Emergent "light" and the high temperature superconductors

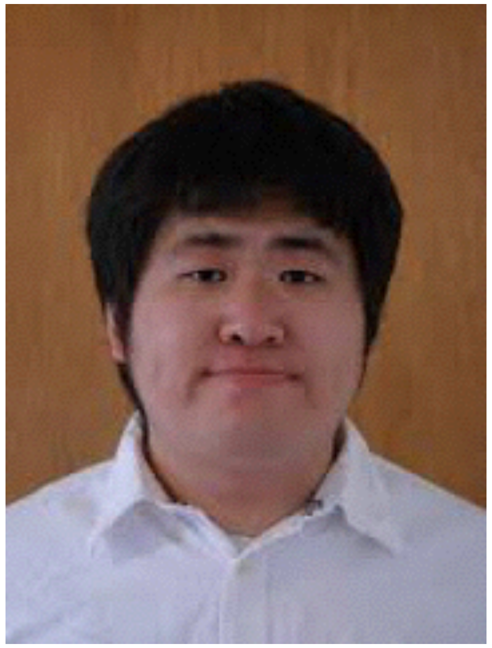
Perimeter Institute
January 19, 2016

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

Debanjan Chowdhury

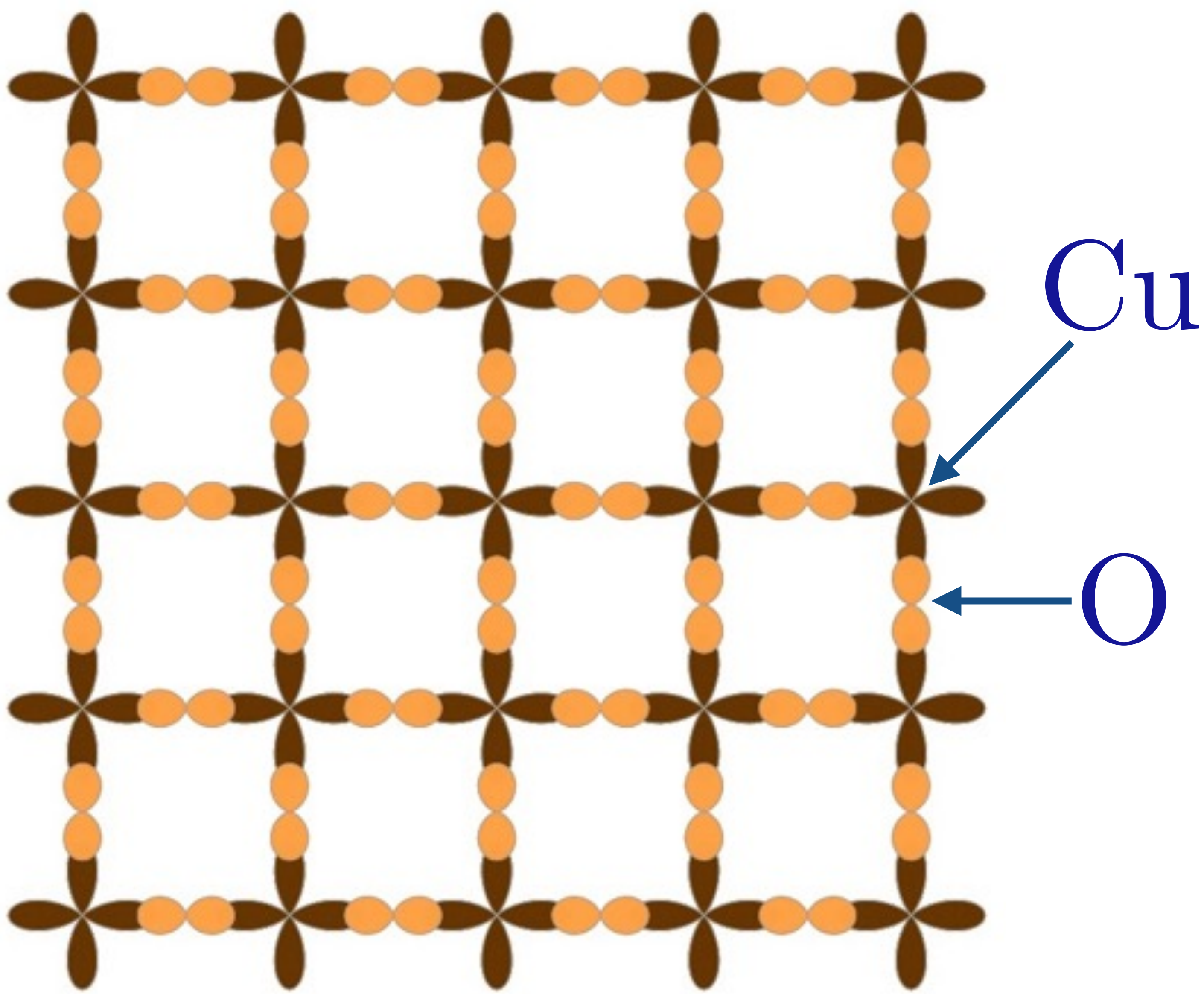
Andrea Allais



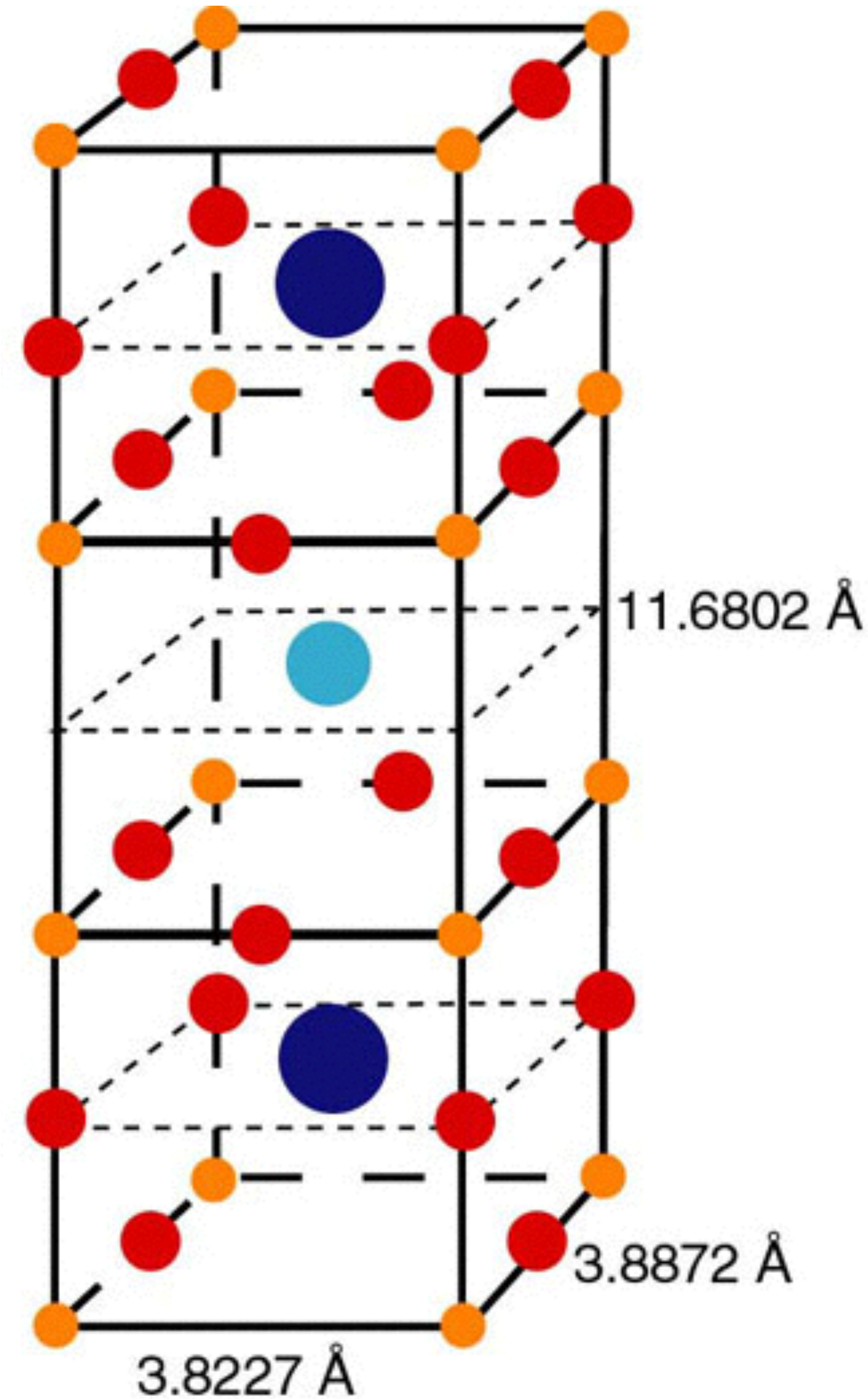
Yang Qi

Matthias Punk

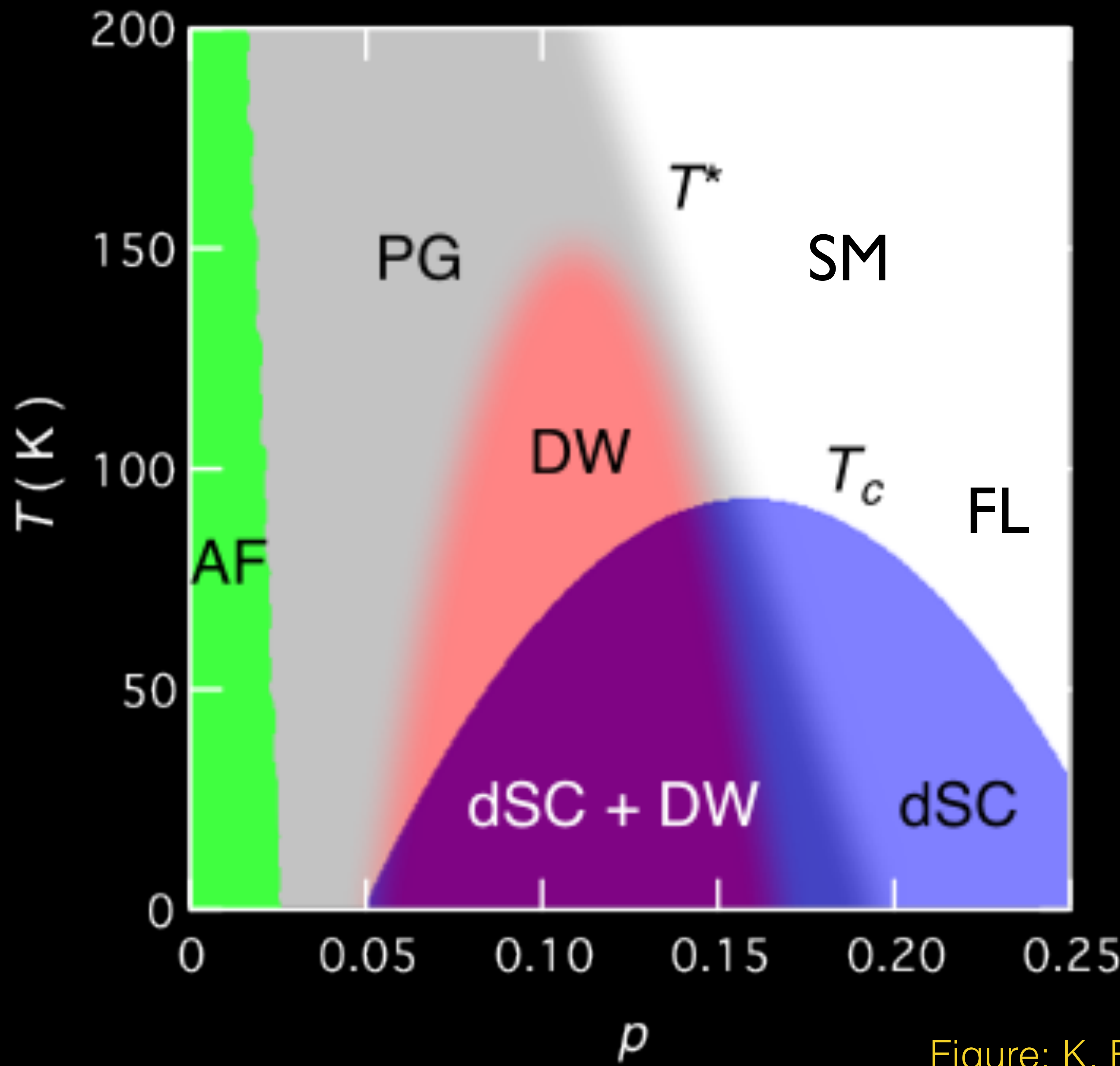
High temperature superconductors



CuO_2 plane



$YBa_2Cu_3O_{6+x}$



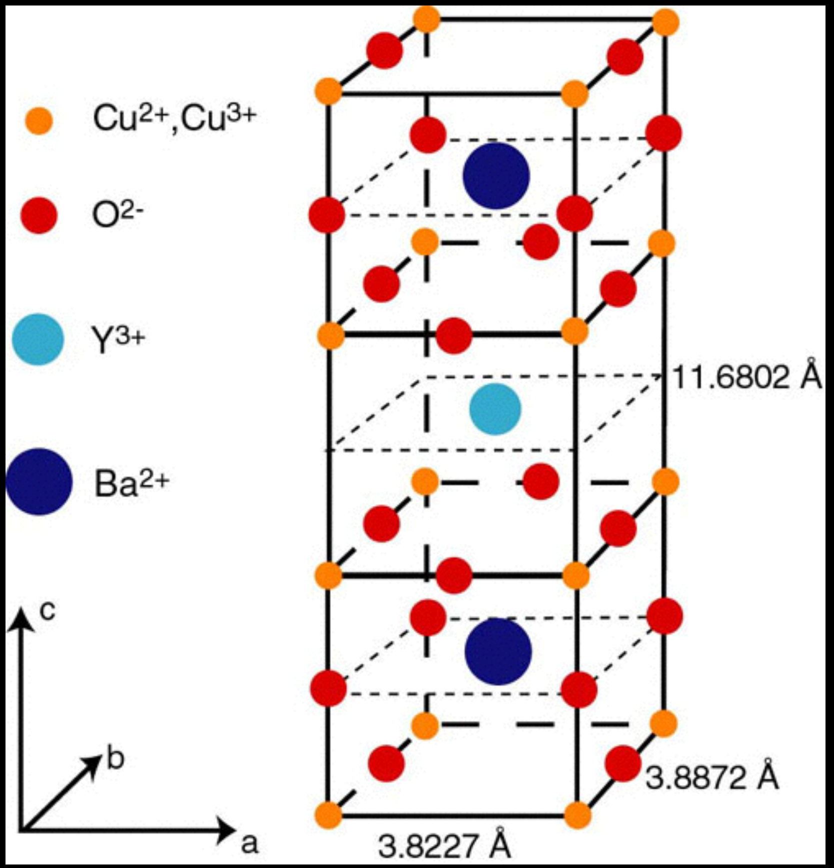


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Figure: K. Fujita and J. C. Seamus Davis

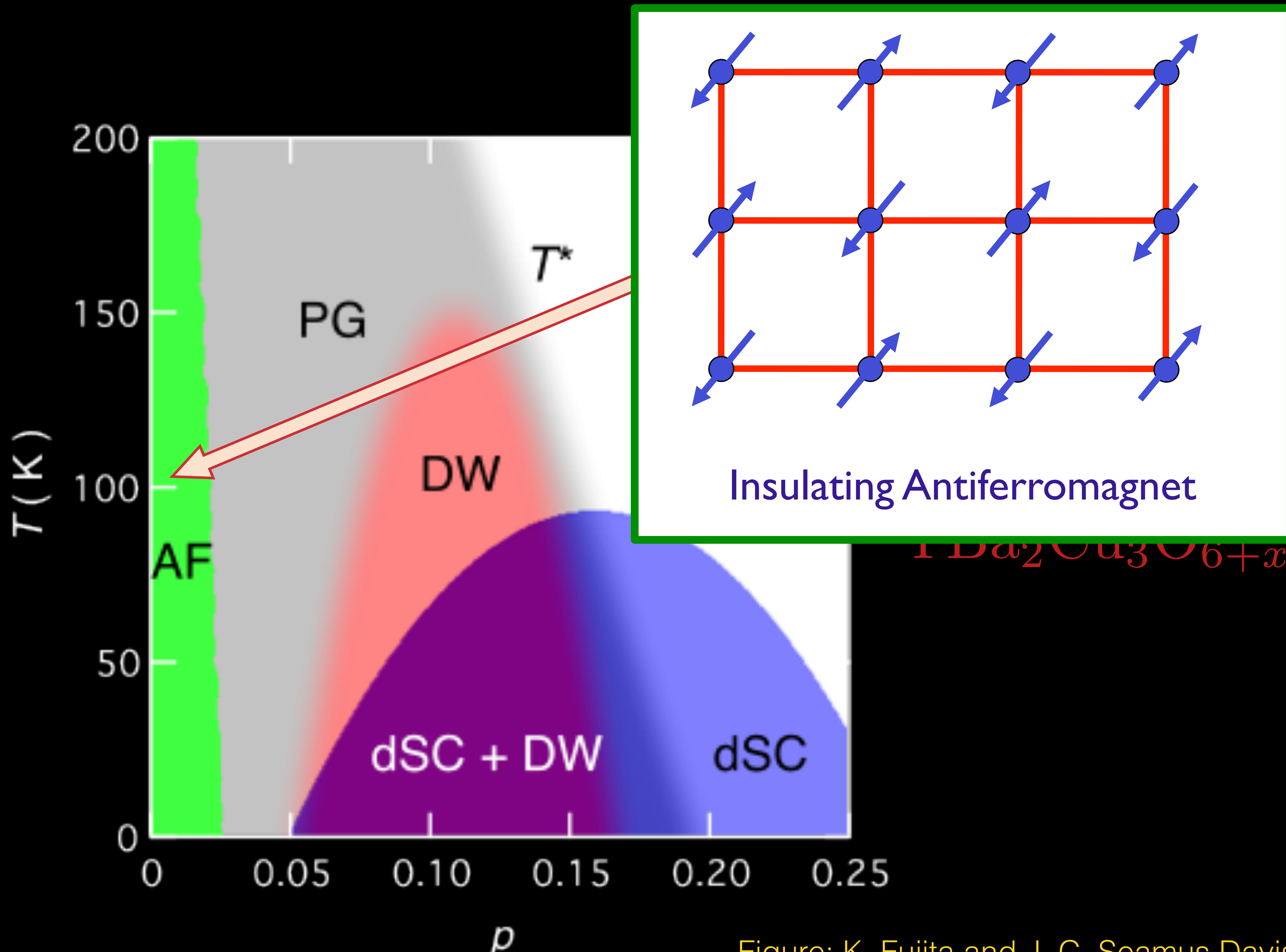
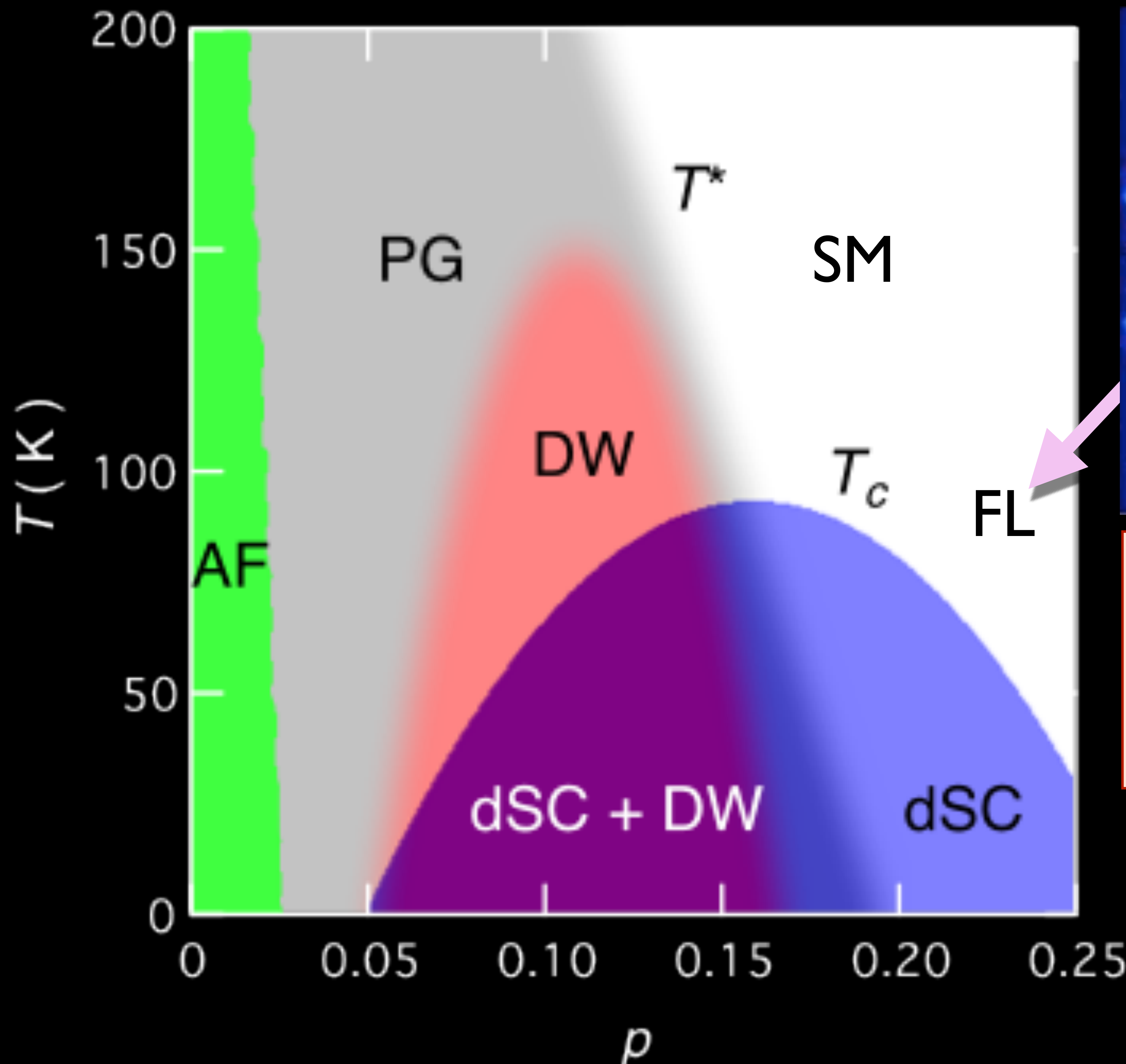
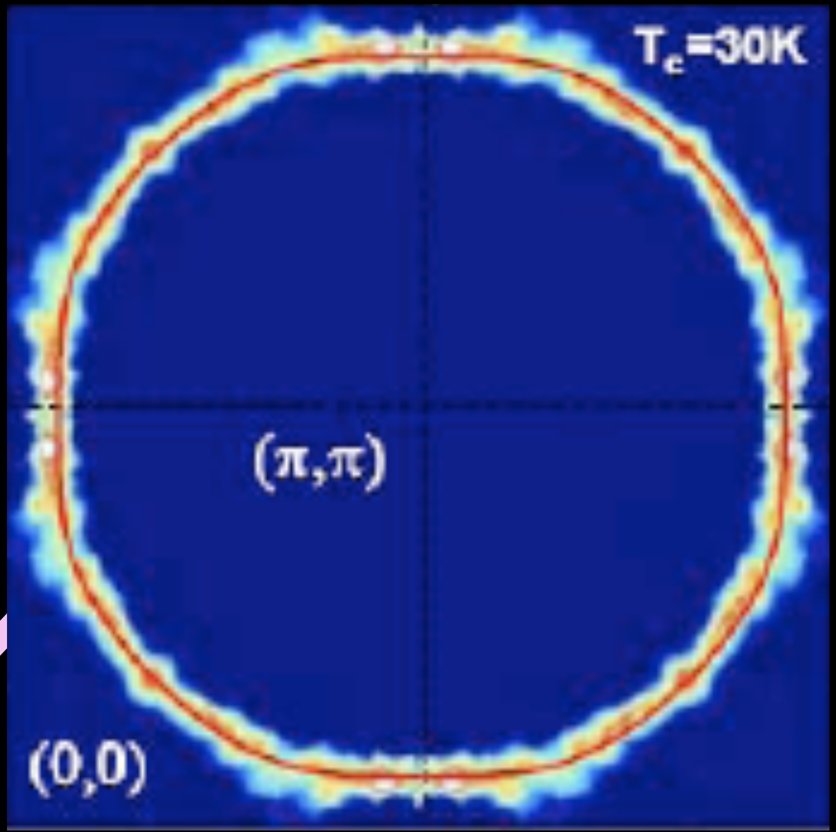


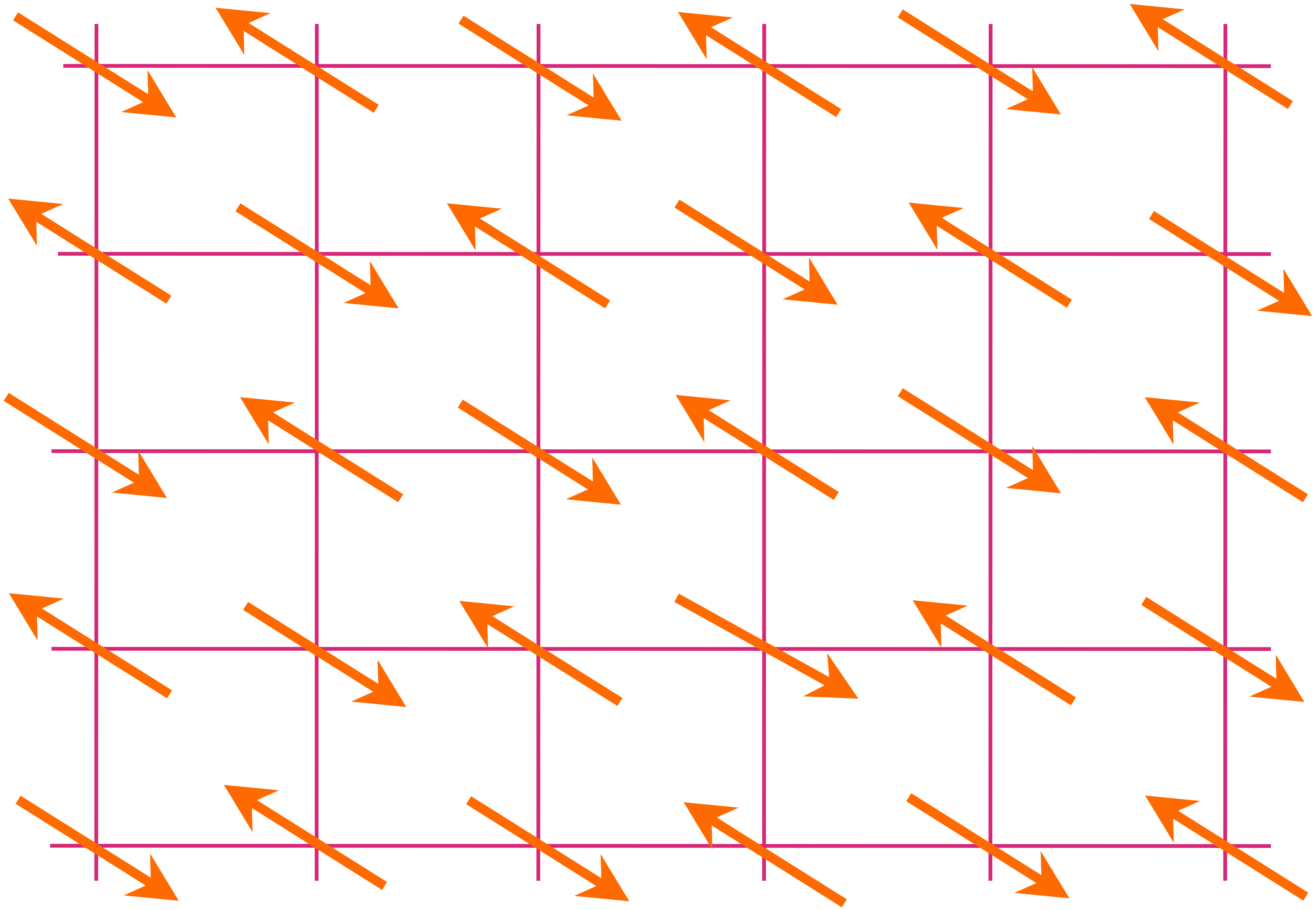
Figure: K. Fujita and J. C. Seamus Davis

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)

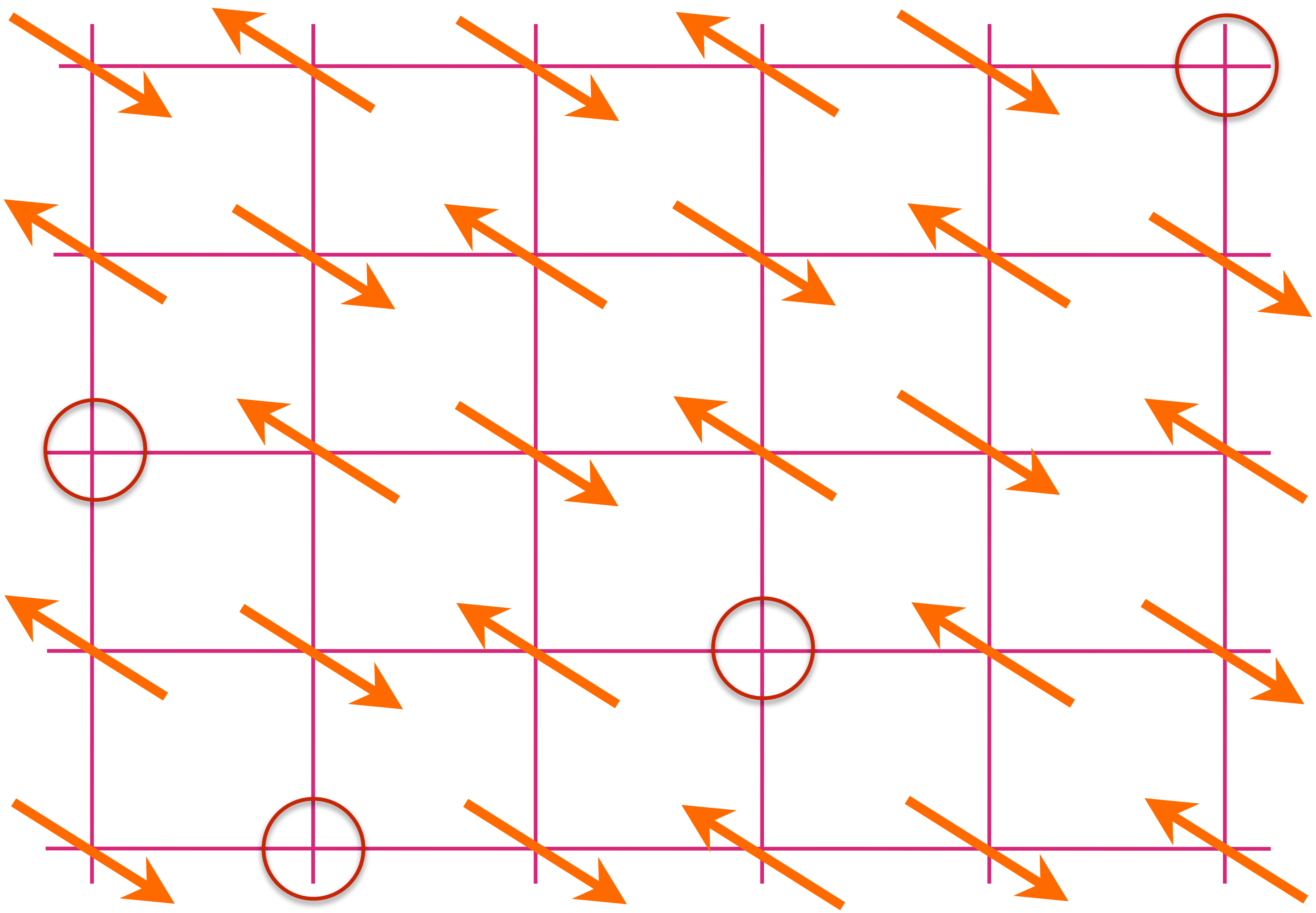




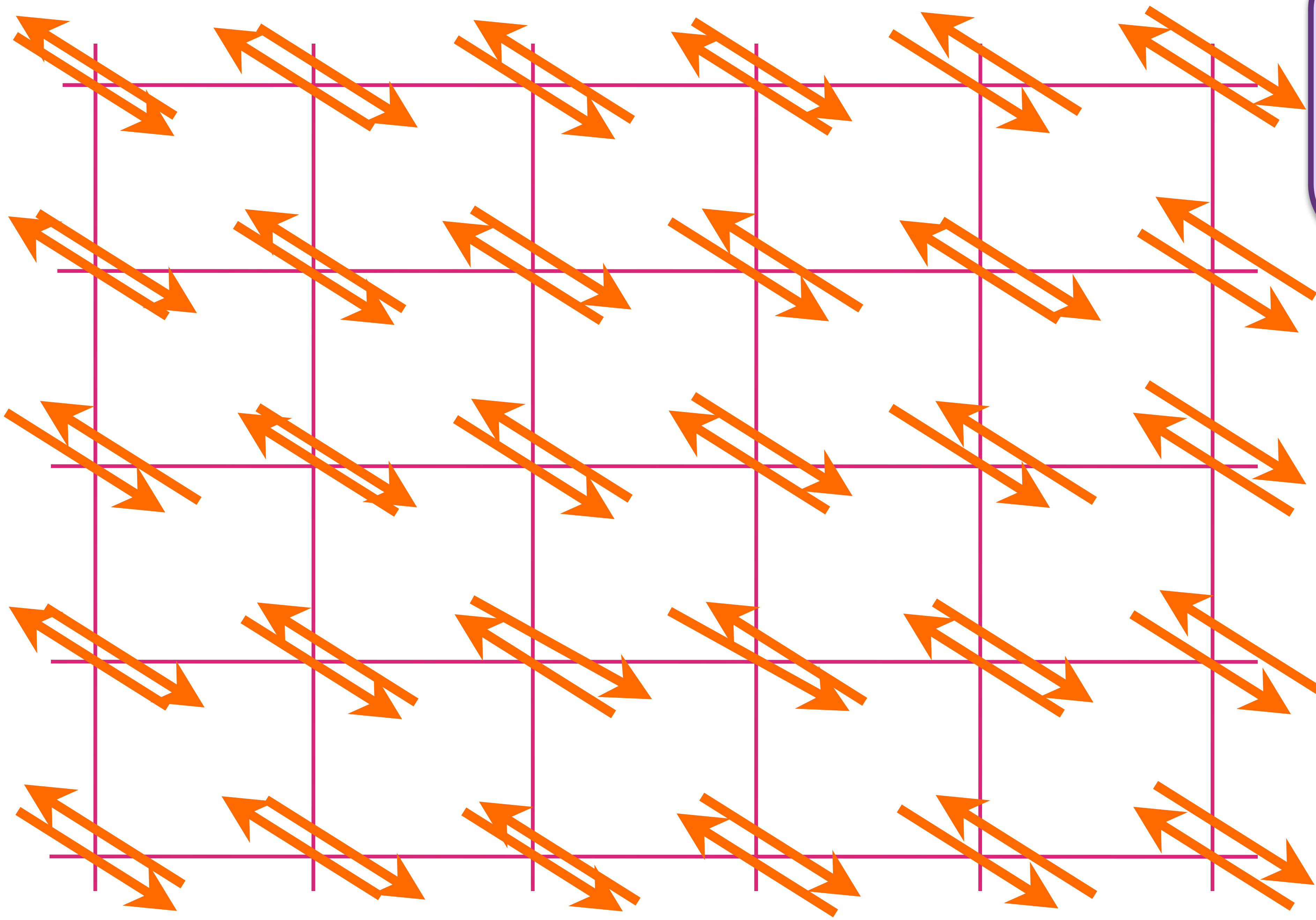
A conventional metal: the Fermi liquid



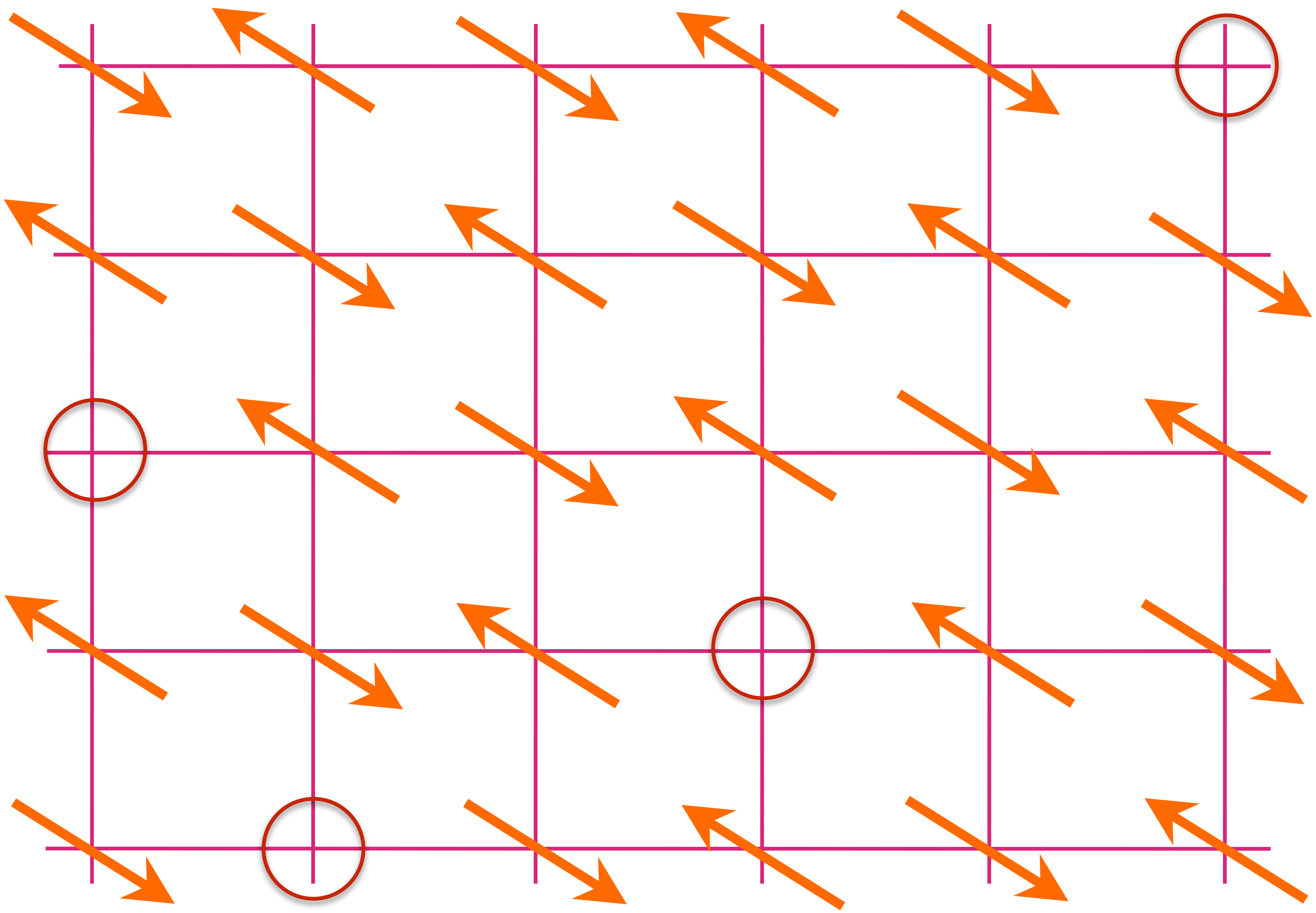
“Undoped” Anti-ferromagnet



Anti-ferromagnet with p holes per square



Filled Band



Anti-ferromagnet with p holes per square

But relative to the band insulator, there are $1+p$ holes per square, and so a Fermi liquid has a Fermi surface of size $1+p$

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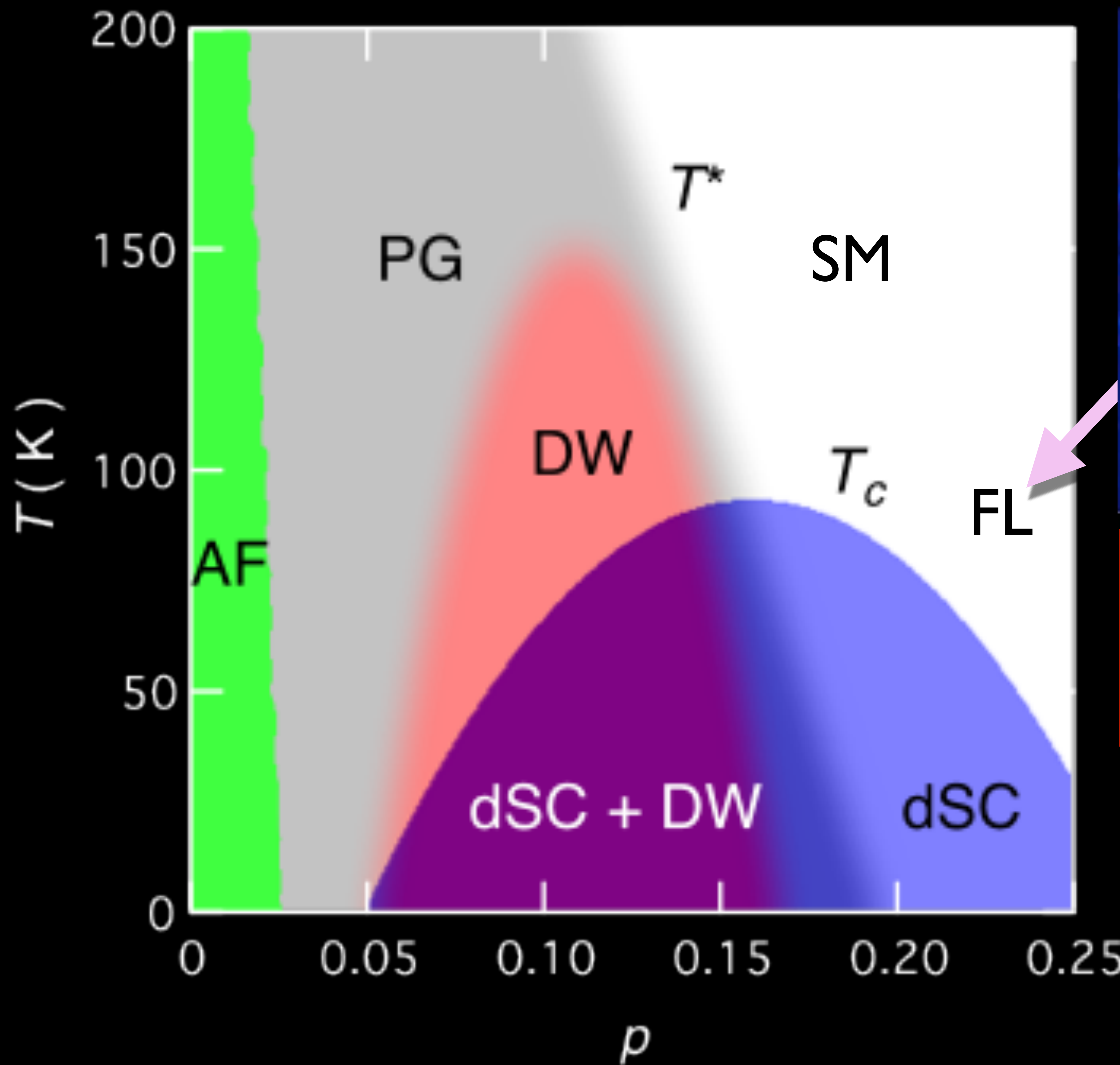
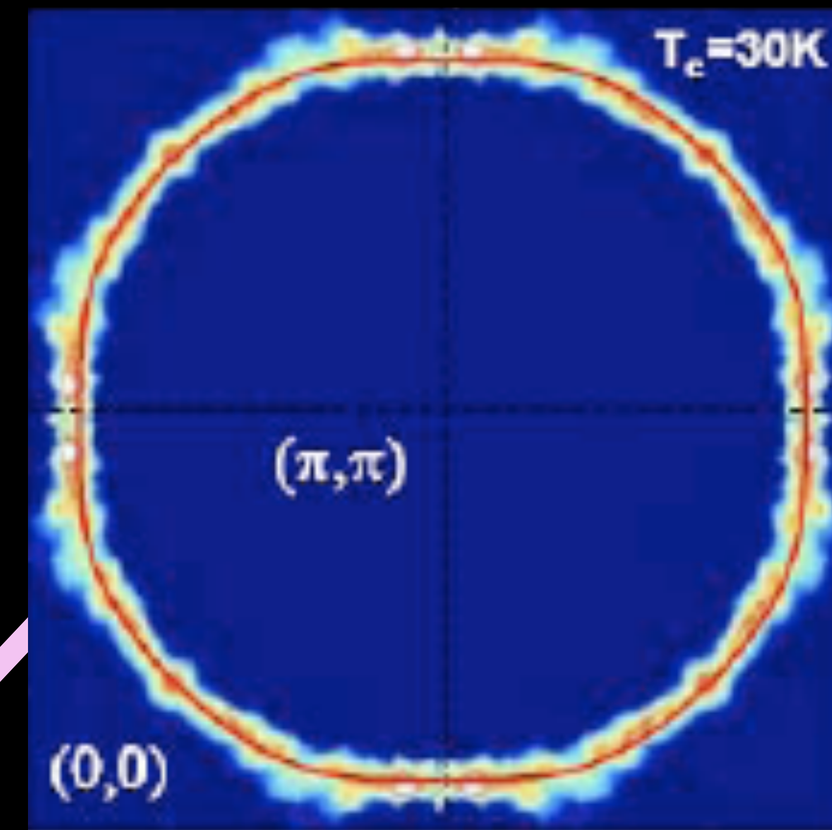
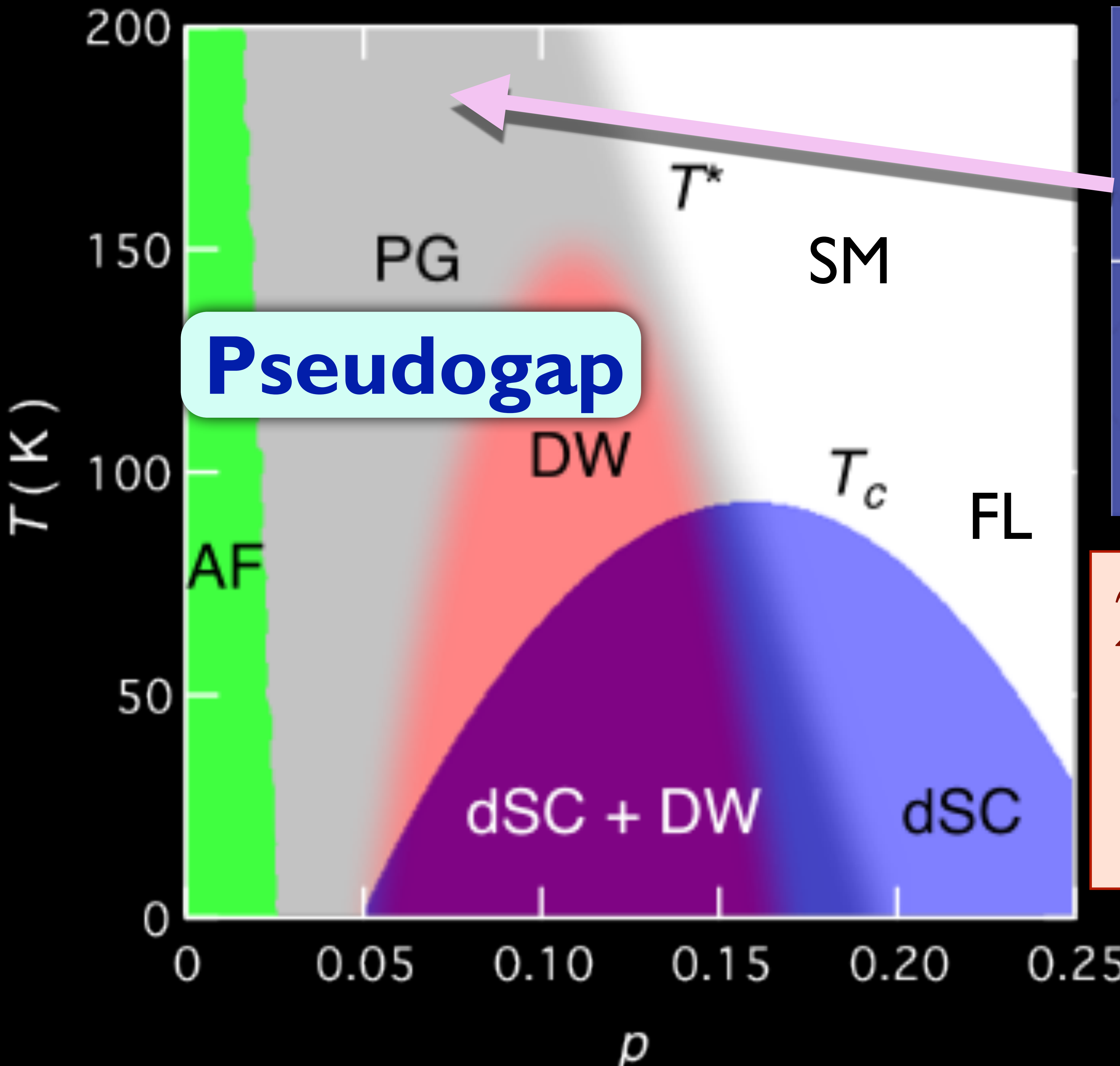


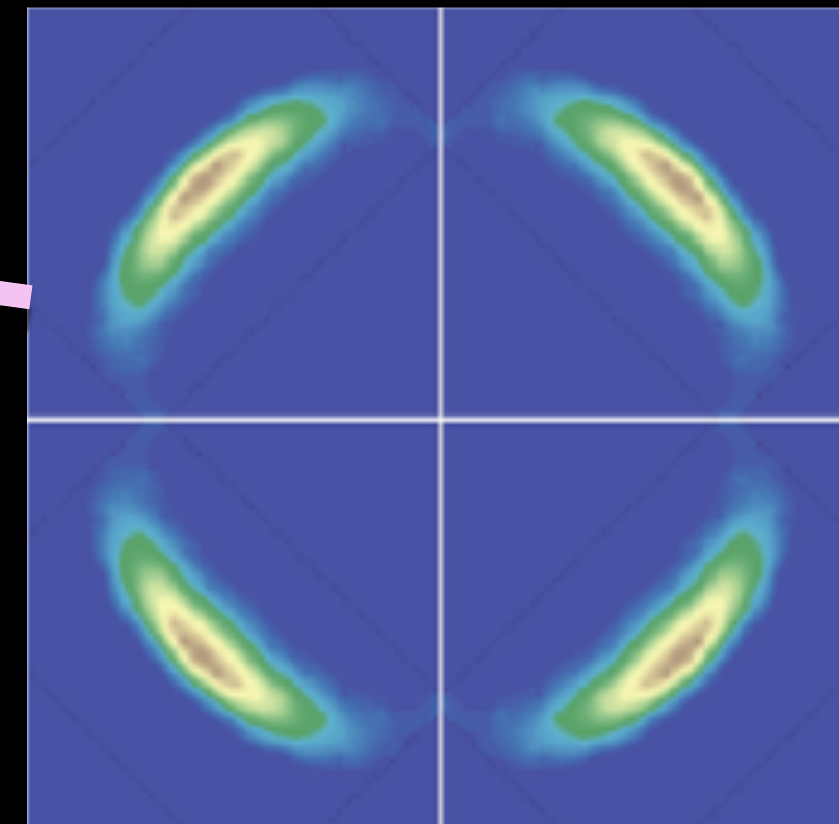


Fermi liquid

Area enclosed by Fermi surface $=1+p$

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)





2. Pseudogap metal at low p

Is the higher temperature pseudogap (with ``Fermi arc'' spectra) described by

(A) Thermal fluctuations of the low temperature orders (superconductivity, density wave, antiferromagnetism…)

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OR

(C) The possibilities (A) and (B) are merely two limits of the same physics?

Is the higher temperature pseudogap (with ``Fermi arc'' spectra) described by

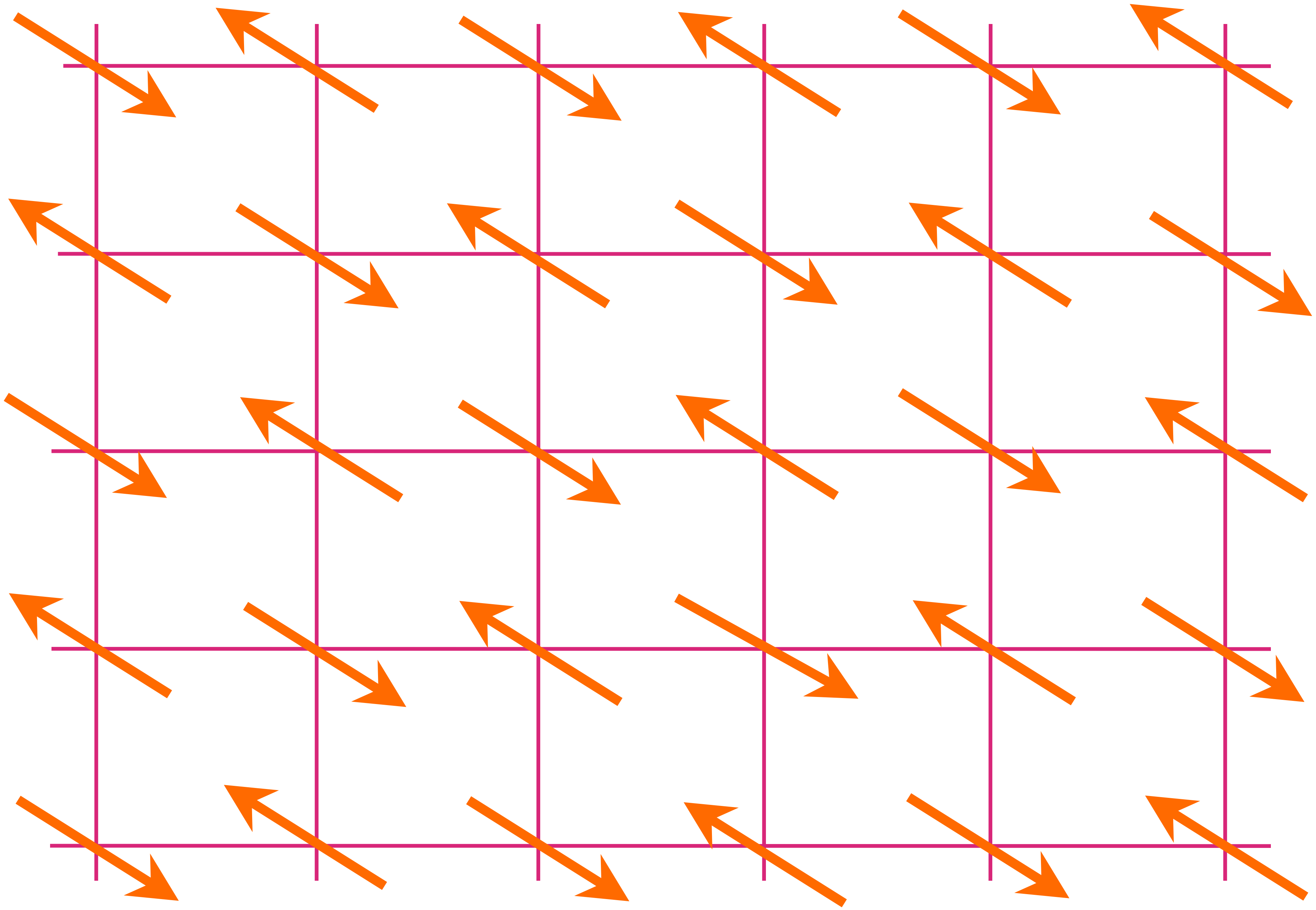
(A) Thermal fluctuations of the low

Answer (B) must have "emergent" gauge fields, and these are (in principle) detectable in low temperature experiments. There are also qualitative differences between (A) and (B) at higher temperatures.

OR

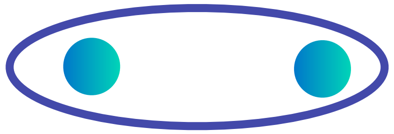
(C) The possibilities (A) and (B) are merely two limits of the same physics?

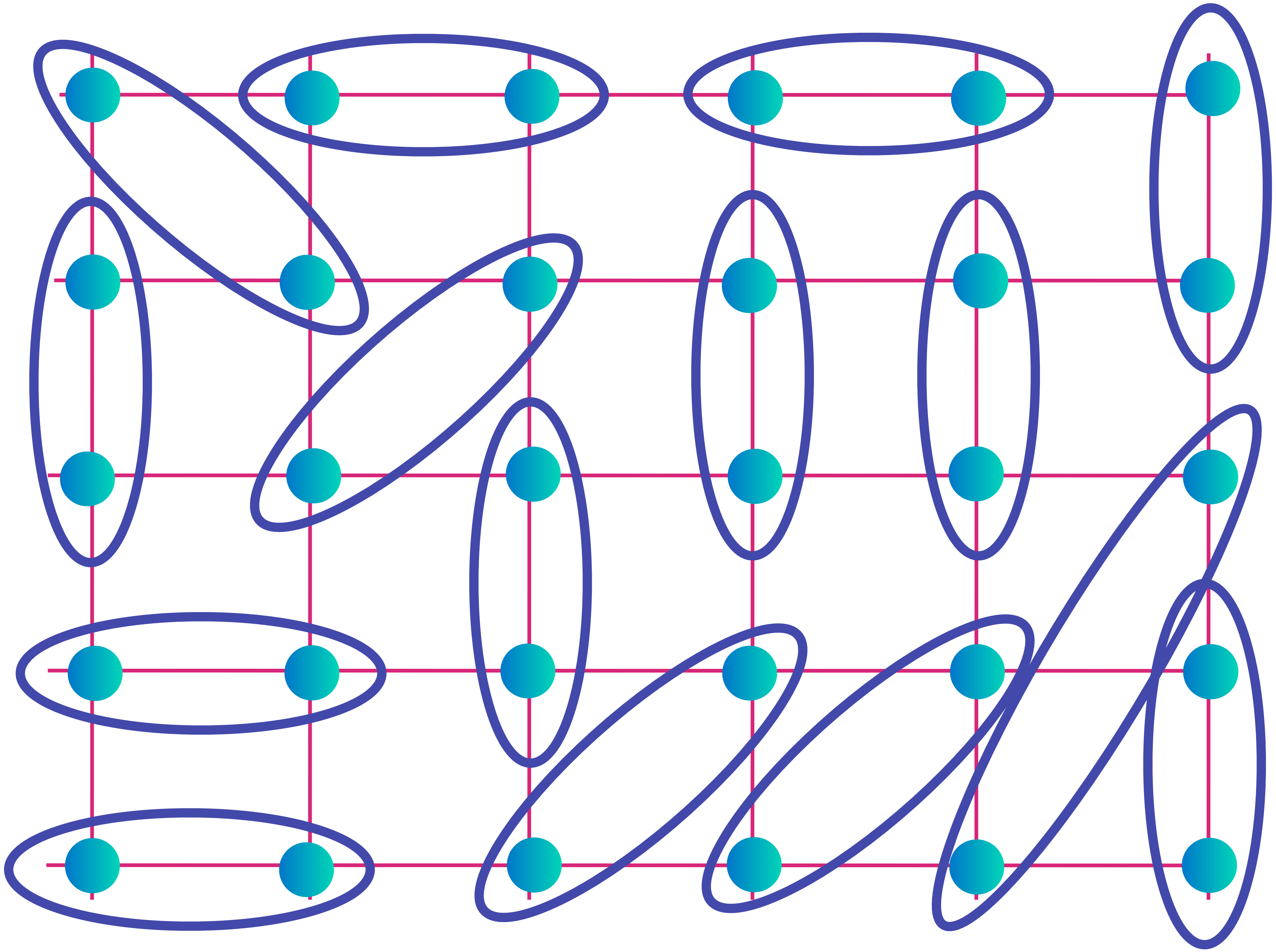
1. Emergent gauge fields and long-range entanglement in insulators



“Undoped” Anti-ferromagnet

Insulating spin liquid


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



An insulator with emergent gauge fields and long-range entanglement

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P. W. Anderson, Materials Research Bulletin **8**, 153 (1973)

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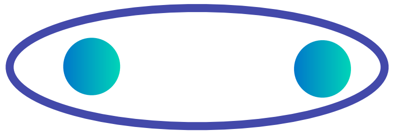

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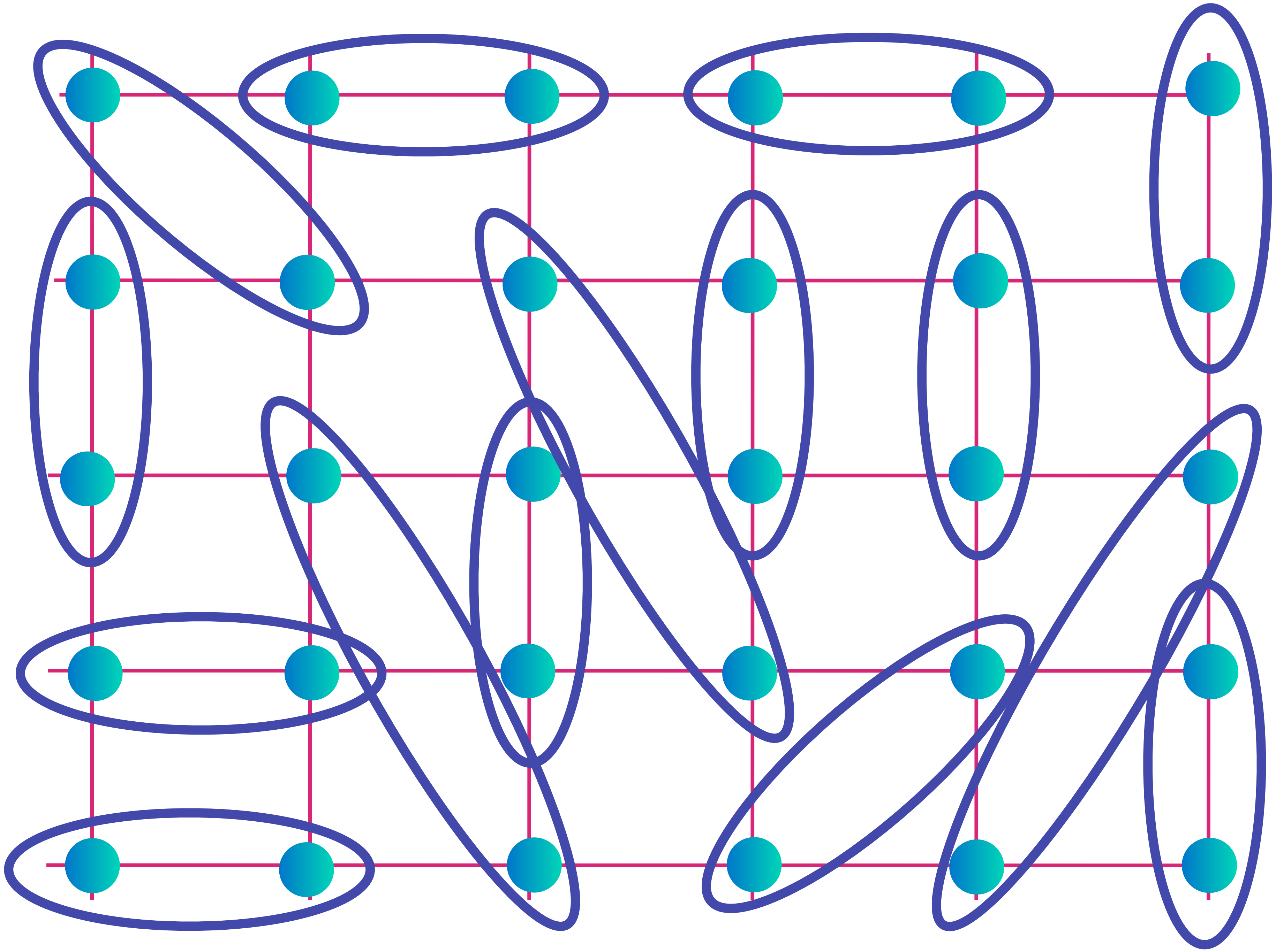

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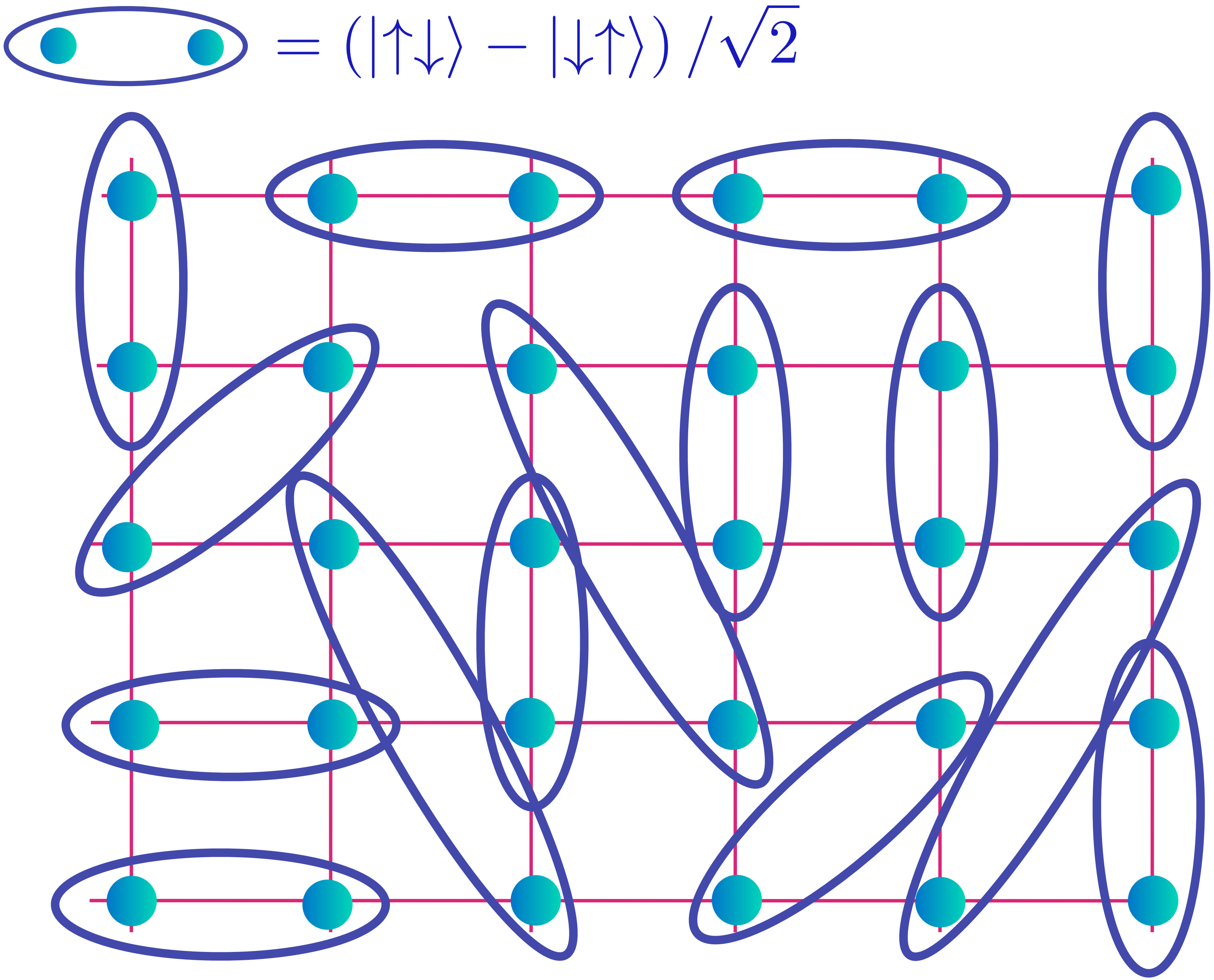

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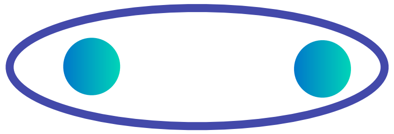
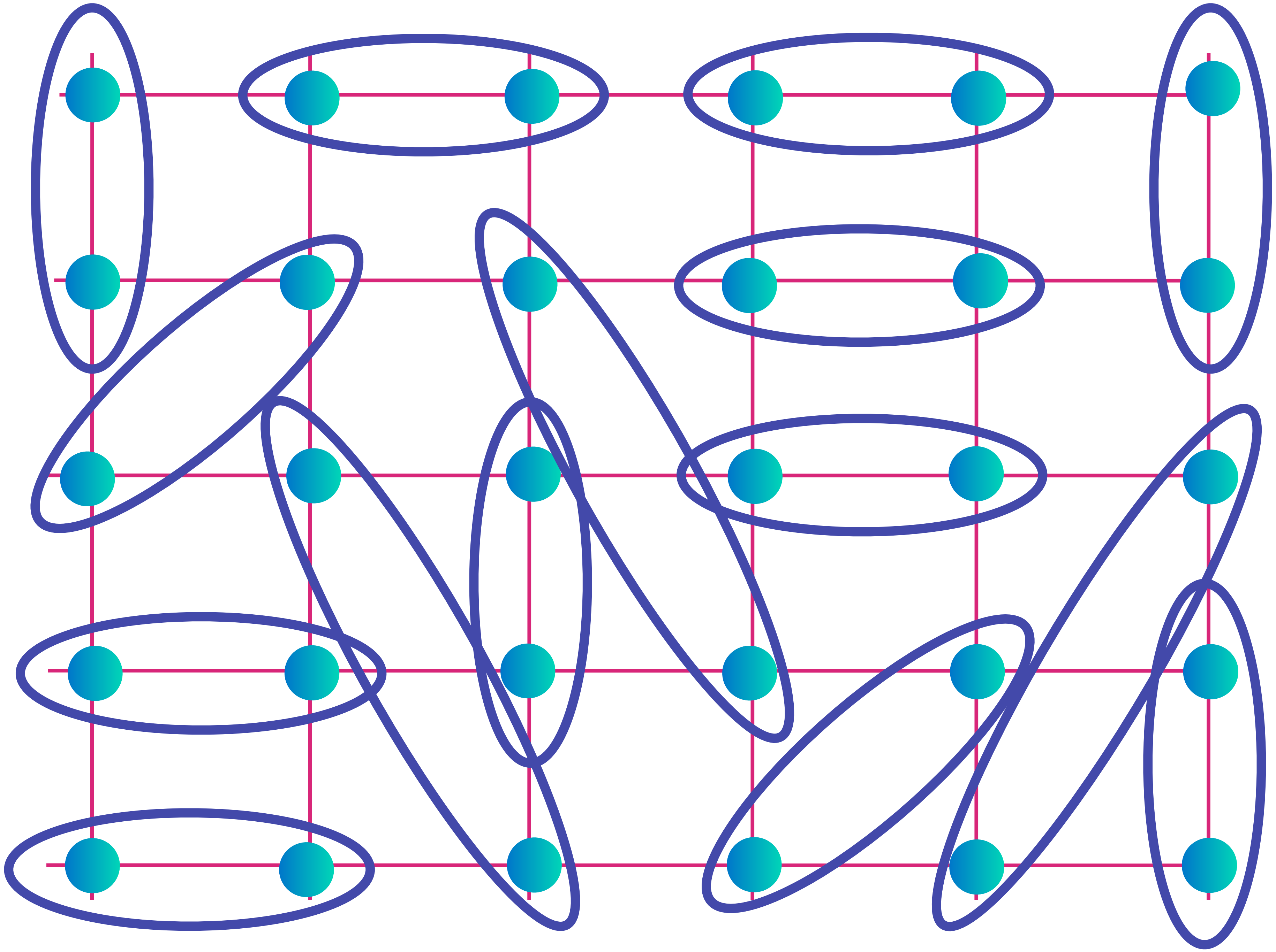
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



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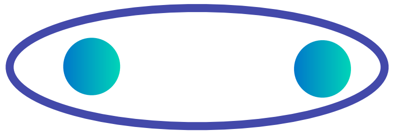

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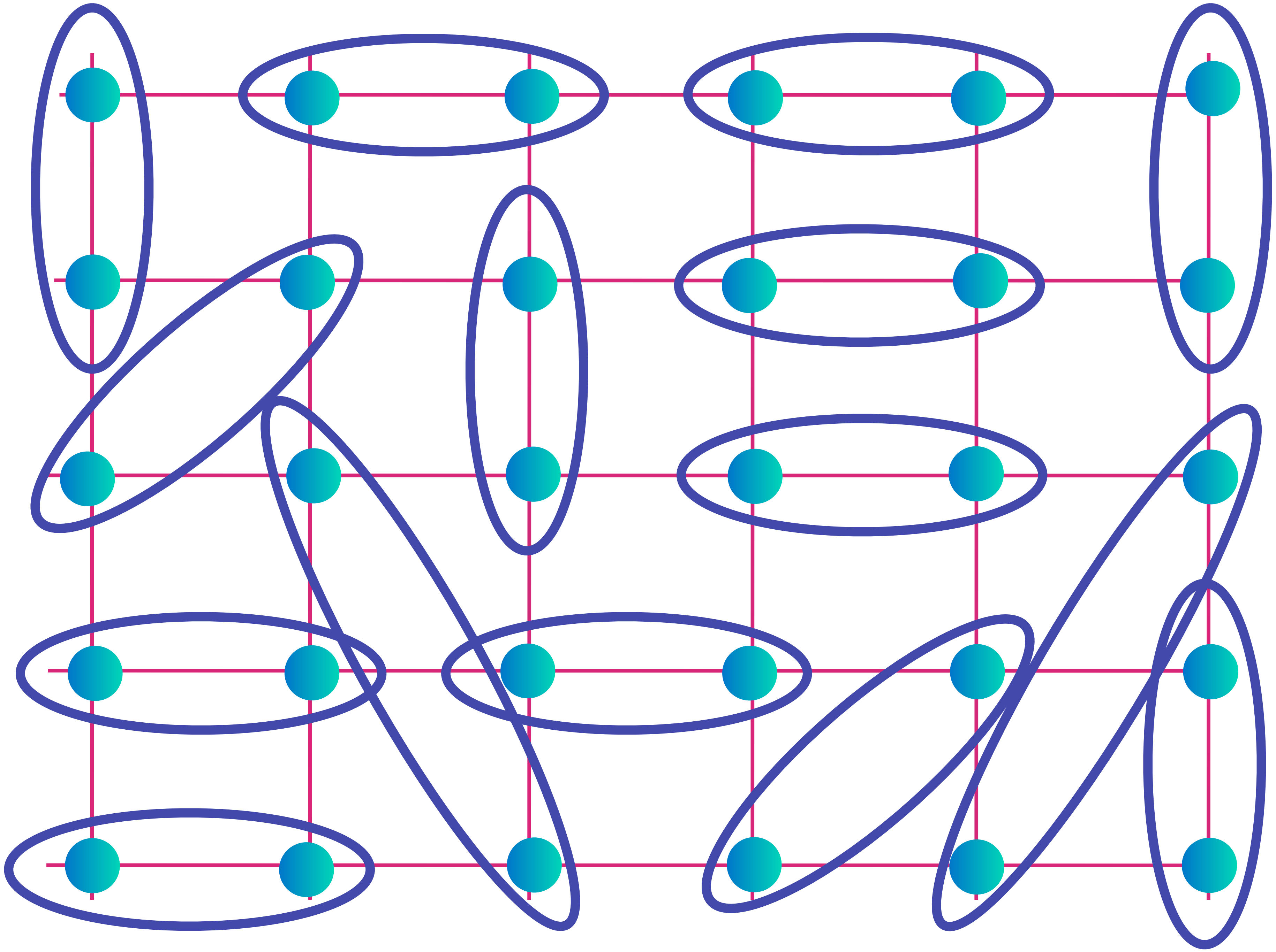

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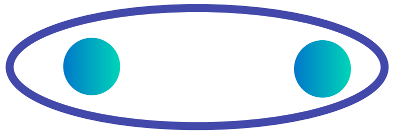

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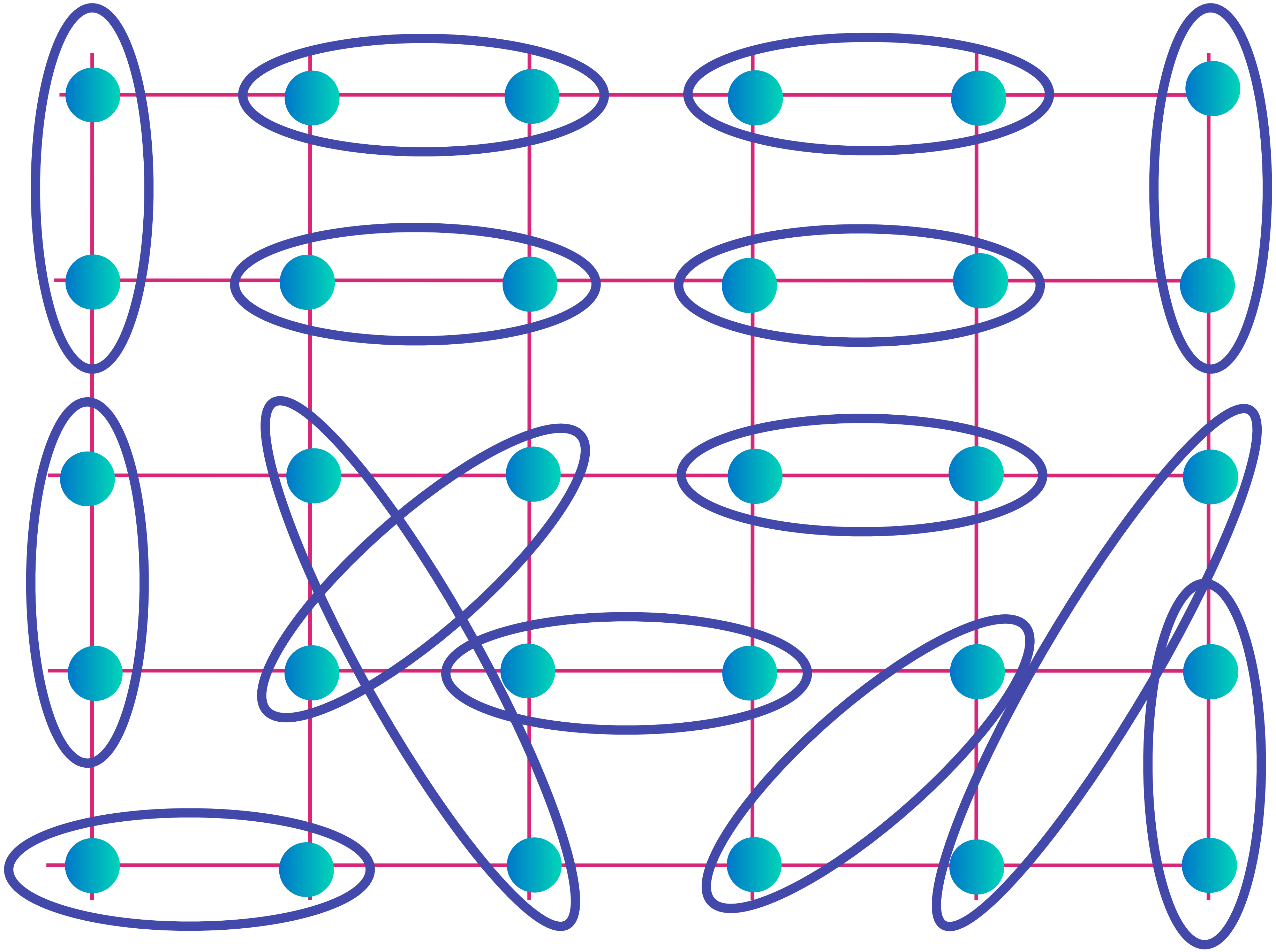

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Ground state degeneracy

Place insulator on a torus;

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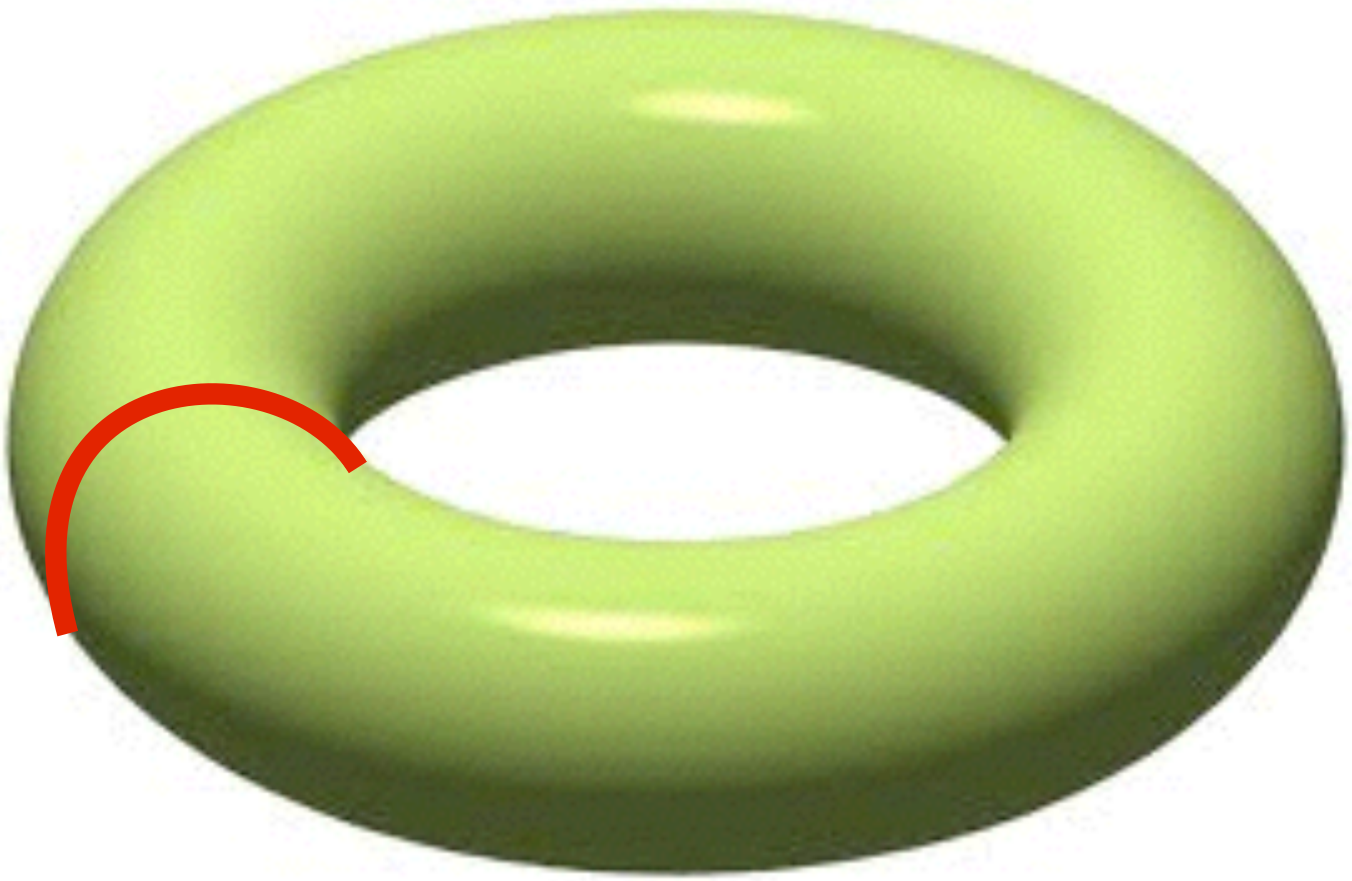

Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

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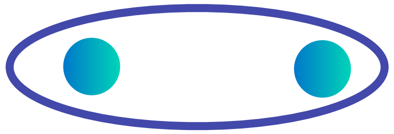
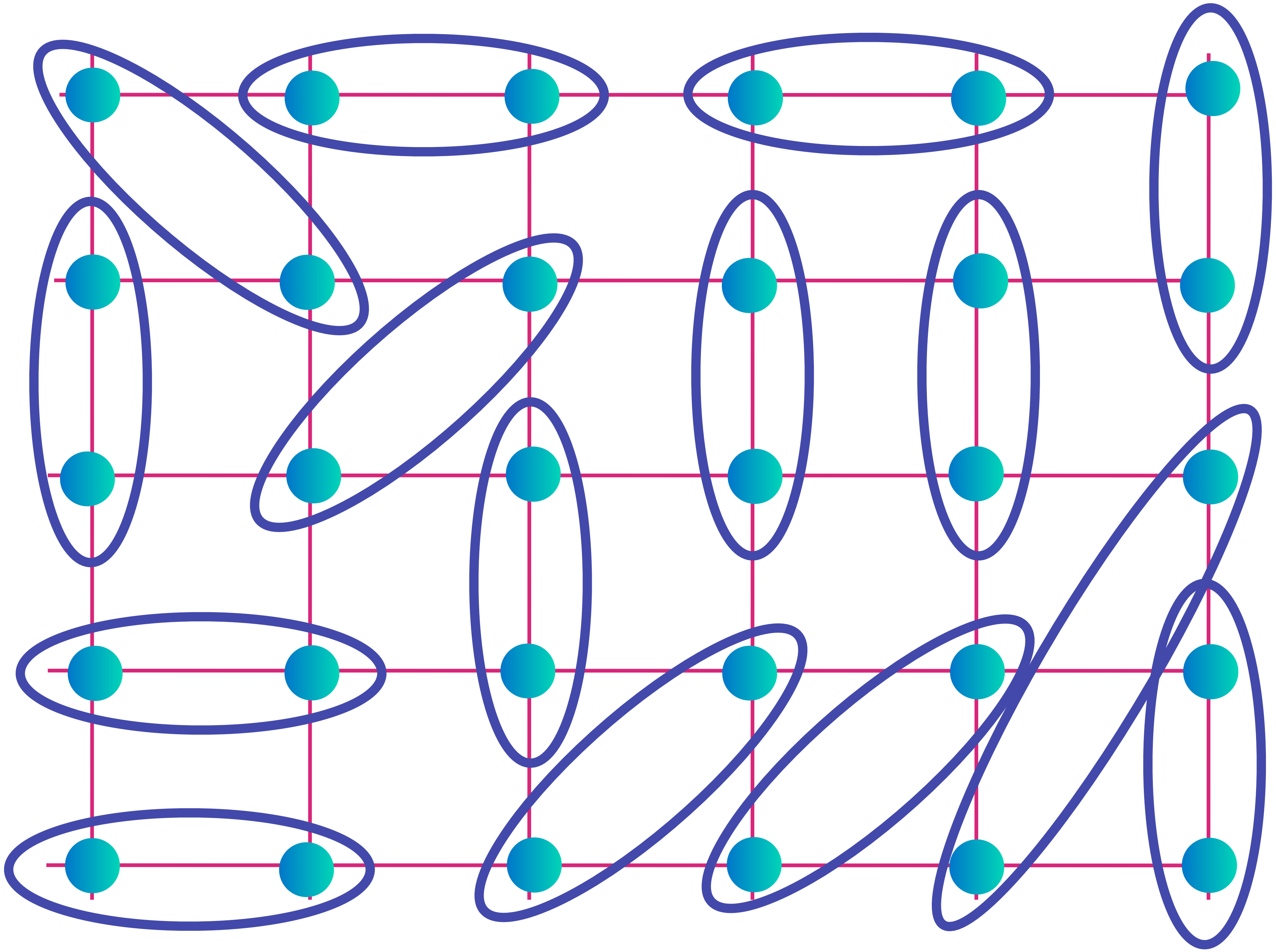
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$



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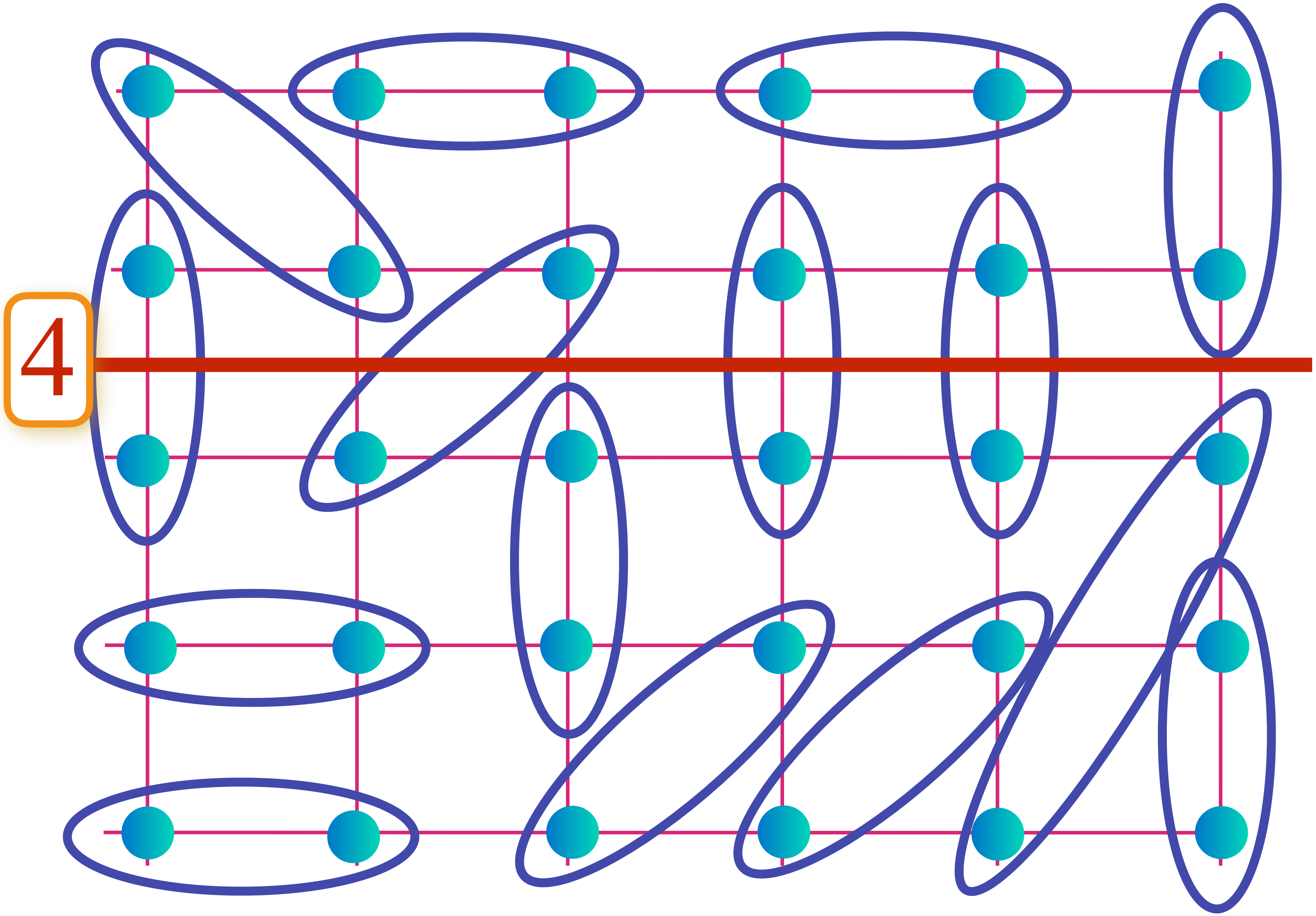

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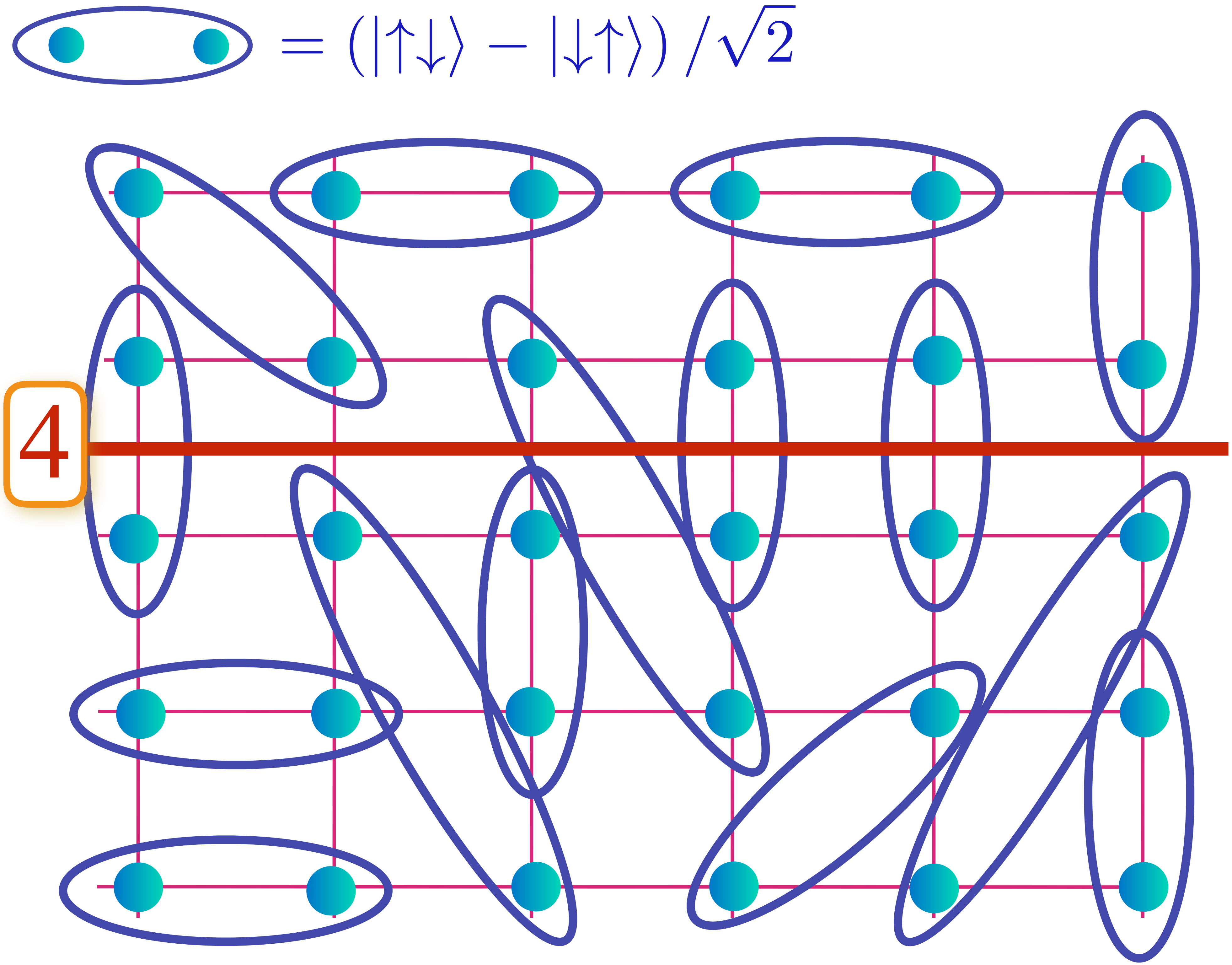

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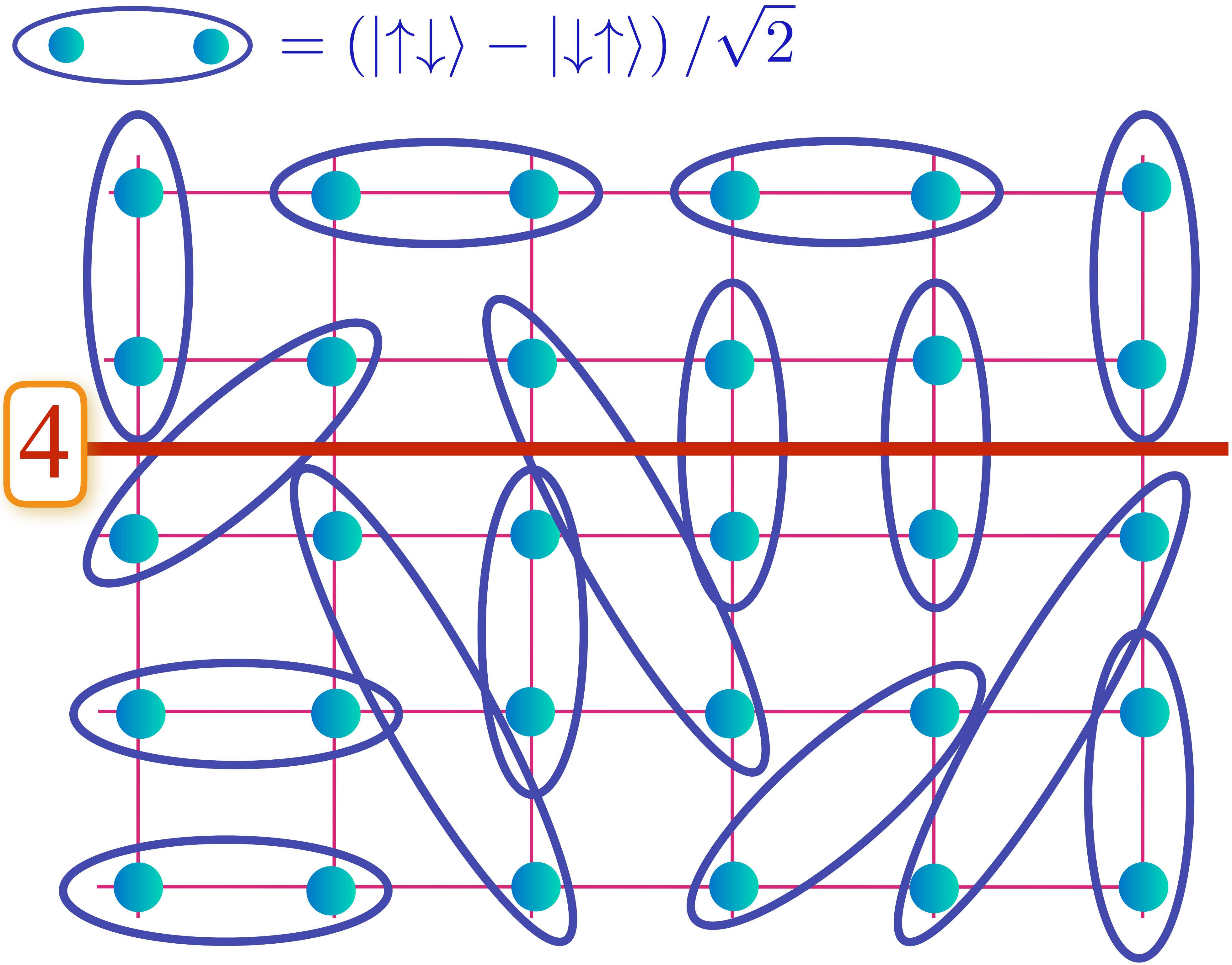

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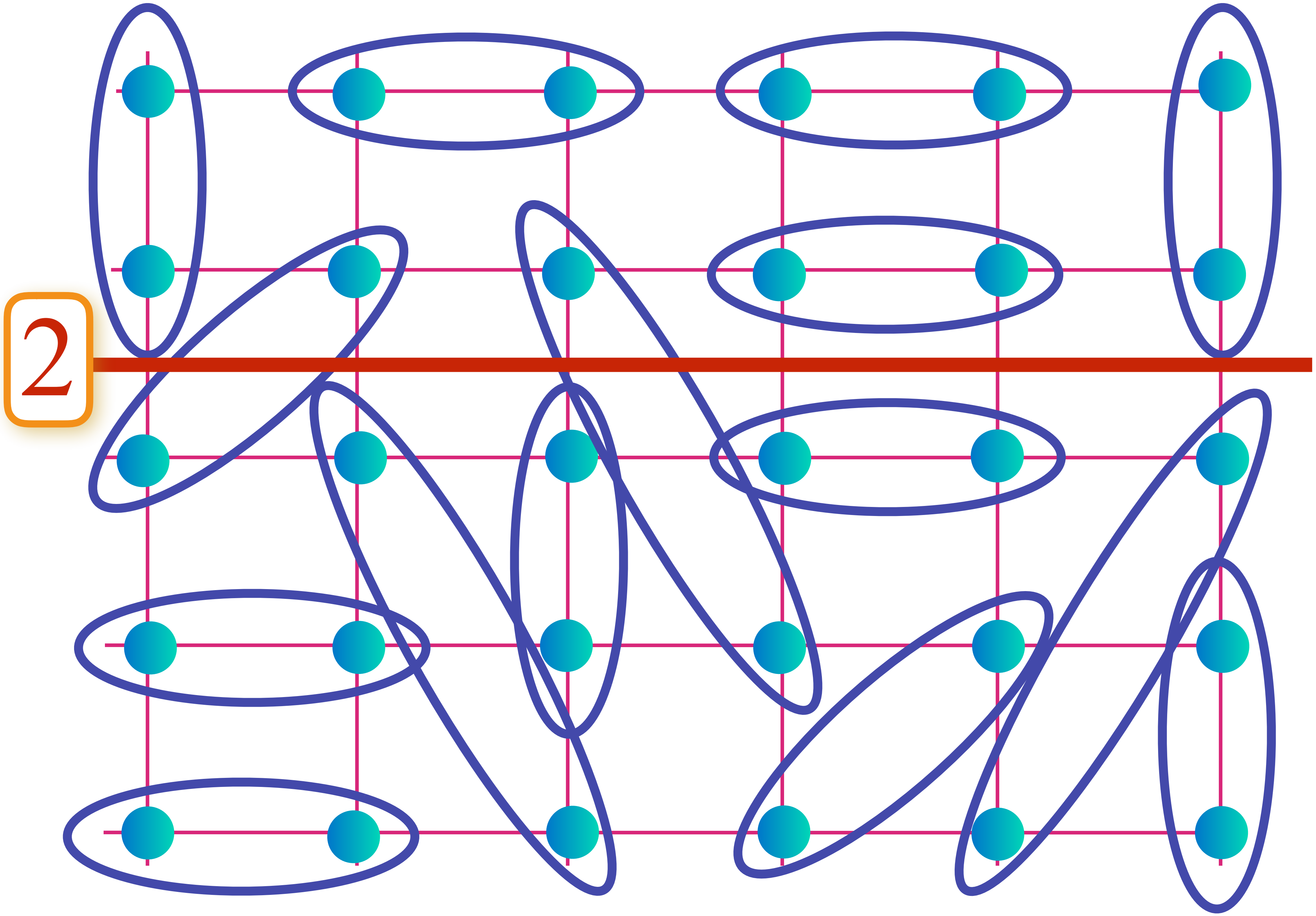

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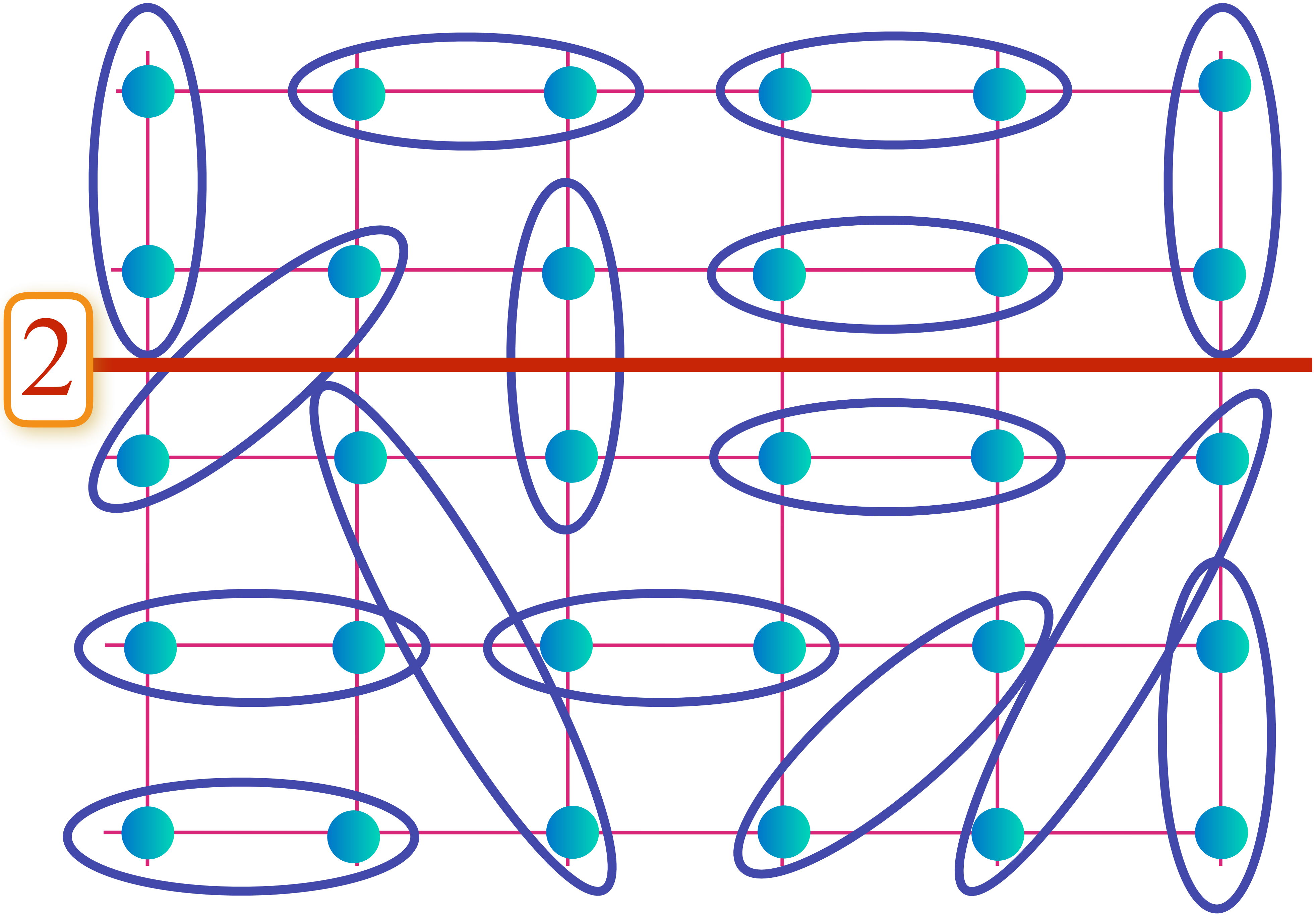

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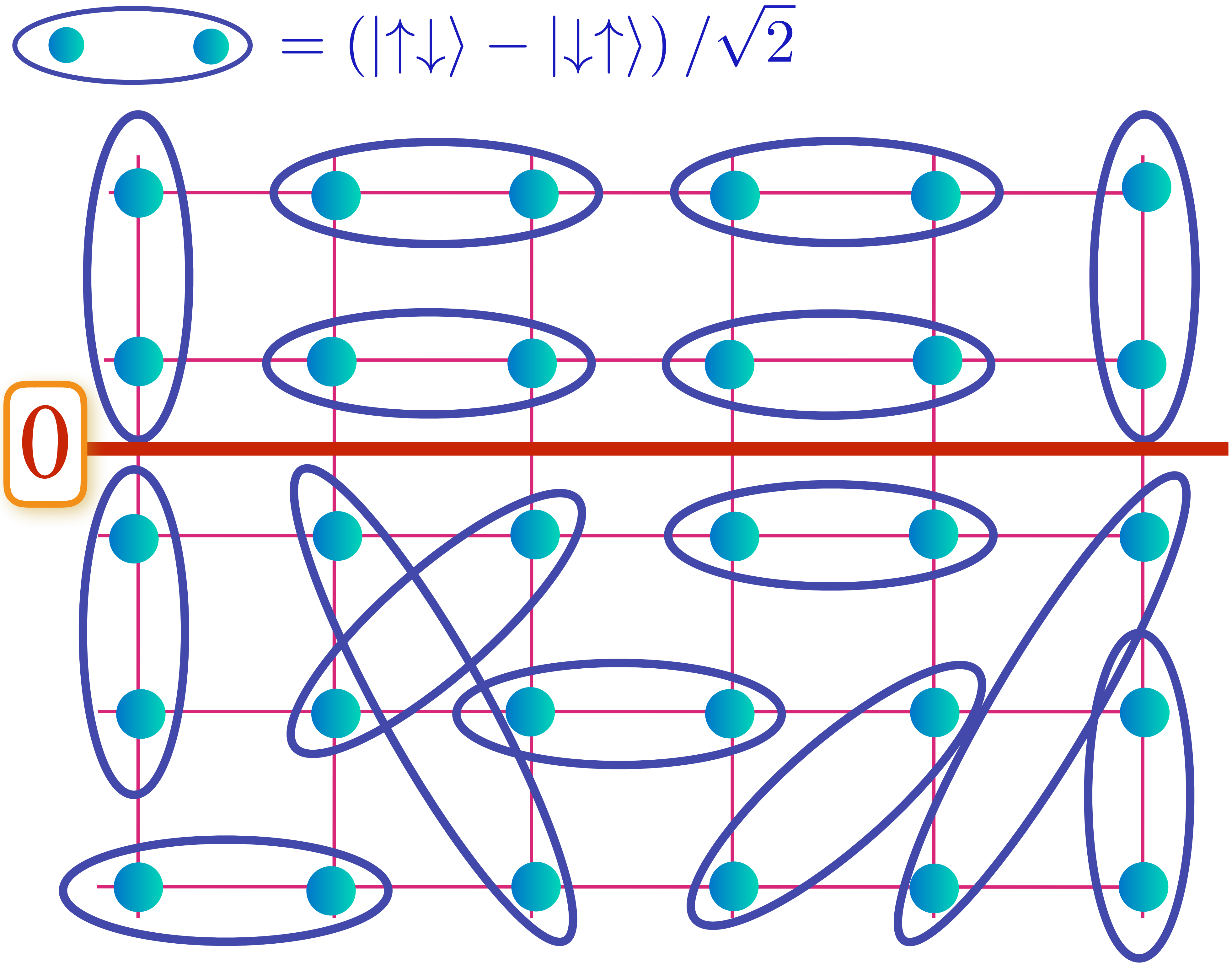

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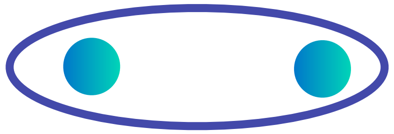
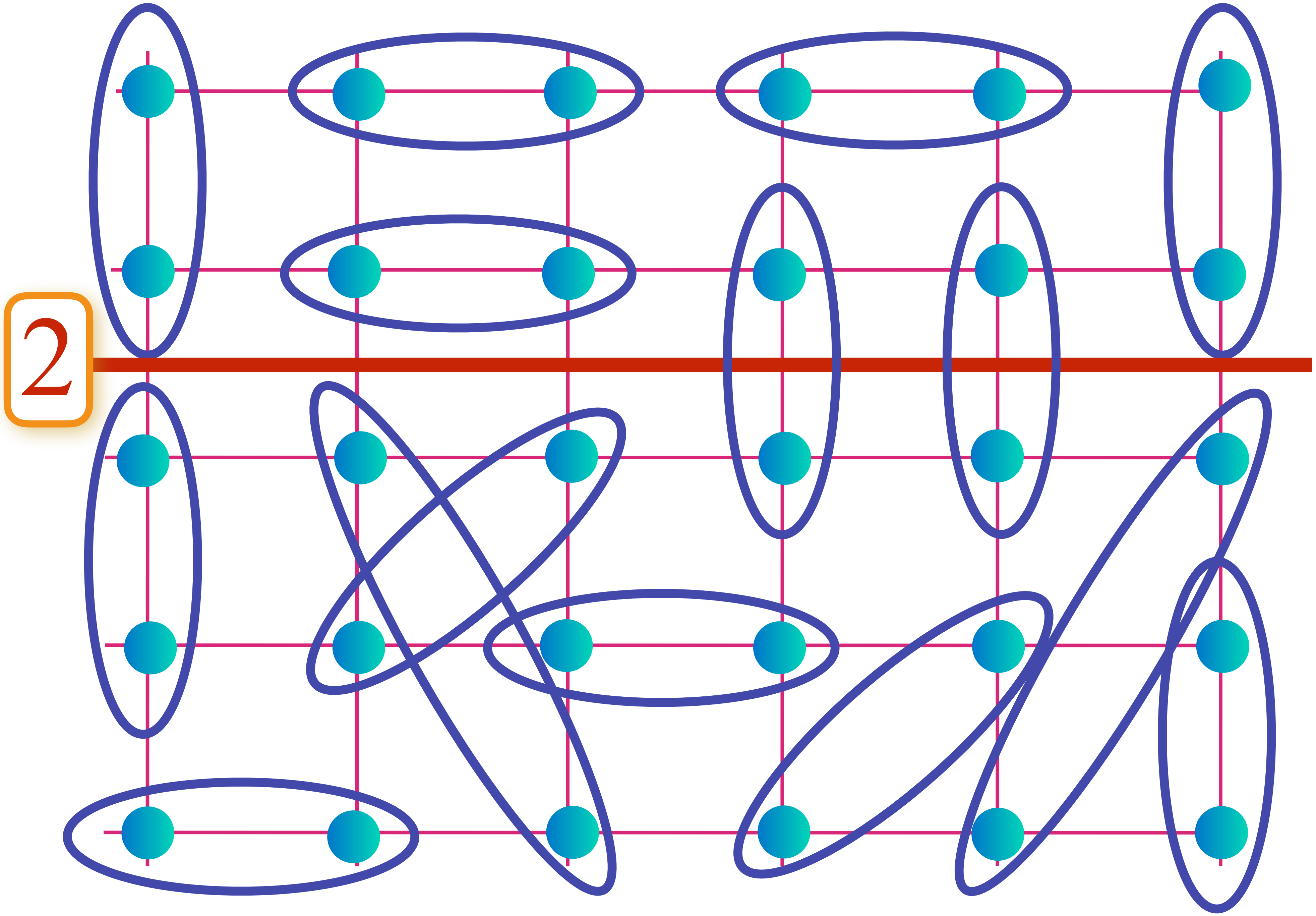
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



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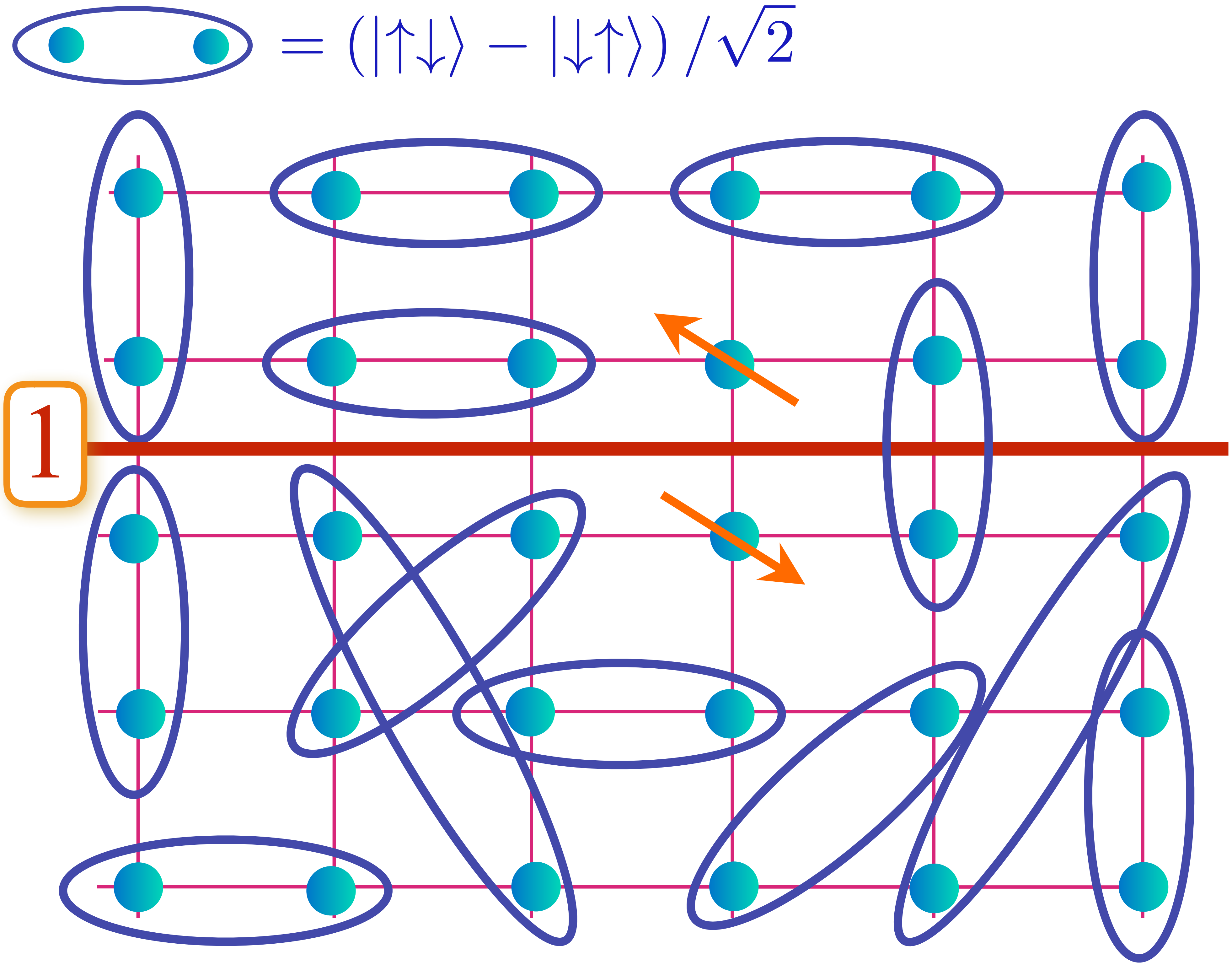

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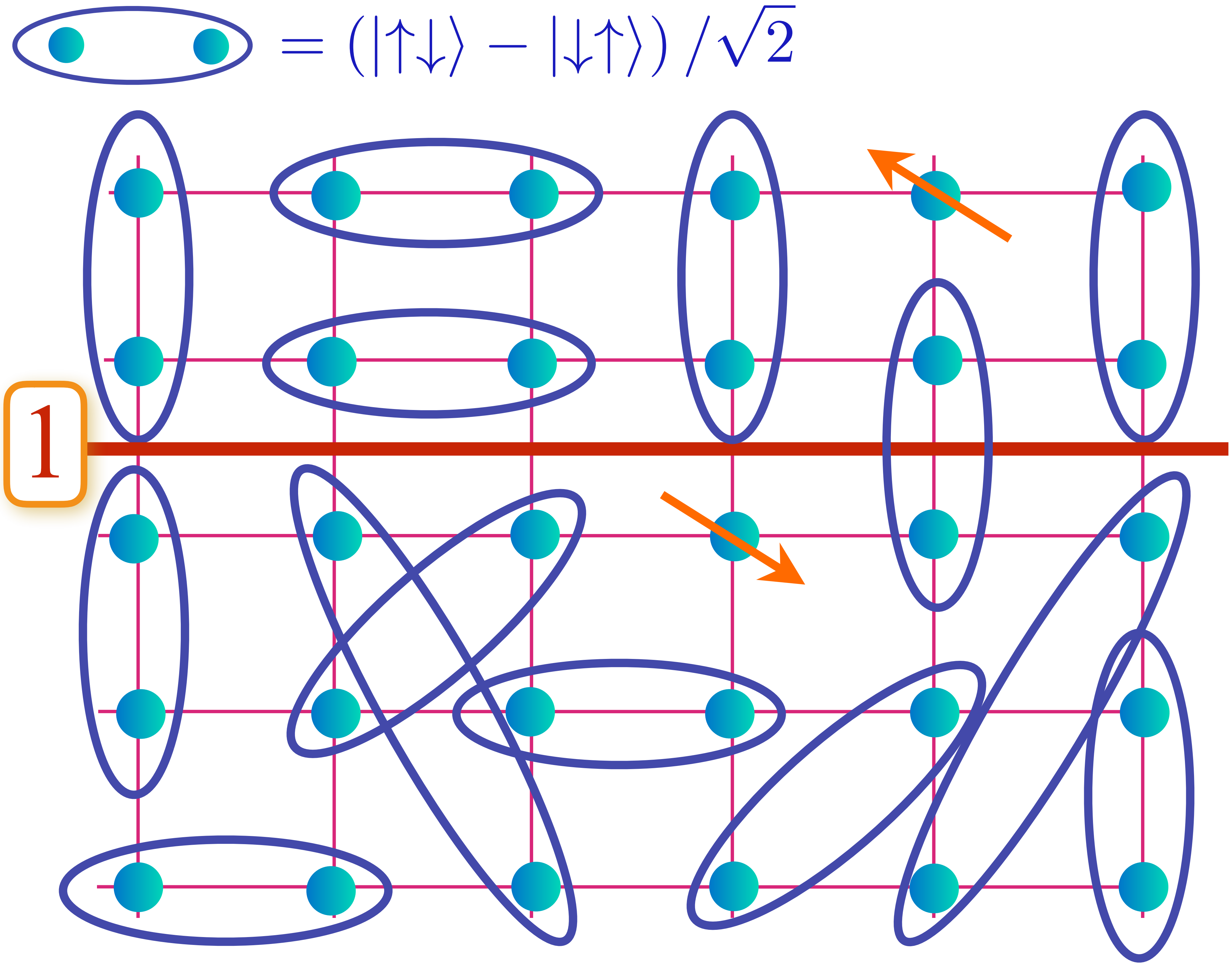

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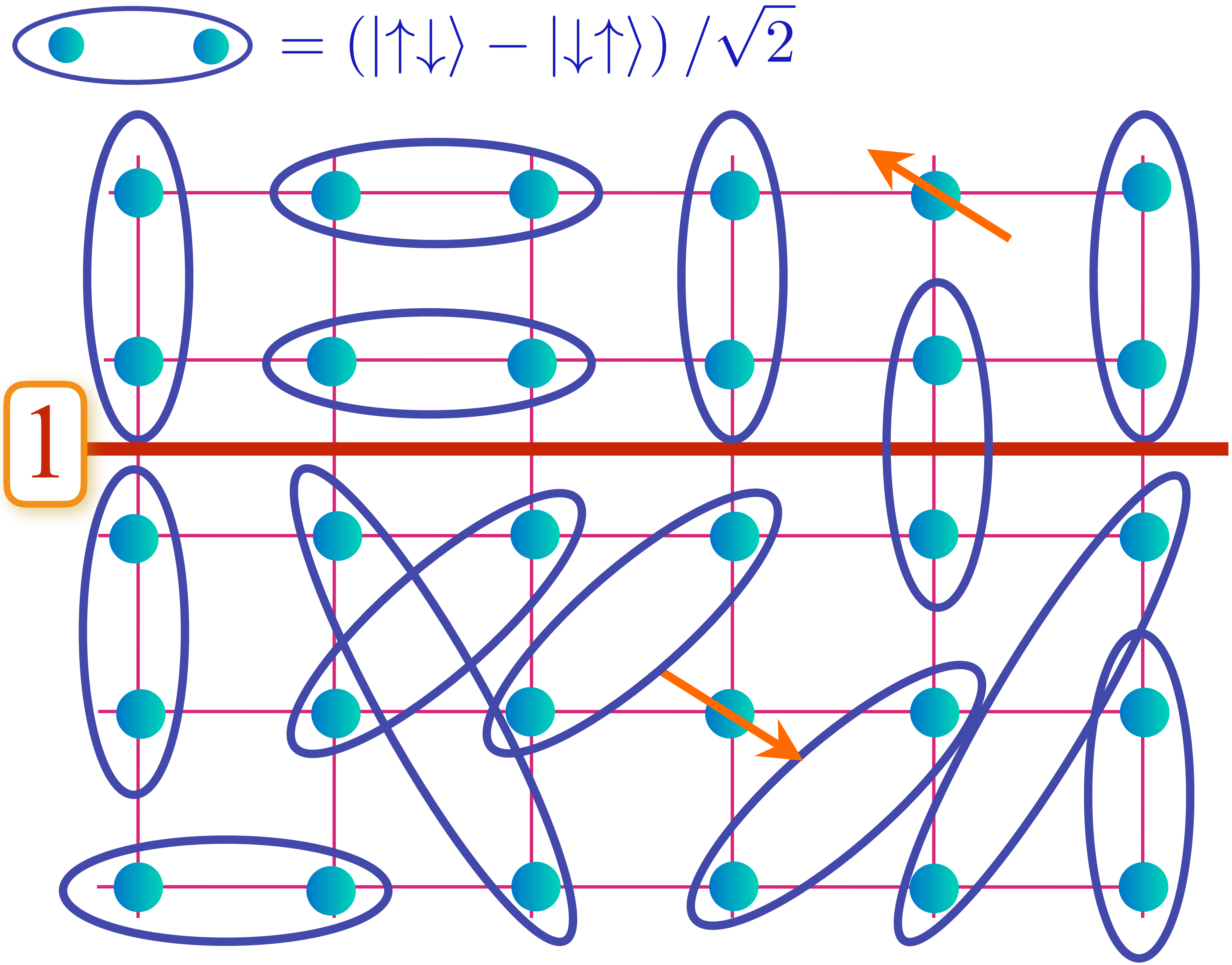

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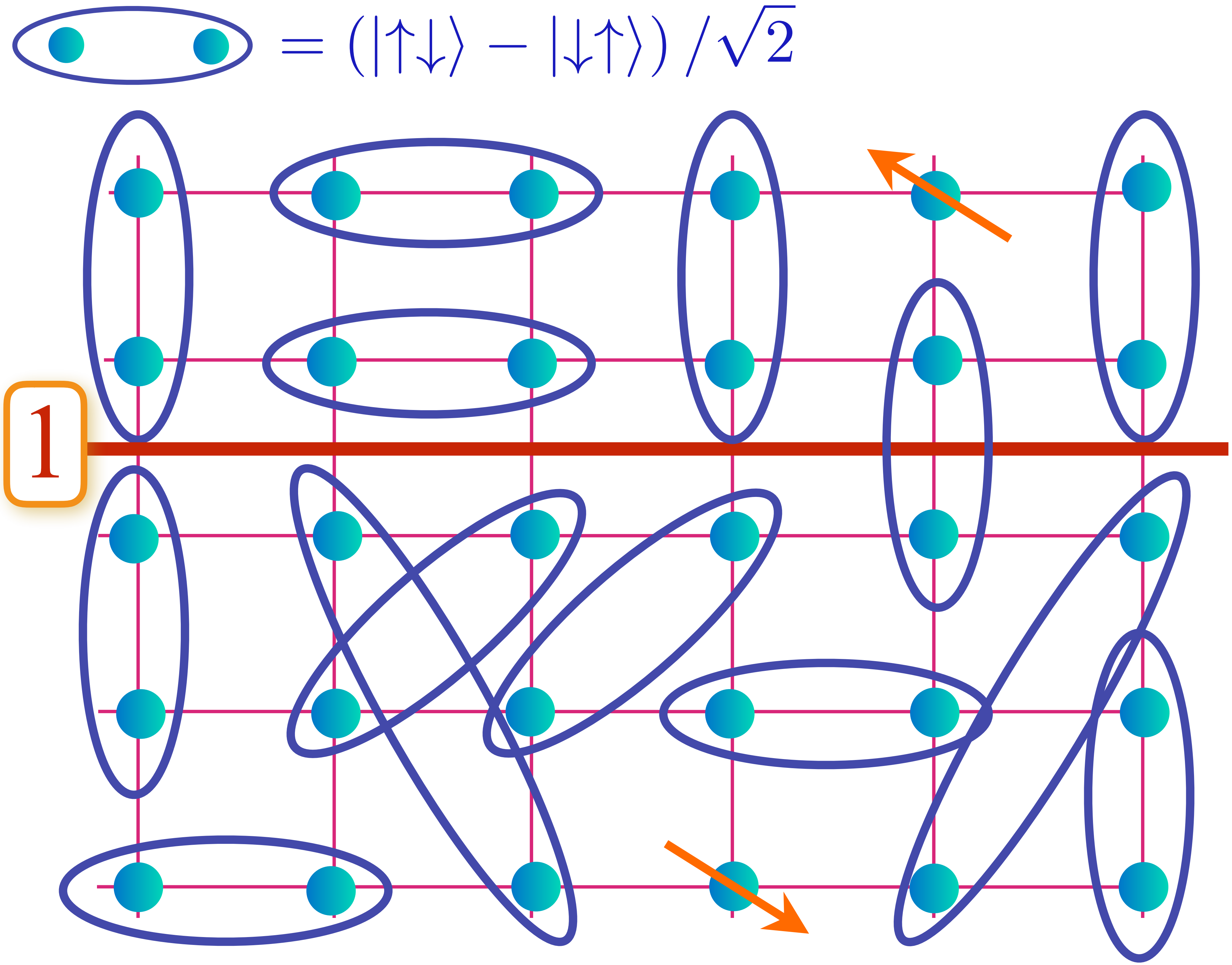

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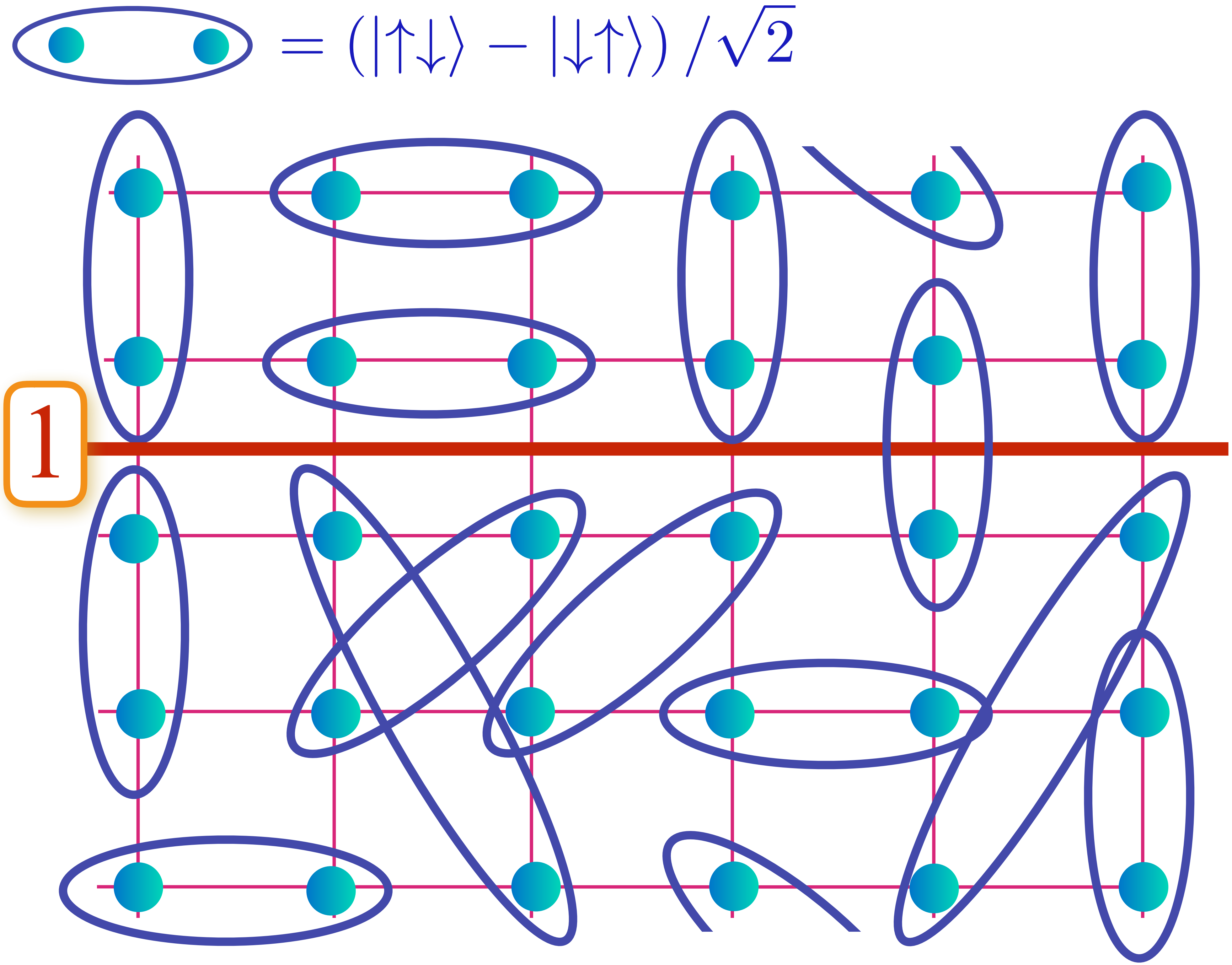

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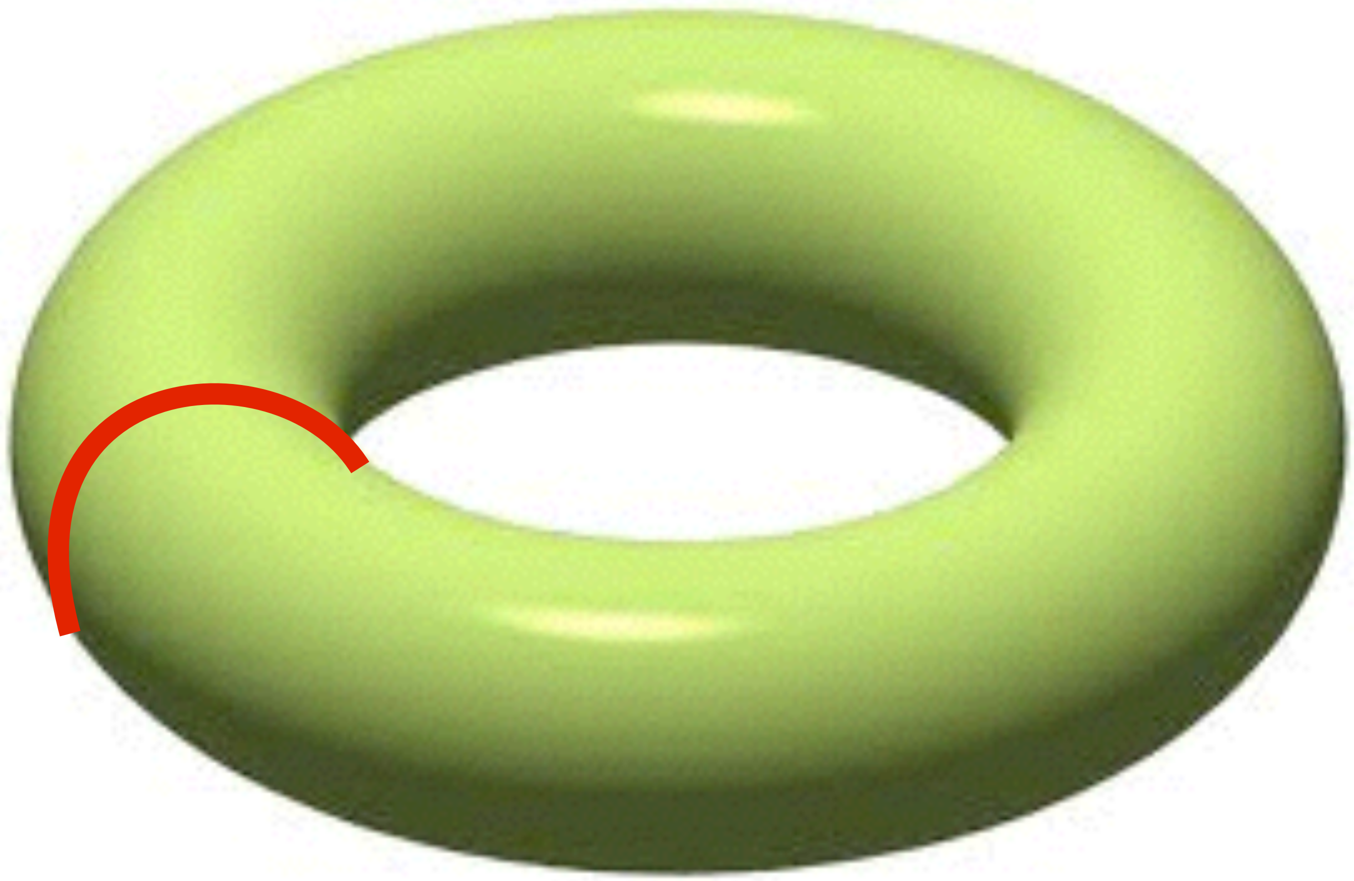

Place insulator on a torus;

The sensitivity of the degeneracy to the global topology indicates long-range quantum entanglement

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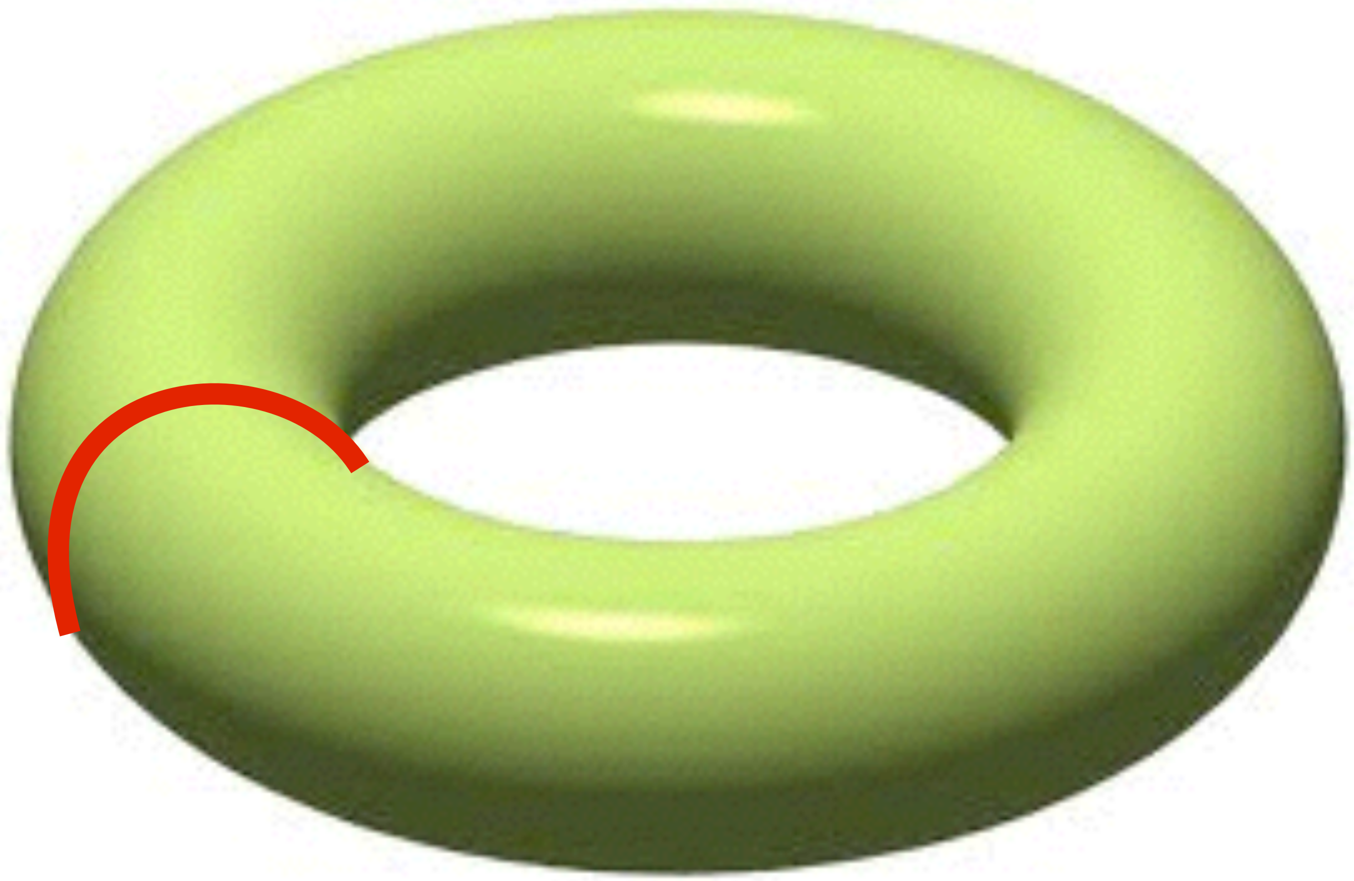

Place insulator on a torus;

The degenerate states are conjugate to the flux of an emergent gauge field piercing the cycles of the torus

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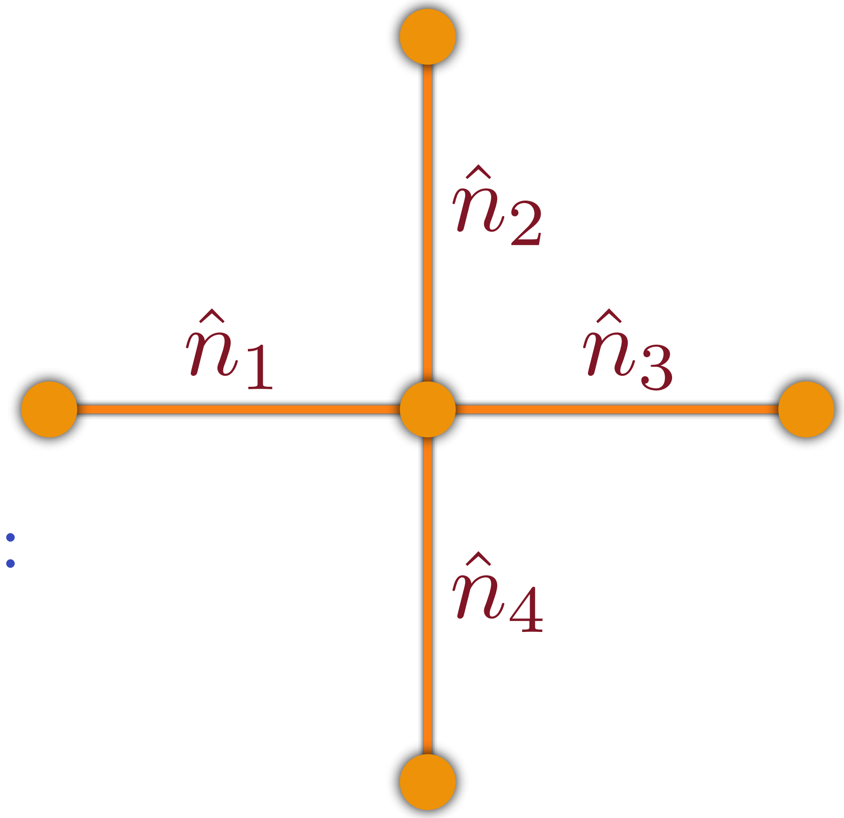
Emergent gauge fields



Local constraint on dimer number operators:

$$\hat{n}_1 + \hat{n}_2 + \hat{n}_3 + \hat{n}_4 = 1.$$

Identify dimer number with an 'electric' field, $\hat{E}_{i\alpha} = (-1)^{i_x+i_y}\,\hat{n}_{i\alpha}$, $(\alpha = x, y)$; the constraint becomes 'Gauss's Law':

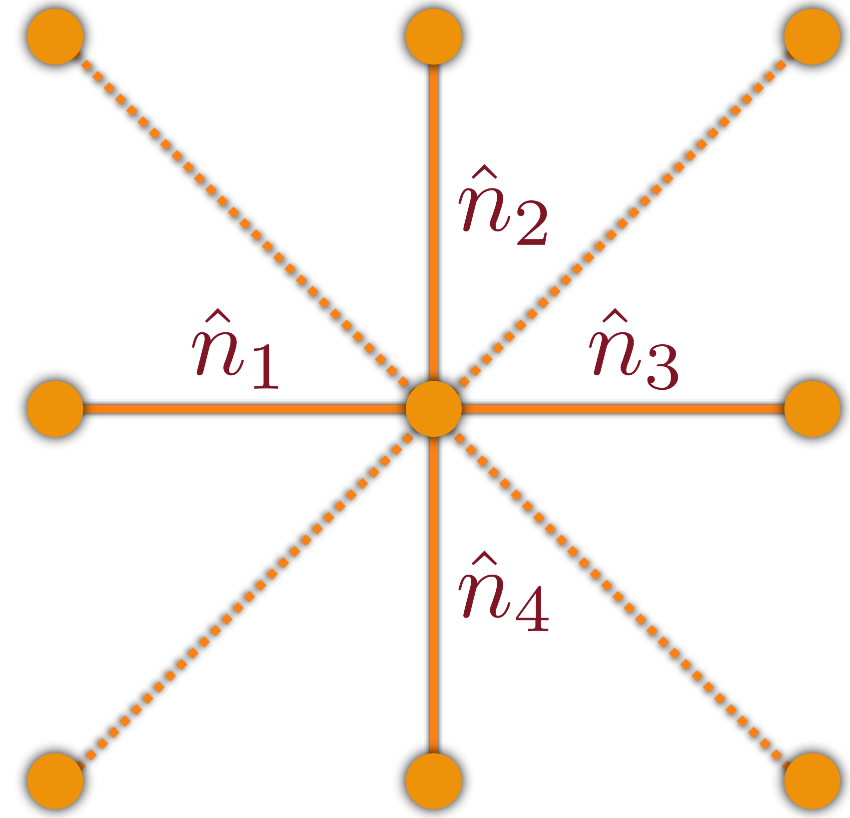
$$\Delta_\alpha \hat{E}_{i\alpha} = (-1)^{i_x+i_y}.$$

The theory of the dimers is *compact* U(1) quantum electrodynamics in the presence of static background charges. The *compact* theory allows the analog of Dirac's magnetic monopoles as tunneling events/excitations.

G. Baskaran and P. W. Anderson, Phys. Rev. B **37**, 580(R) (1988)

E. Fradkin and S. A. Kivelson, Mod. Phys. Lett. B **4**, 225 (1990)

Emergent gauge fields



Including dimers connecting the same sublattice leads to a $\mathbb{Z}_2$ gauge theory in the presence of Berry phases of static background charges. This has a stable deconfined phase in 2+1 dimensions. By varying parameters it can undergoes a confinement transition to a valence bond solid, described by a frustrated Ising model.

R. A. Jalabert and S. Sachdev, Phys. Rev. B **44**, 686 (1991)

S. Sachdev and M. Vojta, J. Phys. Soc. Jpn **69**, Supp. B, 1 (1999)

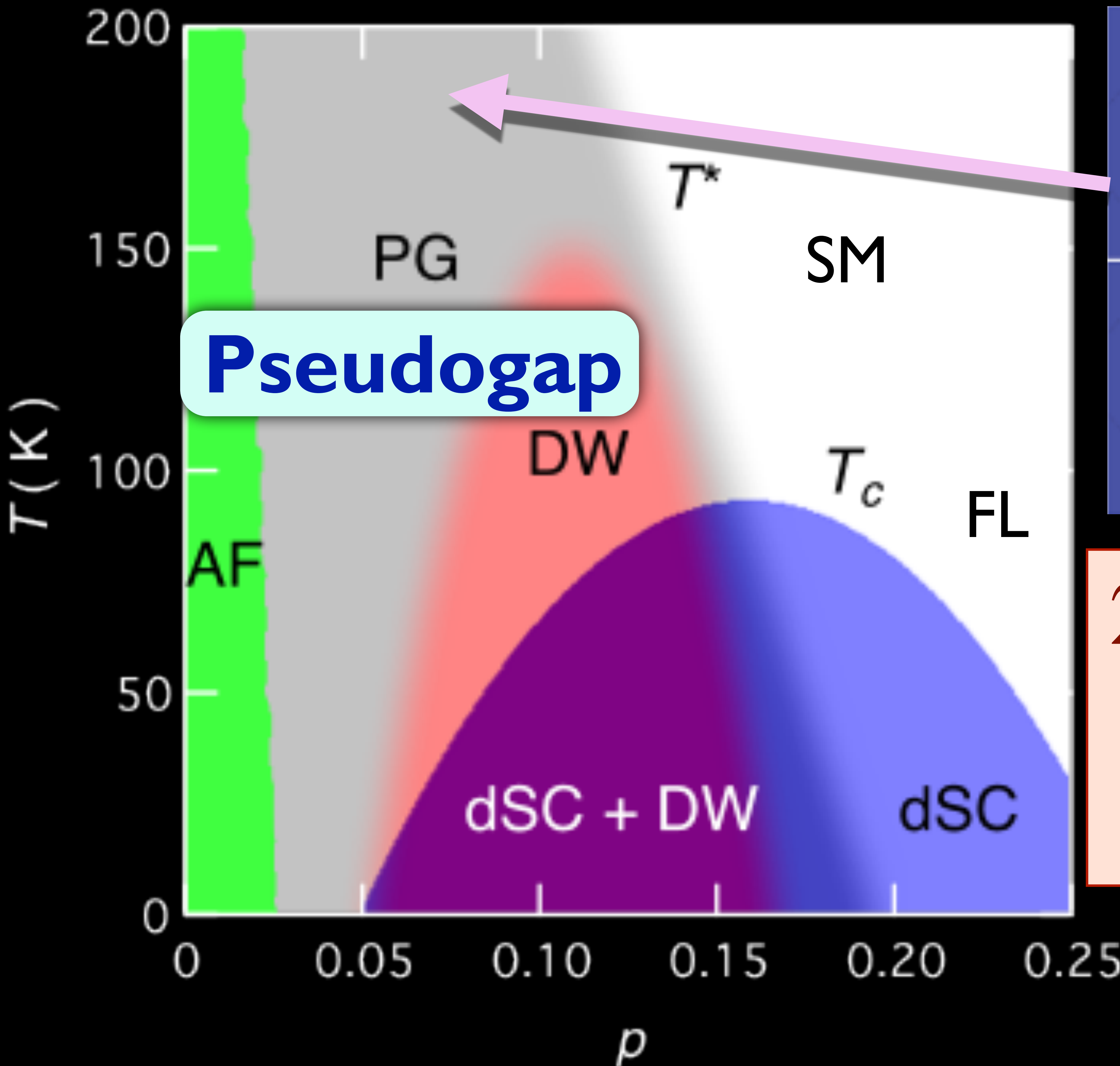
1. Emergent gauge fields and long-range entanglement in insulators

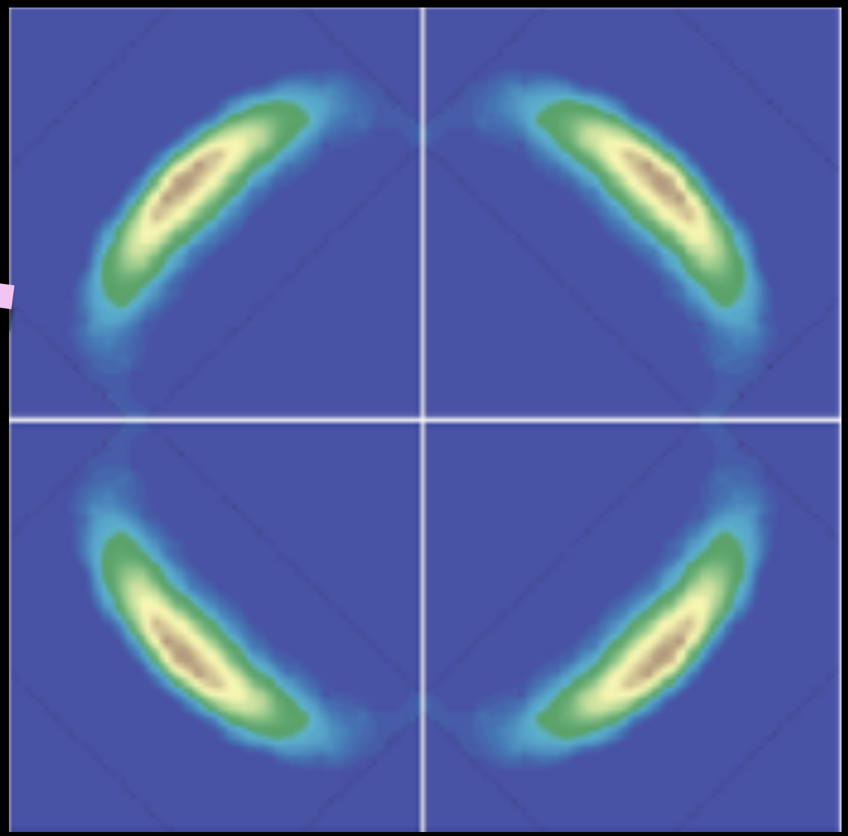
1. Emergent gauge fields and long-range entanglement in insulators

2. Fractionalized Fermi liquids (FL*)

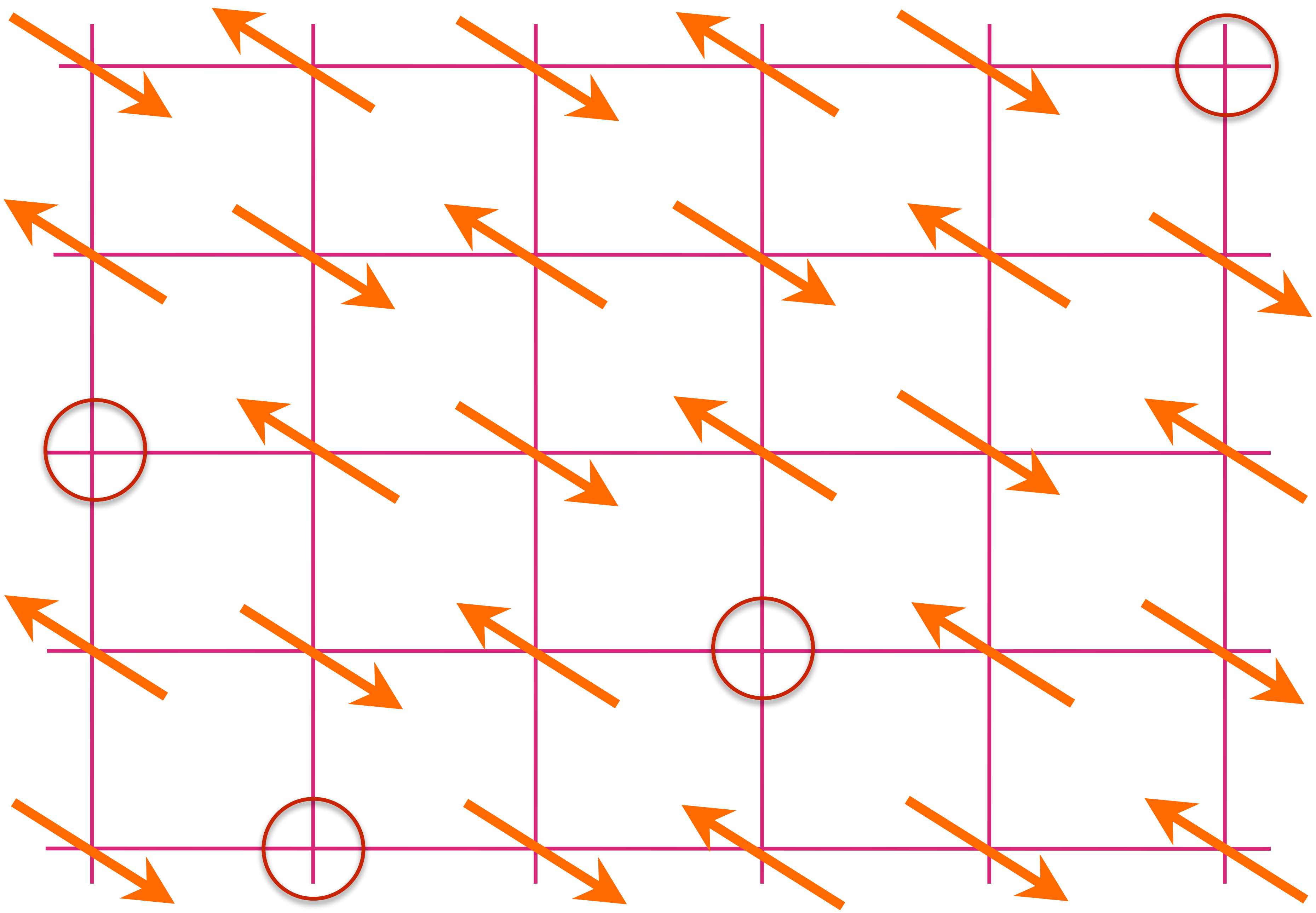
   Quasiparticles with a non-Luttinger volume, and emergent gauge fields

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)

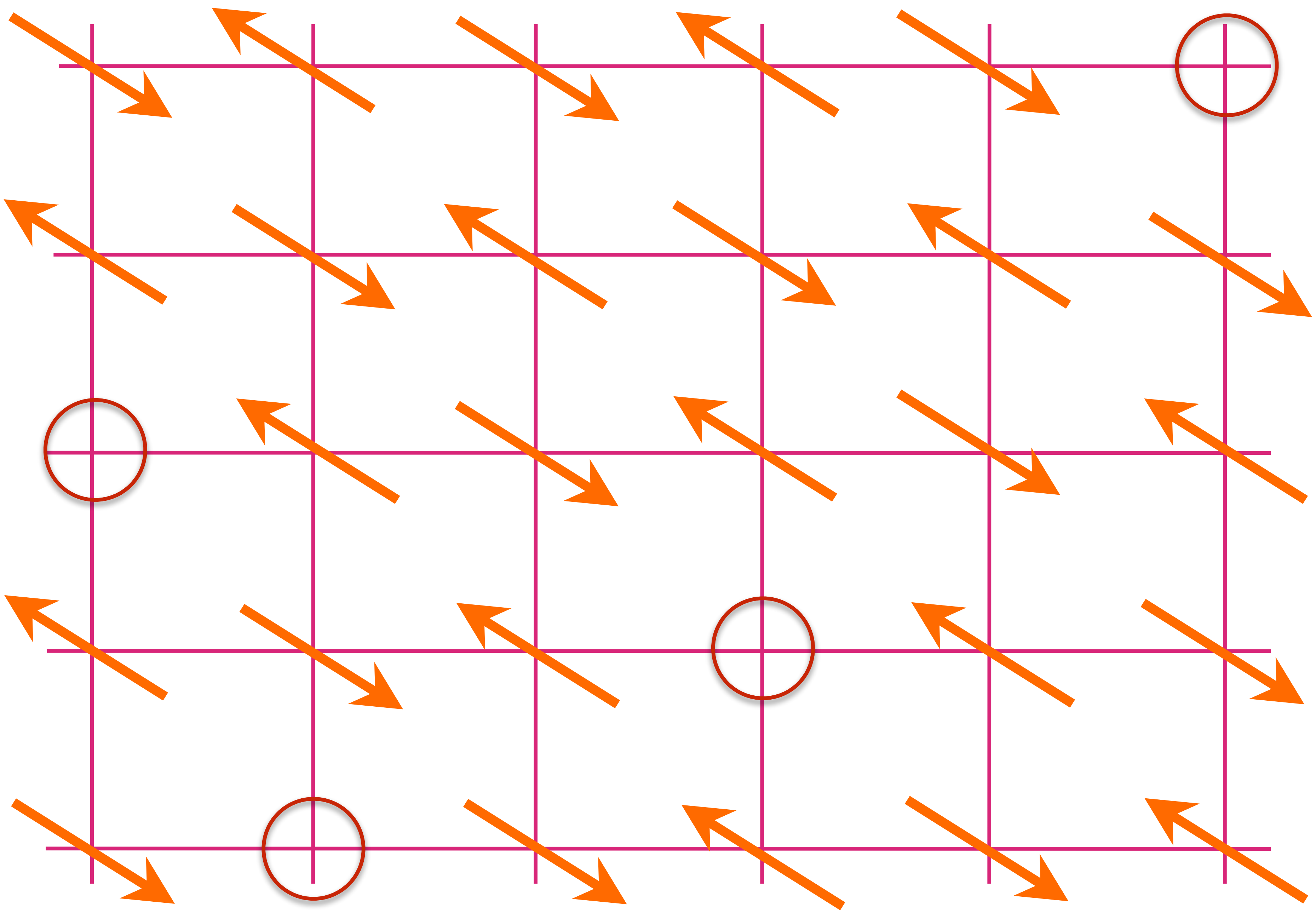




2. Pseudogap metal at low p



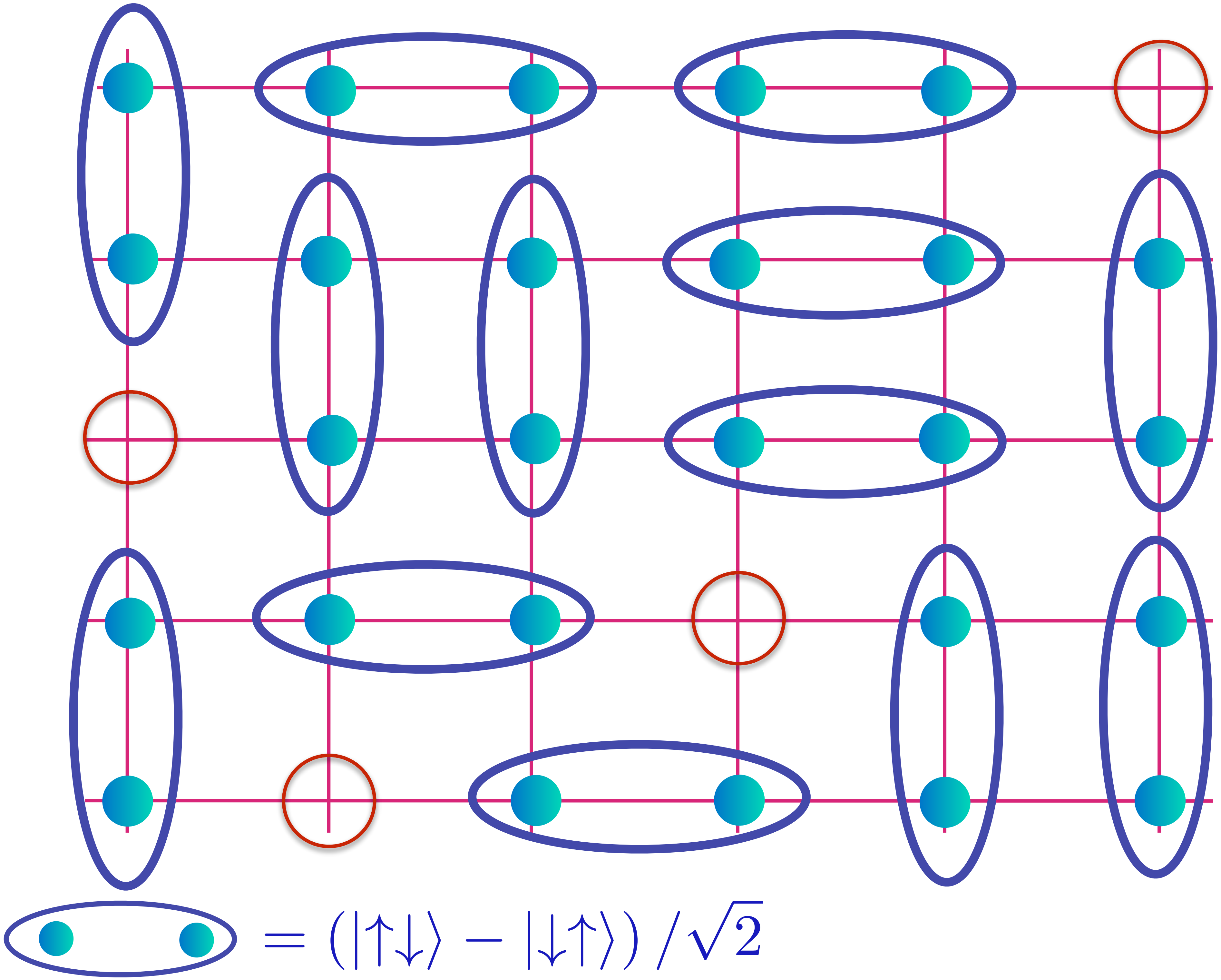
Anti-ferromagnet with p holes per square



Anti-ferromagnet with p holes per square

Can we get a Fermi surface of size p?
(and full square lattice symmetry)

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)
N. Read and B. Chakraborty, PRB **40**, 7133 (1989)



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

Spin liquid with density *p* of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

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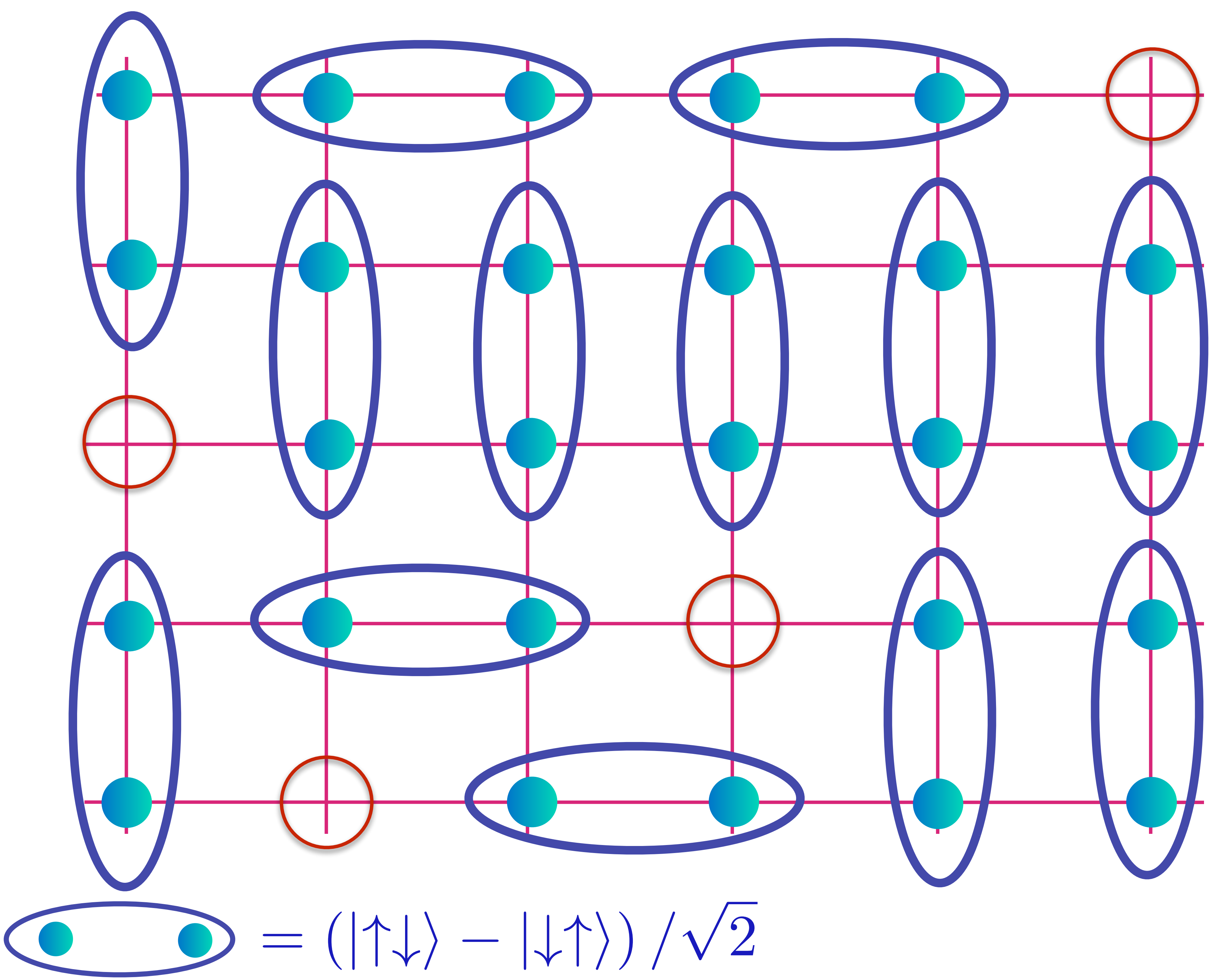

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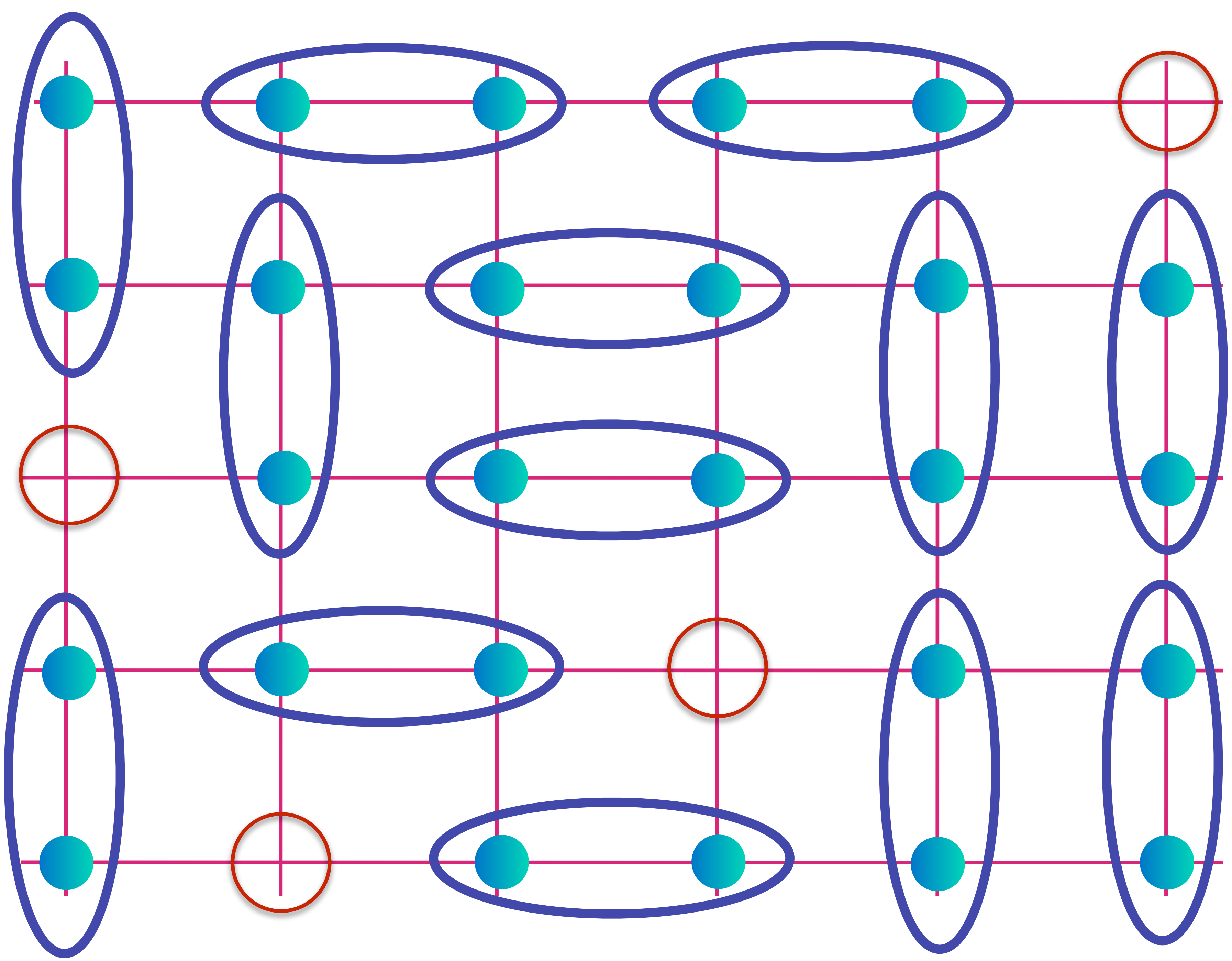

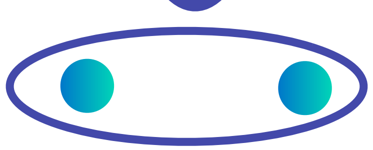

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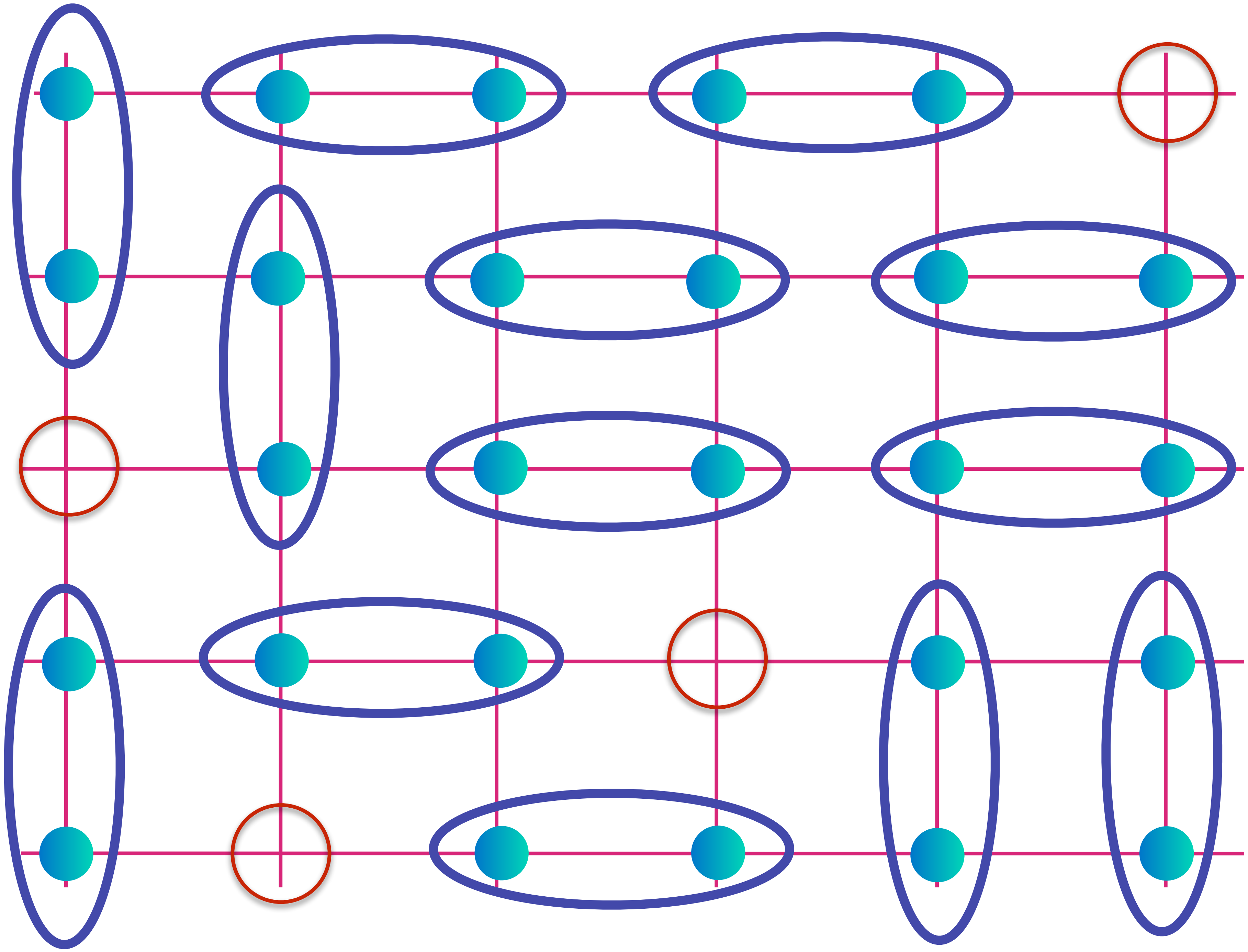

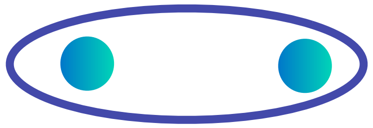 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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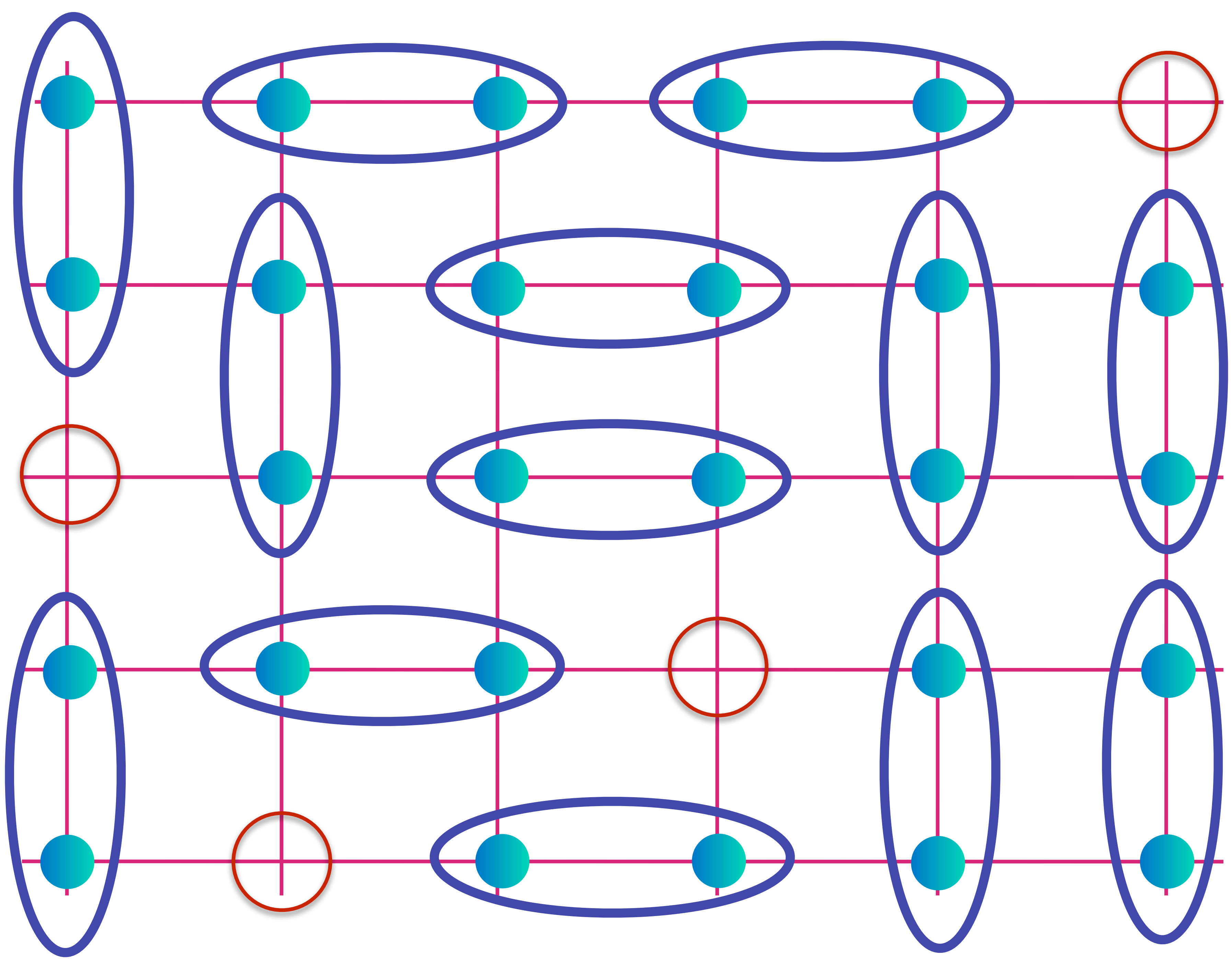

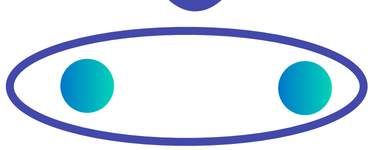 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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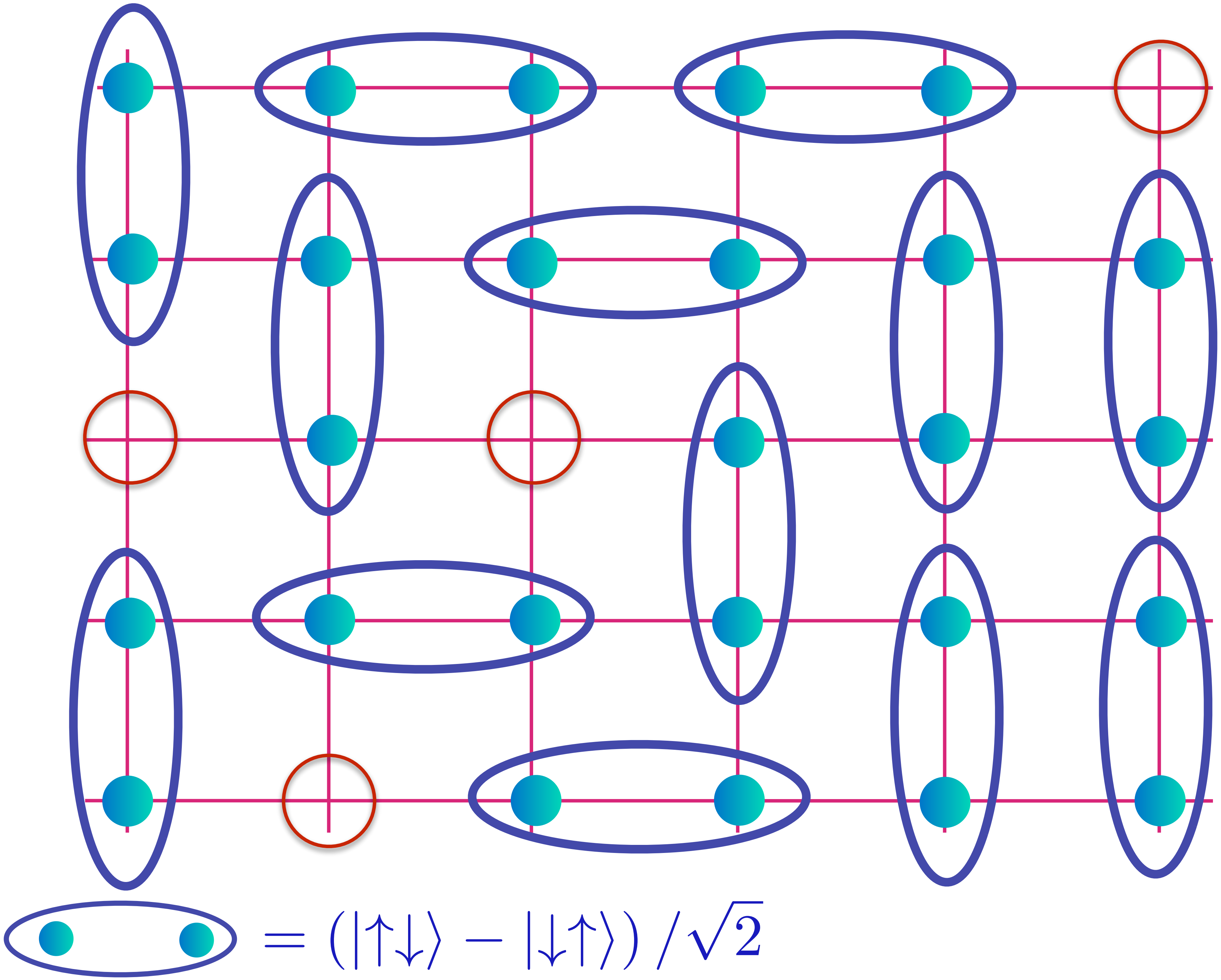

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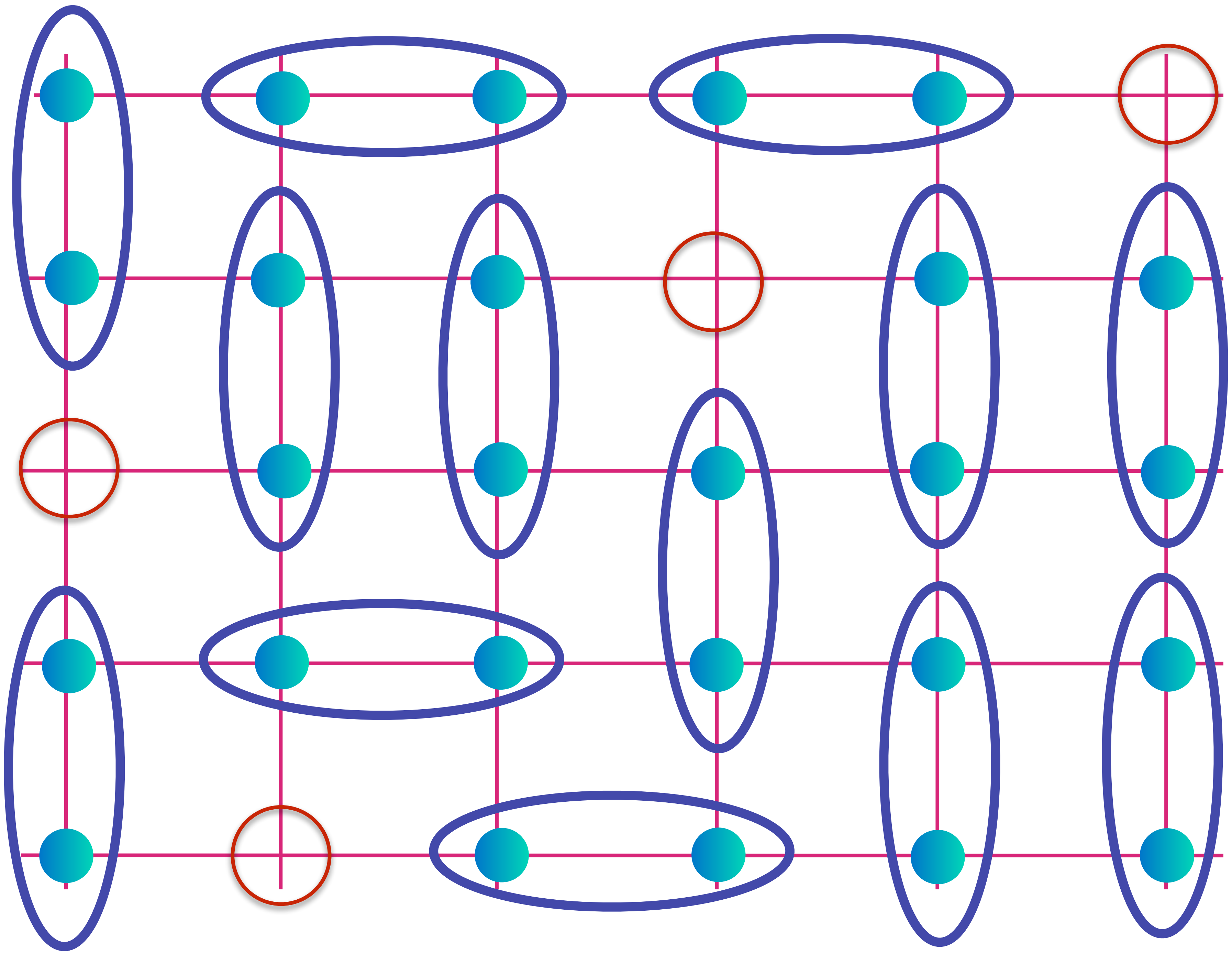

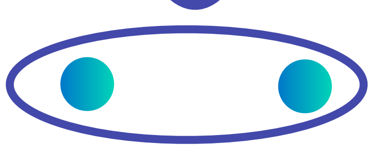 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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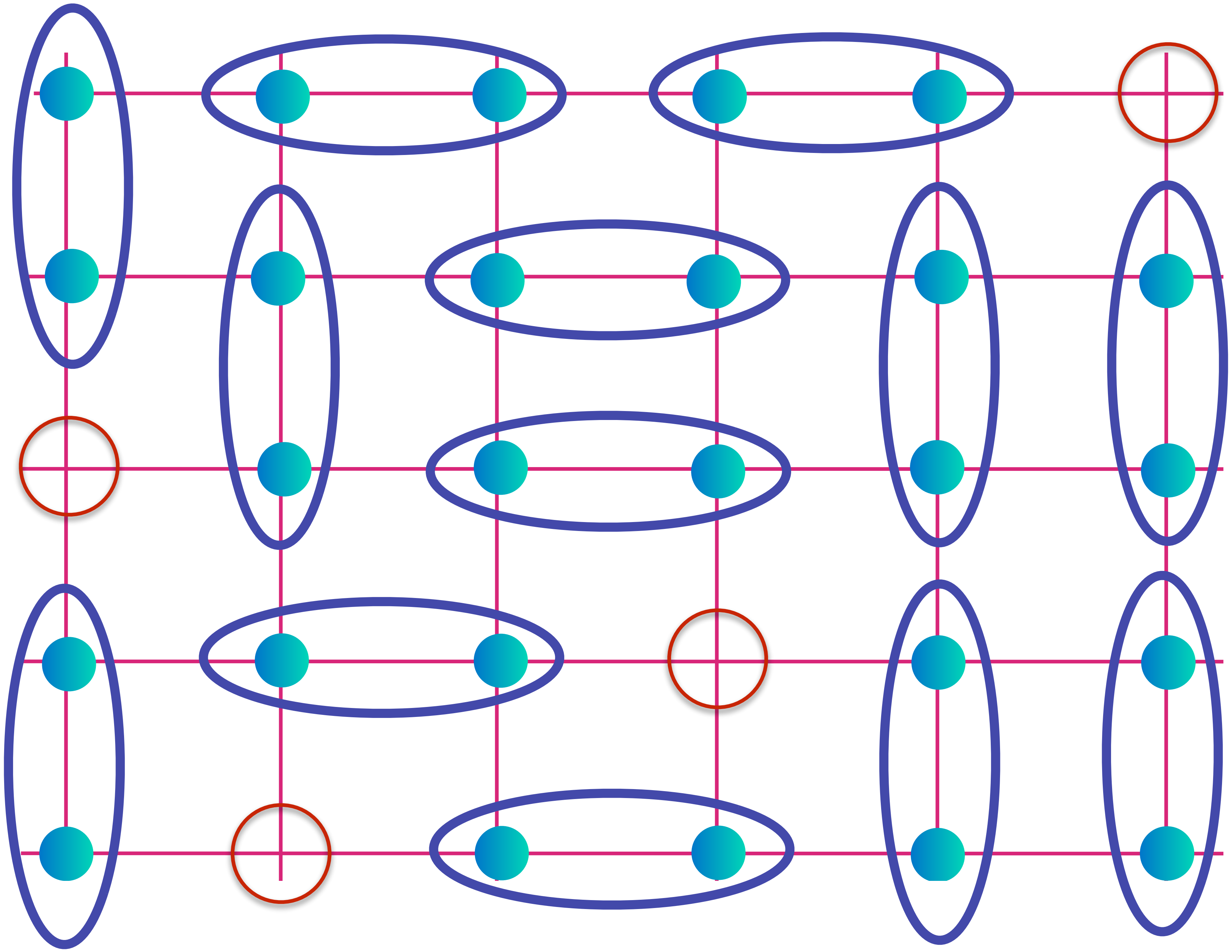

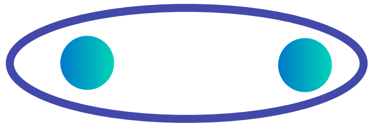 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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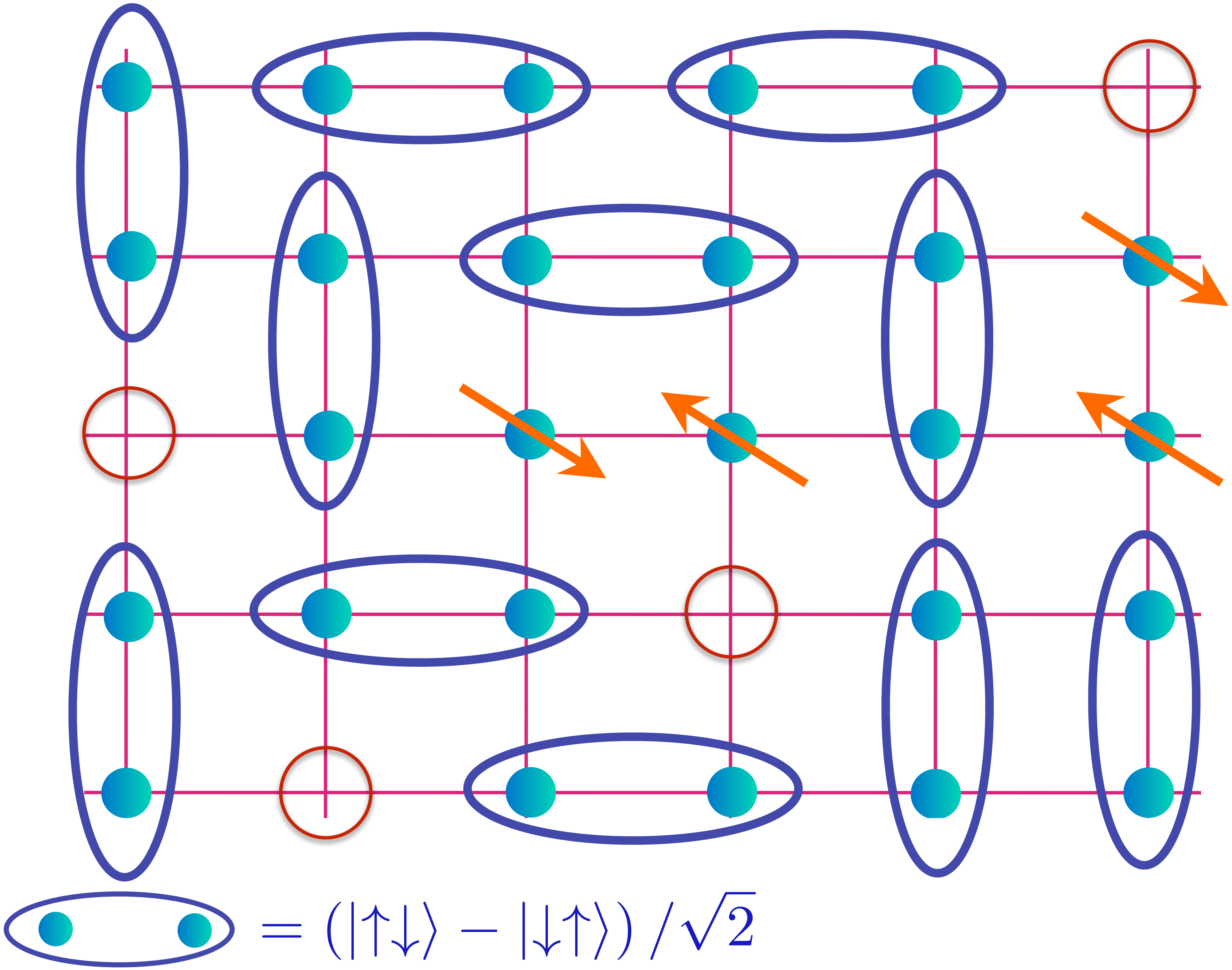
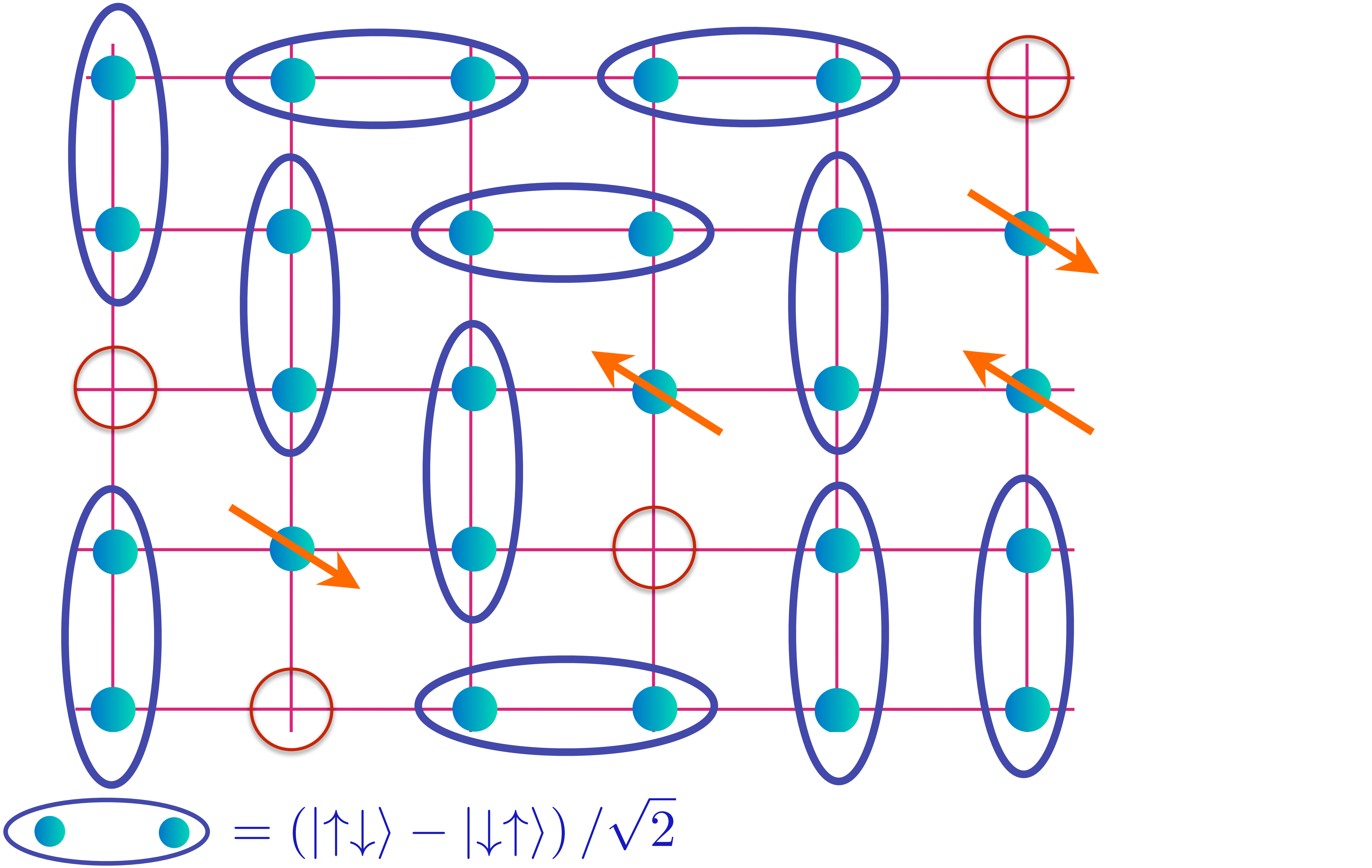
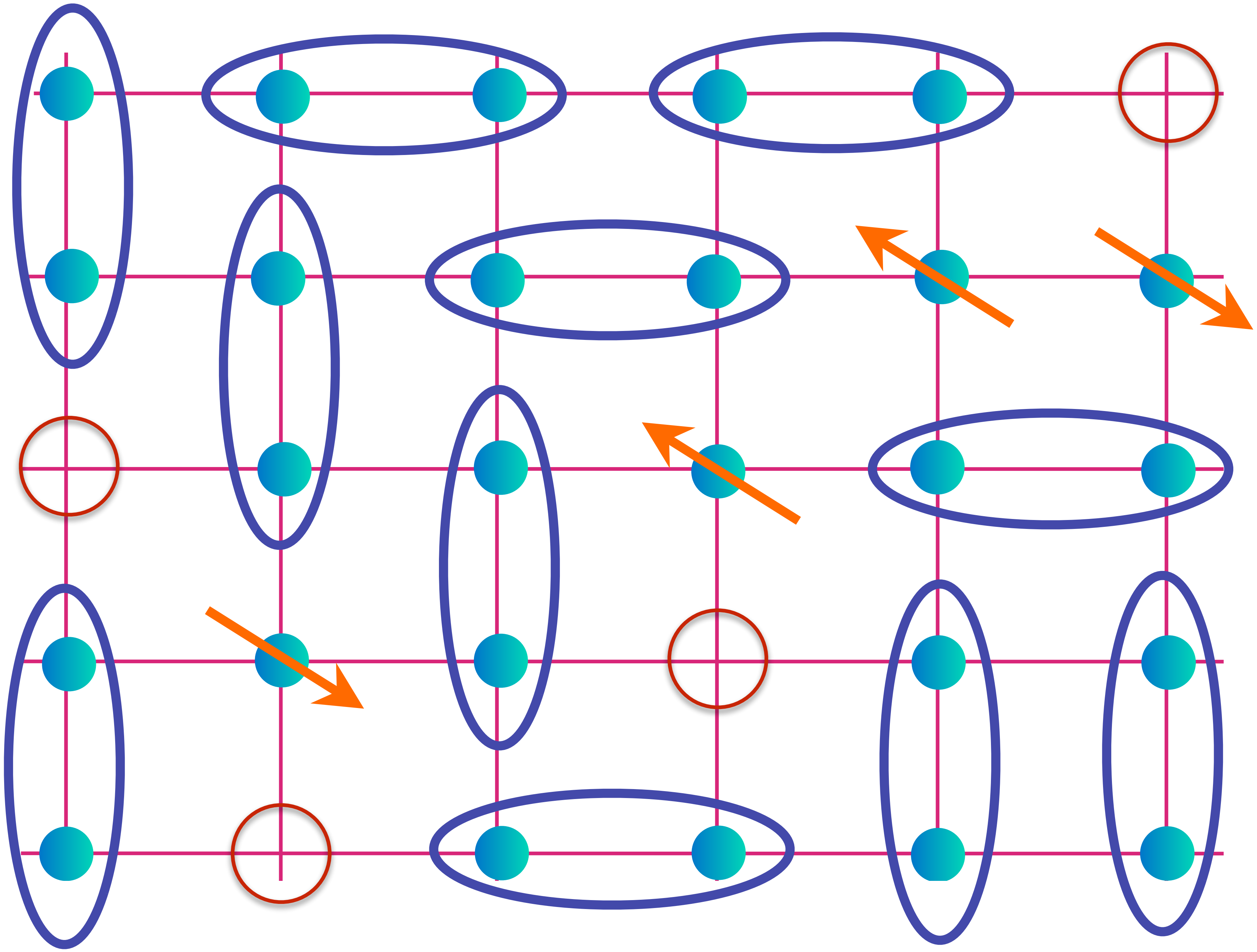
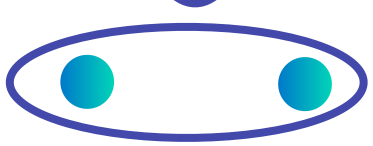
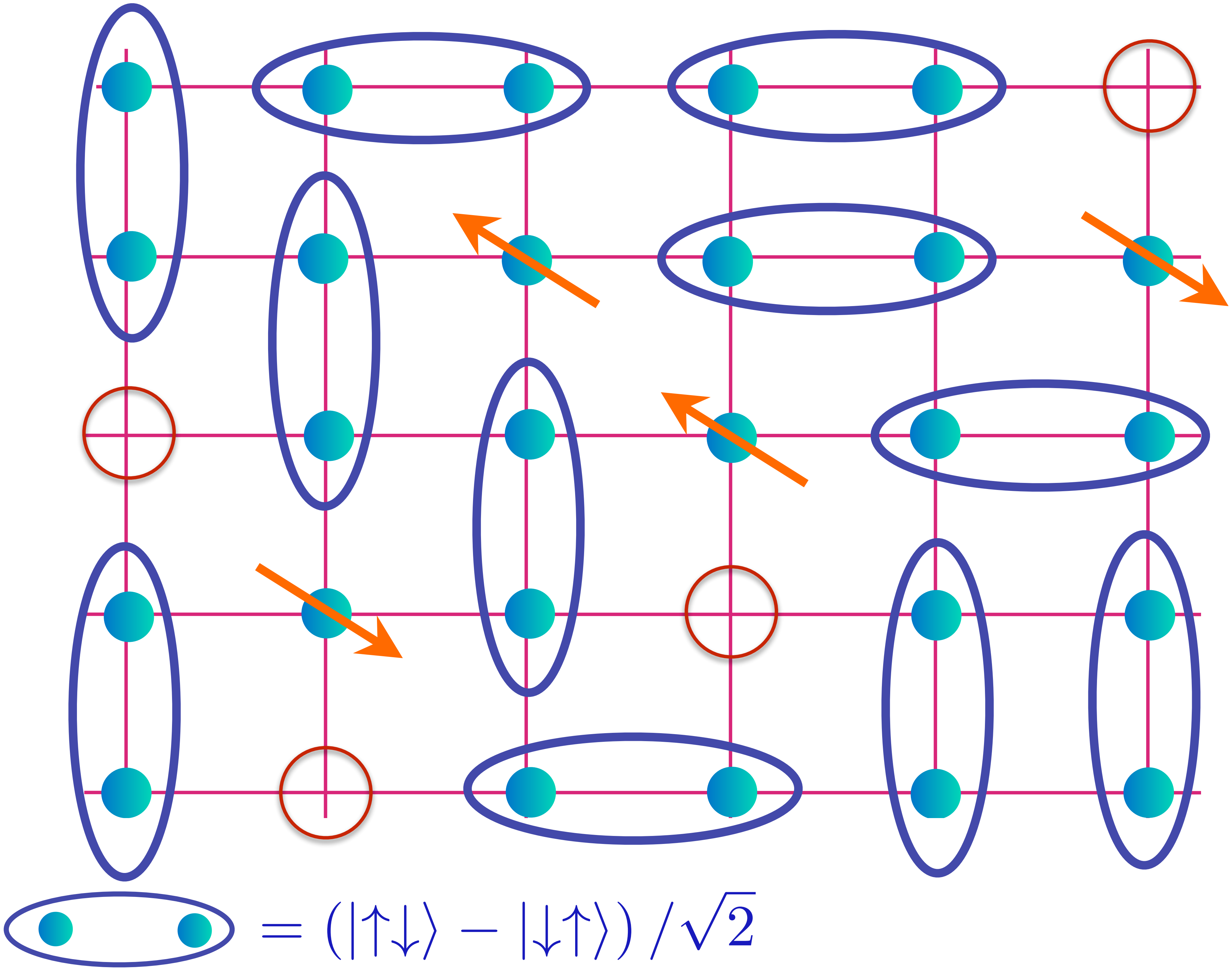

$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$


= (|↑↓⟩ − |↓↑⟩) / √2



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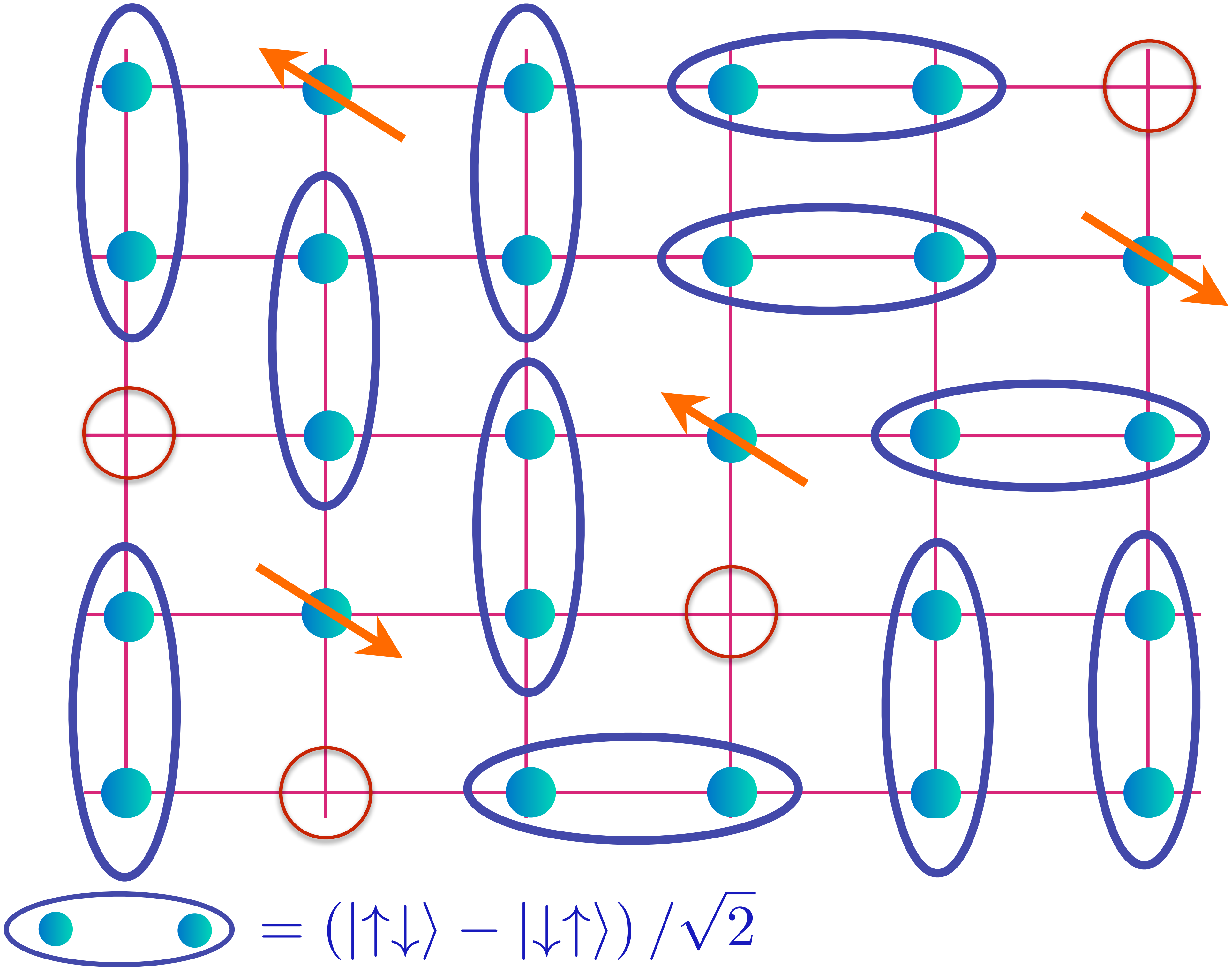
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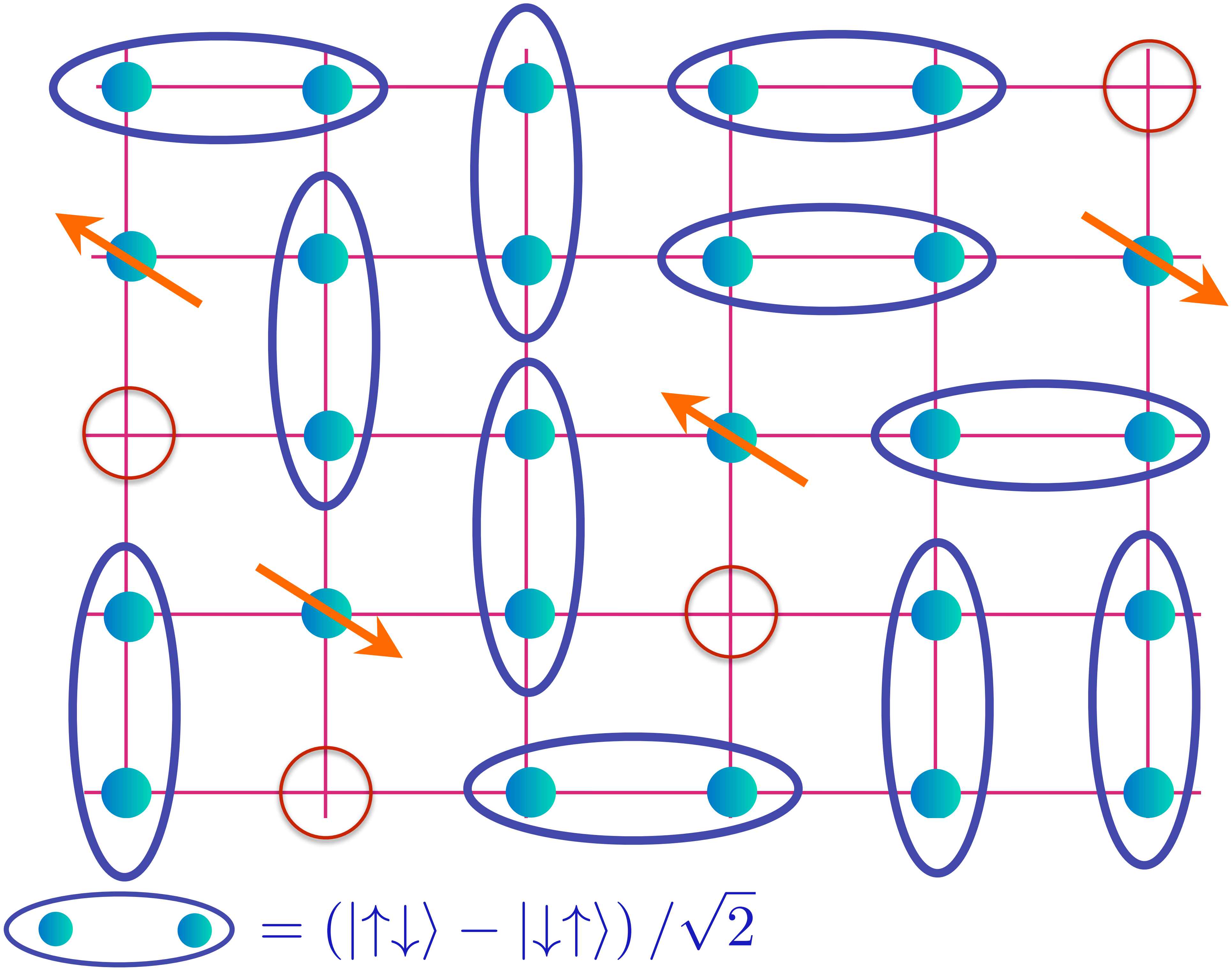
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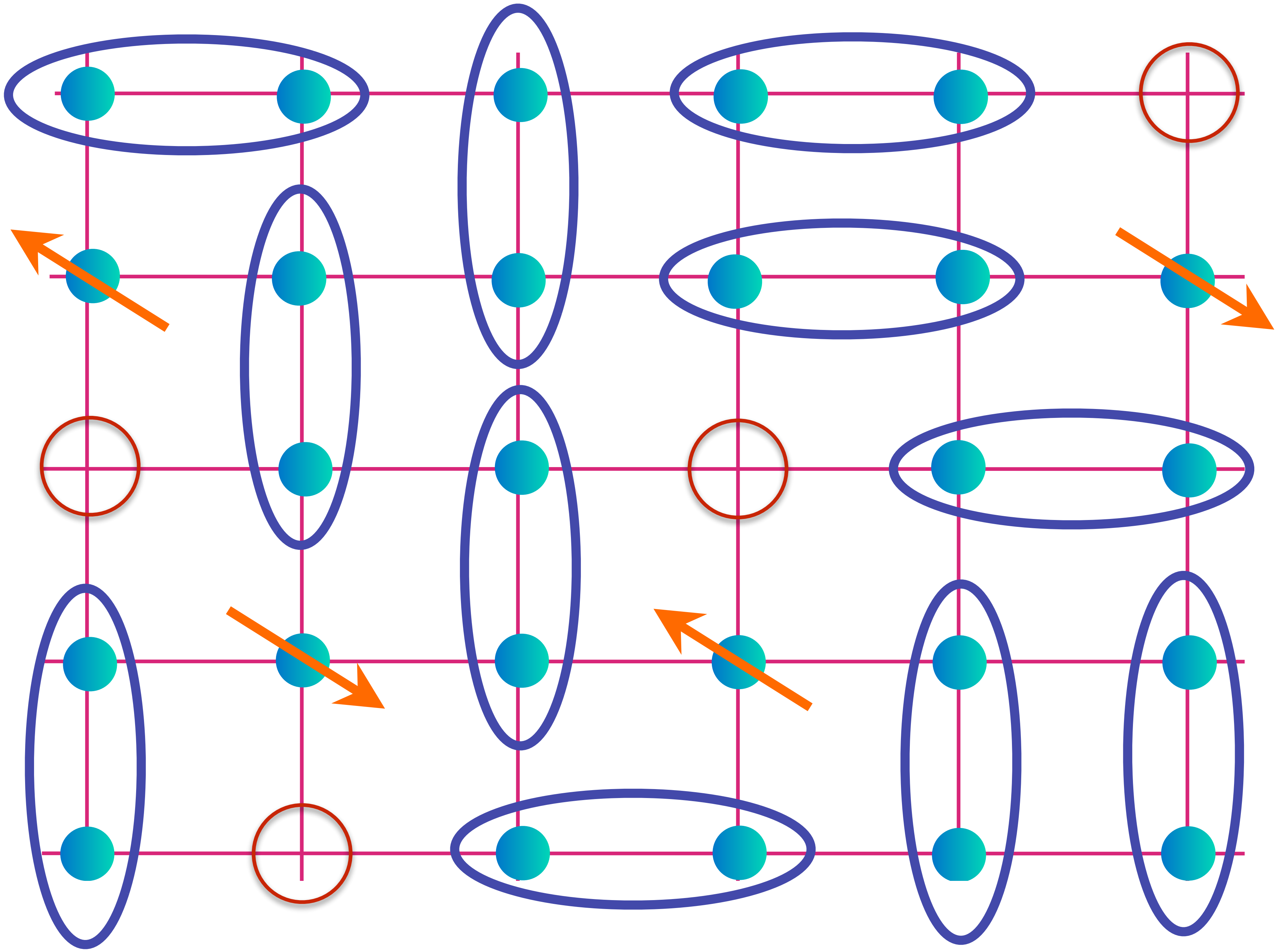

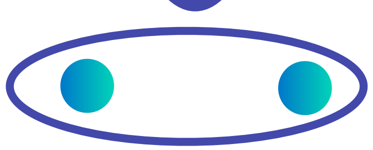

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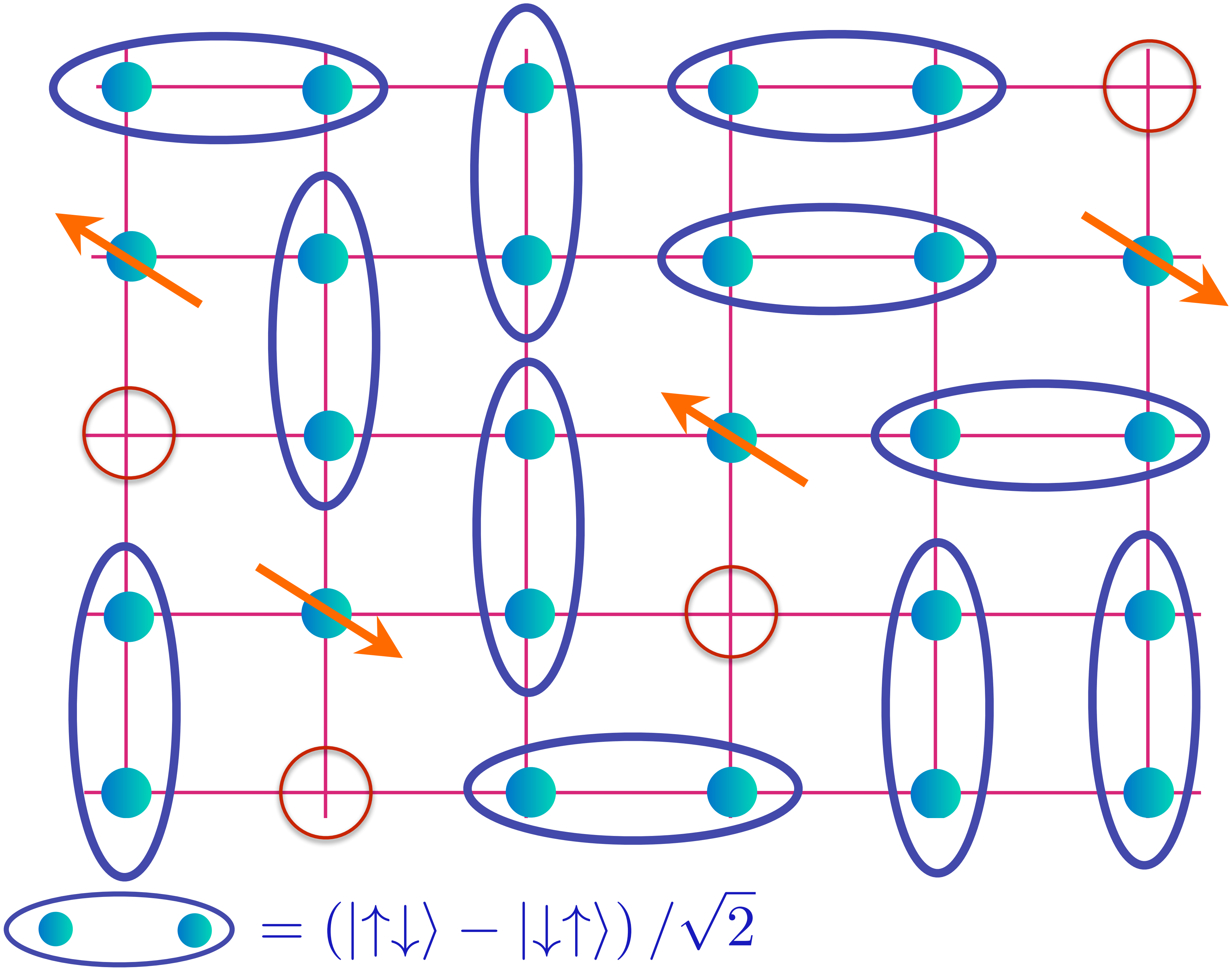

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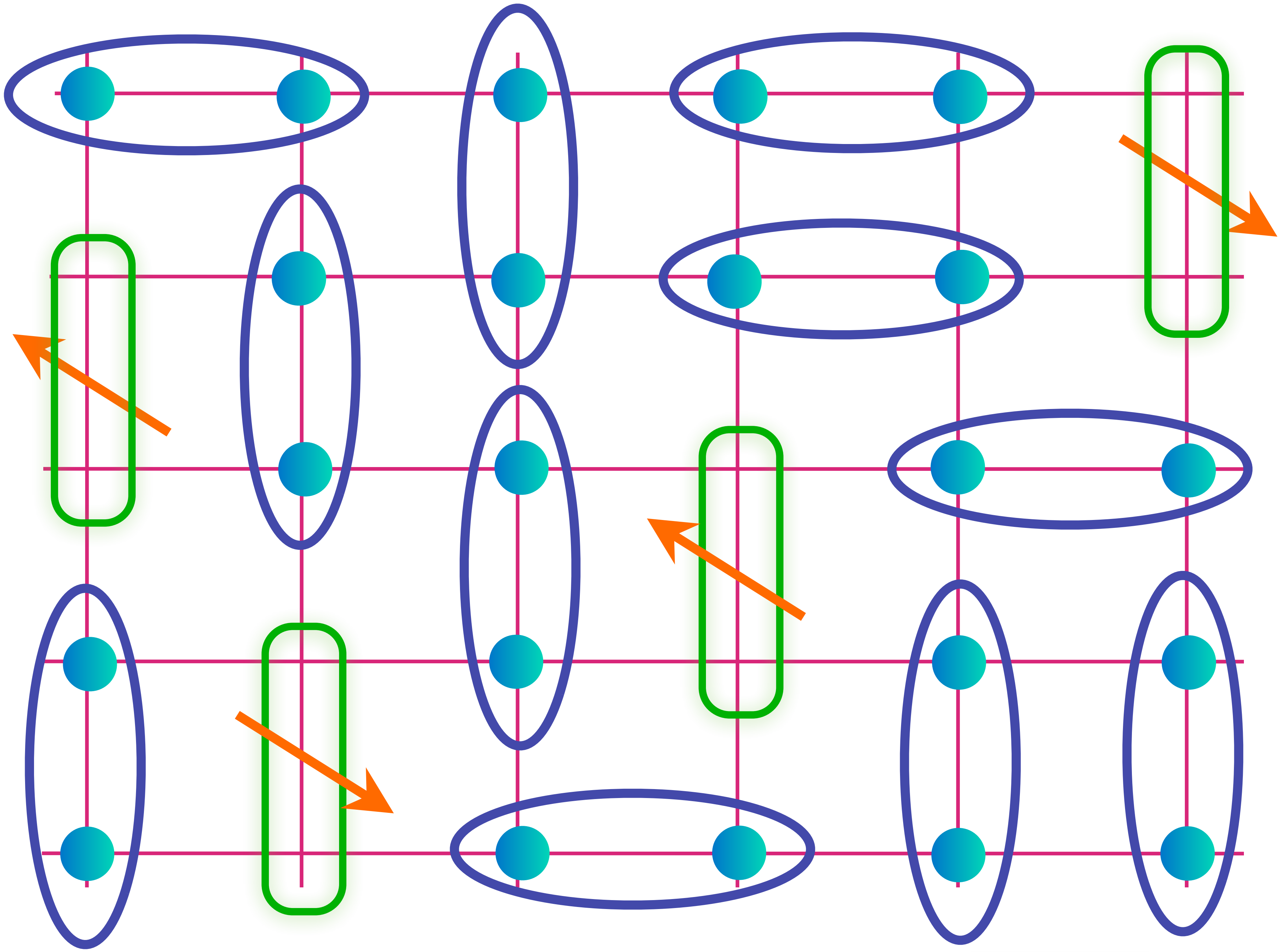
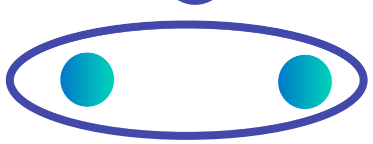
Fractionalized Fermi liquid (FL*)

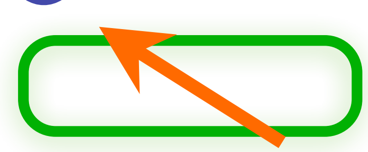
S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)

R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

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

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

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

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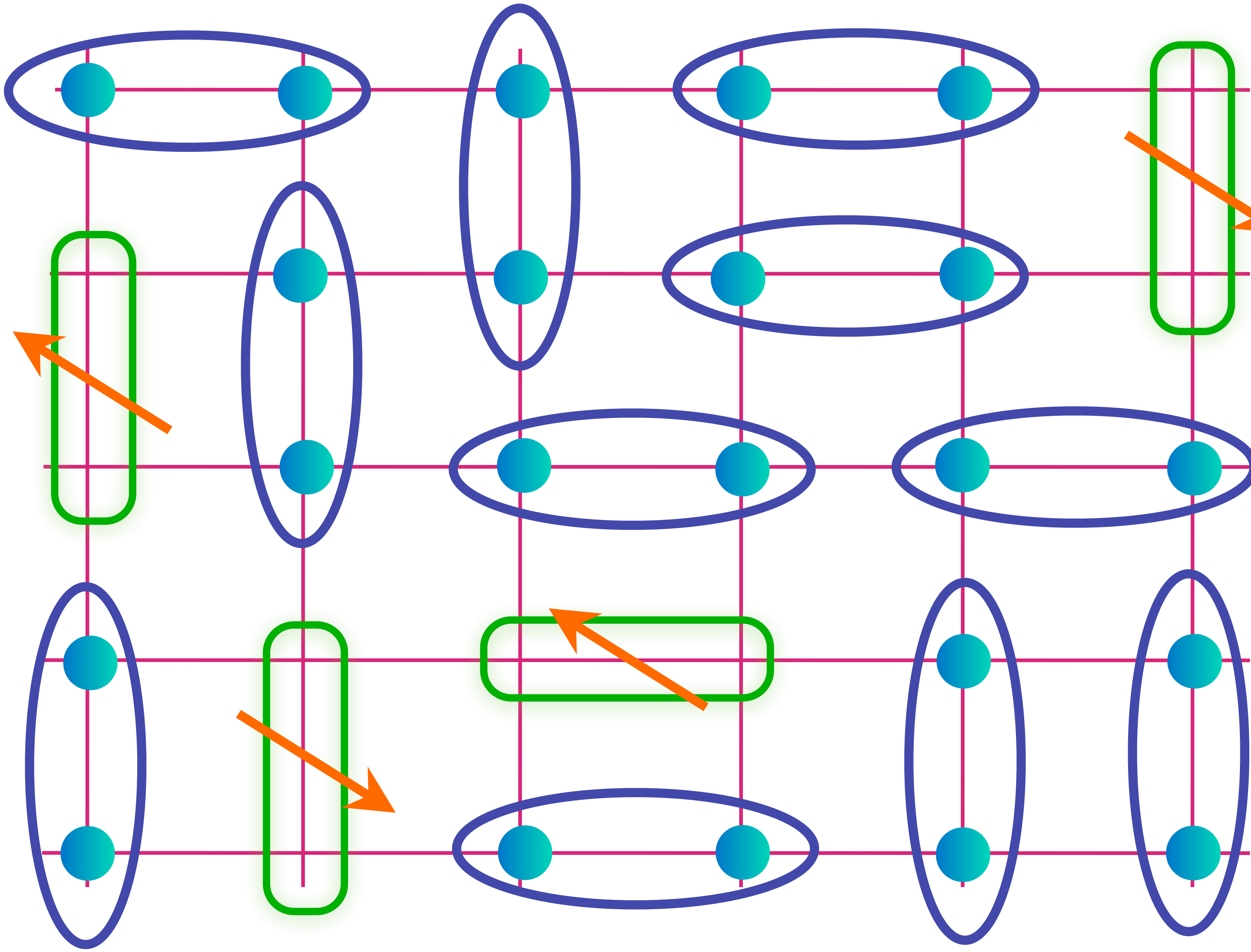

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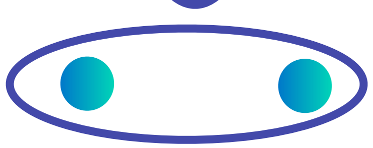
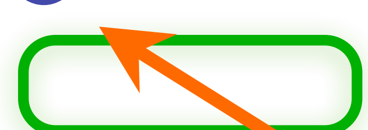
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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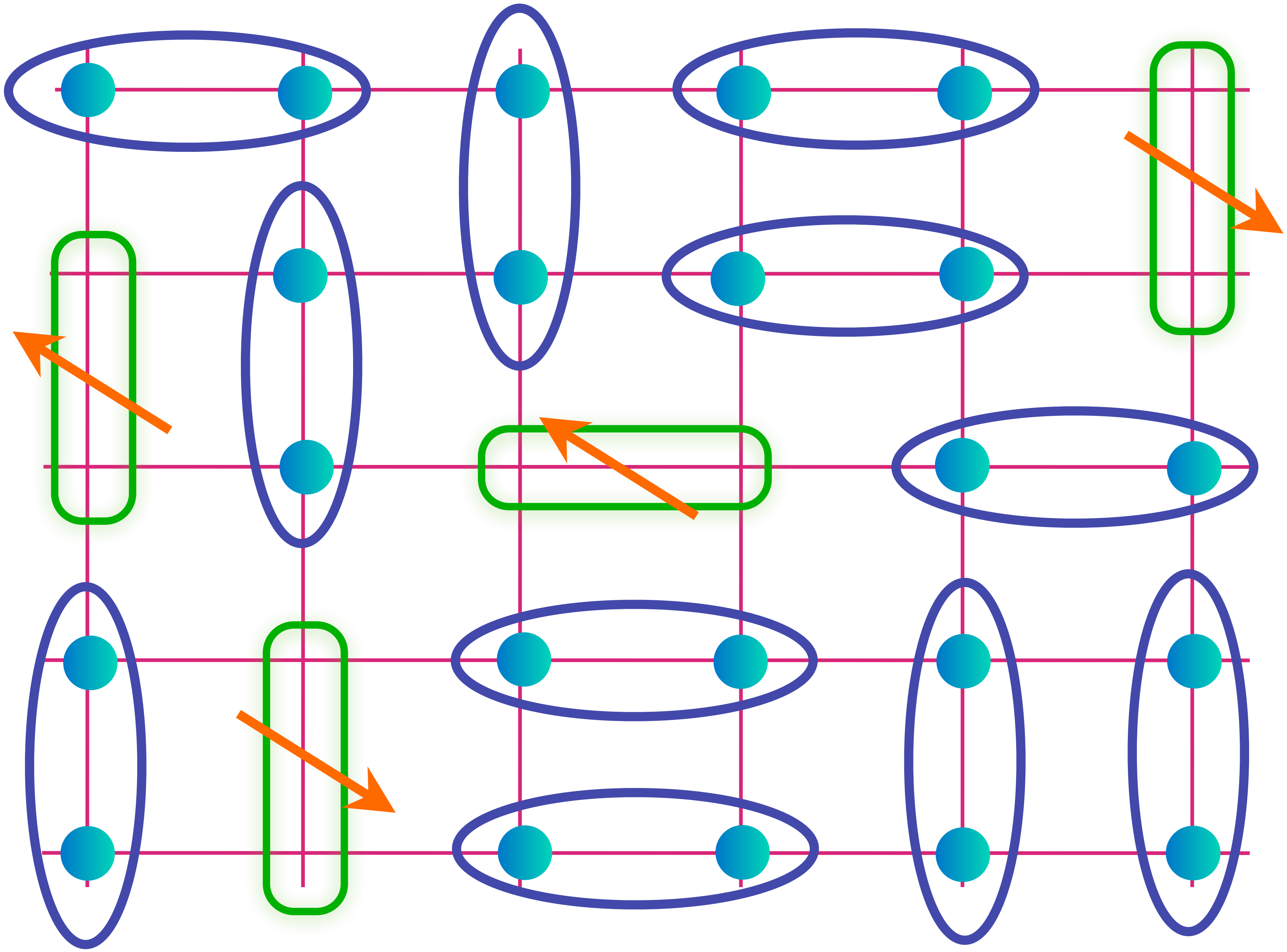

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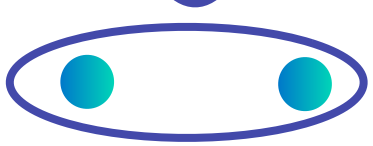
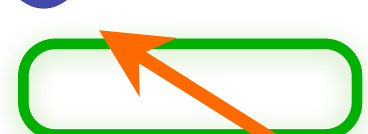
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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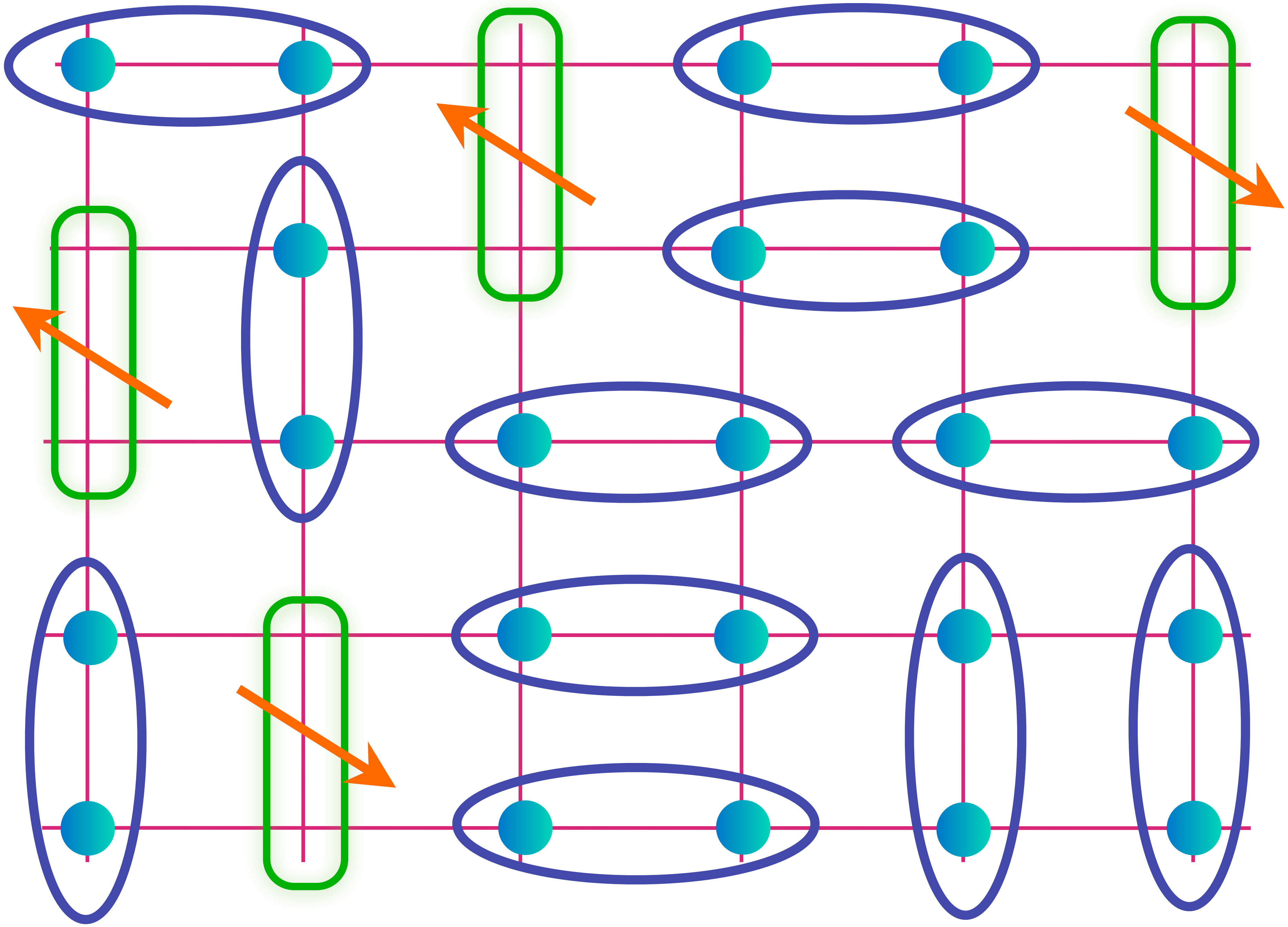

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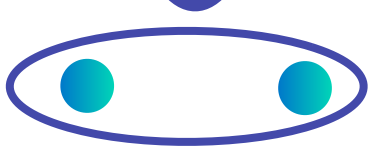
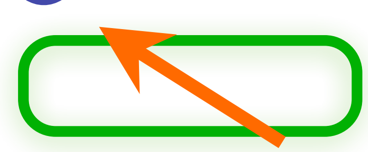
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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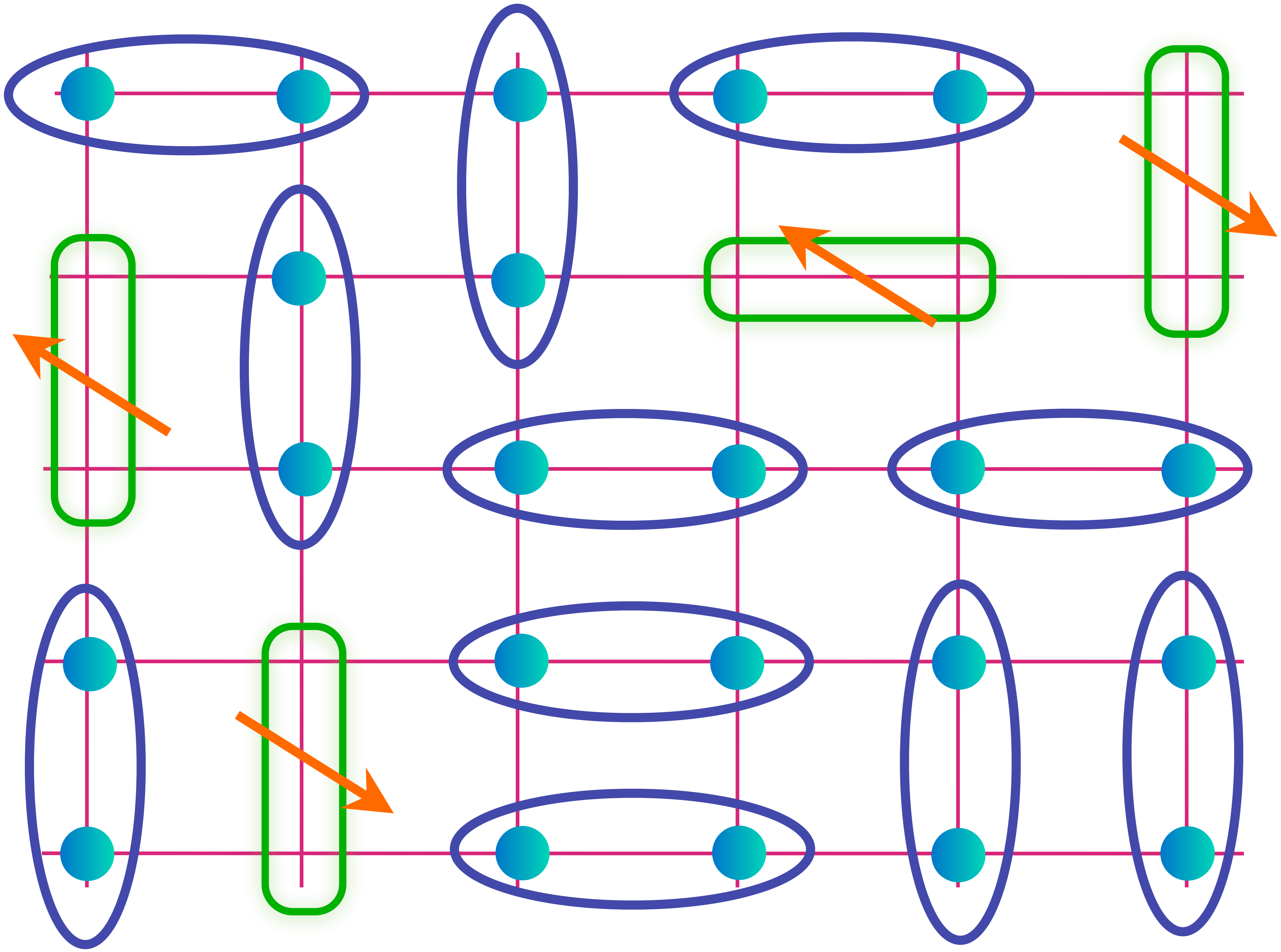

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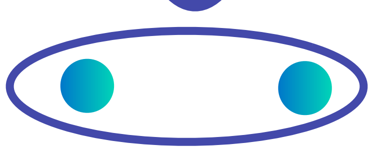
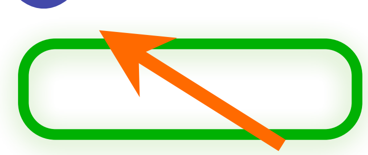
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

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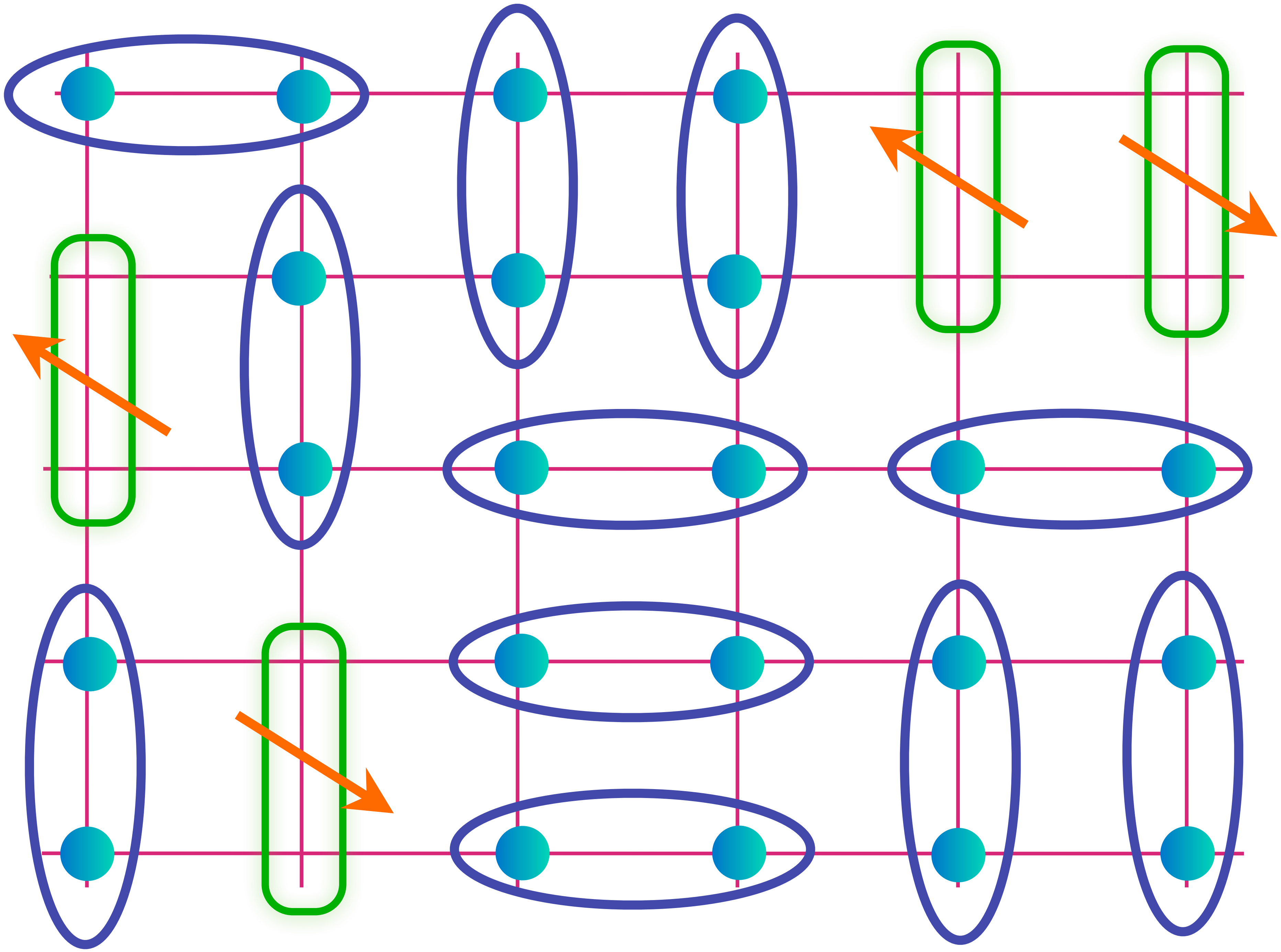

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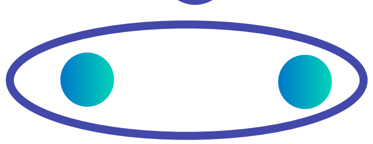
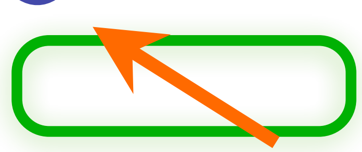
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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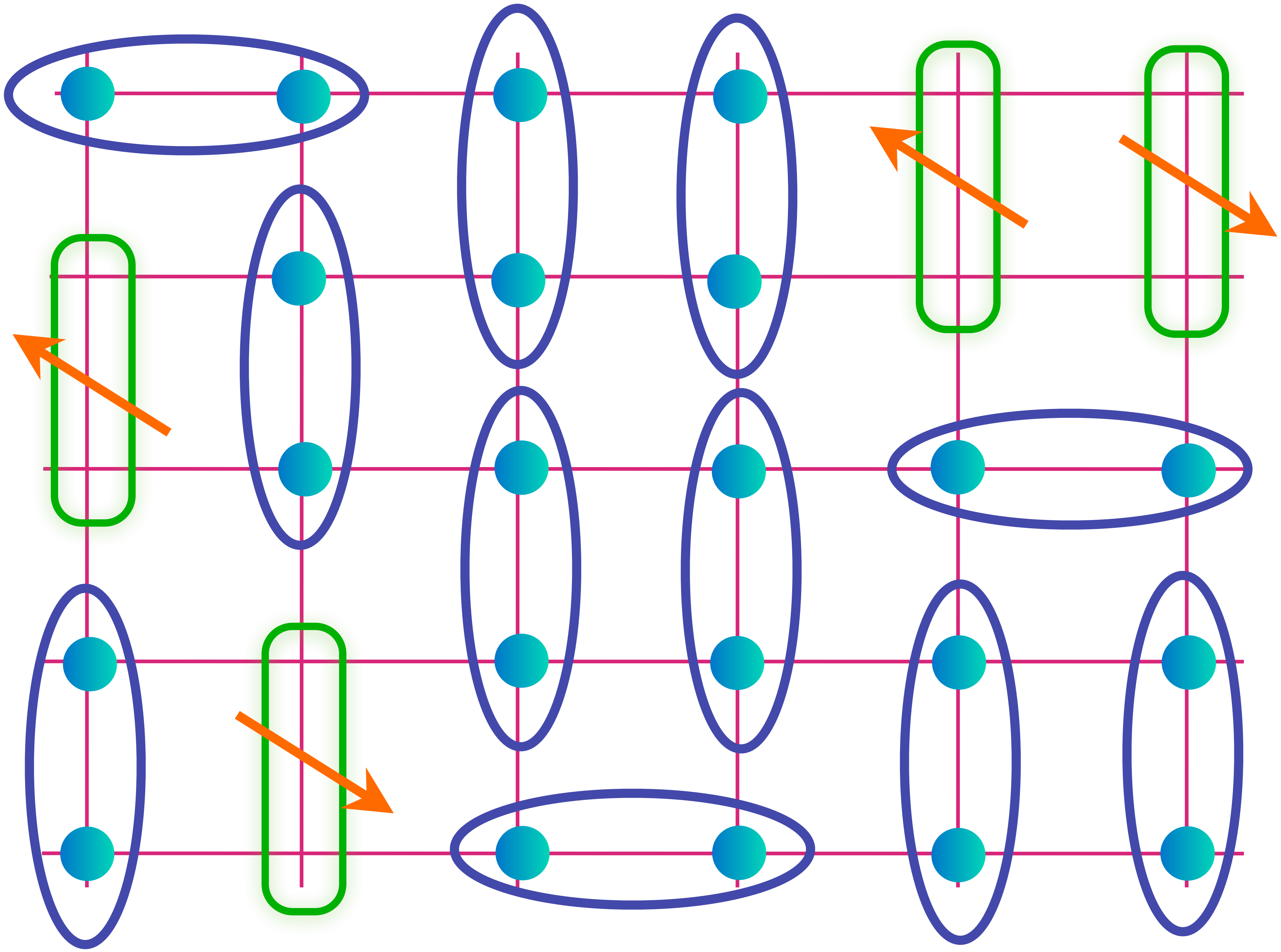

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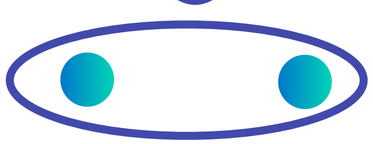
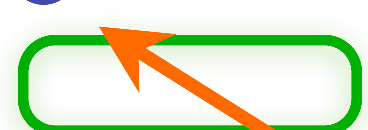
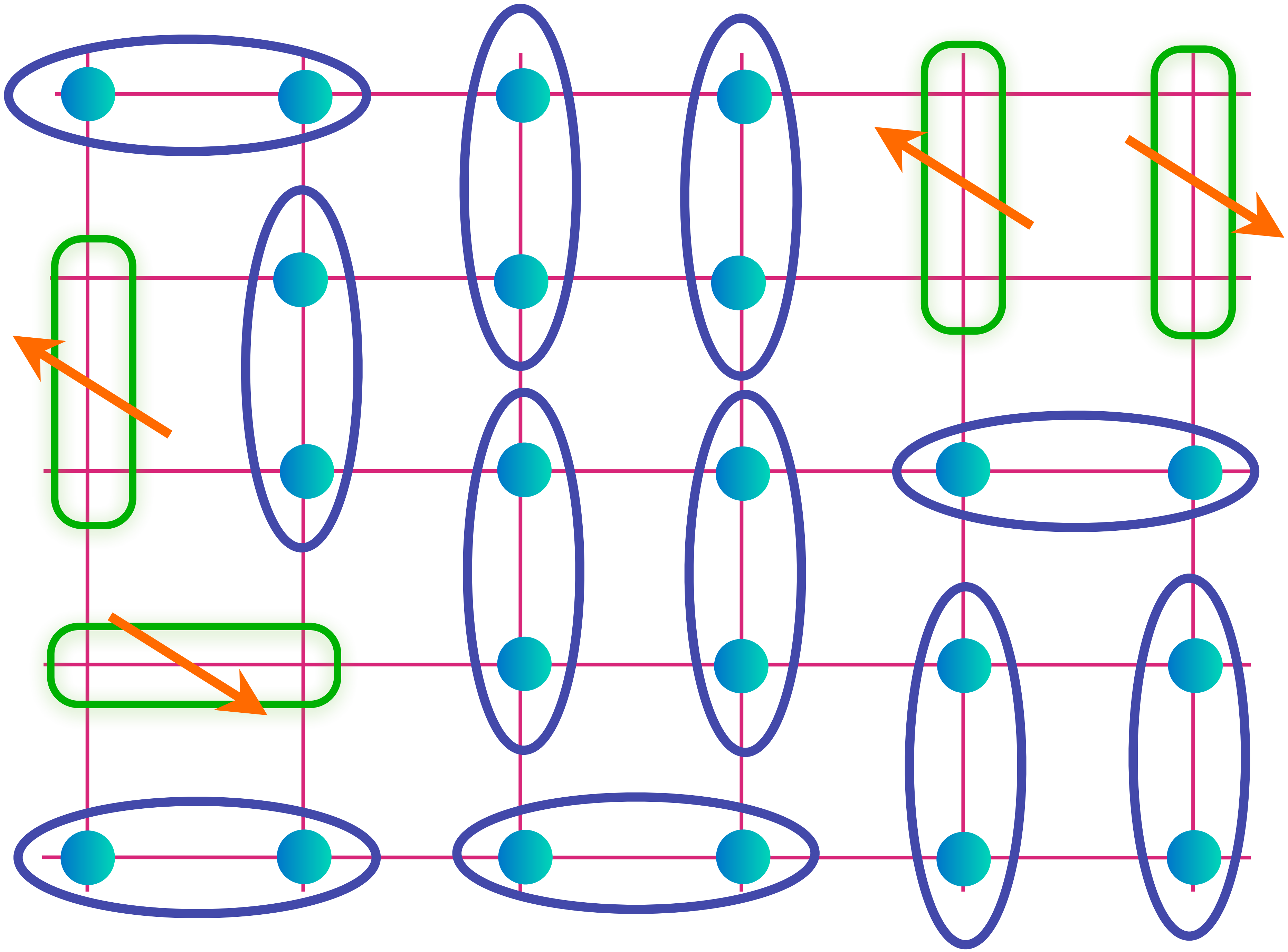
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

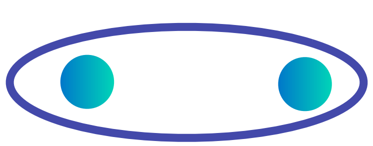
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

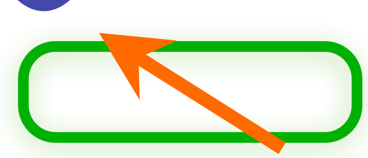
Fractionalized Fermi liquid (FL*)

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

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

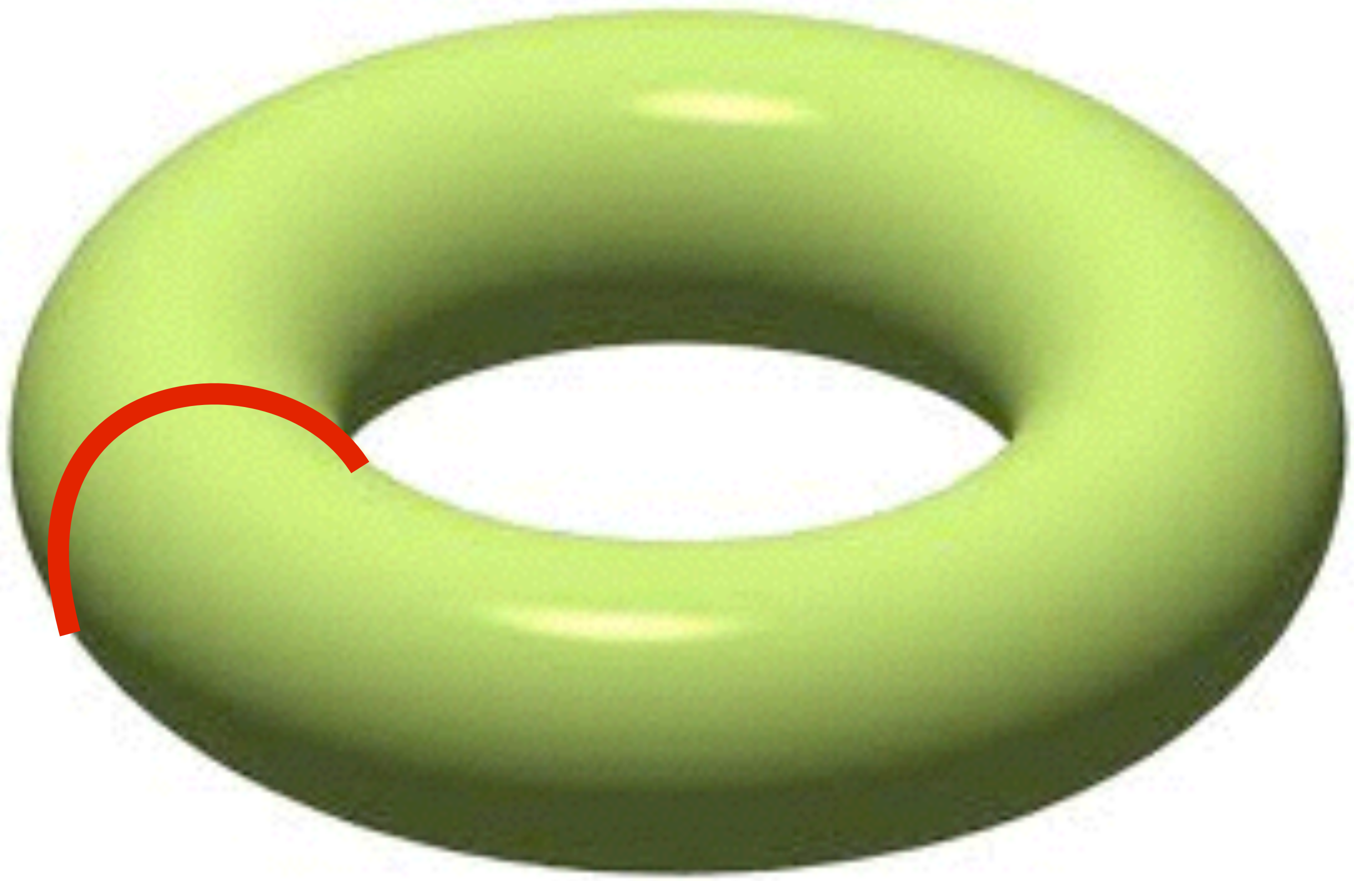
 $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

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

Ground state degeneracy

Place FL*
on a torus:

Ground state degeneracy



Place FL* on a torus:

obtain "topological" states nearly degenerate with quasiparticle states: number of dimers crossing red line is conserved modulo 2

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

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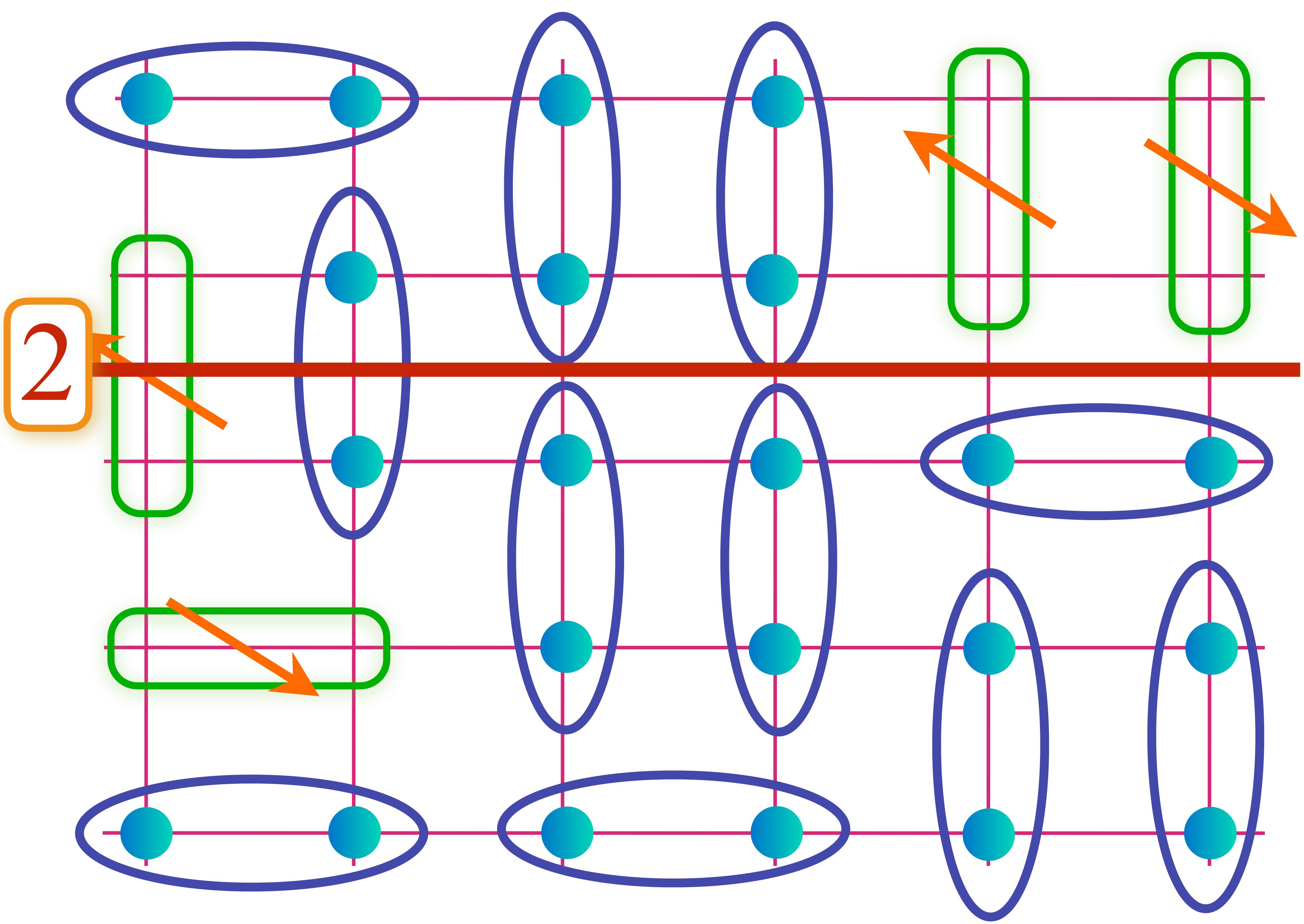

Place FL* on a torus:

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(blue ellipse) $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$ (green box) $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

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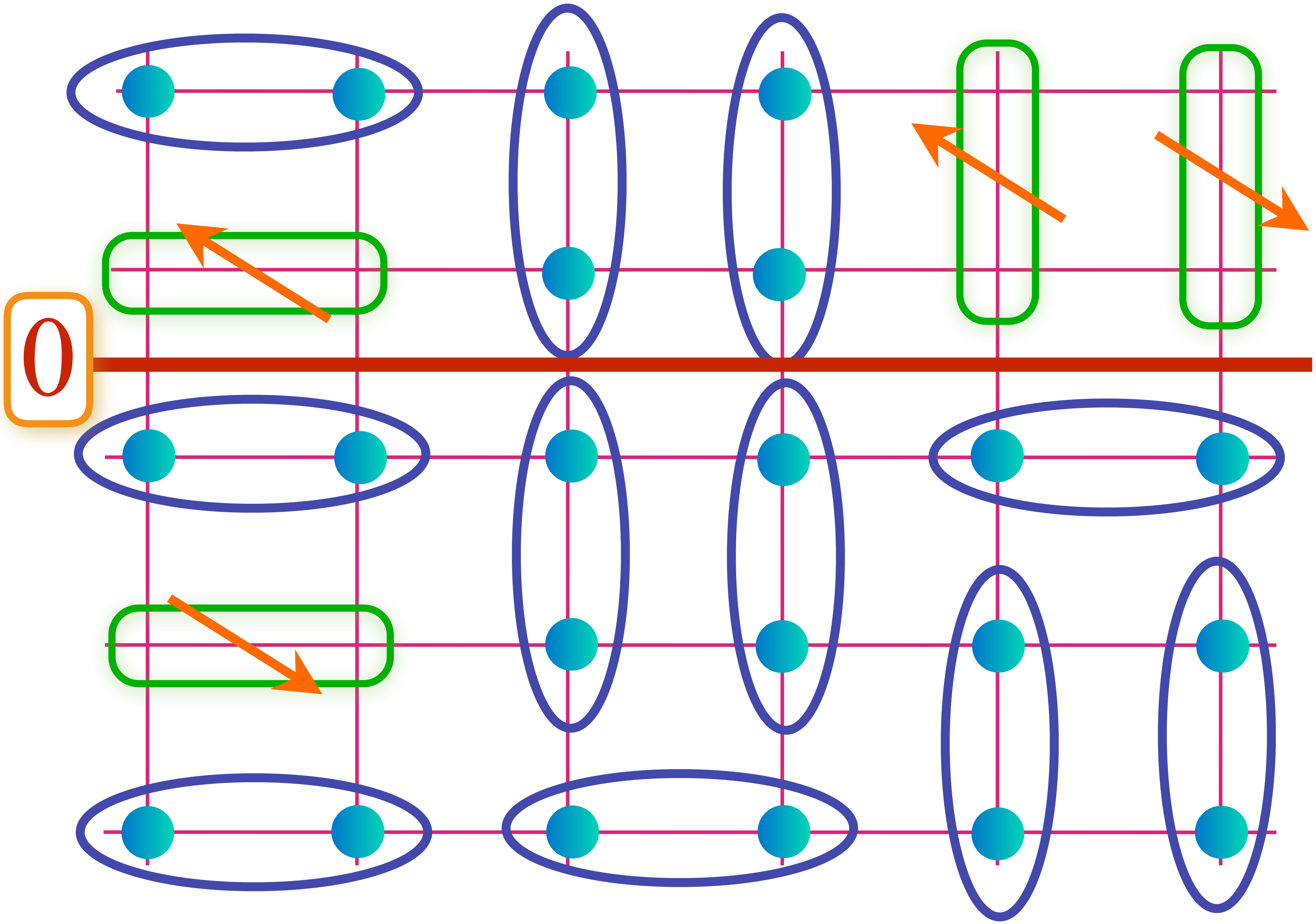

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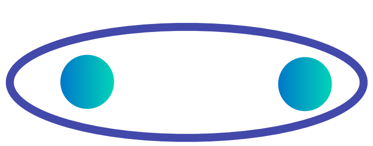
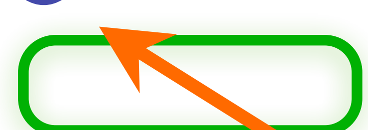


$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$



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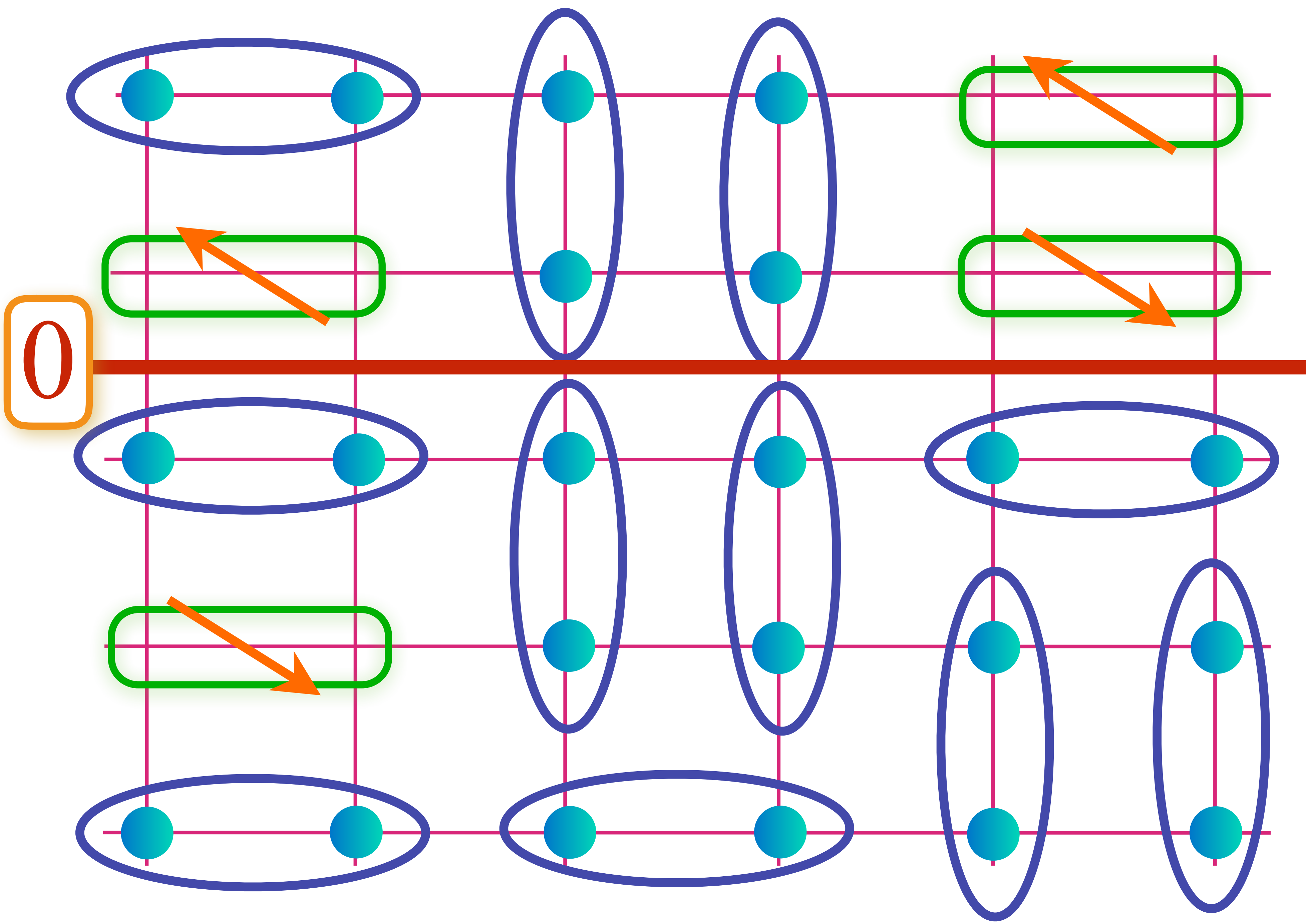

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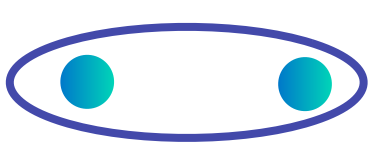
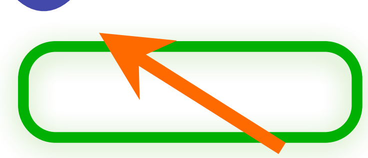
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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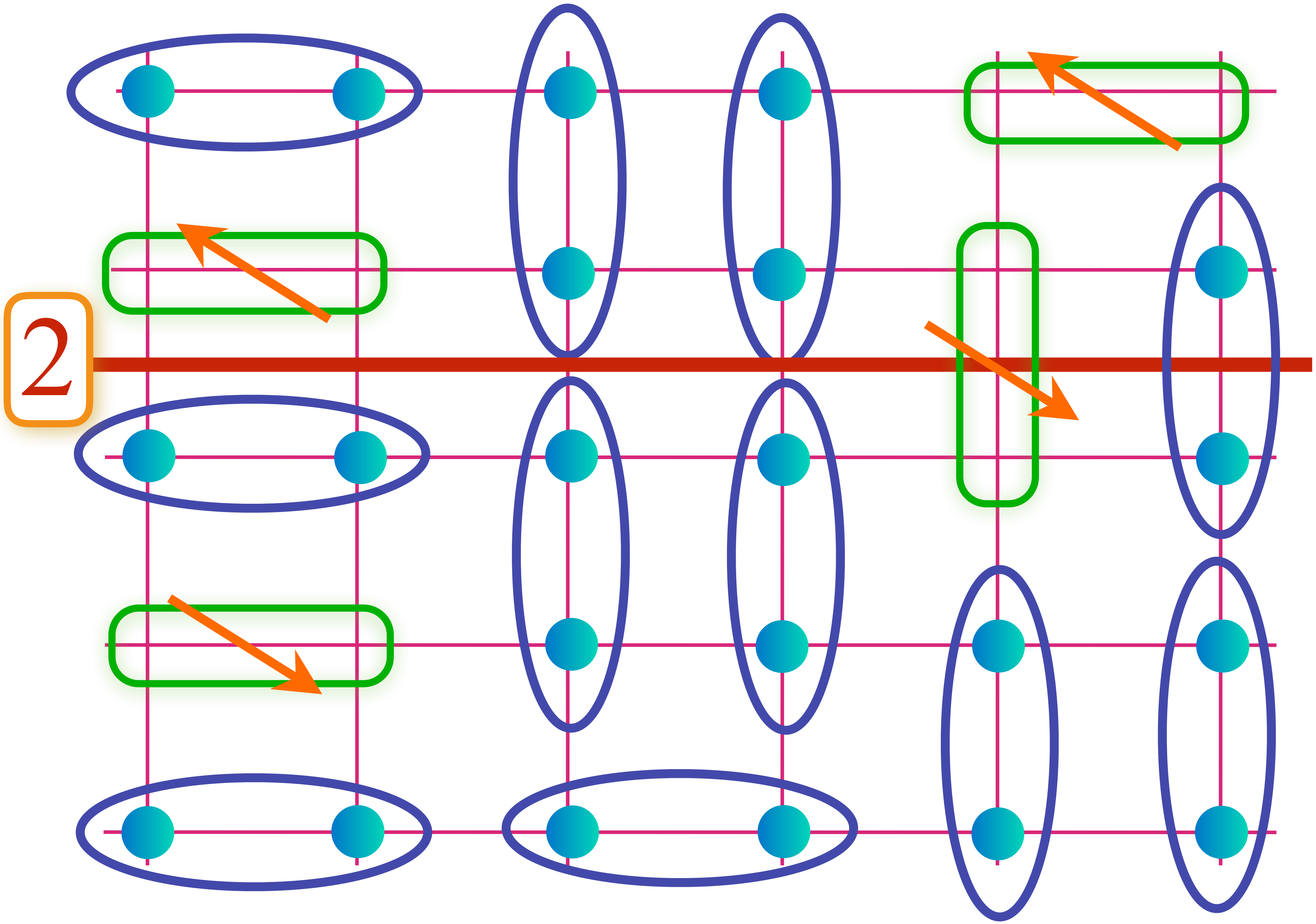

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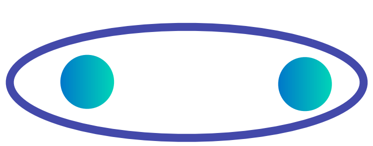
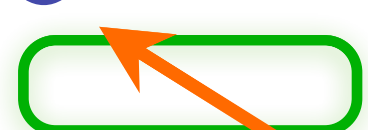
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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We have described a metal with:

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There is a general and fundamental relationship between these two characteristics.

M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

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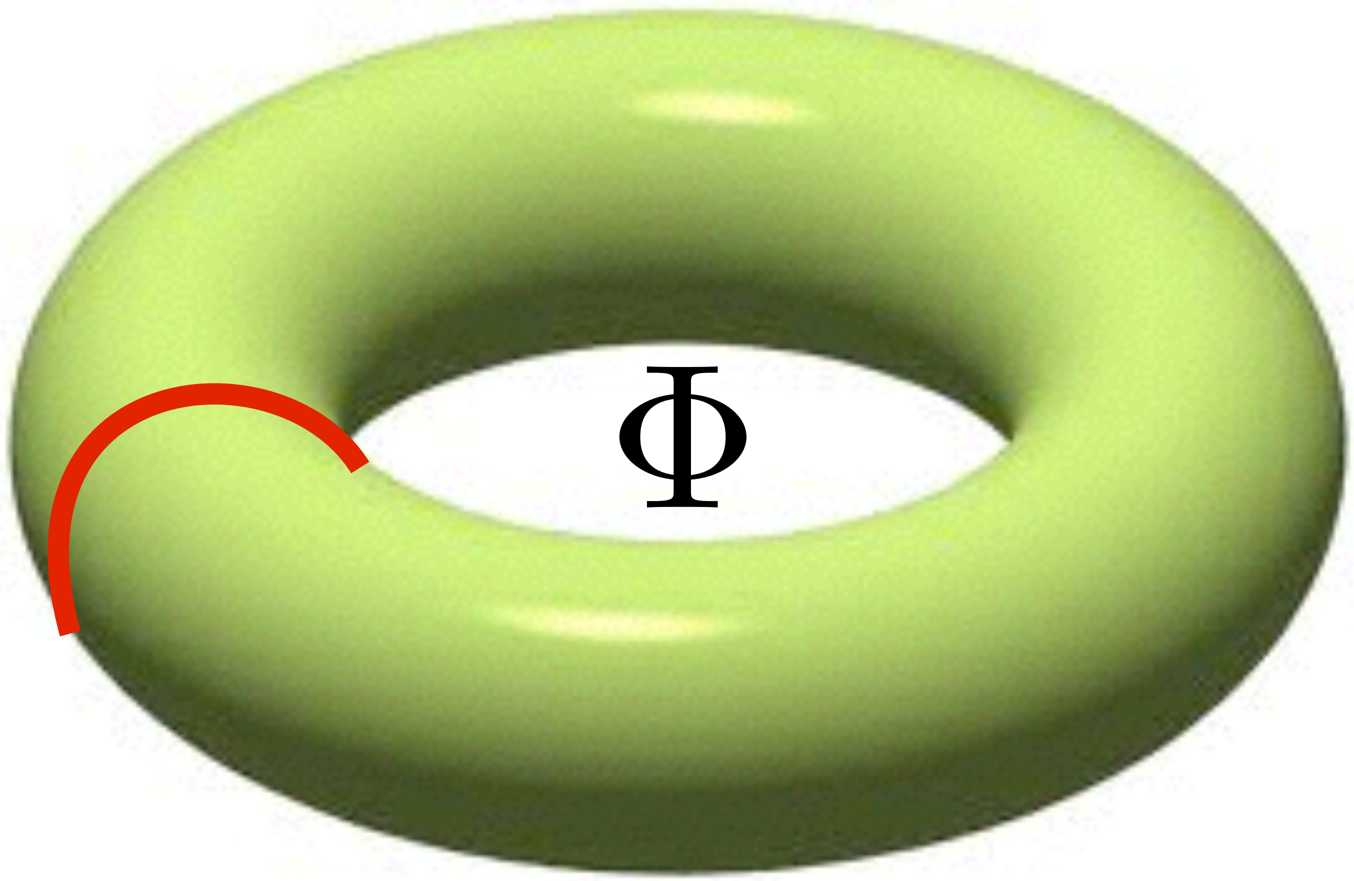

Following the evolution of the quantum state under adiabatic insertion of a flux quantum leads to a non-perturbative argument for the volume enclosed by the Fermi surface

M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)
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1. Emergent gauge fields and long-range entanglement in insulators

2. Fractionalized Fermi liquids (FL*)

Quasiparticles with a non-Luttinger volume, and emergent gauge fields

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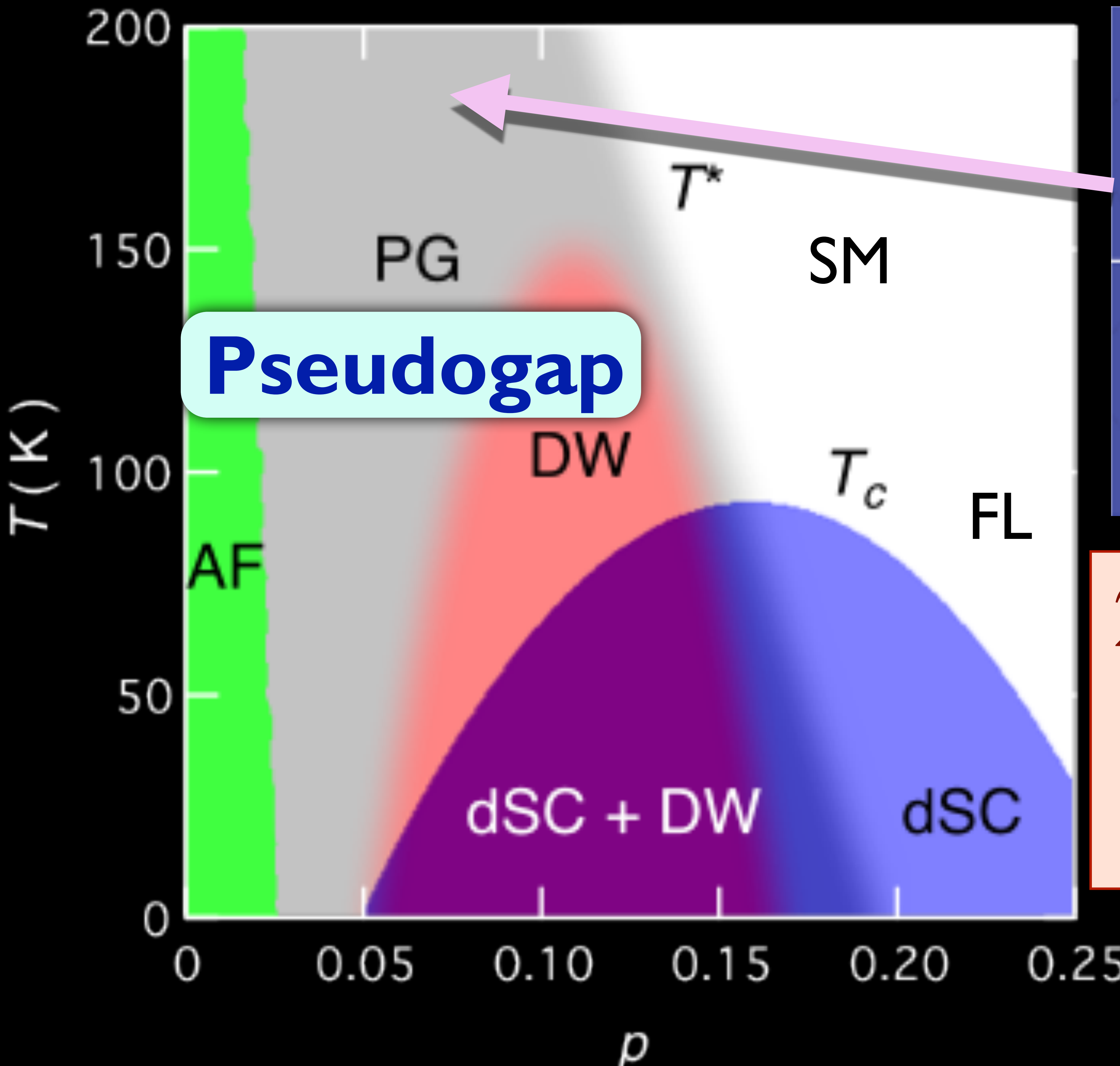
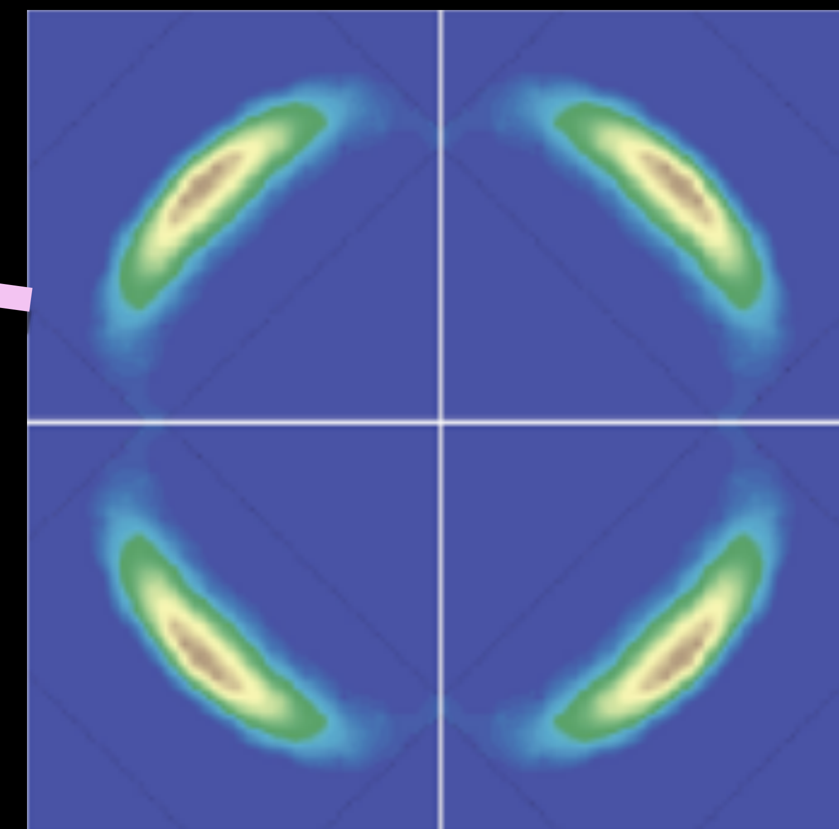
3. The pseudogap metal of the cuprate superconductors

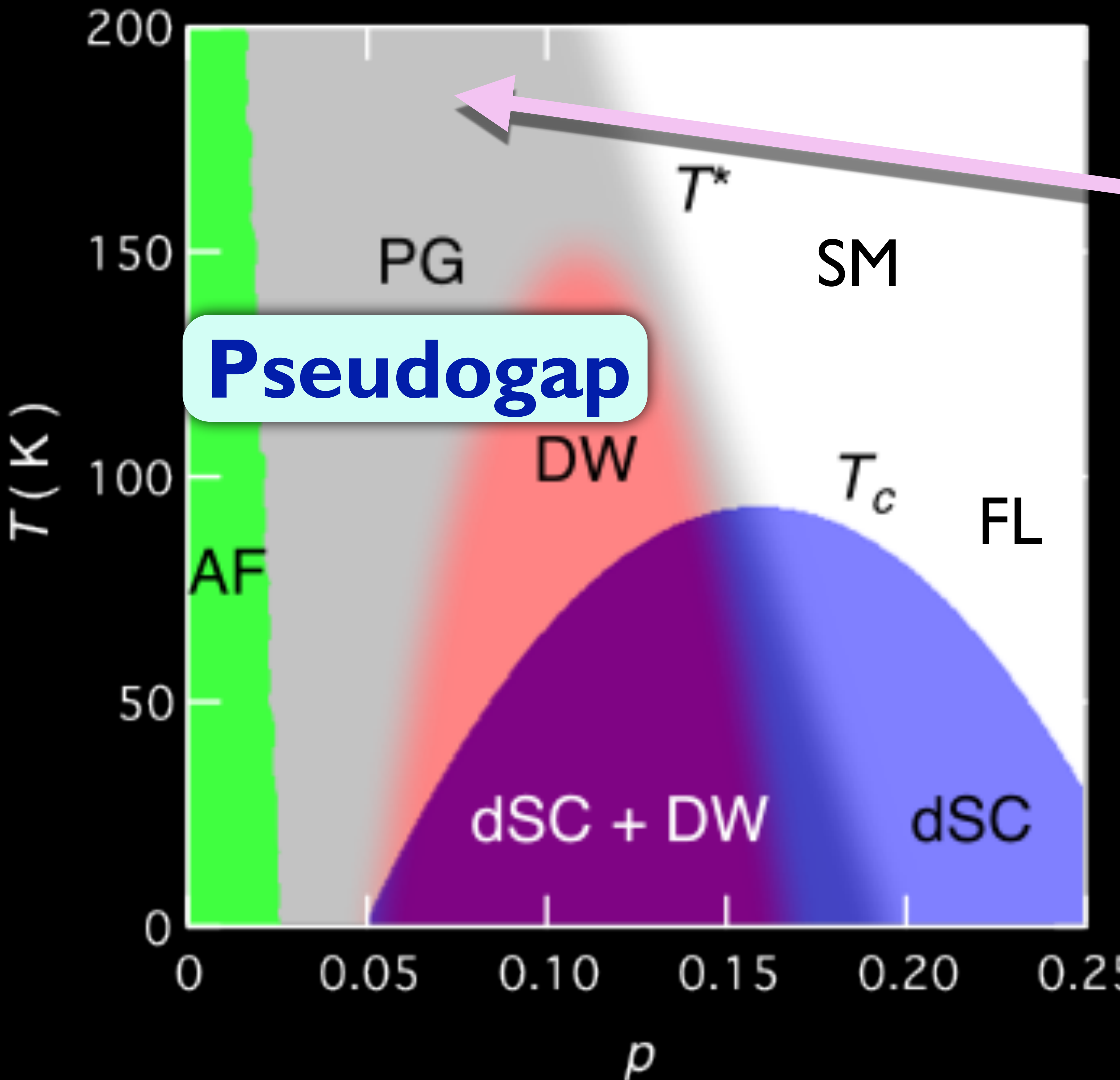
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

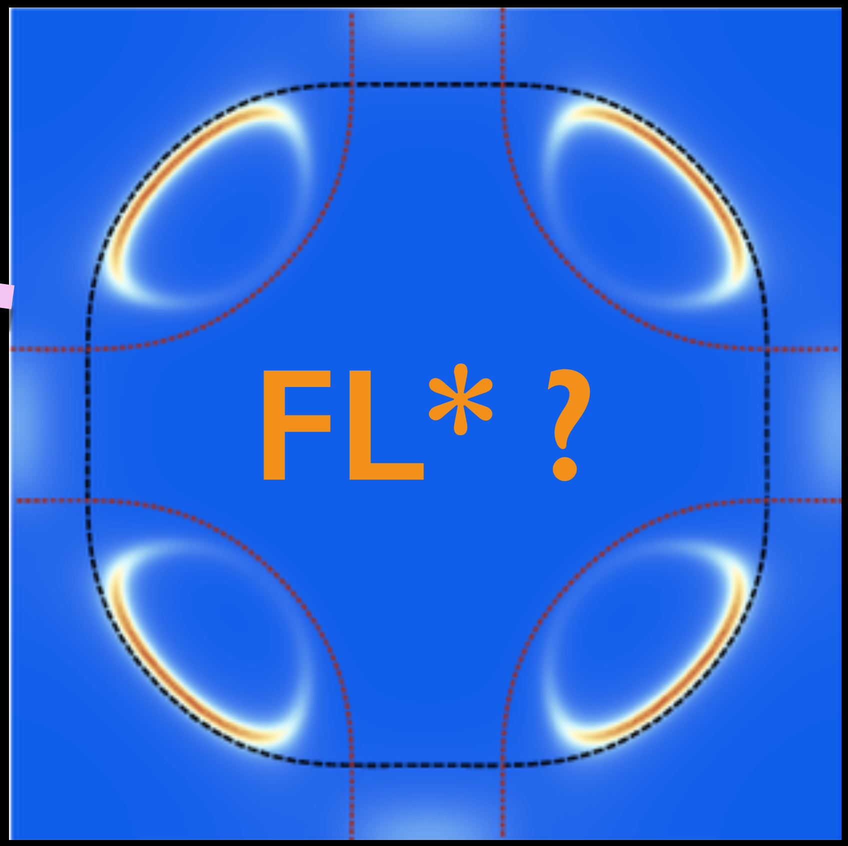




2. Pseudogap metal at low p

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)





A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size p

Recent evidence for pseudogap metal as FL*

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- Optical conductivity $\sim 1/(-i\omega + 1/\tau)$ with $1/\tau \sim \omega^2 + T^2$, with carrier density p (Mirzaei *et al.*, PNAS **110**, 5774 (2013)).

Optical evidence for Fermi surface of long-lived quasiparticles of density p

Spectroscopic evidence for Fermi liquid-like energy and temperature dependence of the relaxation rate in the pseudogap phase of the cuprates

Seyed Iman Mirzaei[a], Damien Stricker[a], Jason N. Hancock[a,b], Christophe Berthod[a], Antoine Georges[a,c,d], Erik van Heumen[a,e], Mun K. Chan[f], Xudong Zhao[f,g], Yuan Li[h], Martin Greven[f], Neven Barišić[f,i,j], and Dirk van der Marel[a,1]

PNAS **110**, 5774 (2013)

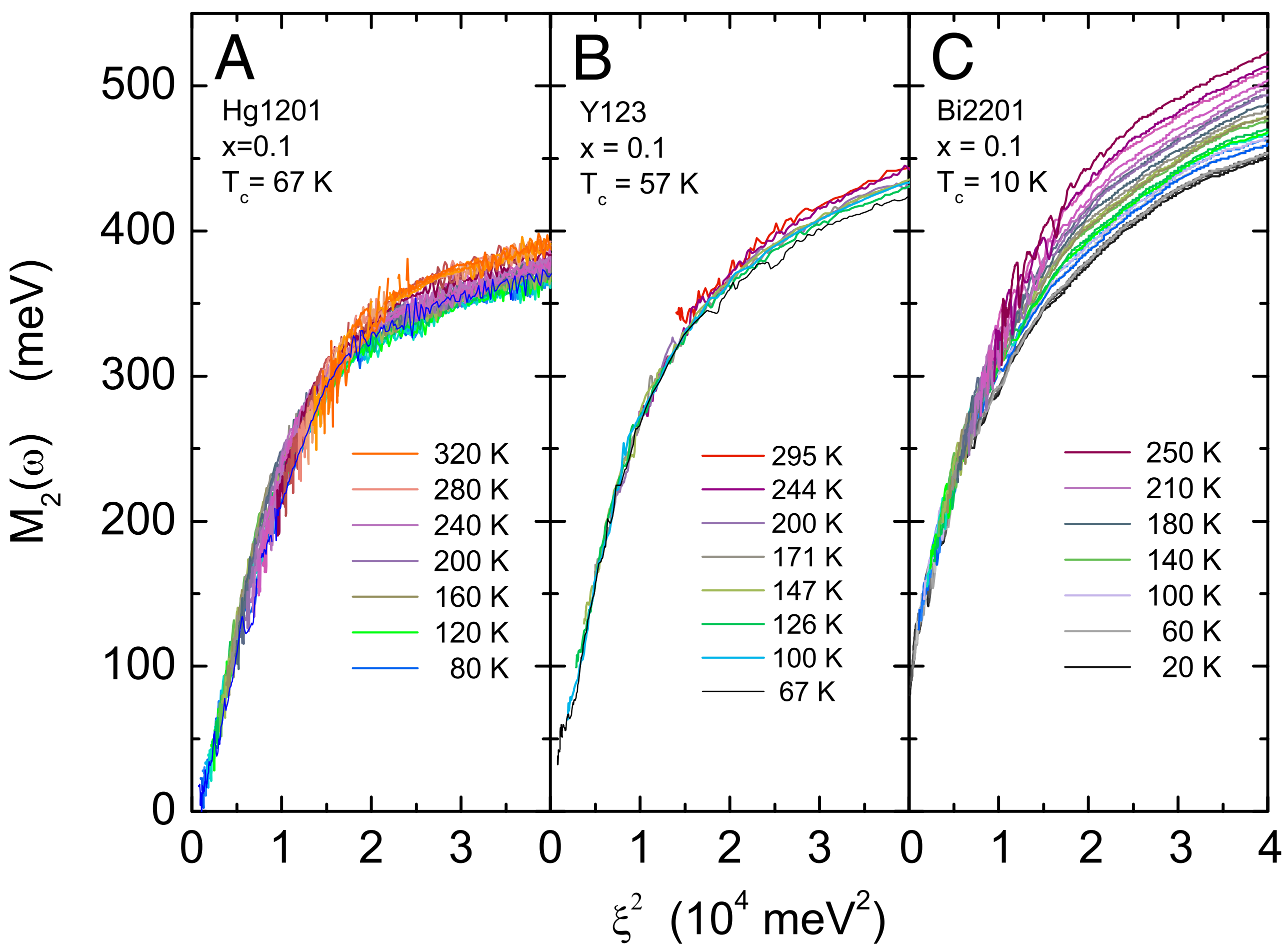

Fig. 6. Collapse of the frequency and temperature dependence of the relaxation rate of underdoped cuprate materials. Normal state $M_2(\omega, T)$ as a function of $\xi^2 \equiv (\hbar\omega)^2 + (p\pi k_B T)^2$

$$\sigma_{xx} \sim \frac{1}{(-i\omega + 1/\tau)}$$

$$\text{with } \frac{1}{\tau} \sim \omega^2 + T^2$$

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Electrical evidence for Fermi surface of long-lived quasiparticles of density p

In-Plane Magnetoresistance Obeys Kohler's Rule in the Pseudogap Phase of Cuprate Superconductors

M. K. Chan,[1,*] M. J. Veit,[1] C. J. Dorow,[1,†] Y. Ge,[1] Y. Li,[1] W. Tabis,[1,2] Y. Tang,[1] X. Zhao,[1,3] N. Barišić,[1,4,5,‡] and M. Greven[1,§]

PRL 113, 177005 (2014)

We report in-plane resistivity (ρ) and transverse magnetoresistance (MR) measurements for underdoped $HgBa_2CuO_{4+\delta}$ (Hg1201). Contrary to the long-standing view that Kohler's rule is strongly violated in underdoped cuprates, we find that it is in fact satisfied in the pseudogap phase of Hg1201. The transverse MR shows a quadratic field dependence, $\delta\rho/\rho_0 = aH^2$, with $a(T) \propto T^{-4}$. In combination with the observed $\rho \propto T^2$ dependence, this is consistent with a single Fermi-liquid quasiparticle scattering rate. We show that this behavior is typically masked in cuprates with lower structural symmetry or strong disorder effects.

$$\rho_{xx} \sim \frac{1}{\tau}(1 + aH^2\tau^2 + \ldots)$$

$$\text{with } \frac{1}{\tau} \sim T^2$$

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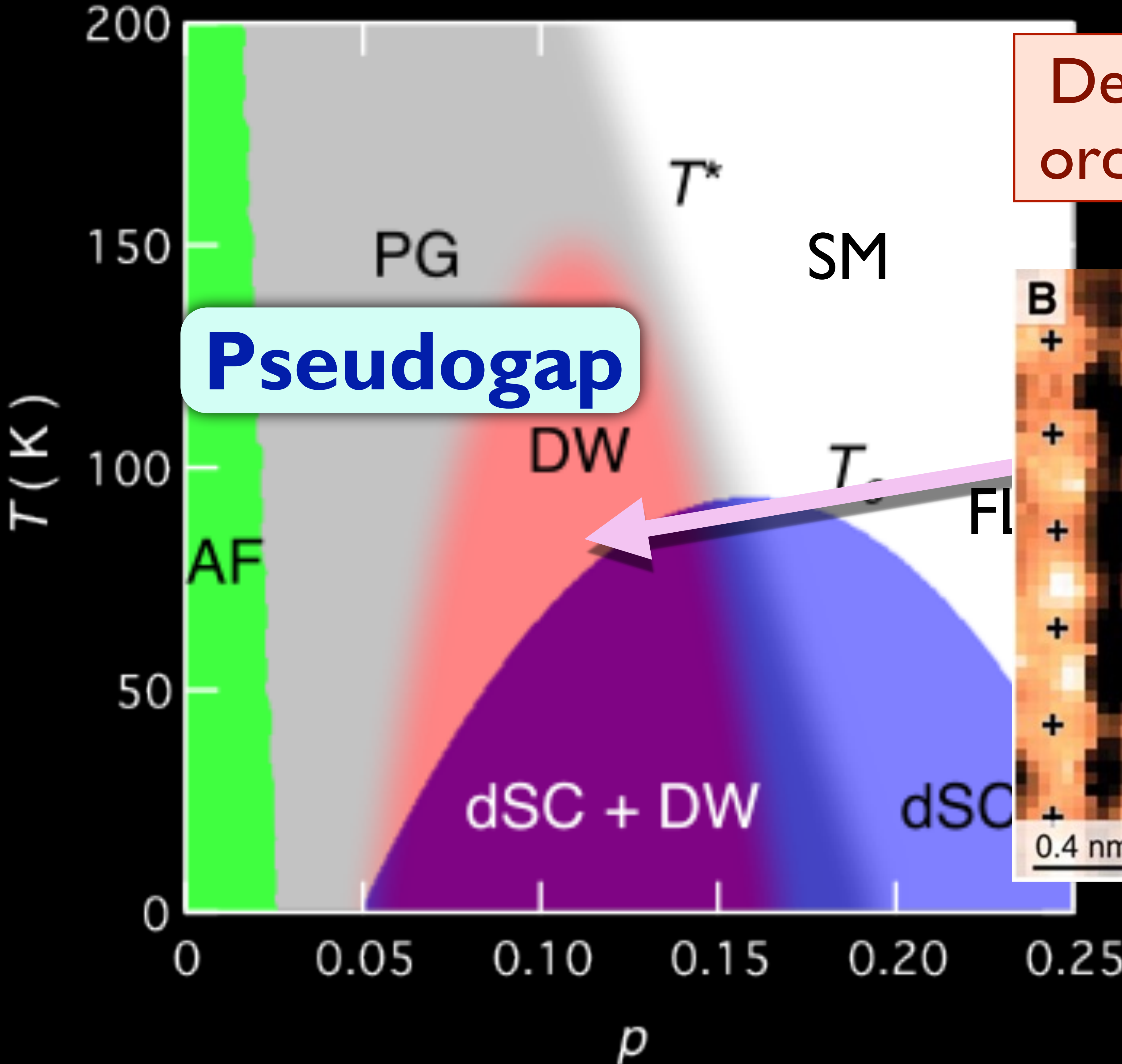
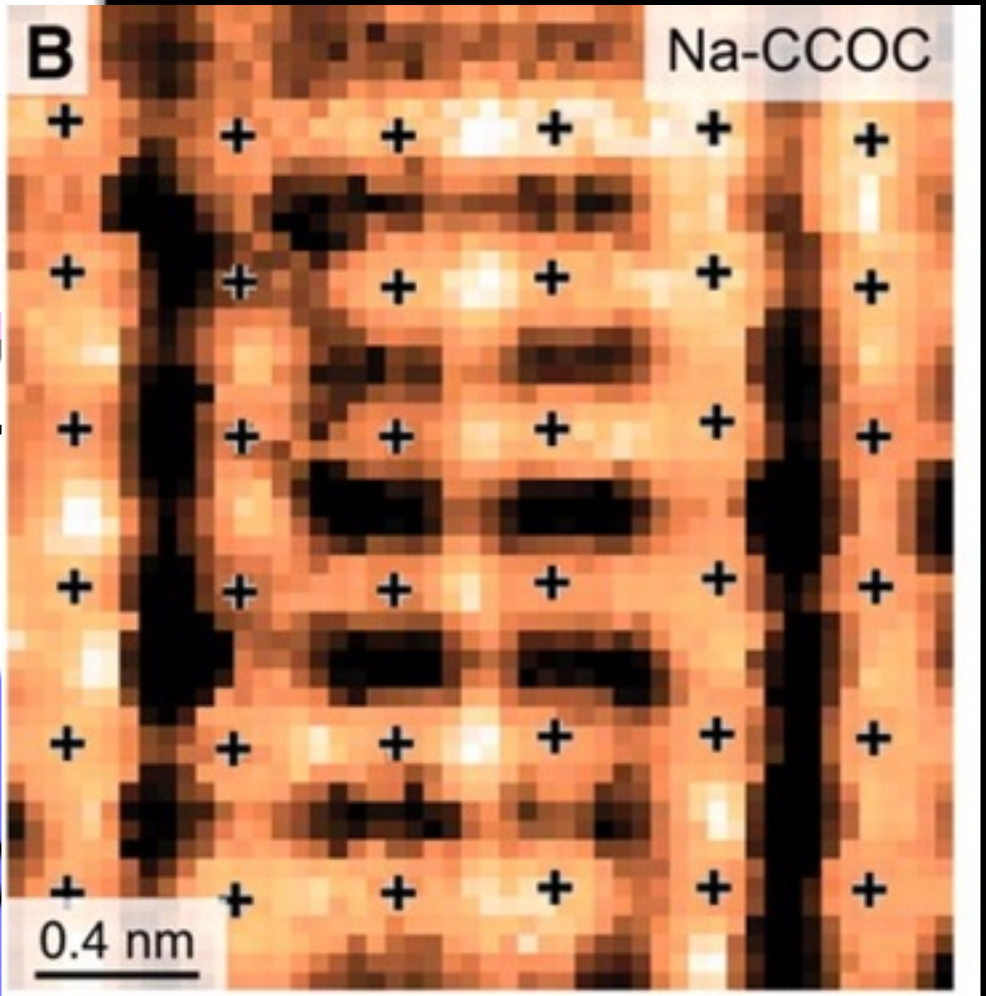
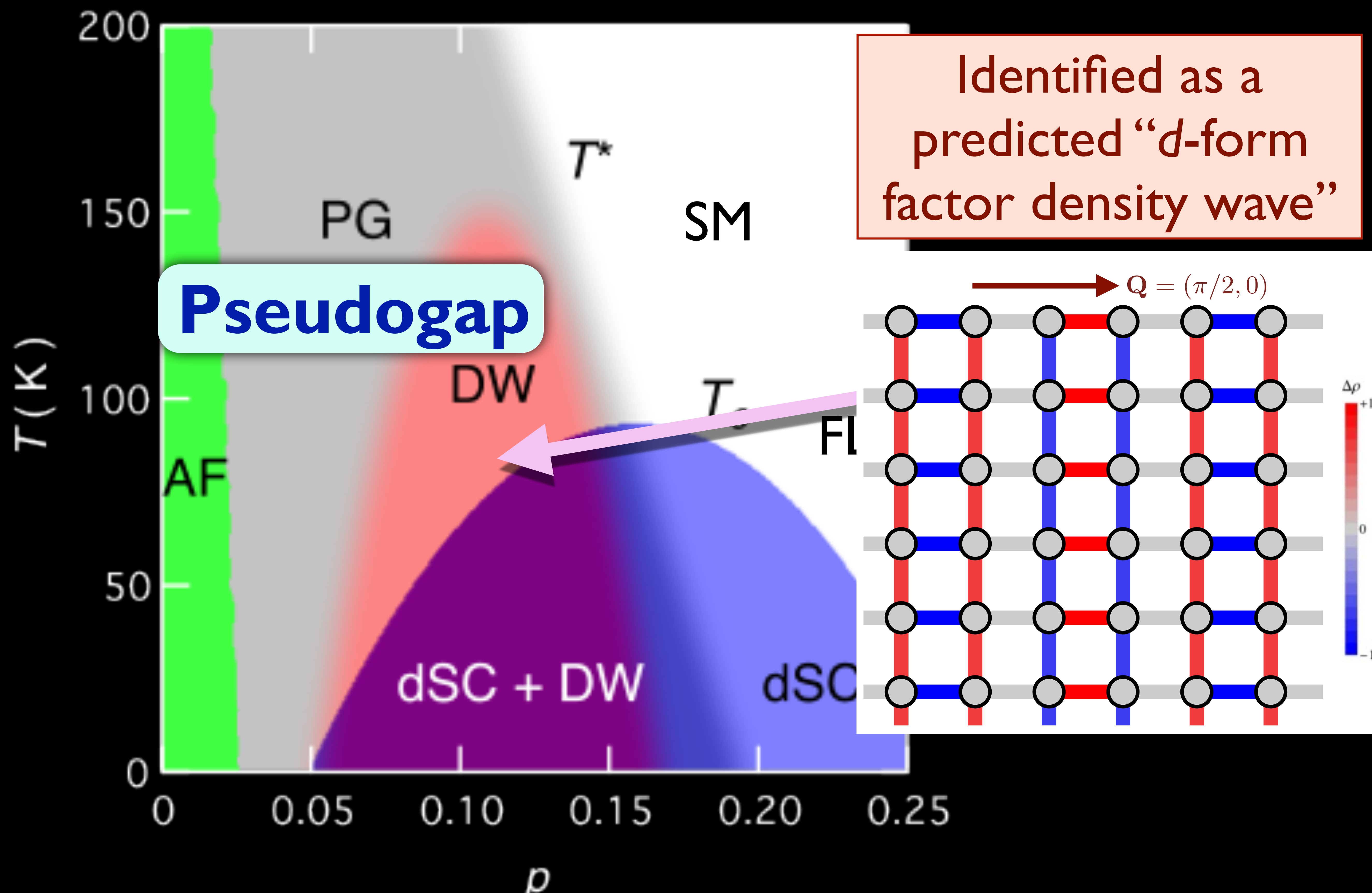
Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

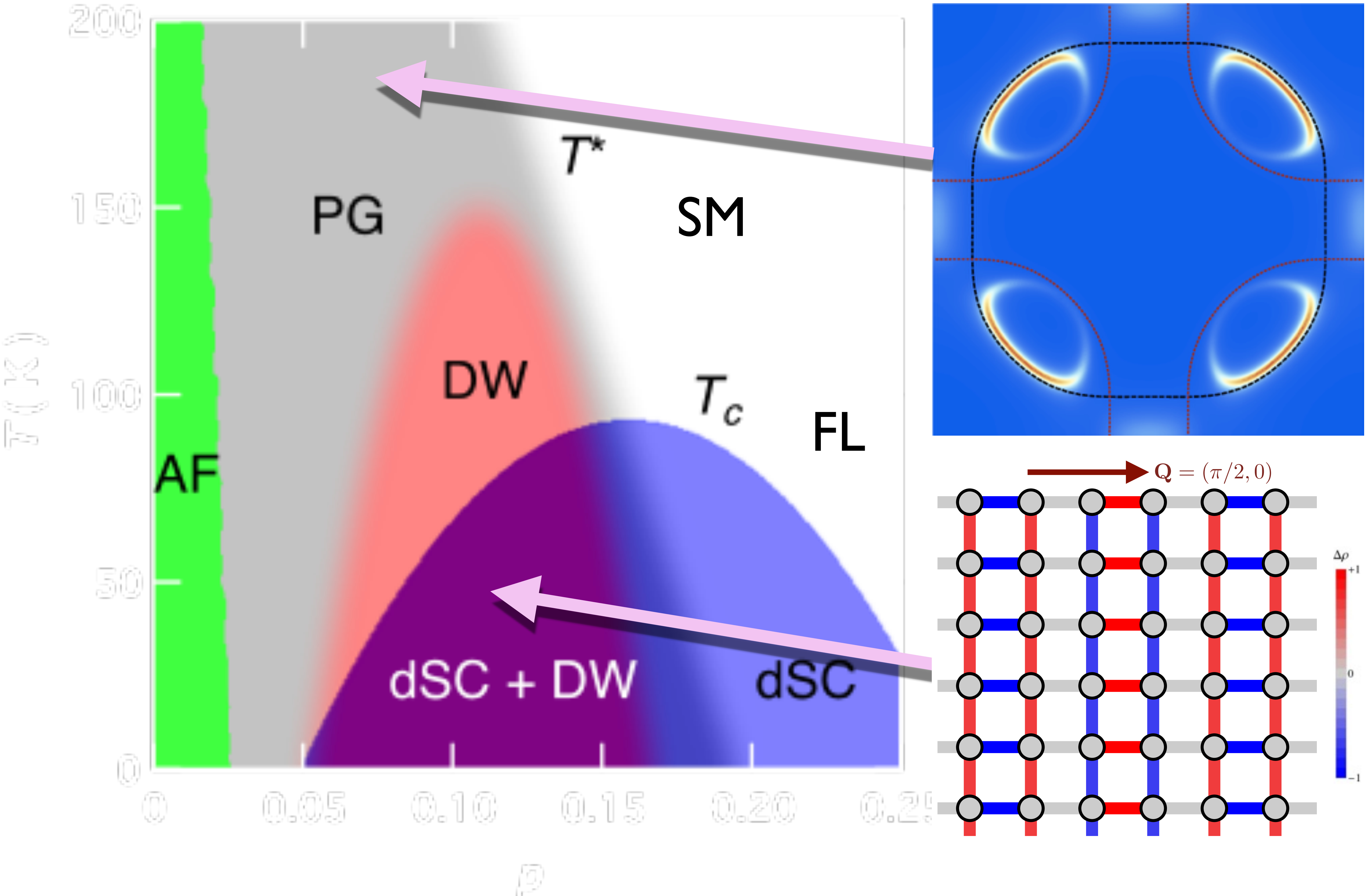


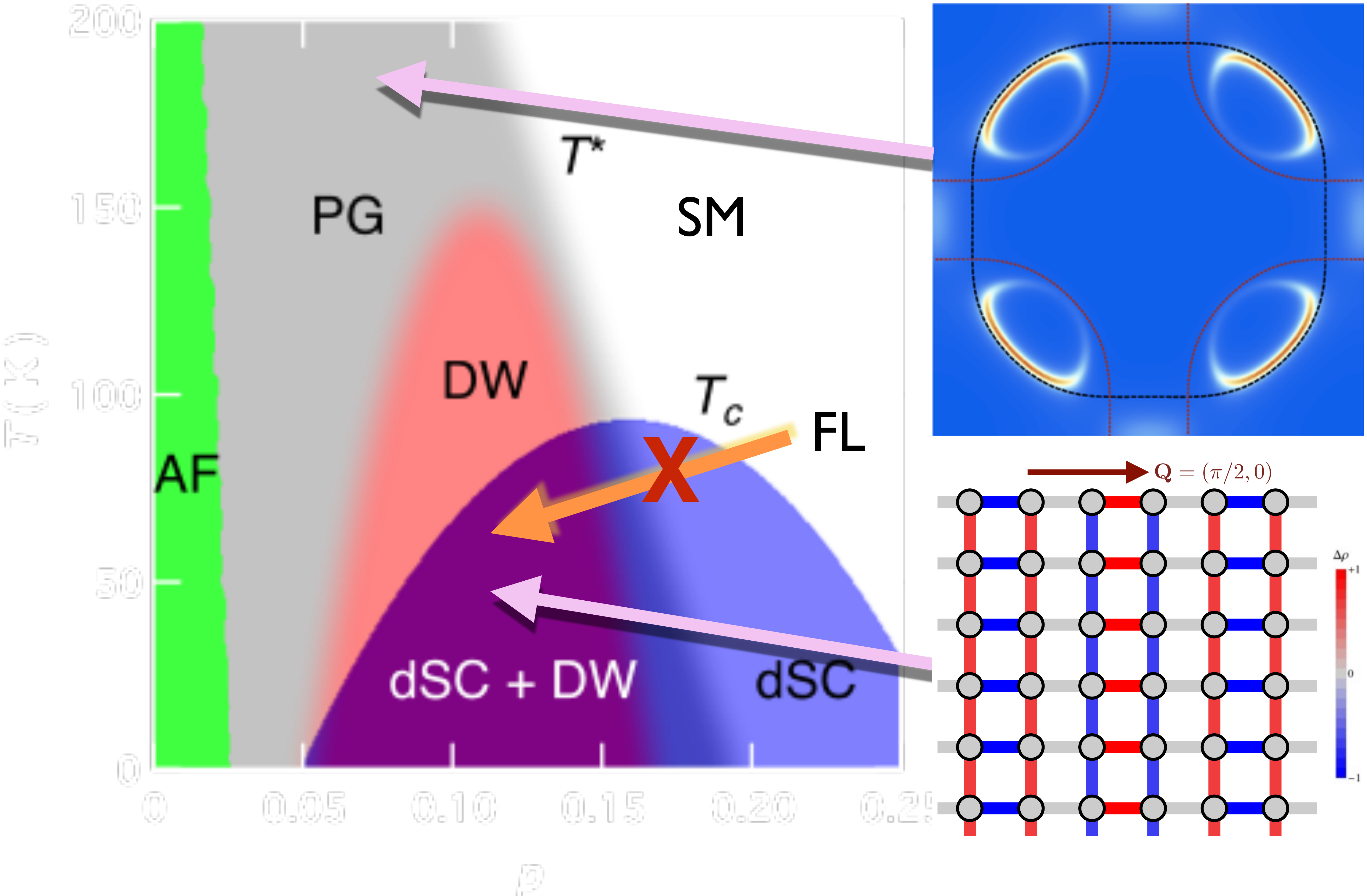
Density wave (DW) order at low T and p



M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi,
H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)




200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
p
AF
PG
T*
SM
DW
T_c
FL
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$
Δρ
+1
0
−1



200
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T (K)
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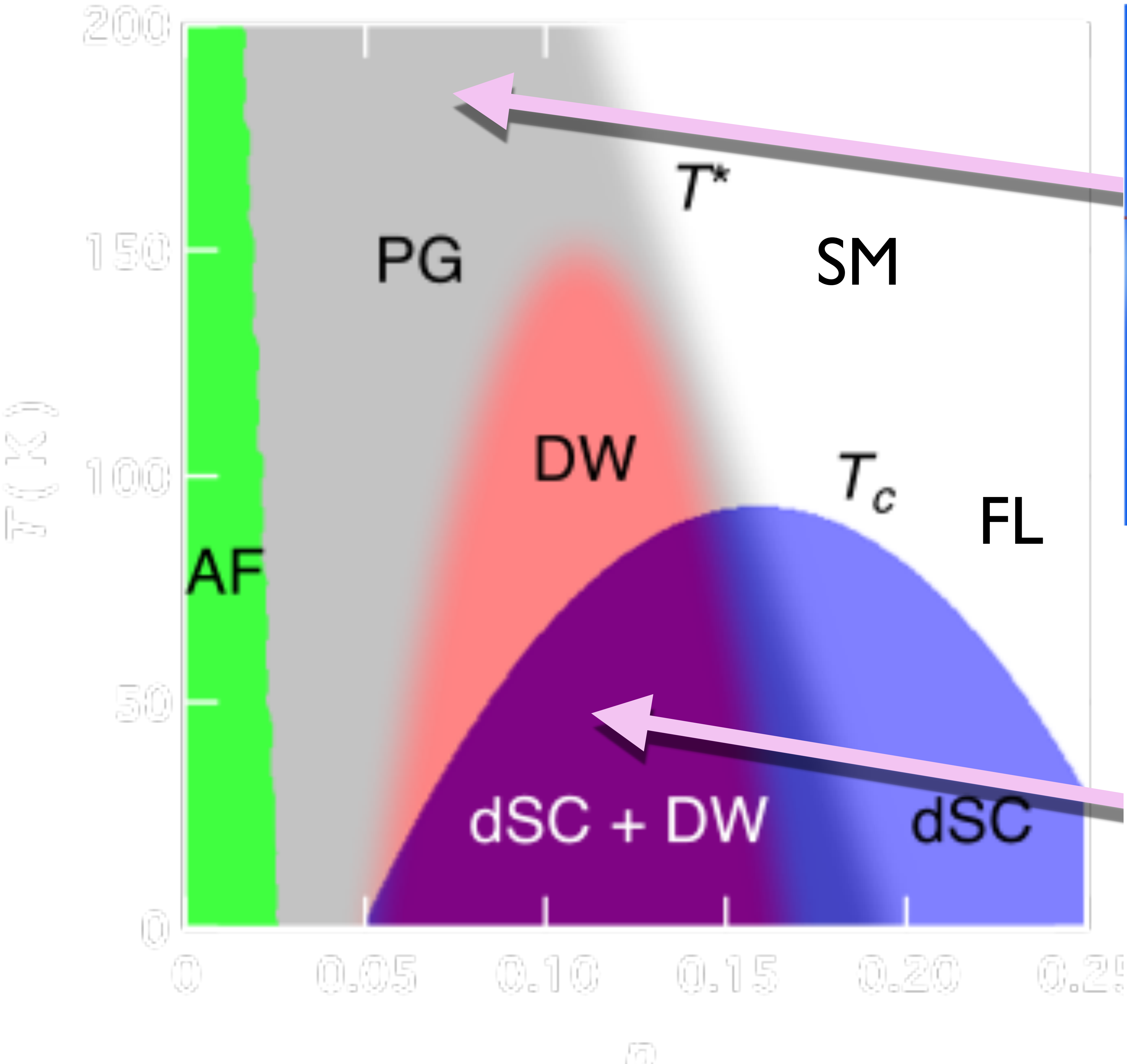
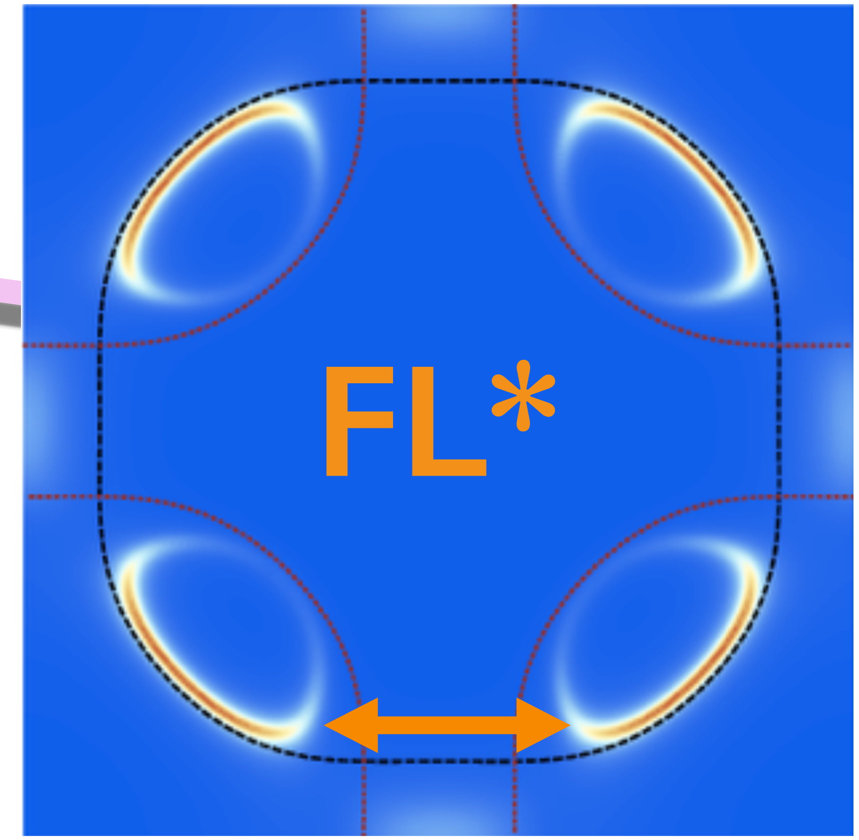
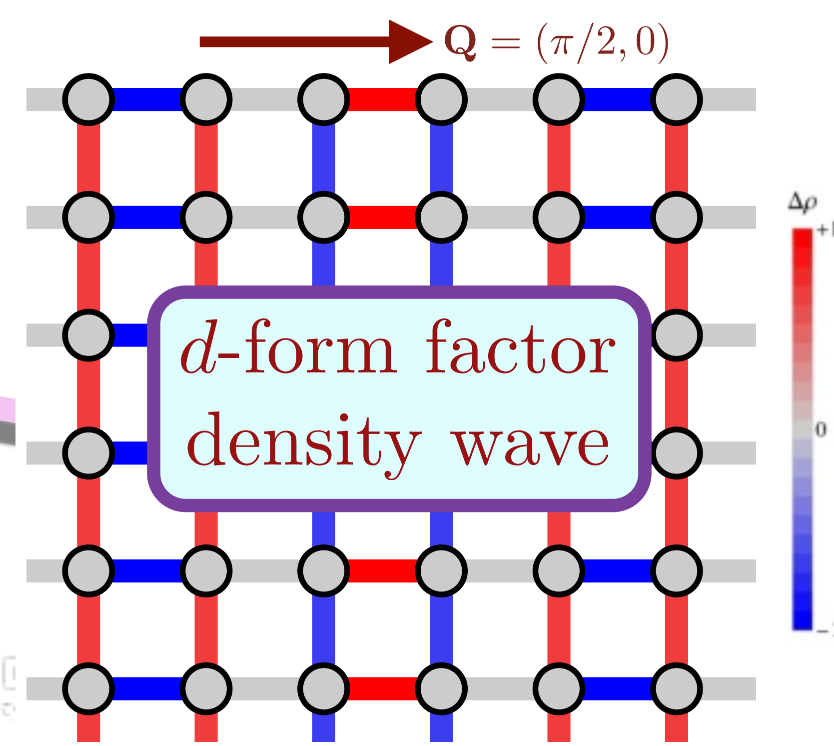
The high T FL* can help explain the "d-form factor density wave" observed at low T







D. Chowdhury and S.S., Phys. Rev. B **90**, 245136 (2014)

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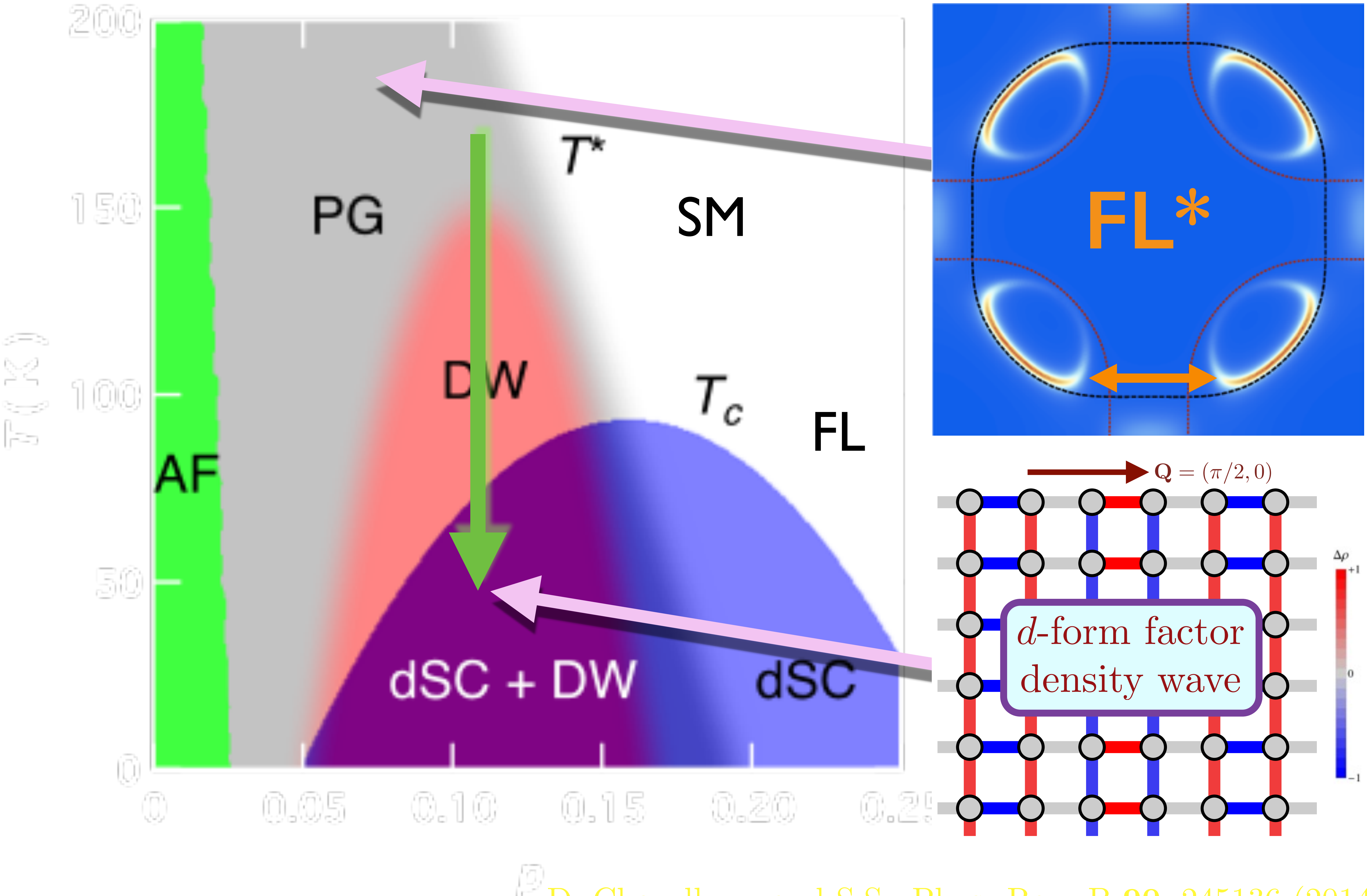

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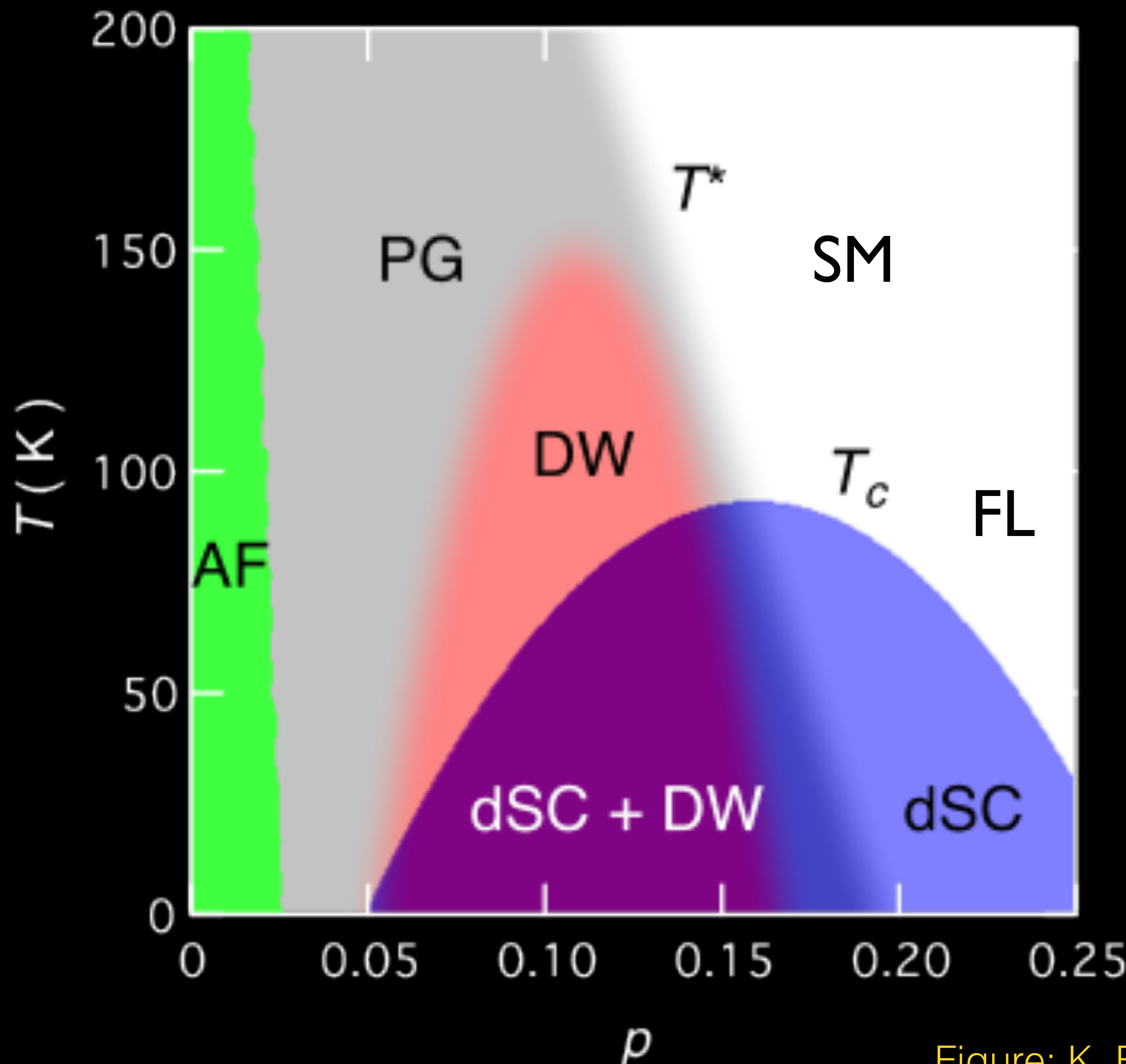
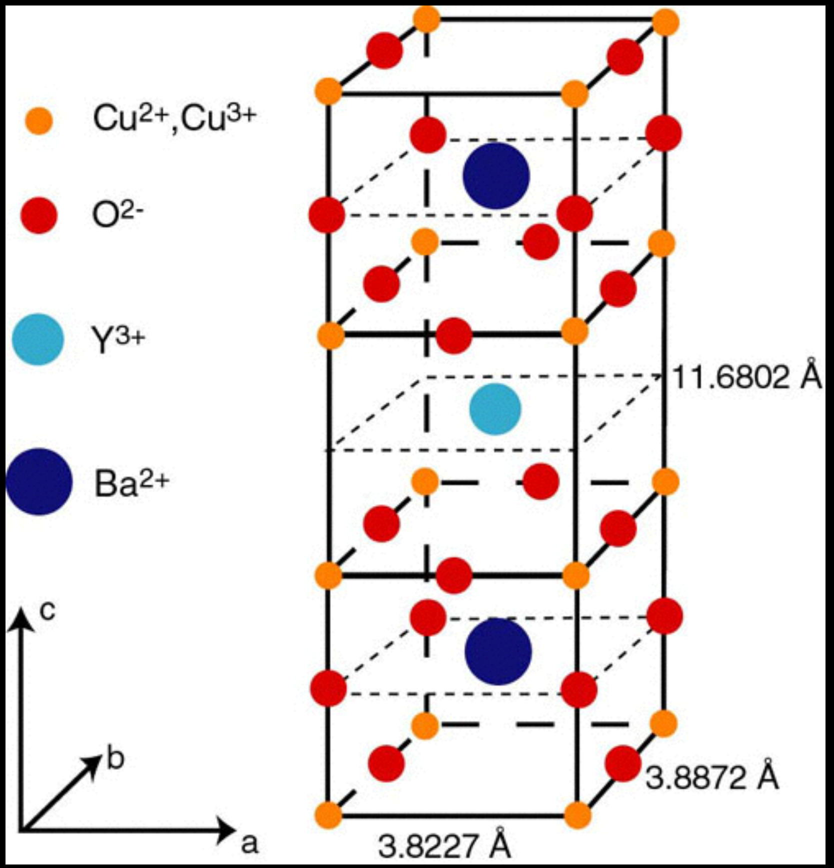
- T-independent positive Hall co-efficient, R_H, corresponding to carrier density p in the higher temperature pseudogap (Ando *et al.*, PRL **92**, 197001 (2004)) *and* in recent measurements at high fields, low T, and around $p \approx 0.16$ in YBCO (Proust-Taillefer-UBC collaboration, Badoux *et al.*, arXiv:1511.08162).





$YBa_2Cu_3O_{6+x}$

Figure: K. Fujita and J. C. Seamus Davis

High field, low T measurements show a positive Hall co-efficient corresponding to carriers of density $1 + p$

Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

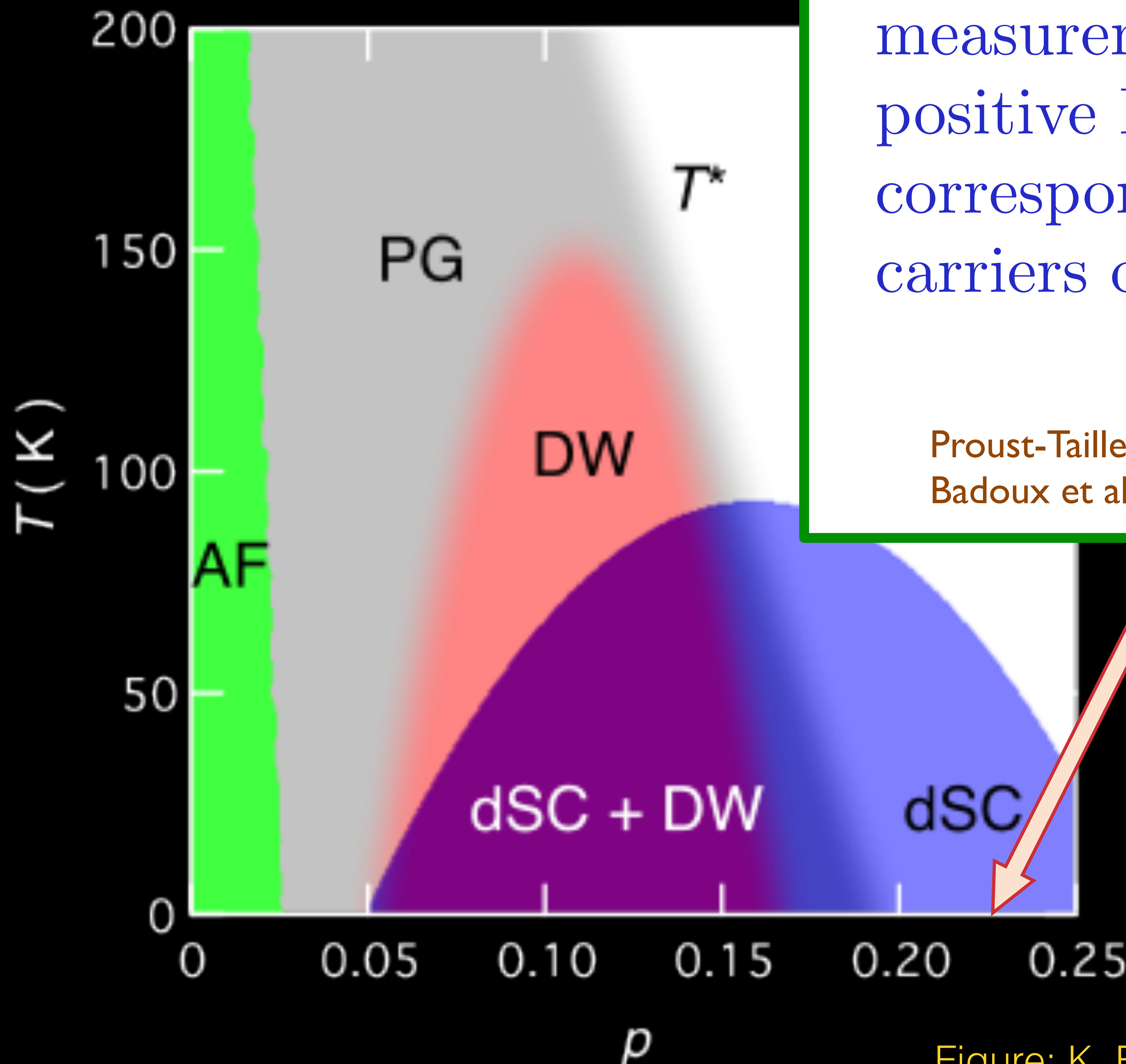
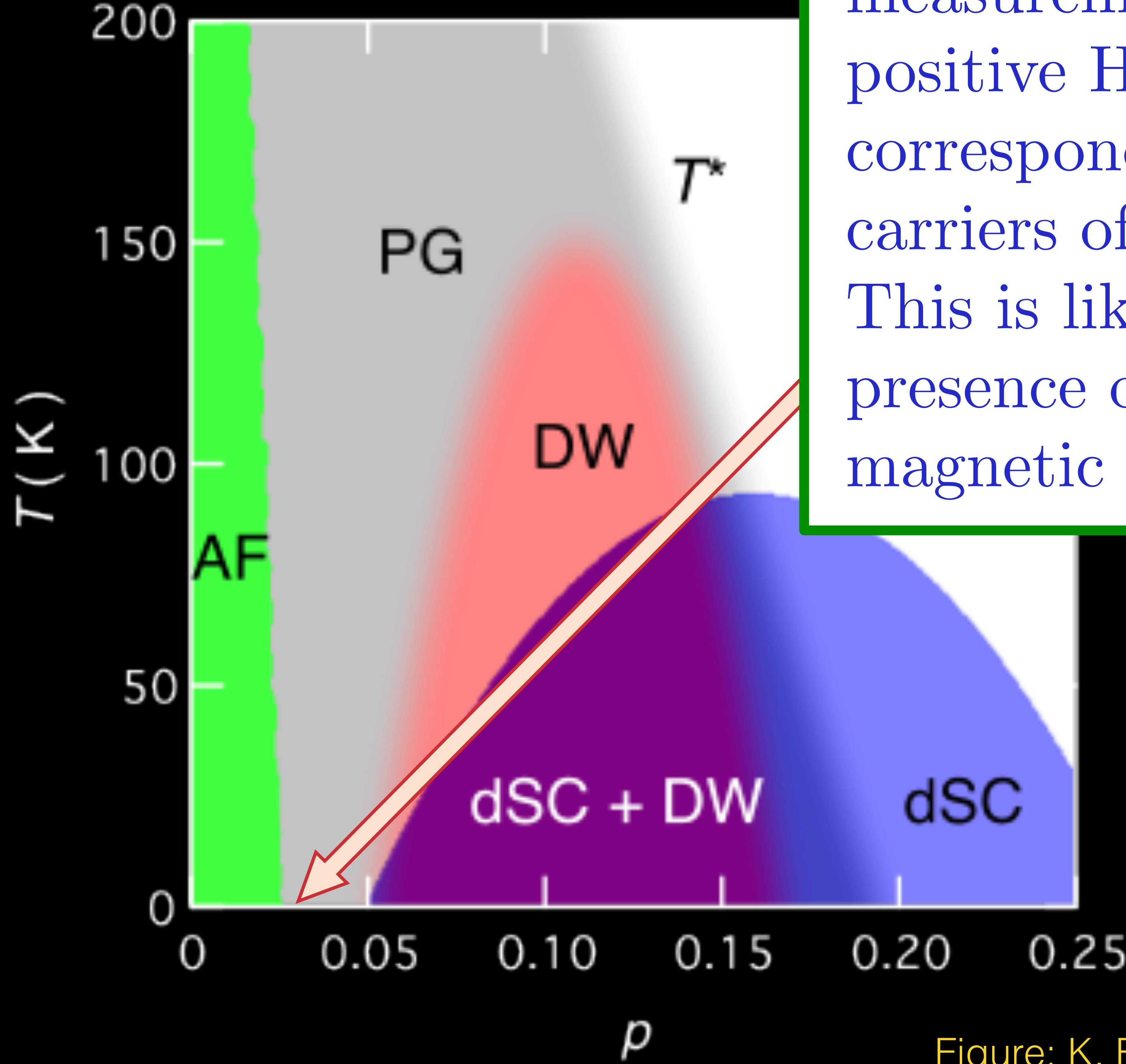


Figure: K. Fujita and J. C. Seamus Davis

High field, low T measurements show a positive Hall co-efficient corresponding to carriers of density p. This is likely due to the presence of antiferro-magnetic order.

$YBa_2Cu_3O_{6+x}$



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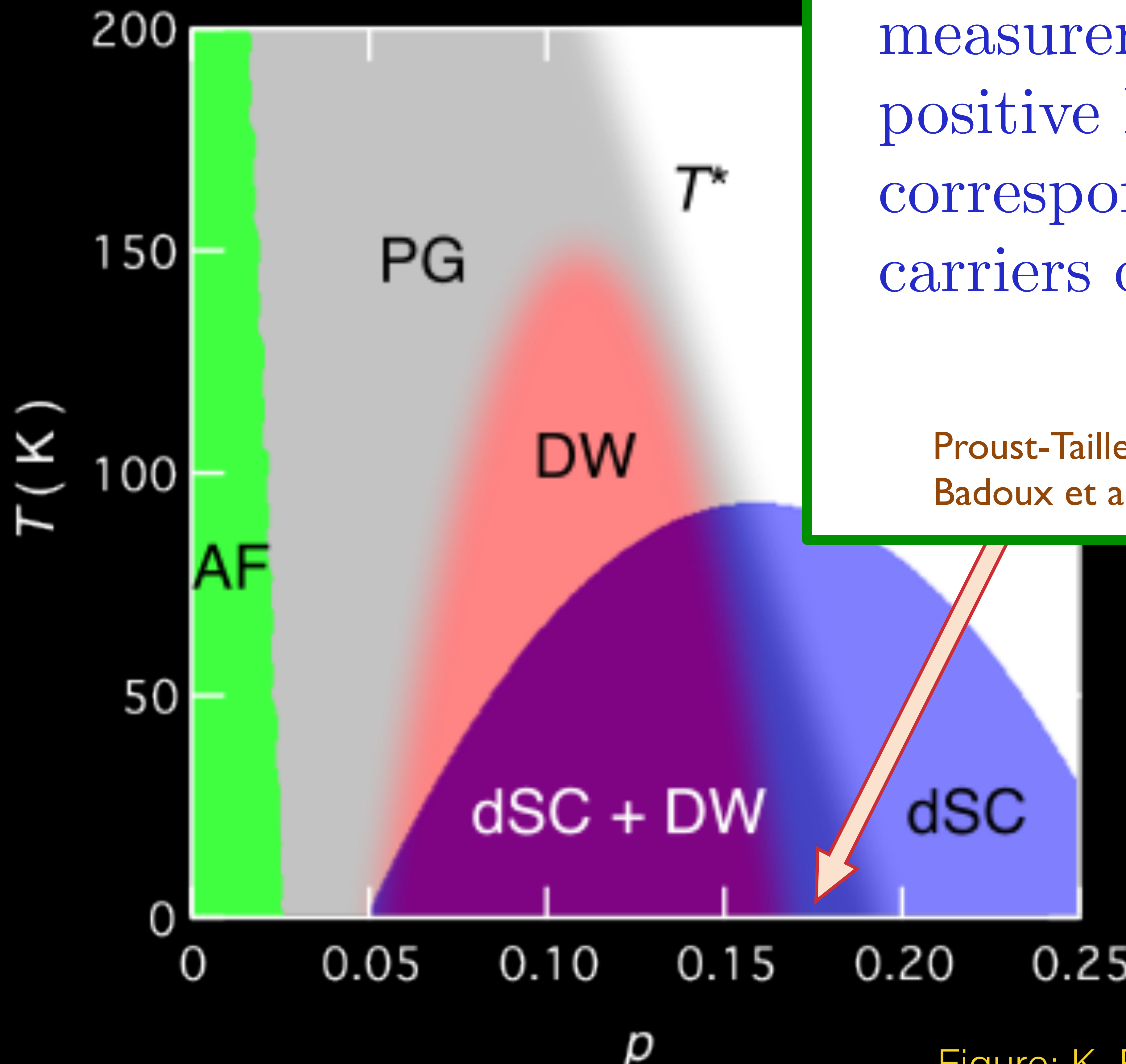
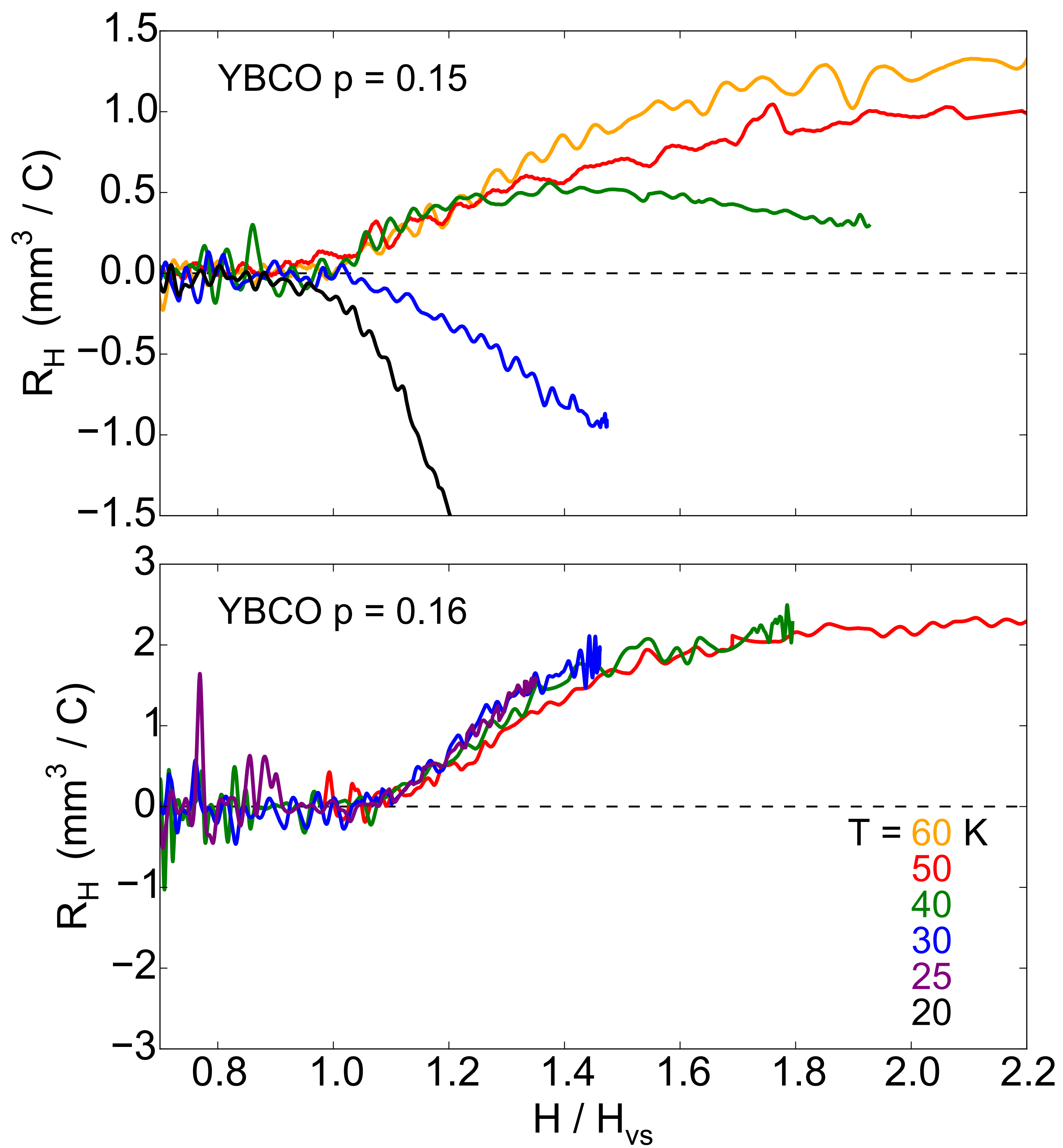


Figure: K. Fujita and J. C. Seamus Davis

Recent evidence for pseudogap metal as FL*



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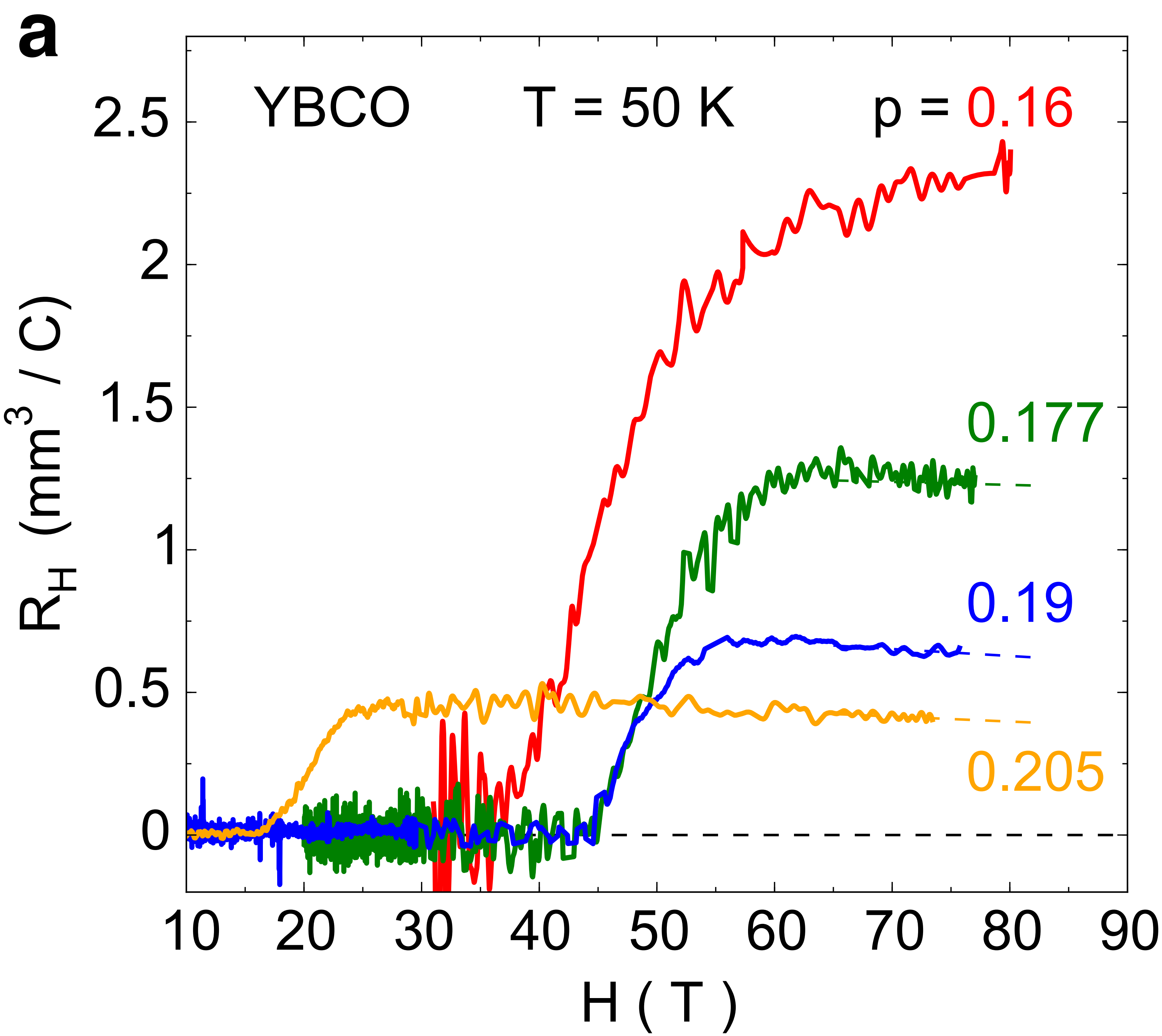

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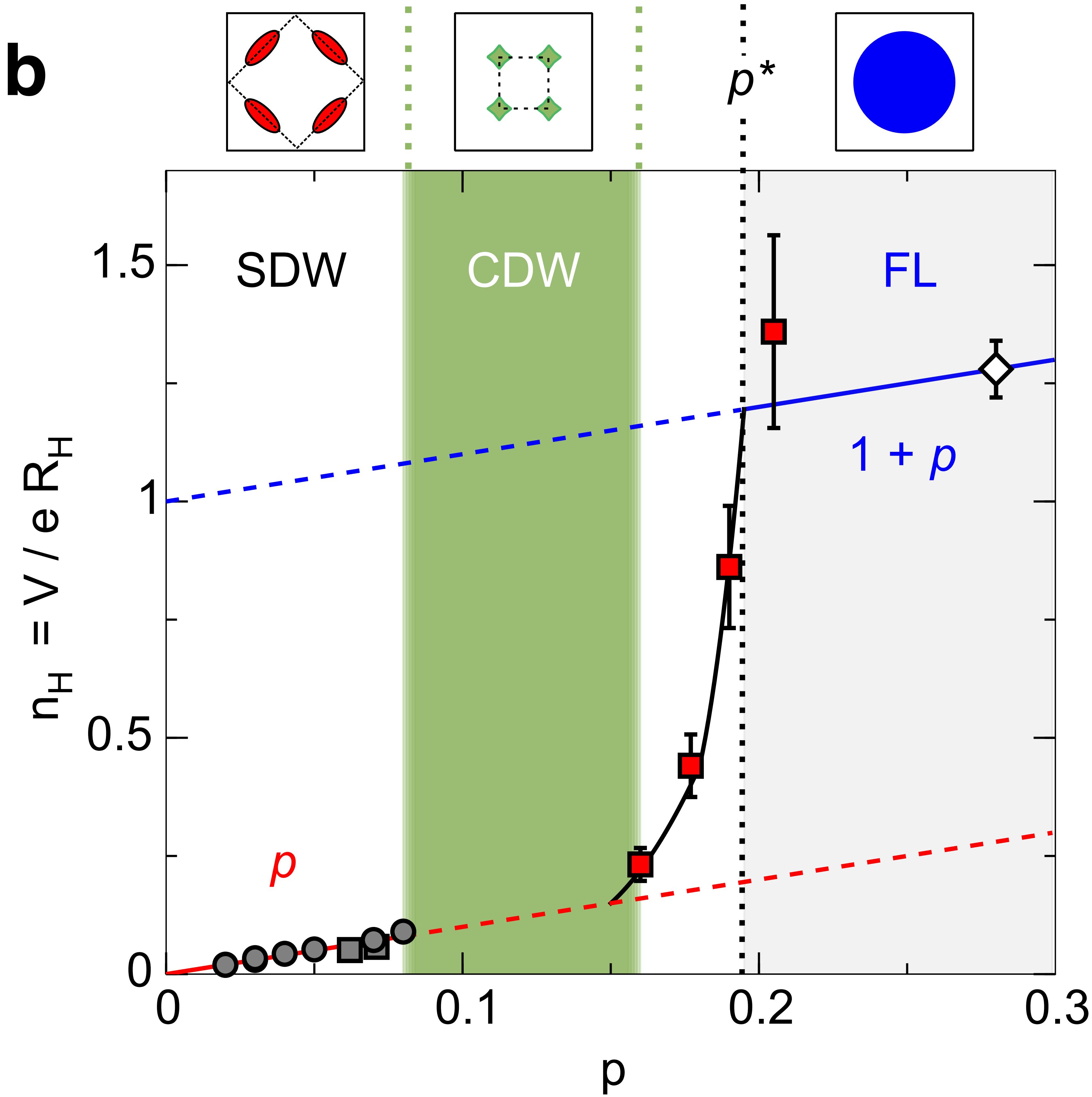
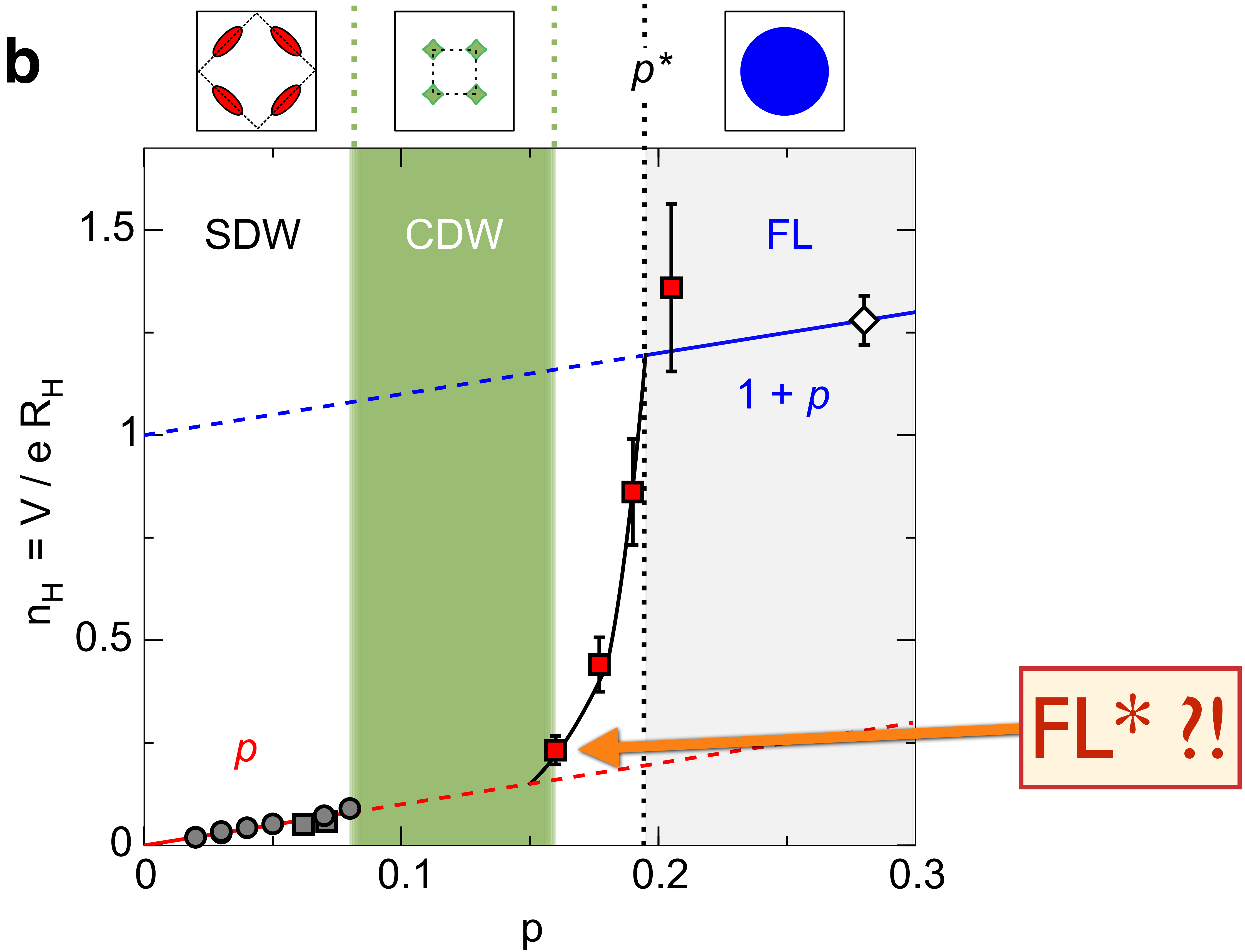


Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

Recent evidence for pseudogap metal as FL*



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Fractionalized Fermi liquid (FL*)

We have described a metal with:

- A Fermi surface of electrons enclosing volume p, and not the Luttinger volume of $1+p$
- Additional low energy quantum states on a torus not associated with quasiparticle excitations *i.e.* emergent gauge fields

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There is a general and fundamental relationship between these two characteristics. Promising indications that such a metal describes the pseudogap of the cuprate supercondutors