# Fermi surfaces, large and small

2021 H.L. Welsh Lectures in Physics
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Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
VE RI TAS
HARVARD

Maria Tikhanovskaya


Yahui Zhang

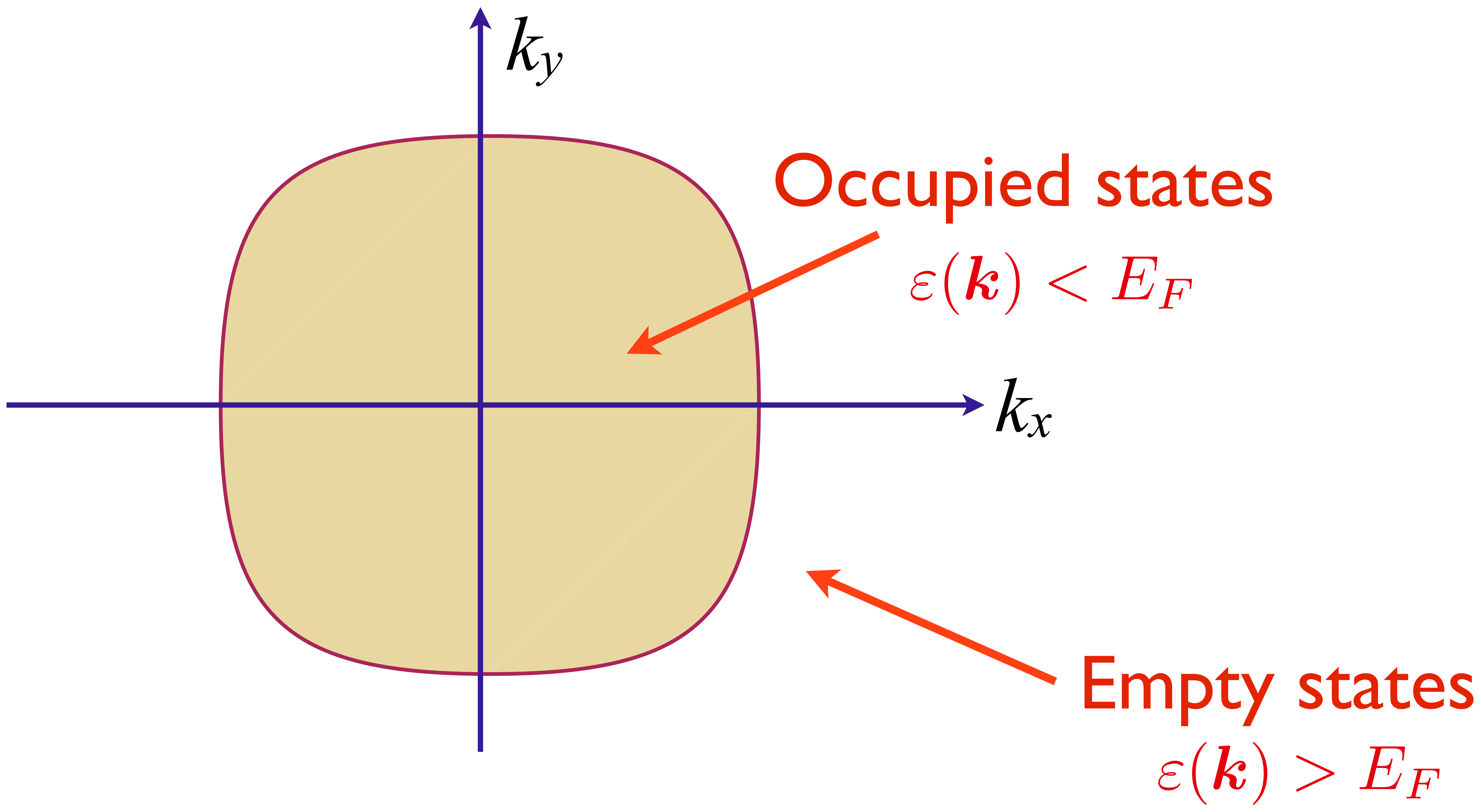
Alexander Nikolaenko

# *Ordinary metals*


Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal

# Theory of metals

Electrons move with momentum **k** through the lattice with dispersion $\varepsilon(\boldsymbol{k})$



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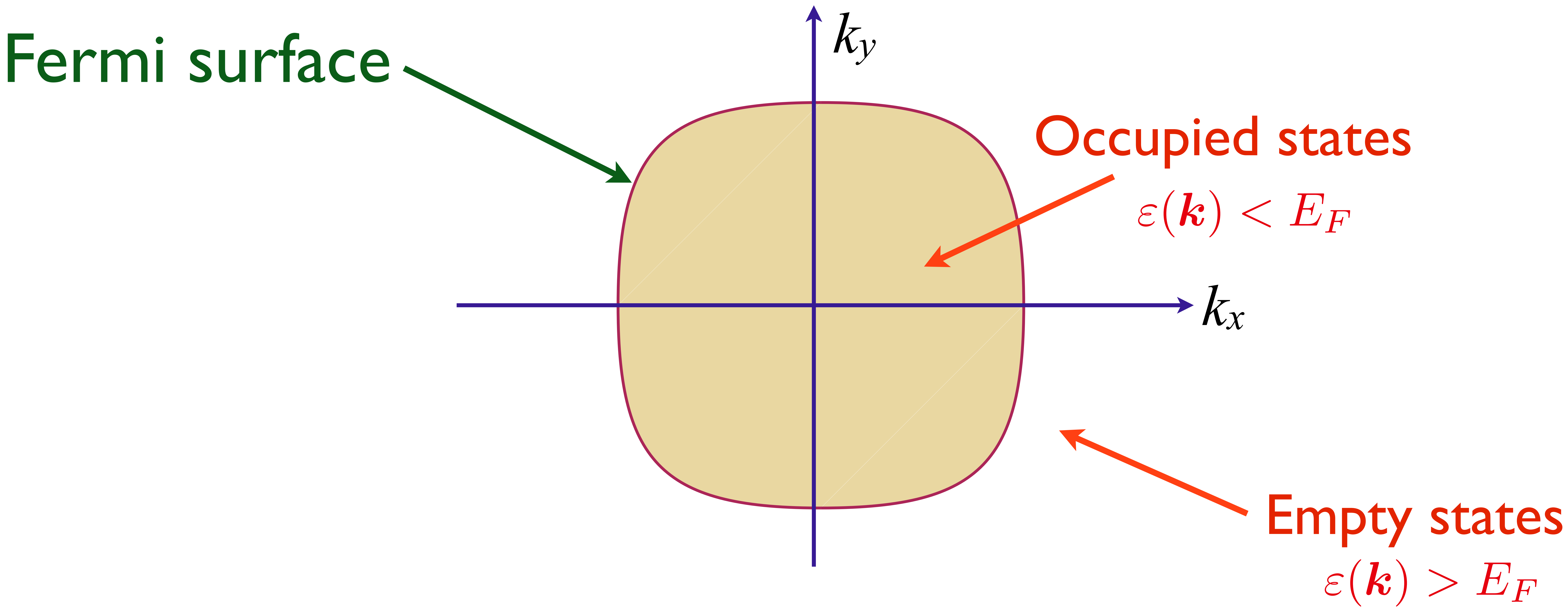

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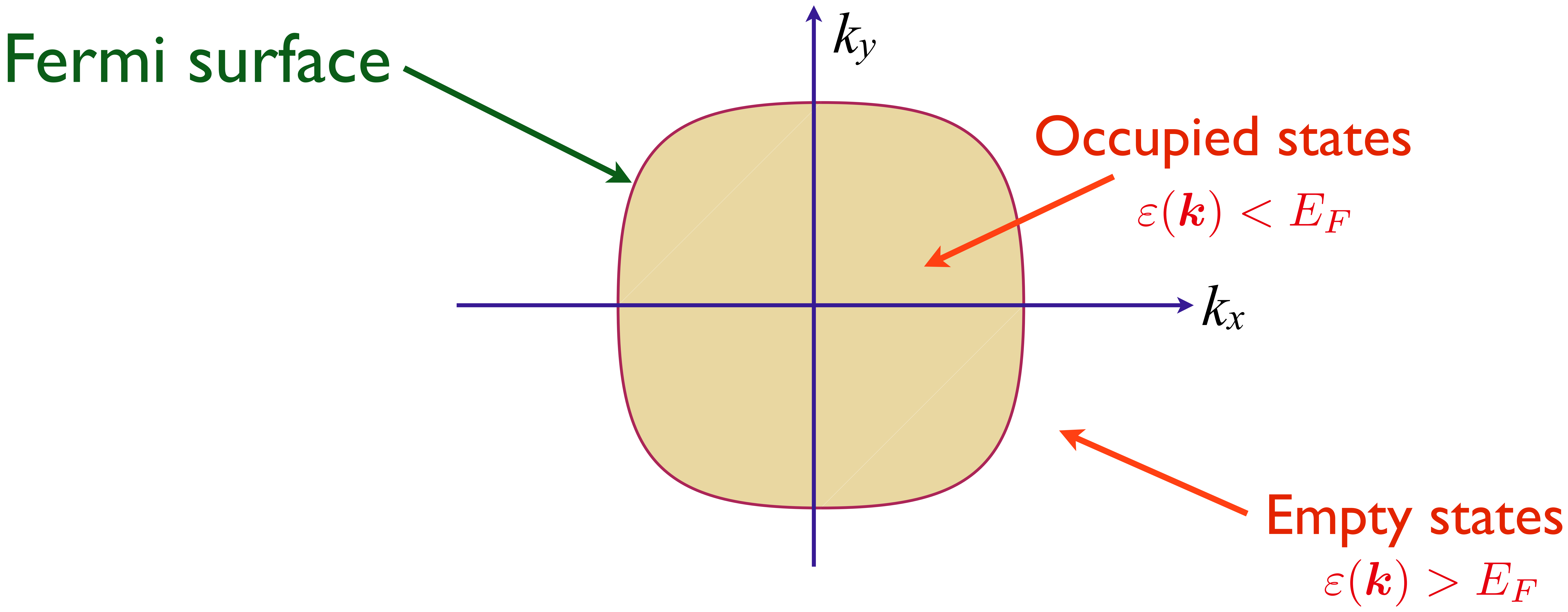


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- (Can be understood by an 'anomaly' argument, under which we gauge the U(1) symmetry to $c_\alpha \to c_\alpha e^{i\Omega t}$, so that the electron Green's function $G(\boldsymbol{k},\omega) \to G(\boldsymbol{k},\omega+\Omega)$. The effect of interactions are accounted for by the Luttinger-Ward functional, which remains invariant $\Phi_{LW}[G(\boldsymbol{k},\omega)] = \Phi_{LW}[G(\boldsymbol{k},\omega+\Omega)]$.)

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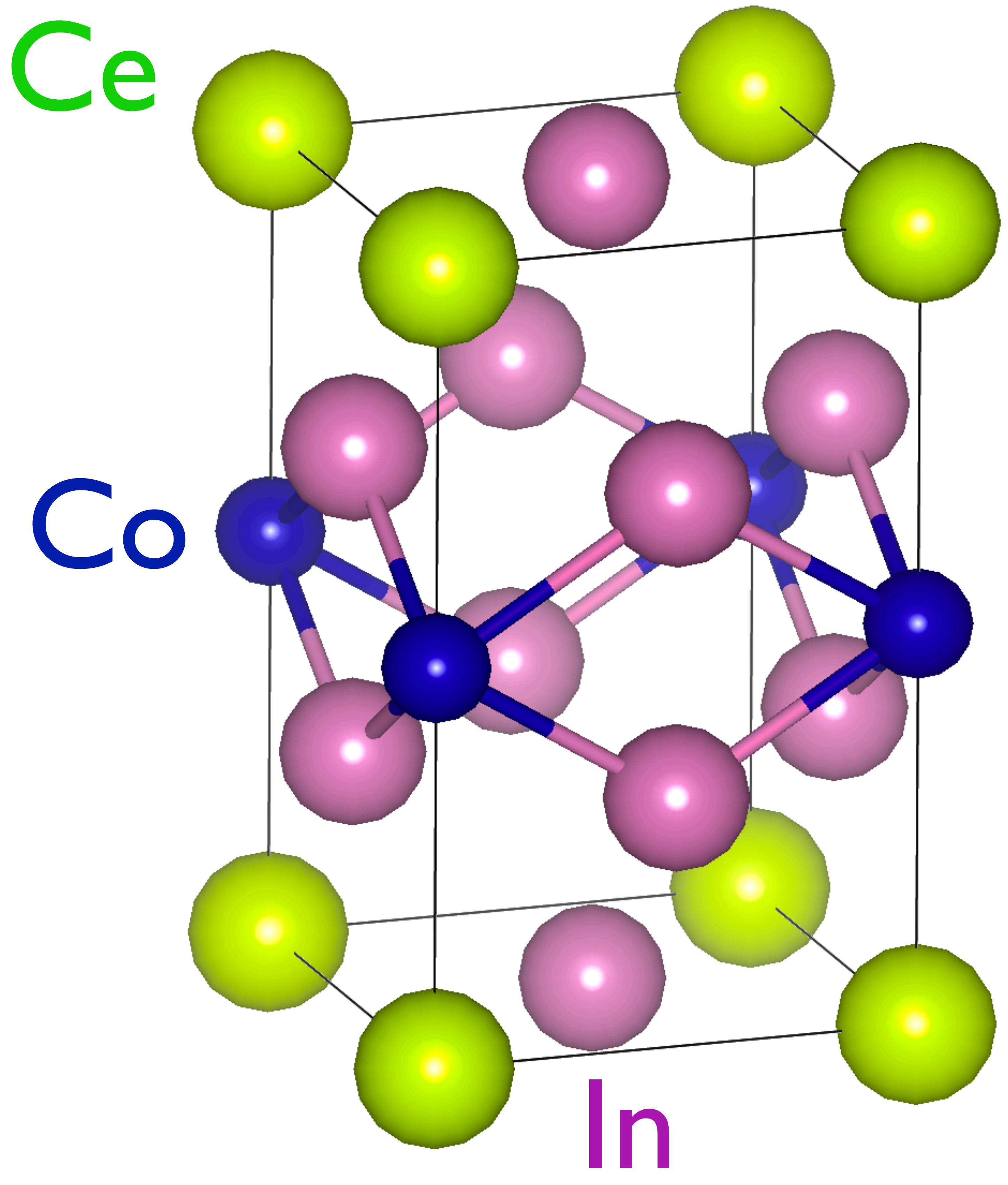


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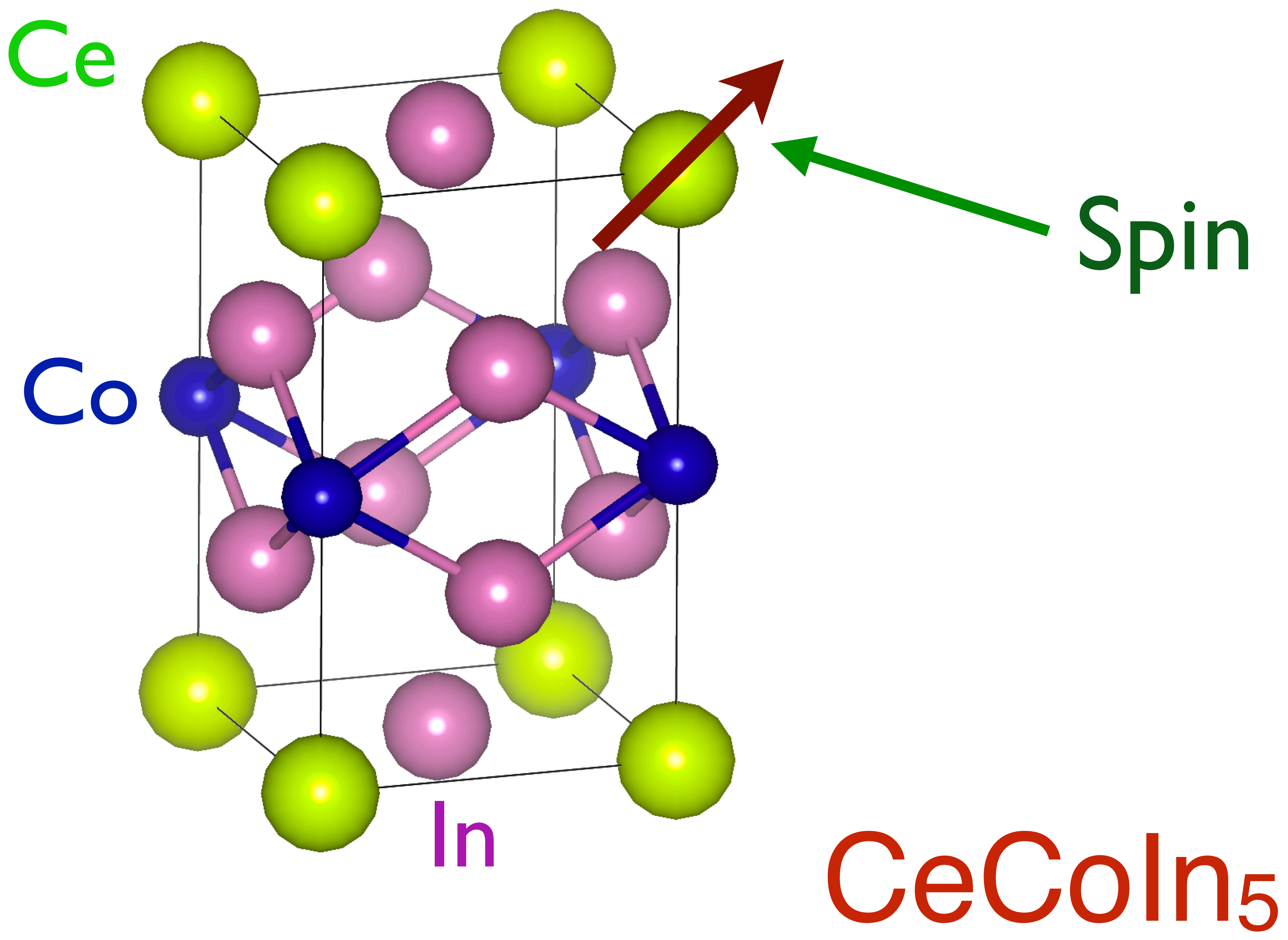

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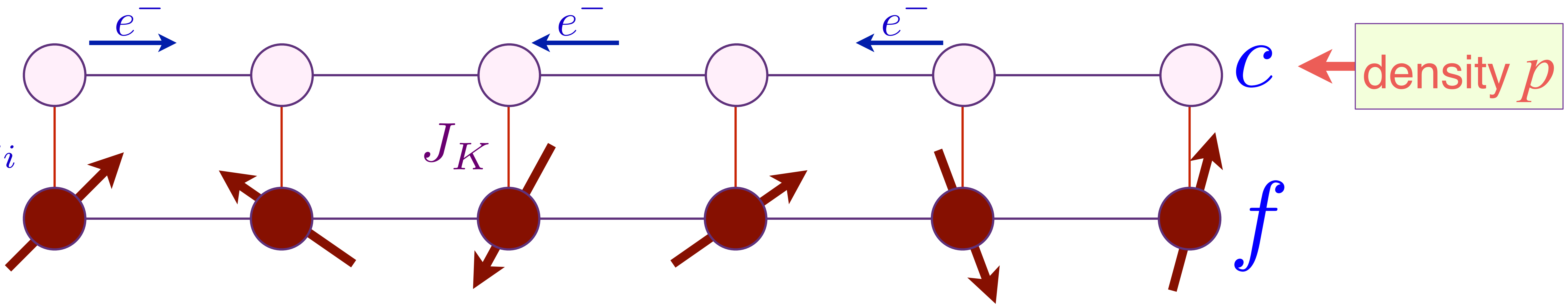


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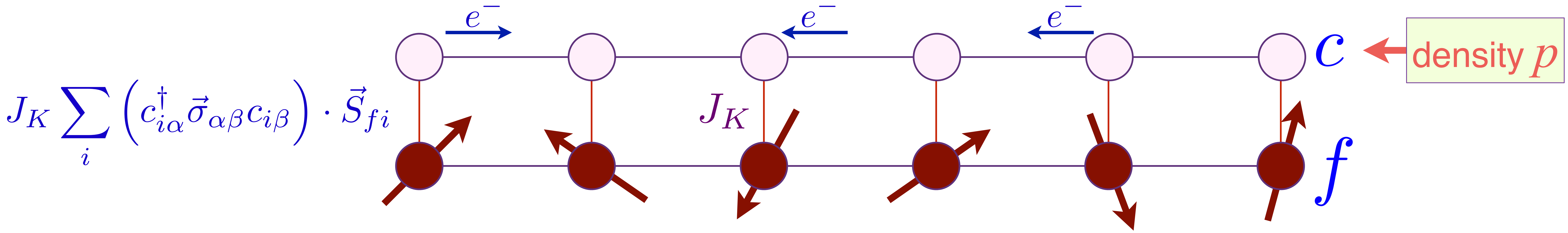


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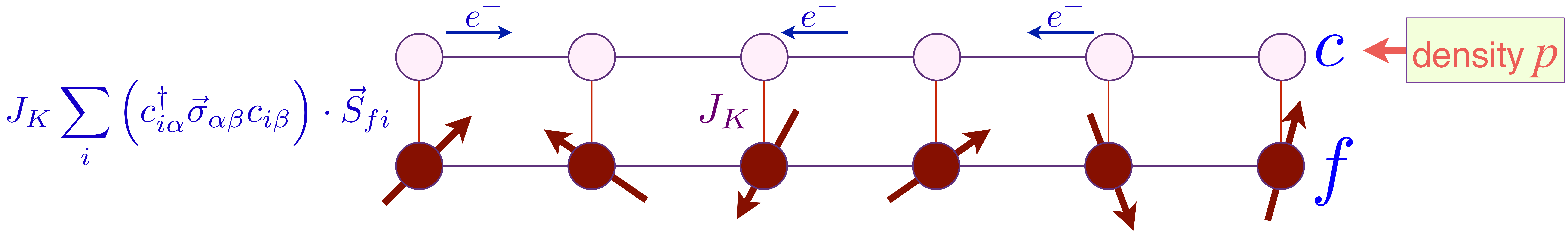


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For non-infinite interactions, Luttinger's theorem states the Fermi surface should be large.

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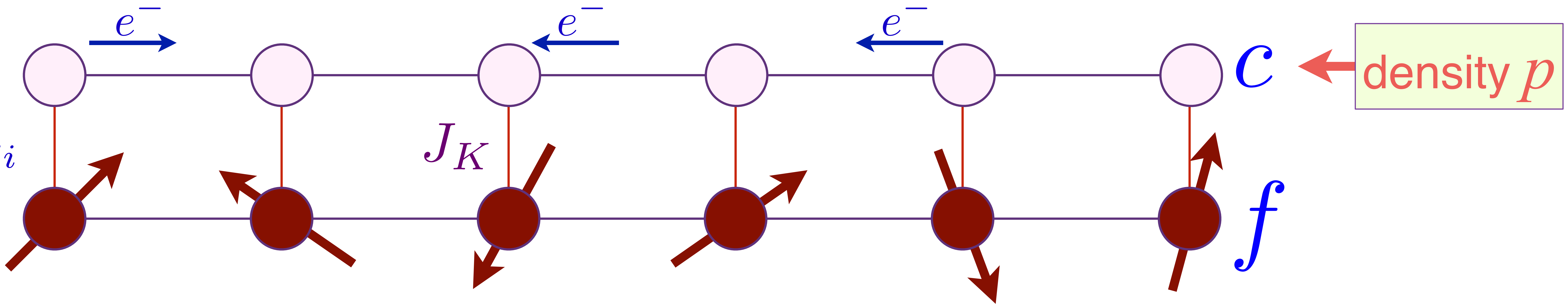


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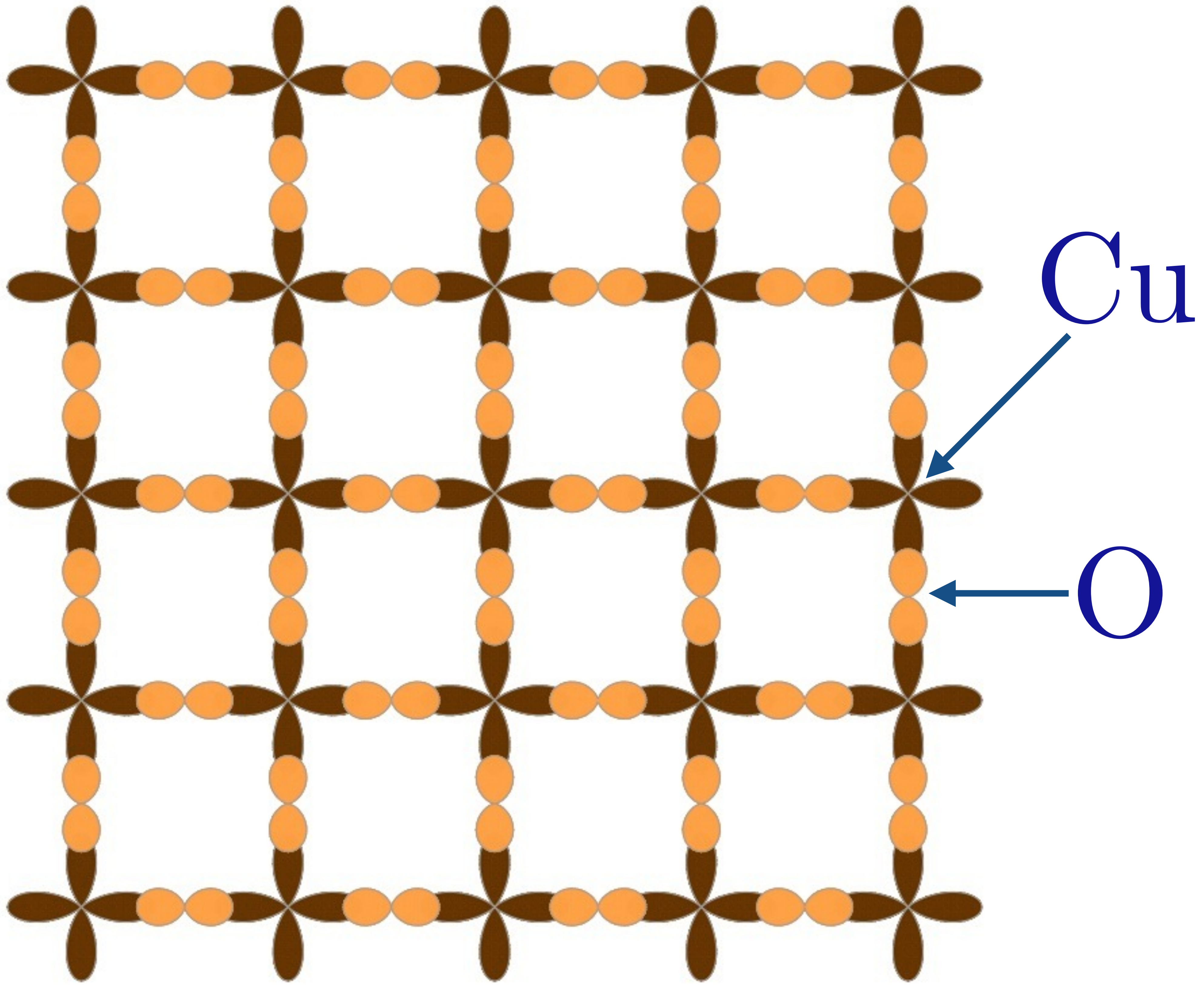
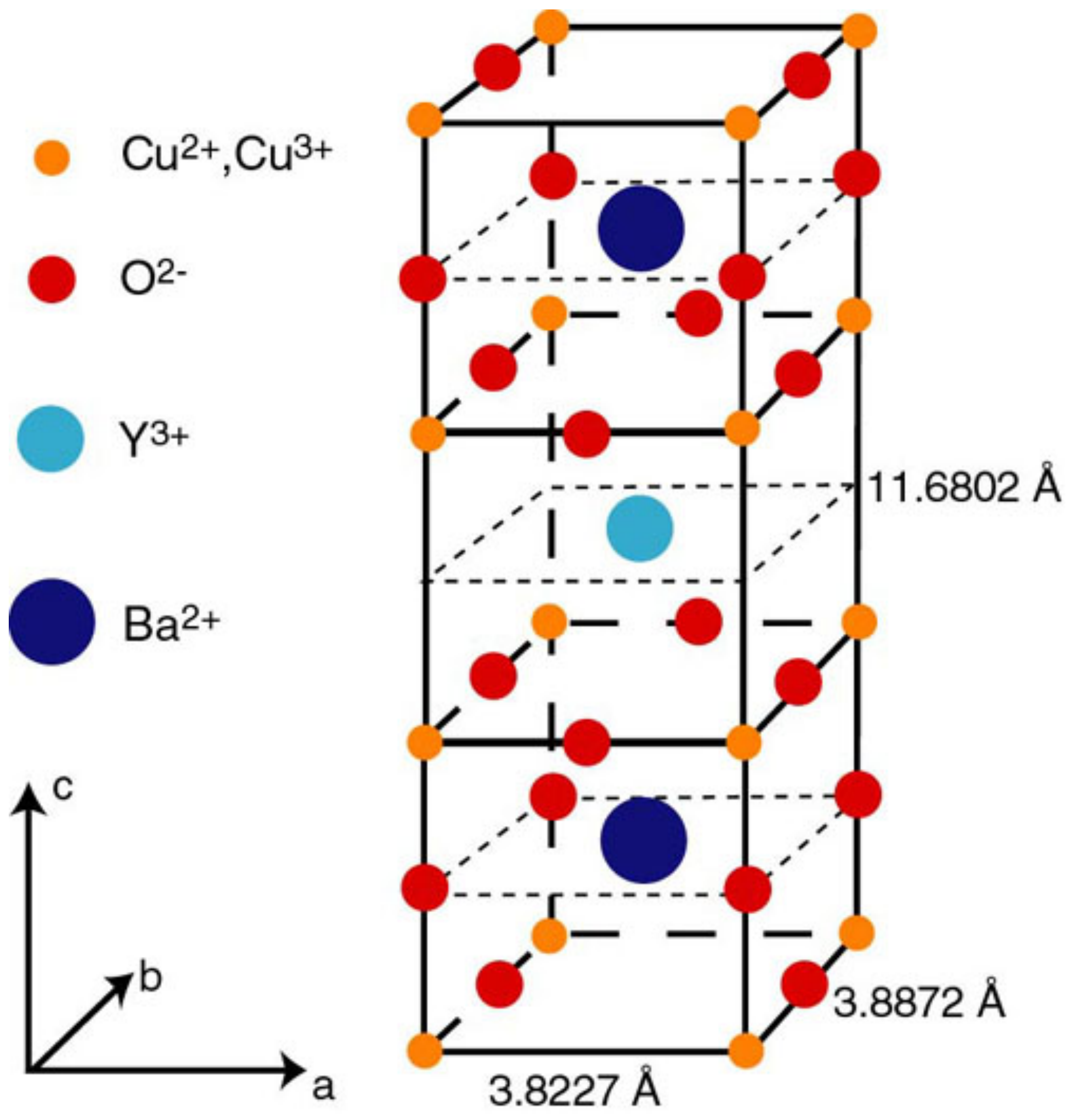
High temperature superconductors




$CuO_2$ plane

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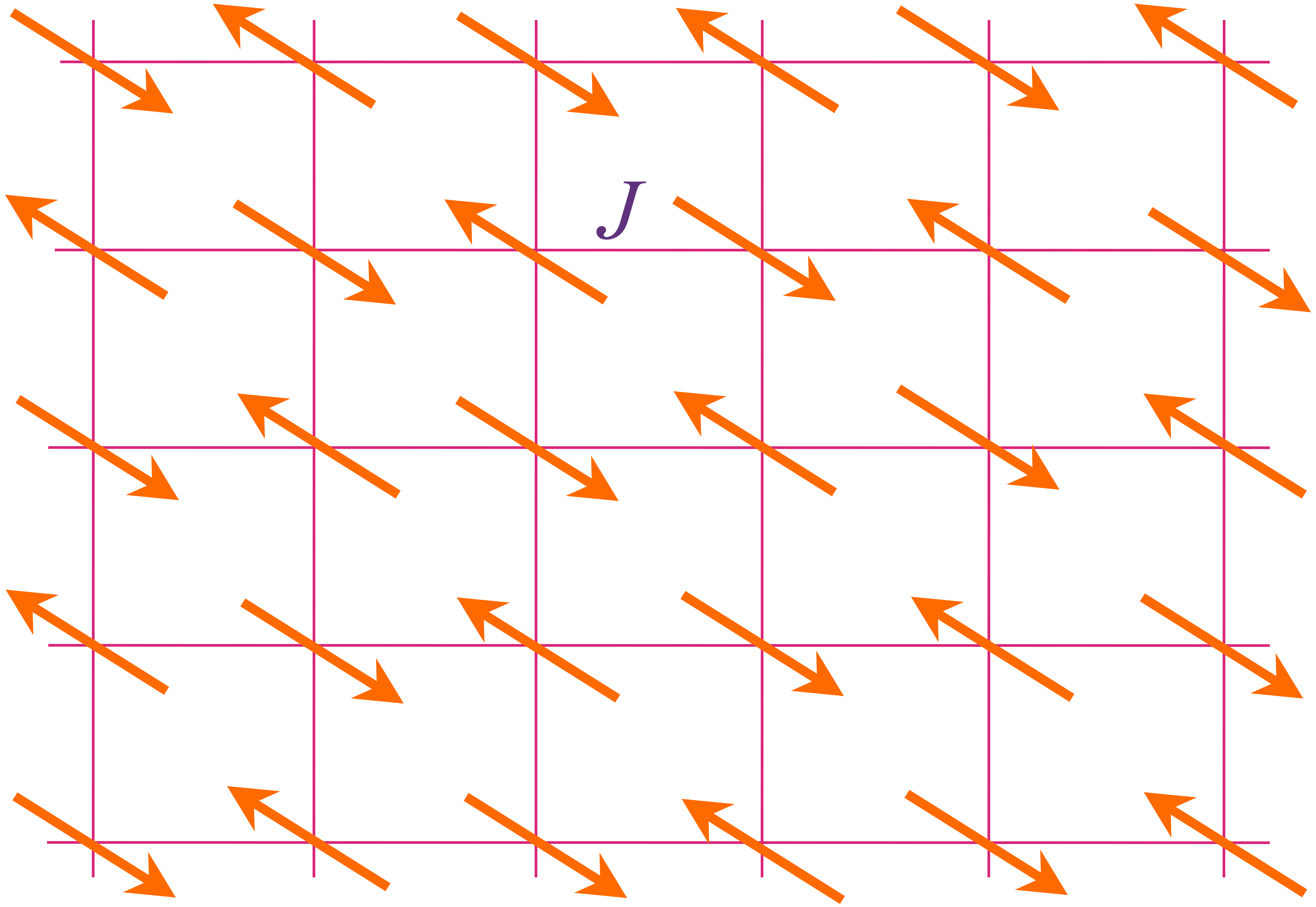


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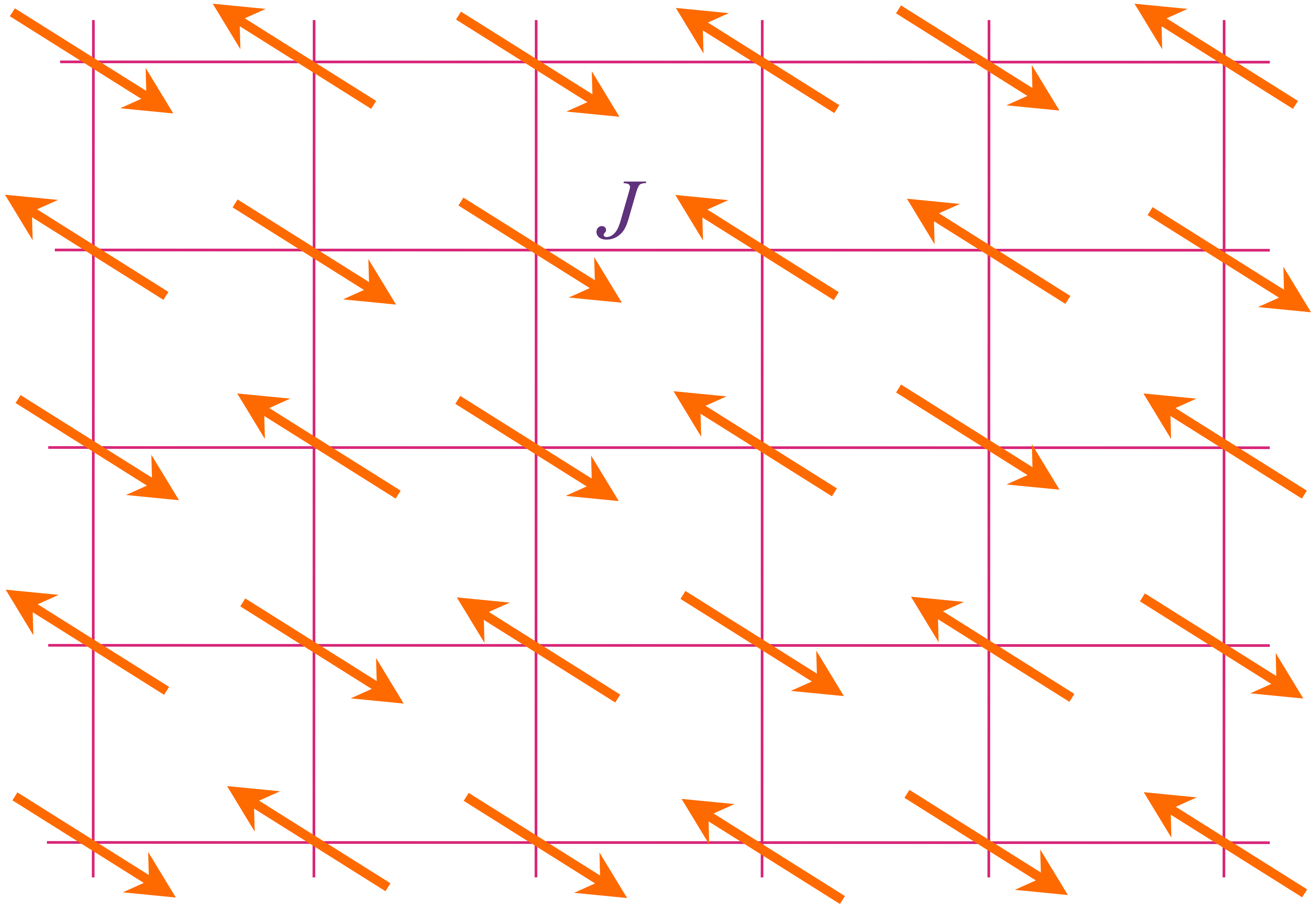


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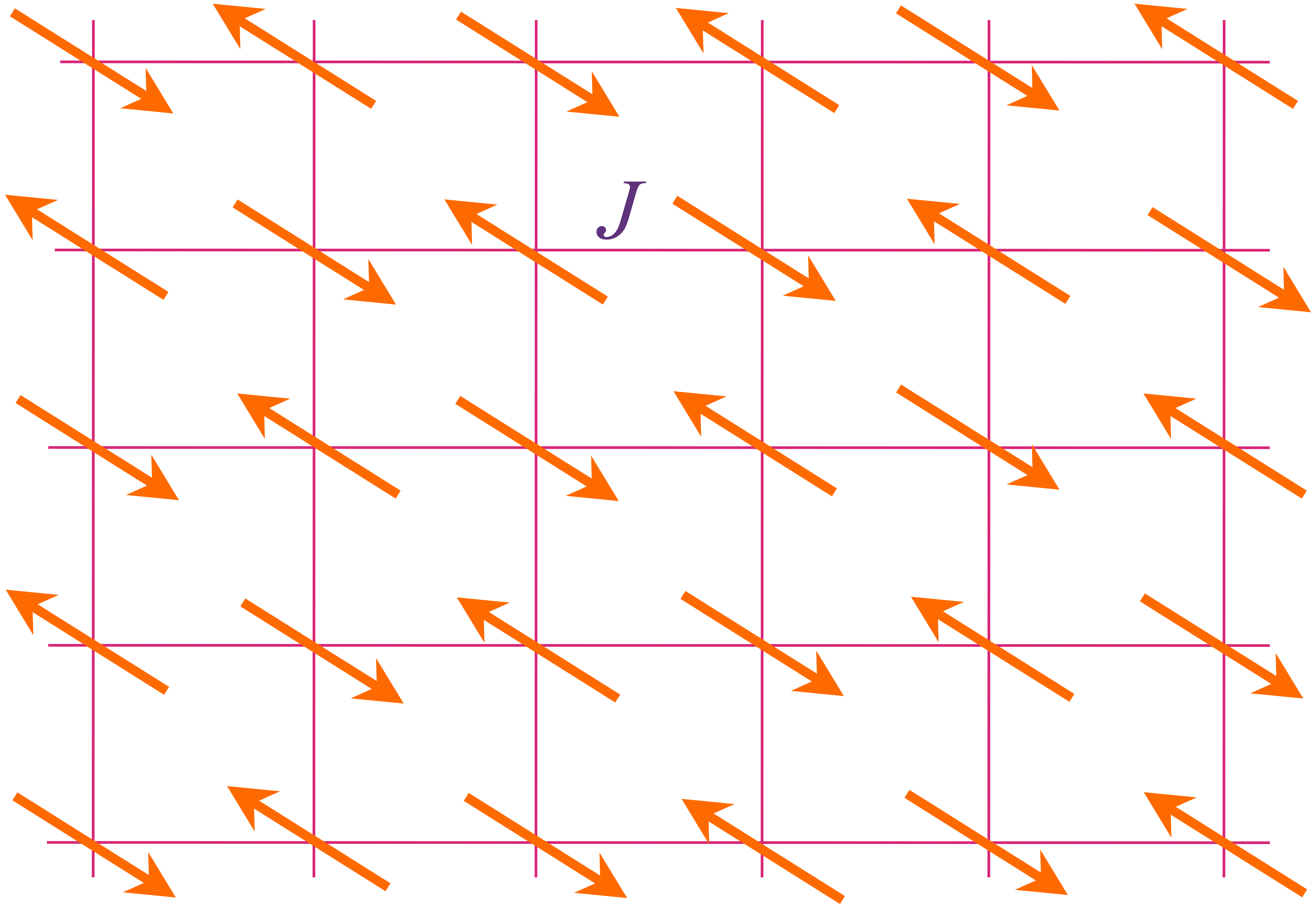


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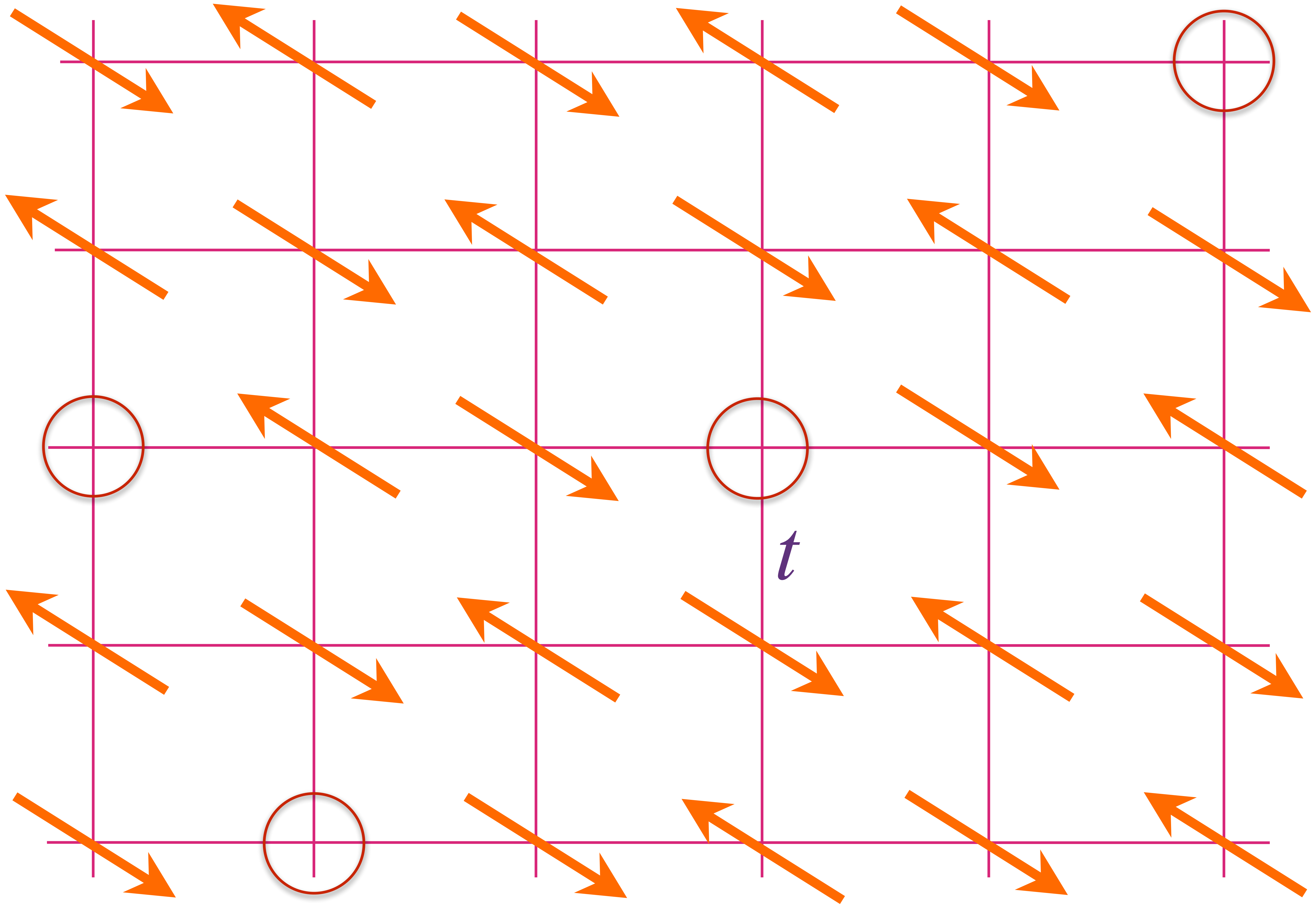


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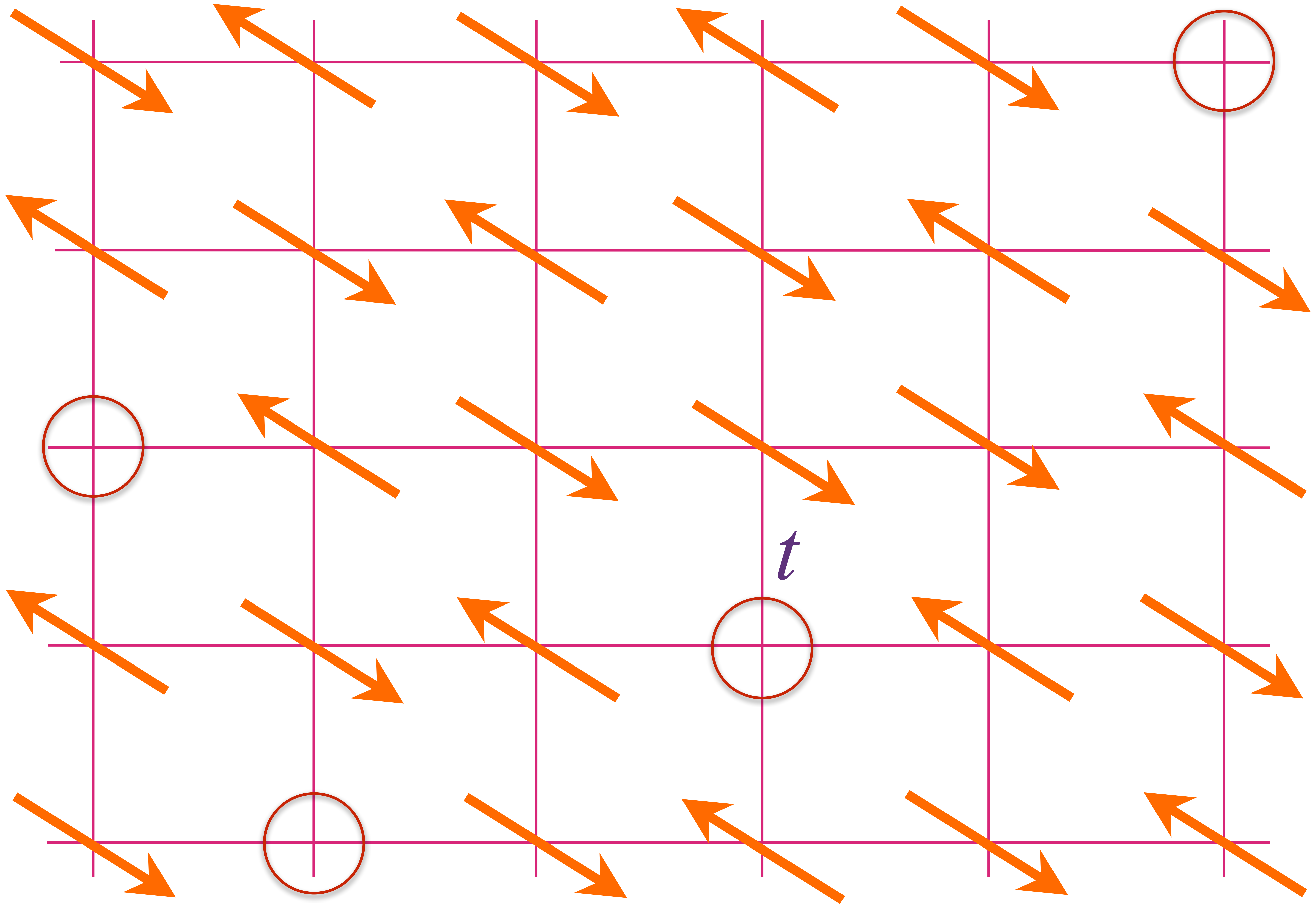


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$p$ mobile holes in a background of fluctuating spins

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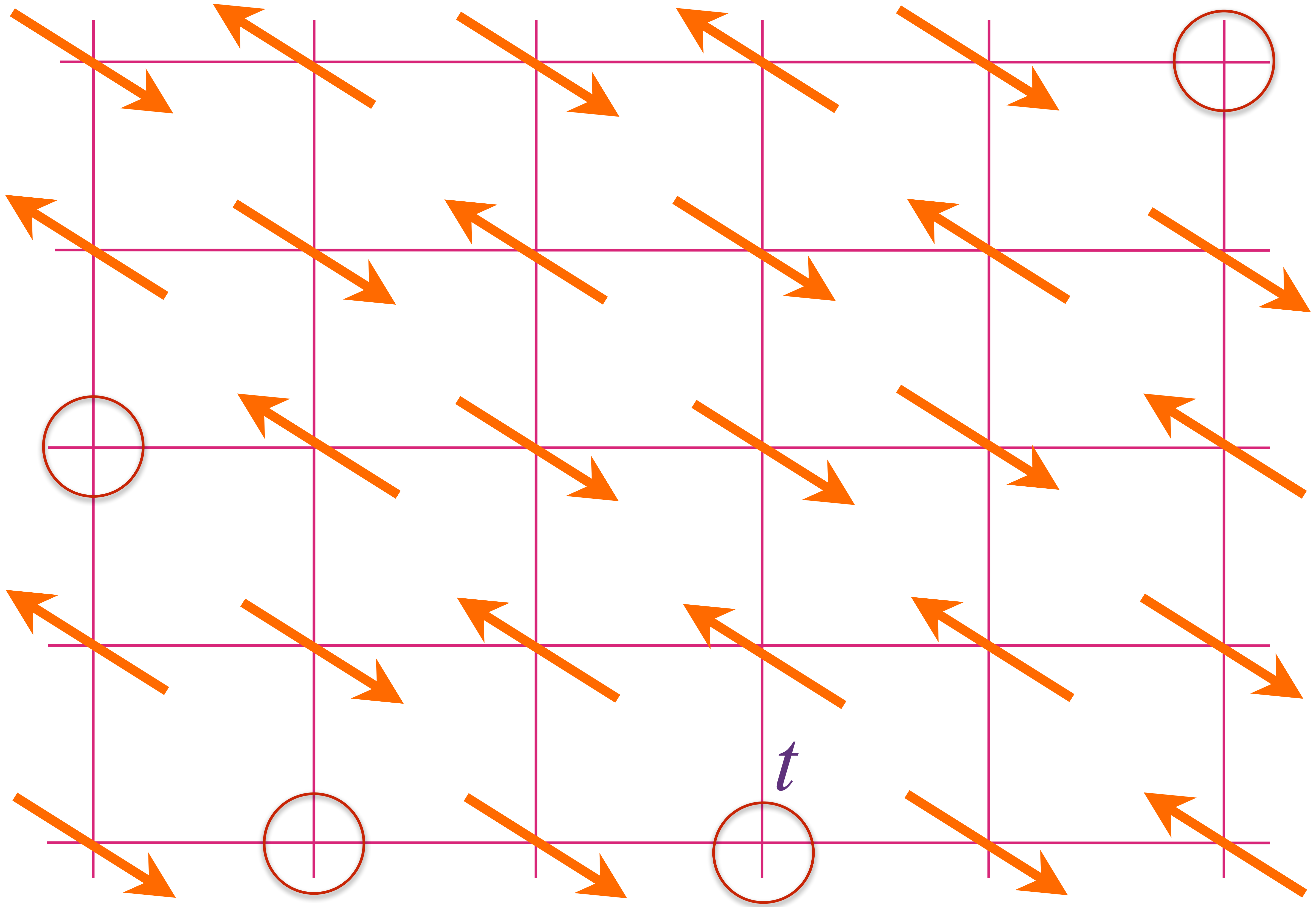


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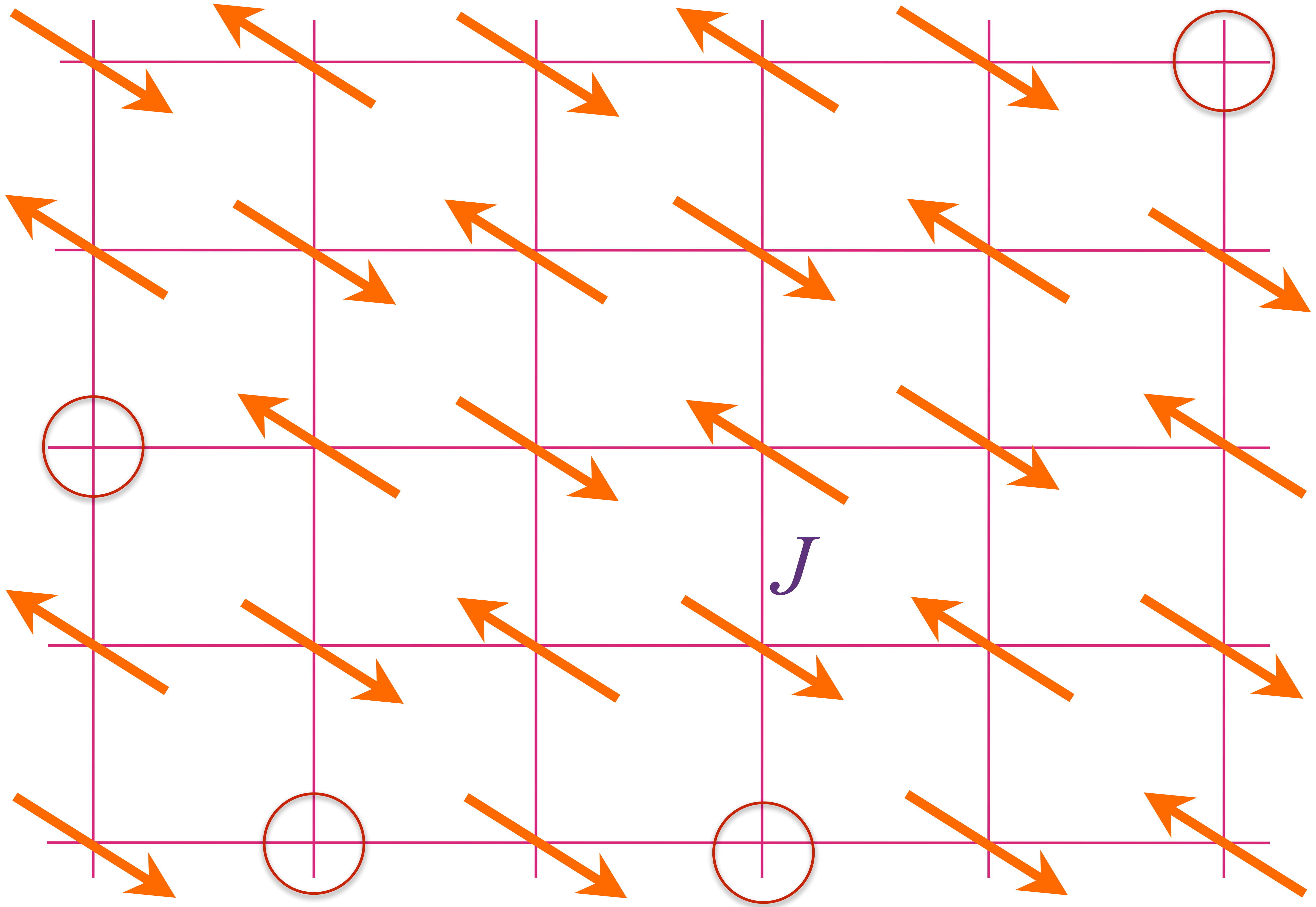


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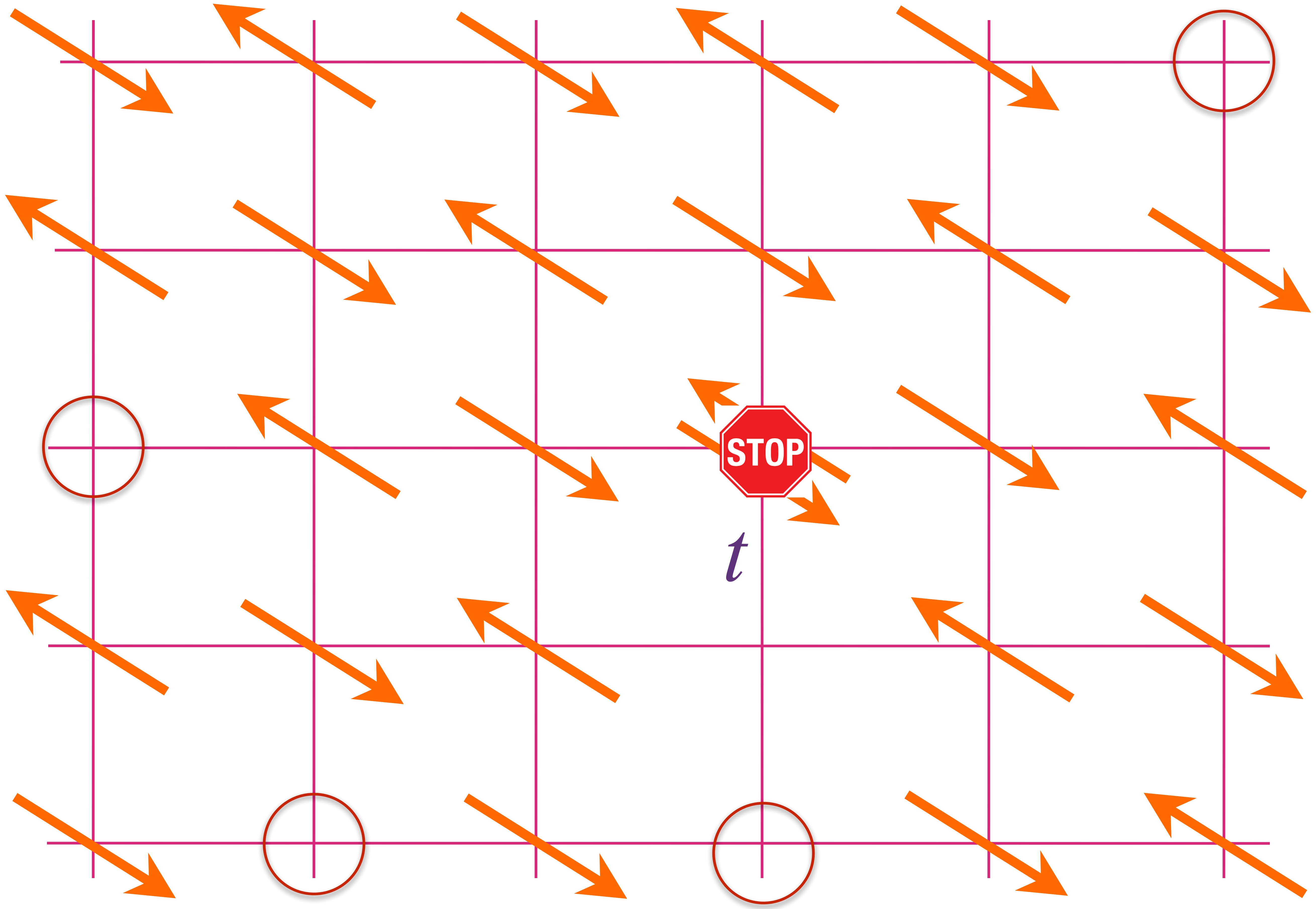


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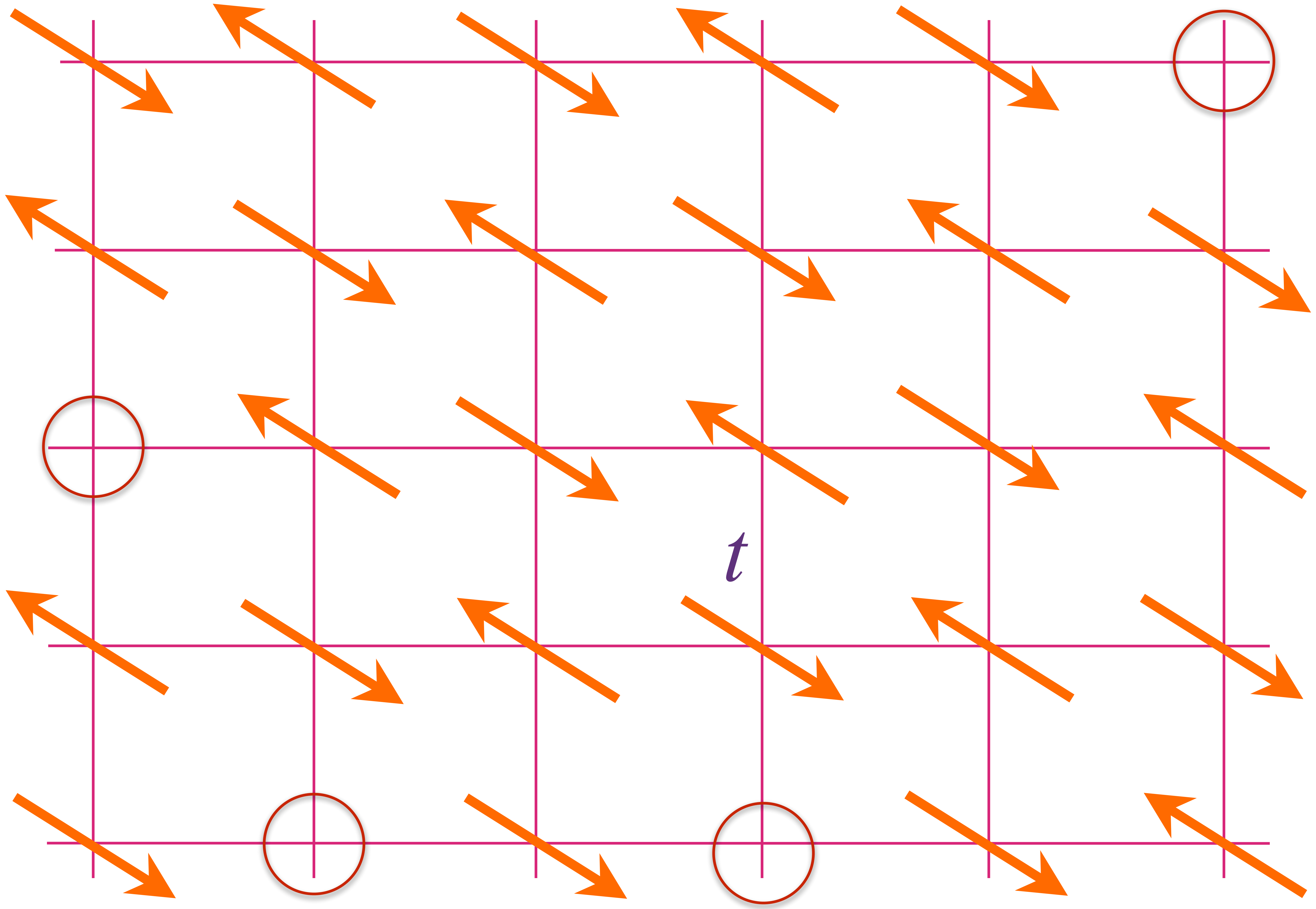


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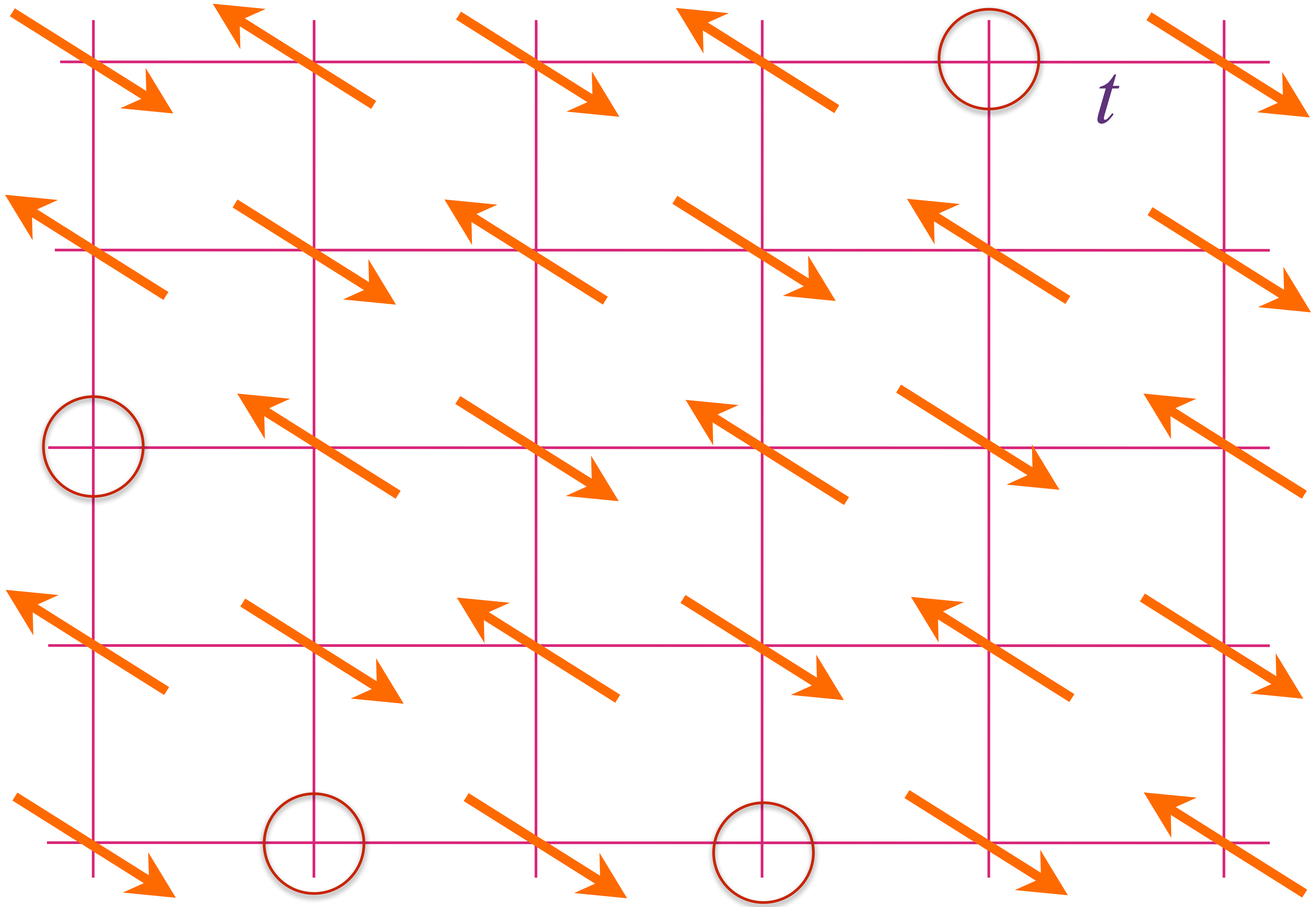


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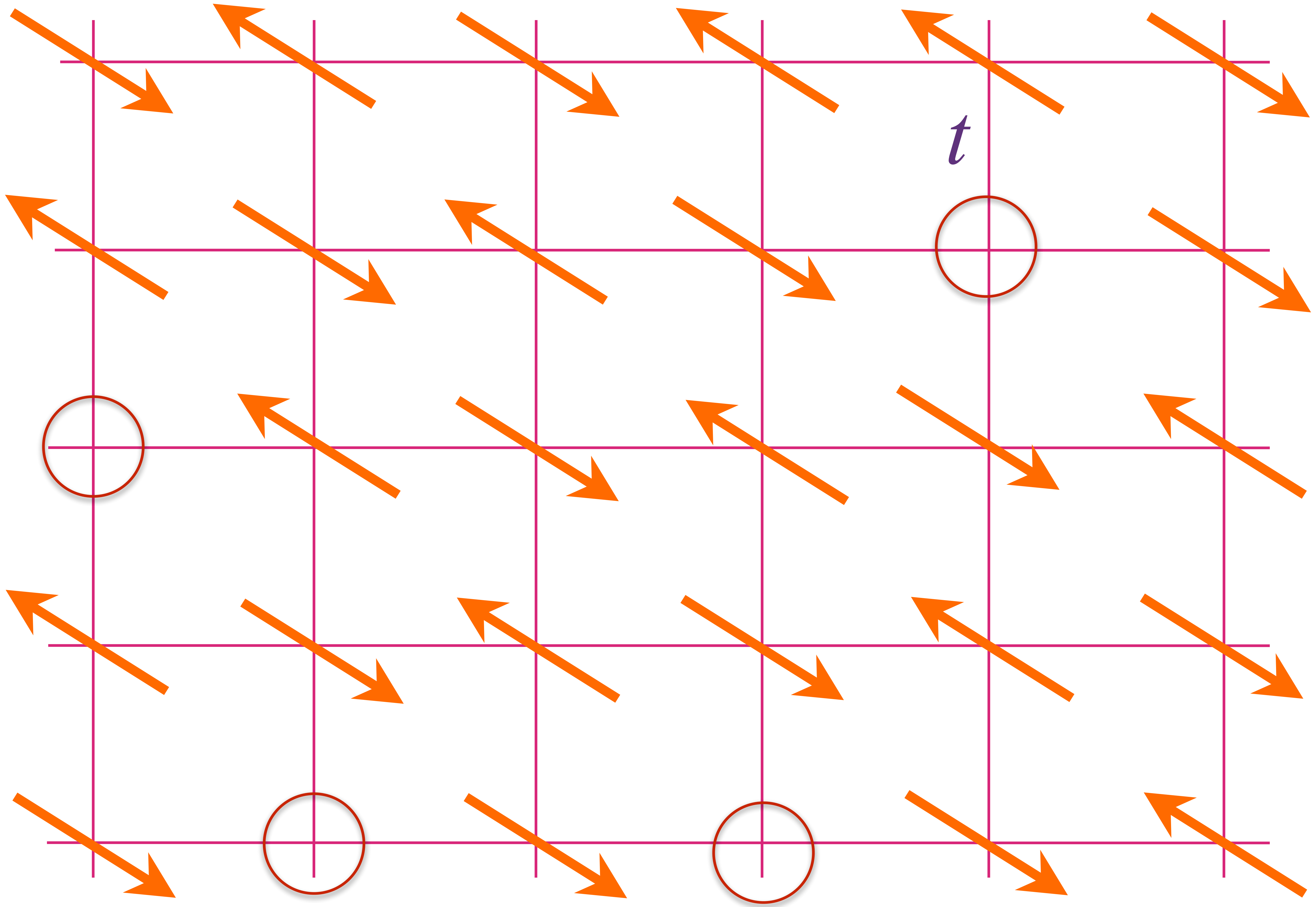


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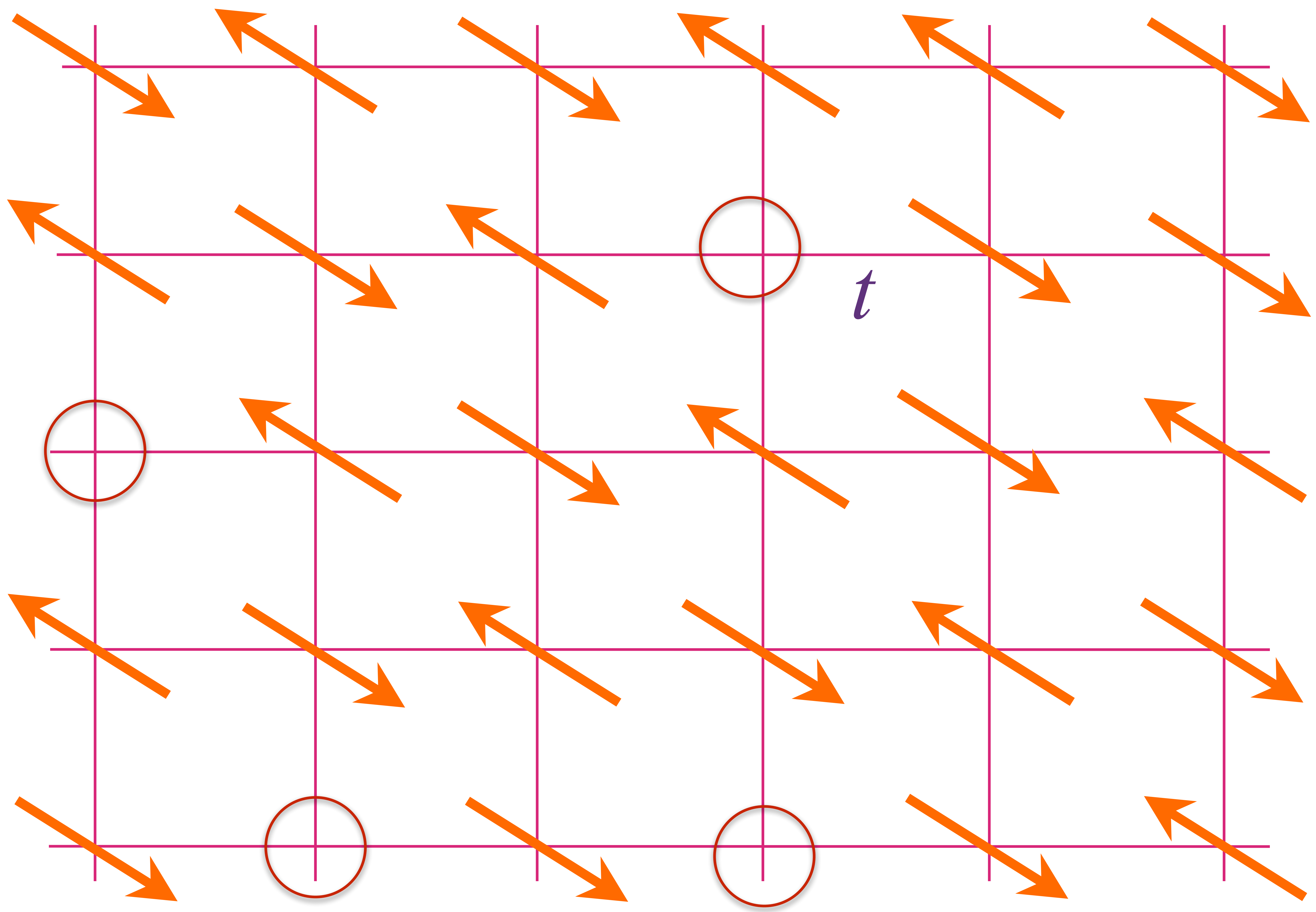


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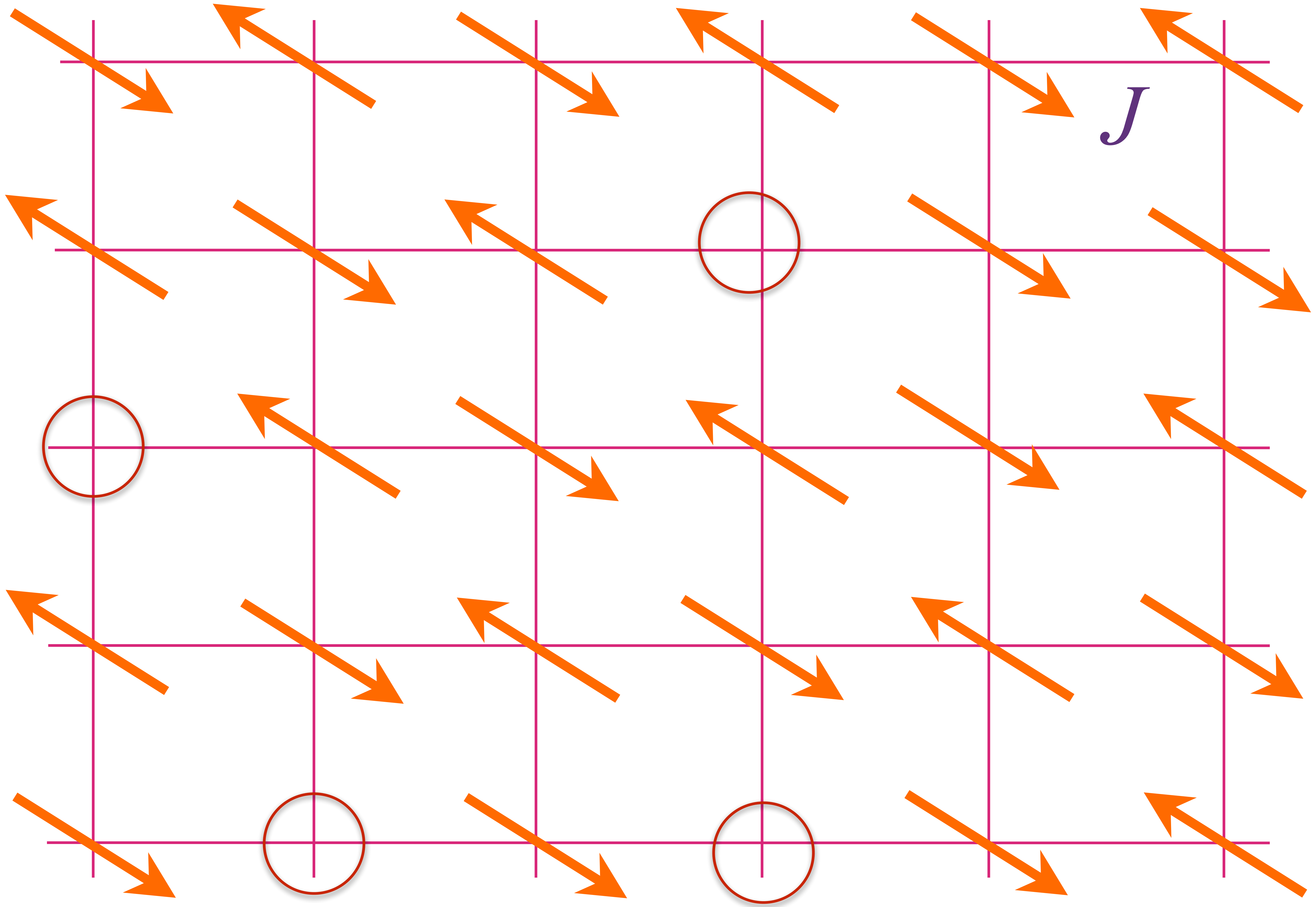


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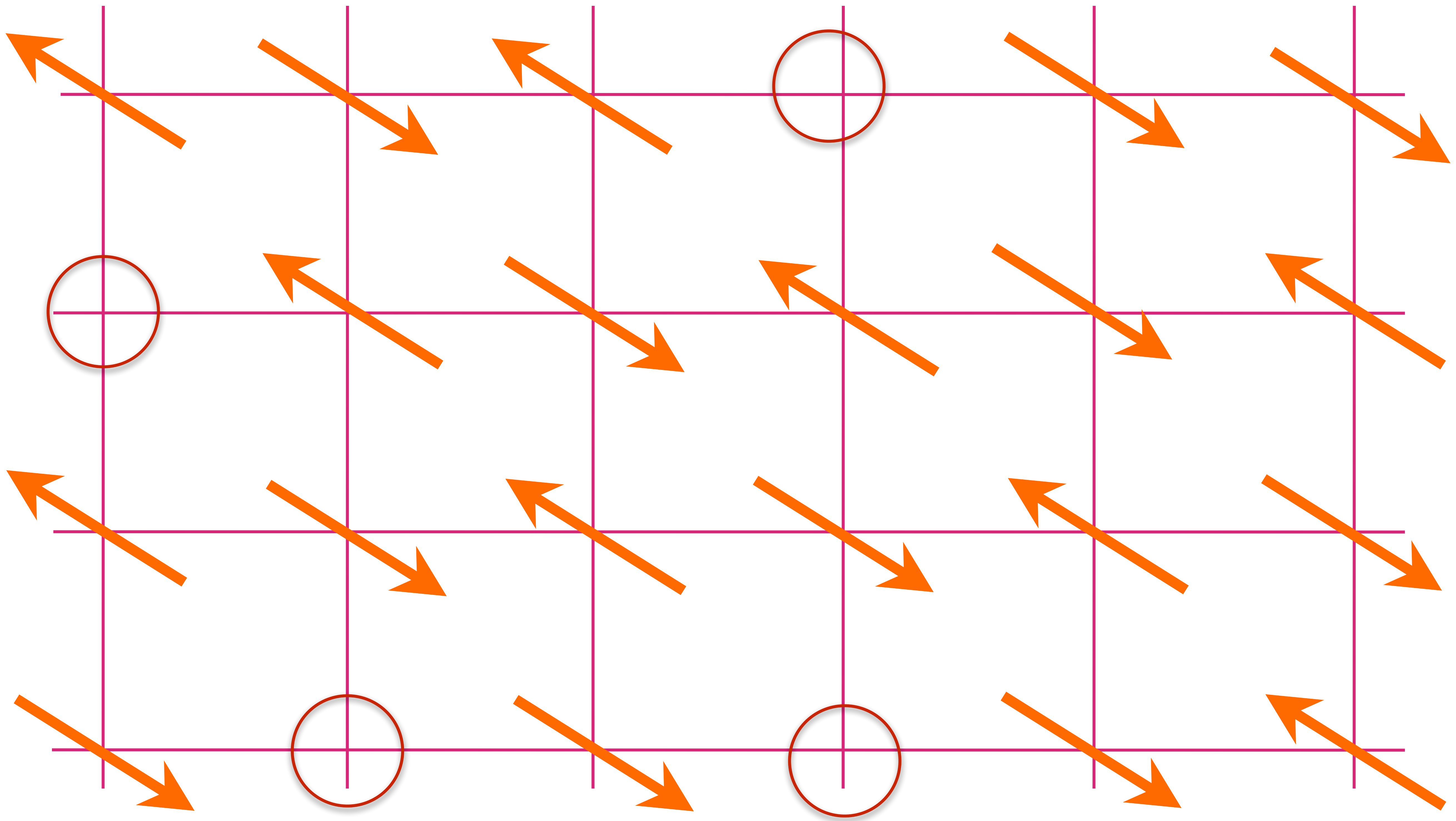

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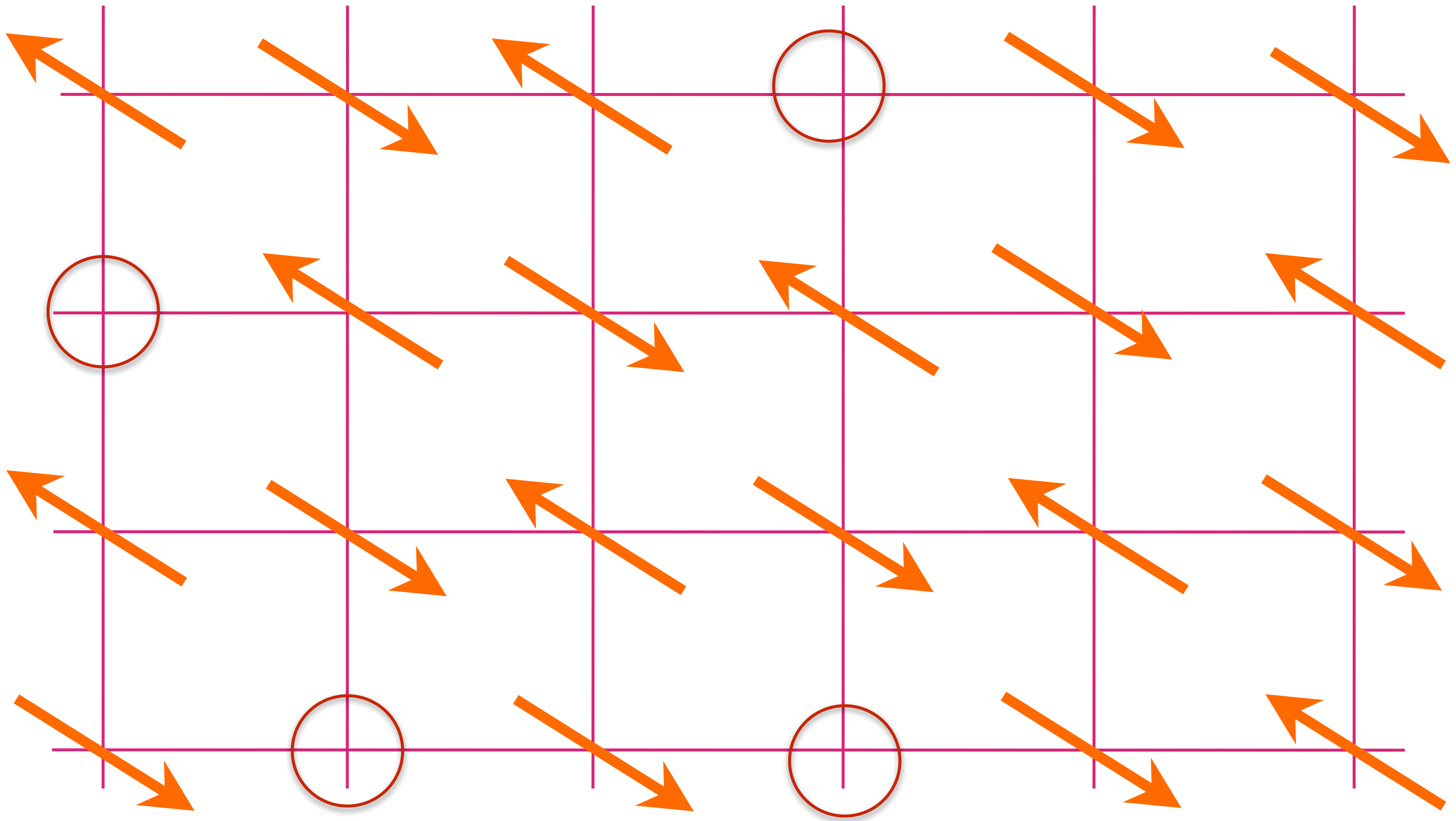

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1. Luttinger volume violation in Kondo lattice models

*The FL* phase and $CeCoIn_5$*

2. Luttinger volume violation a *t-J* model

*Ancilla qubits and a small to large Fermi surface transition*

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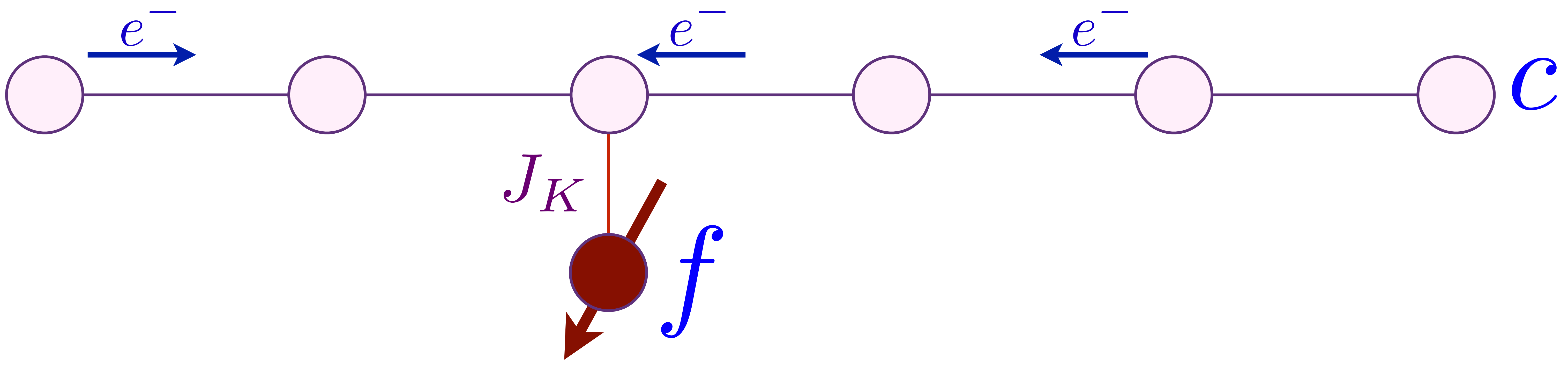

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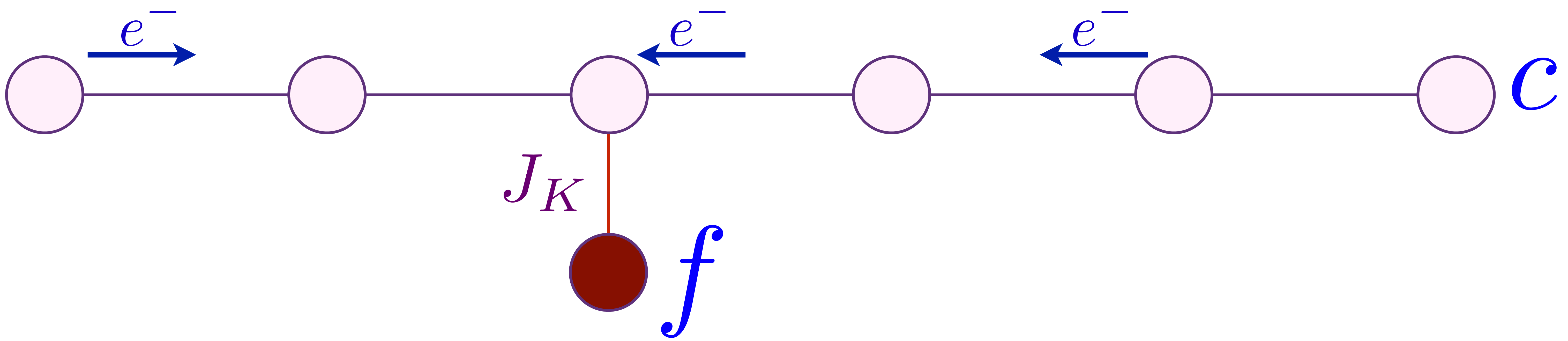


The $c$ electrons ‘Kondo screen’ the $f$ spin at low energies:
The $f$ electron ‘dissolves’ into the Fermi sea.

# Luttinger volume in ***Kondo lattice*** models

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

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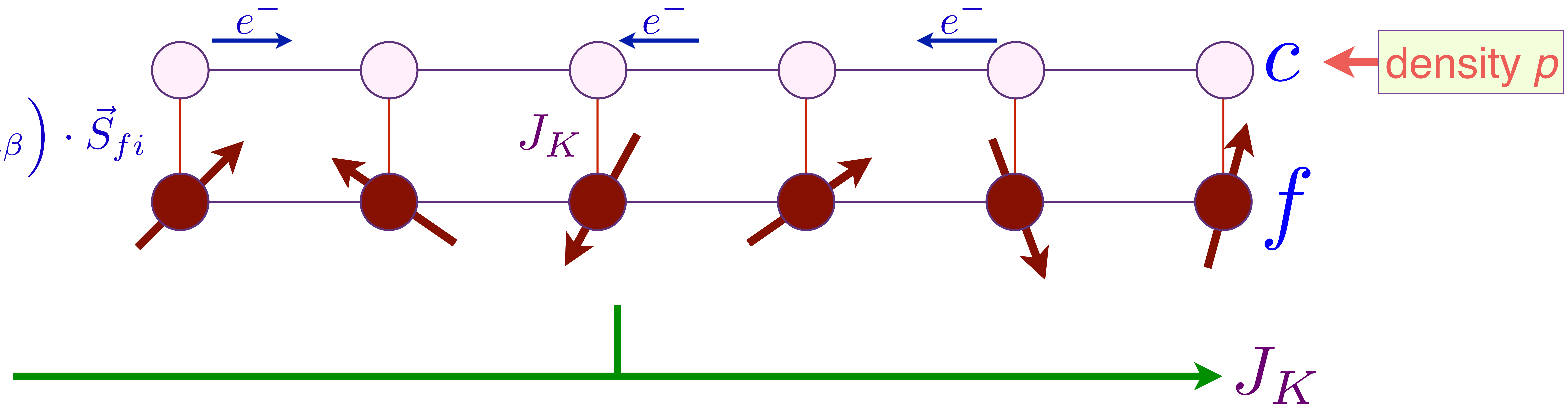

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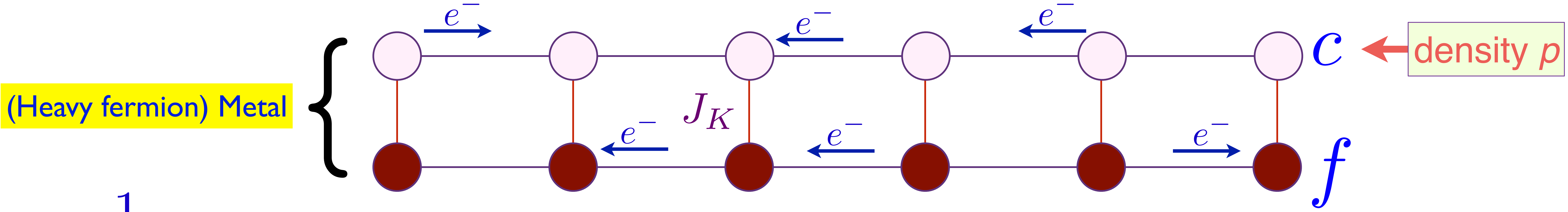
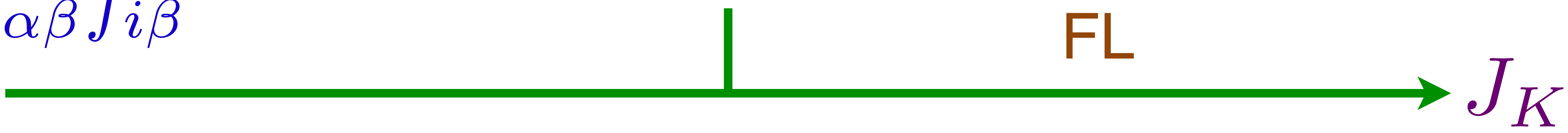



$$\vec{S}_{fi} = \frac{1}{2} f^{\dagger}_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

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Varma, Coleman, Millis, P.A. Lee, Auerbach, Levin, Hae-Young Kee, , Q. Si….

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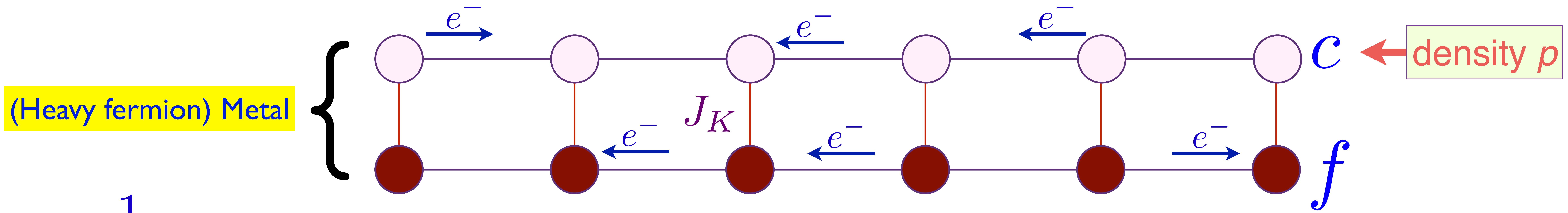


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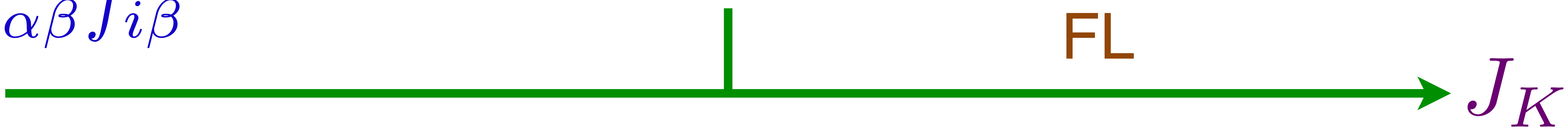


The $c$ electrons 'Kondo screen' the $f$ spins in the FL phase:
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The Fermi surface is <u>large</u>: encloses volume of $1 + p$ electrons.

Varma, Coleman, Millis, P.A. Lee, Auerbach, Levin, Hae-Young Kee, , Q. Si....

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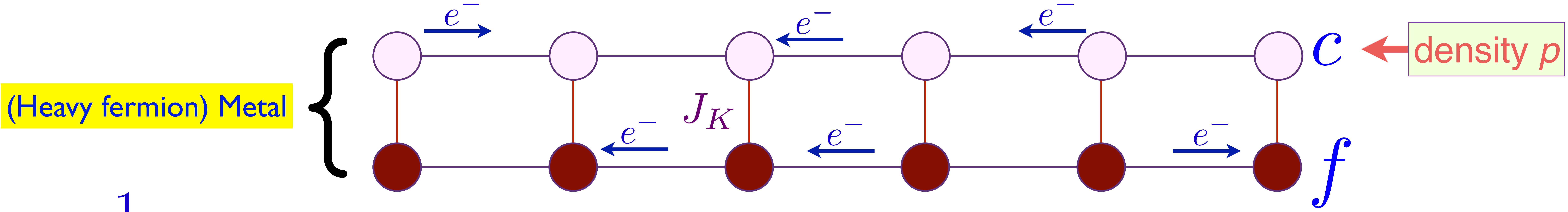


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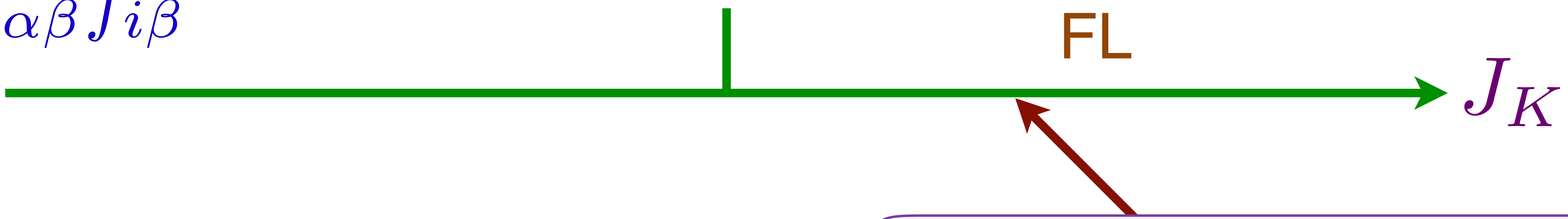


Large Fermi surface of size $1 + p$

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

Varma, Coleman, Millis, P.A. Lee, Auerbach, Levin, Hae-Young Kee, , Q. Si….

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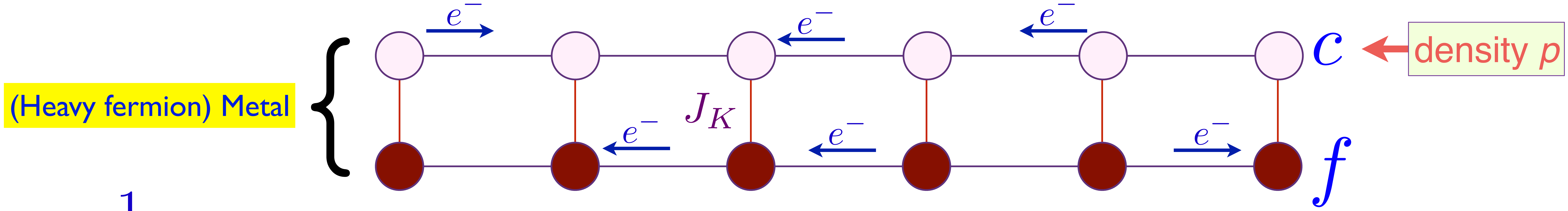


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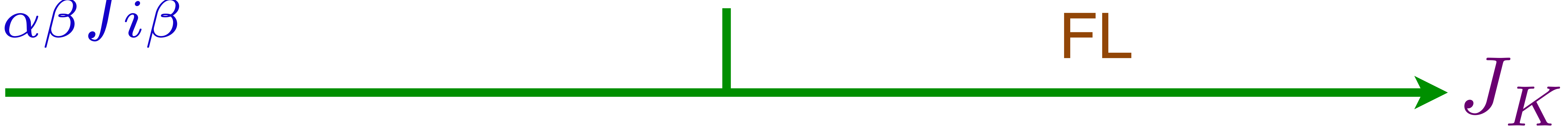
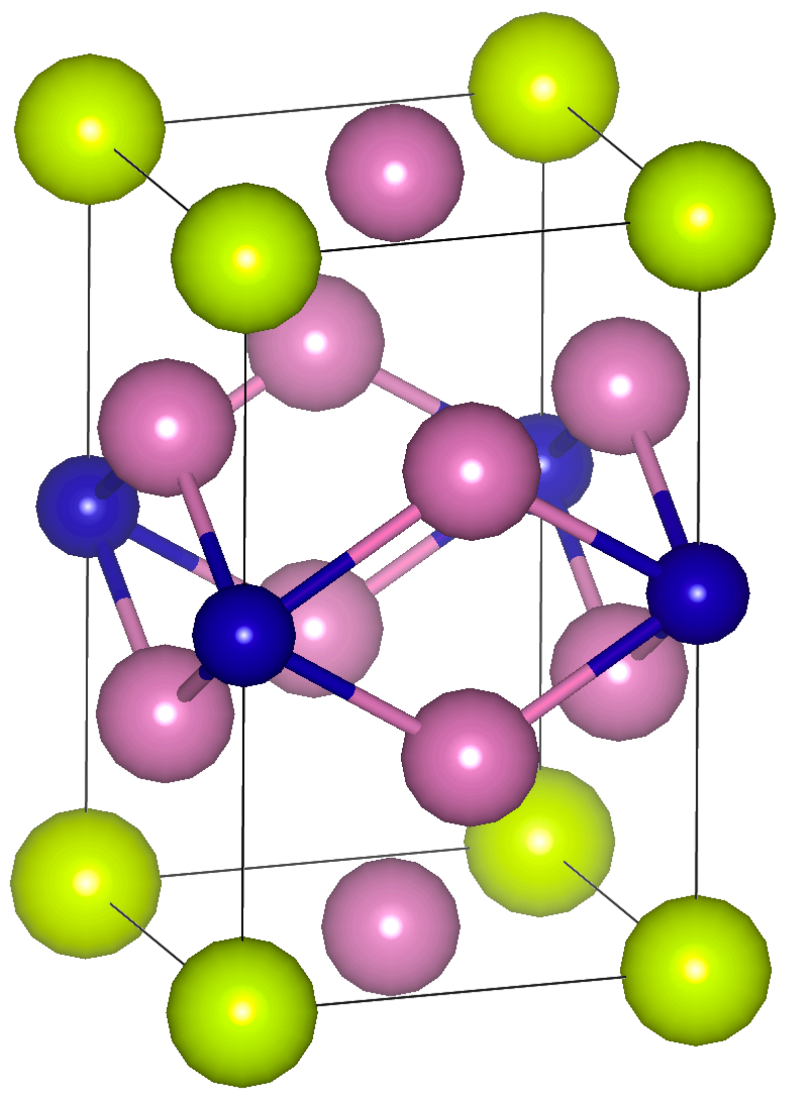


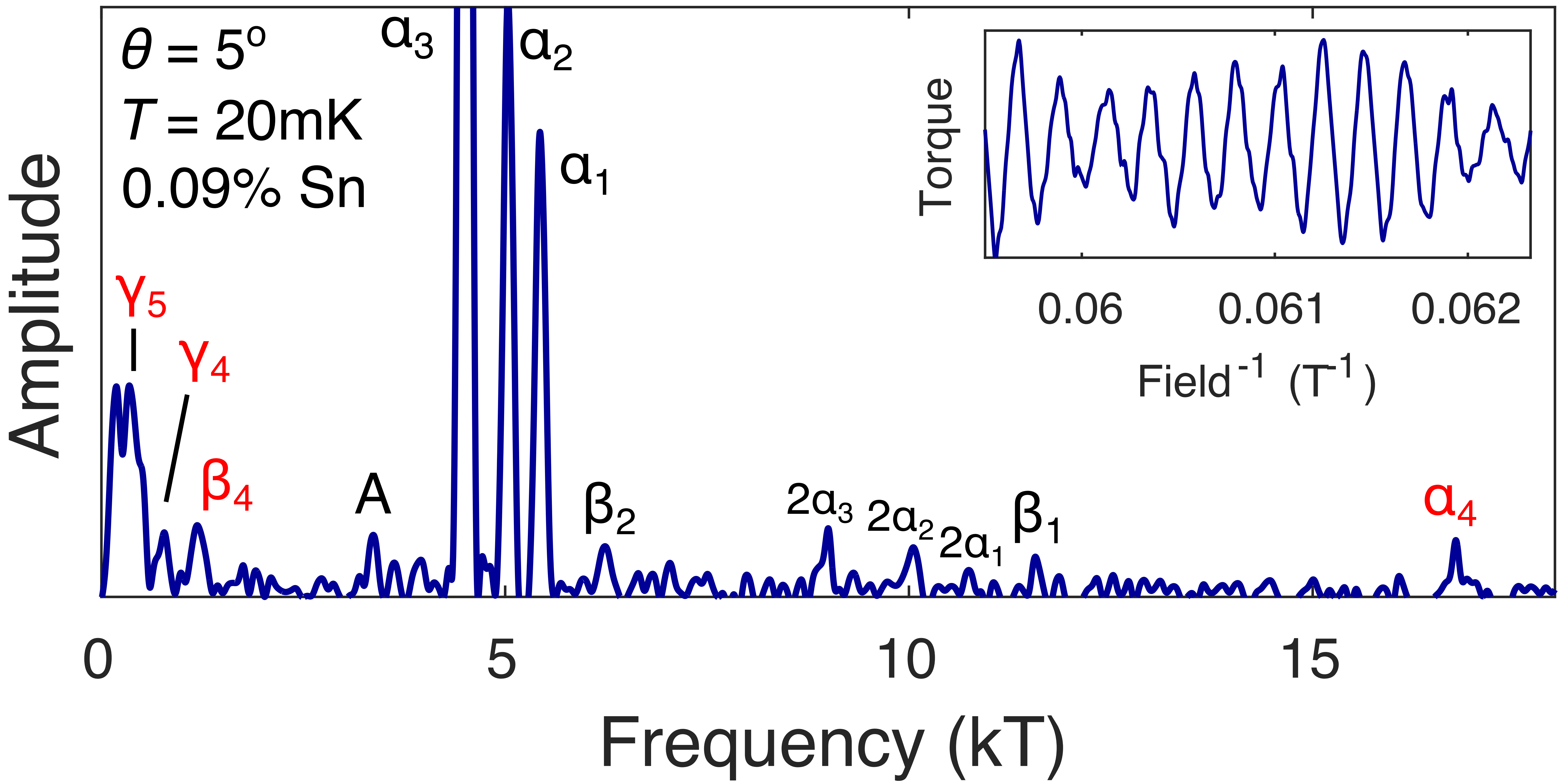

$$\langle c^\dagger_\alpha f_\alpha \rangle \neq 0$$

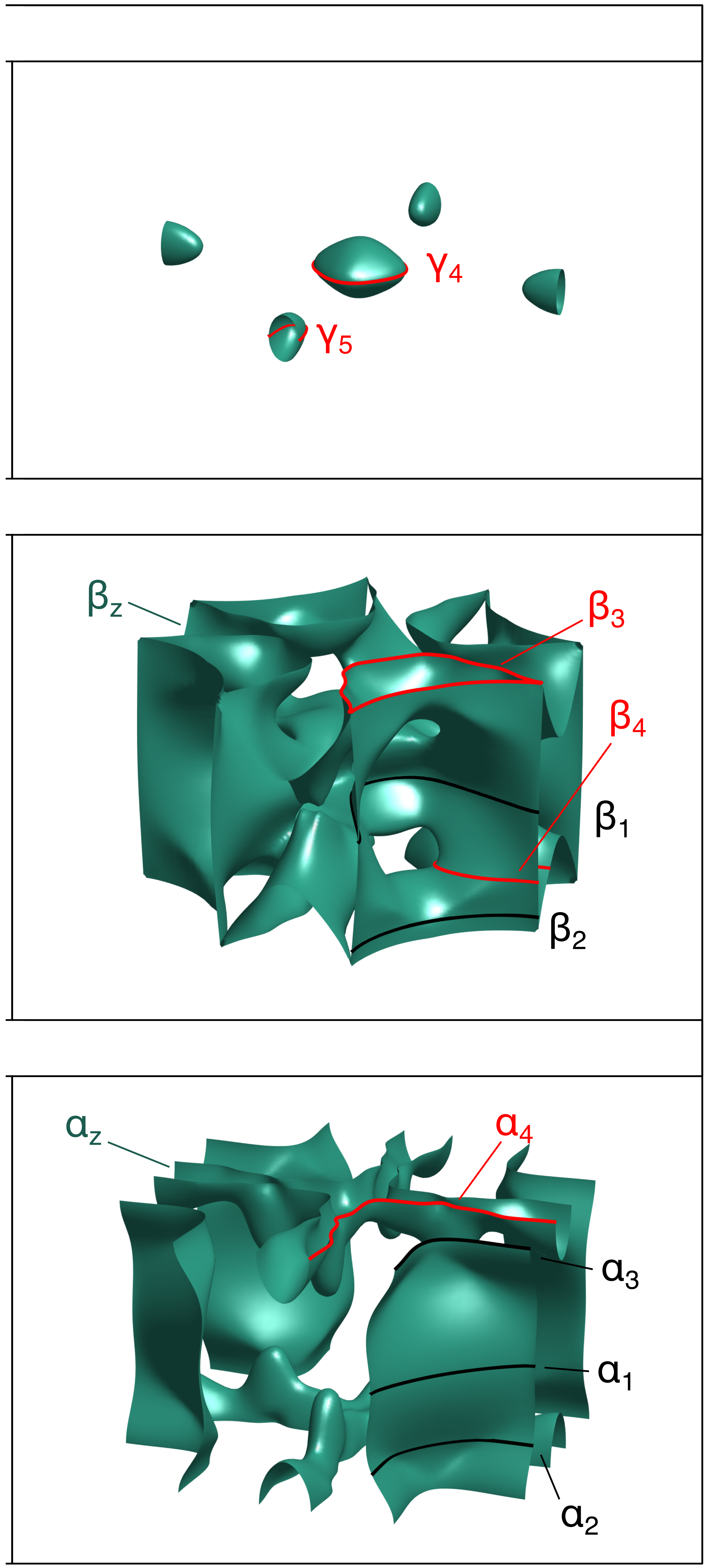
The Kondo lattice model has a gauge symmetry: $f_{i\alpha} \rightarrow e^{i\theta_i} f_{i\alpha}$,
because $\sum_i f^\dagger_{i\alpha} f_{i\alpha} = 1$ for all $i$.
This gauge symmetry is fully broken by a Higgs condensate $\langle c^\dagger_\alpha f_\alpha \rangle$ in the FL phase.

# Large Fermi surface 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





# Luttinger volume violation

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T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)
A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004)

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- When the gauge field is fully Higgsed, the gauge charge effectively becomes identical to the electron number, and there is only a single Luttinger theorem for *all* electrons: *i.e.* a large Fermi surface.

T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)
A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004)

# Luttinger volume violation

- The Luttinger volume can be violated in a metal when there is a deconfined emergent gauge field and fractionalized excitations *i.e.* 'bulk topological order'.

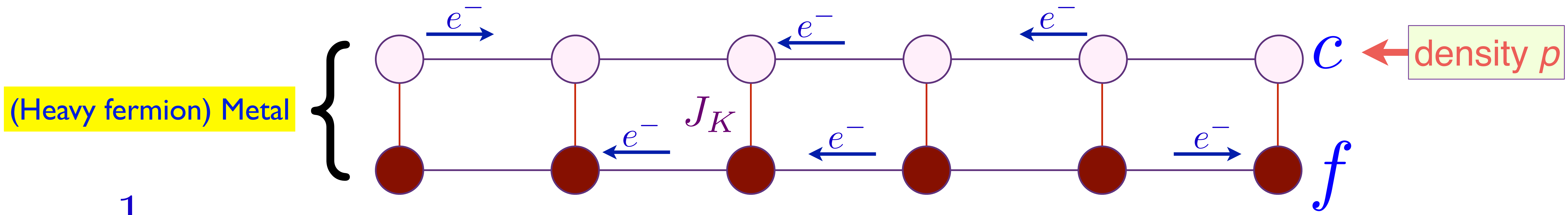
- When the gauge field is fully Higgsed, the gauge charge effectively becomes identical to the electron number, and there is only a single Luttinger theorem for *all* electrons: *i.e.* a large Fermi surface.

- When the gauge field is deconfined, there are separate Luttinger anomalies for the gauge and global charges. In this manner with obtain the FL* phase: a metallic phase with a Fermi surface of Fermi-liquid-like electronic quasiparticles, enclosing a non-Luttinger small volume.

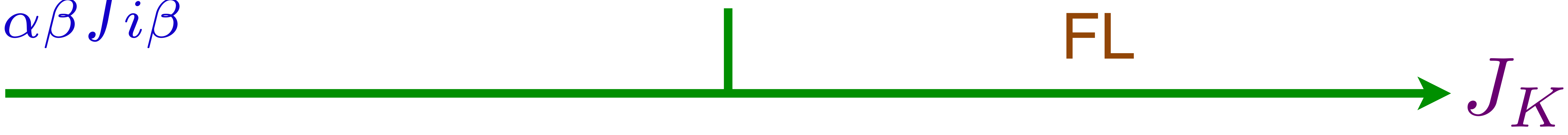
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)
A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004)

# Luttinger volume in ***Kondo lattice*** models

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




$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

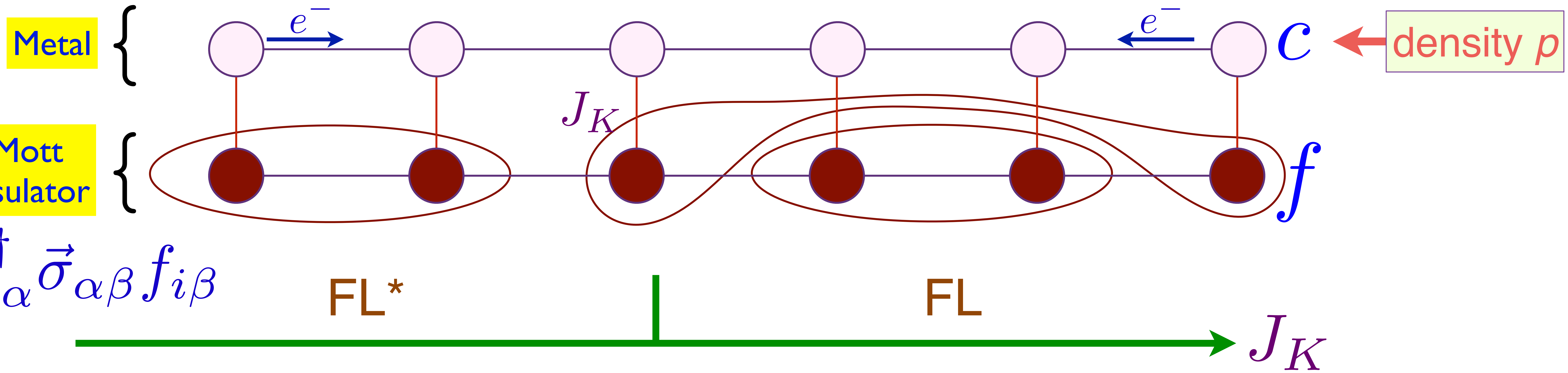



$$\langle c^\dagger_\alpha f_\alpha \rangle \neq 0$$

The Kondo lattice model has a gauge symmetry: $f_{i\alpha} \to e^{i\theta_i} f_{i\alpha}$,
because $\sum_i f^\dagger_{i\alpha} f_{i\alpha} = 1$ for all $i$.
This gauge symmetry is fully broken by a Higgs condensate $\langle c^\dagger_\alpha f_\alpha \rangle$ in the FL phase.

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

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




$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

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This gauge symmetry is unbroken in the FL* phase, and there are gauge-charged spin excitations, and an emergent gauge field.


S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)
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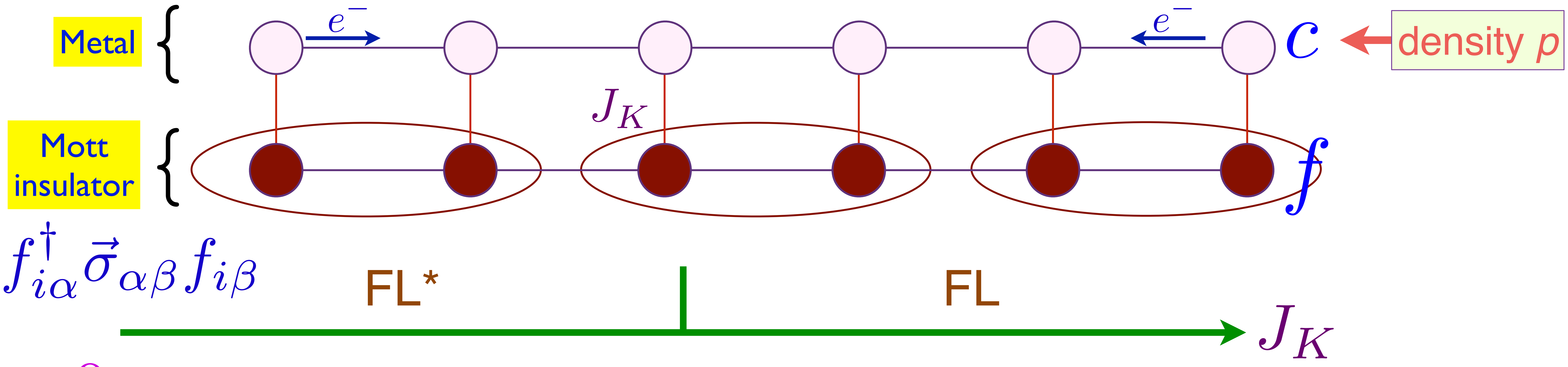


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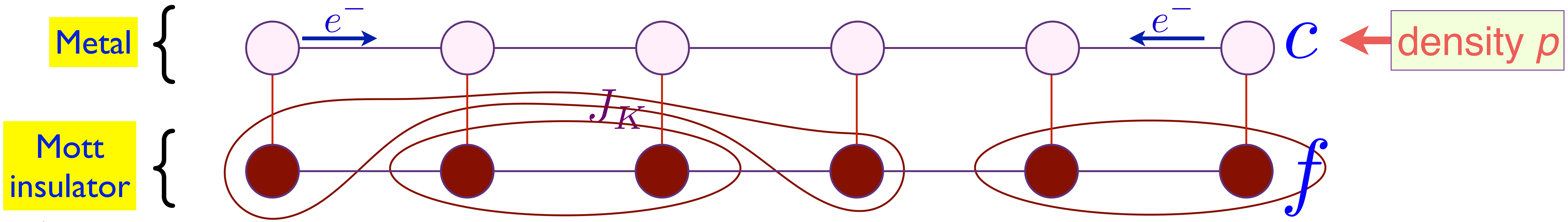


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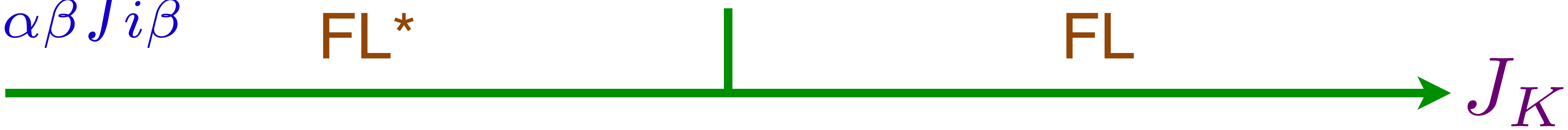


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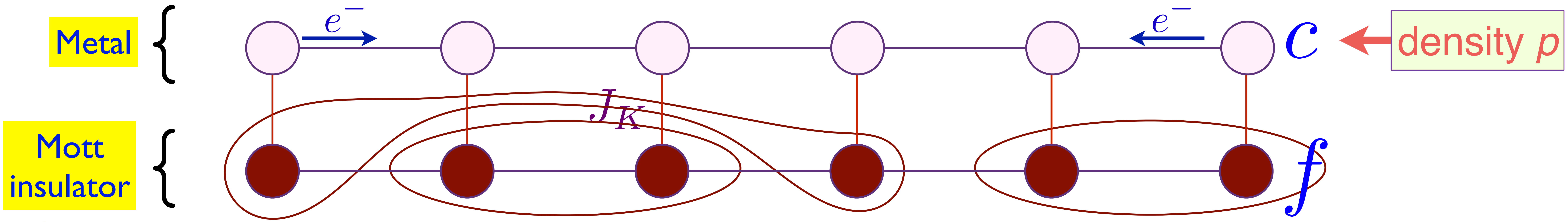


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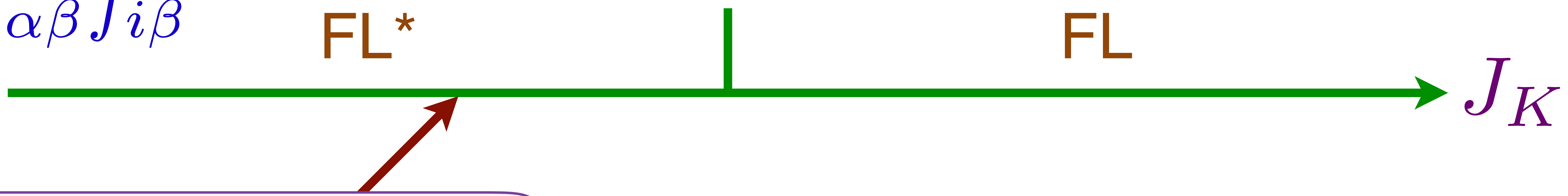


Small Fermi surface of size $p$

$|\Phi\rangle =$ [Projection onto one $f$ per site]
$\bowtie$ $|$Slater determinant of $f\rangle$
$\otimes$ $|$Slater determinant of $c\rangle$

S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)
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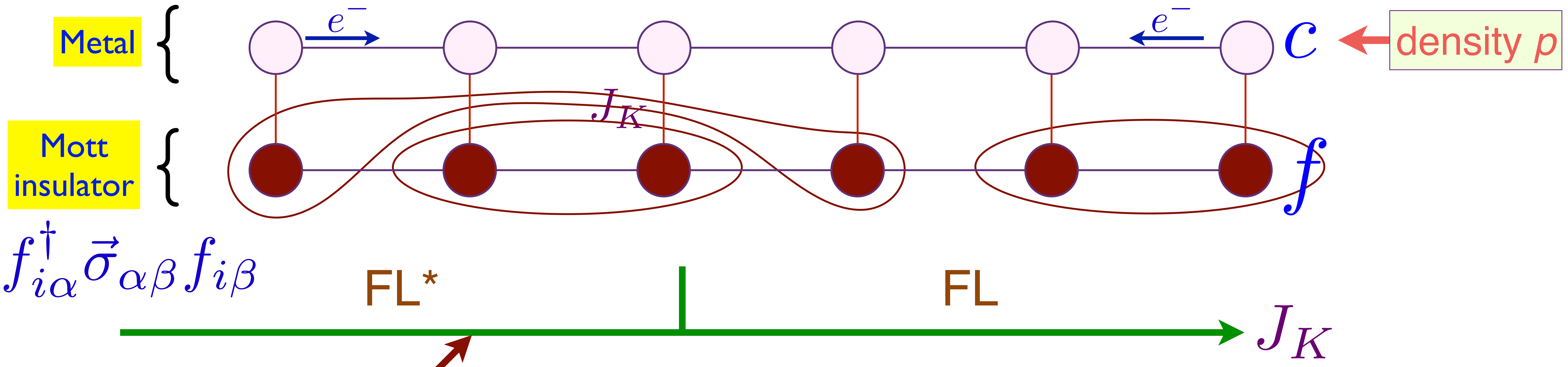
V.I. Anisimov, I.A. Nekrasov, D.E. Kondakov, T.M. Rice & M. Sigrist, EPJB **25**, 191 (2002)
L. de' Medici, A. Georges, S. Biermann, PRB **72**, 205124 (2005)

Kondo-breakdown or 'selective Mott' transition




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

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A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004)

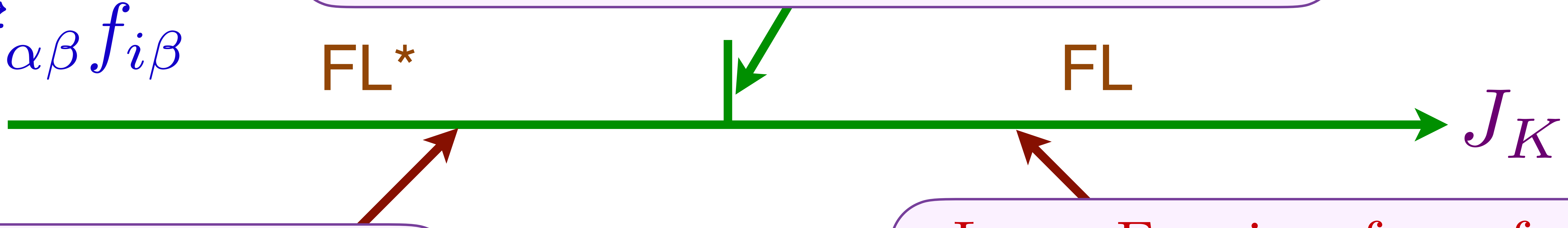
# Metal-metal transitions in ***Kondo lattice*** models

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

Kondo-breakdown or 'selective Mott' transition

U(1) gauge theory of a
'hybridization-Higgs' boson $b \sim f_\alpha^\dagger c_\alpha$
which condenses on the
'Large Fermi surface' side.

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




Small Fermi surface of size $p$

Deconfined gauge fields and
fractionalized spin excitations

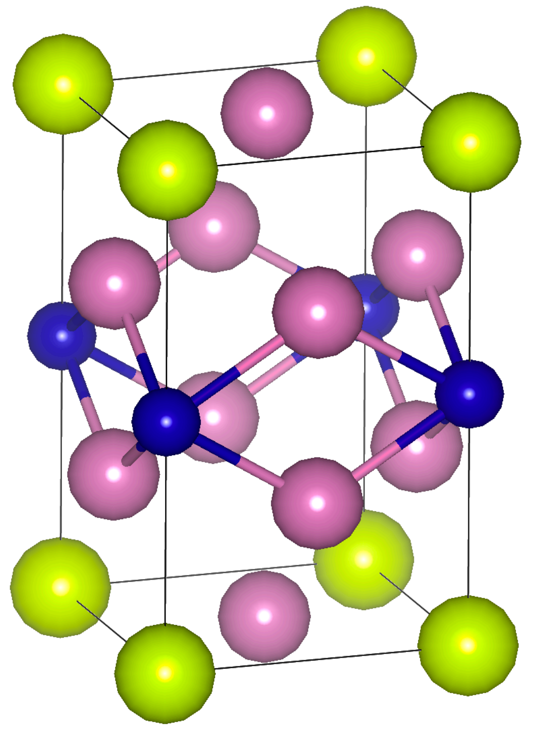
Large Fermi surface of size $1 + p$

All gauge symmetry is Higgsed.
No fractionalization: excitations are
electron-like or composites.

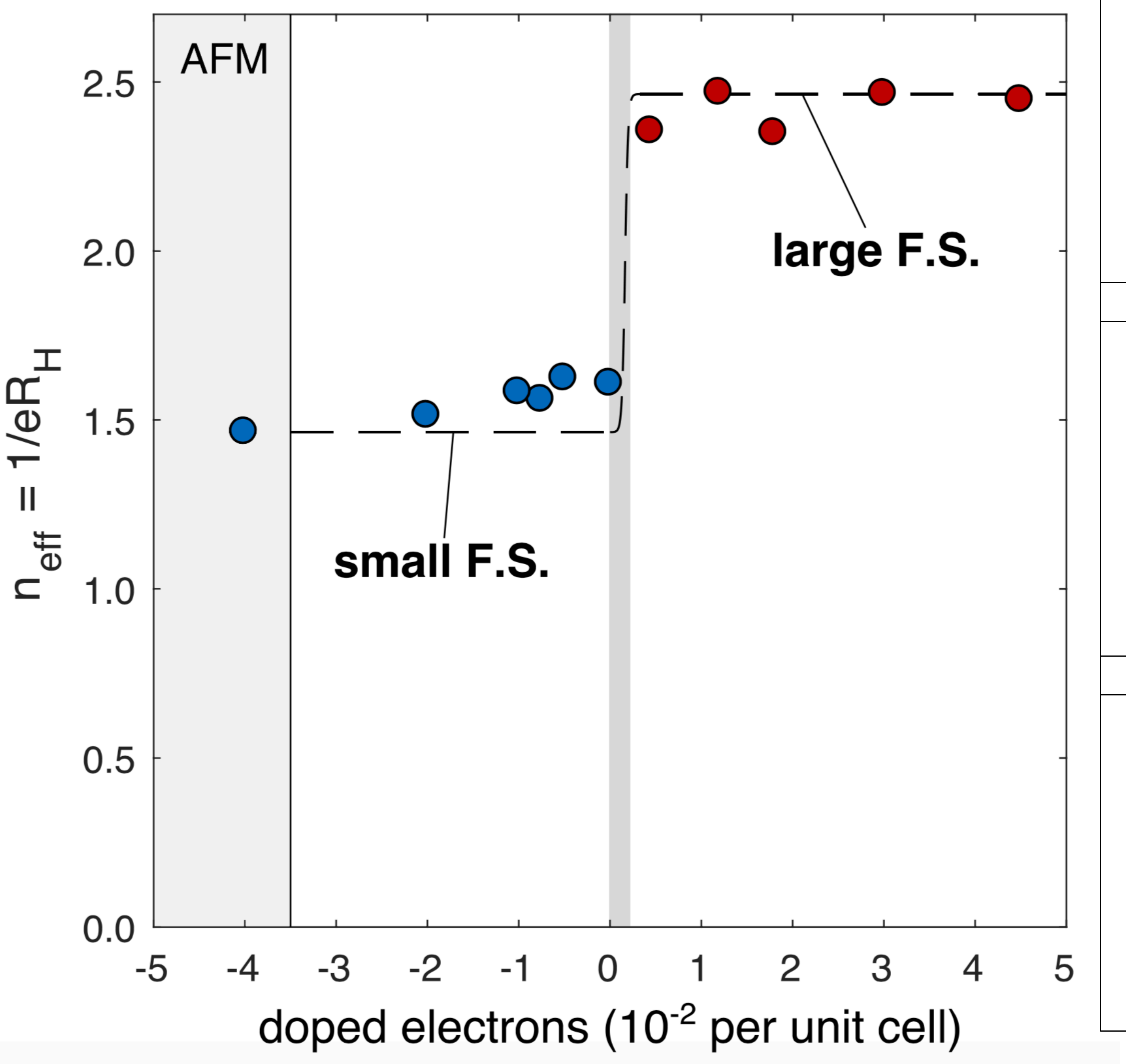
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)

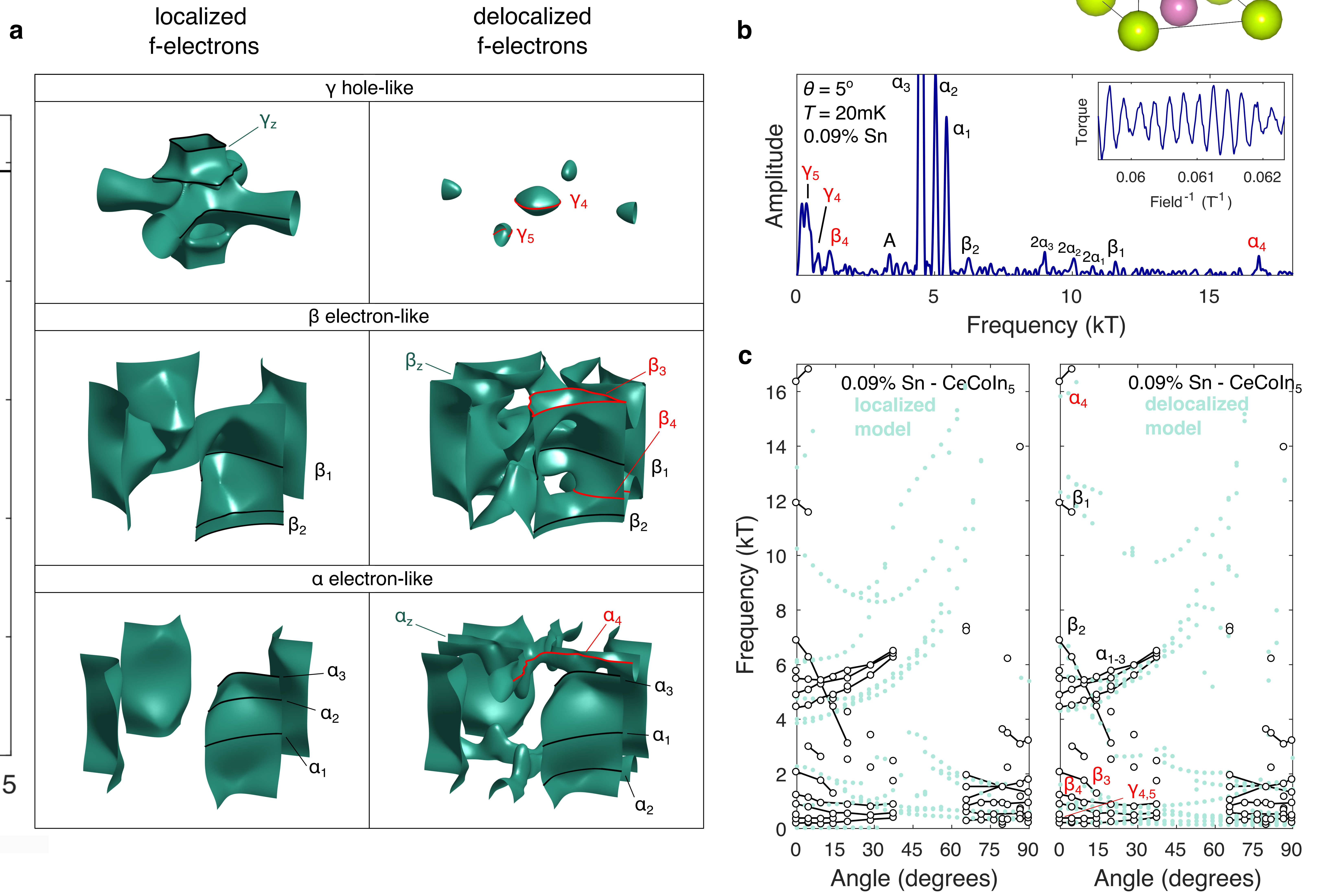
# Evidence for freezing of charge degrees of freedom across a critical point in $CeCoIn_5$

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



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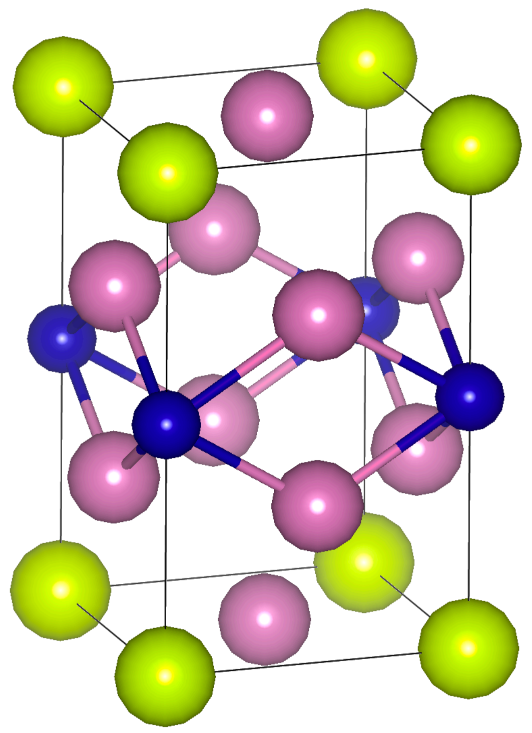
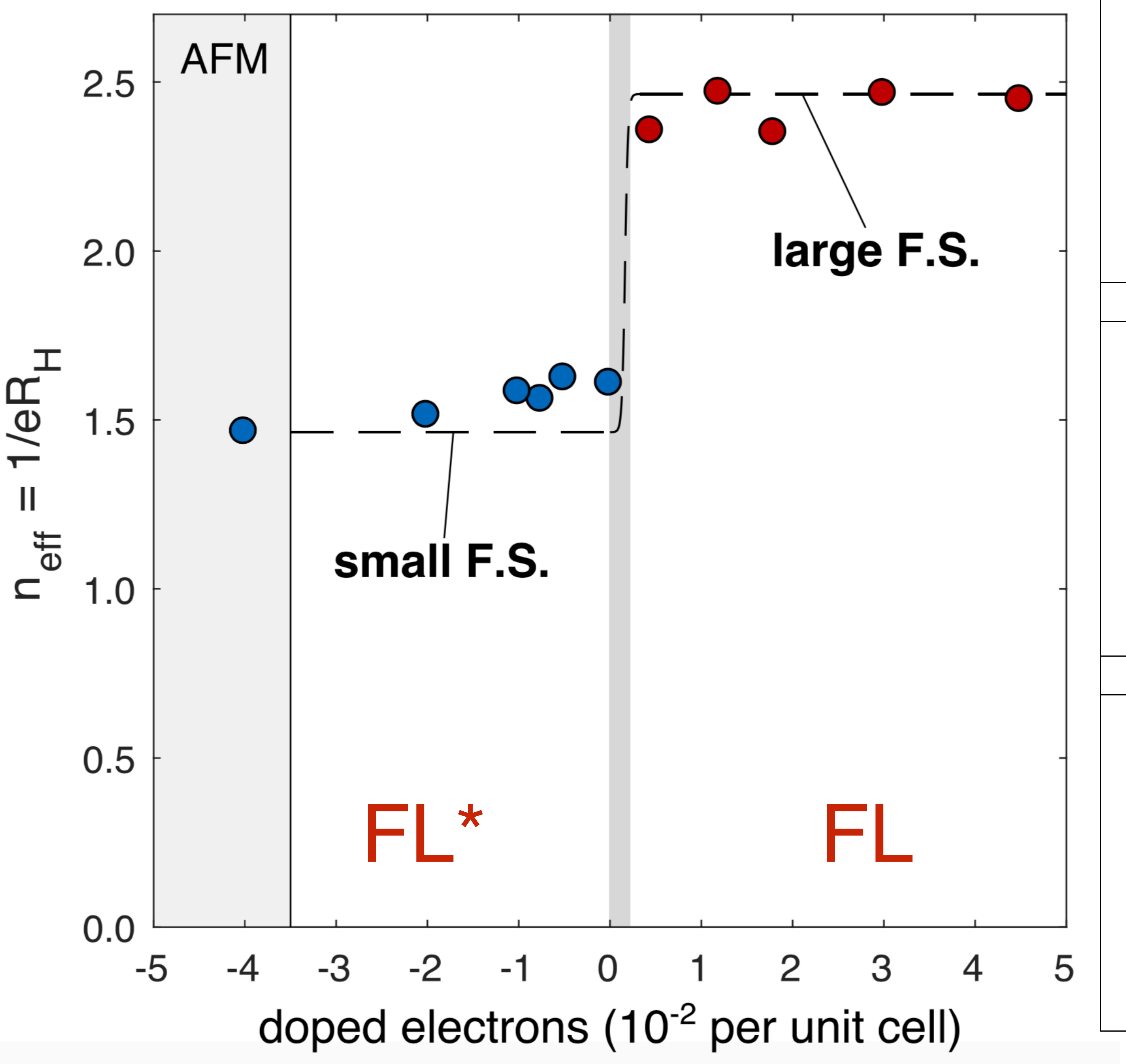
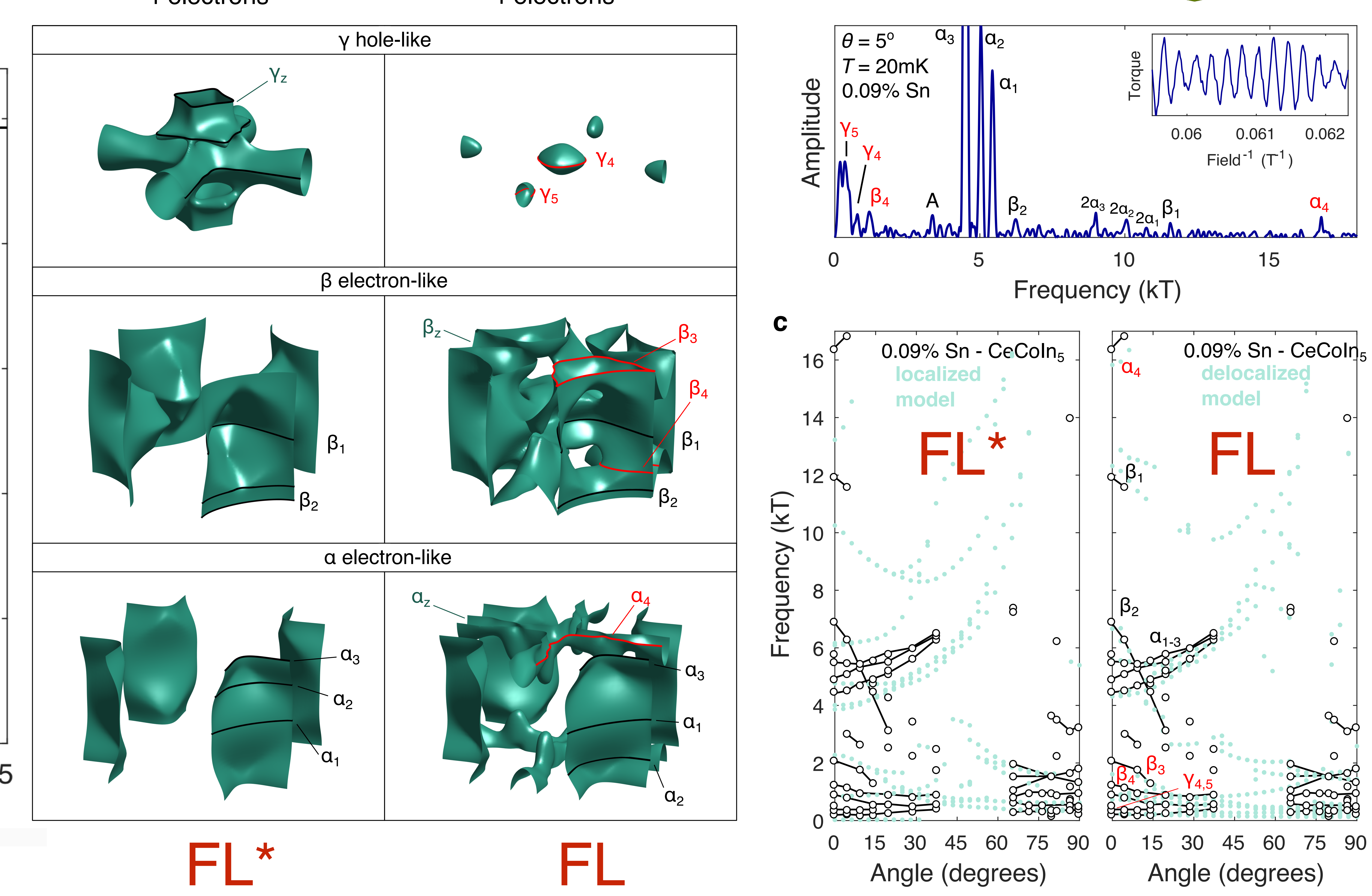




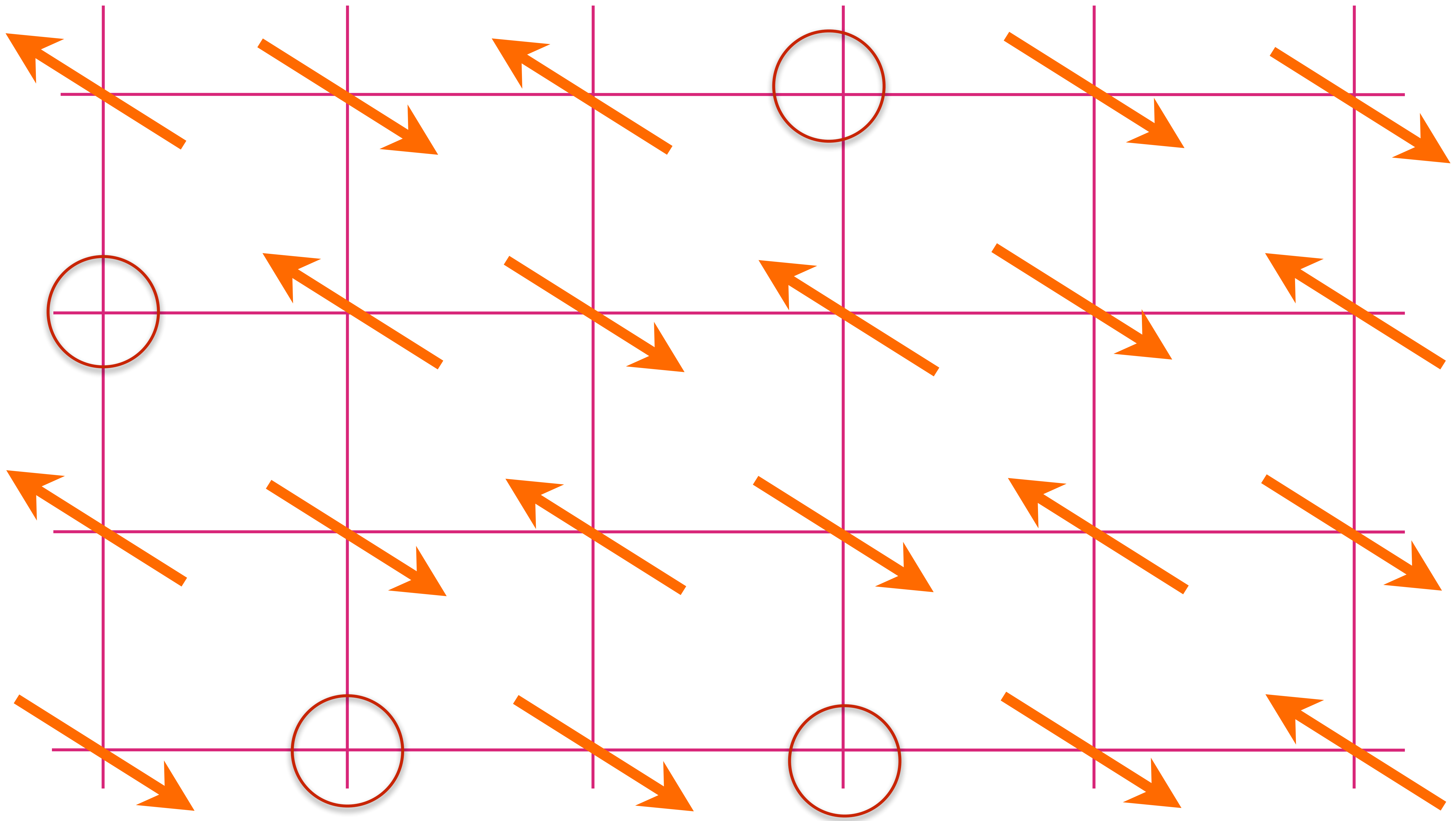
1. Luttinger volume violation in Kondo lattice models

*The FL* phase and* $CeCoIn_5$

2. Luttinger volume violation a *t-J* model

*Ancilla qubits and a small to large Fermi surface transition*

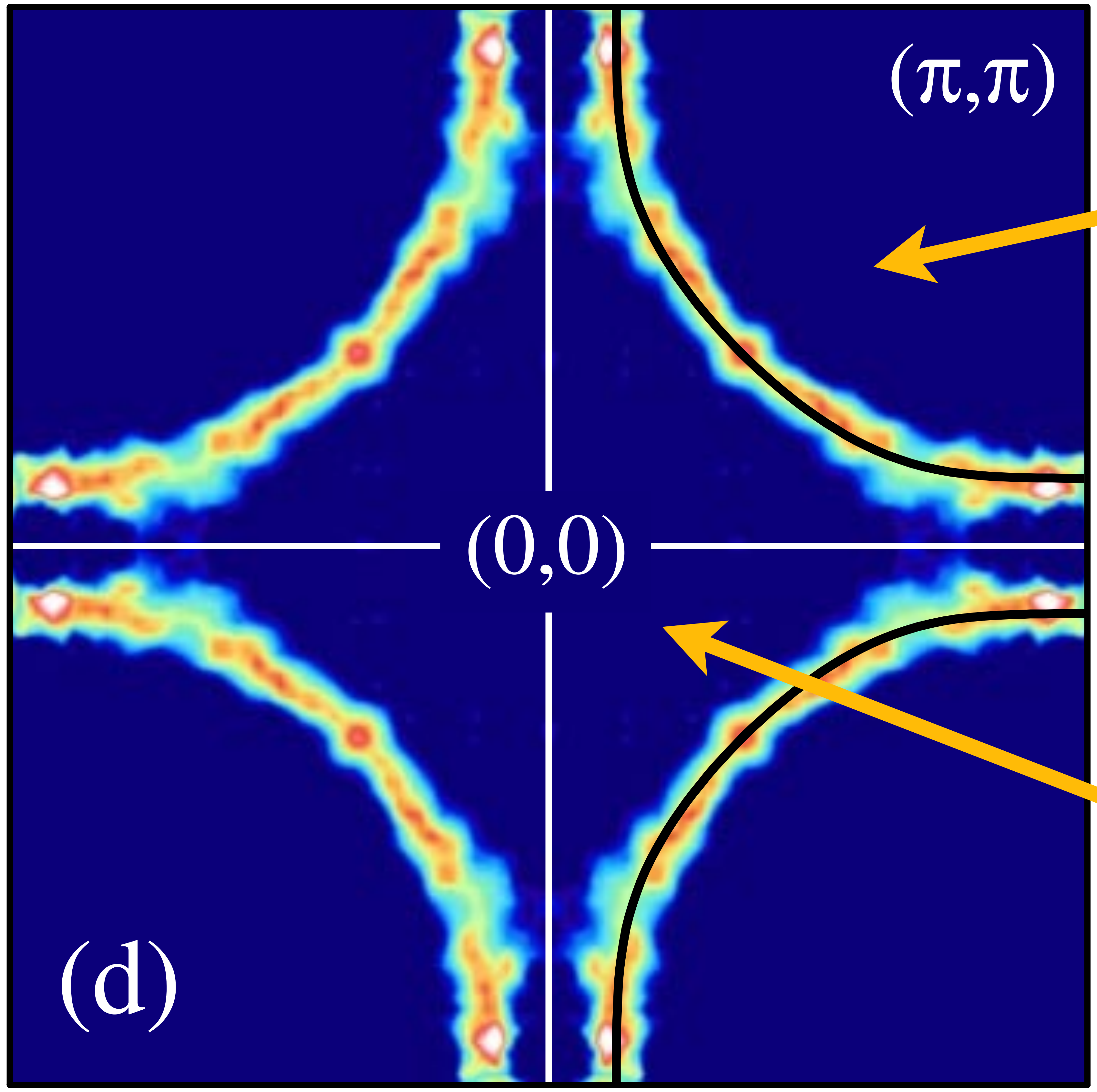
- What happens if the repulsive interaction between electrons becomes essentially infinite on all or some sites ?
- In the cuprates, all Cu sites prohibit more than one electron: the *t-J* model.
- Luttinger's theorem states the Fermi surface should have a <u>large</u> size <u>1-p</u> electrons (equivalent to 1+p holes).
- Or should there be a <u>small</u> Fermi surface of size p holes ?



Antiferromagnet doped with hole density $p$

$p$ mobile holes in a background of fluctuating spins

# Momentum-space view at large $p$




$1+p$ holes

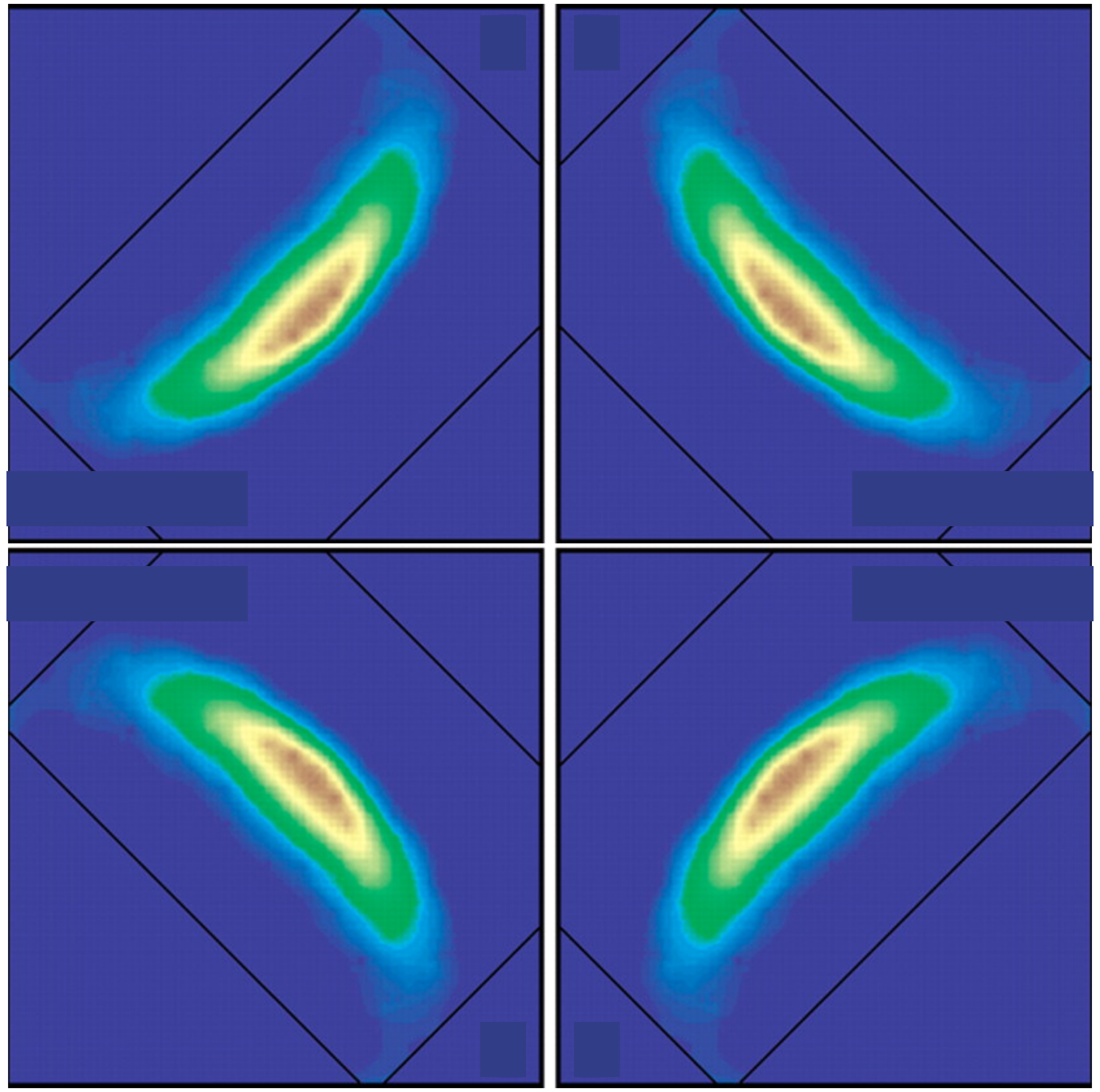
$1-p$ electrons

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

$1+p$ 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)

# Momentum-space view at small $p$



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

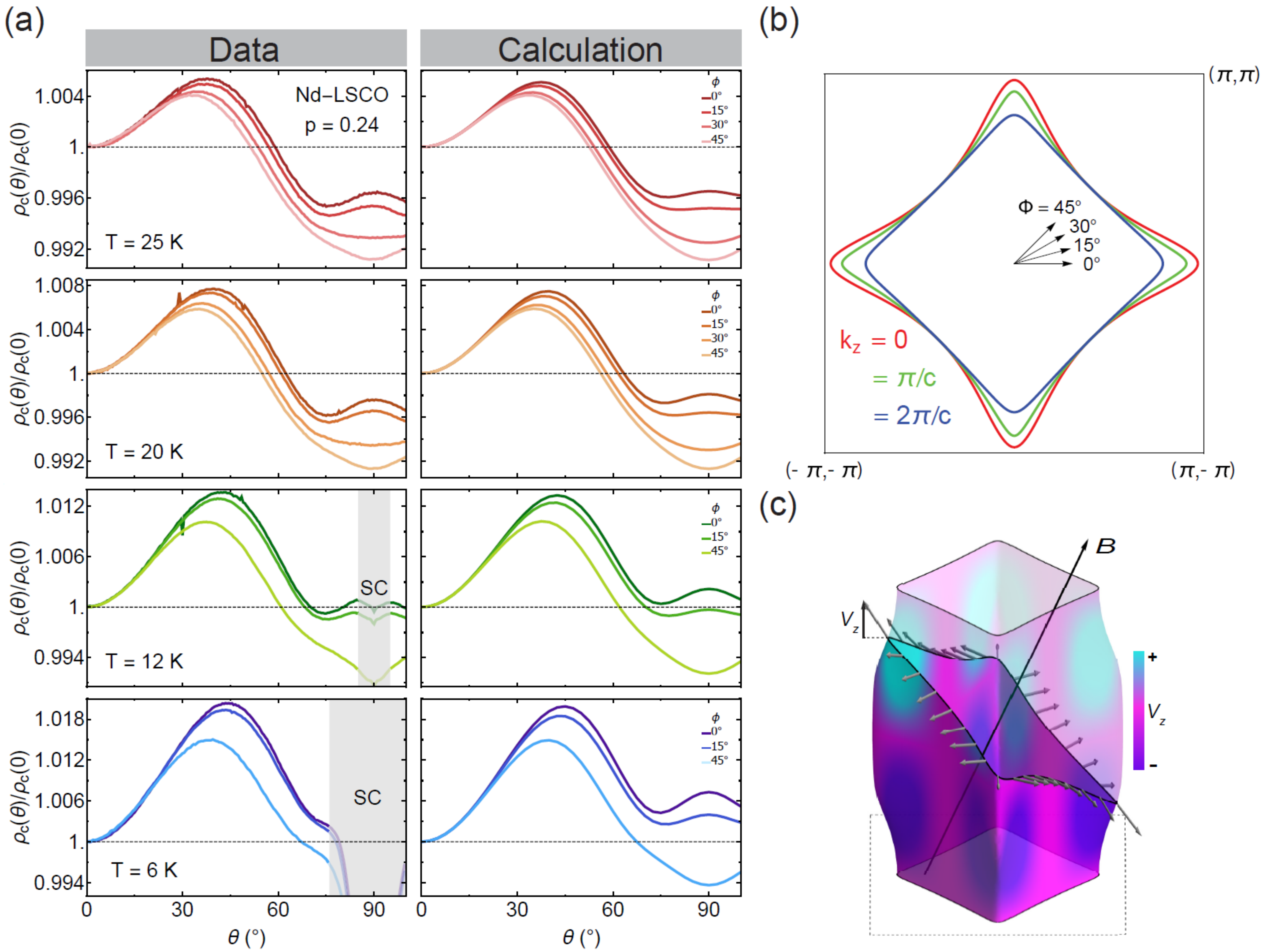
*"Fermi arcs"*

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)

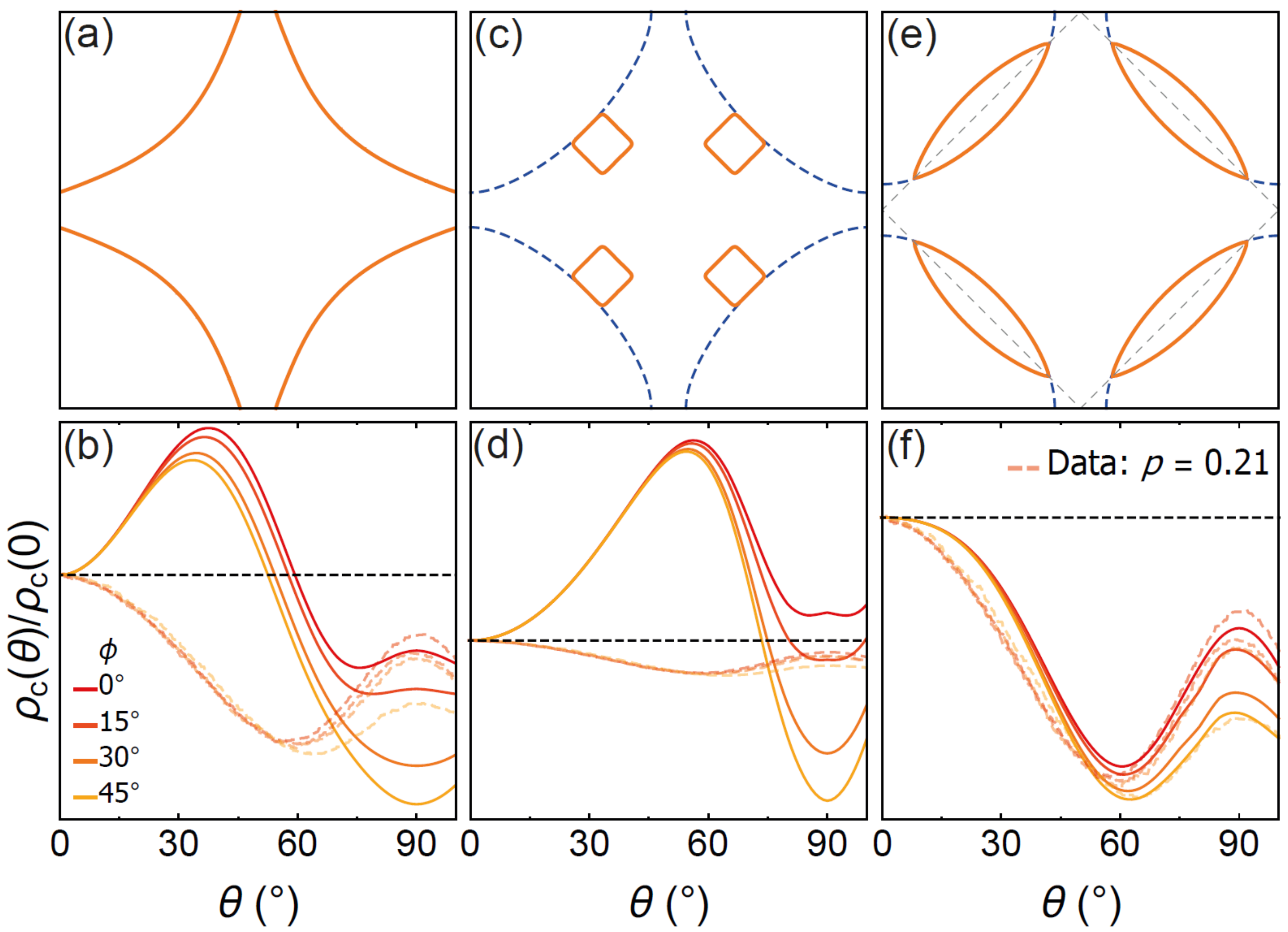
# Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

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

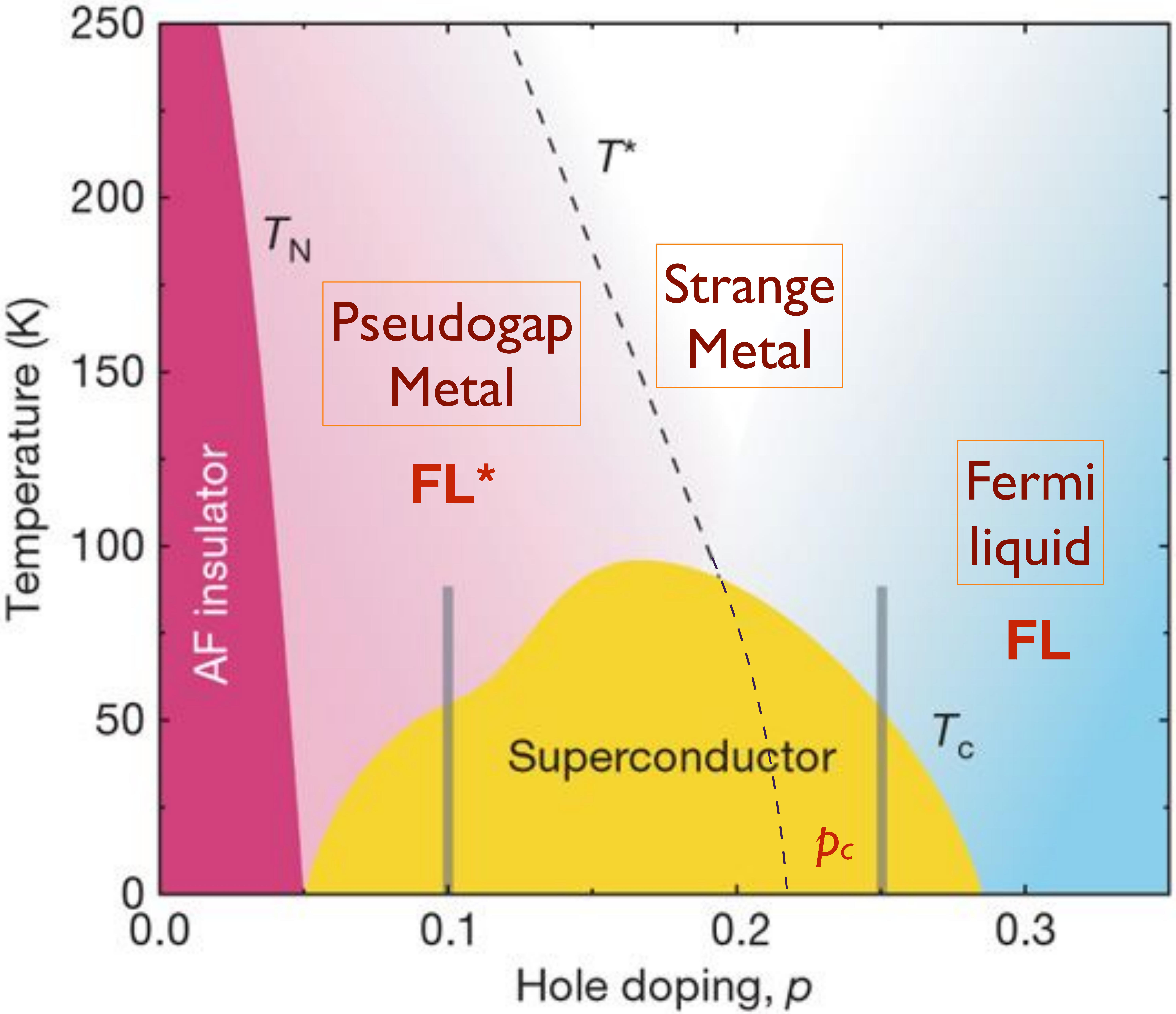
We use angle-dependent magnetoresistance (ADMR) to measure the Fermi surface of the cuprate $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$. Above the critical doping p*—outside of the pseudogap phase—we find a Fermi surface that is in quantitative agreement with angle-resolved photoemission. Below p*, however, the ADMR 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

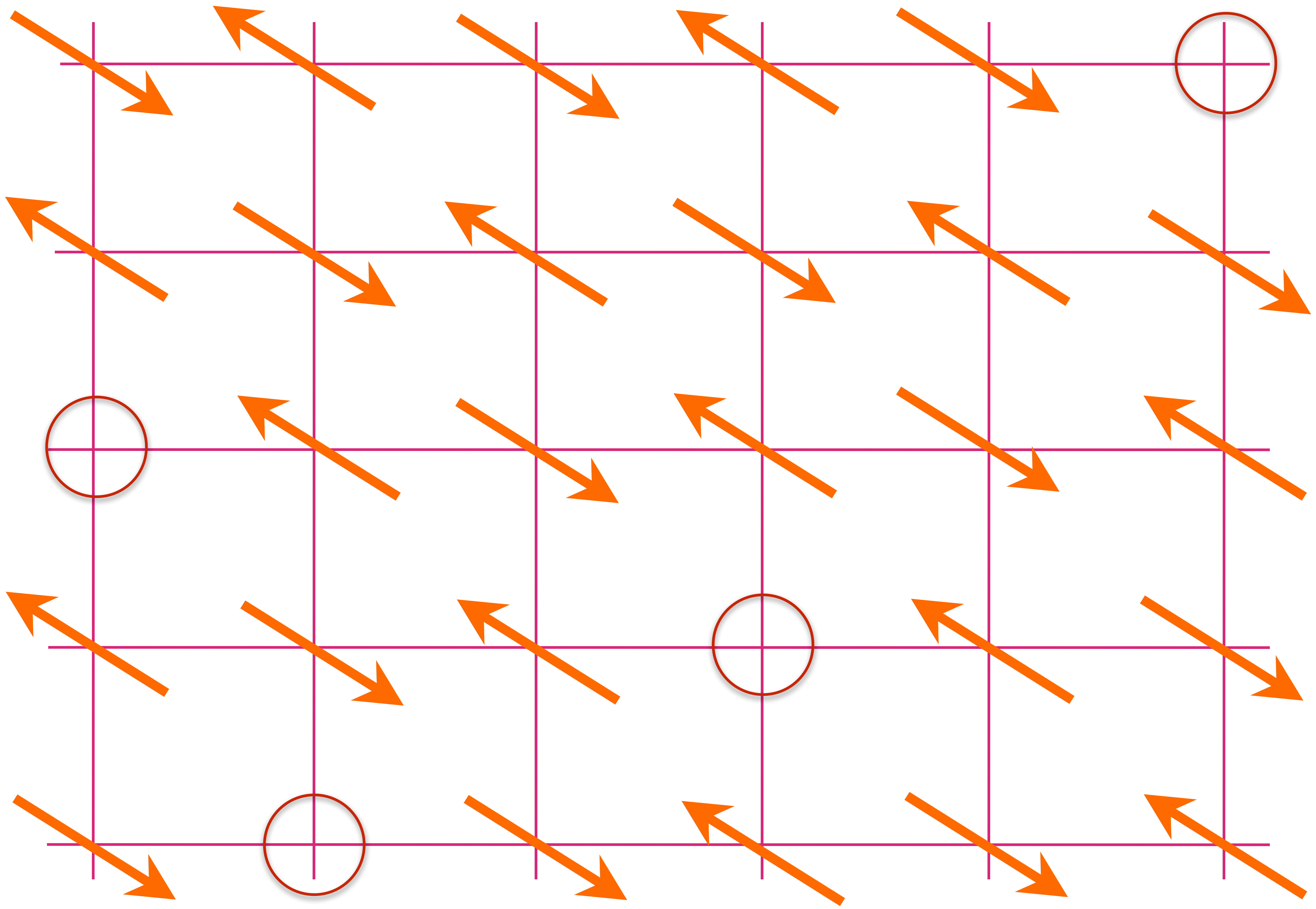



$p < p_c$ Reconstructed Fermi surface


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

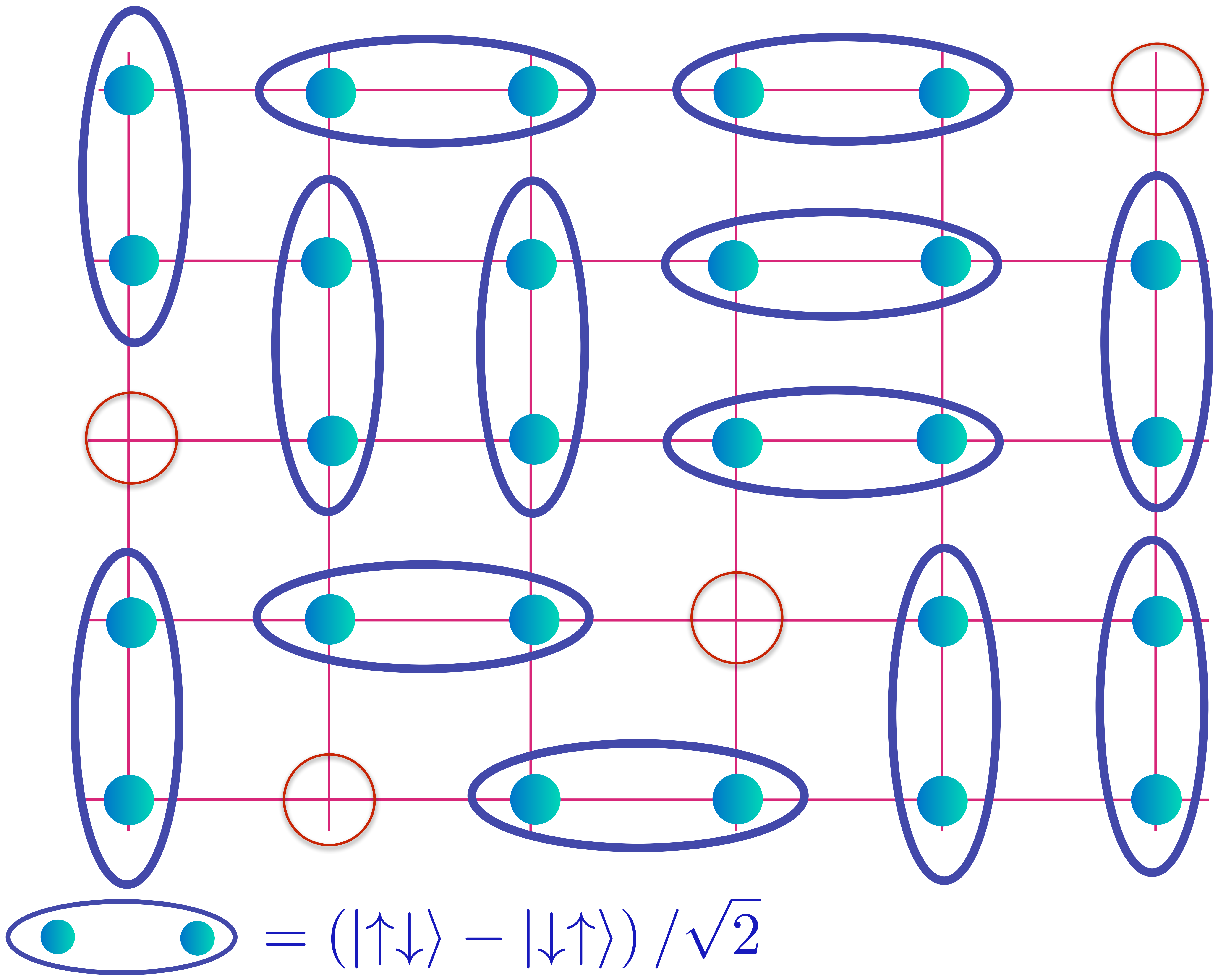
# Earlier approach to FL* in a ***one-band*** model

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)



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

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

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

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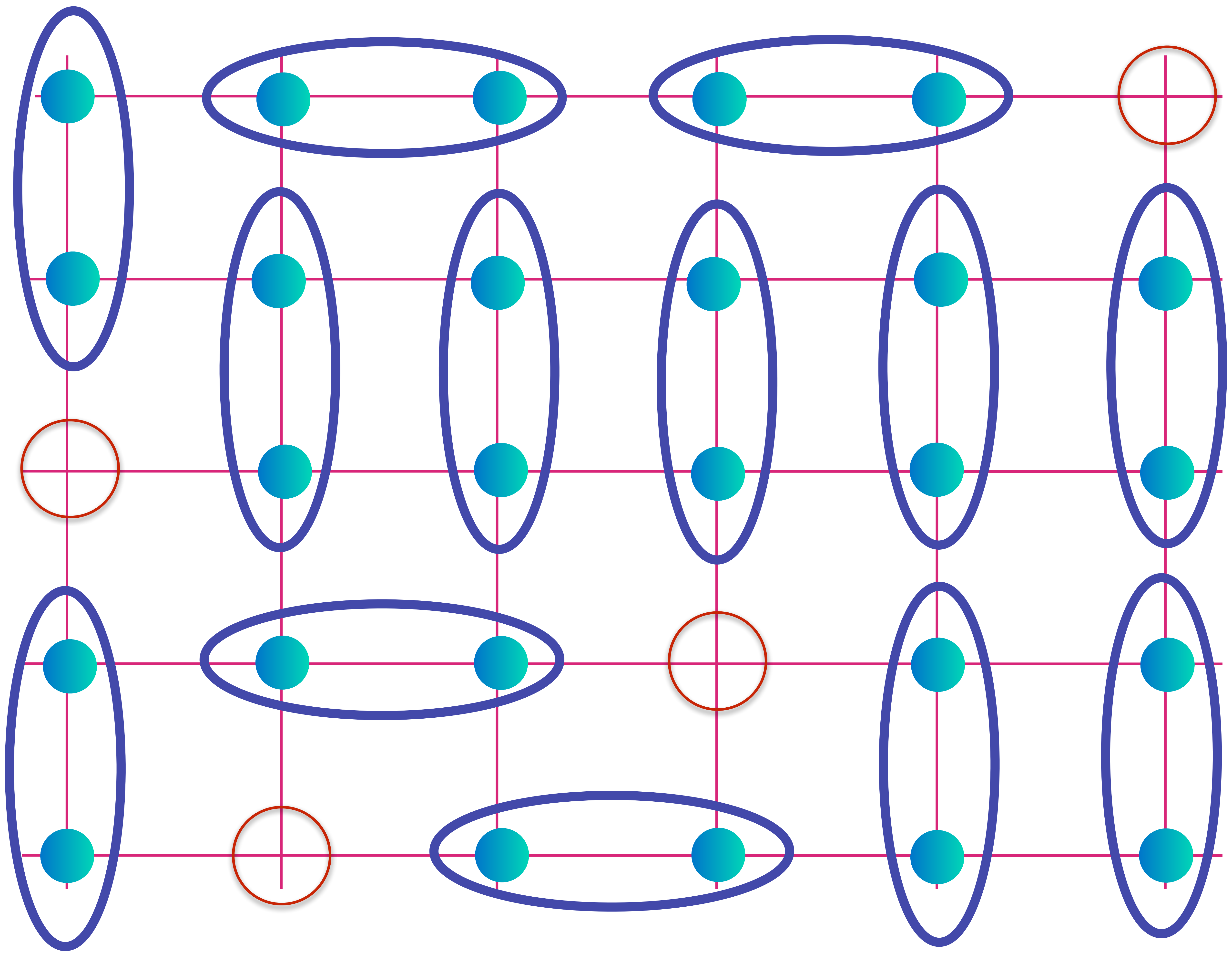

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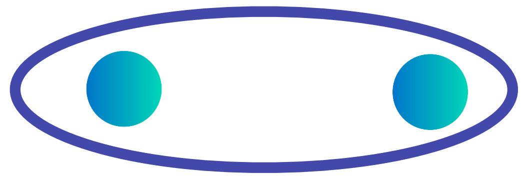

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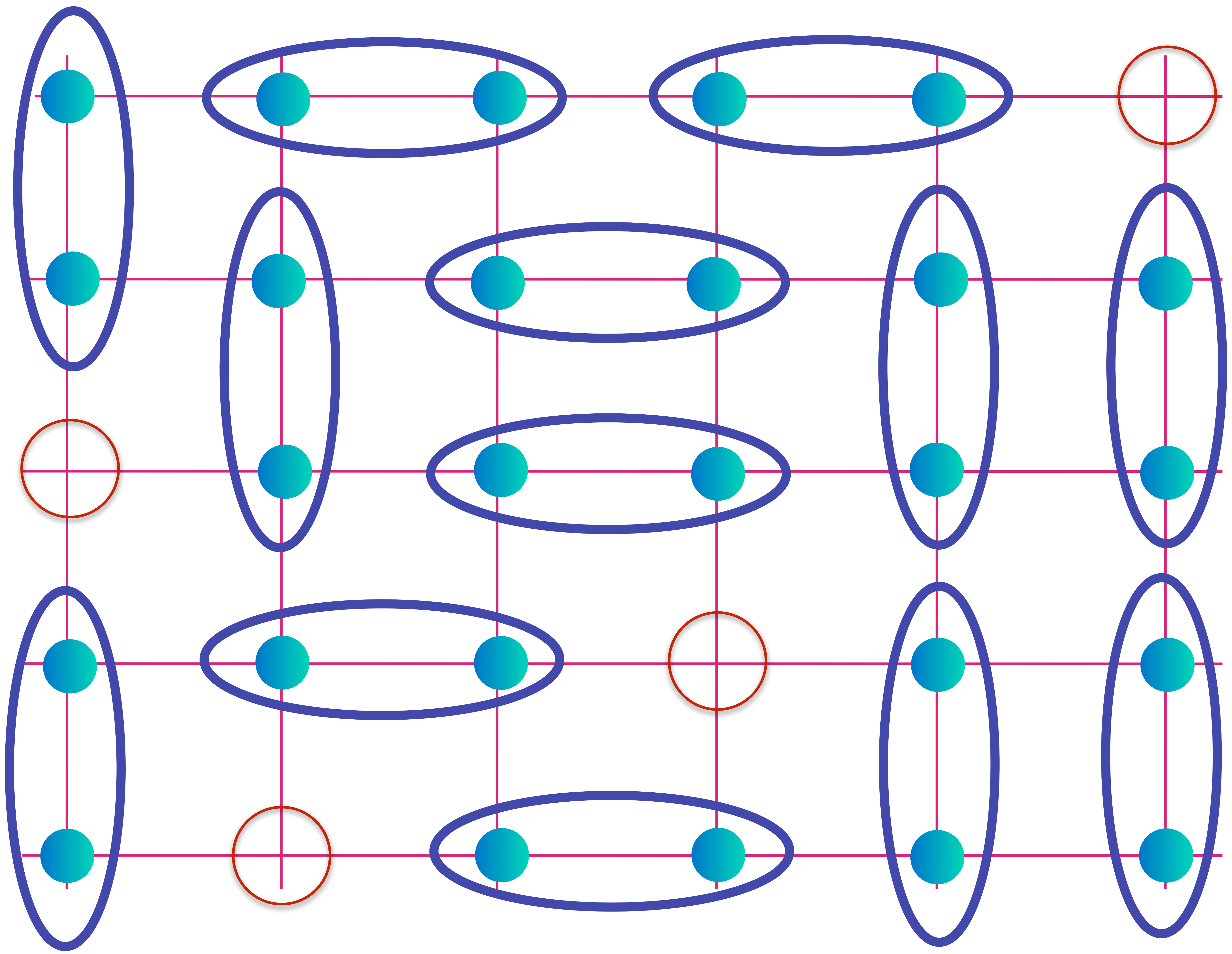

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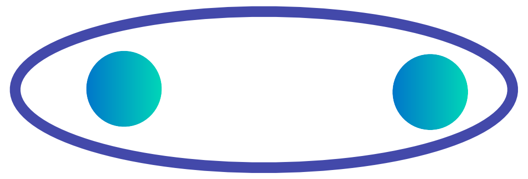 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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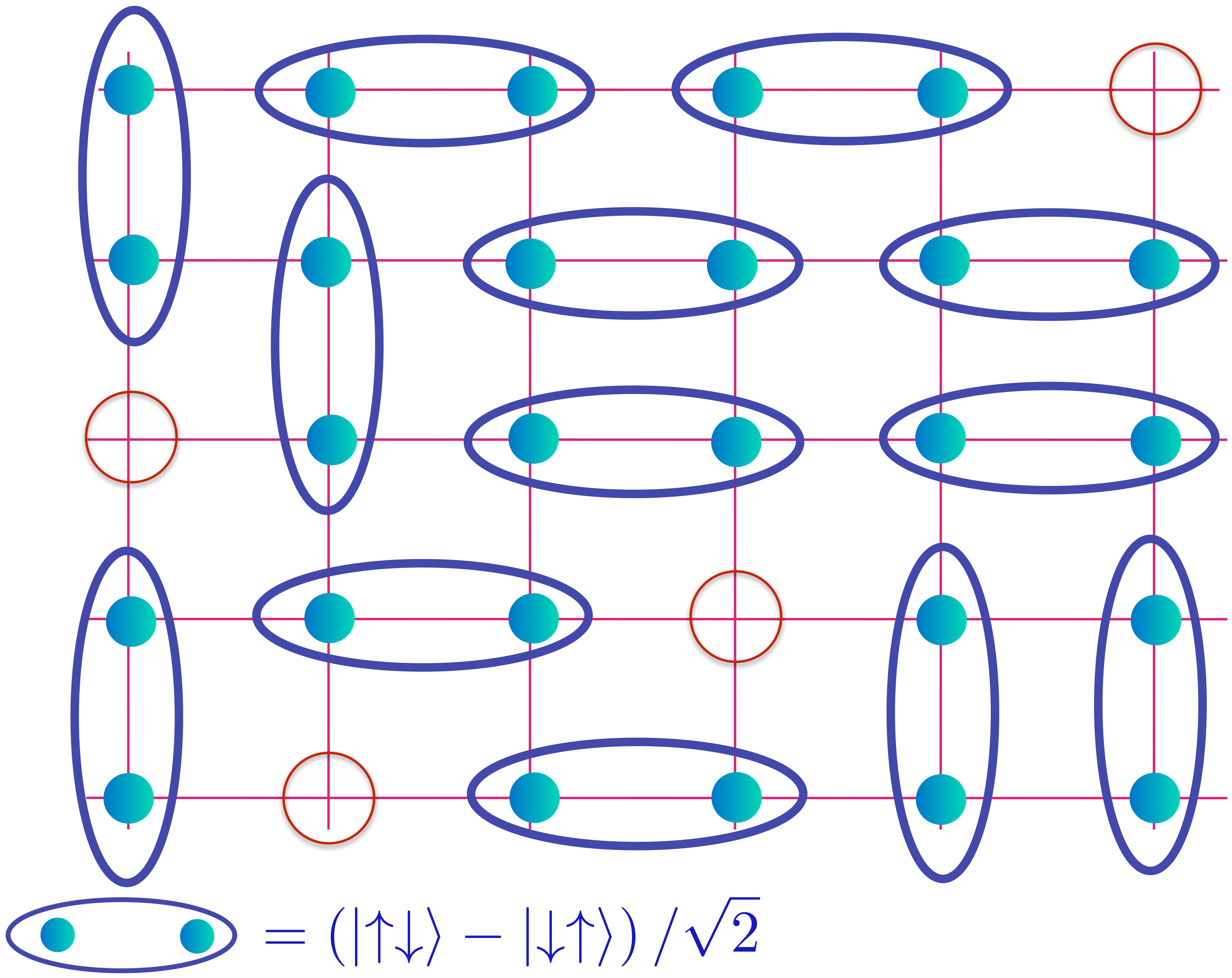

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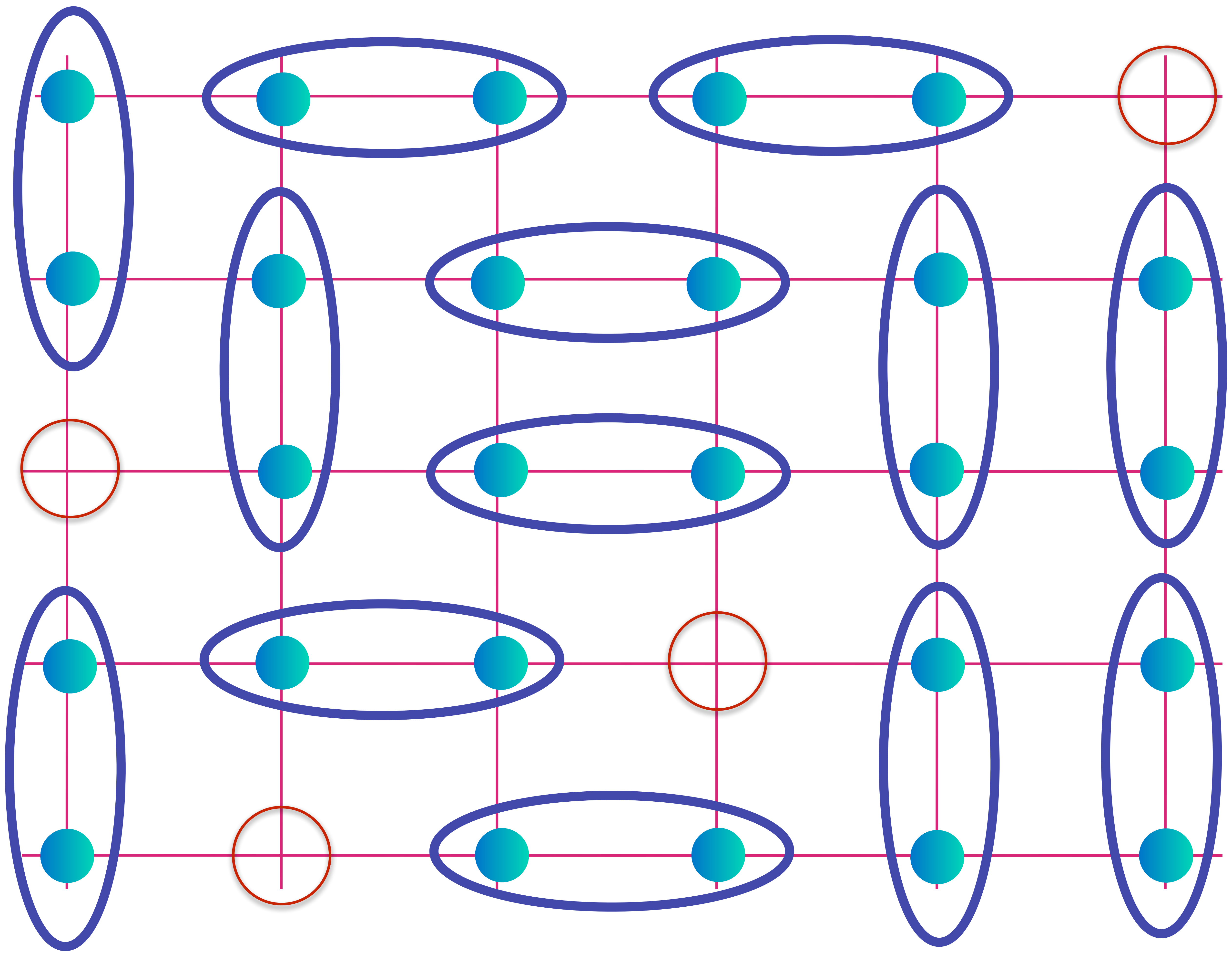

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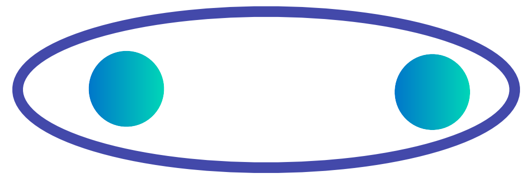

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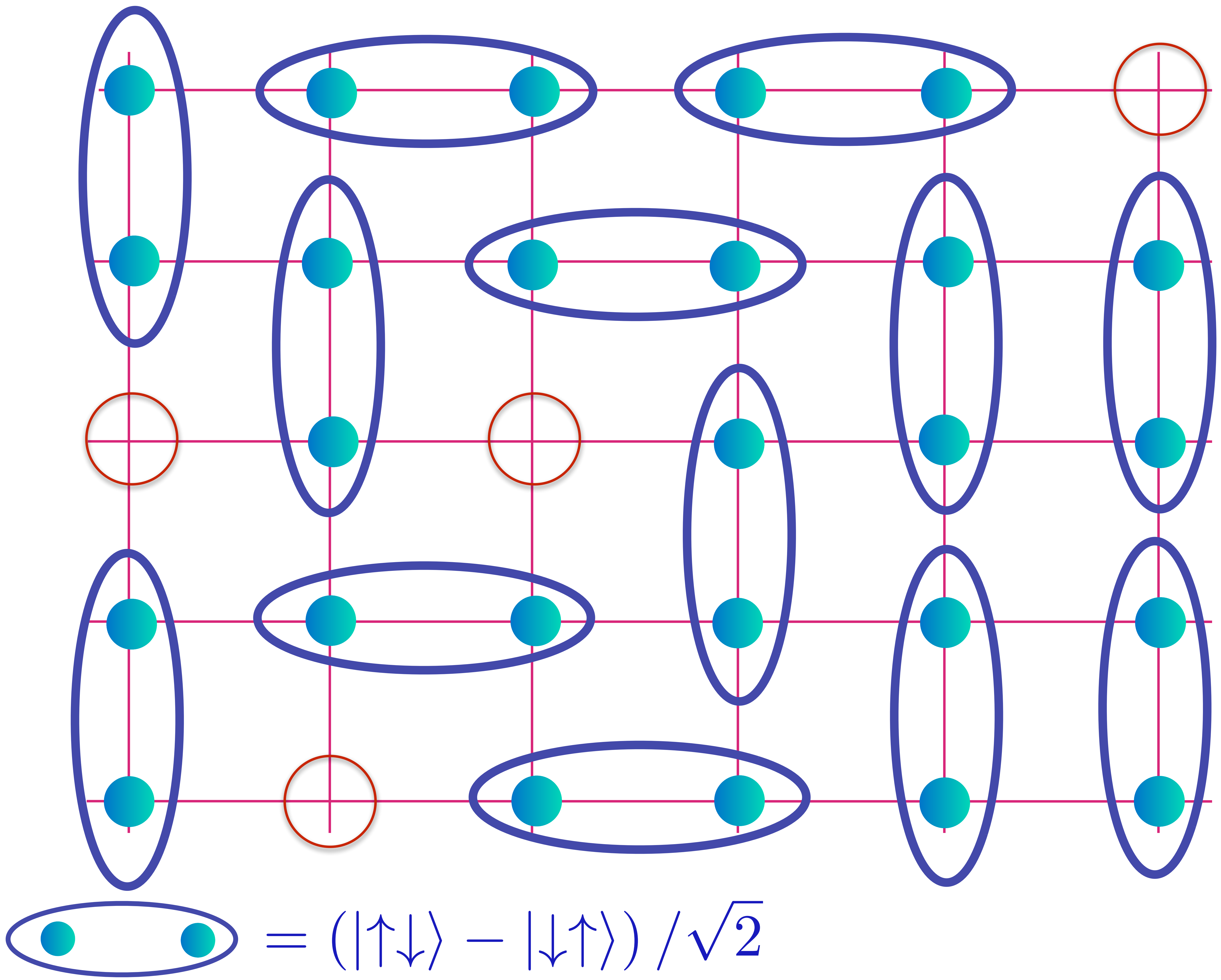

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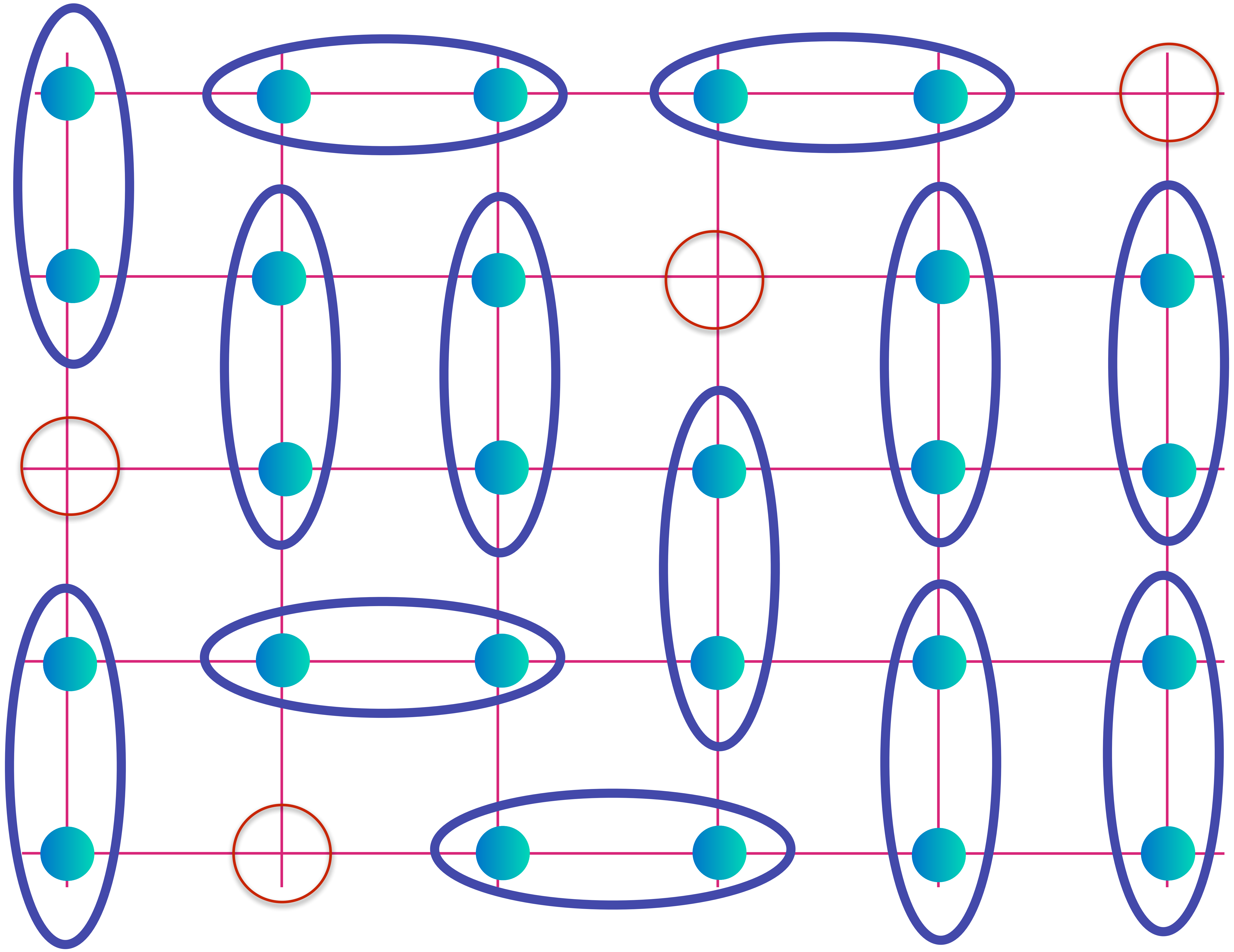

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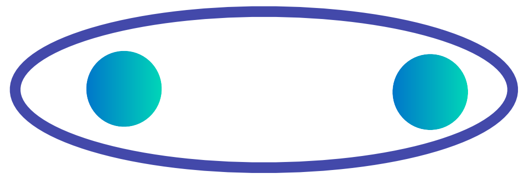
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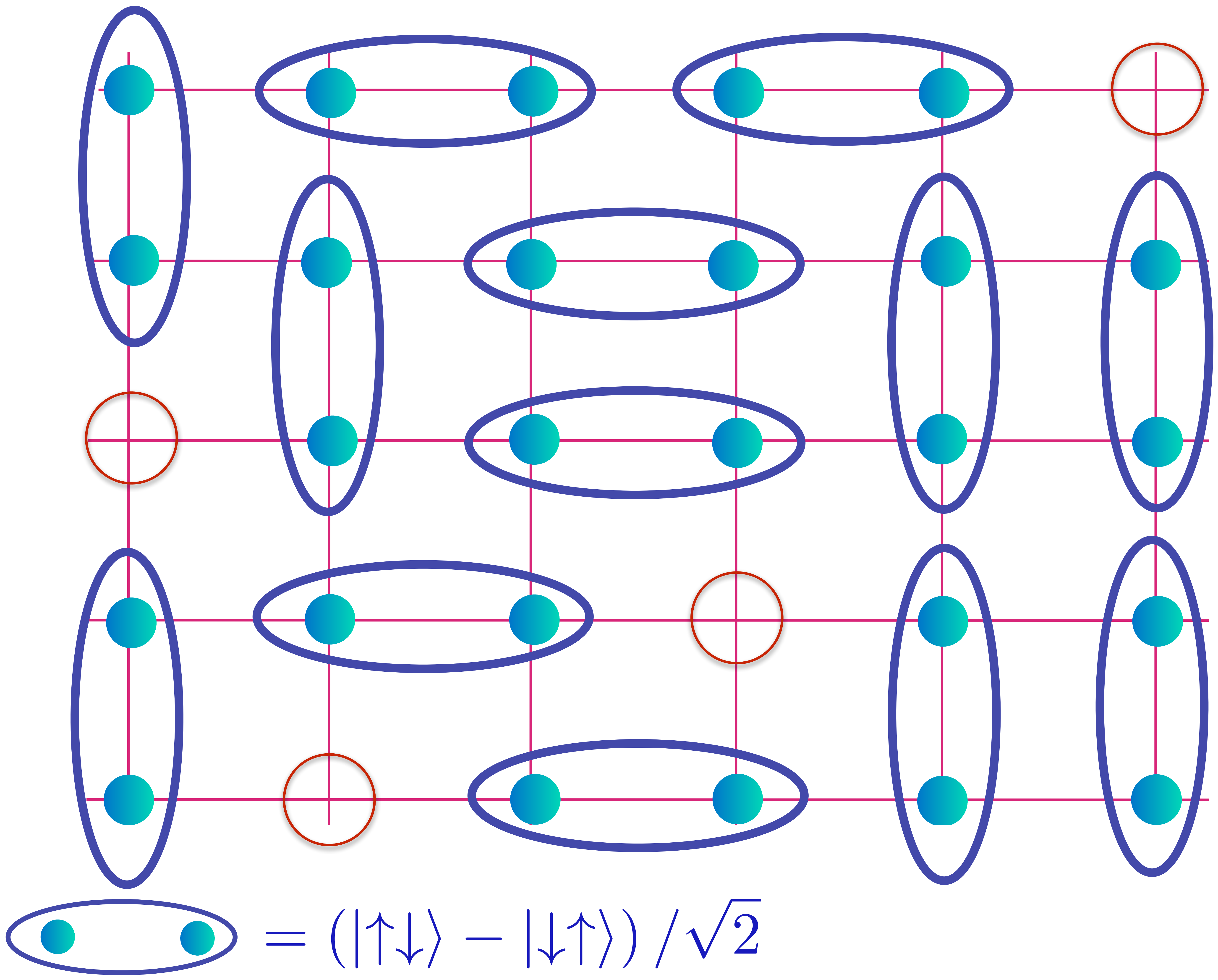

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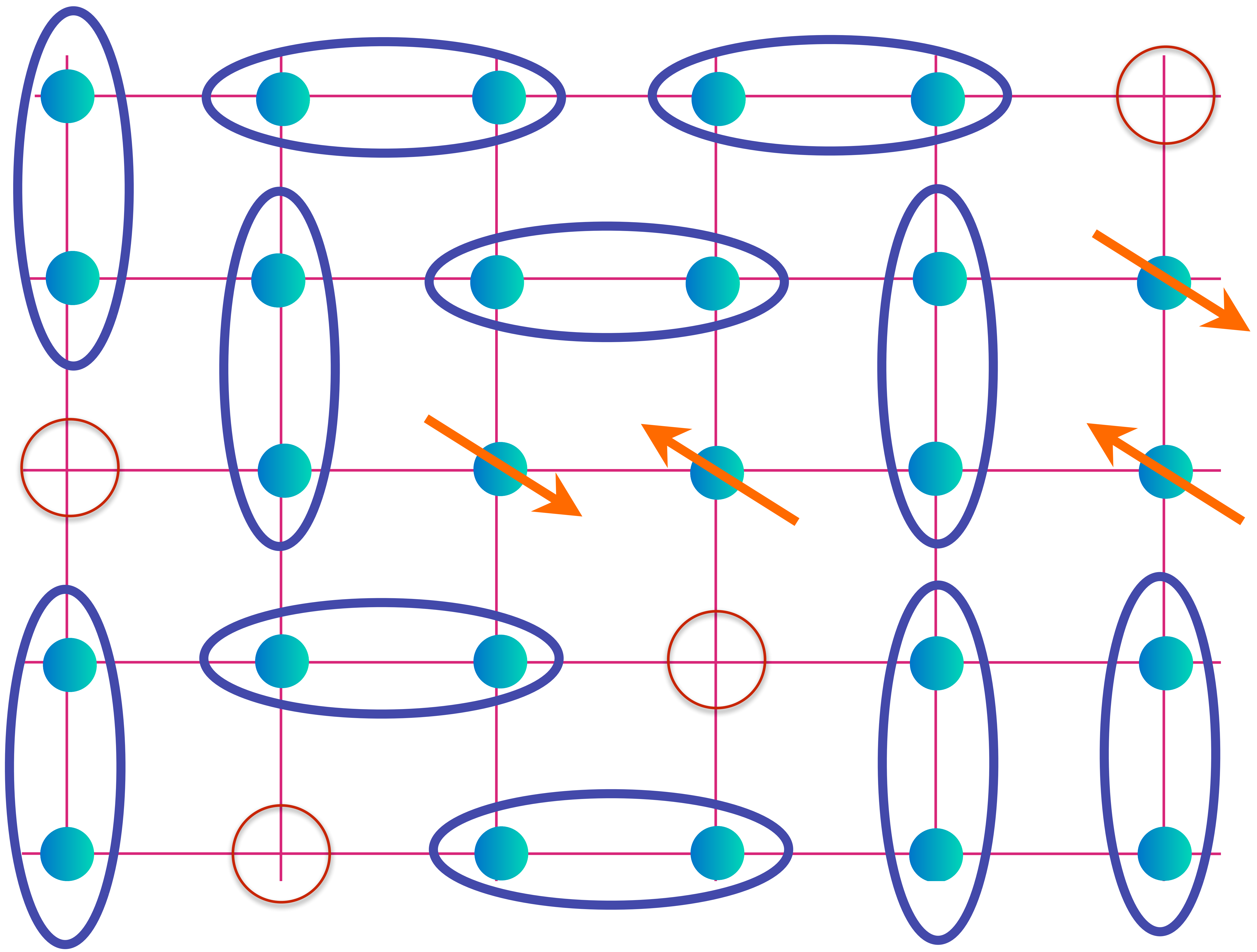

Spin liquid with density $p$ of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

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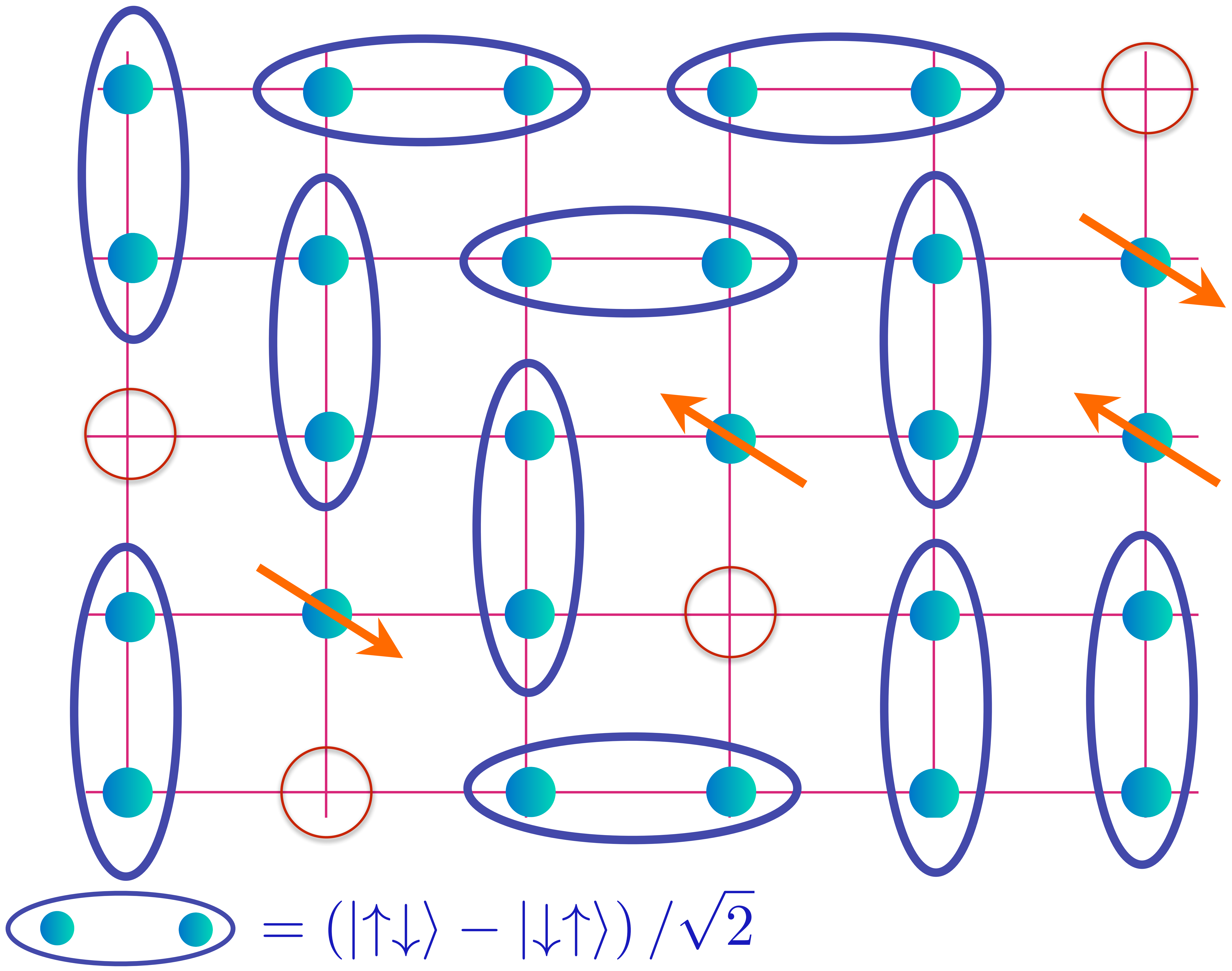

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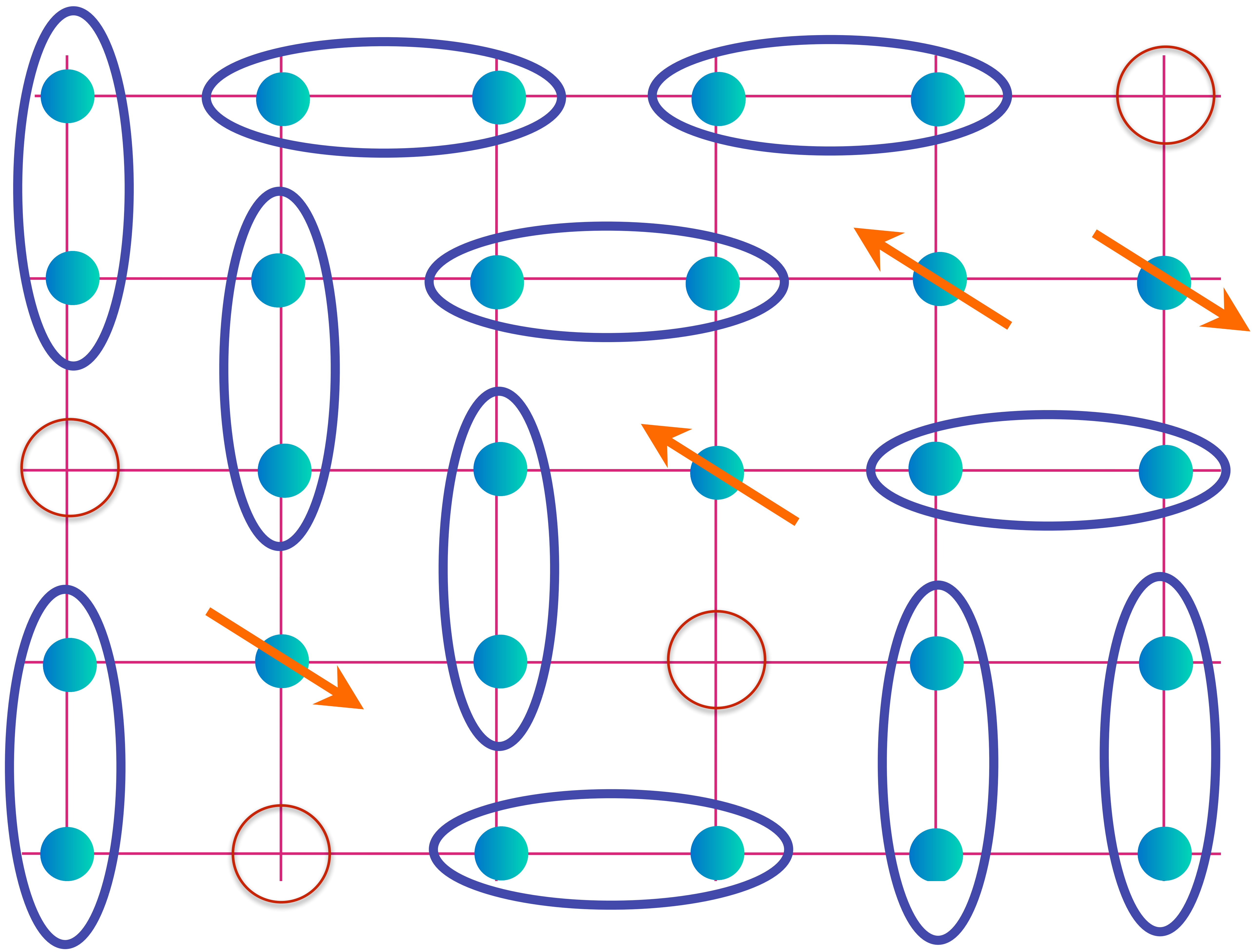

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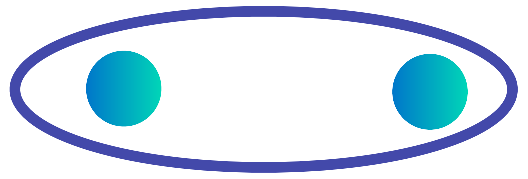

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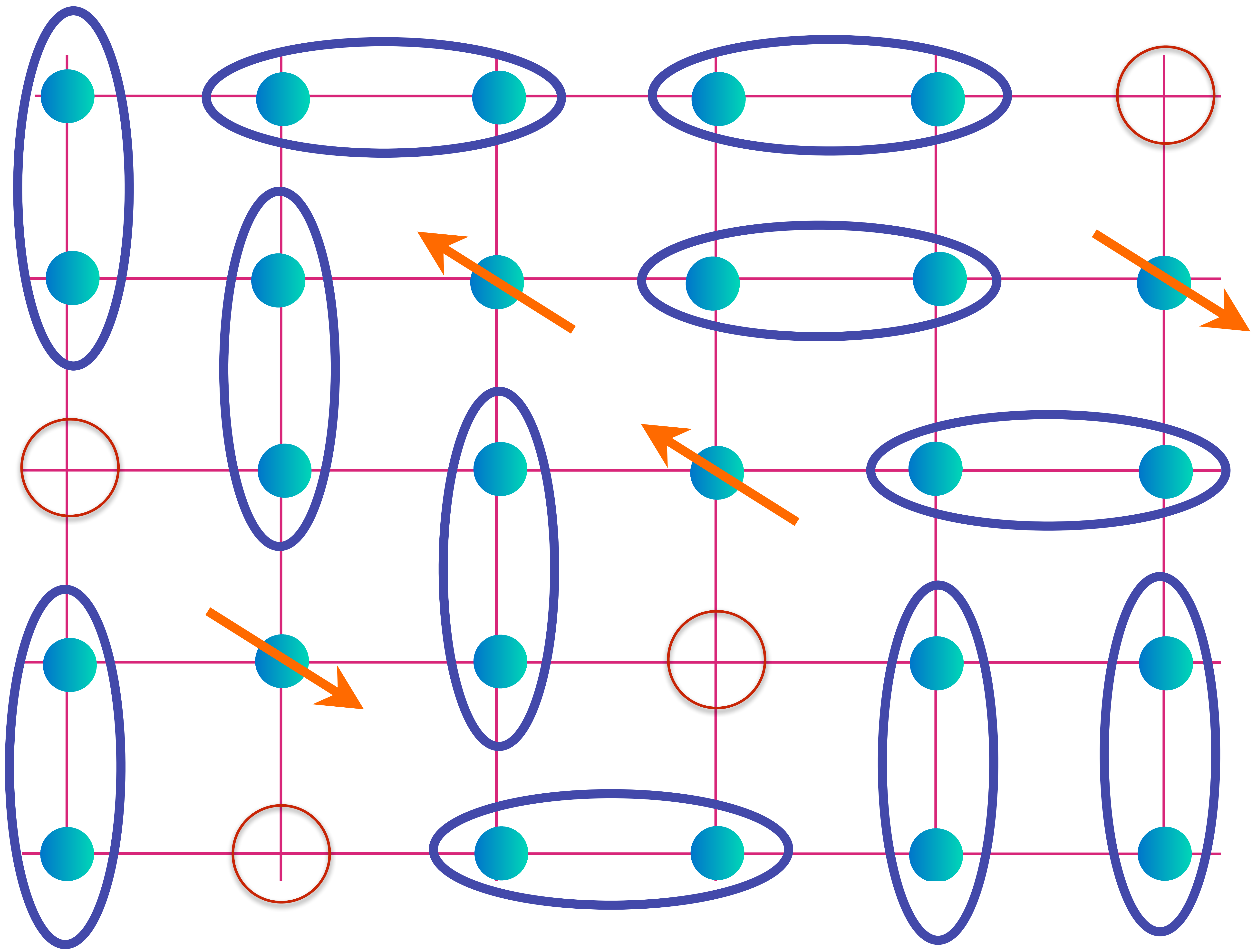

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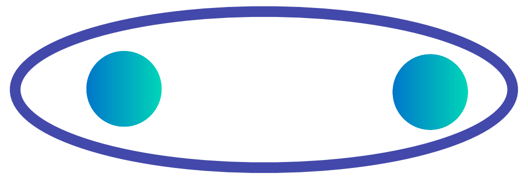 $= \left( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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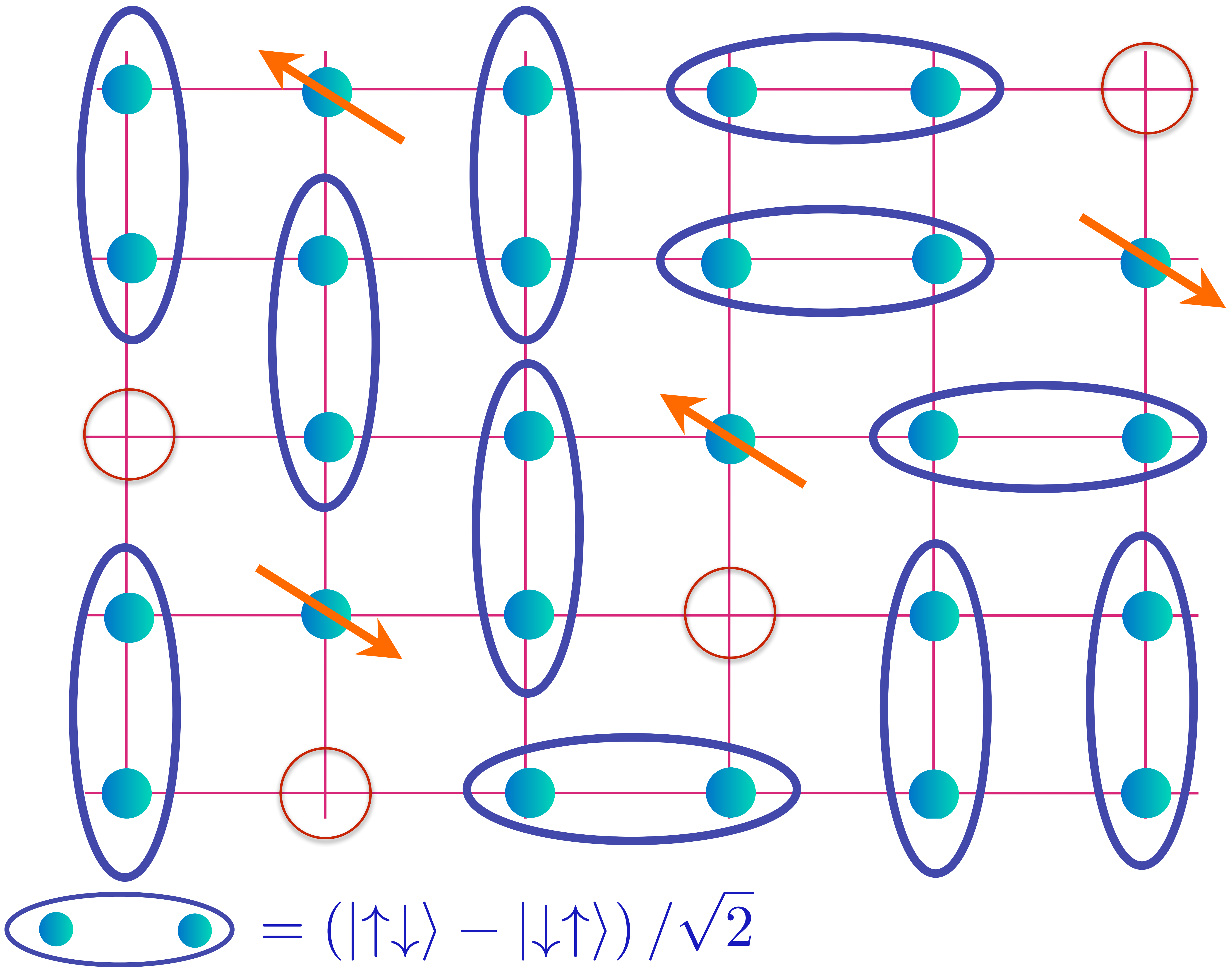

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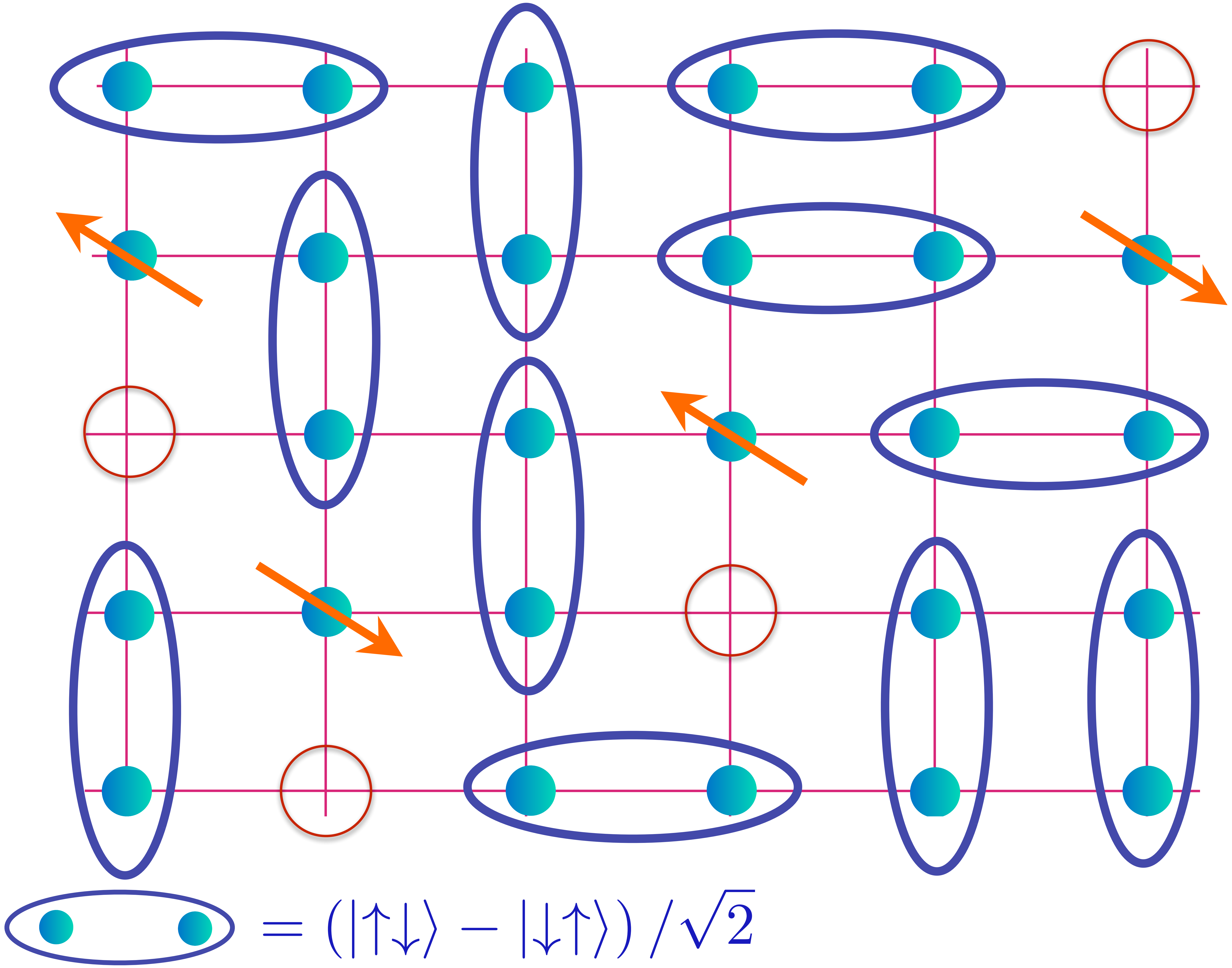

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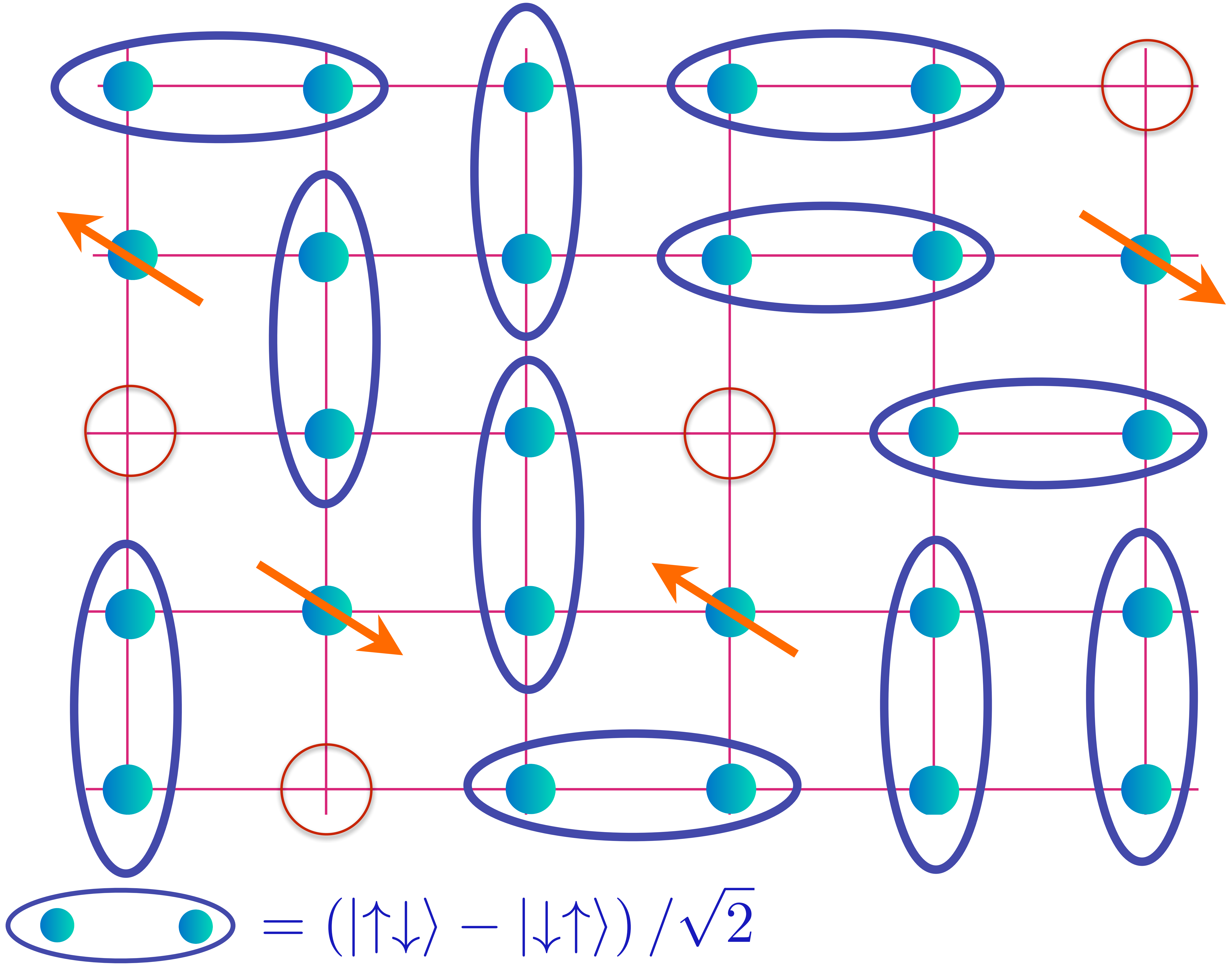

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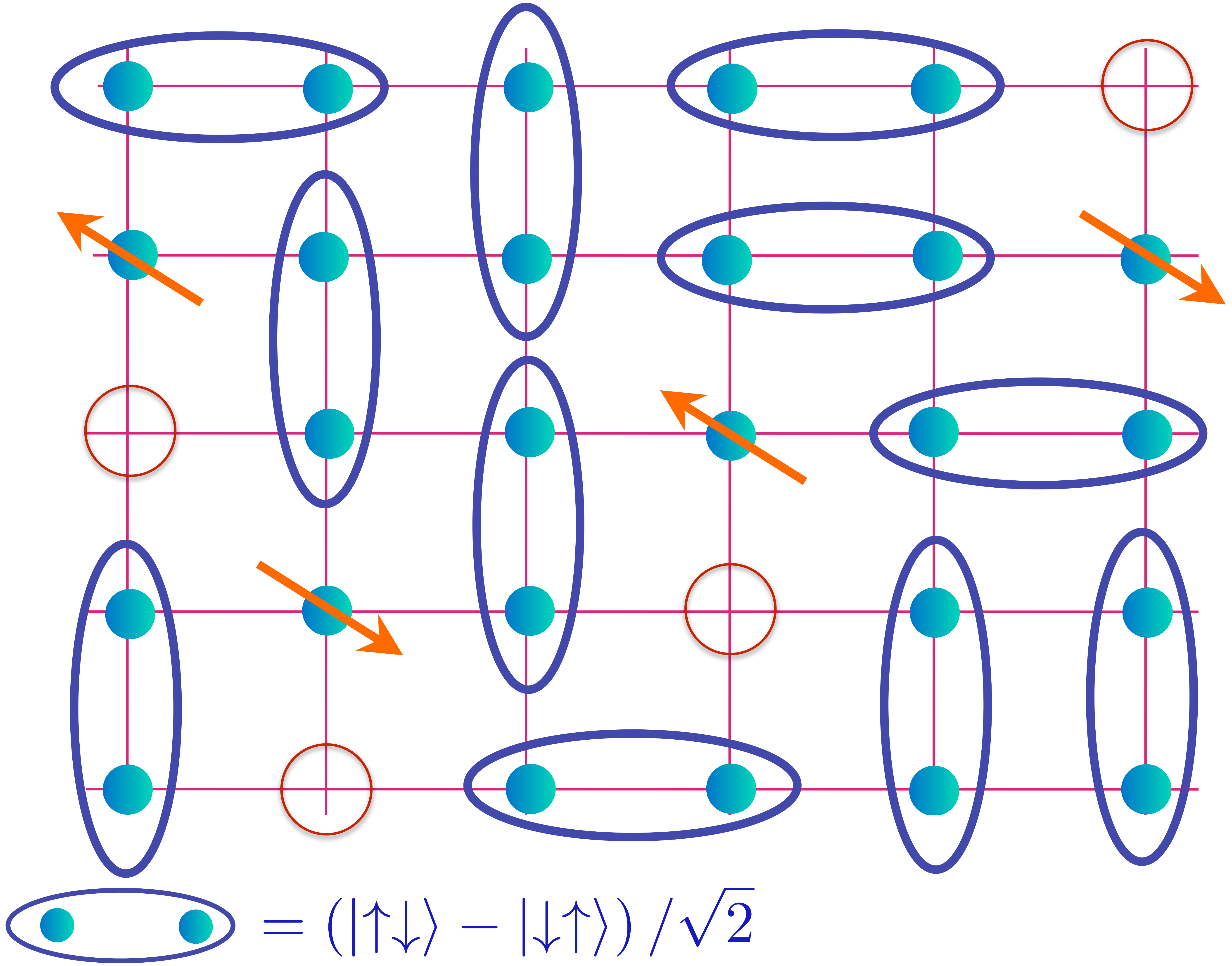

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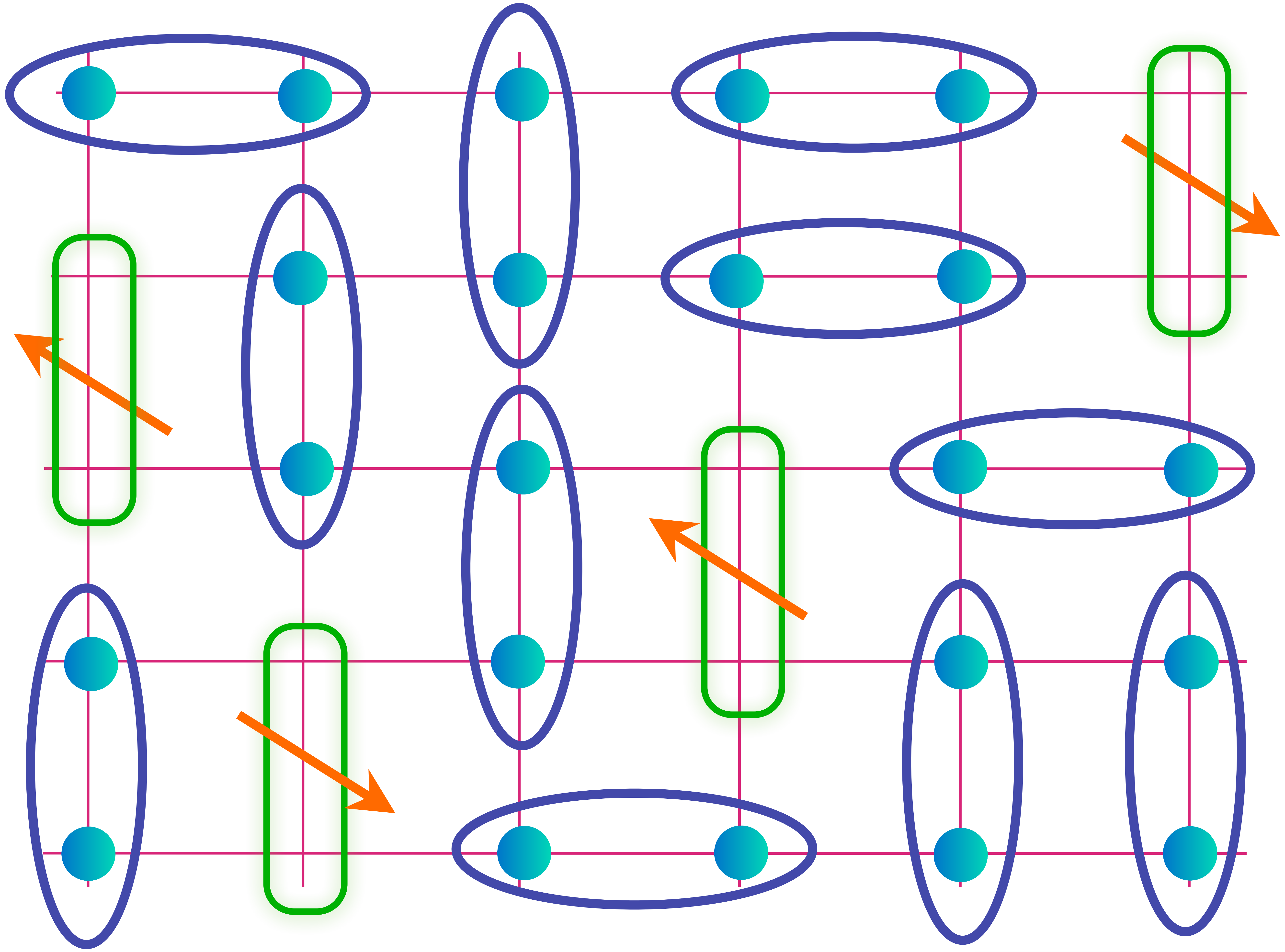

Each green "dimer" is a "bound state" of a vacancy and a free spin

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

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

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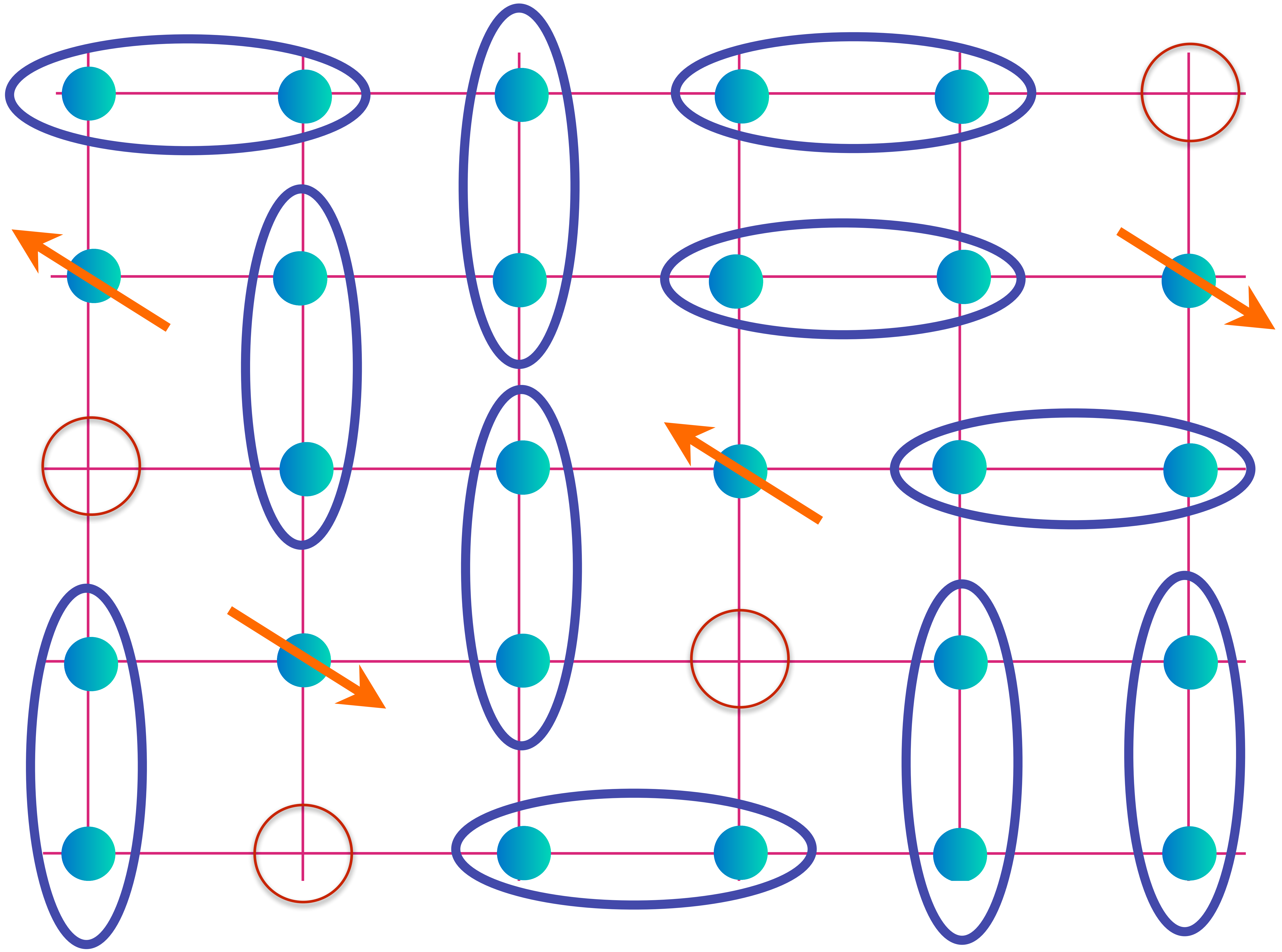

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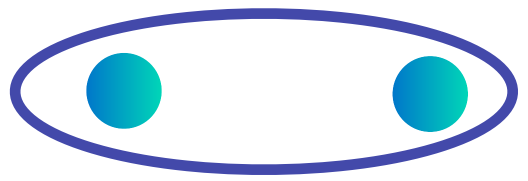
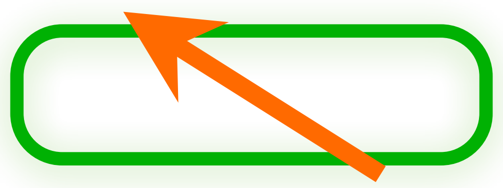
 $= \left( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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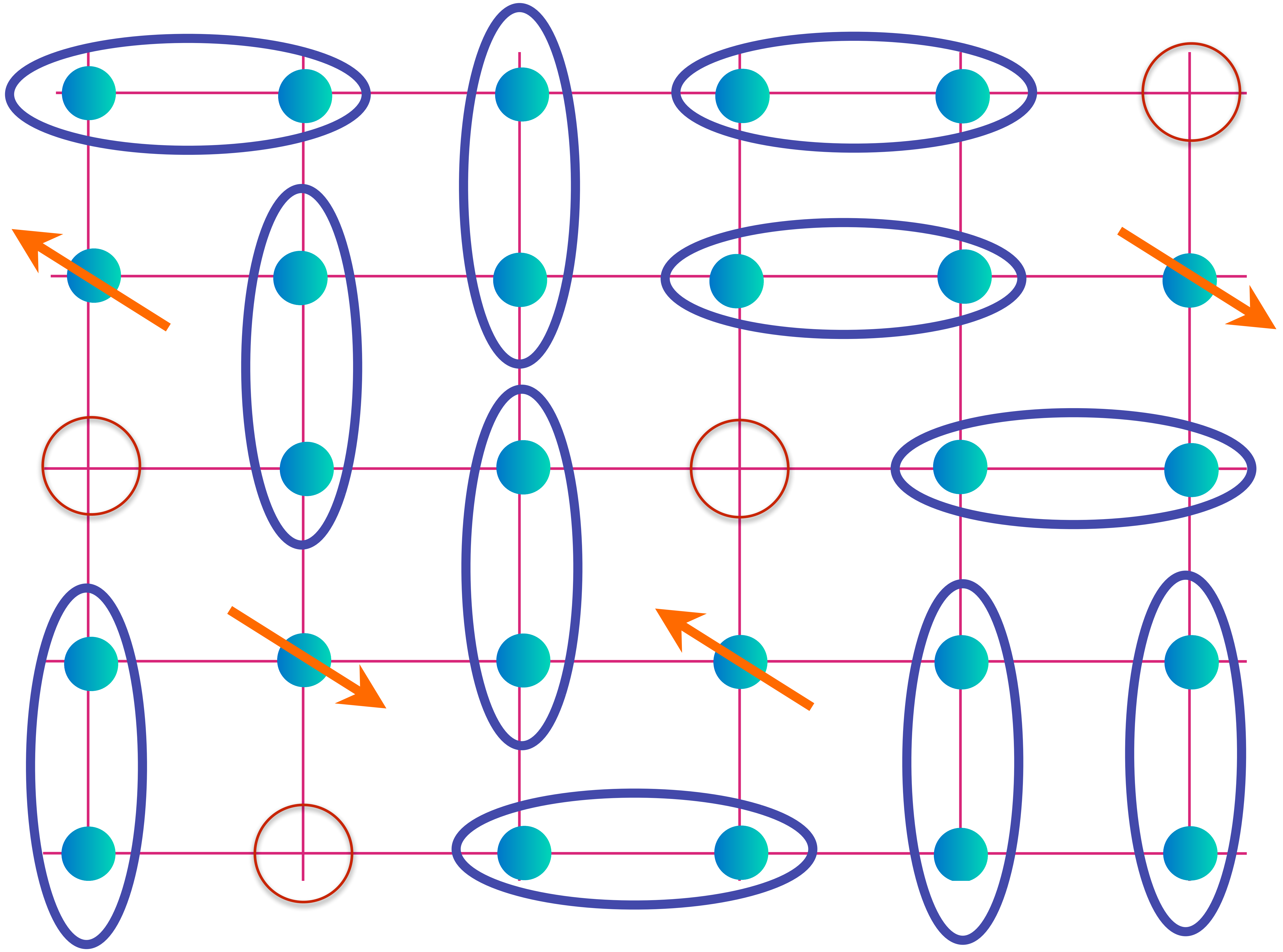

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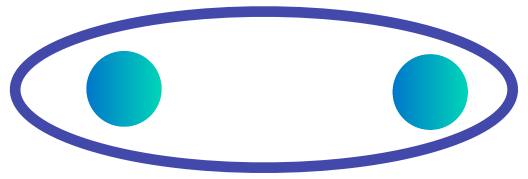
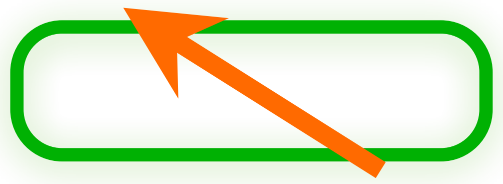
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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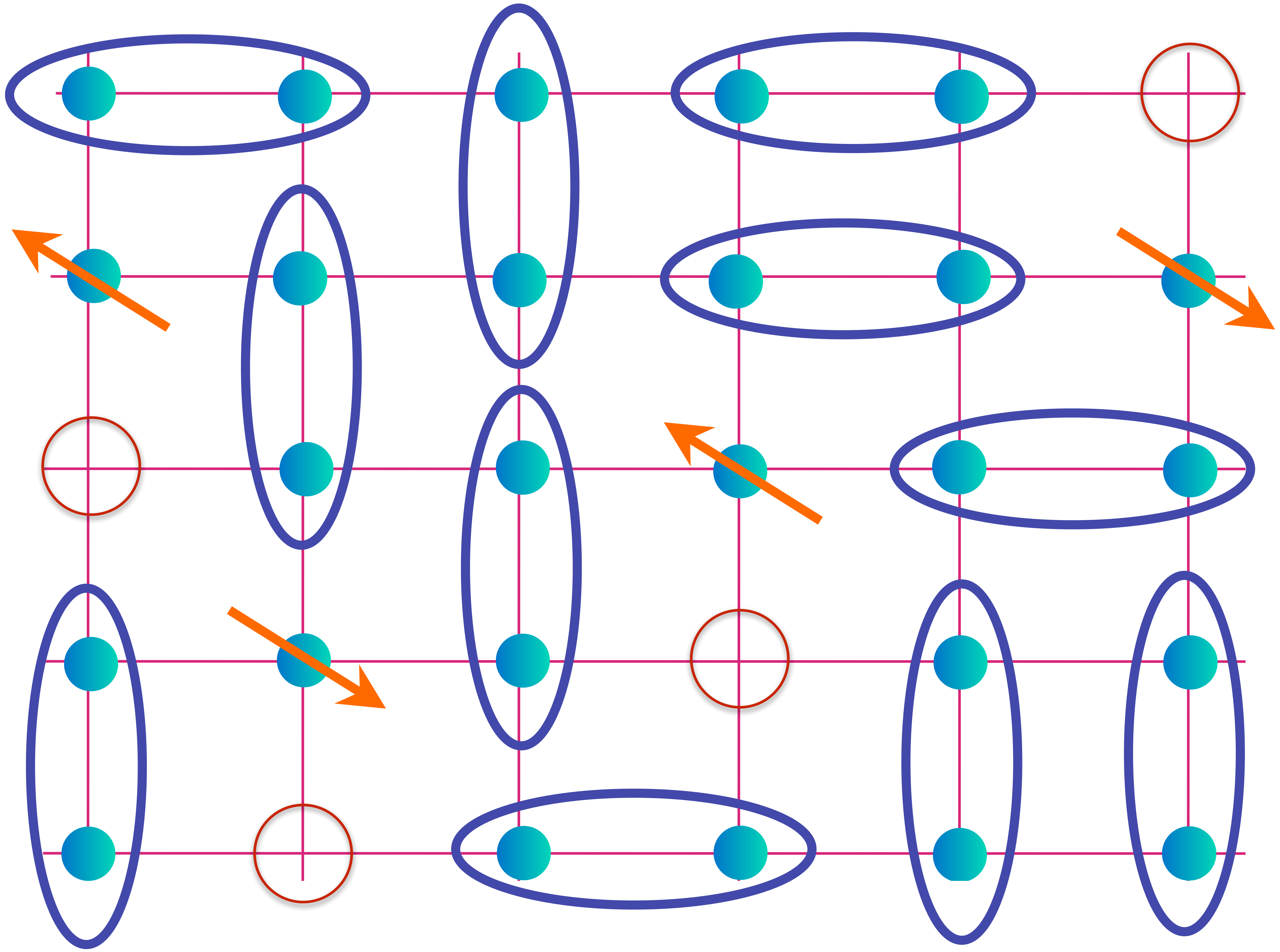

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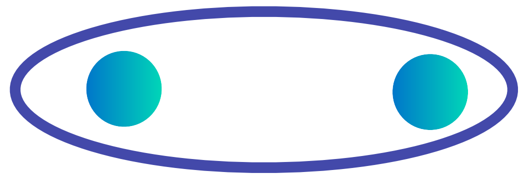
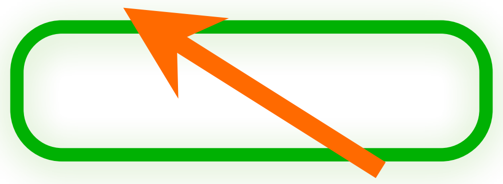
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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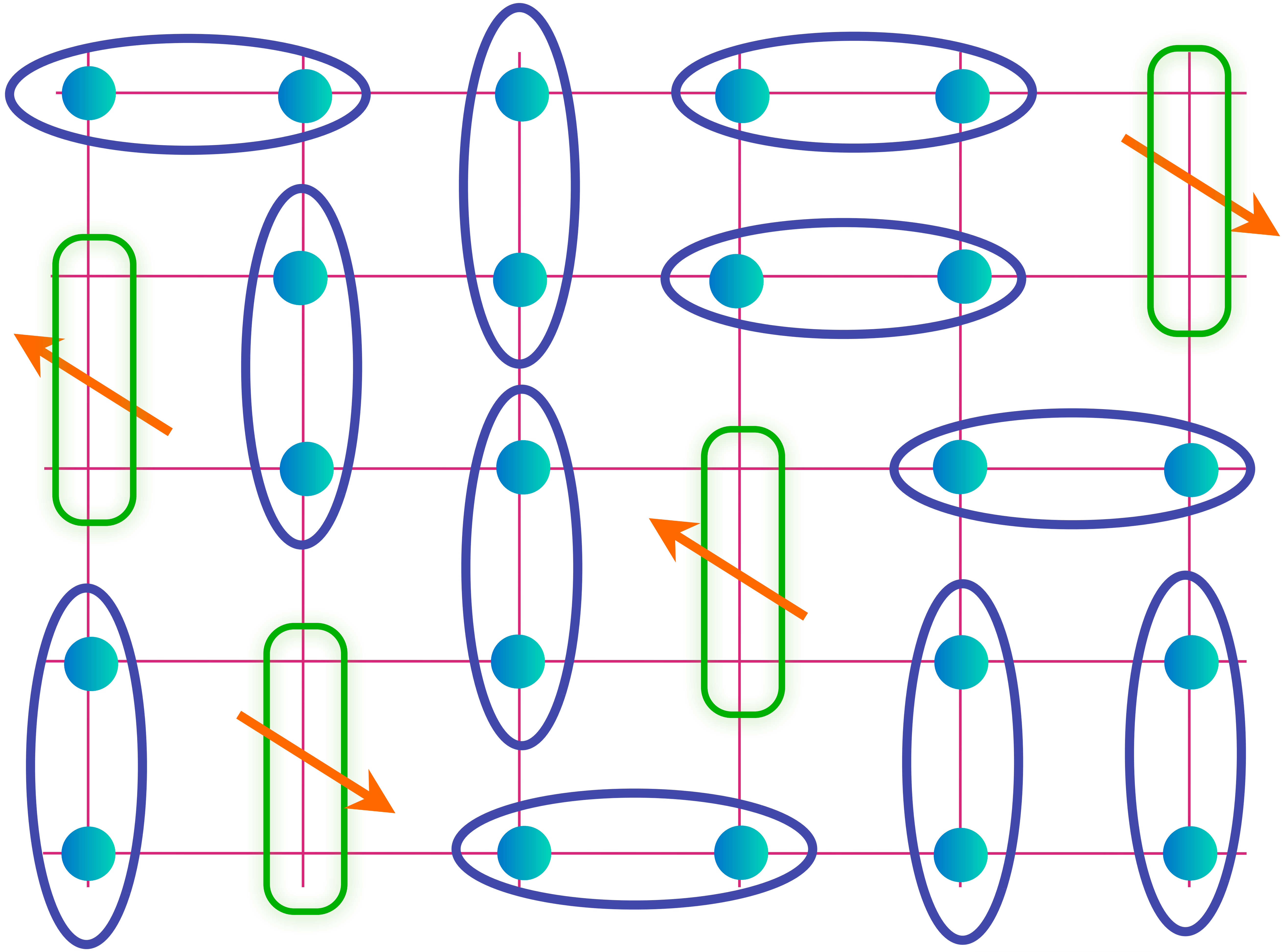
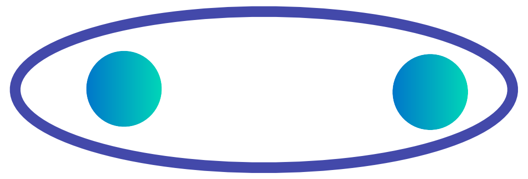


Metal with electron-like quasiparticles on a Fermi surface of size $p$, and emergent gauge fields



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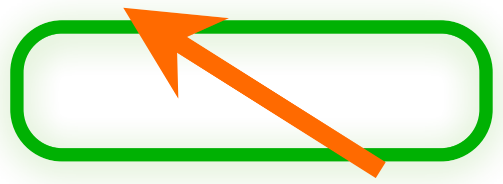

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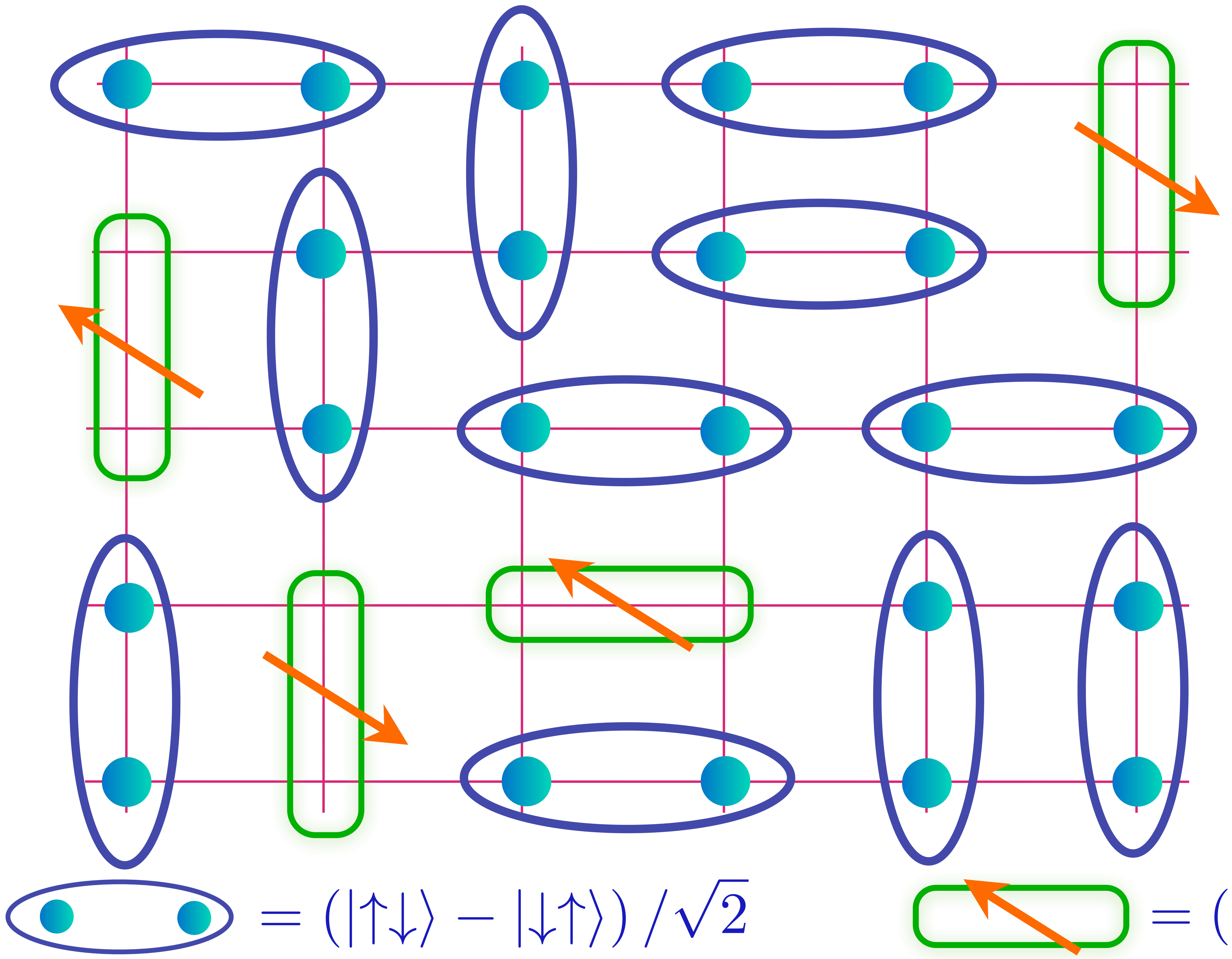

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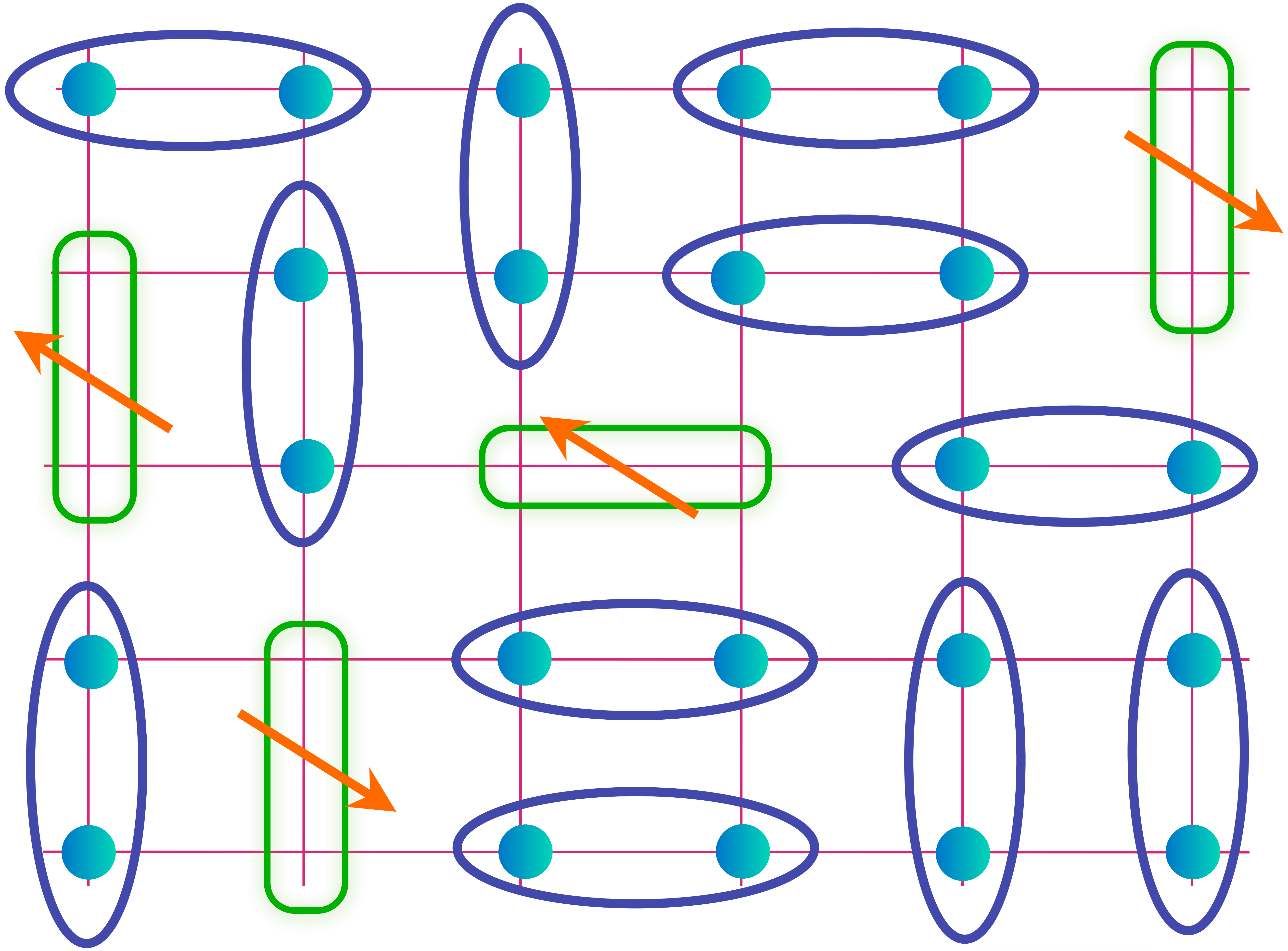

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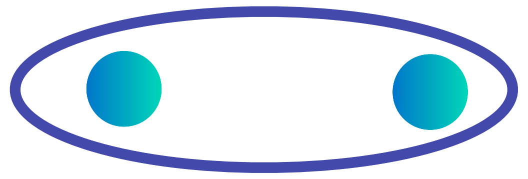
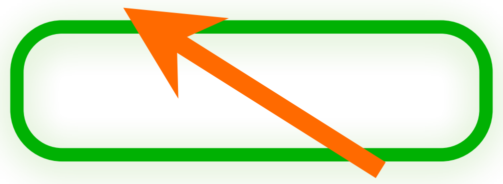
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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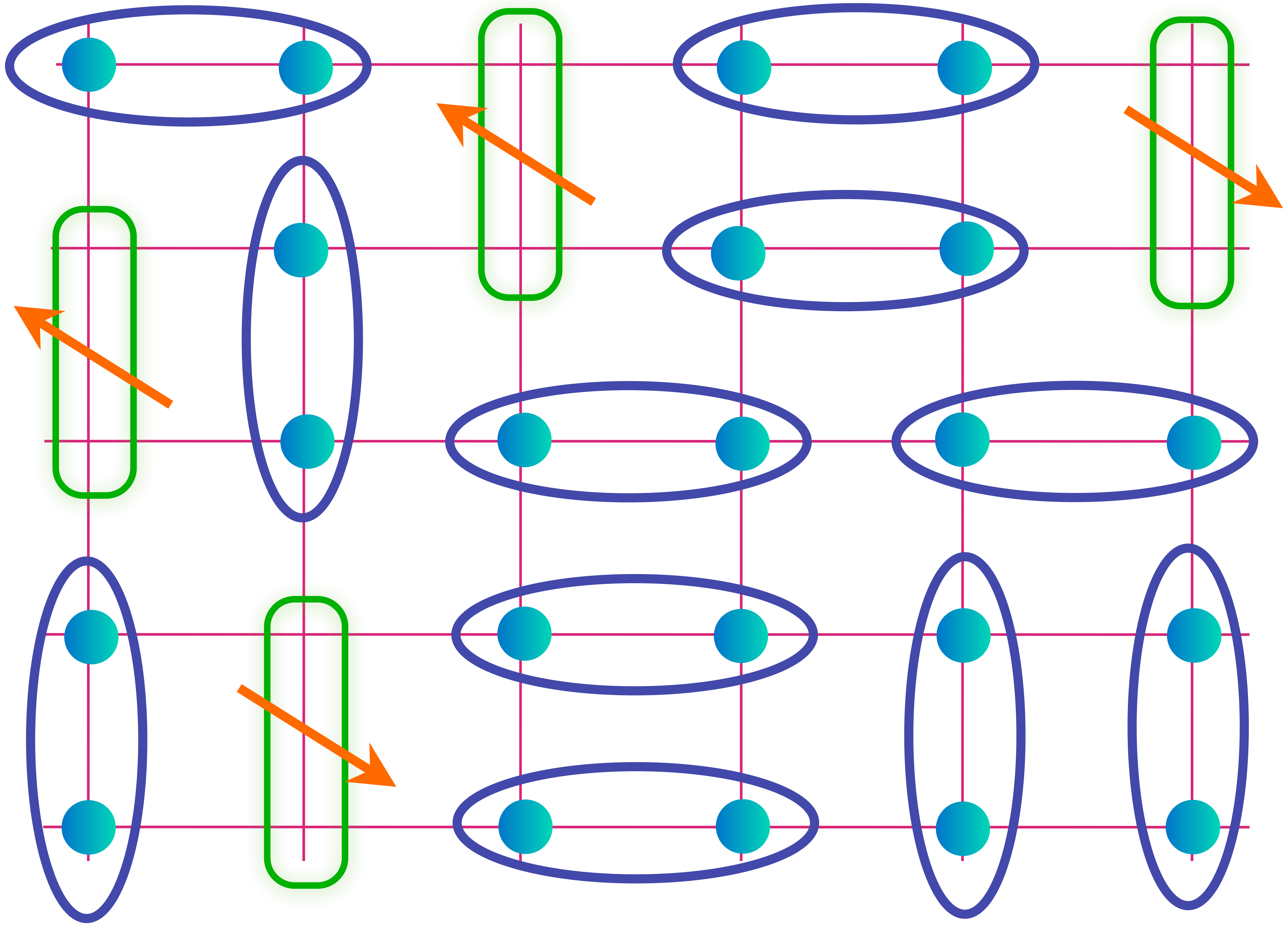

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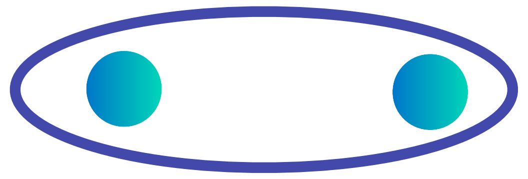
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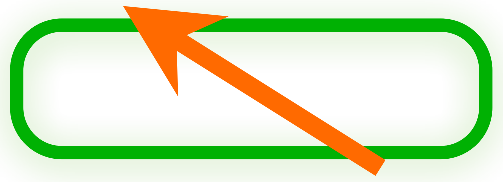
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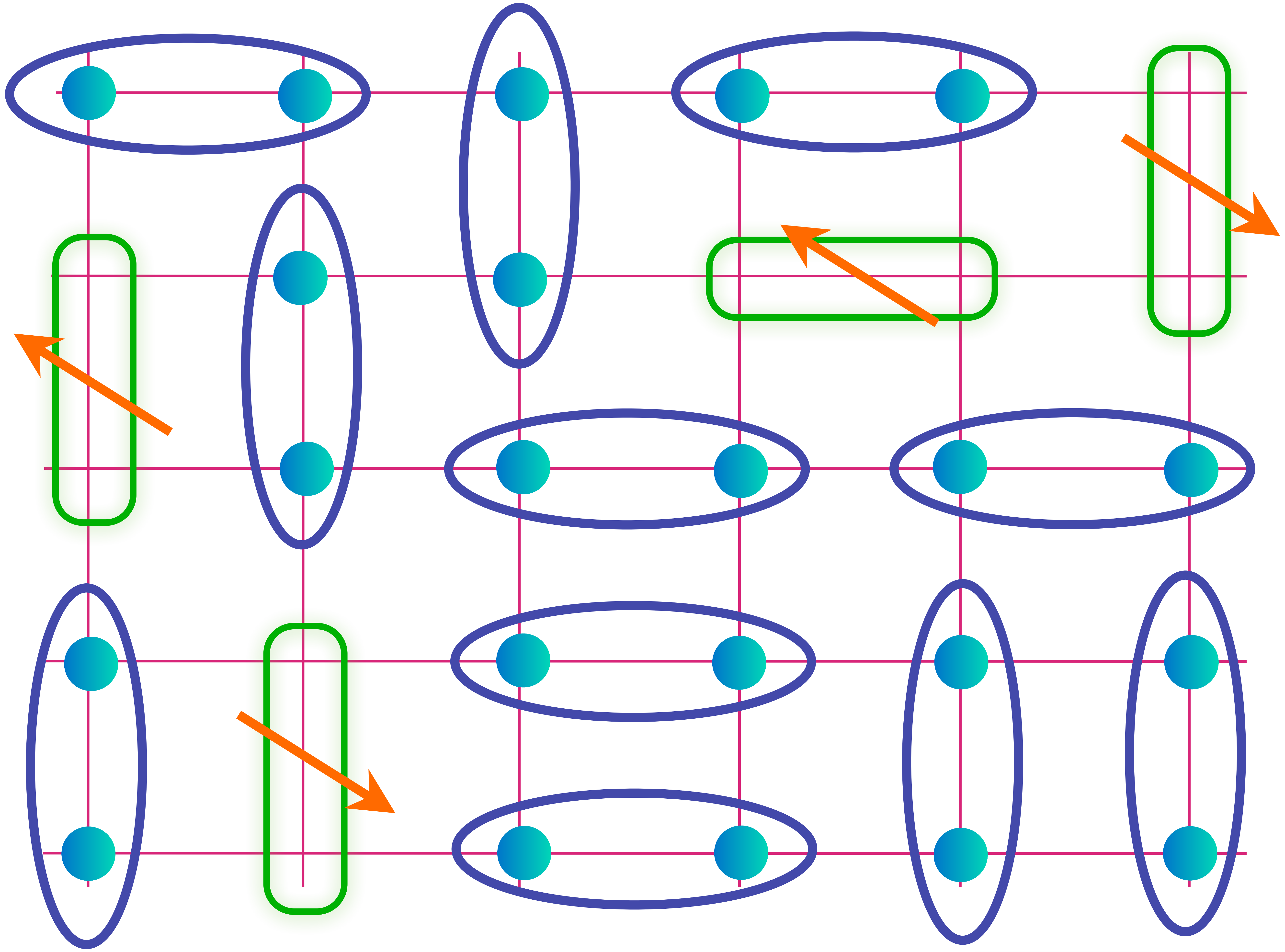

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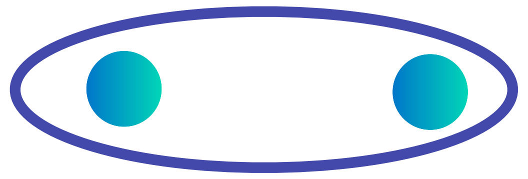
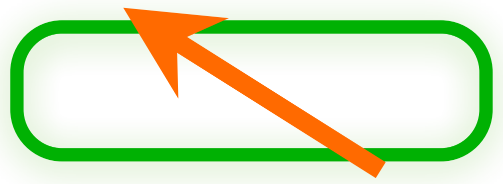
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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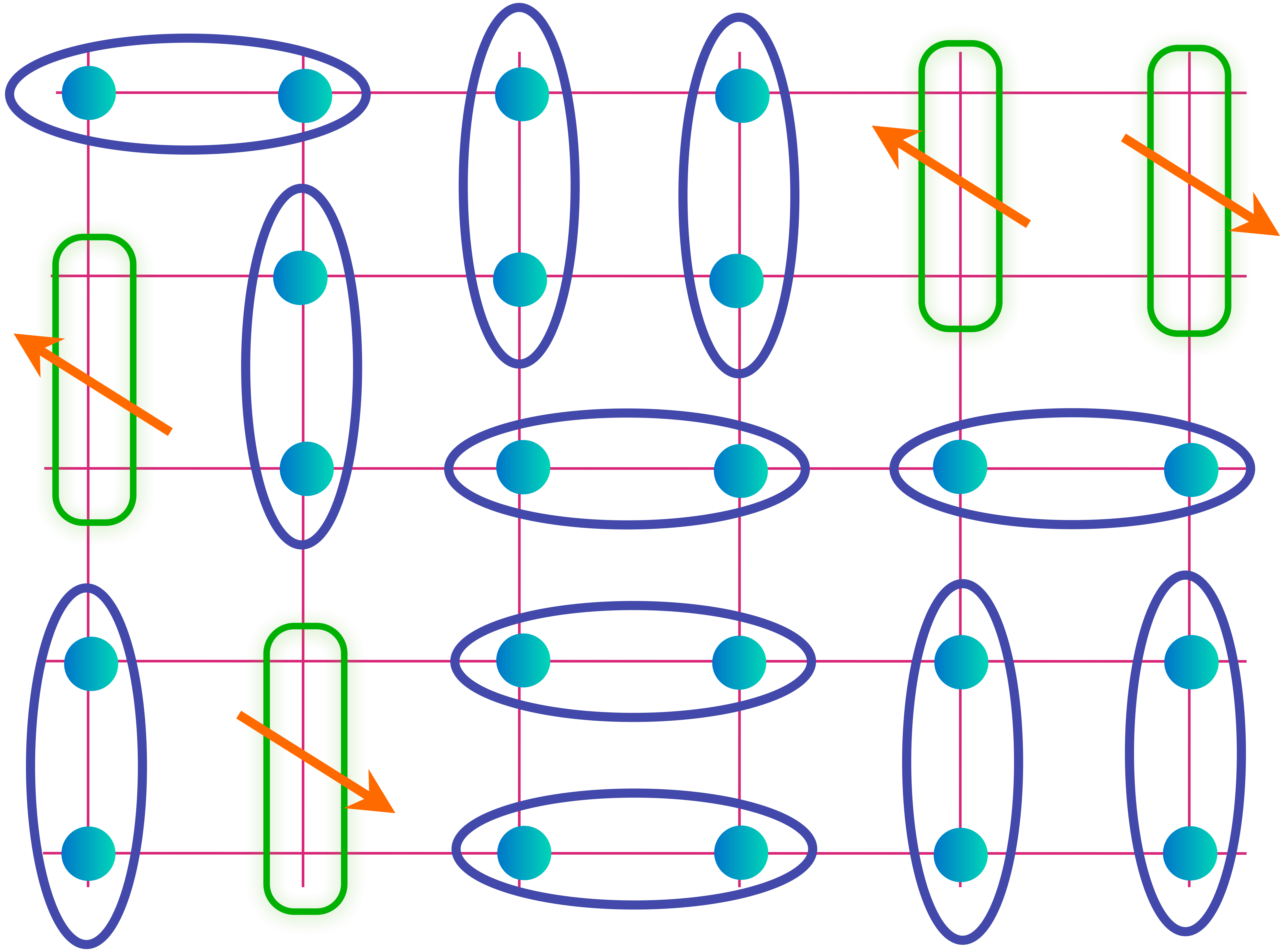

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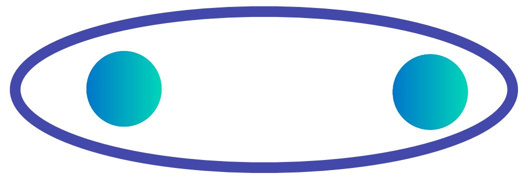

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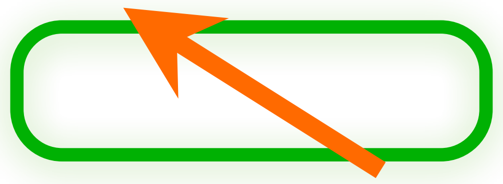

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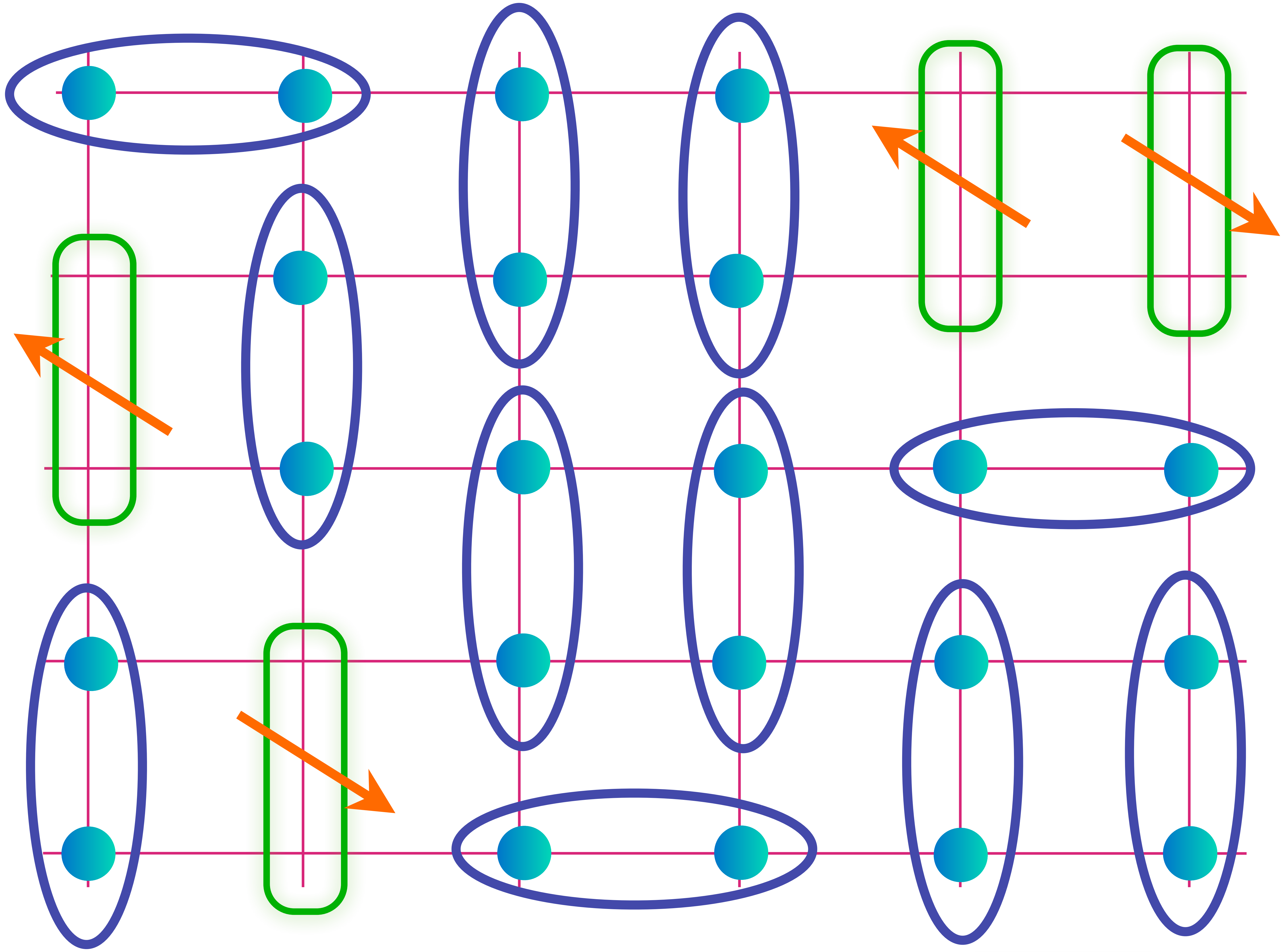

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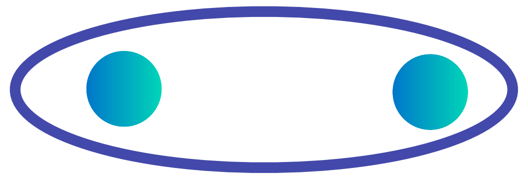
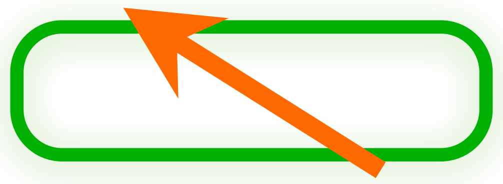
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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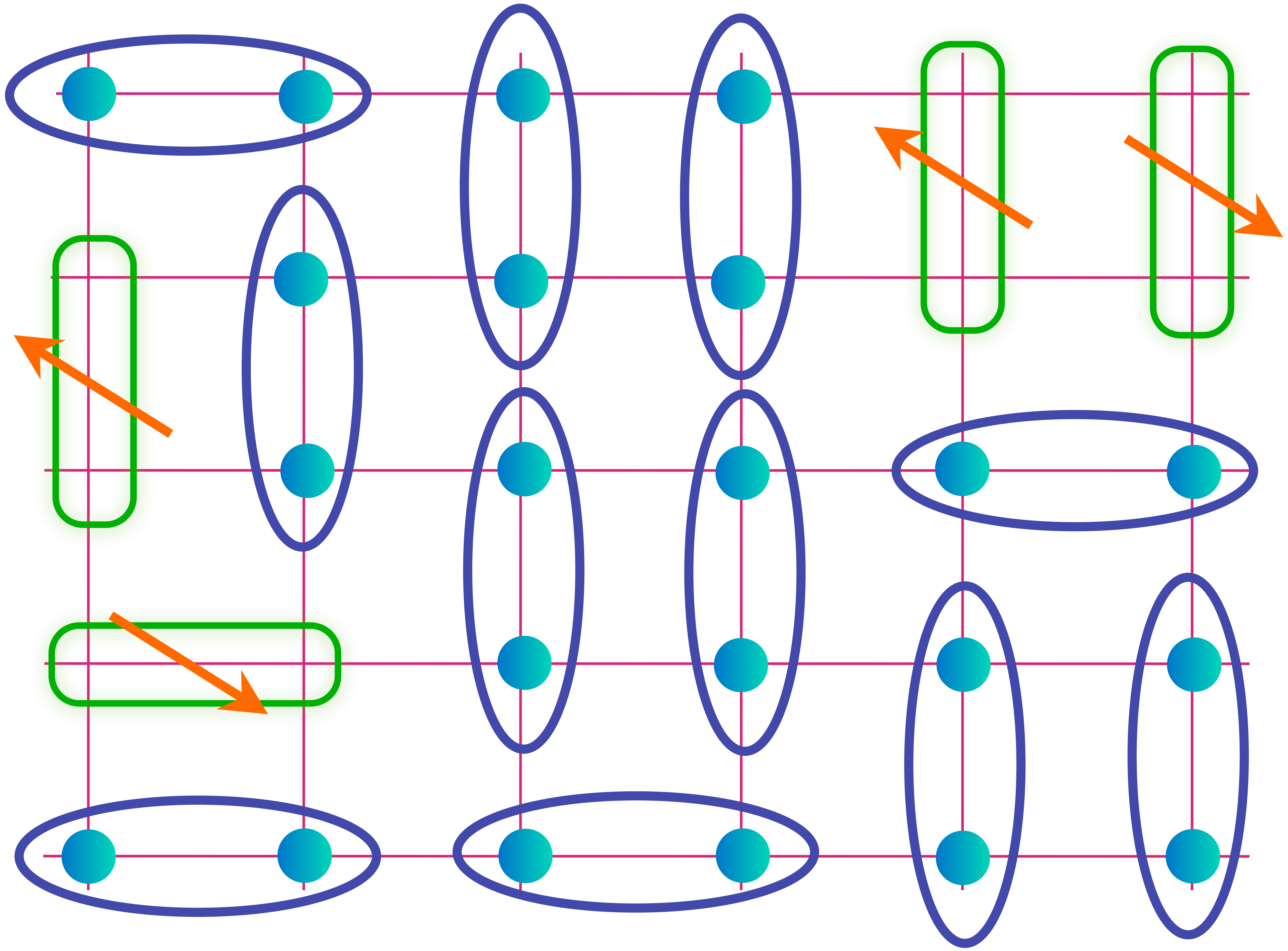
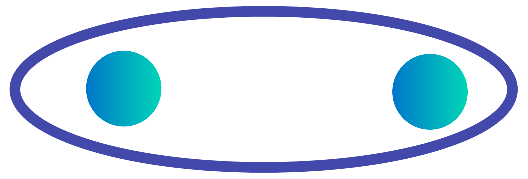
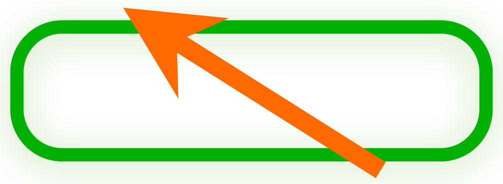


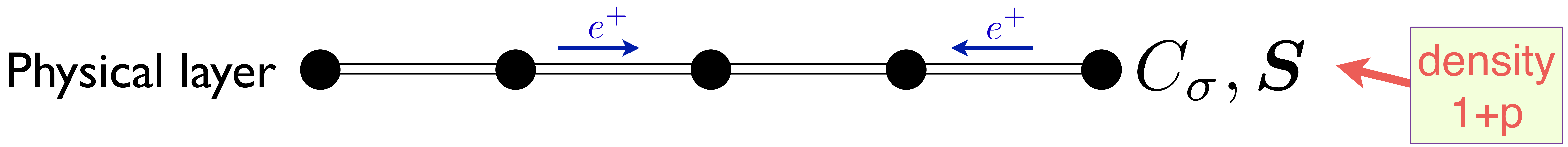
Metal with electron-like quasiparticles on a Fermi surface of size $p$, and emergent gauge fields

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

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

E. G. Moon and S. Sachdev, PRB **83**, 224508 (2011); M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

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



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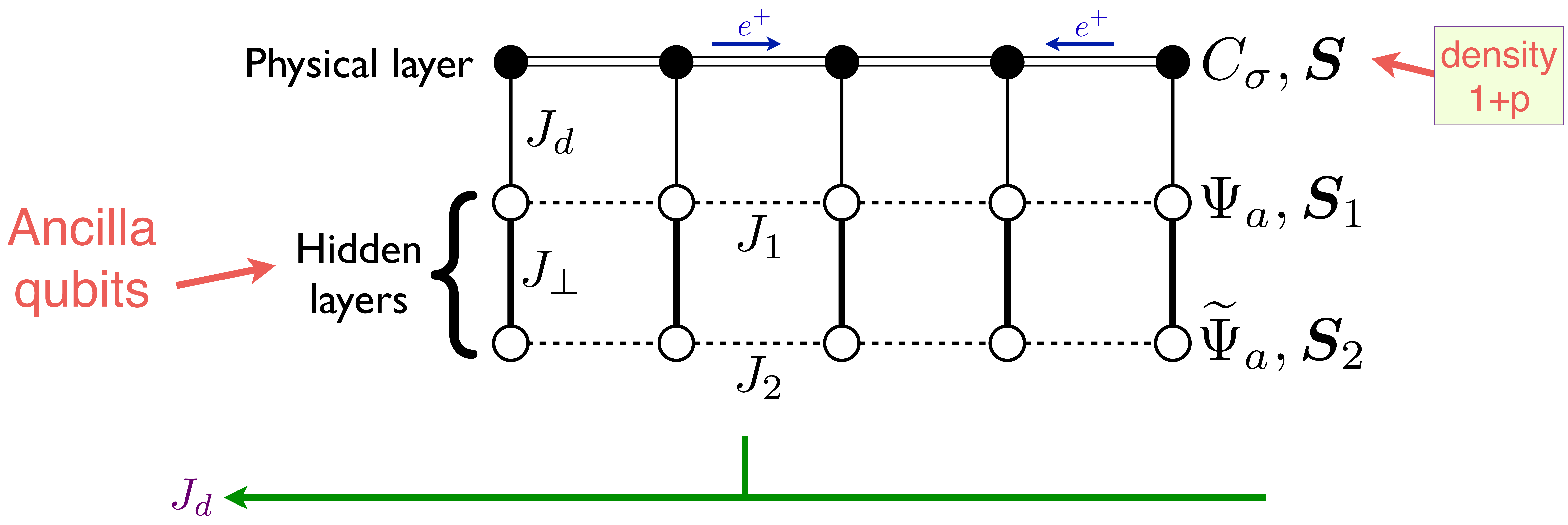



Ya-Hui Zhang

Precursor with one extra band of fermions in FL* phase:
Y. Qi and S. Sachdev, PRB **81**, 115129 (2010)
E. G. Moon and S. Sachdev, PRB **83**, 224508 (2011)

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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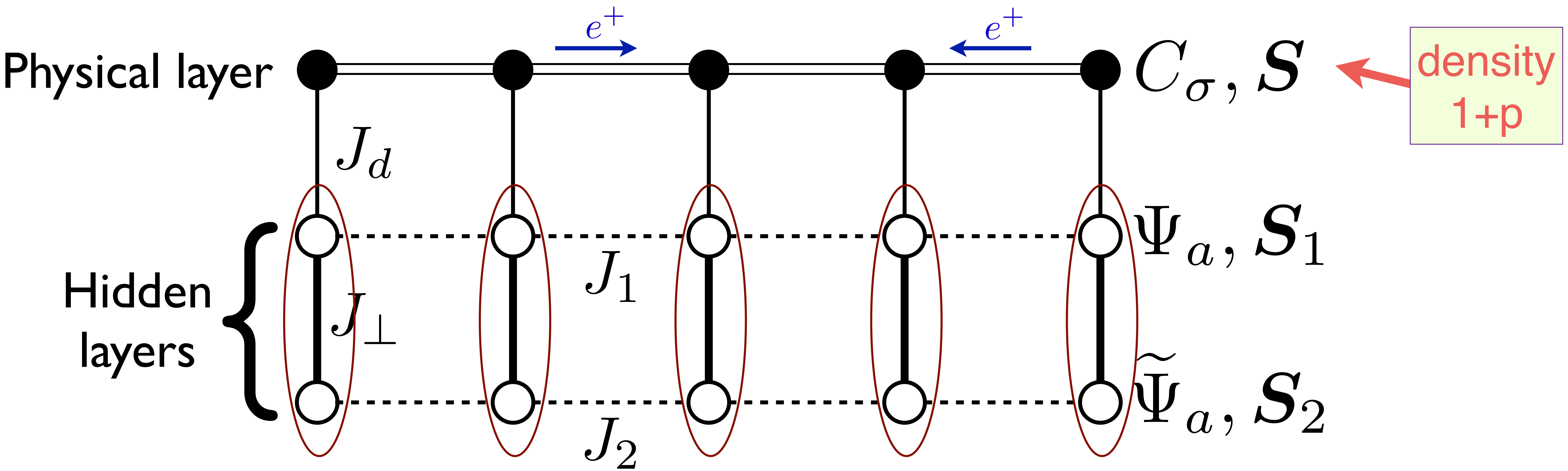


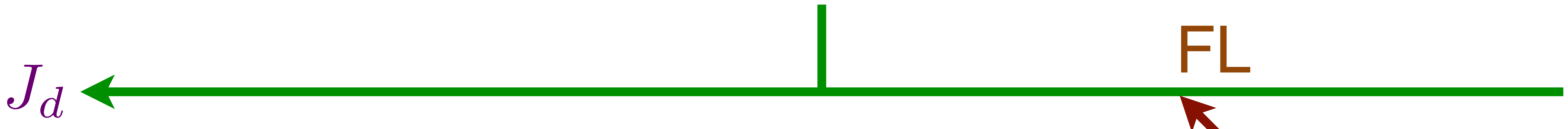


Large Fermi surface of size $1 + p$

$$|\Phi\rangle = \left|\text{Rung singlets of } \Psi, \widetilde{\Psi}\right\rangle \otimes |\text{Slater determinant of } C\rangle$$

Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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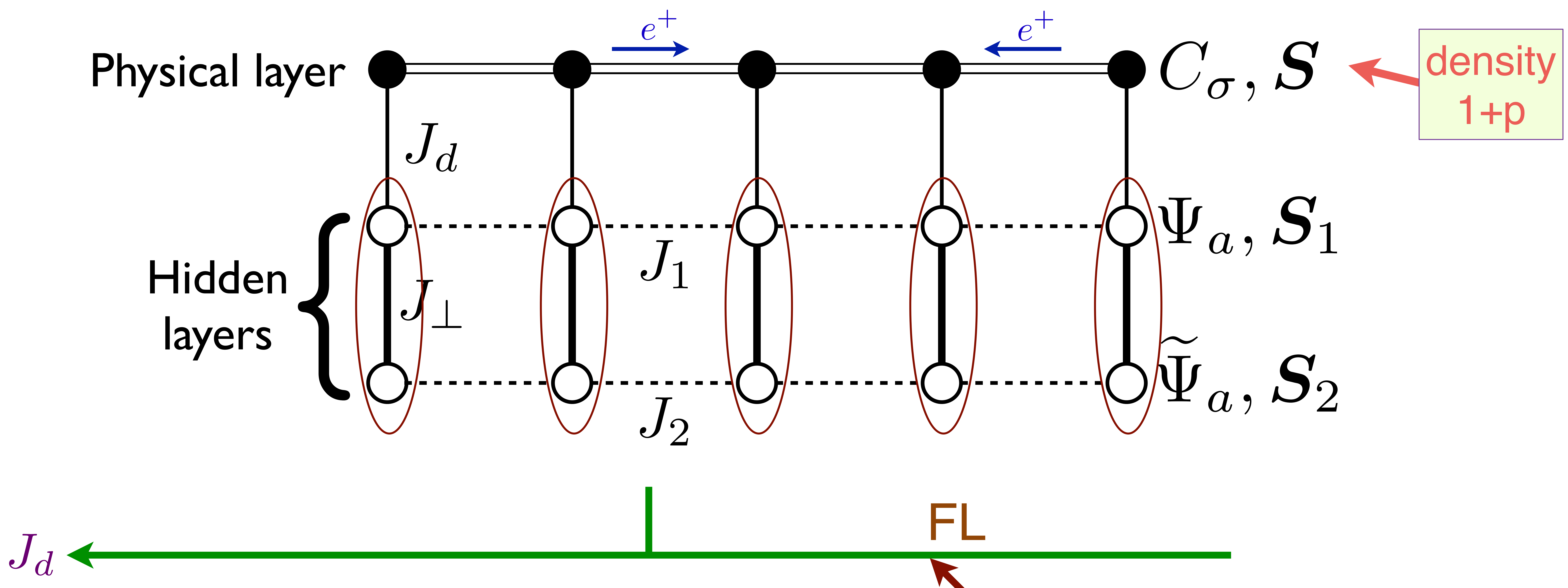



Large Fermi surface of size $1 + p$

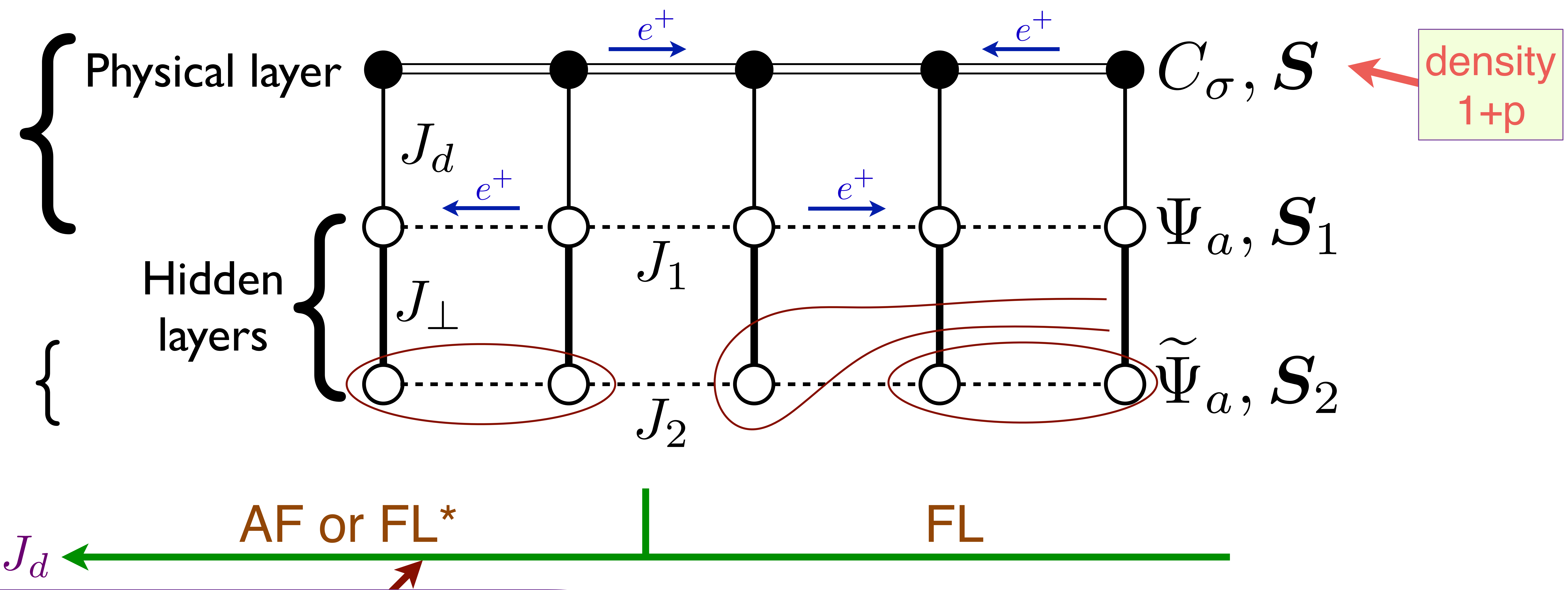
All gauge symmetries are confined.
No fractionalization.

Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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

Metal.
Density
$2 + p \cong p$




Small Fermi surface of size $p$

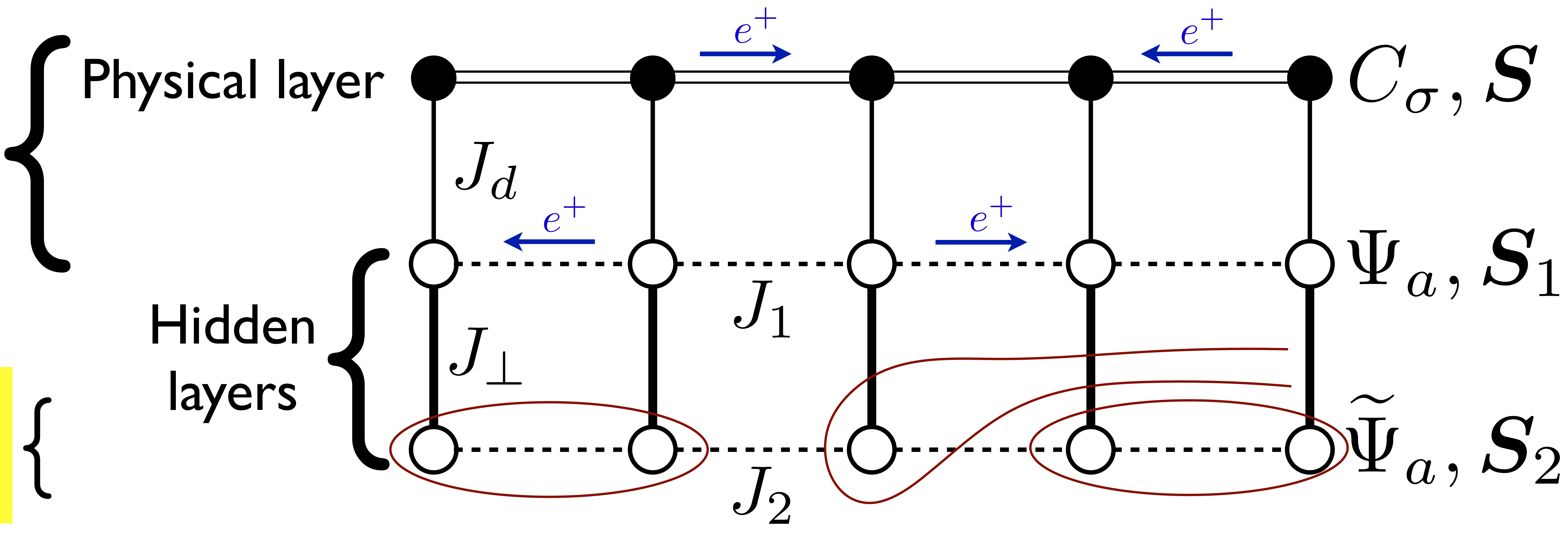
$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie \left|\text{Slater determinant of } (C, \Psi)\right\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

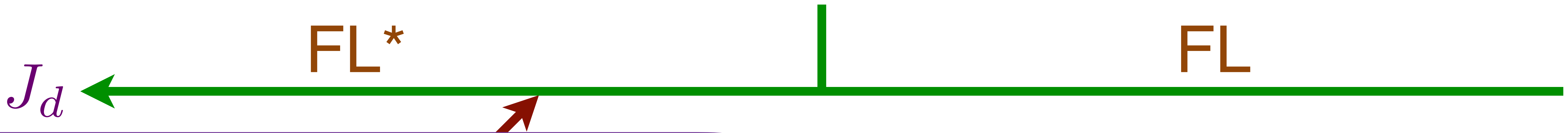
# FL* and FL in a ***one-band*** model

Metal.
Density
$2 + p \cong p$

Mott insulator
Spin liquid




density
1+p




Small Fermi surface of size $p$

$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right]$$
$$\bowtie \left|\text{Slater determinant of } (C, \Psi)\right\rangle$$
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Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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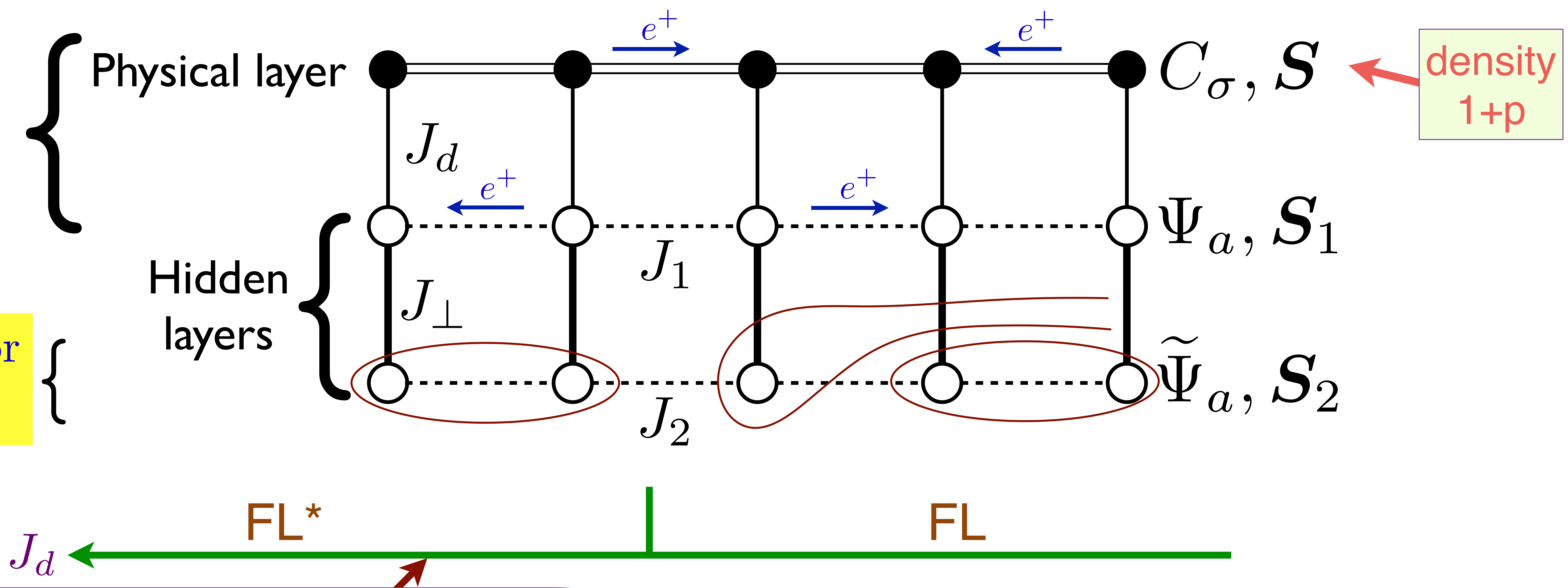
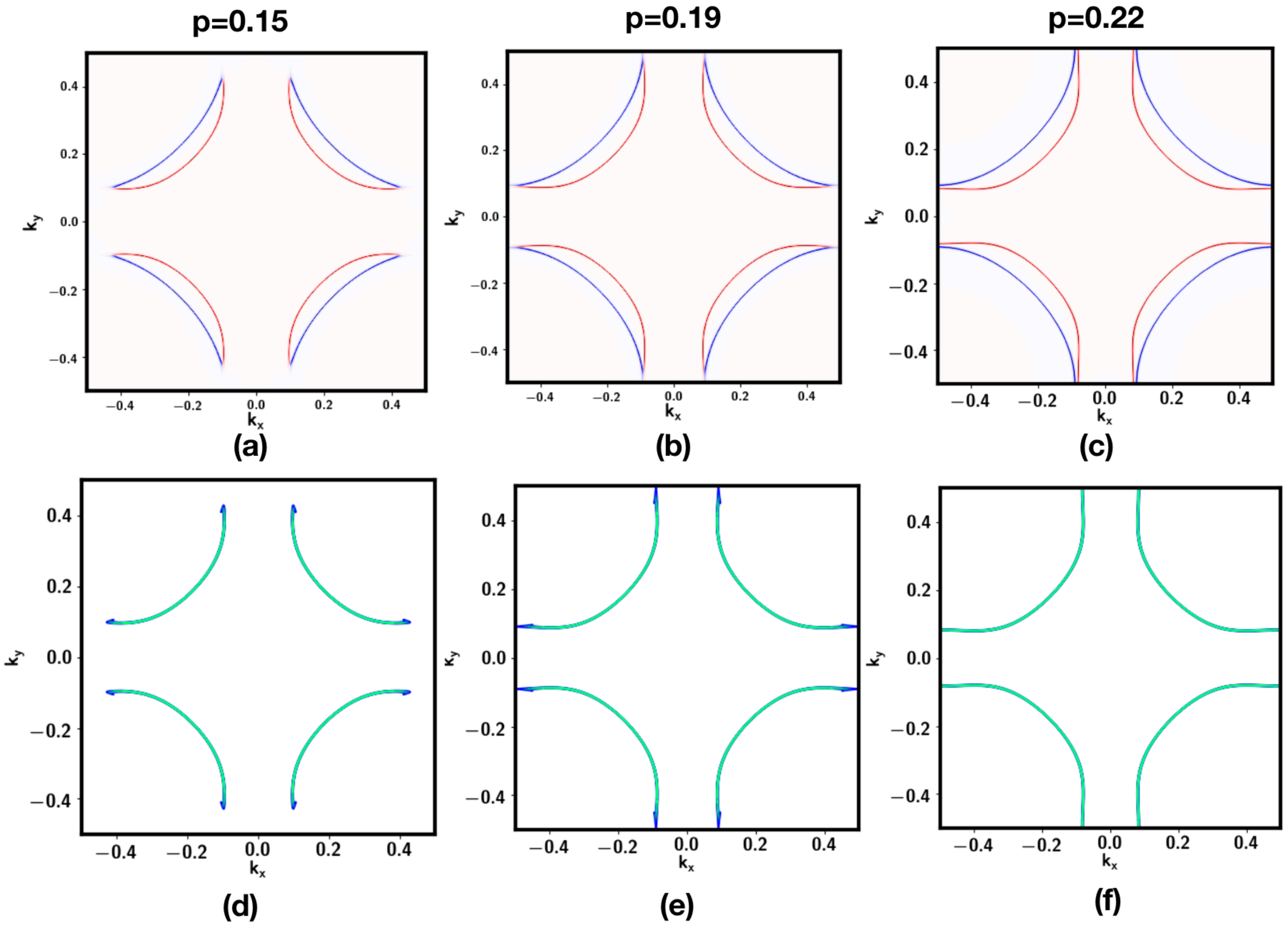



Small Fermi surface of size $p$

Gauge symmetry on $\Psi$ layer is Higgsed.
Gauge symmetry on $\widetilde{\Psi}$ layer is deconfined.
Fractionalization is present.

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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



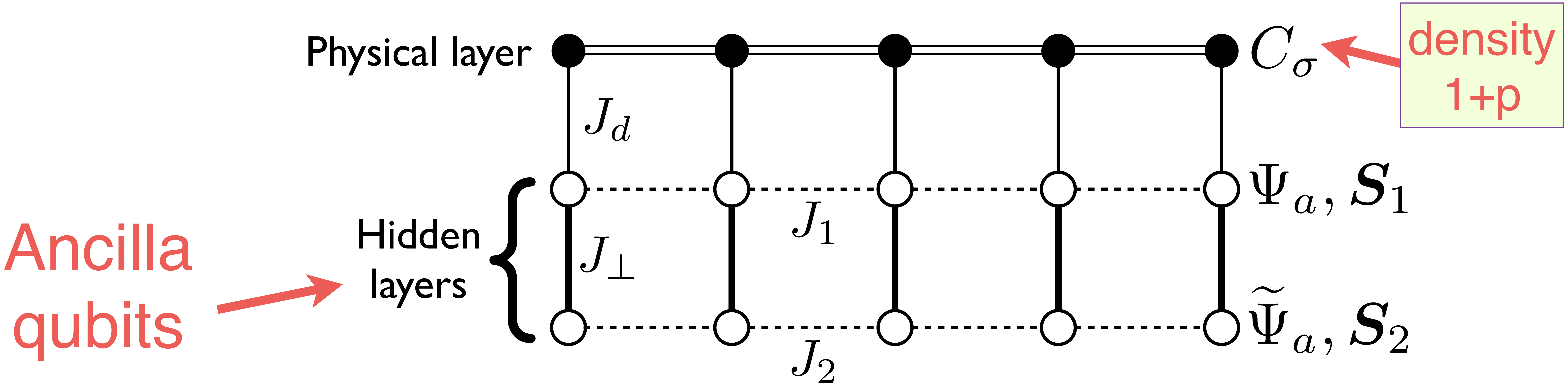

Zero frequency spectral density of electrons (red) and ghosts (blue)

"Fermi arc" spectral functions in the FL* phase

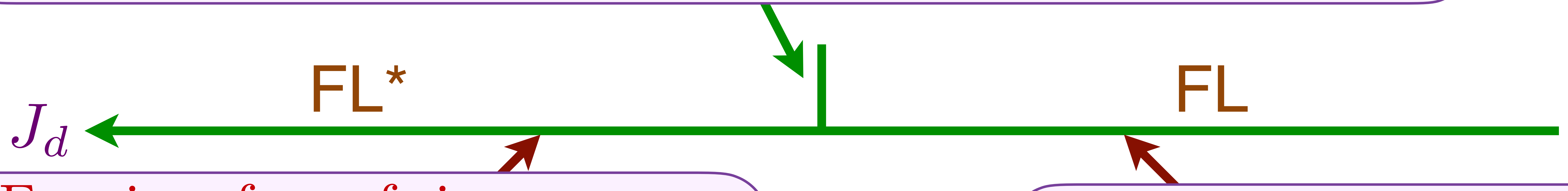
Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

# Metal-metal transitions in a ***one-band*** model




$(\mathrm{SU}(2)_S \times \mathrm{U}(1)_1)/Z_2$ gauge theory of a $\Psi$ ghost Fermi surface and a 'hybridization-Higgs' boson $\sim C_\sigma^\dagger \Psi_a$ which condenses on the 'Small Fermi surface' side.




Small Fermi surface of size $p$

Gauge symmetry on $\Psi$ layer is Higgsed.
Gauge symmetry on $\widetilde{\Psi}$ layer is deconfined.
Fractionalization is present.

Large Fermi surface of size $1 + p$

All gauge symmetries are confined.
No fractionalization.

See also Liujun Zou, D. Chowdhury, PRR **2**, 023344 (2020)

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

# FL*

- Evidence for a FL* phase in a Kondo lattice: $CeCoIn_5$. (Also in CePdAl, Zhao *et al.*, Nature Physics **15**, 1261 (2019))

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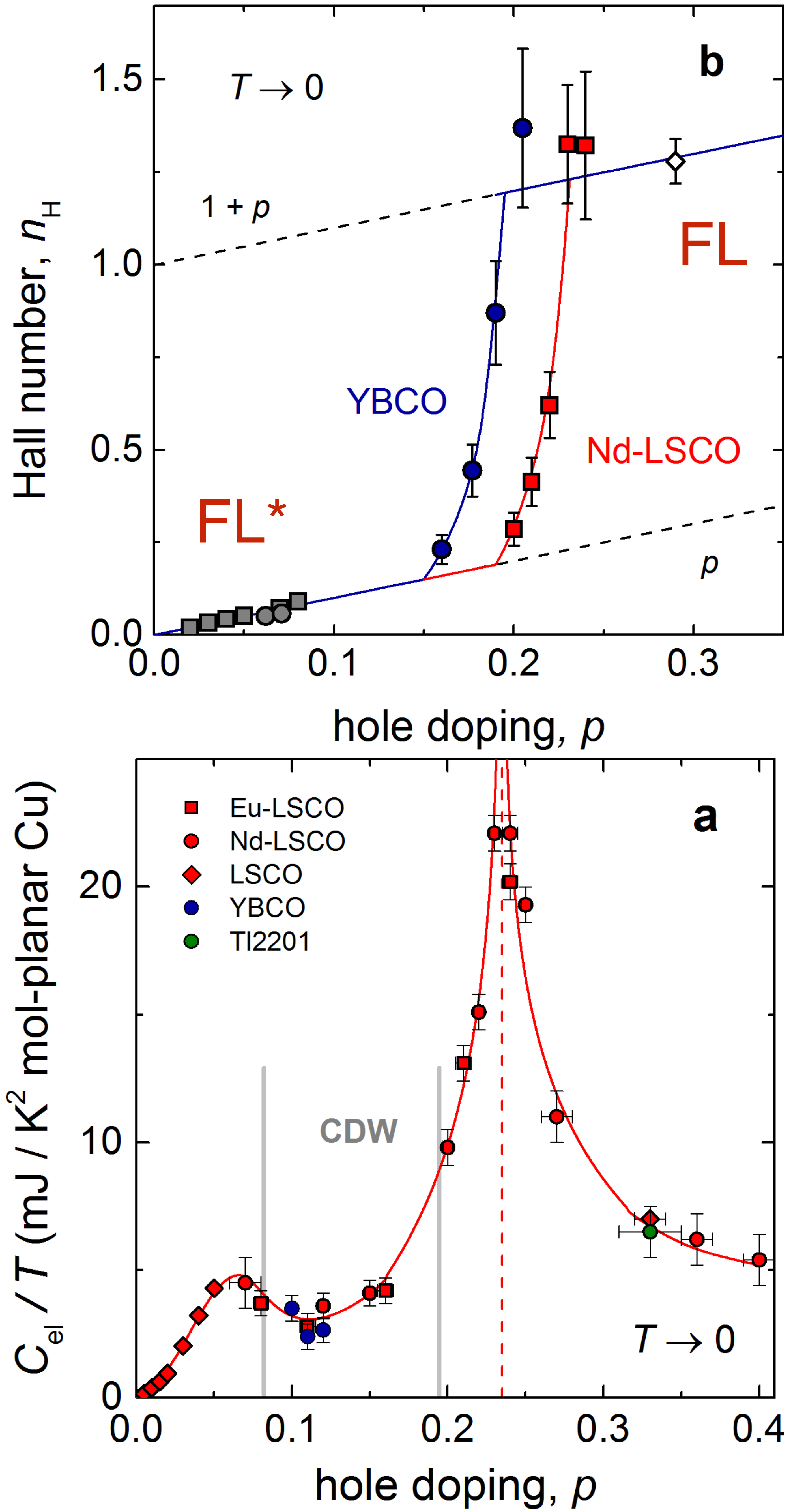
- Theory for a FL* phase in a $t$-$J$ model for cuprates: ancilla qubits. This achieves a 'democratic' localization of some of the electrons into an insulator of spins, while the others form a Luttinger-volume-violating Fermi surface.

- Ancilla method yields a SU(2)×U(1) gauge theory for a metal-metal quantum phase transition with a change in carrier density from $p$ in a FL* phase, to $1 + p$ in a FL phase. Prediction: critical 'ghost' Fermi surfaces near the transition.

# Cuprates




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

# CeCoIn₅