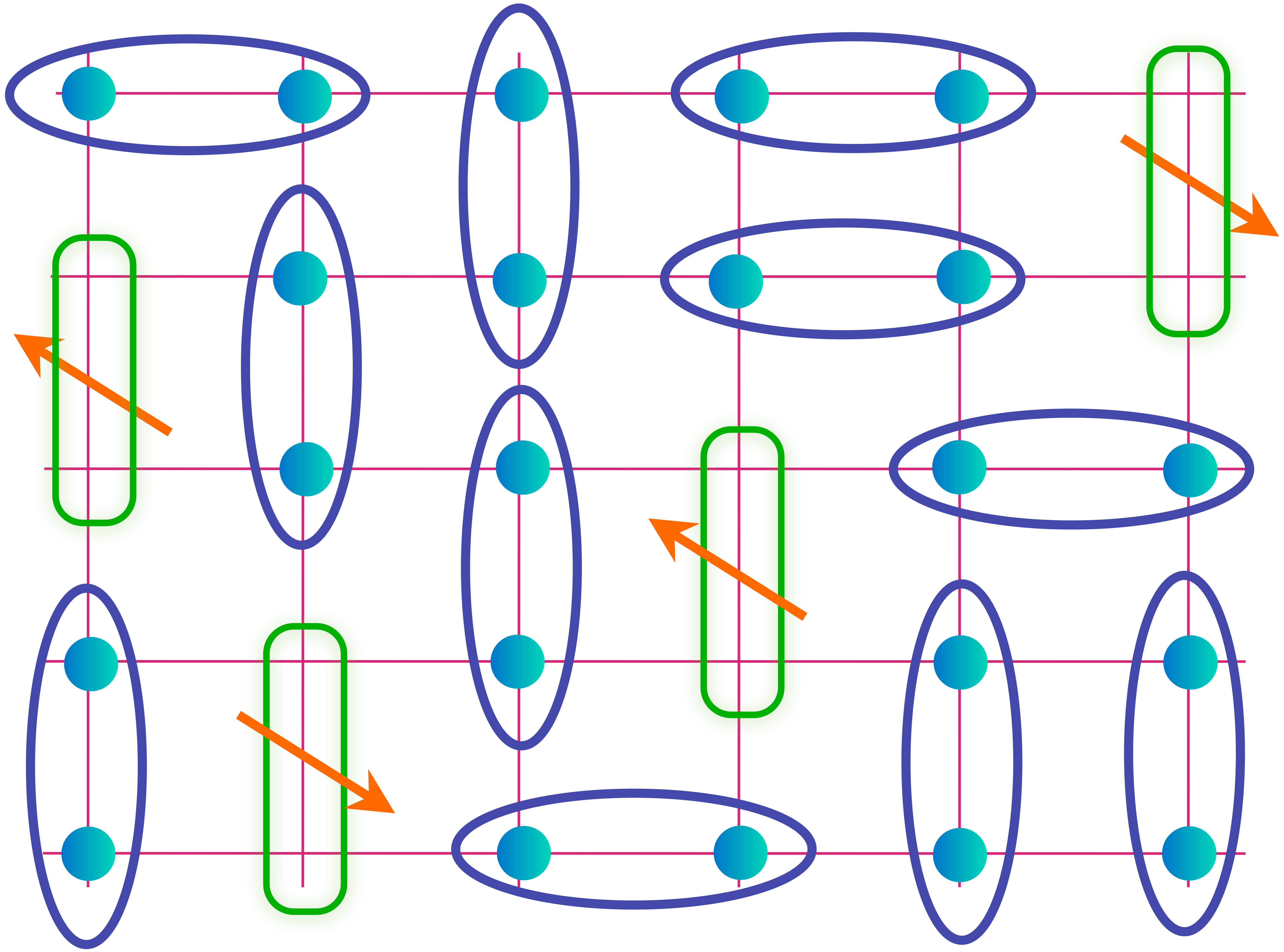

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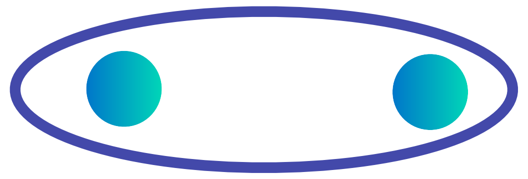
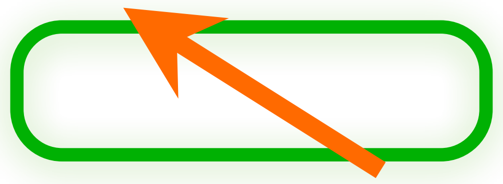
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

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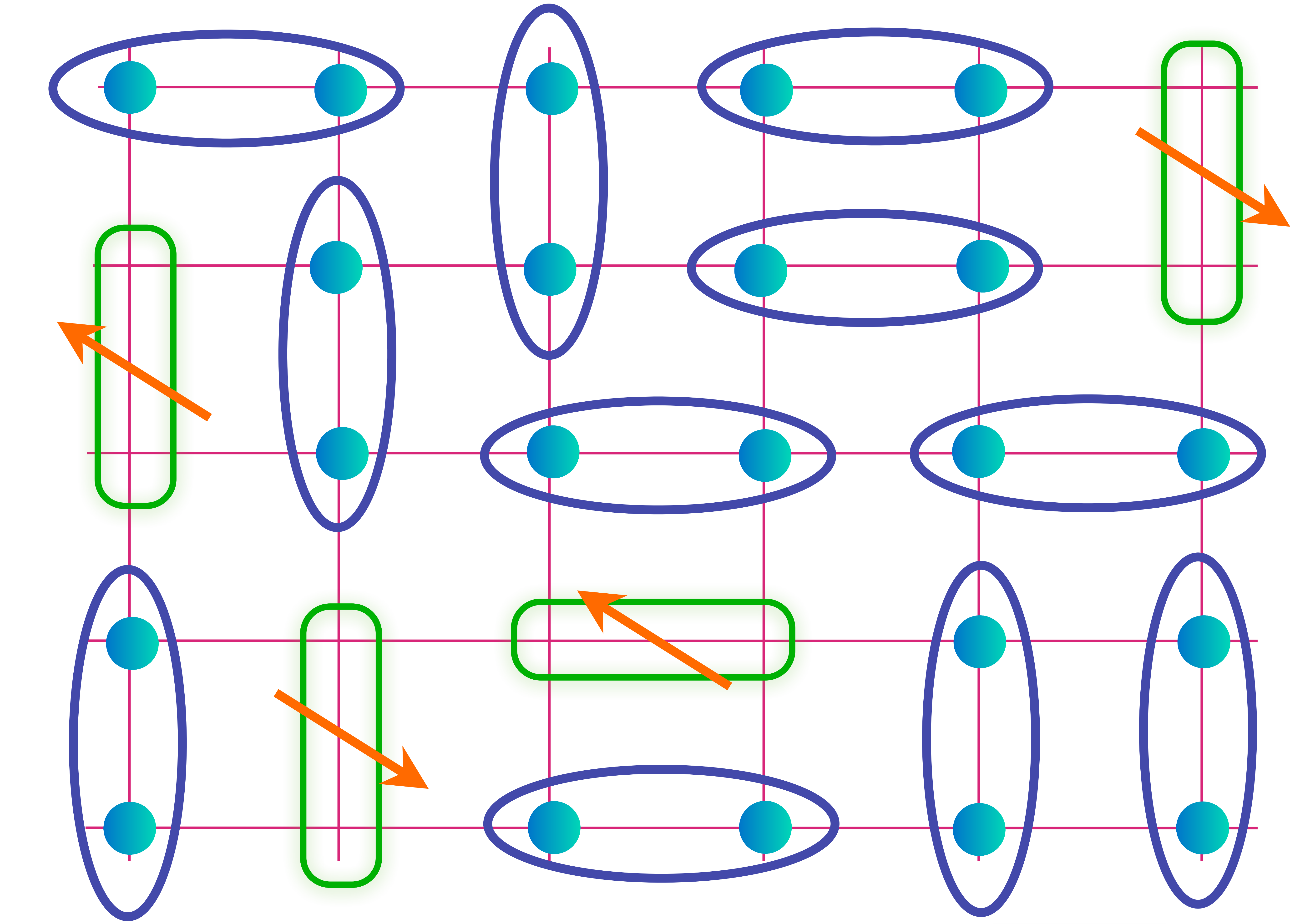

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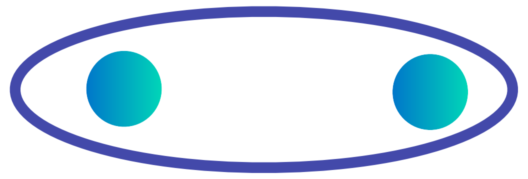
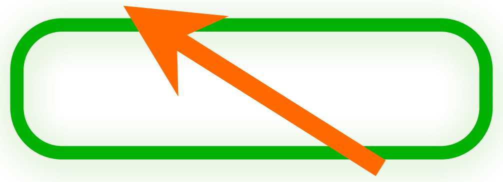
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

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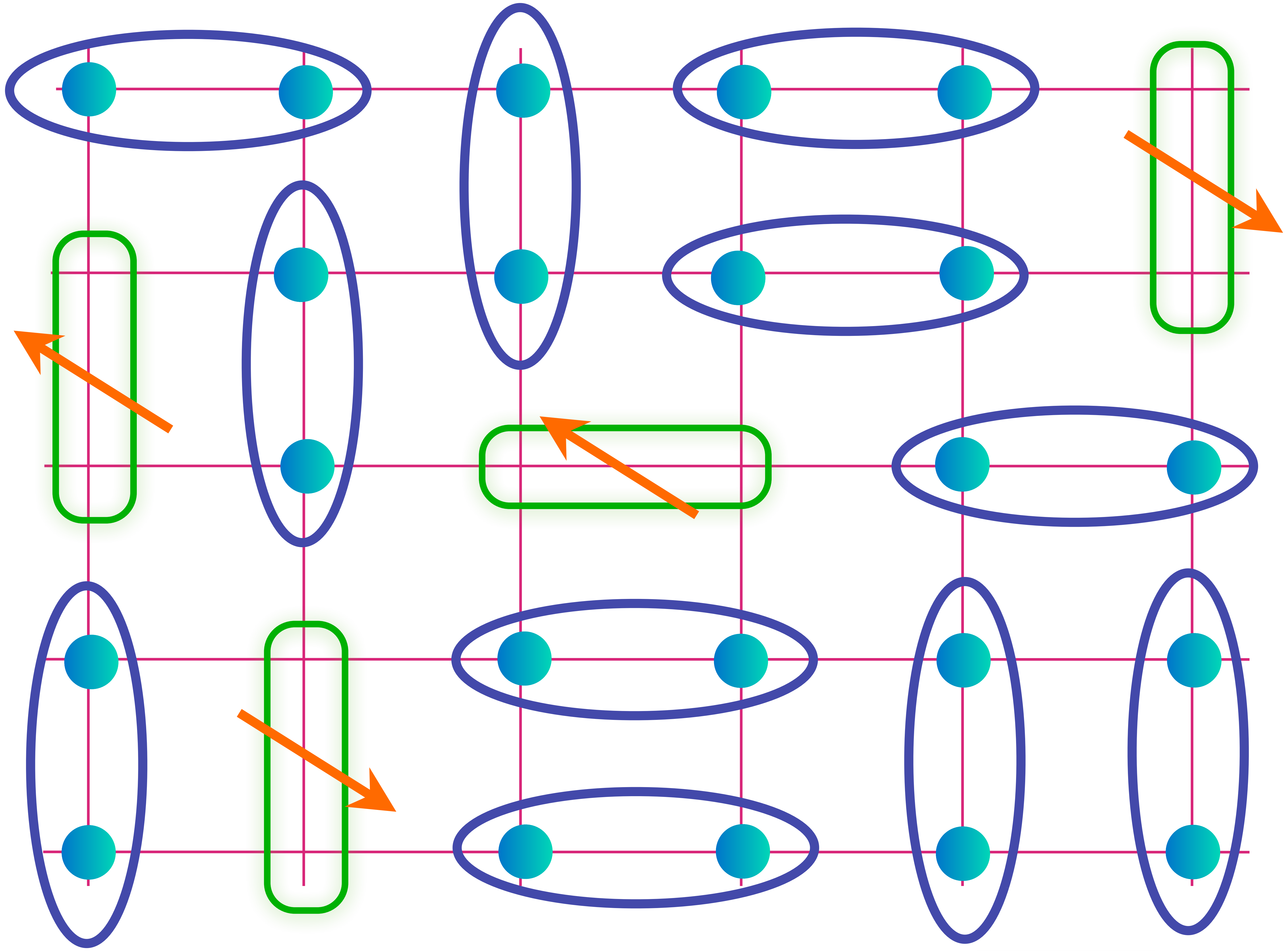

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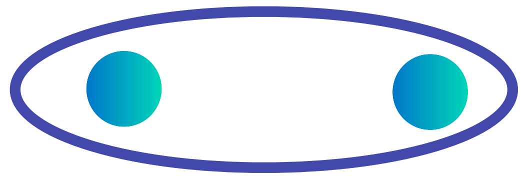

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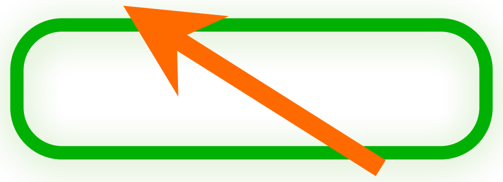

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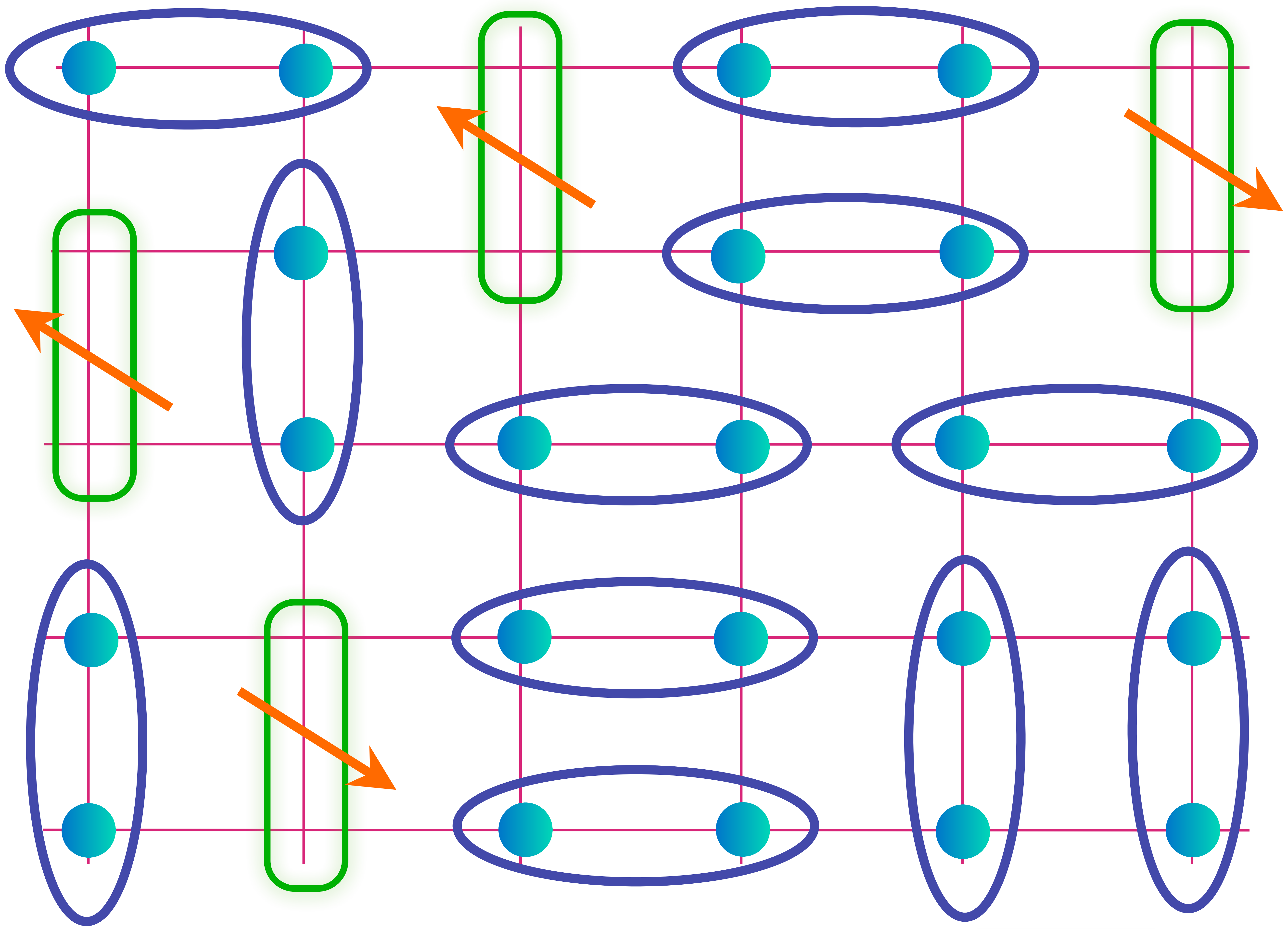

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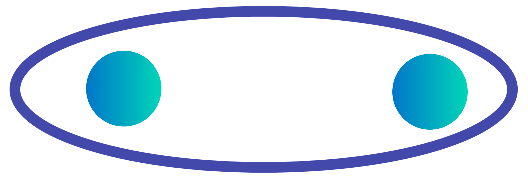
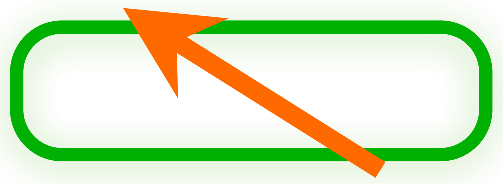
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

 $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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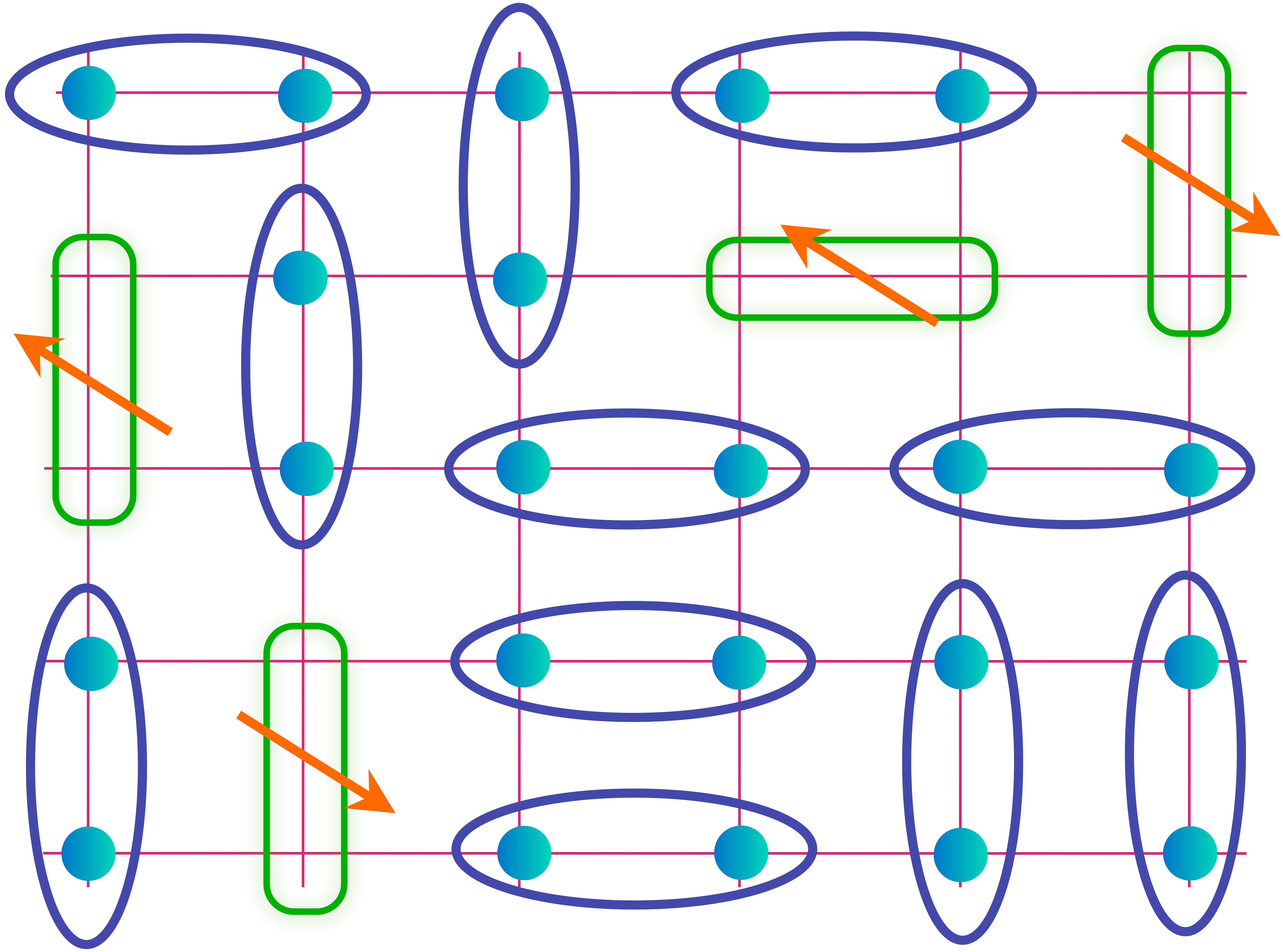

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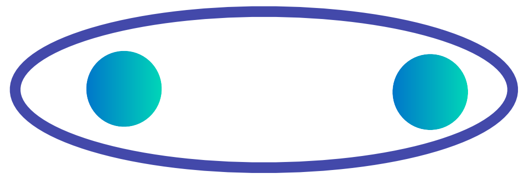
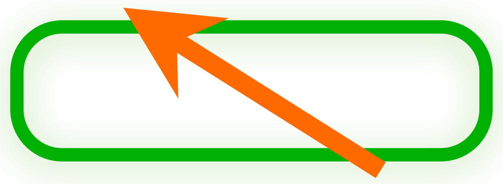
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle\right)/\sqrt{2}$

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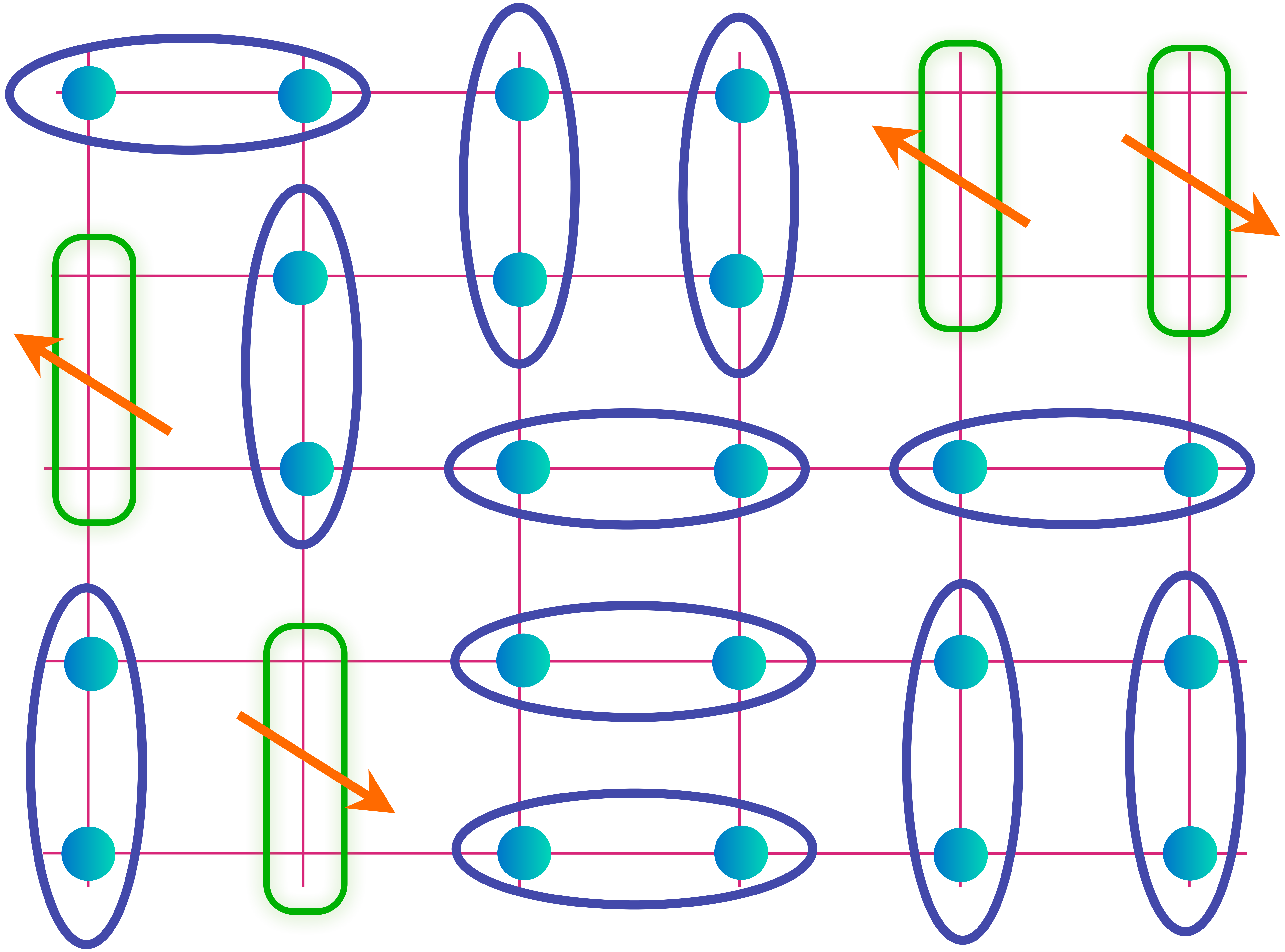

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$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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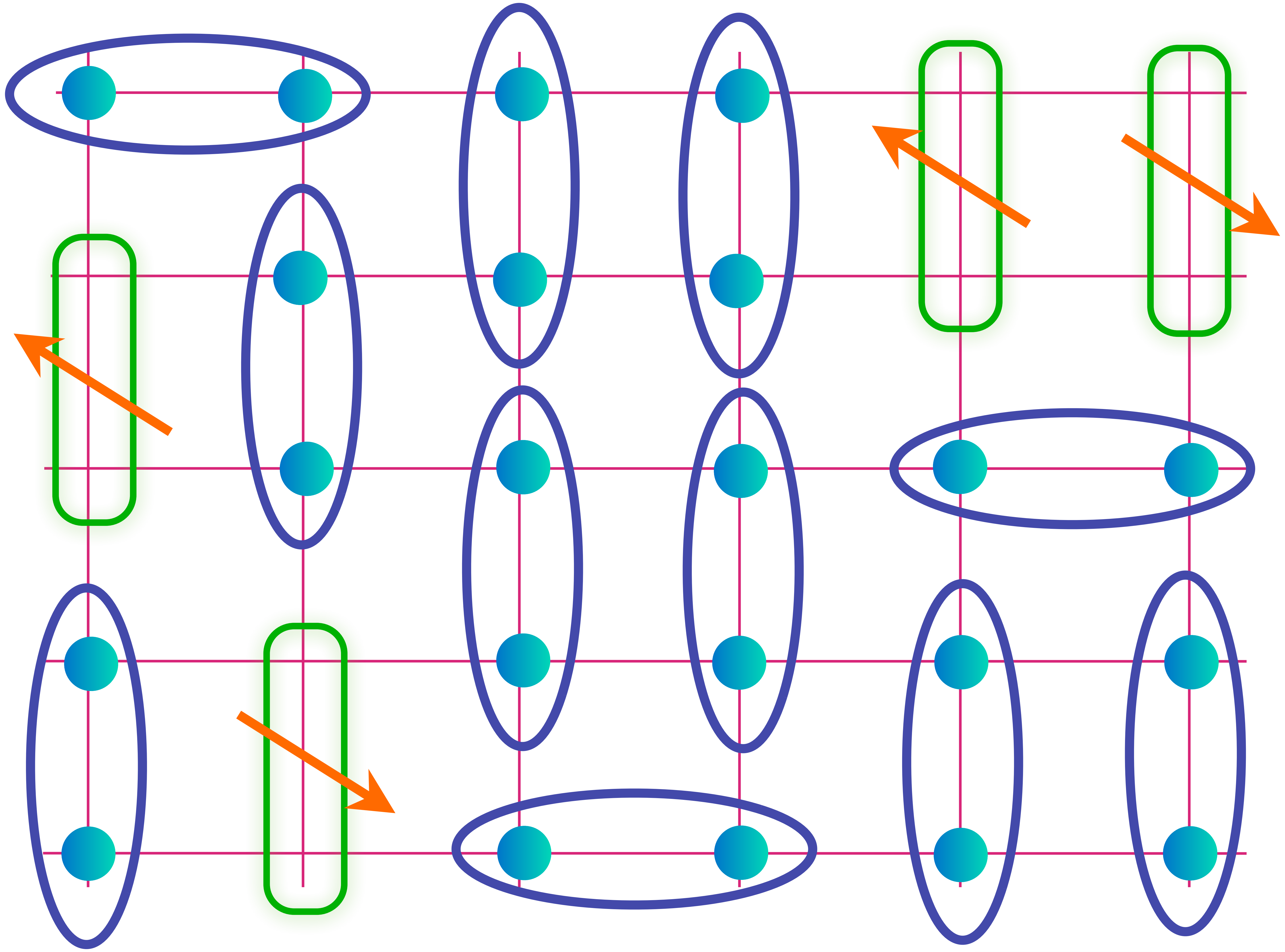

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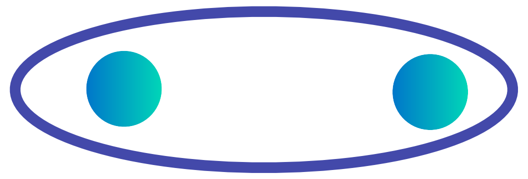
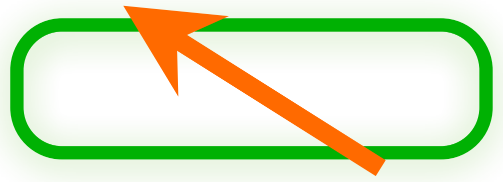


$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$



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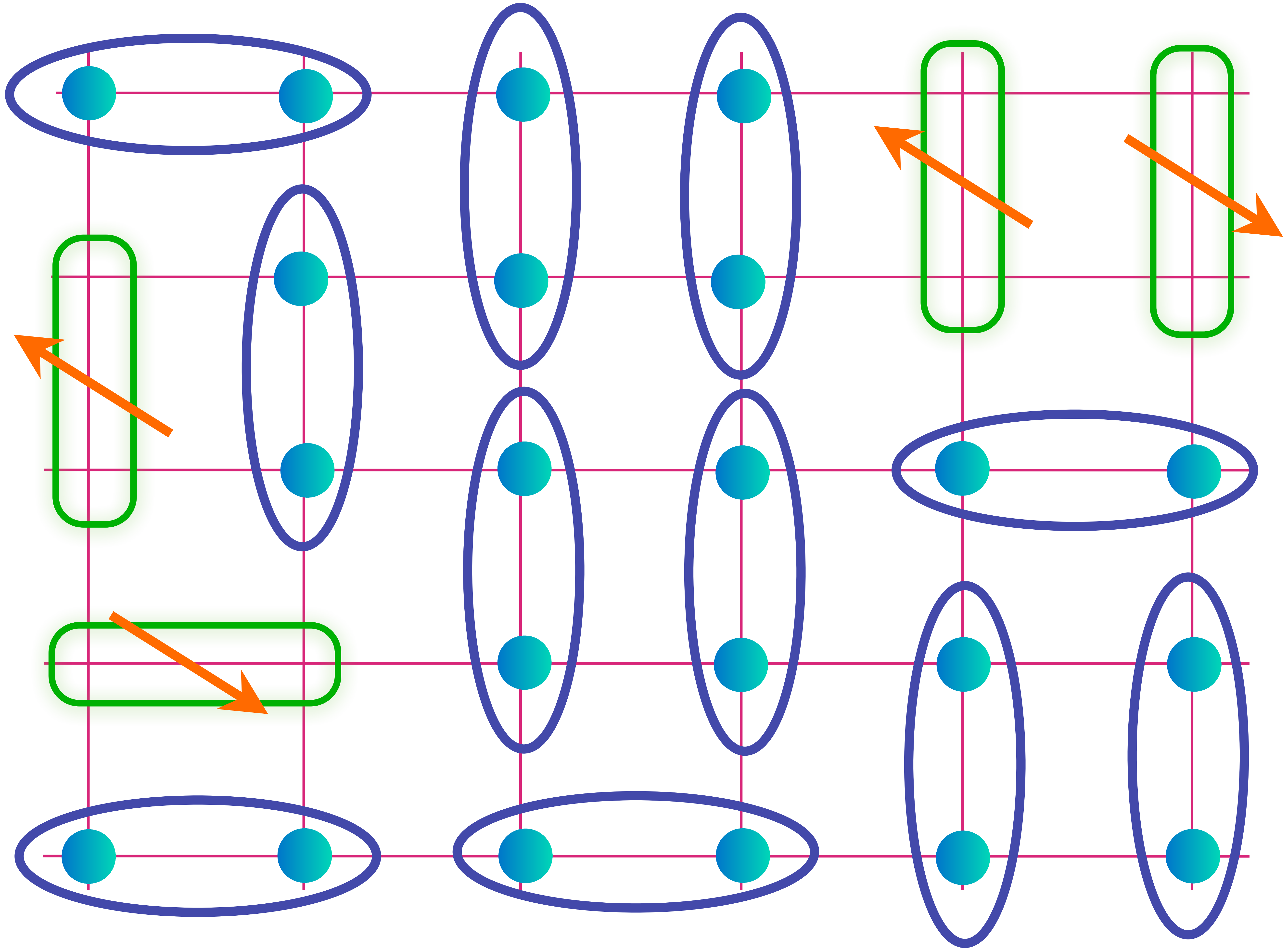

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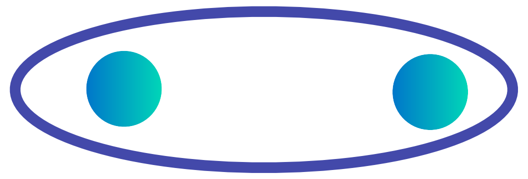
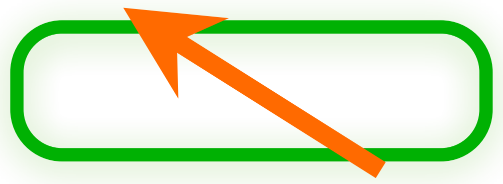
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

 $= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$

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Yahui Zhang

arXiv: 2001.09159
arXiv: 2006.01140
arXiv: 2103.05009

Maria Tikhanovskaya

Alexander Nikolaenko

Paramagnon theory of the Hubbard model

$$H = -\sum_{i<j} t_{ij} c_{i\sigma}^\dagger c_{j\sigma} + U \sum_i \left(n_{i\uparrow} - \frac{1}{2}\right)\left(n_{i\downarrow} - \frac{1}{2}\right) - \mu \sum_i c_{i\sigma}^\dagger c_{i\sigma}$$

We use the operator equation (valid on each site i):

$$U\left(n_\uparrow - \frac{1}{2}\right)\left(n_\downarrow - \frac{1}{2}\right) = -\frac{2U}{3}\boldsymbol{S}^2 + \frac{U}{4}$$

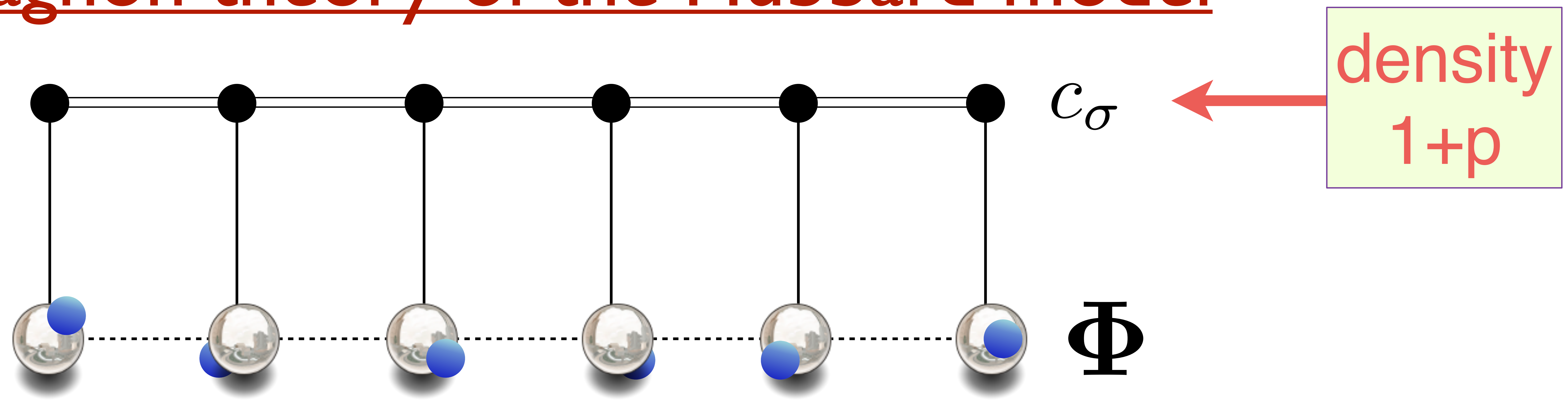
Then we decouple the interaction via

$$\exp\left(\frac{2U}{3}\sum_i \int d\tau \boldsymbol{S}_i^2\right) = \int \mathcal{D}\boldsymbol{\Phi}_i(\tau) \exp\left(-\sum_i \int d\tau \left[\frac{3}{8U}\boldsymbol{\Phi}_i^2 - \boldsymbol{\Phi}_i \cdot c_{i\sigma}^\dagger \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'}\right]\right)$$

This yields the 'Hertz-Millis' theory for a 'paramagnon quantum rotor' $\boldsymbol{\Phi}_i$ coupled to otherwise free fermions $c_{i\sigma}$.

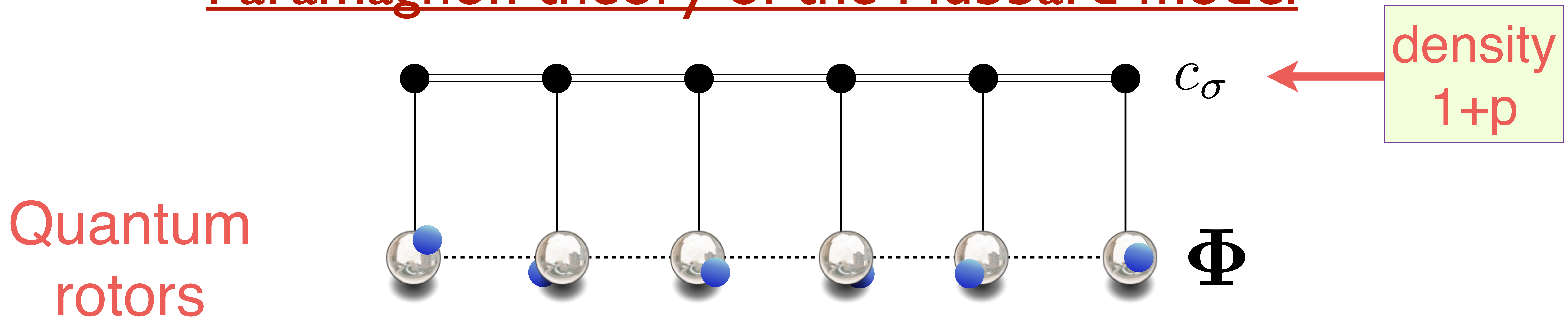
Paramagnon theory of the Hubbard model

Quantum rotors



$$\mathcal{H}_{\rm rotor} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + \sum_i \left[\widetilde{t}\, \boldsymbol{L}_i^2 + \frac{3}{8U} \mathbf{\Phi}_i^2 \right] - \sum_i c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \mathbf{\Phi}_i$$

Paramagnon theory of the Hubbard model

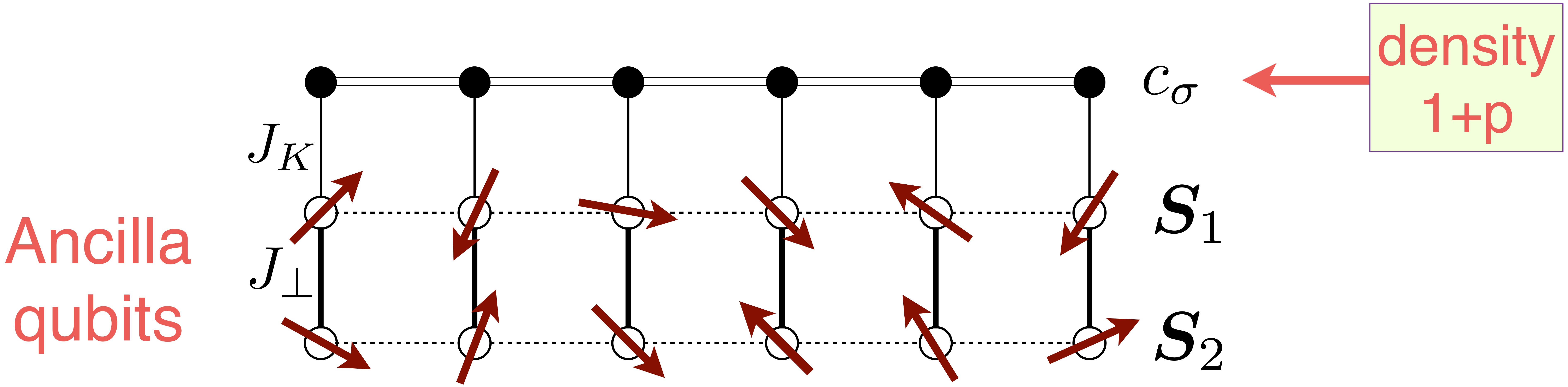


$$\mathcal{H}_{\rm rotor} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c_{\mathbf{p}\sigma}^\dagger c_{\mathbf{p}\sigma} + \sum_i \left[\widetilde{t}\, \boldsymbol{L}_i^2 + \frac{3}{8U} \mathbf{\Phi}_i^2 \right] - \sum_i c_{i\sigma}^\dagger \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \mathbf{\Phi}_i$$

Key idea:

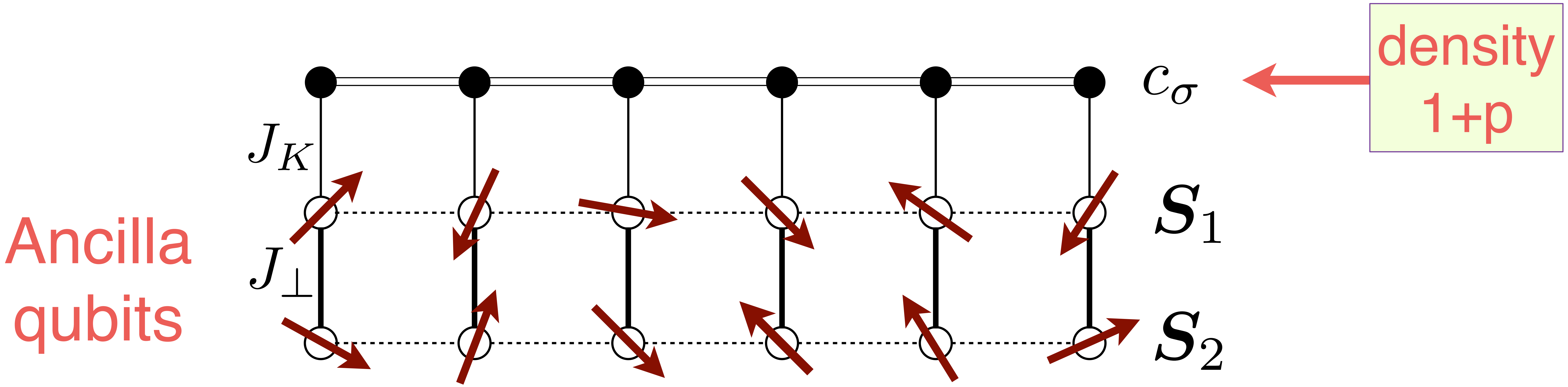
Fractionalize the ‘paramagnon rotor’ $\mathbf{\Phi}_i$
into 2 “ancilla qubits”,
$S = 1/2$ spins $\boldsymbol{S}_{1i}$ and $\boldsymbol{S}_{2i}$ on each site,
and don’t fractionalize the mobile electron $c_{i\sigma}$.

Ancilla theory of the Hubbard model



$$\mathcal{H}_{\rm ancilla} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c_{\mathbf{p}\sigma}^\dagger c_{\mathbf{p}\sigma} + \sum_i \left[J_K \, c_{i\sigma}^\dagger \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \boldsymbol{S}_{1i} + J_\perp \, \boldsymbol{S}_{1i} \cdot \boldsymbol{S}_{2i} \right] + \sum_{\langle ij \rangle} \left[J_1 \, \boldsymbol{S}_{1i} \cdot \boldsymbol{S}_{1j} + J_2 \, \boldsymbol{S}_{2i} \cdot \boldsymbol{S}_{2j} \right]$$

Ancilla theory of the Hubbard model



$$\mathcal{H}_{\text{ancilla}} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + \sum_i \left[J_K \, c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \cdot \boldsymbol{S}_{1i} + J_\perp \, \boldsymbol{S}_{1i} \cdot \boldsymbol{S}_{2i} \right] + \sum_{\langle ij \rangle} \left[J_1 \, \boldsymbol{S}_{1i} \cdot \boldsymbol{S}_{1j} + J_2 \, \boldsymbol{S}_{2i} \cdot \boldsymbol{S}_{2j} \right]$$

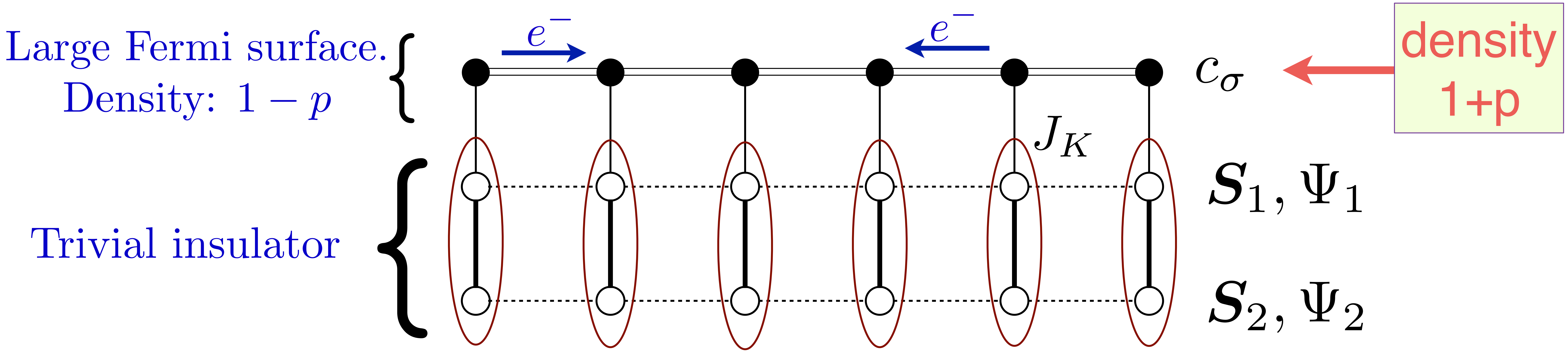
Performing a Schrieffer-Wolff transformation in powers of $1/J_\perp$, we obtain

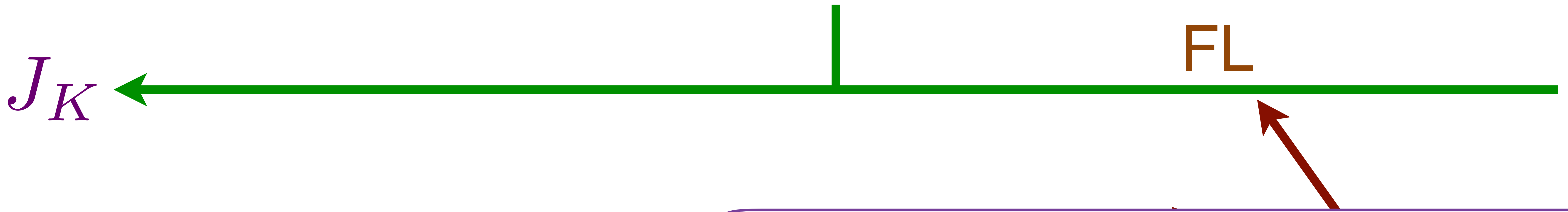
$$\mathcal{H} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + U \sum_i \left[c^\dagger_{i\uparrow} c_{i\uparrow} \right] \left[c^\dagger_{i\downarrow} c_{i\downarrow} \right] + J \sum_{\langle ij \rangle} \left[c^\dagger_{i\sigma} \frac{\boldsymbol{\tau}_{\sigma\sigma'}}{2} c_{i\sigma'} \right] \cdot \left[c^\dagger_{j\rho} \frac{\boldsymbol{\tau}_{\rho\rho'}}{2} c_{j\rho'} \right]$$

i.e. we recover a Hubbard-Heisenberg model with *no ancillas* and

$$U = \frac{3J_K^2}{8J_\perp} + \frac{3J_K^3}{16J_\perp^2} + \ldots \quad , \quad J = \frac{J_K^2 (J_1 + J_2)}{4J_\perp^2}$$

Ancilla theory of the Hubbard model

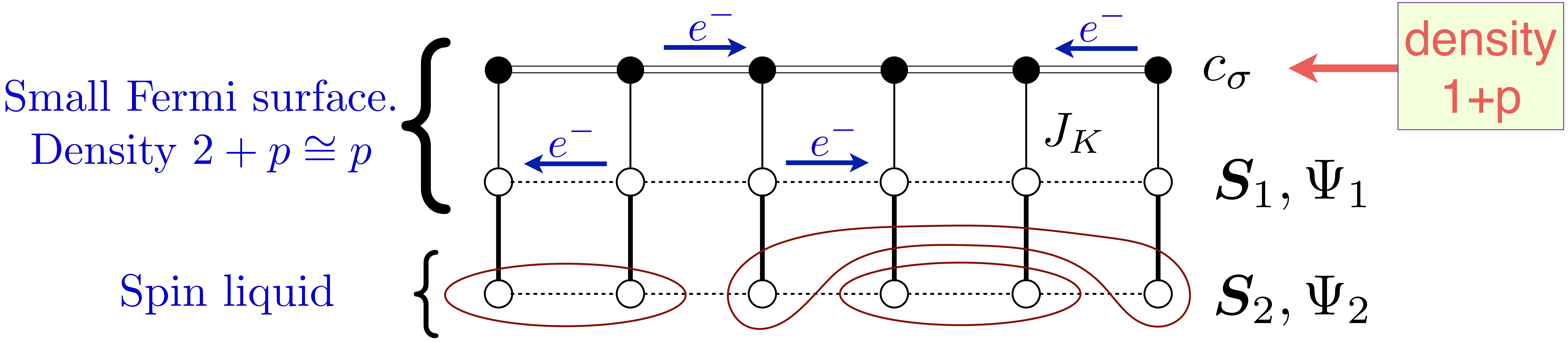


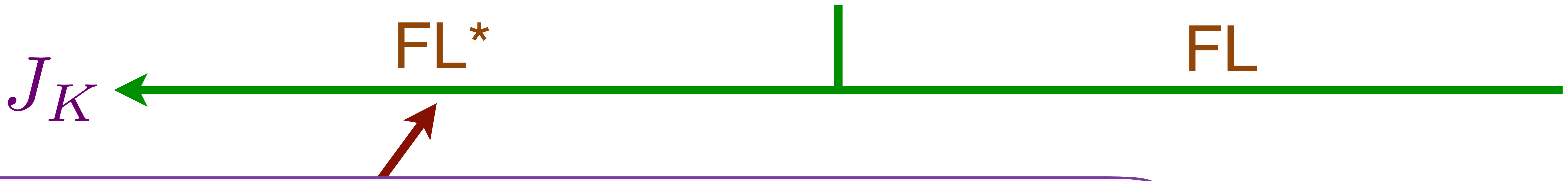


Large Fermi surface of size $1 + p$

$$|\mathrm{FL}\rangle = |\text{Rung singlets of } \Psi_1, \Psi_2\rangle$$
$$\otimes\, |\text{Slater determinant of } c\rangle$$

Ancilla theory of the Hubbard model

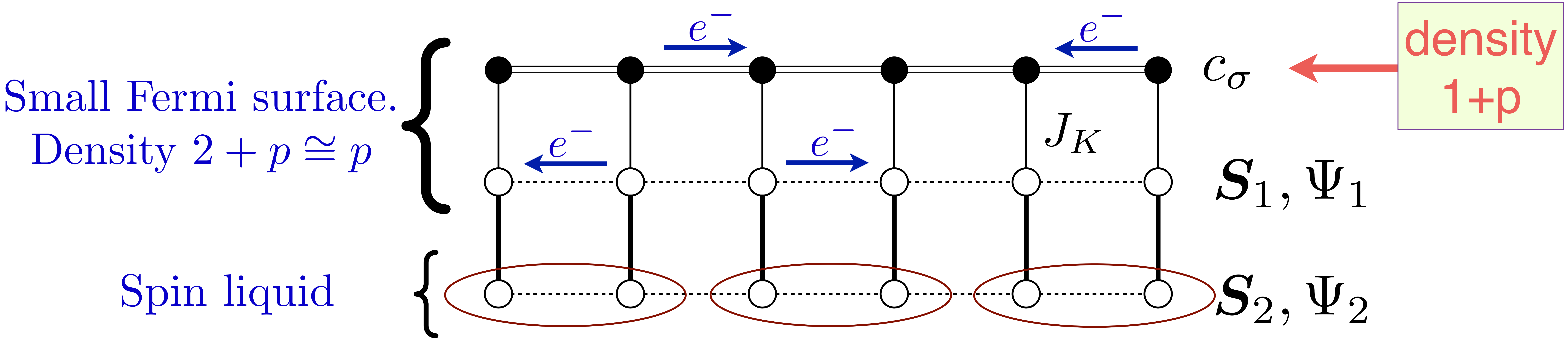


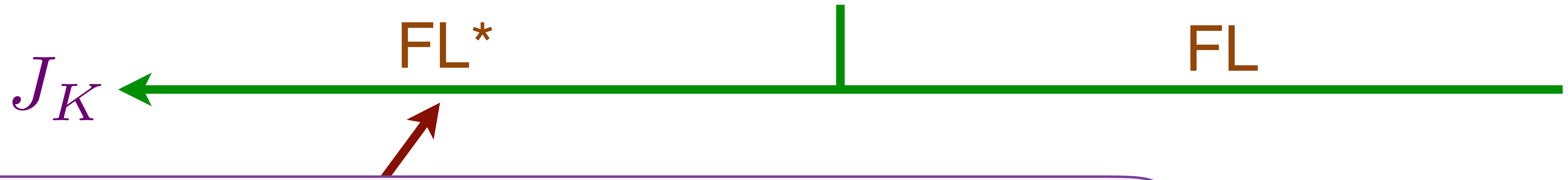


Small Fermi surface of size p

$$|\mathrm{FL}*\rangle = [\text{Projection onto rung singlets of } \Psi_1, \Psi_2]$$
$$\bowtie |\text{Slater determinant of } (c, \Psi_1)\rangle$$
$$\otimes\, |\text{Slater determinant of } \Psi_2\rangle$$

Ancilla theory of the Hubbard model





Small Fermi surface of size p

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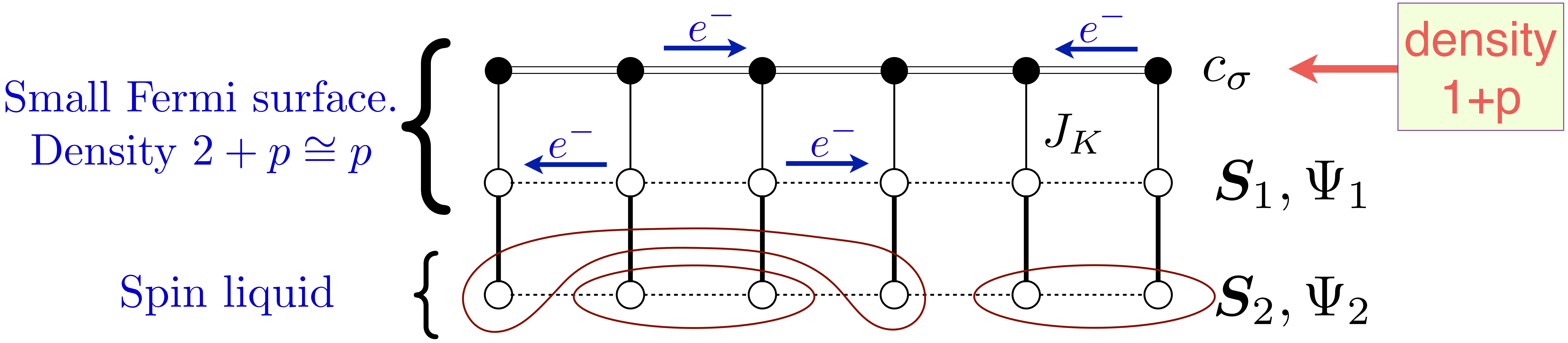
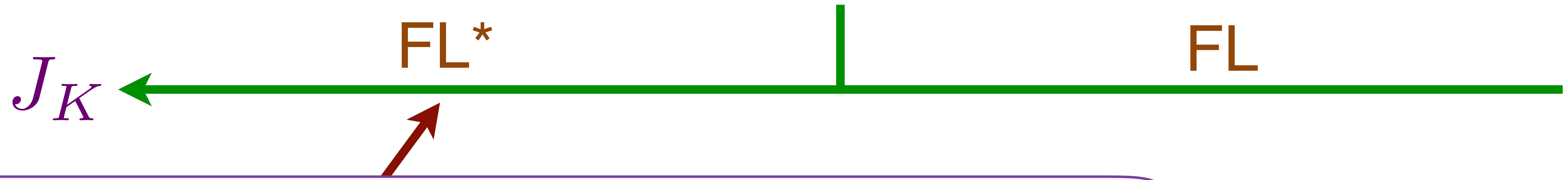
Ancilla theory of the Hubbard model





Small Fermi surface of size p

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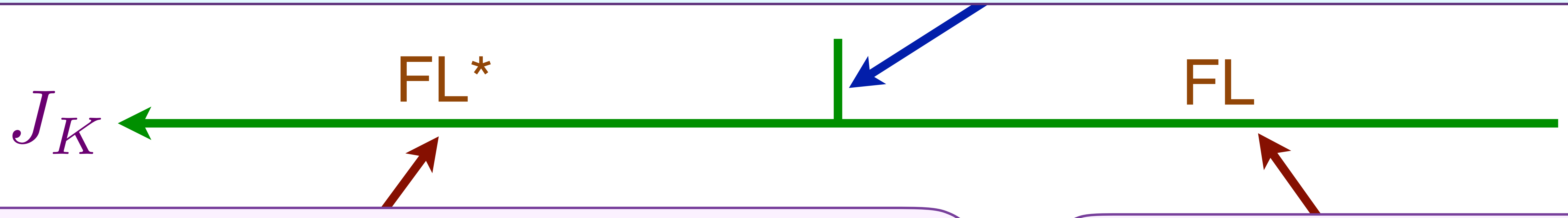
Ancilla theory of the Hubbard model

- Deconfined criticality of a $(\mathrm{SU}(2)_S \times \mathrm{U}(1)_1)/Z_2$ gauge theory.
- 'Hybridization-Higgs' boson $\sim C_\sigma^\dagger \Psi_a$ which condenses on the FL* side (in Kondo lattice, Higgs boson was condensed on the FL side).
- Gauge-charged 'ghost' Fermi surface of Ψ_1 fermions.
- Large Fermi surface of c_σ gauge-neutral electrons.



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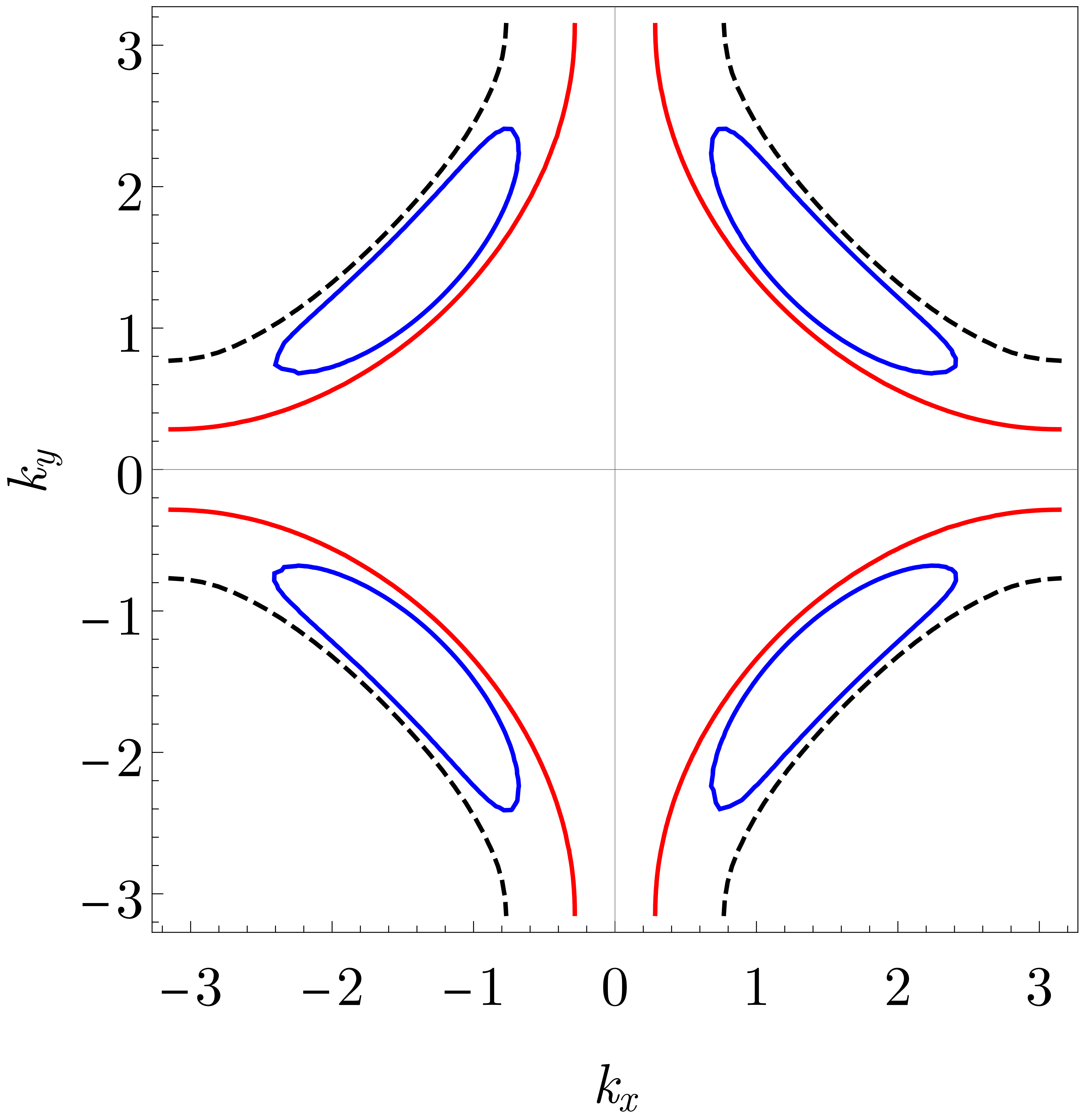
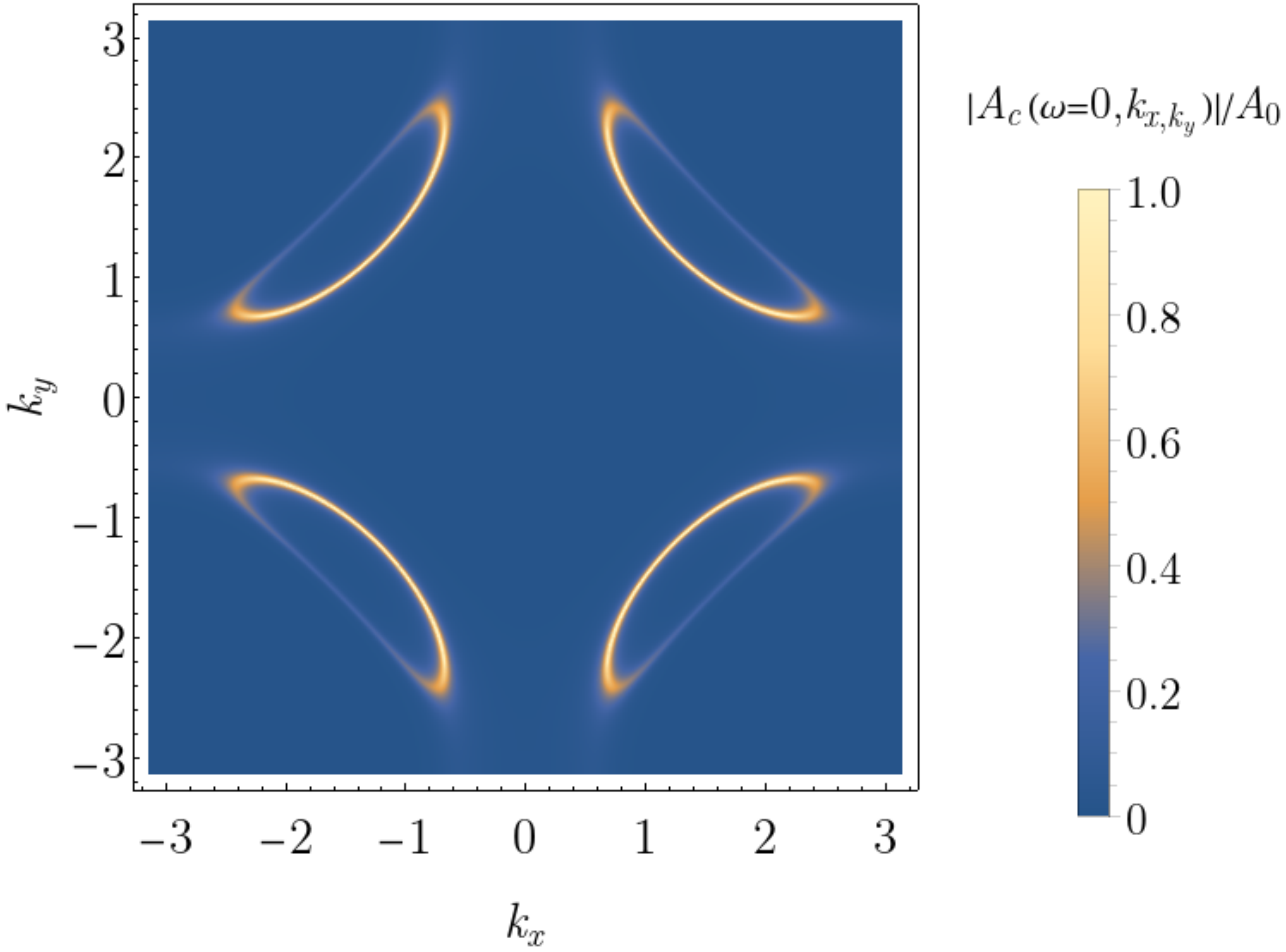
Large Fermi surface of size $1 + p$

$$|\mathrm{FL}\rangle = |\text{Rung singlets of } \Psi_1, \Psi_2\rangle \\ \otimes |\text{Slater determinant of } c\rangle$$

FL* in a ***one-band*** model





"Fermi arc" spectral functions in the FL* phase

FL*

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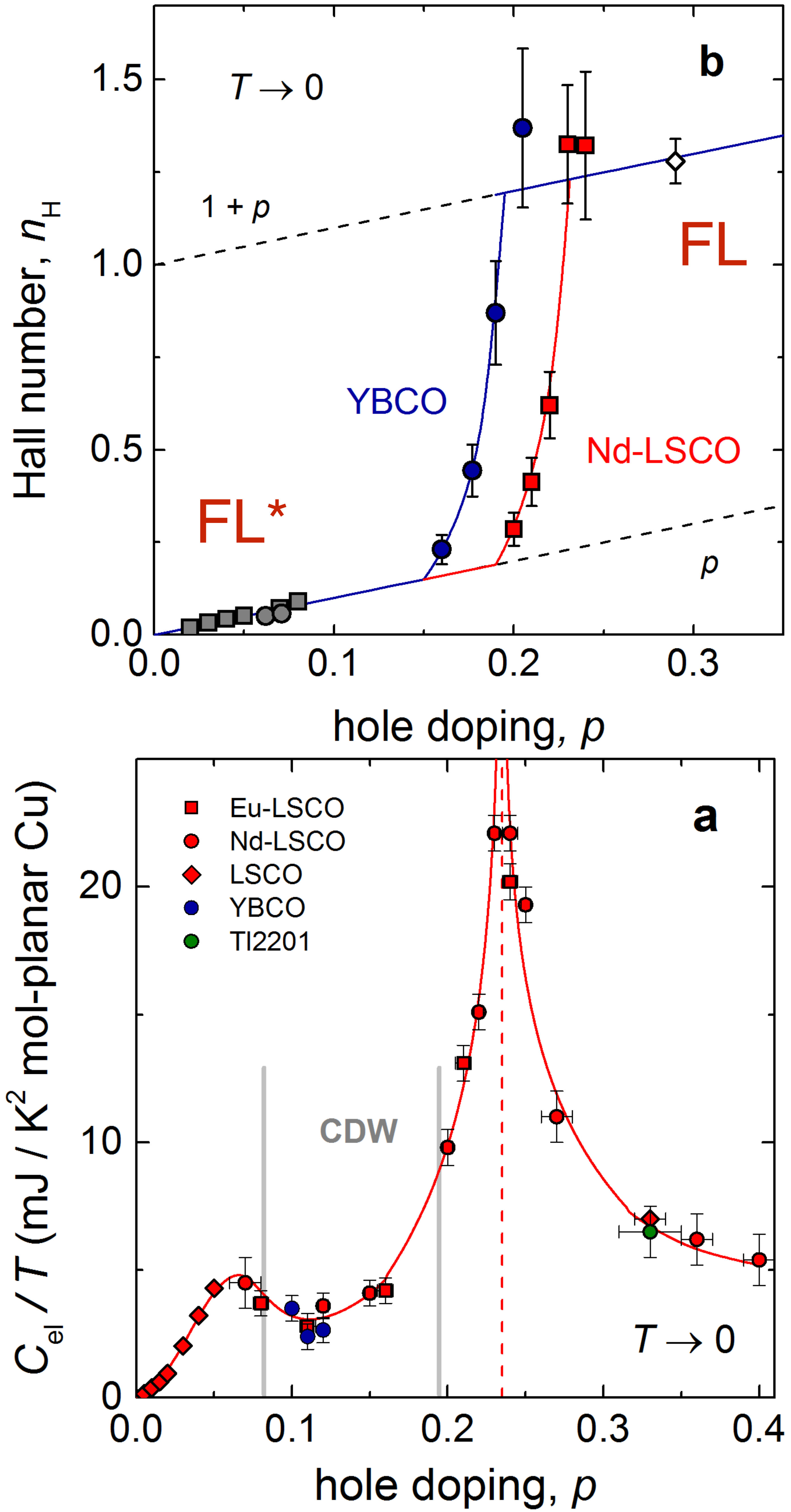
- Theory of FL-FL* transition on a single band Hubbard model: Emergent SU(2)×U(1) gauge theory coupled to hybridization boson, a gauge-neutral *large* Fermi surface of electrons, and a 'ghost' Fermi surface.
  Prediction: critical 'ghost' Fermi surfaces near the transition.

Cuprates



Evidence for
ghost Fermi surfaces
in the
FL*-FL transition
in a
single-band model ?

$CeCoIn_5$