# Exploring quantum matter in the high temperature superconductors

International Center for Theoretical Sciences
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Talk online: sachdev.physics.harvard.edu

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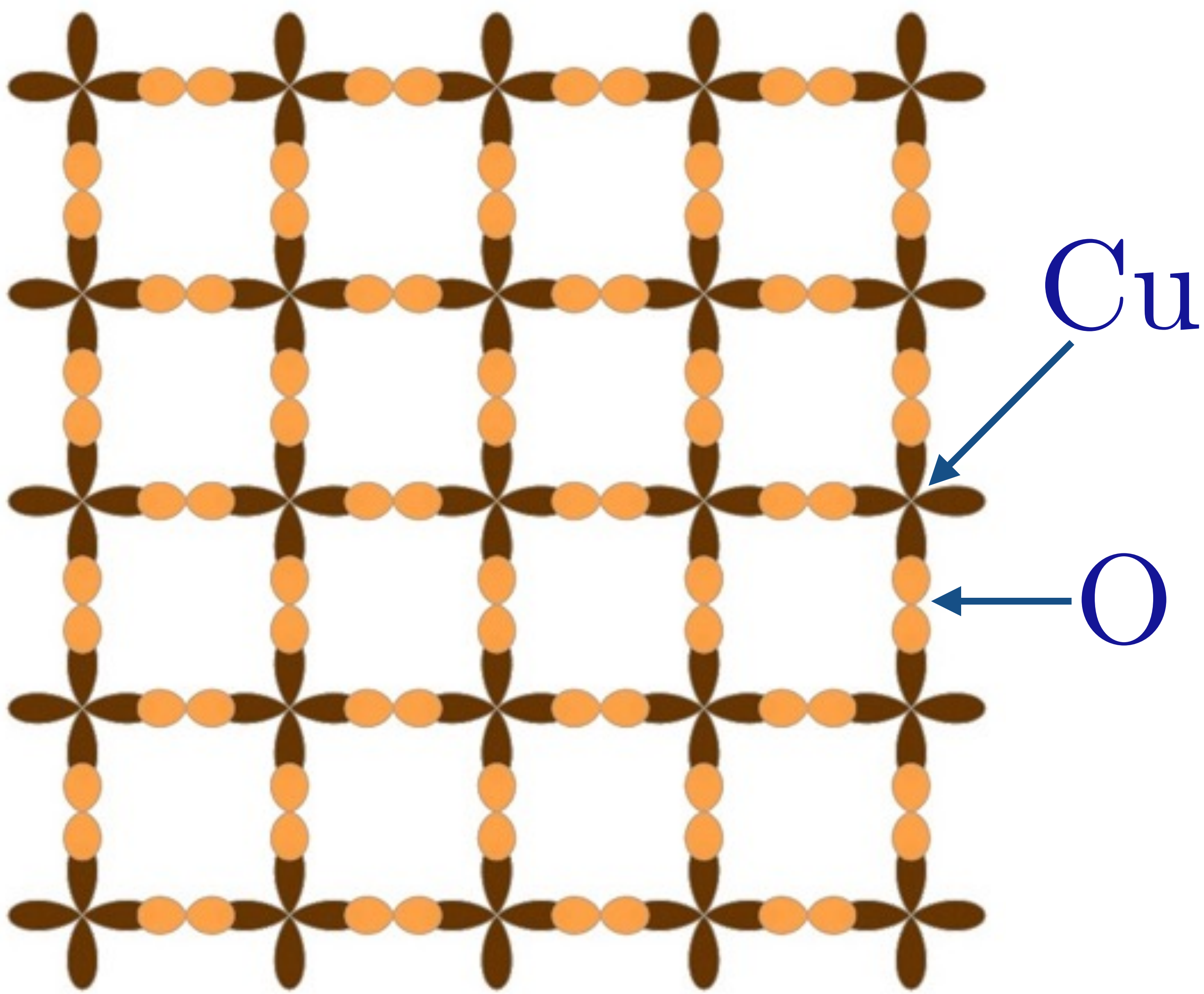
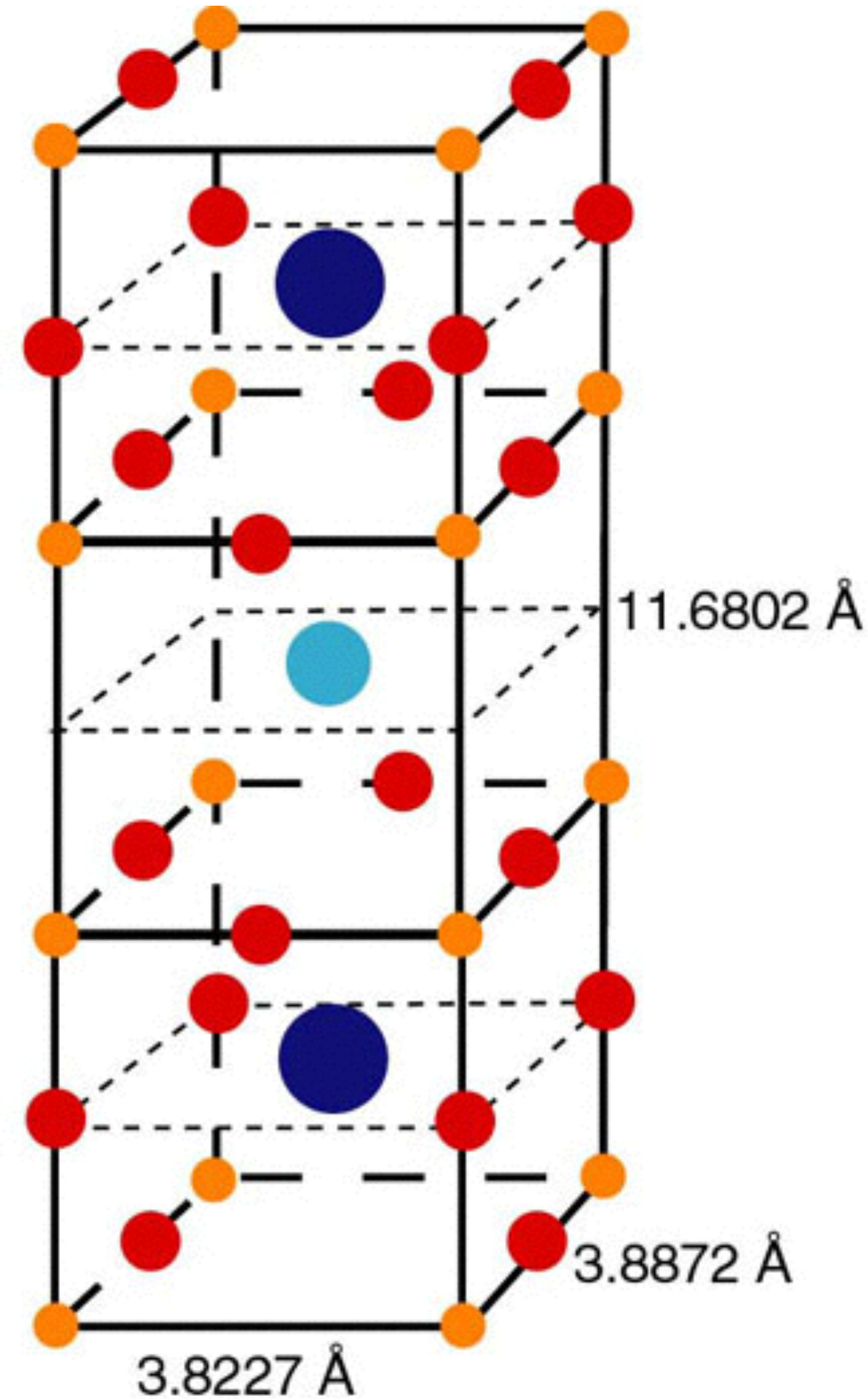
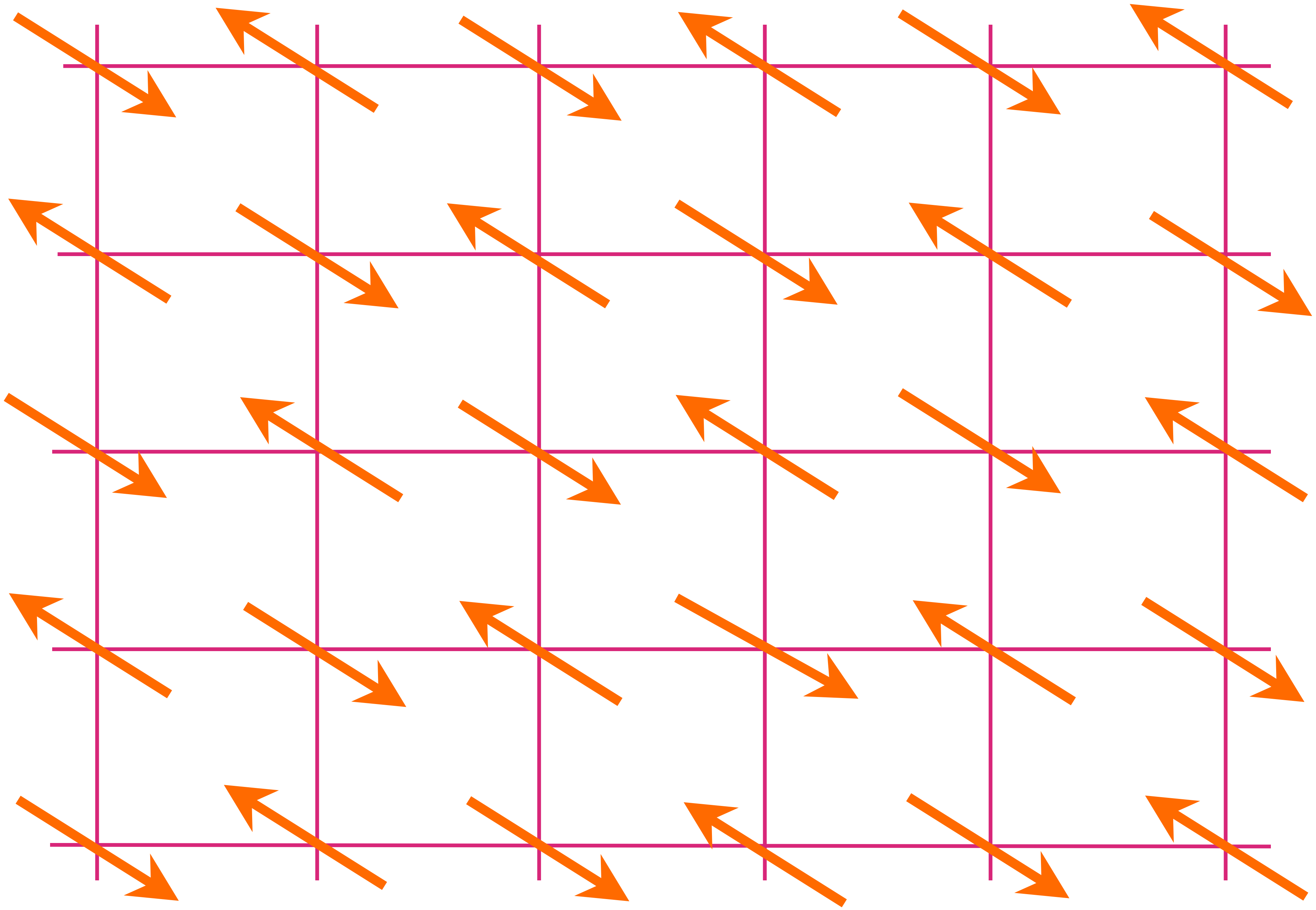
# High temperature superconductors



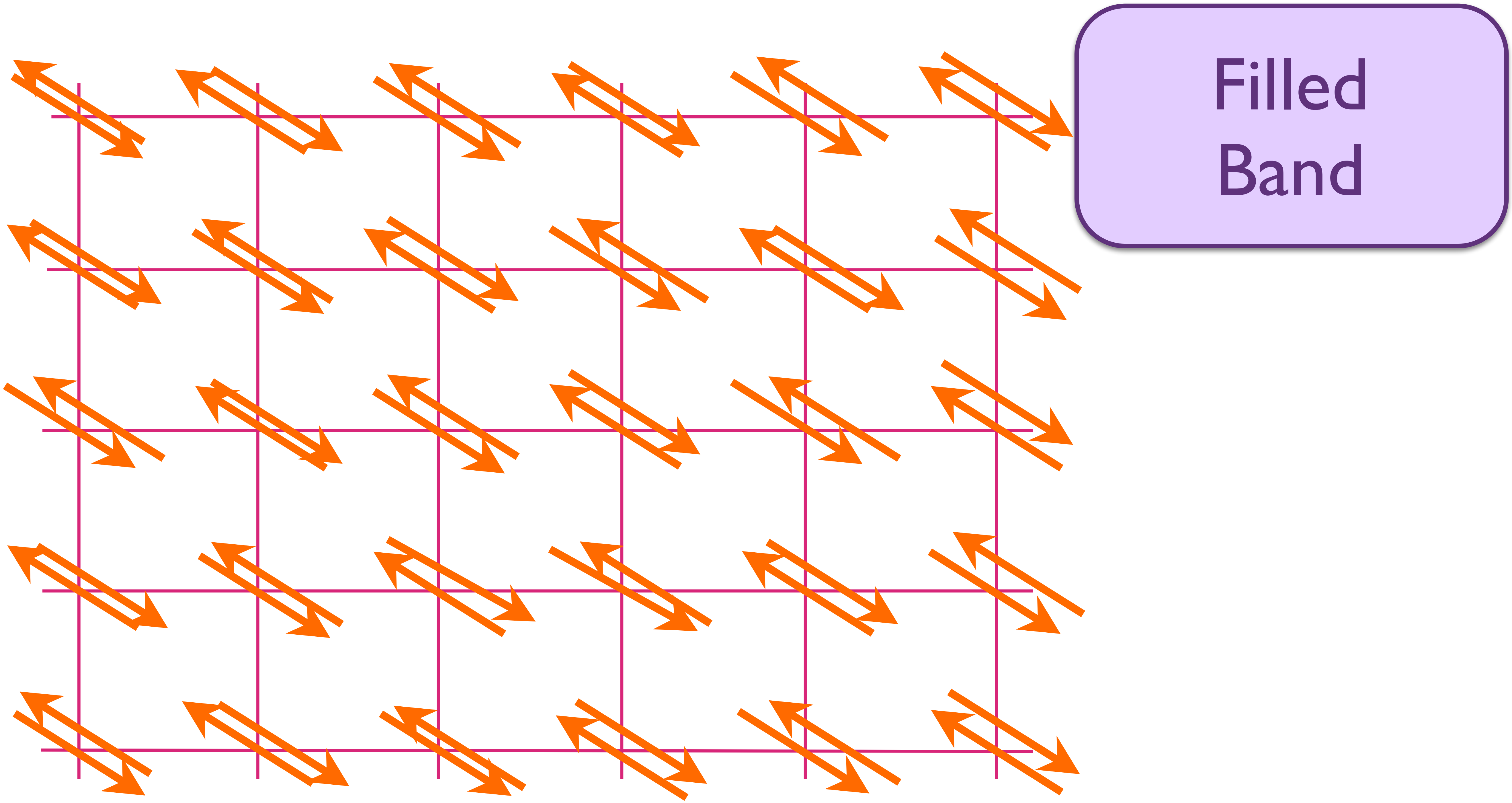

$CuO_2$ plane

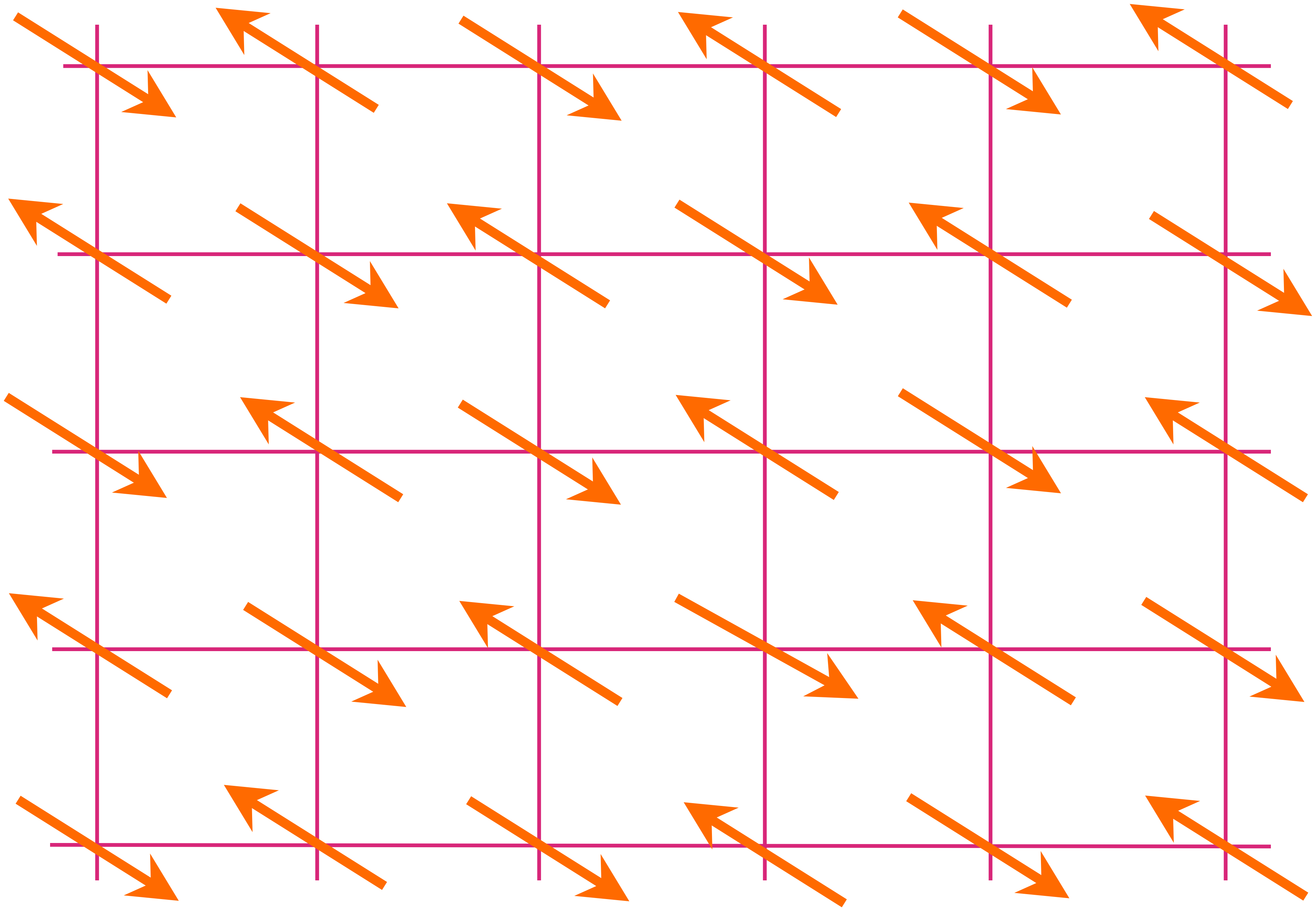



$YBa_2Cu_3O_{6+x}$



"Undoped" Anti-ferromagnet


Filled
Band



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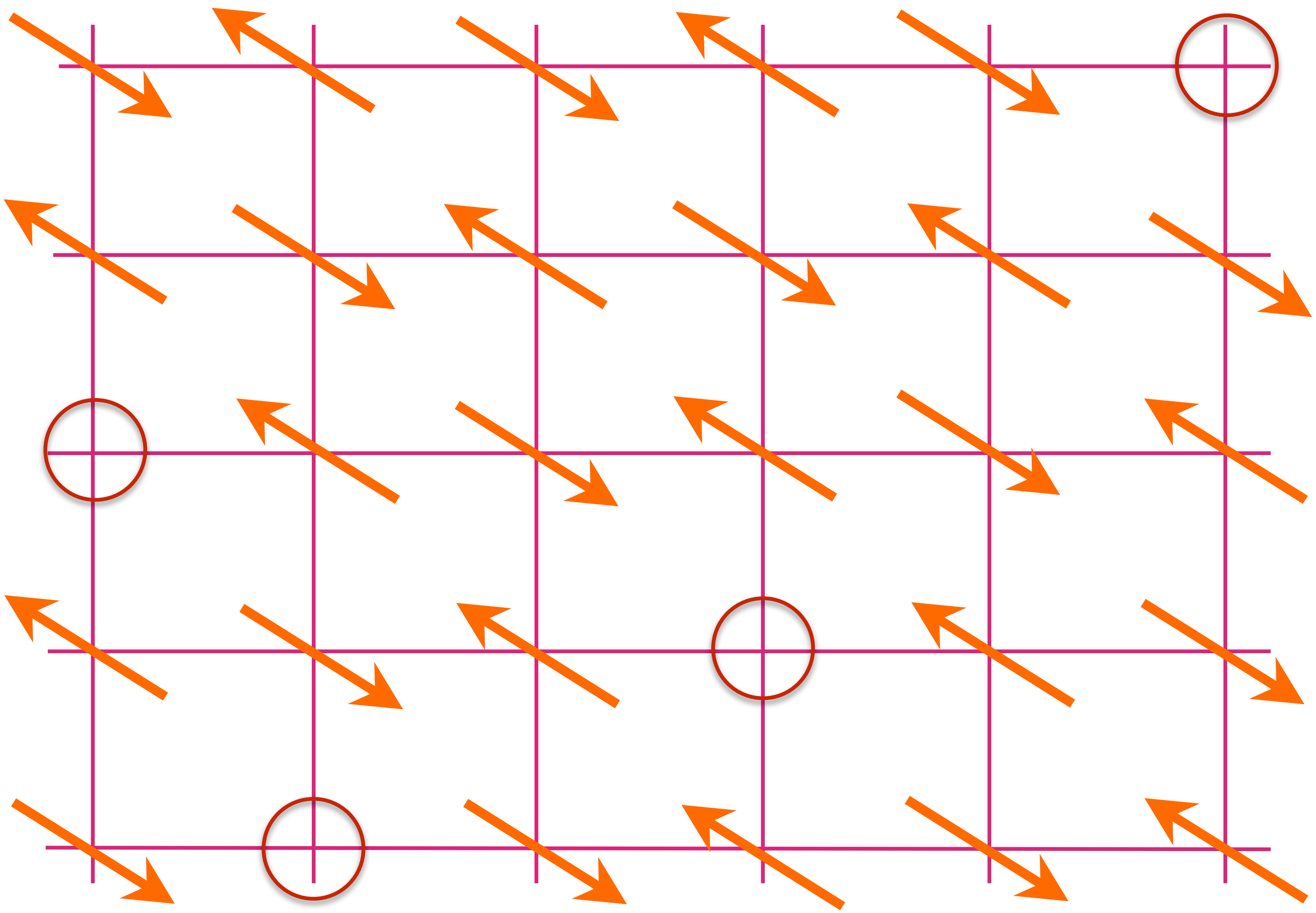
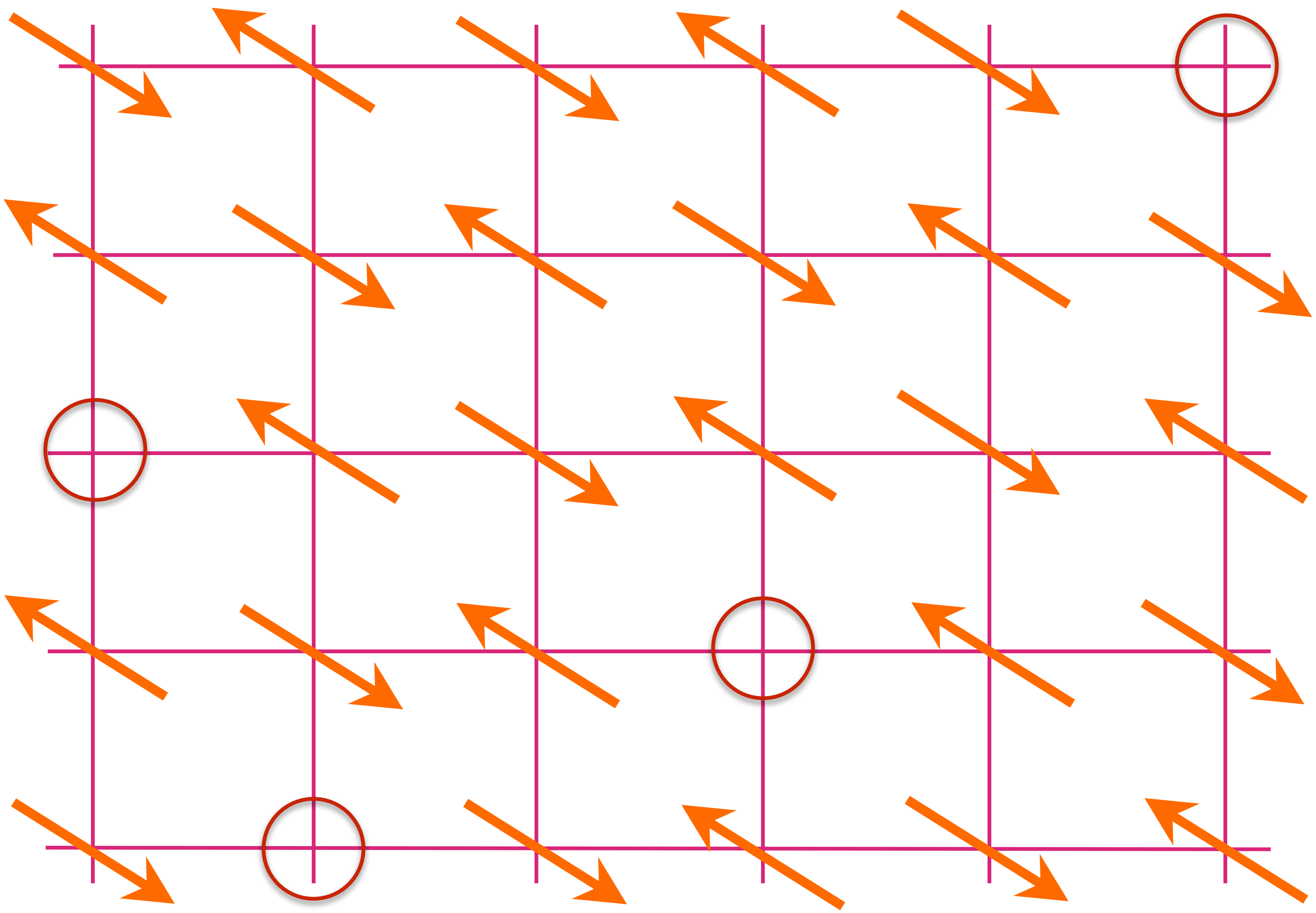


Anti-ferromagnet with $p$ holes per square



Anti-ferromagnet with $p$ holes per square

But relative to the band insulator, there are $1+p$ holes per square

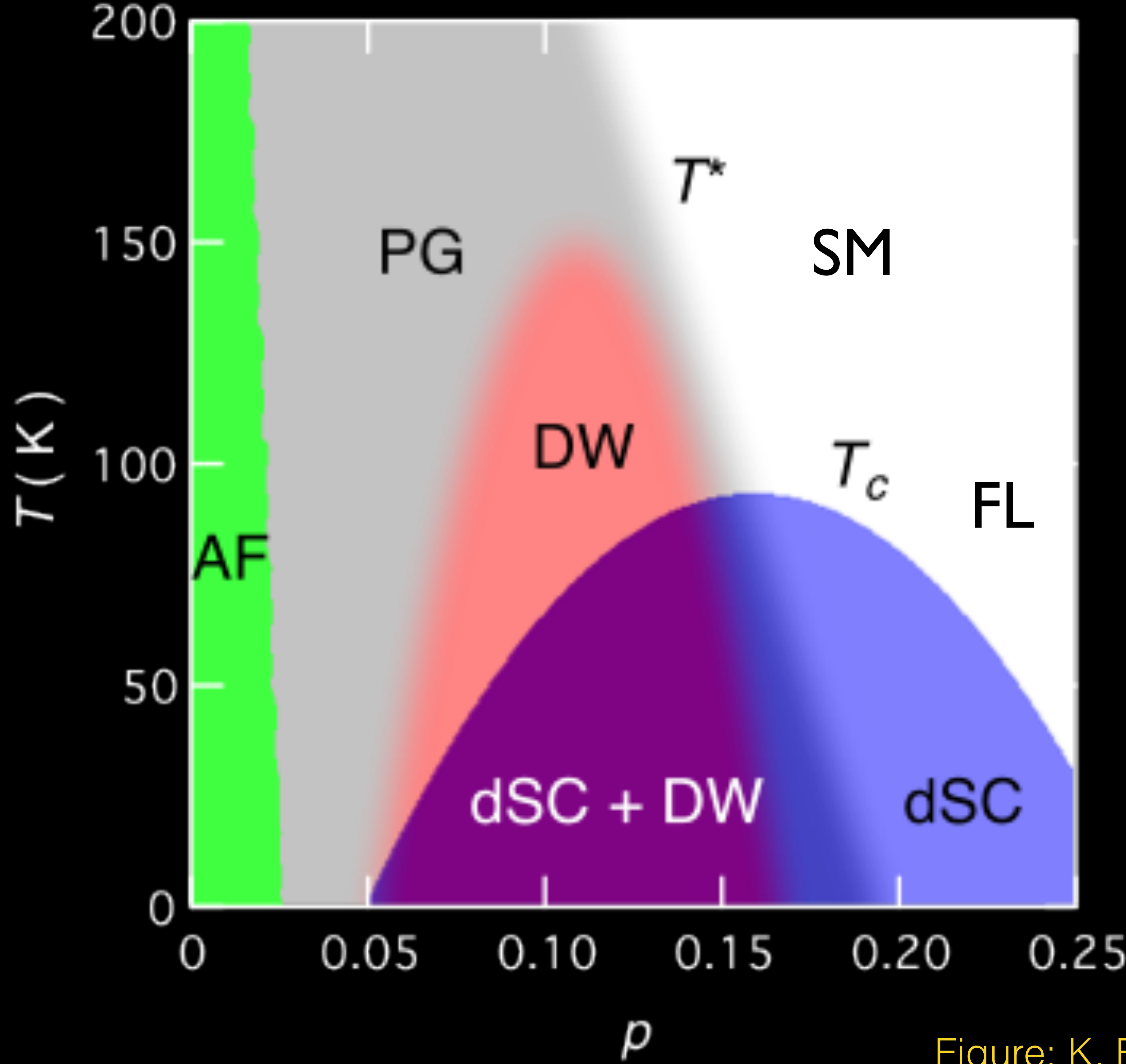



Figure: K. Fujita and J. C. Seamus Davis

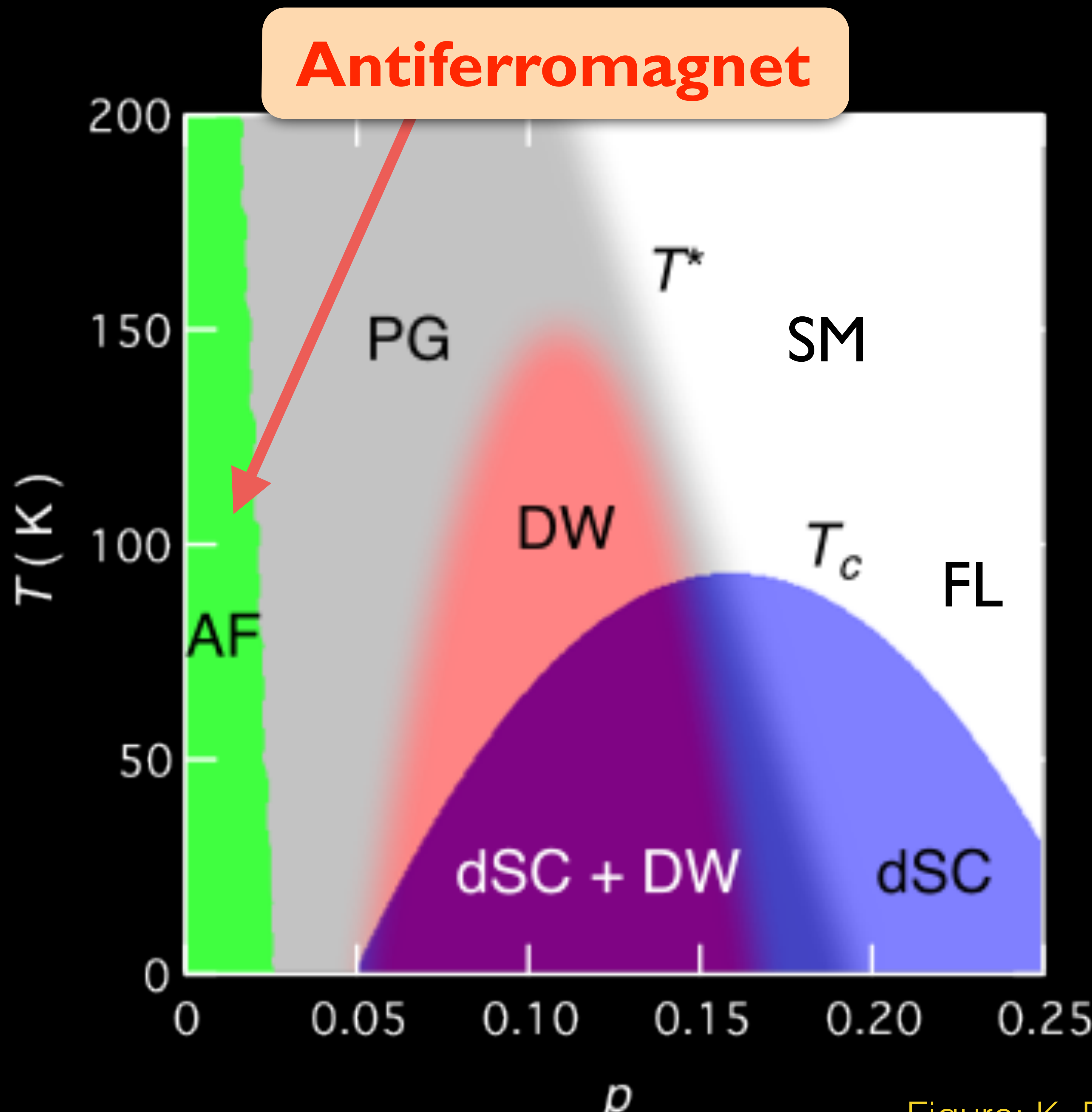


Figure: K. Fujita and J. C. Seamus Davis

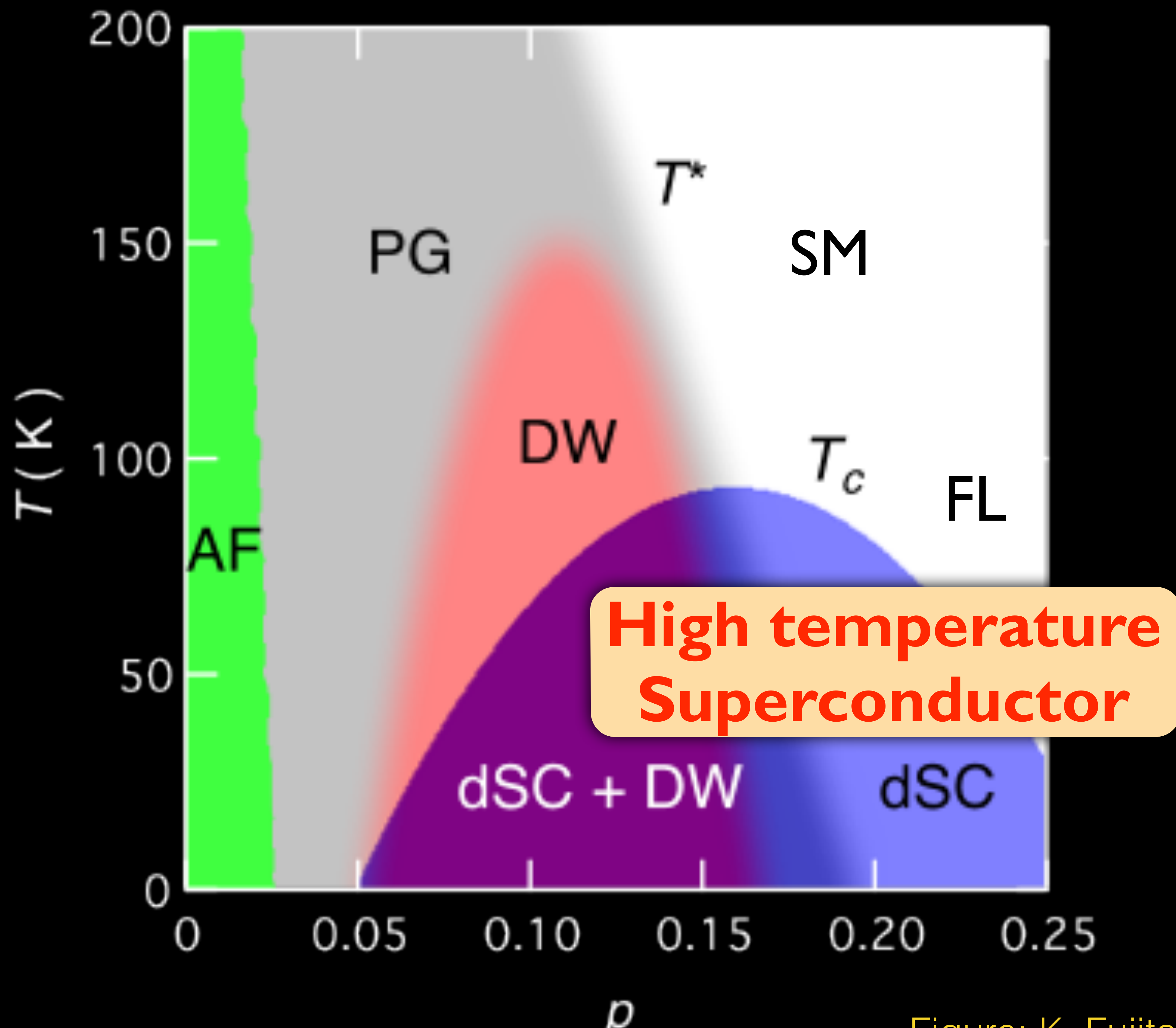
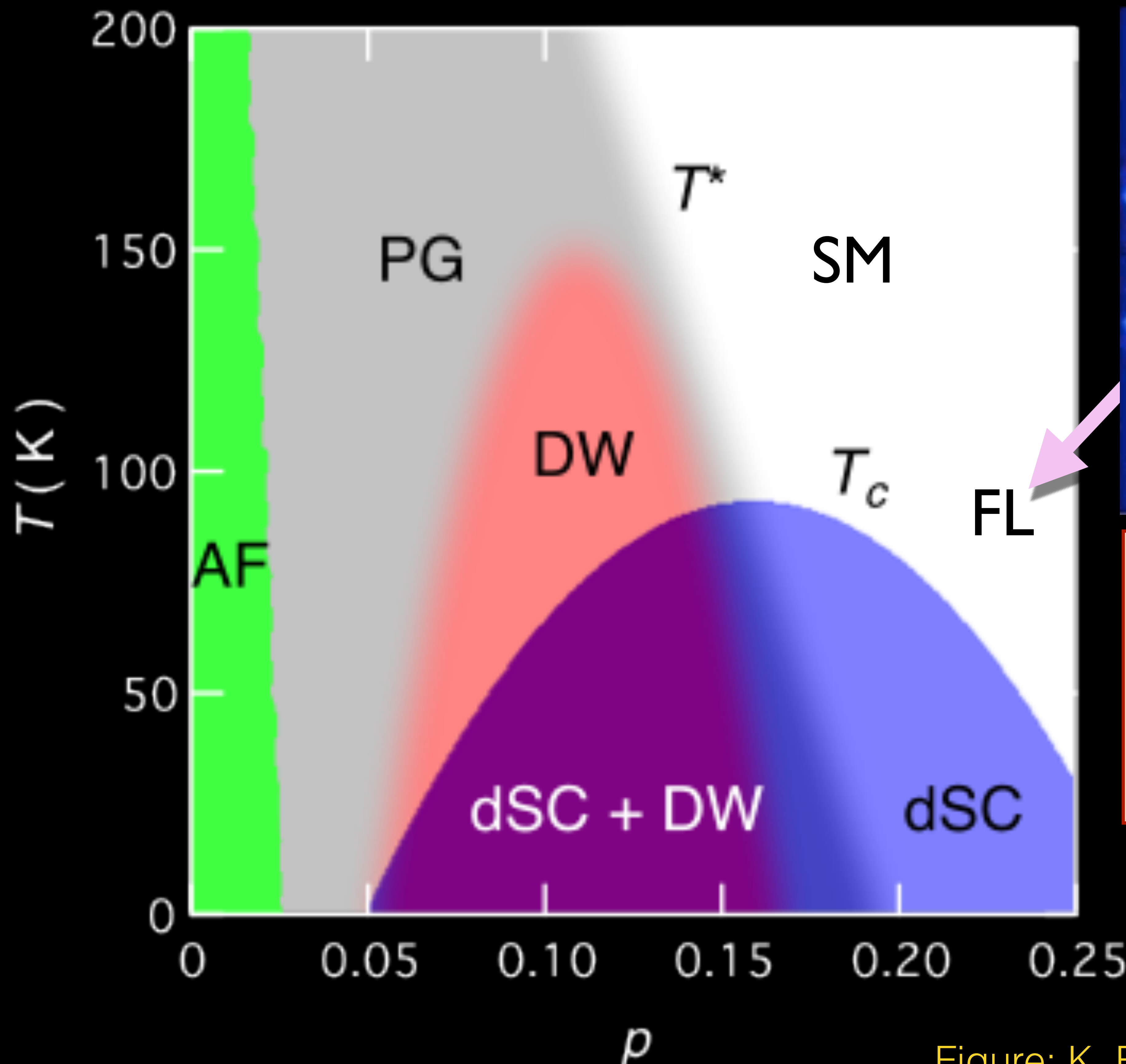
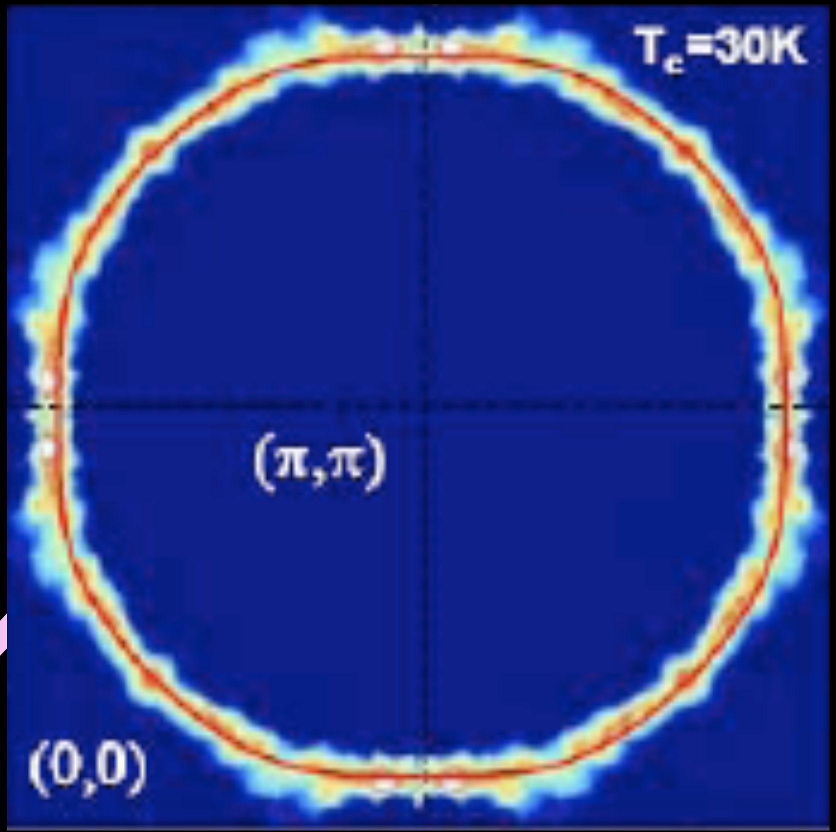


Figure: K. Fujita and J. C. Seamus Davis

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)



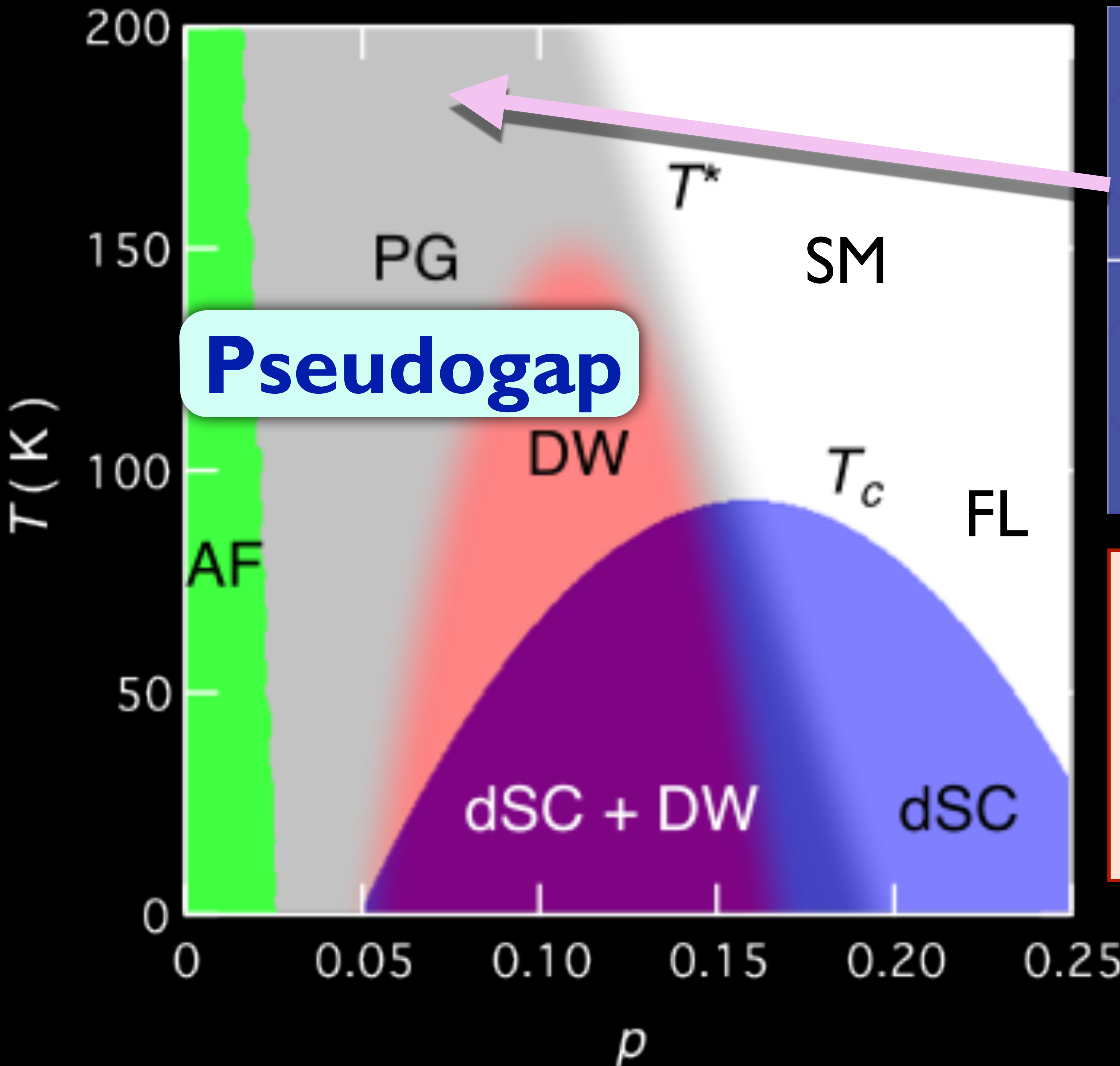



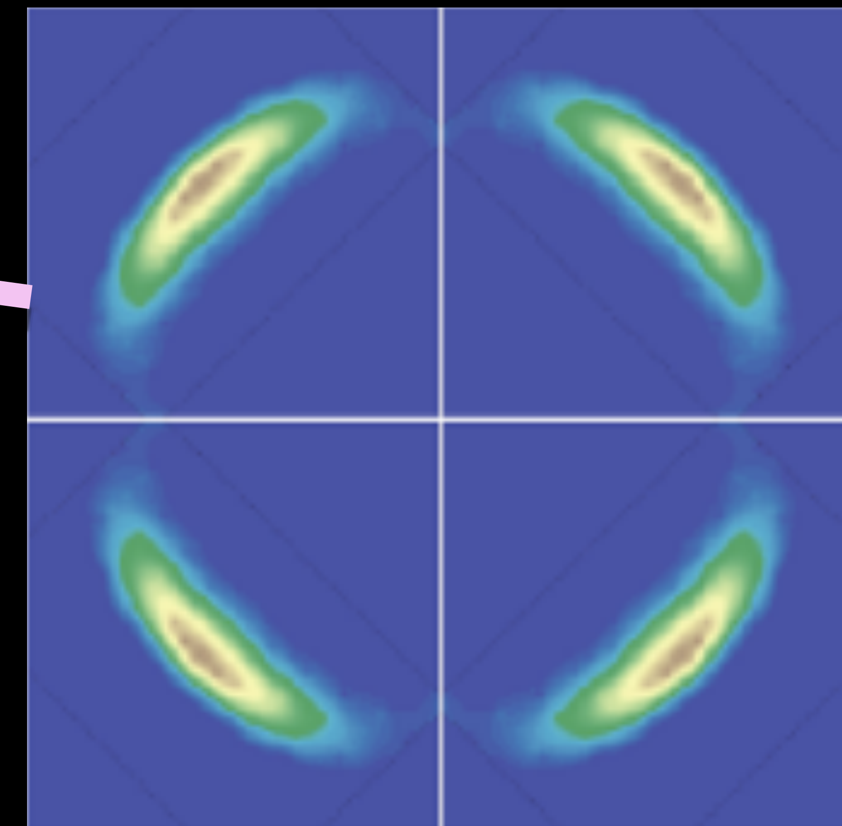

Conventional metal

Area enclosed by Fermi surface =1+$p$

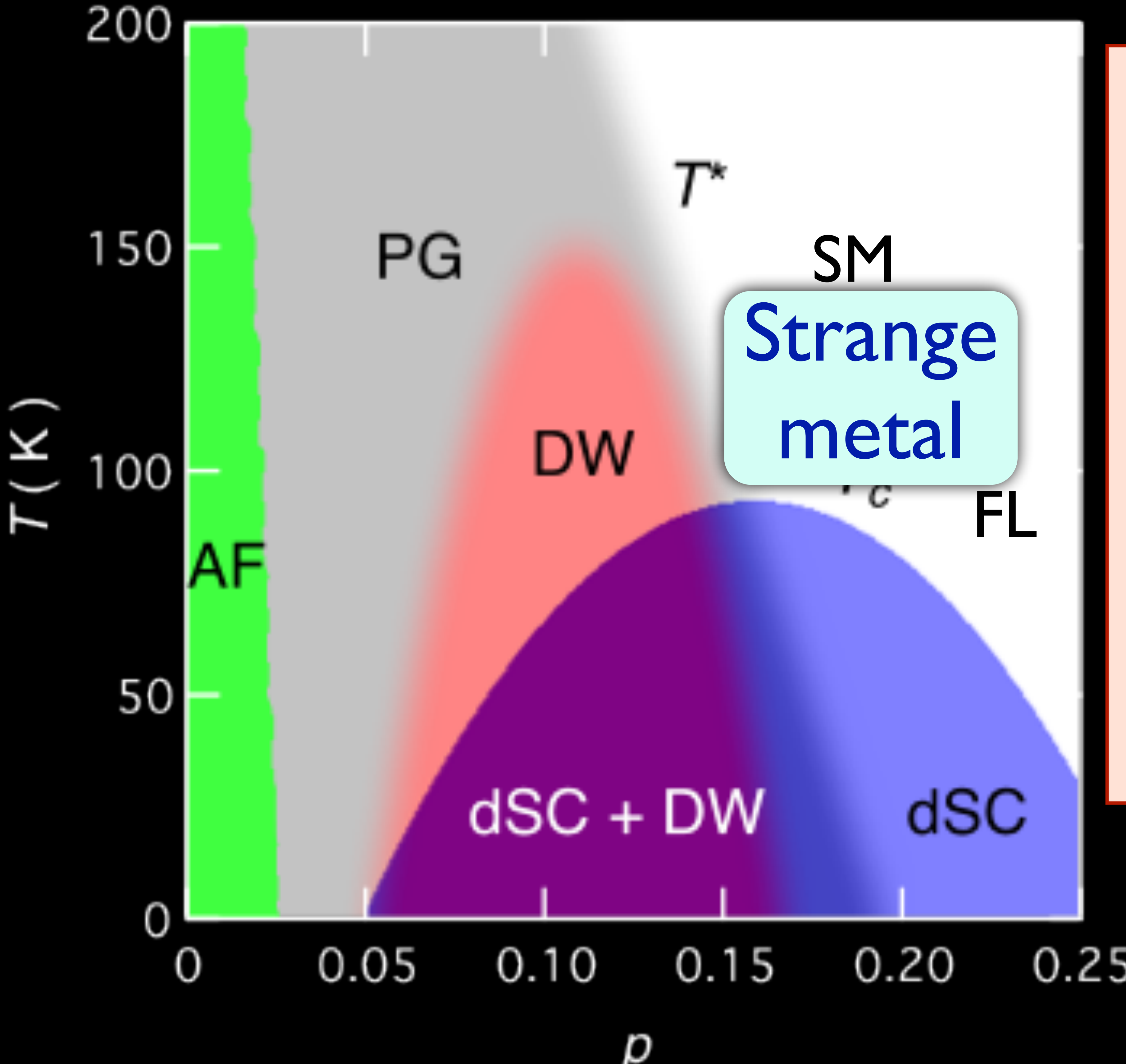
Figure: K. Fujita and J. C. Seamus Davis

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 arcs” at low $p$




Metal (gapless, compressible state) without quasi-particles

# Outline

1. The pseudogap metal

    *Fermi liquid co-existening with topological order*

2. The strange metal

    *Metal without quasiparticles*

    *Infinite-range model: dual to extremal charged black holes and yields Bekenstein-Hawking entropy*

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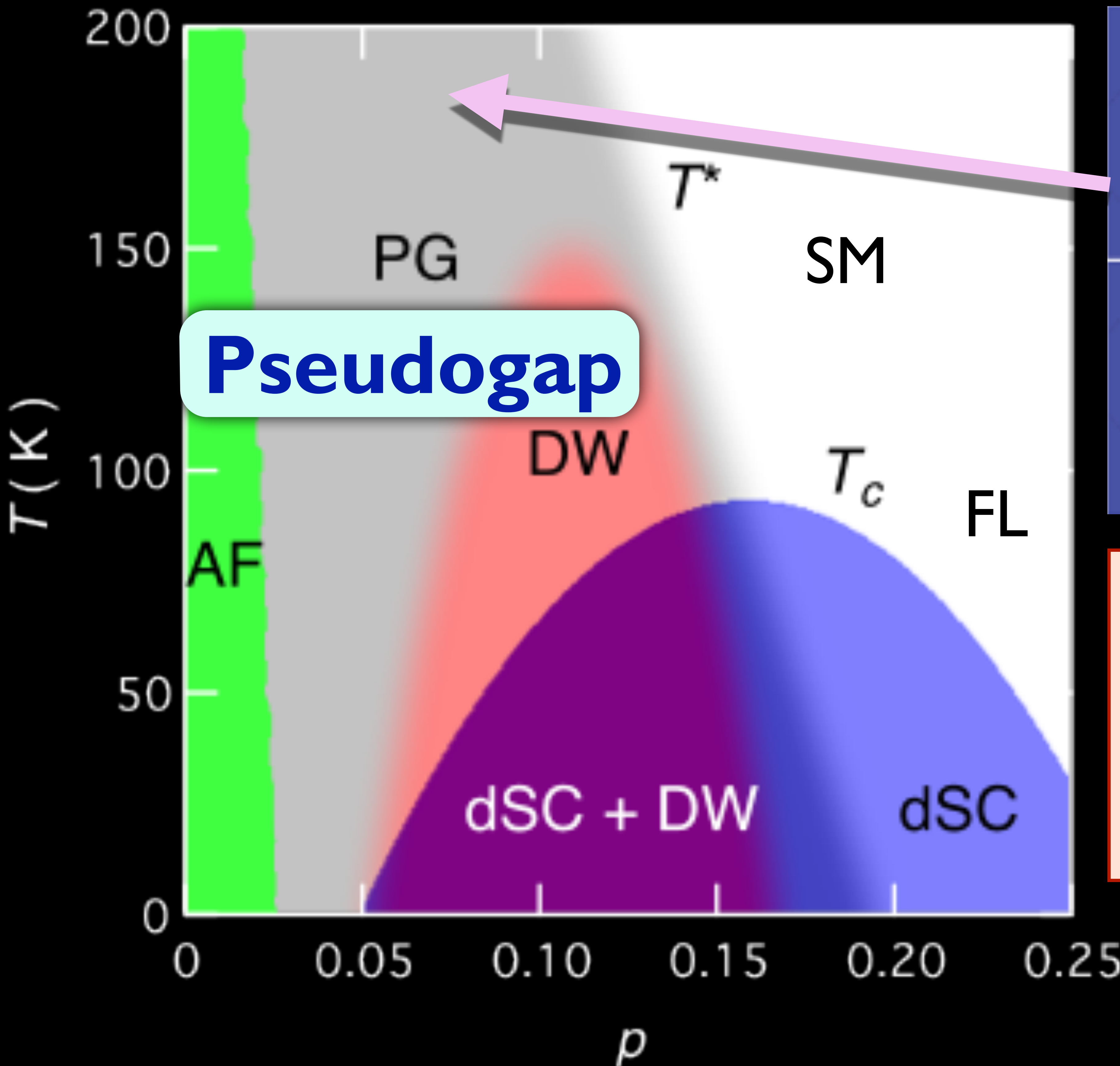


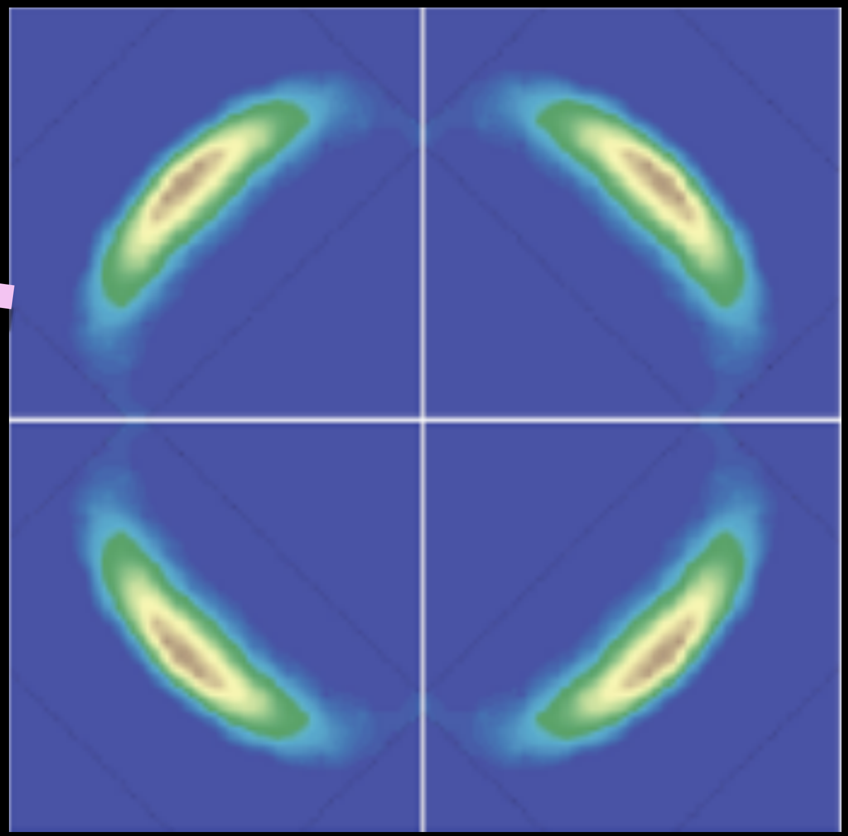

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Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
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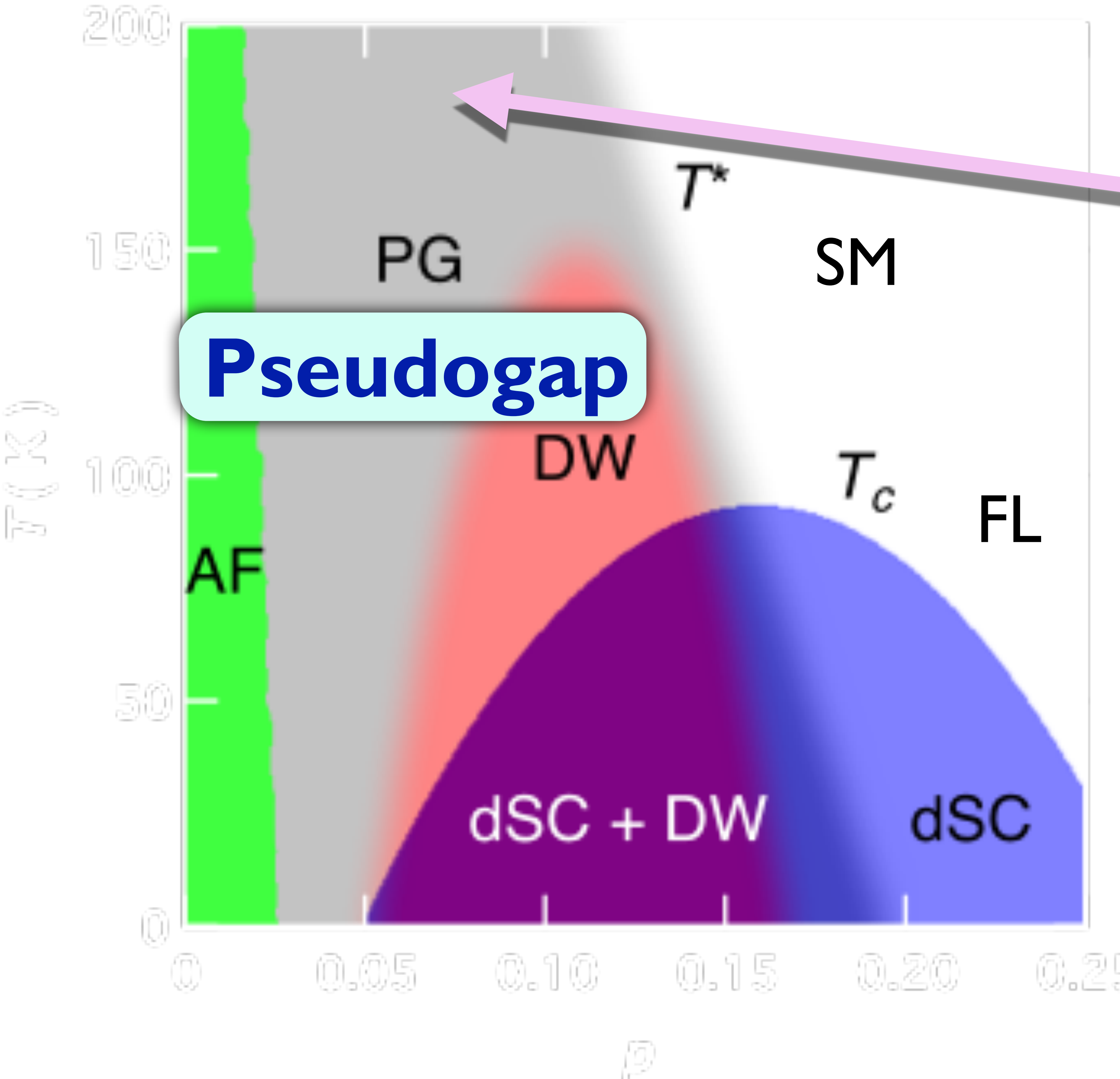
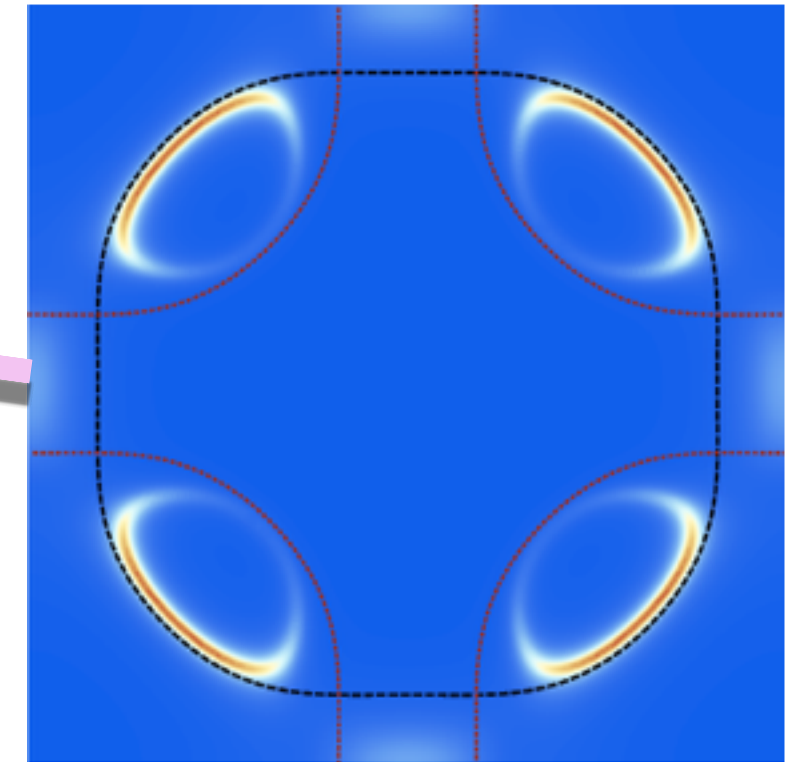
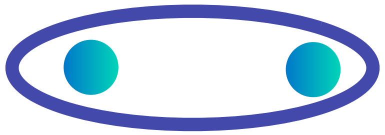
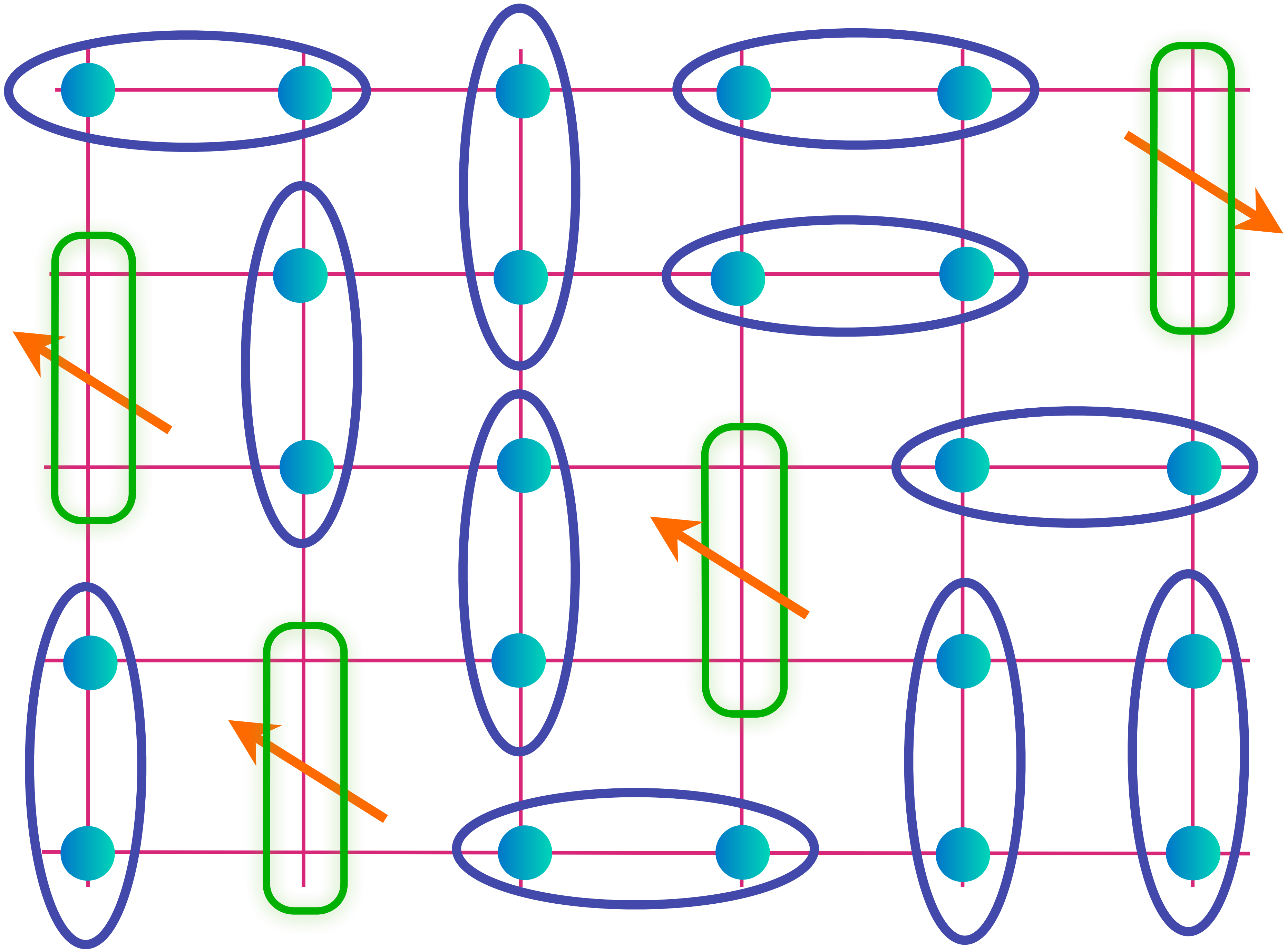


A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size $p$ coexisting with topological order

# Fractionalized Fermi liquid (FL*)

 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



Realizes a metal with a Fermi surface of area $p$ co-existing with "topological order"


T. Senthil, S. S., M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)
R. K. Kaul, A. Kolezhuk, M. Levin, S. S., and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)
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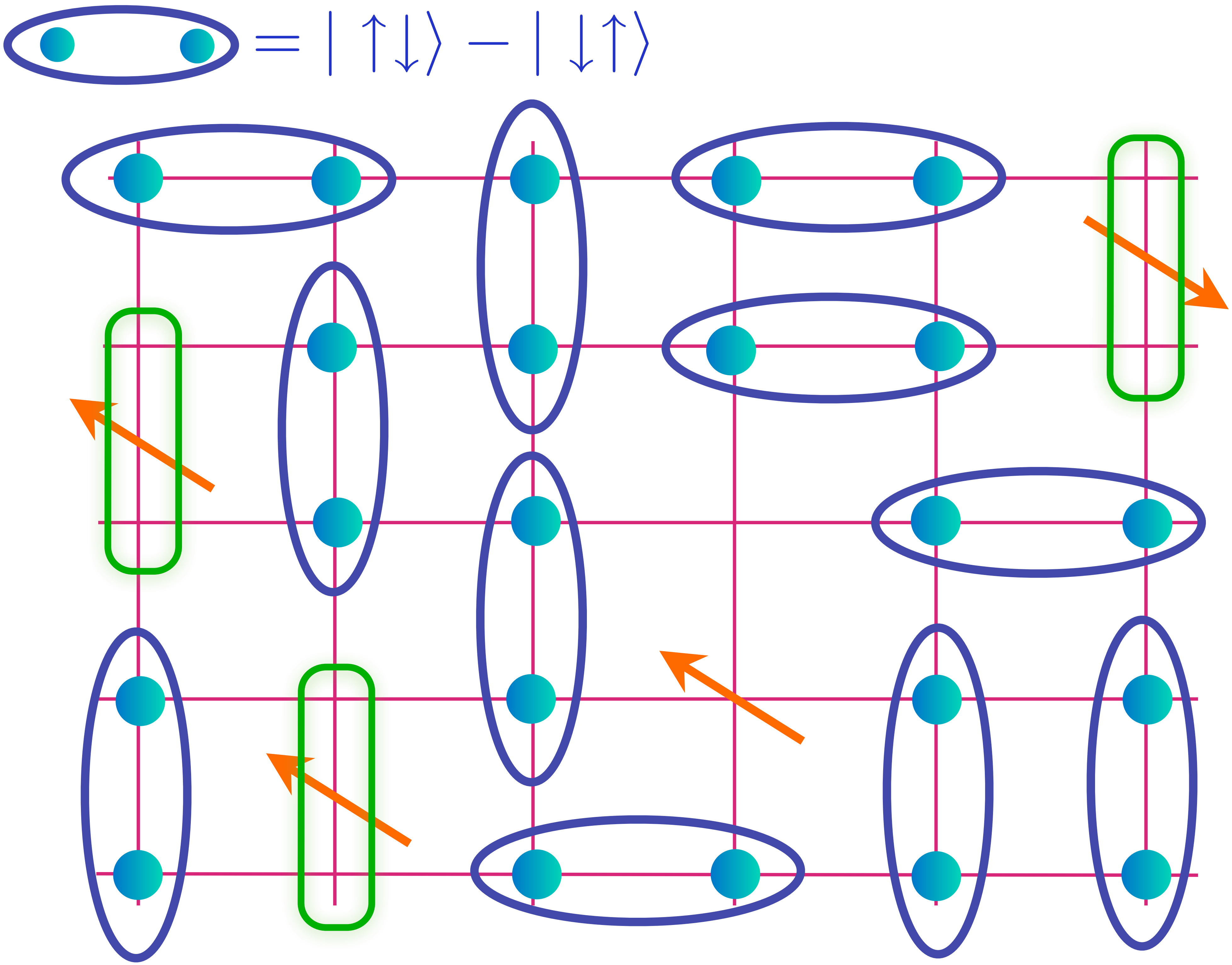


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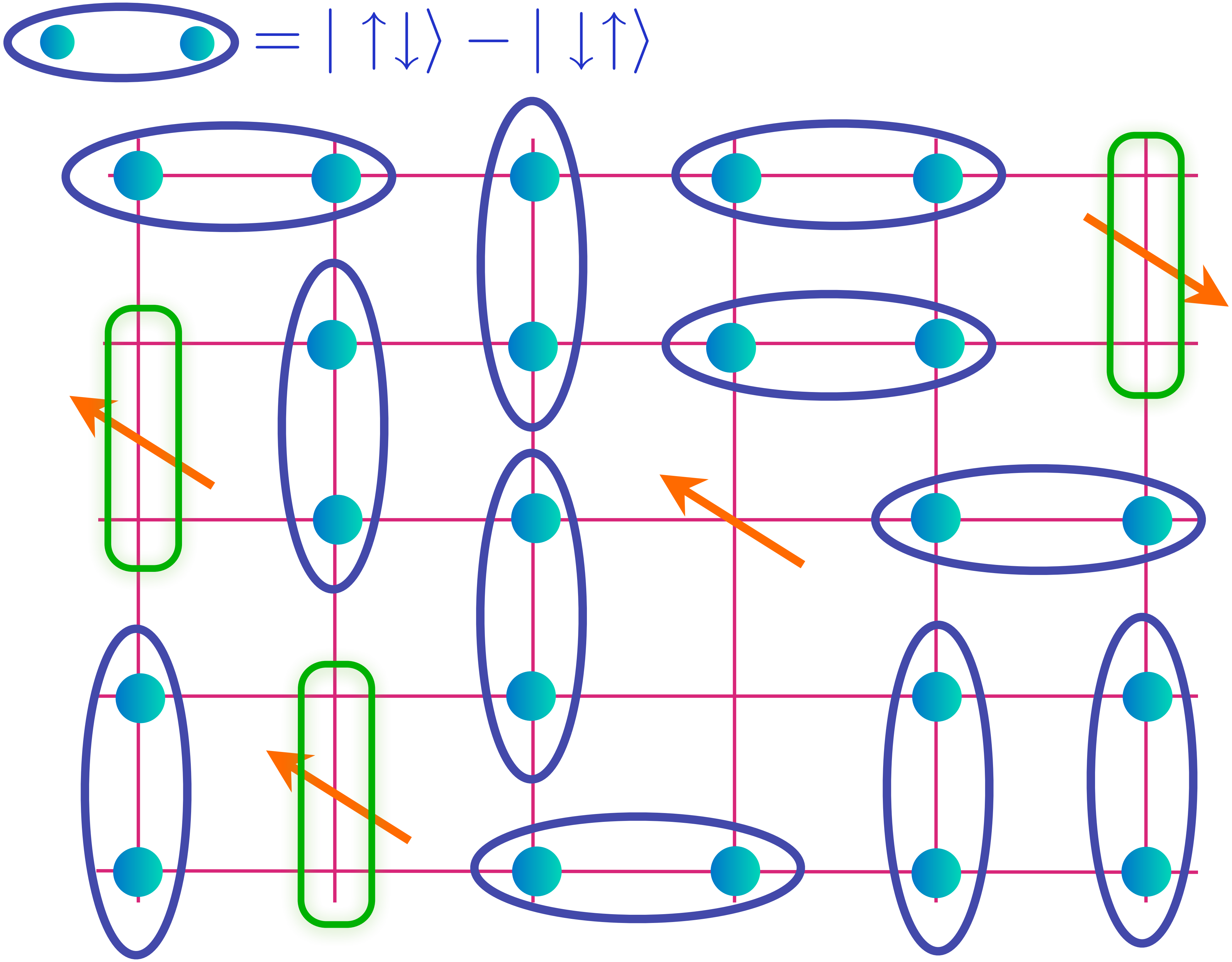


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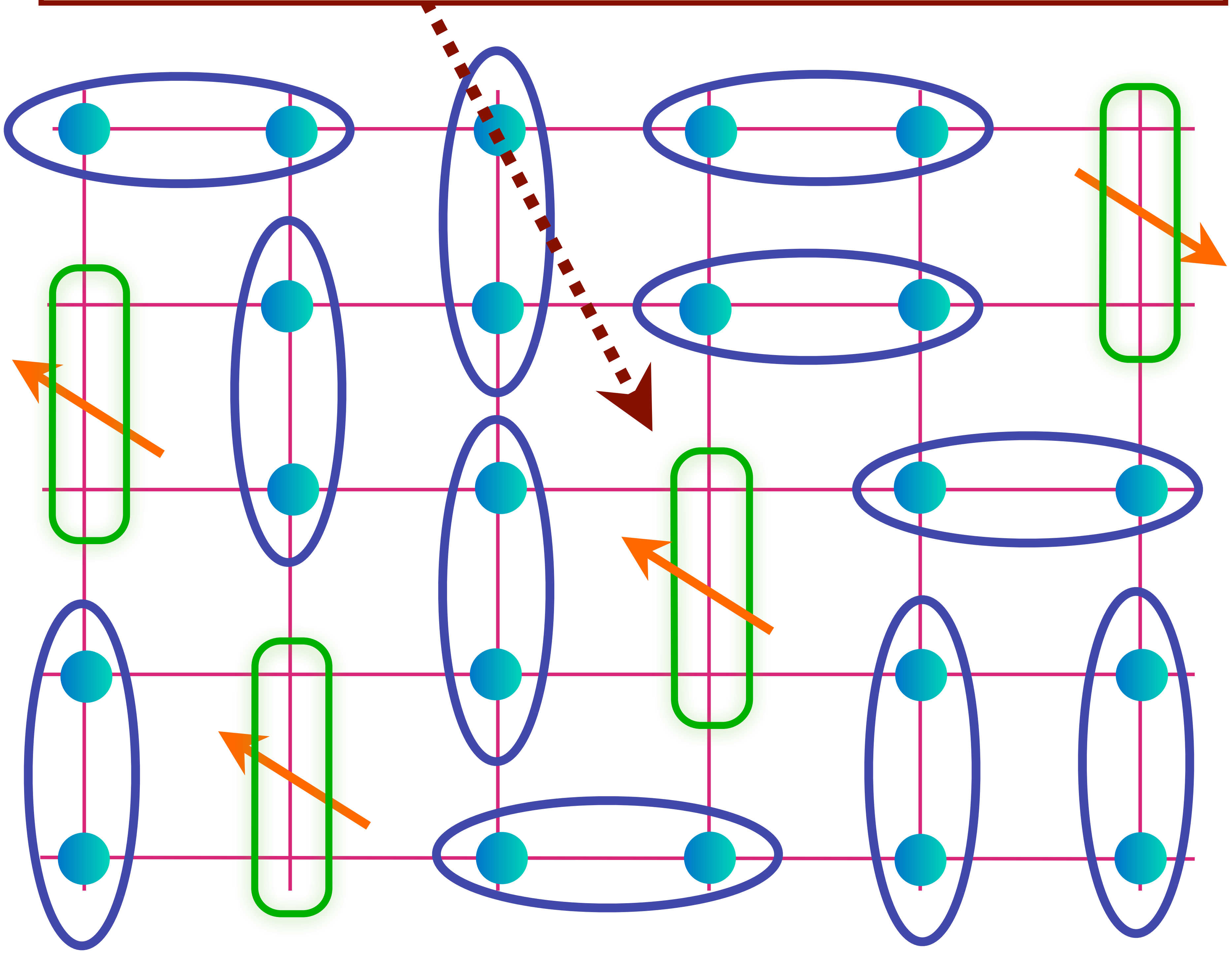
A fermionic "dimer" describing a "bonding" orbital between two sites



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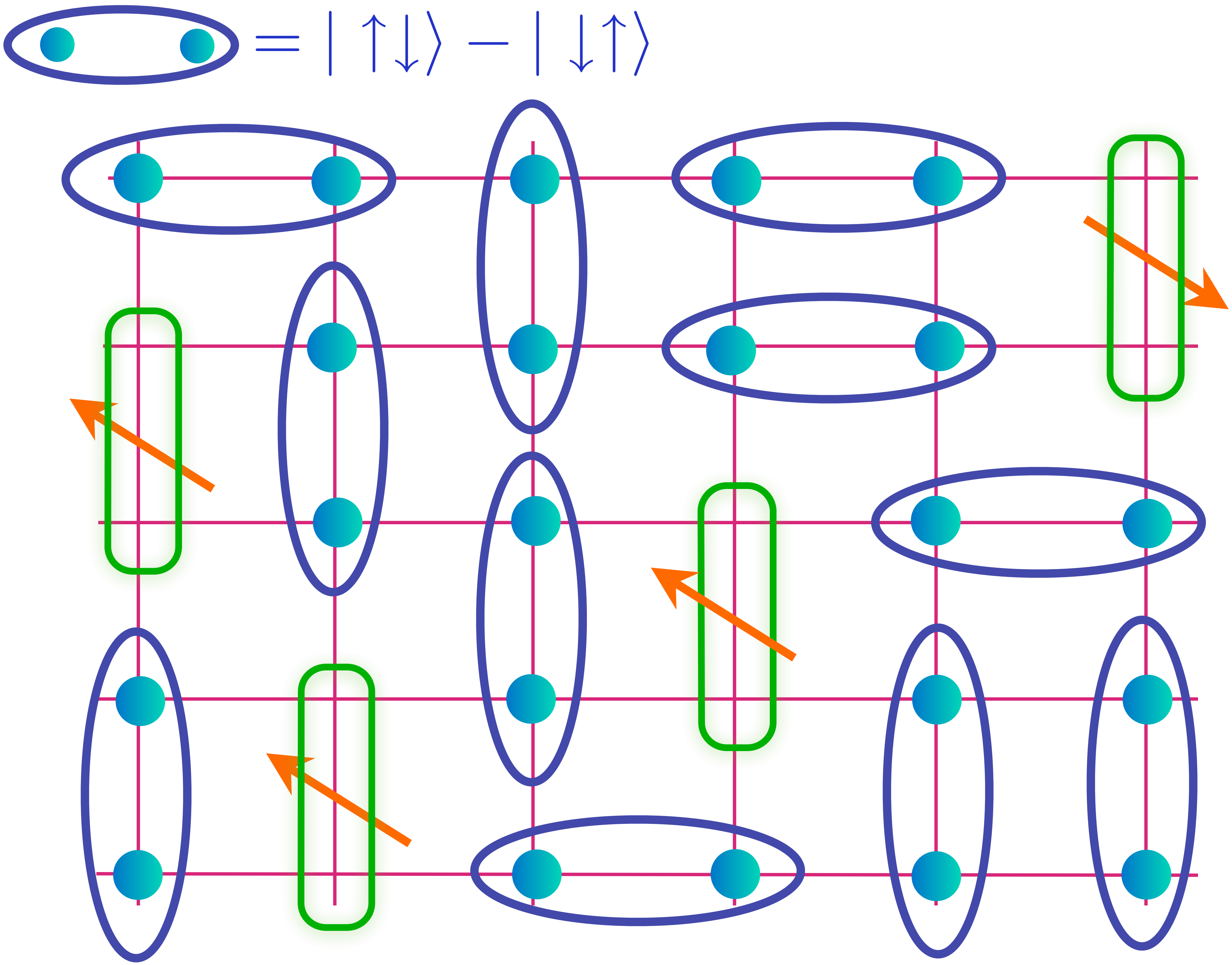


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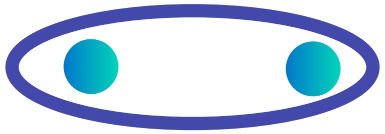
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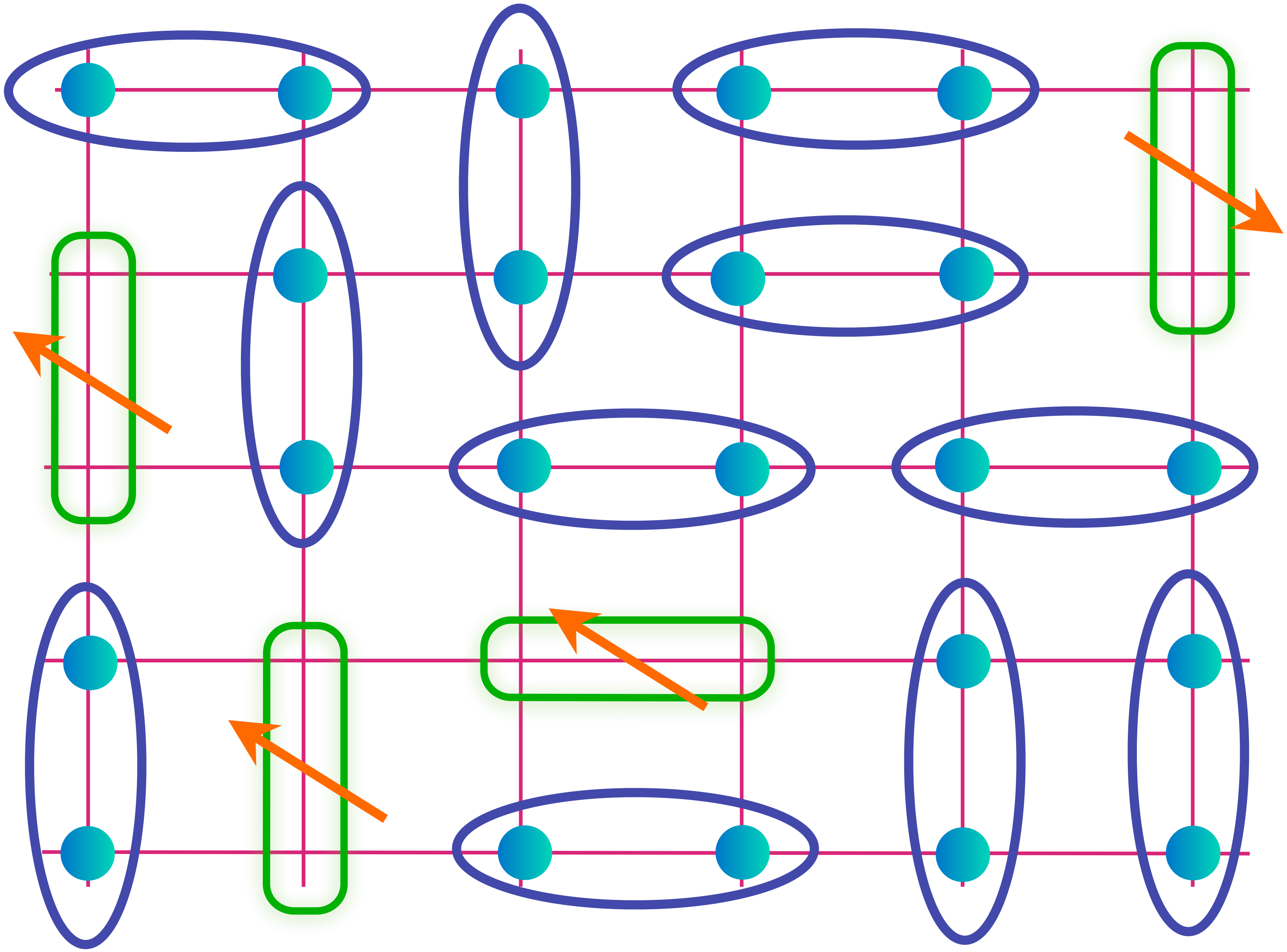

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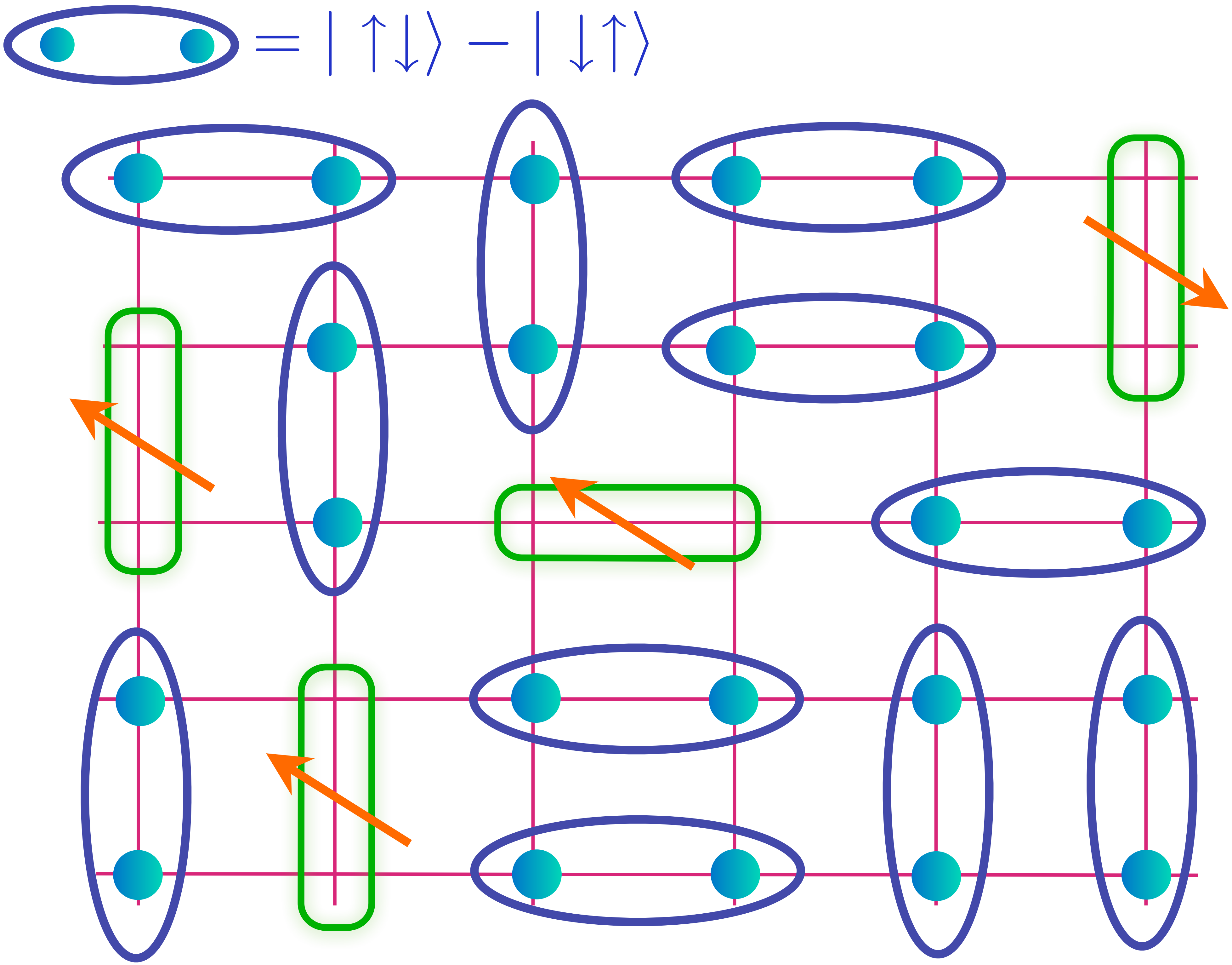


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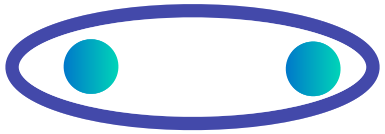
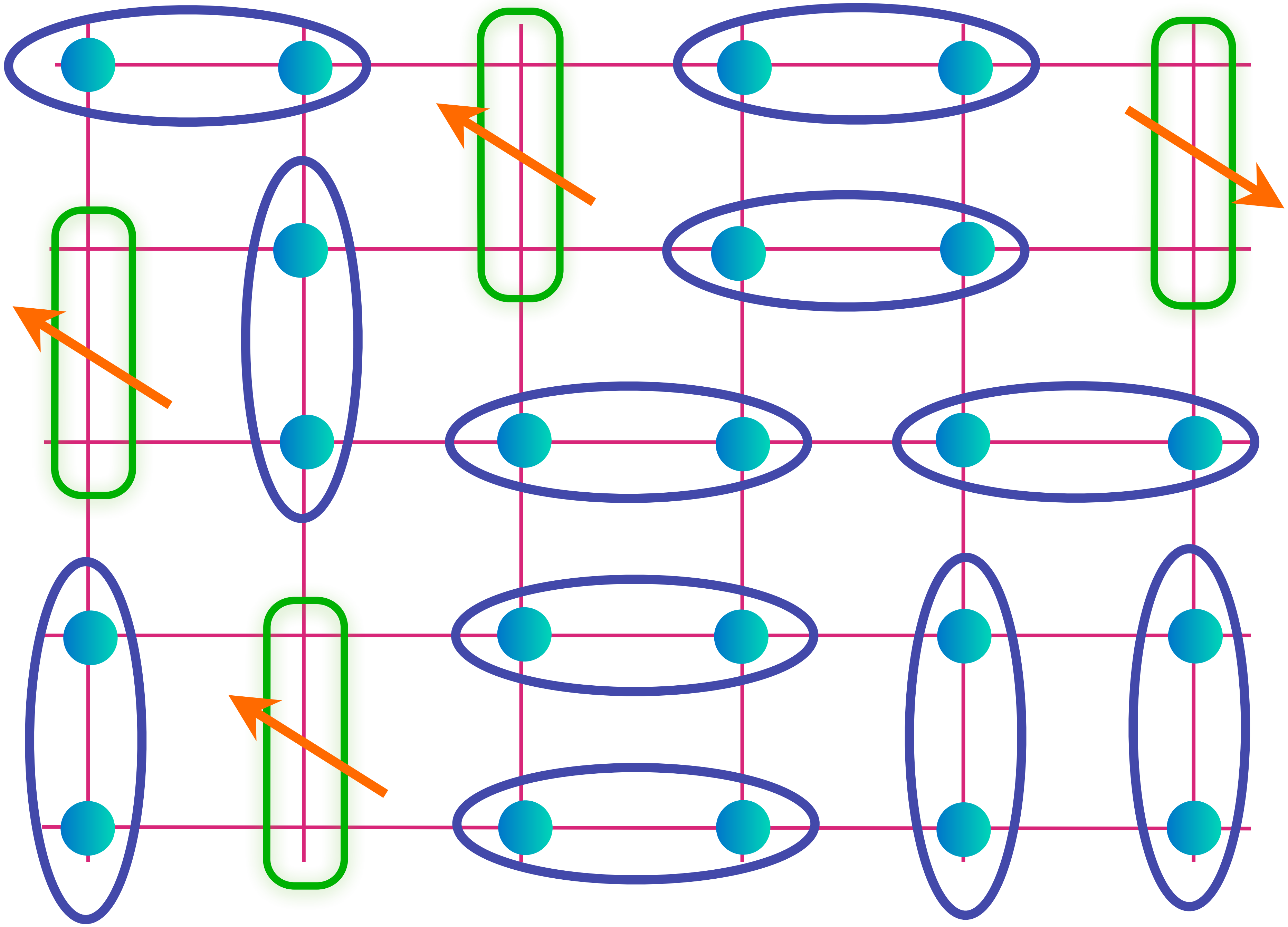
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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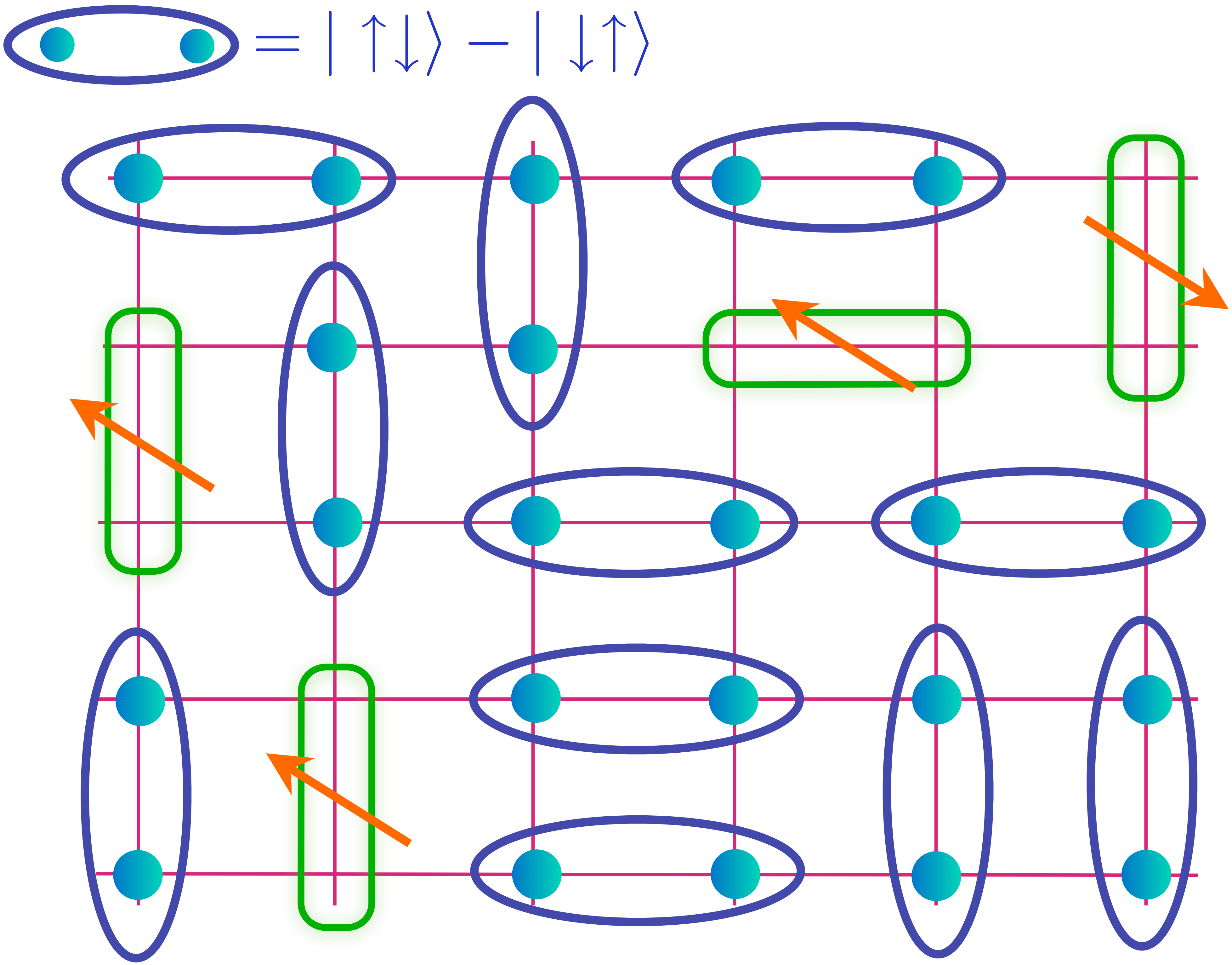


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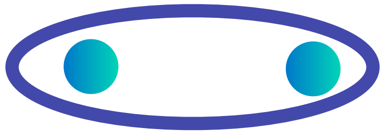

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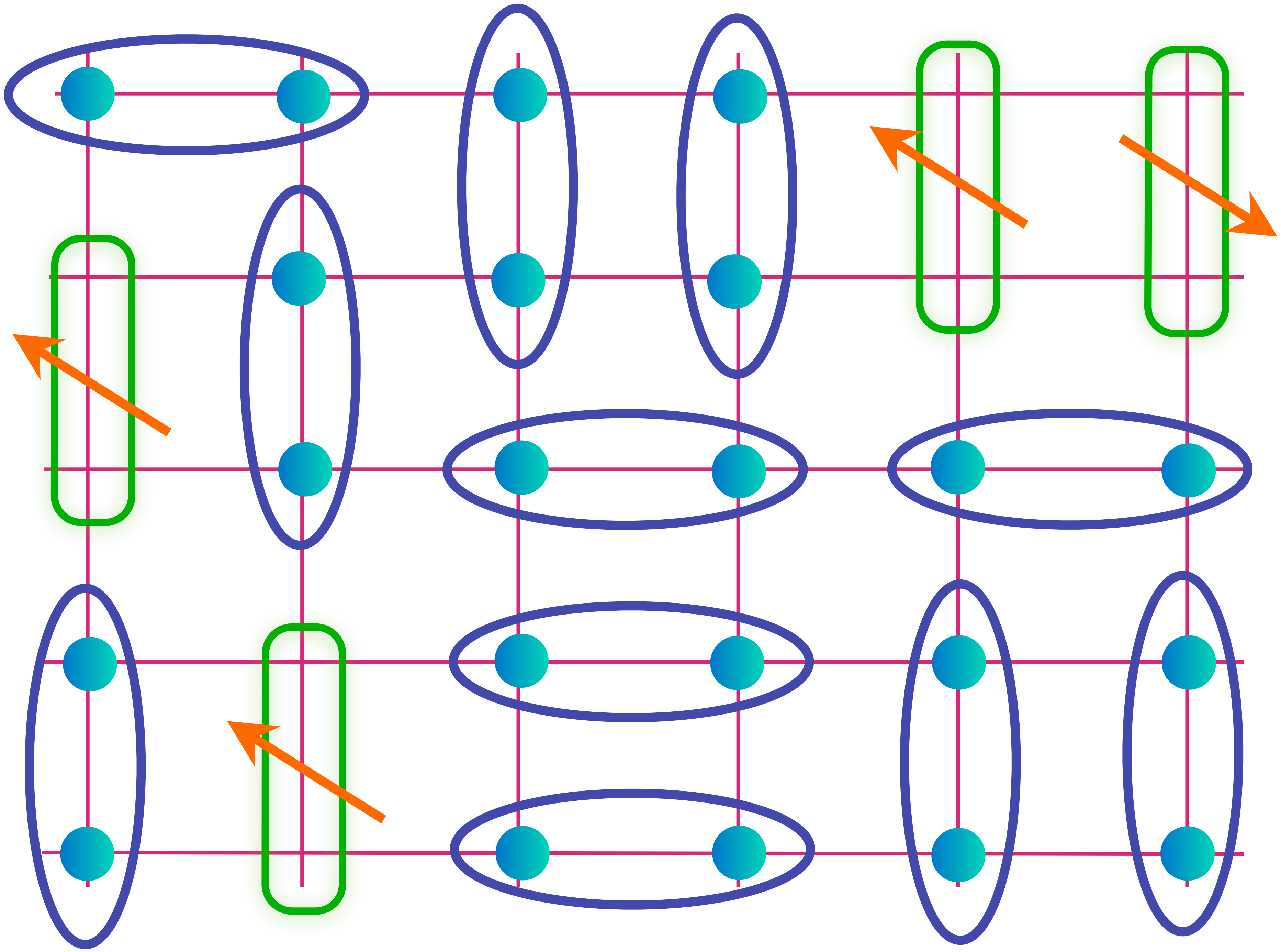

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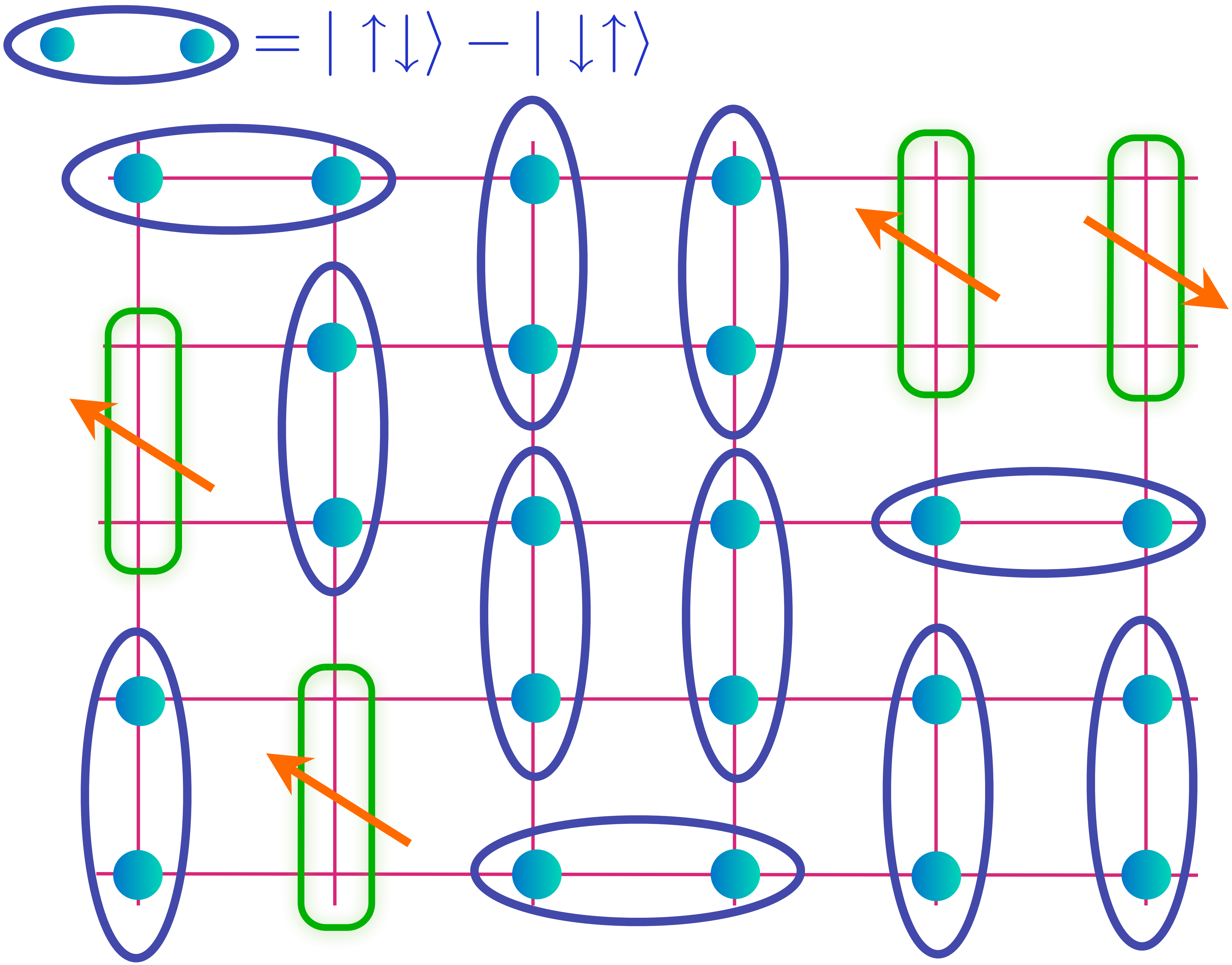


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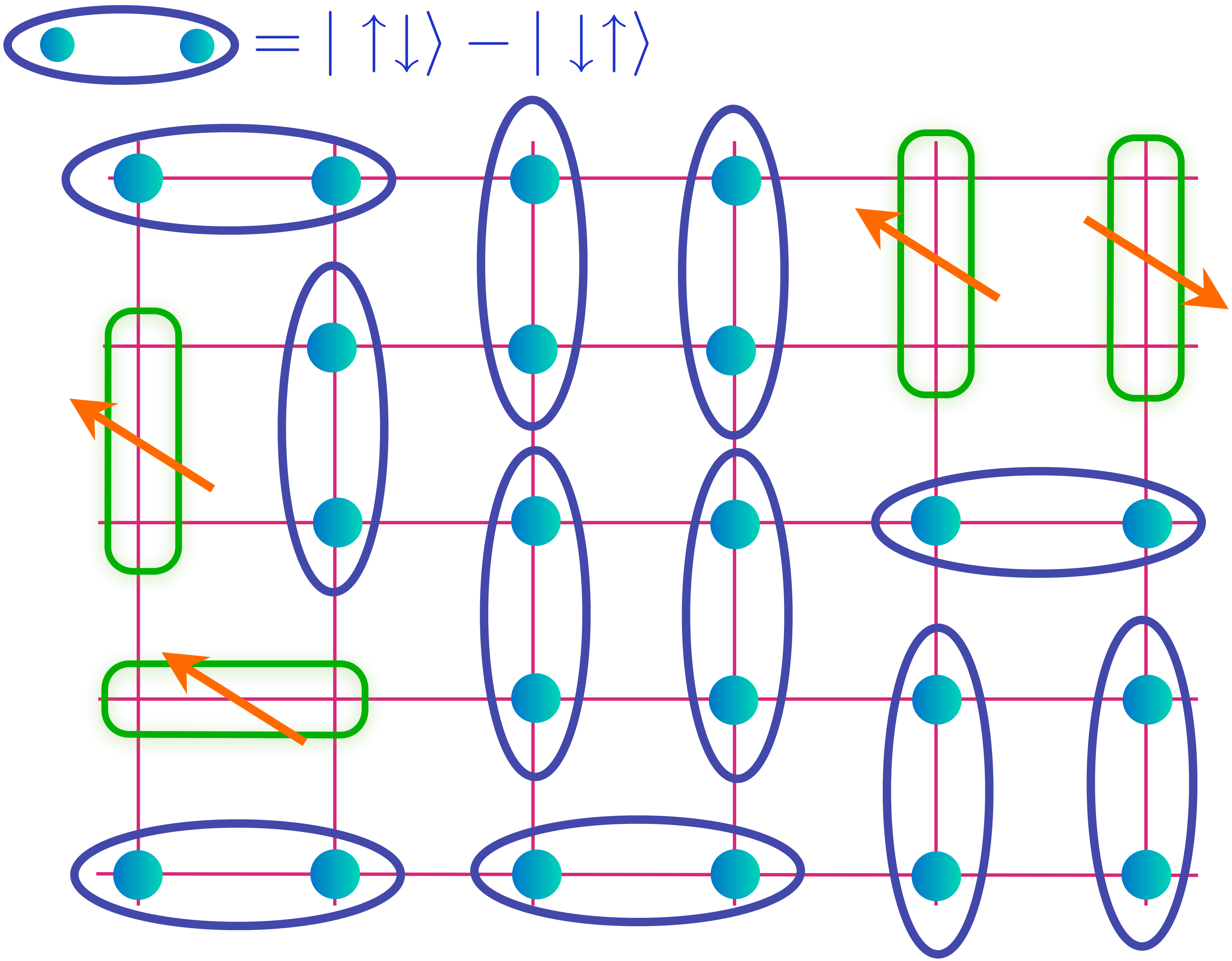


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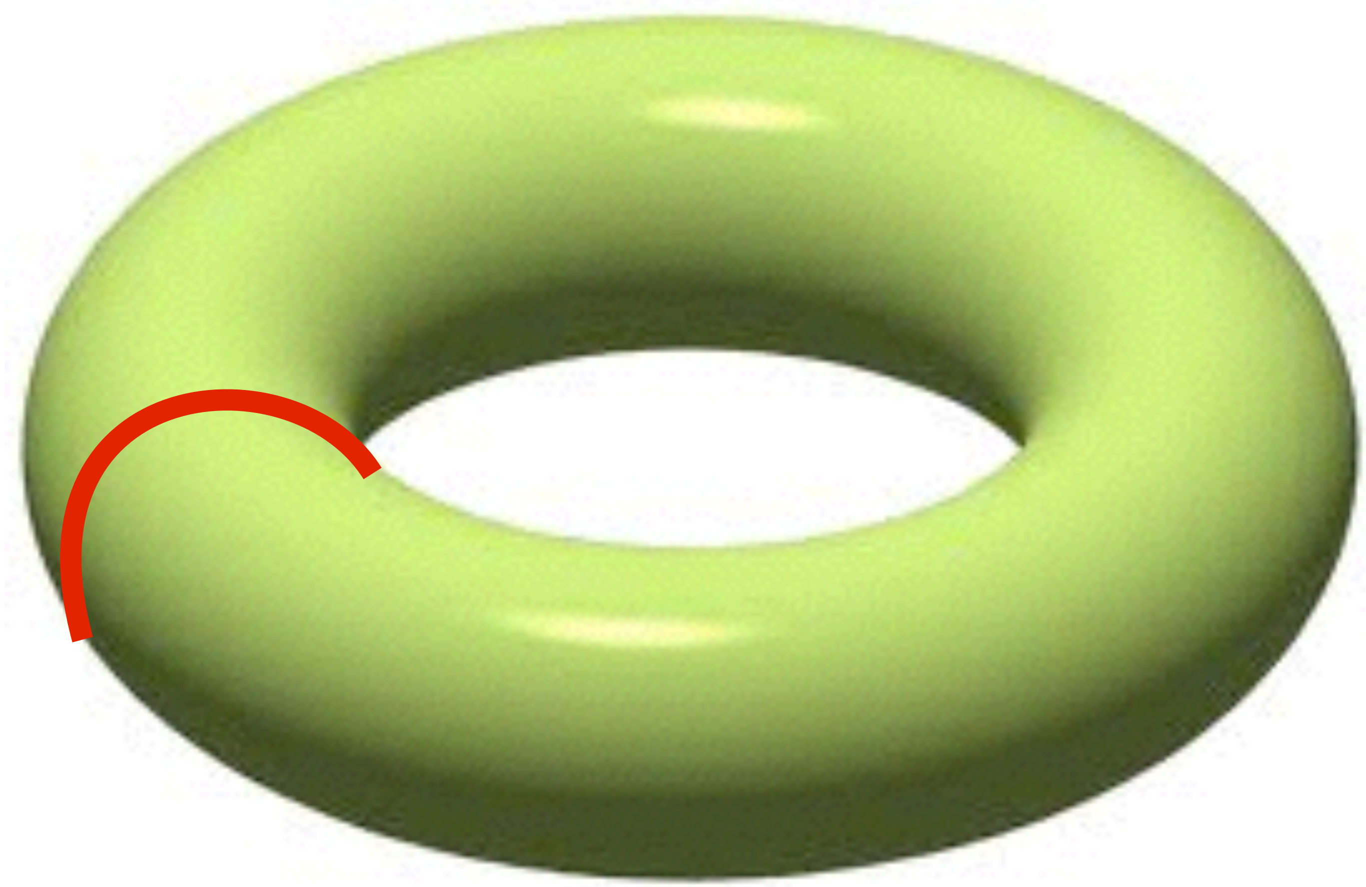
# Topological order

Place pseudogap metal on a torus;

# Topological order



Place pseudogap metal on a torus; obtain "topological" states nearly degenerate with the ground state: change sign of every dimer across red line

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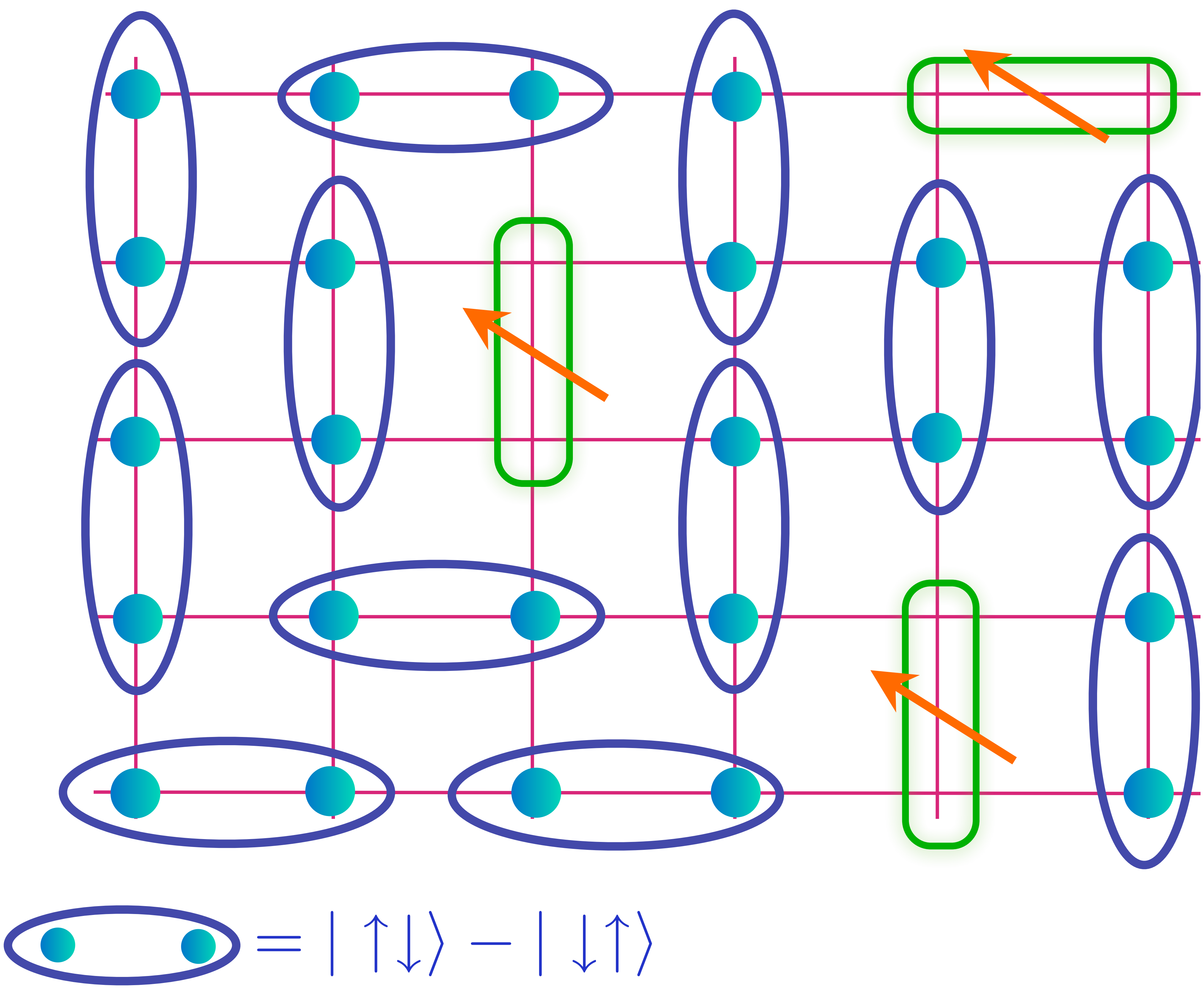

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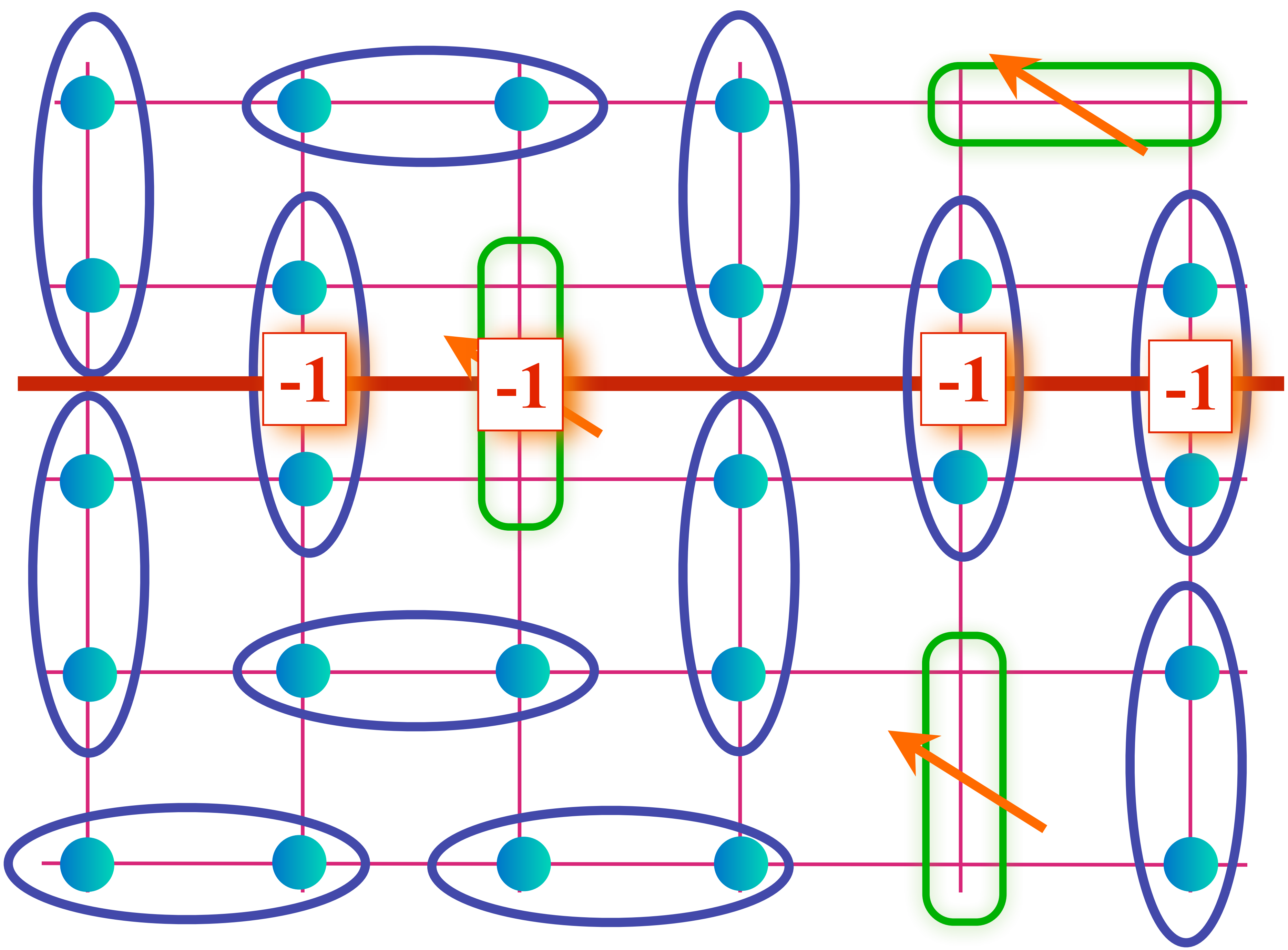


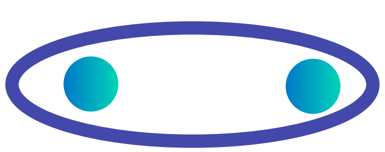
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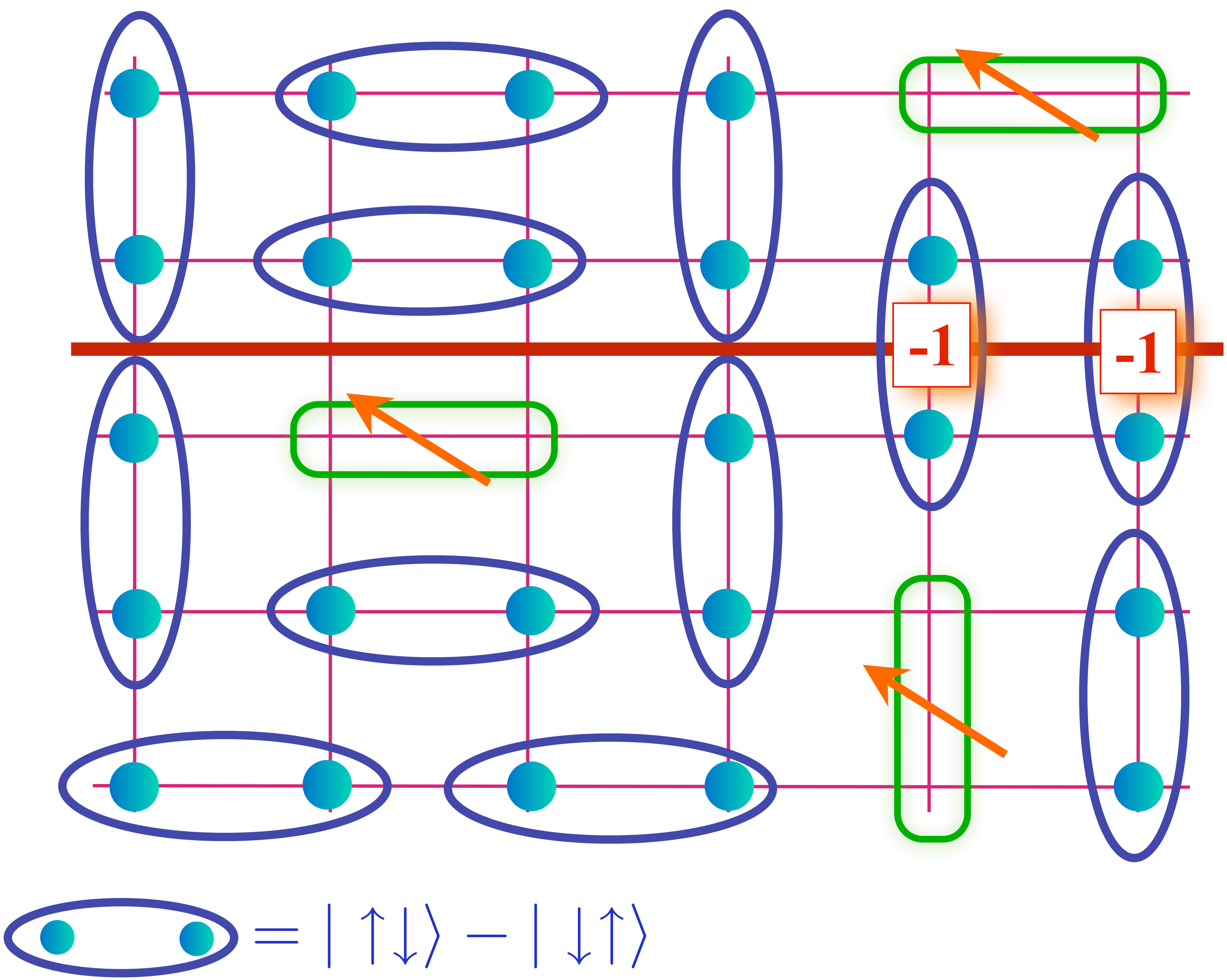


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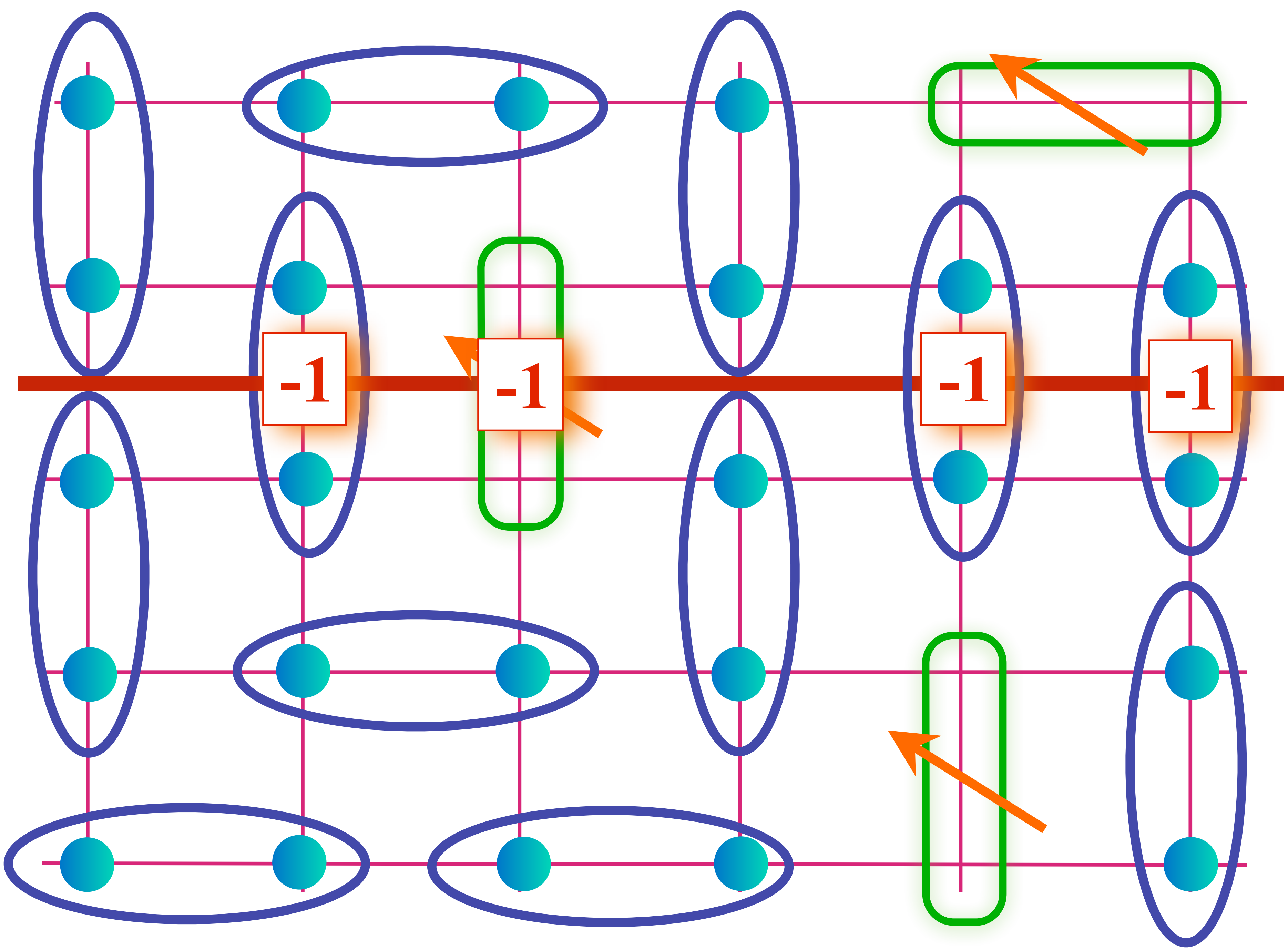


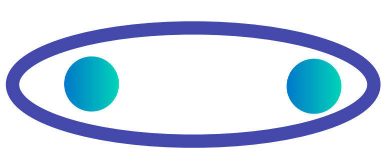


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Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
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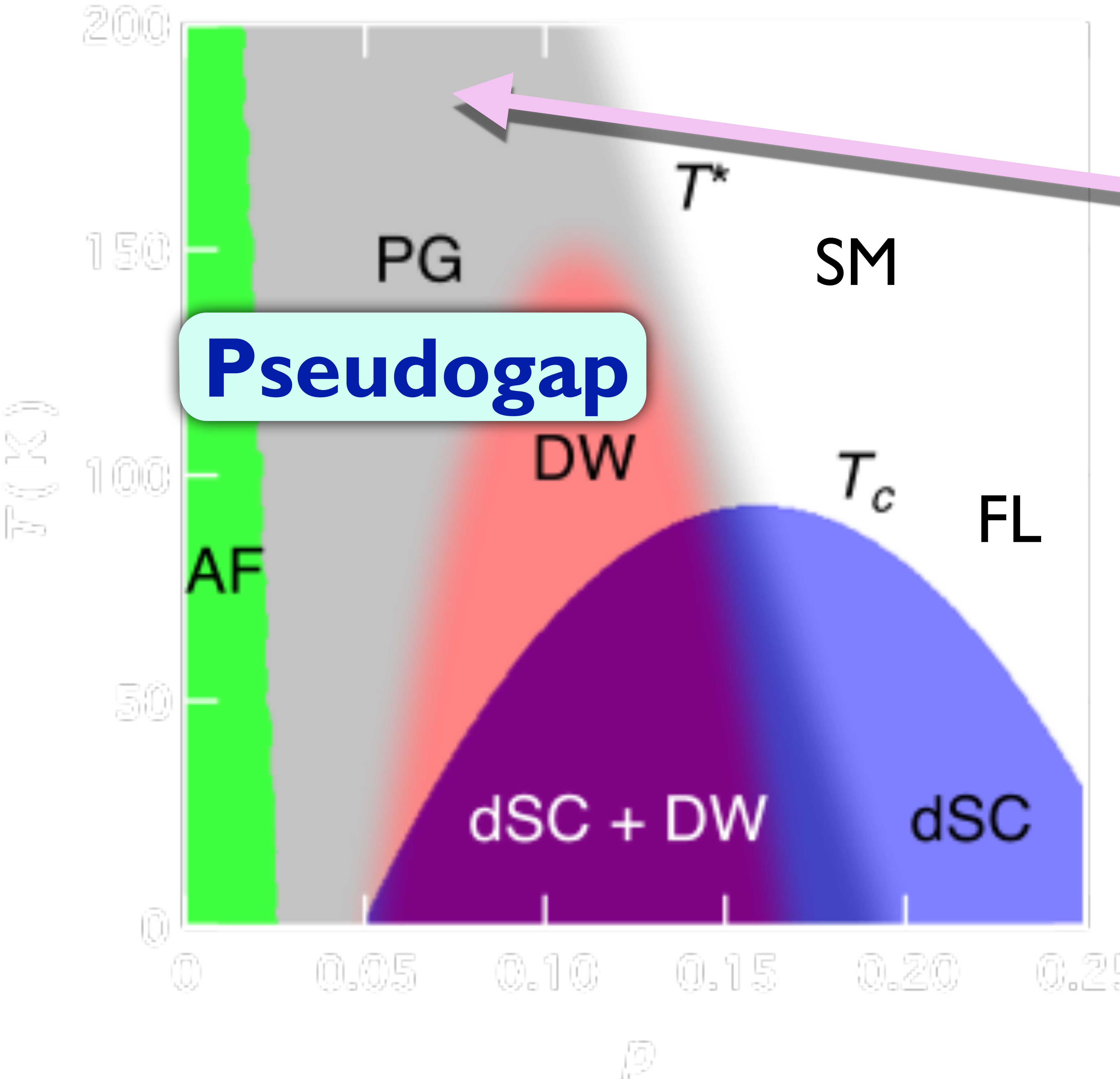
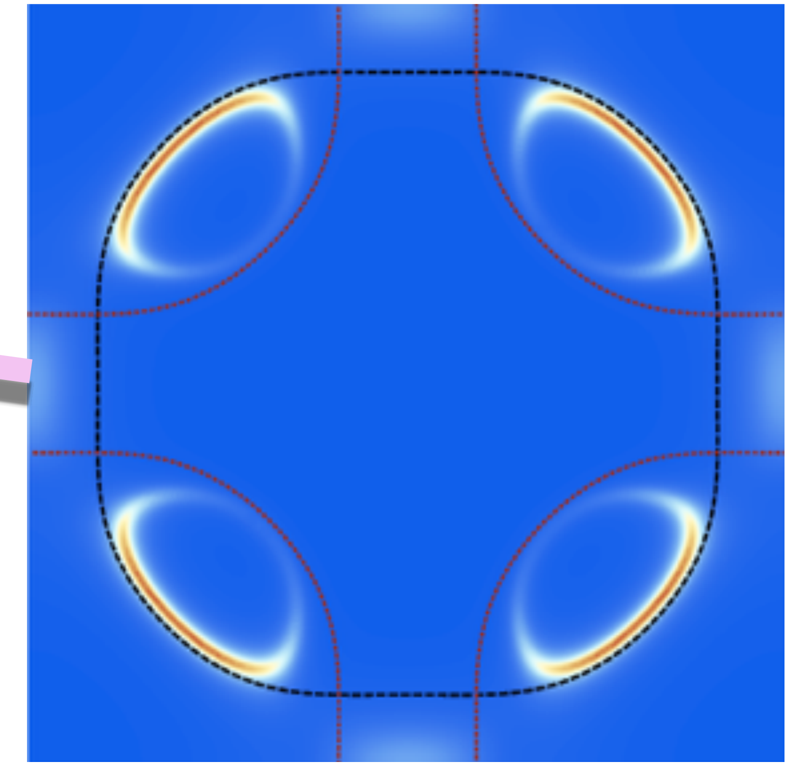


A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size $p$ coexisting with <u>topological order</u>

# Outline

## 1. The pseudogap metal

*Fermi liquid co-existening with topological order*

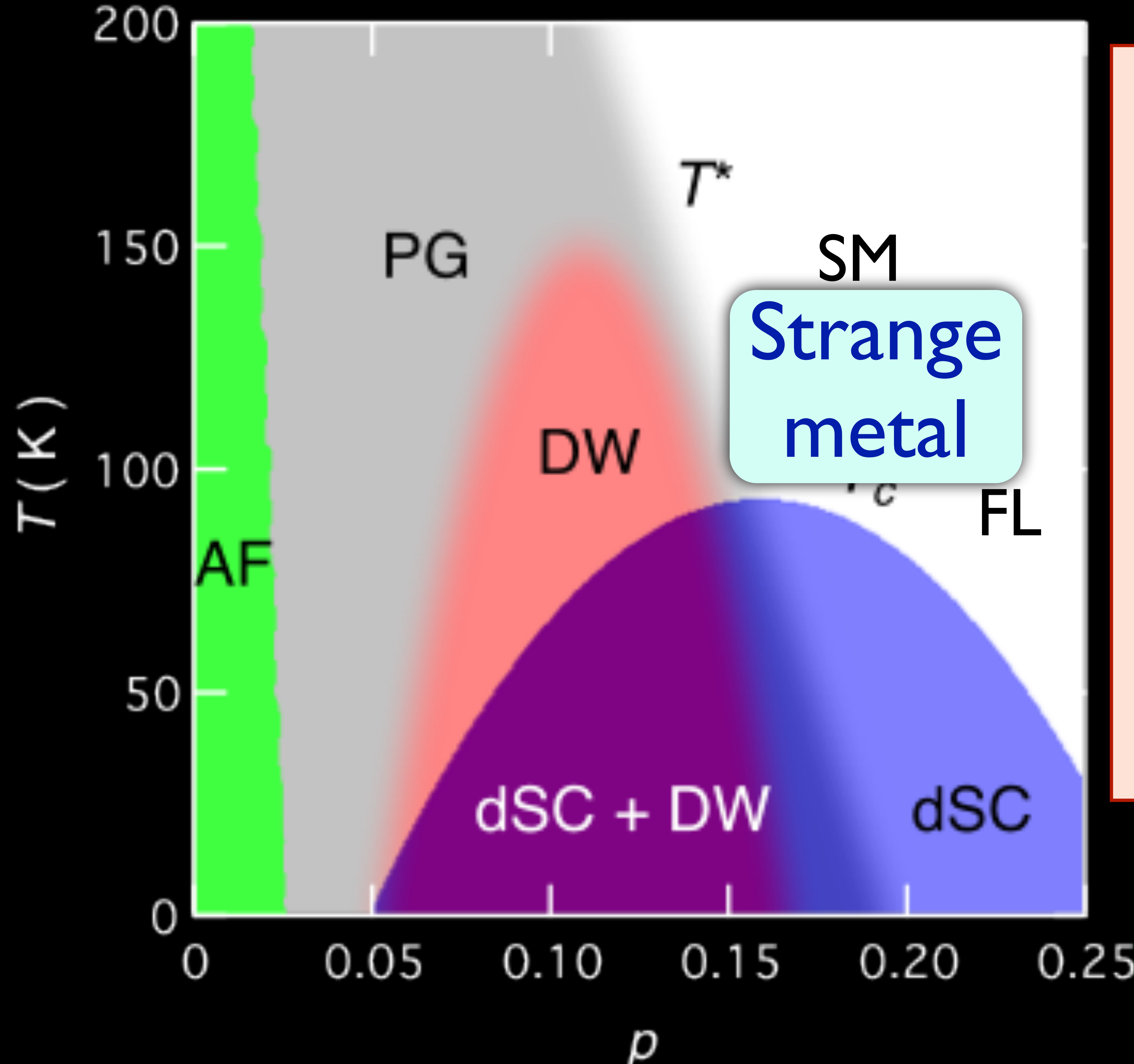
## 2. The strange metal

*Metal without quasiparticles*

*Infinite-range model: dual to extremal charged*

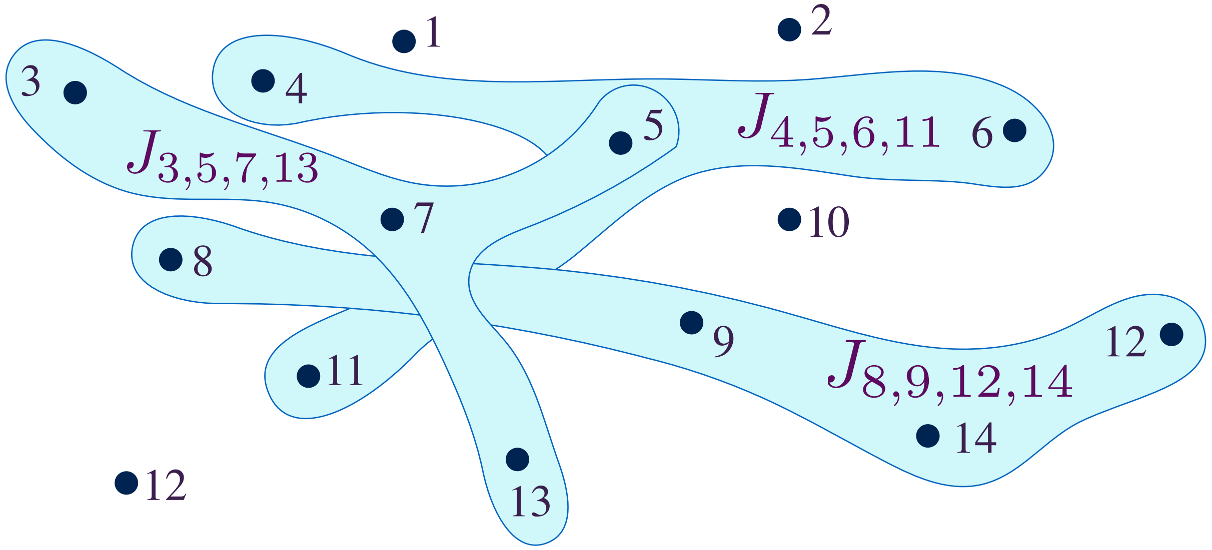
*black holes and yields*

*Bekenstein-Hawking entropy*




Metal (gapless, compressible state) without quasi-particles

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$




$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

# An infinite-range model of a strange metal

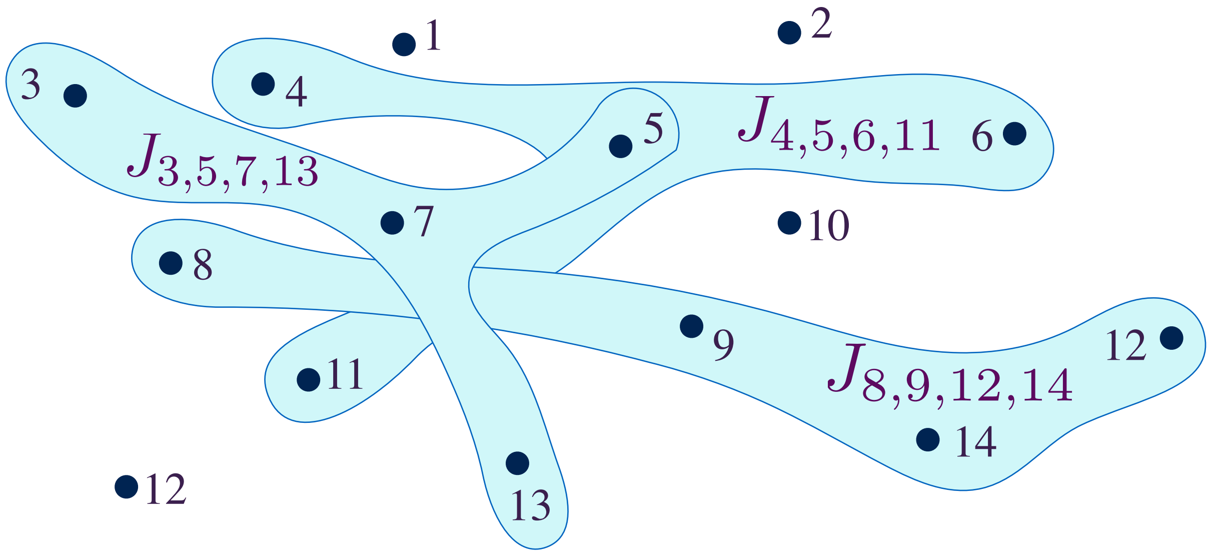
S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)
A. Kitaev, unpublished
S. Sachdev, arXiv:1506.05111

$$c_i c_j + c_j c_i = 0$$

$$c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$J_{ij;k\ell}$ independent random numbers

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$

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Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}} \, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)

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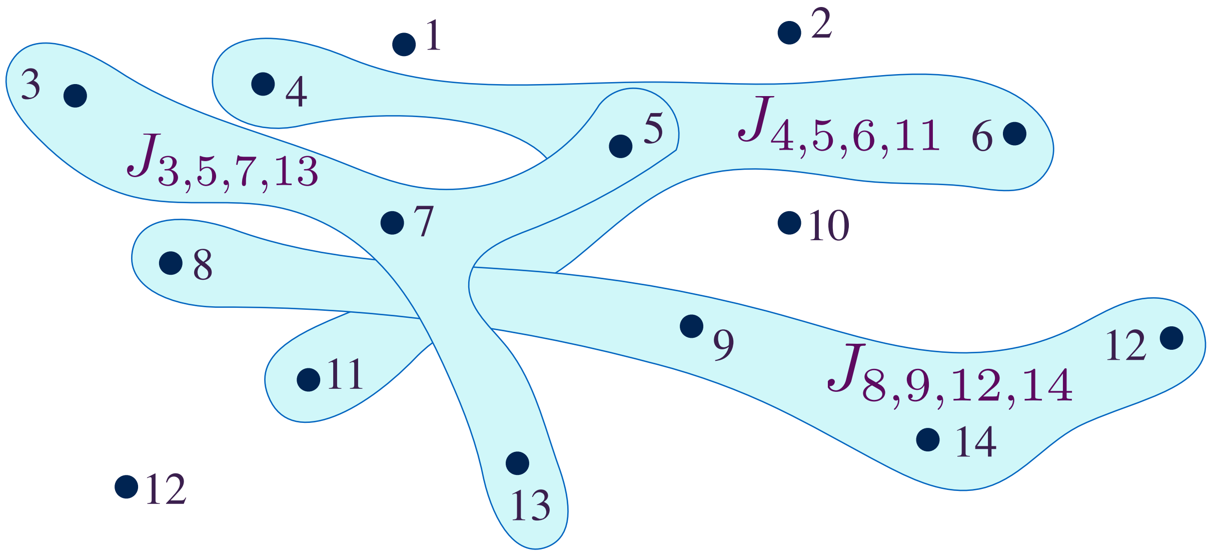


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A. Georges, O. Parcollet, and S. Sachdev
Phys. Rev. B **63**, 134406 (2001)

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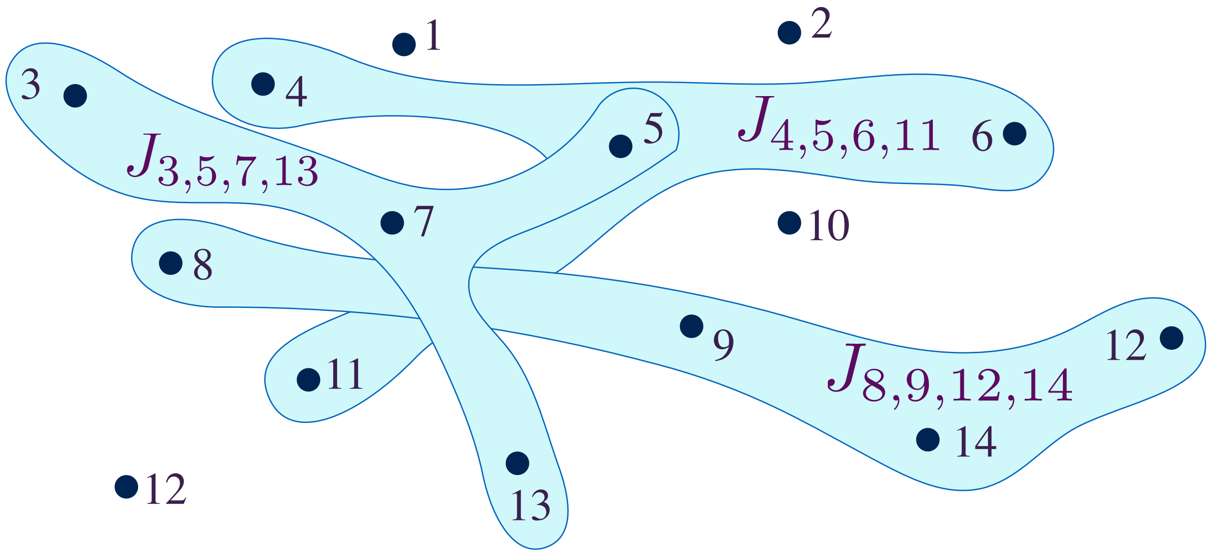


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$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

O. Parcollet, A. Georges, G. Kotliar, and A. Sengupta
Phys. Rev. B **58**, 3794 (1998)

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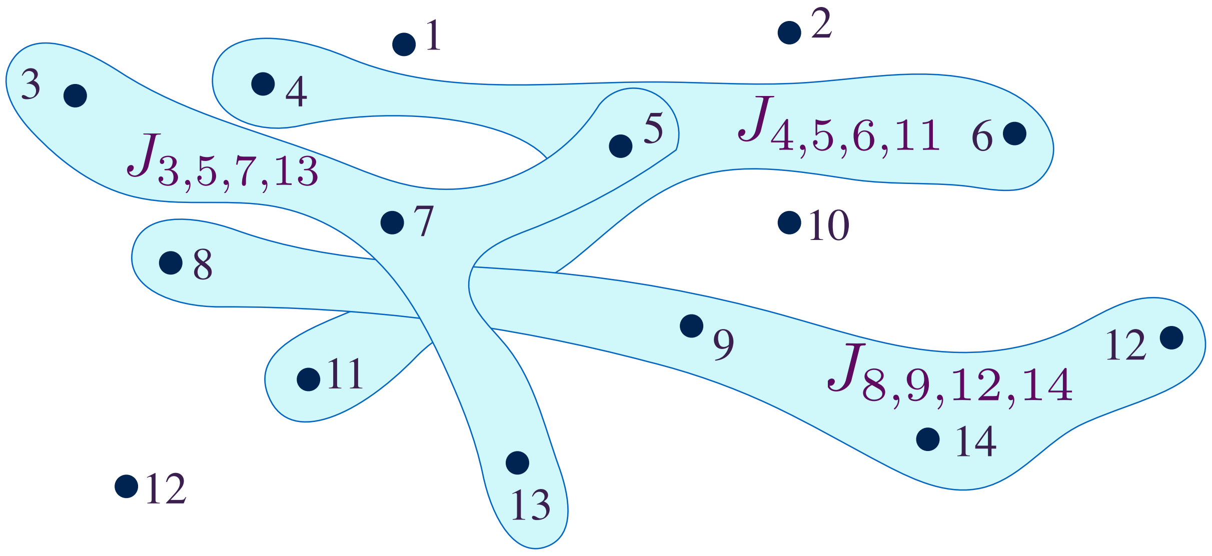


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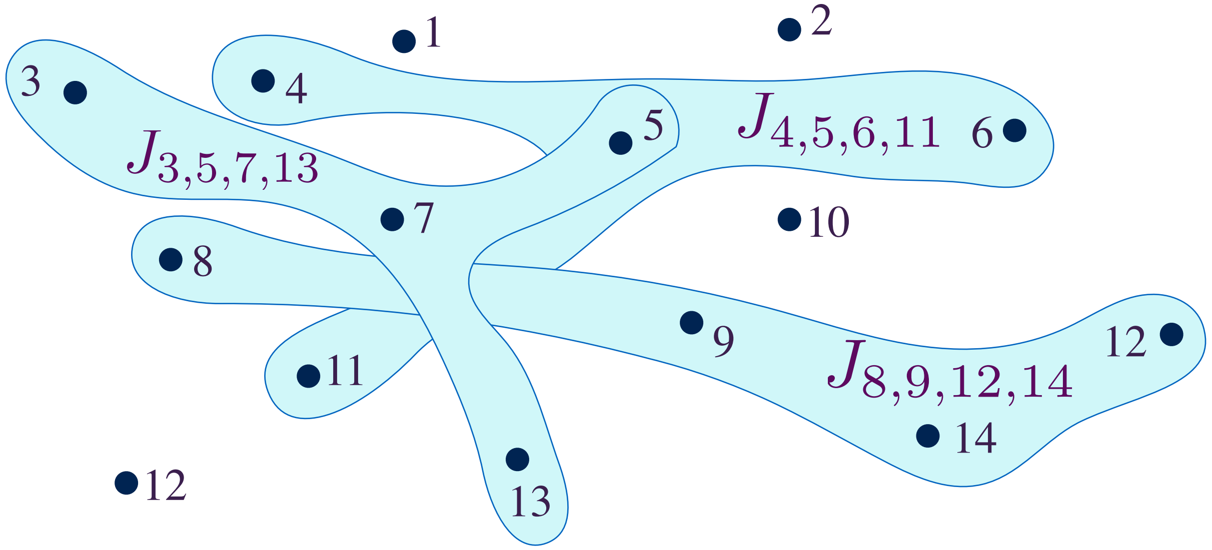


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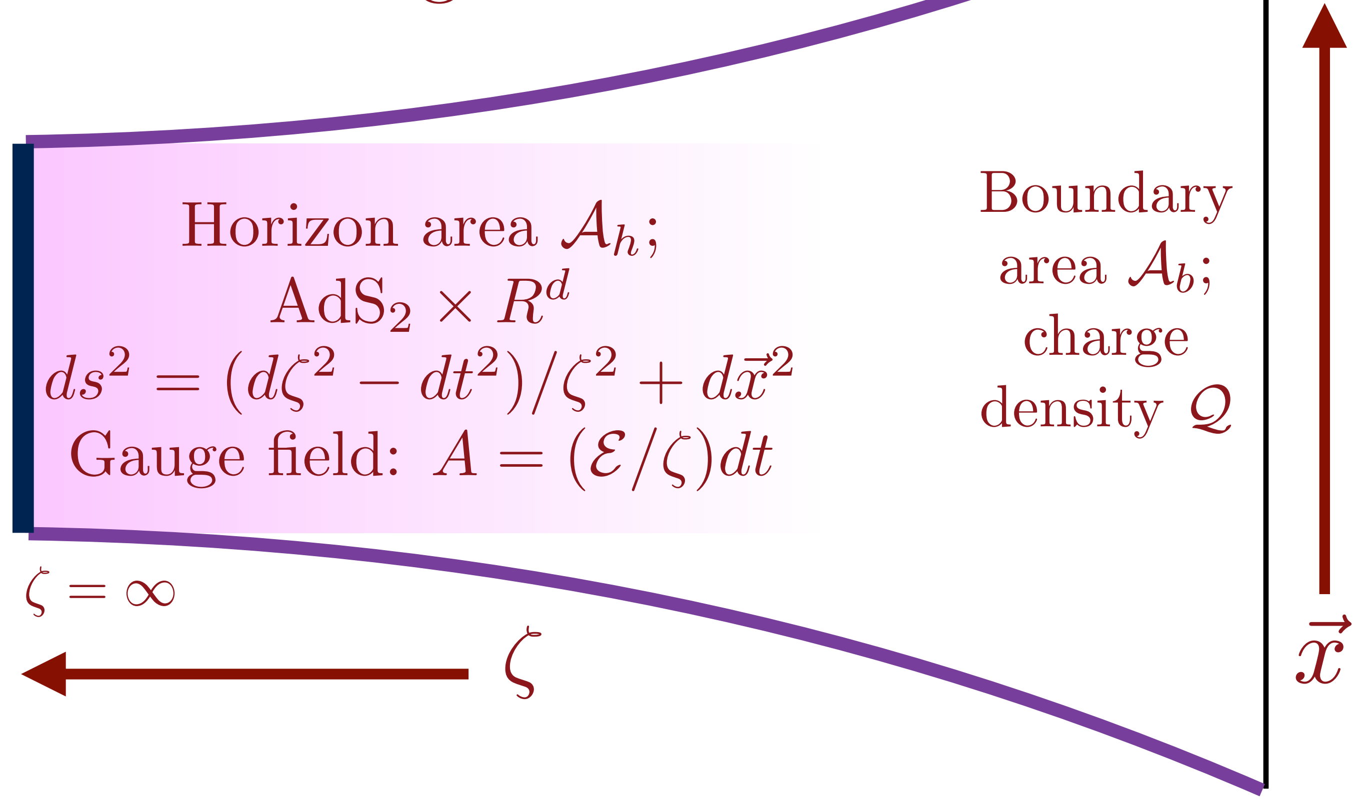


A. Chamblin, R. Emparan, C.V. Johnson, and R.C. Myers
Phys. Rev. D **60**, 064018 (1999)

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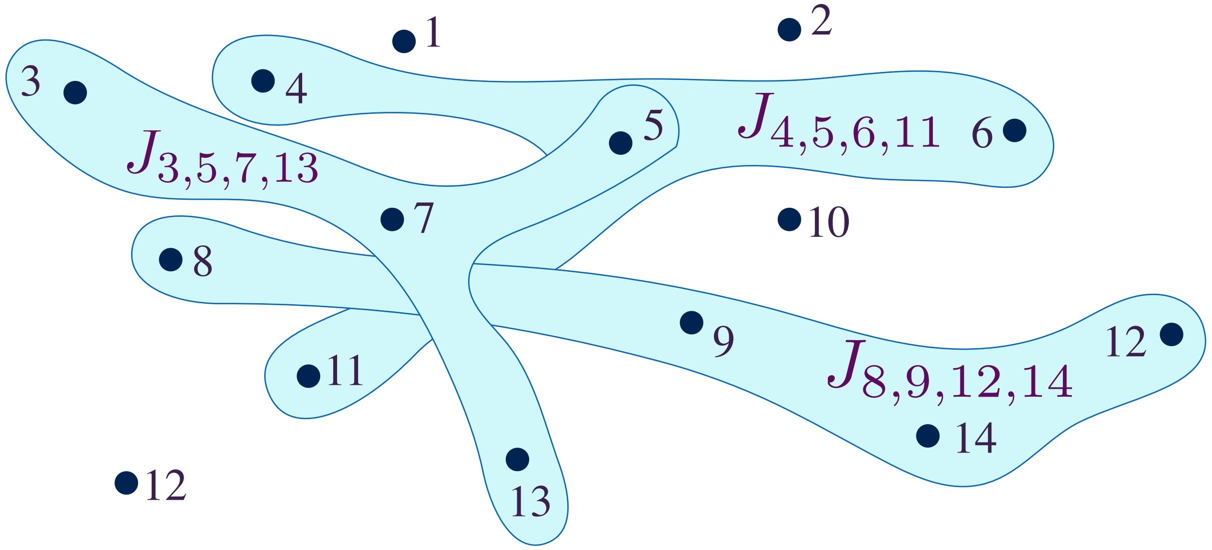


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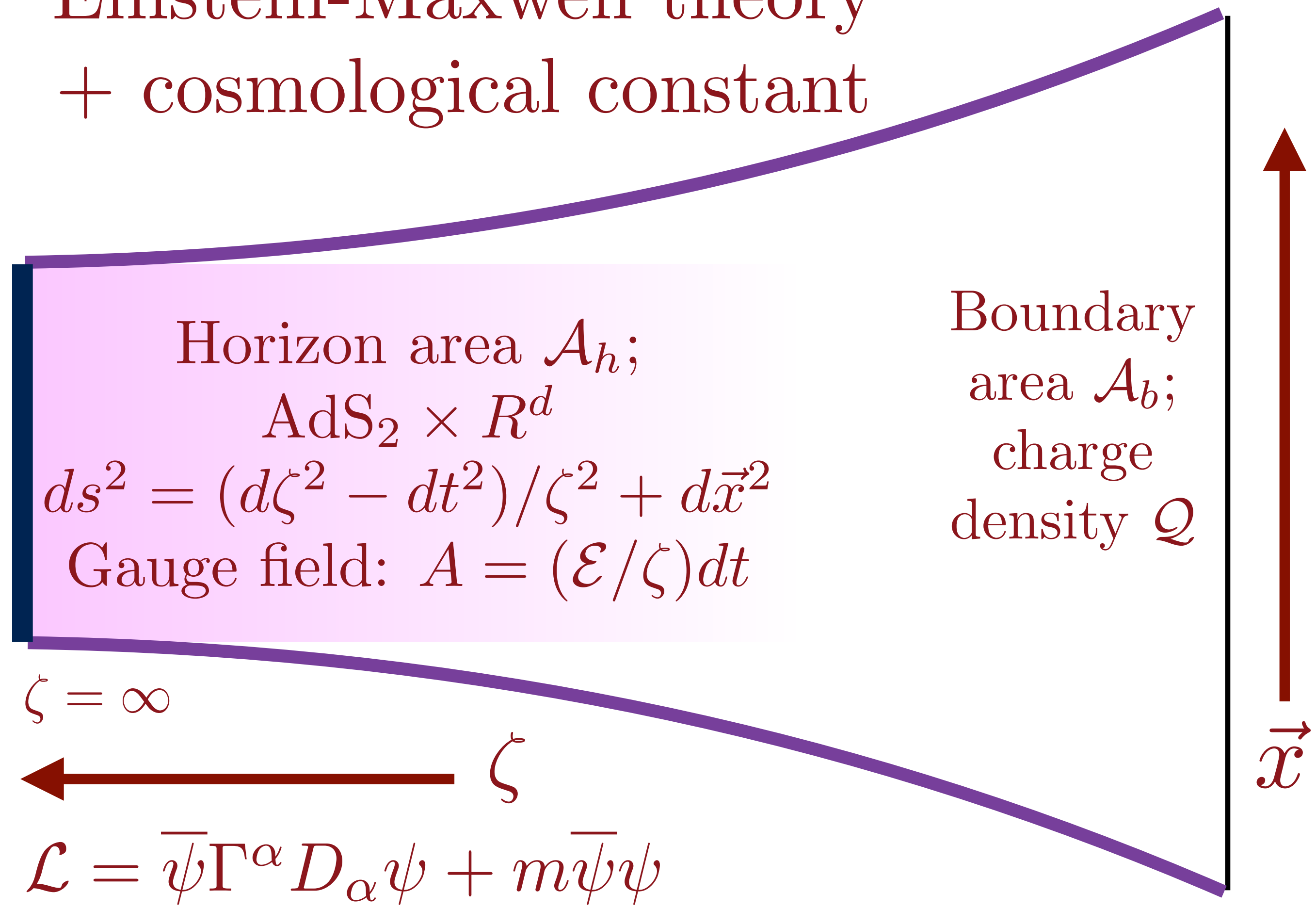


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T. Faulkner, Hong Liu, J. McGreevy, and D. Vegh
Phys. Rev. D **83**, 125002 (2011)

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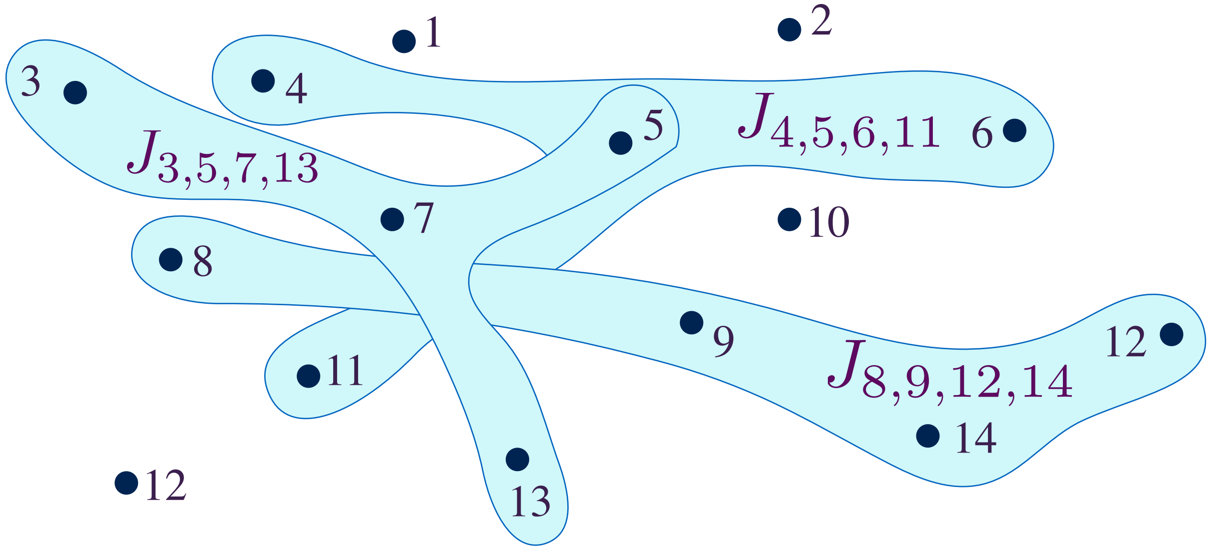


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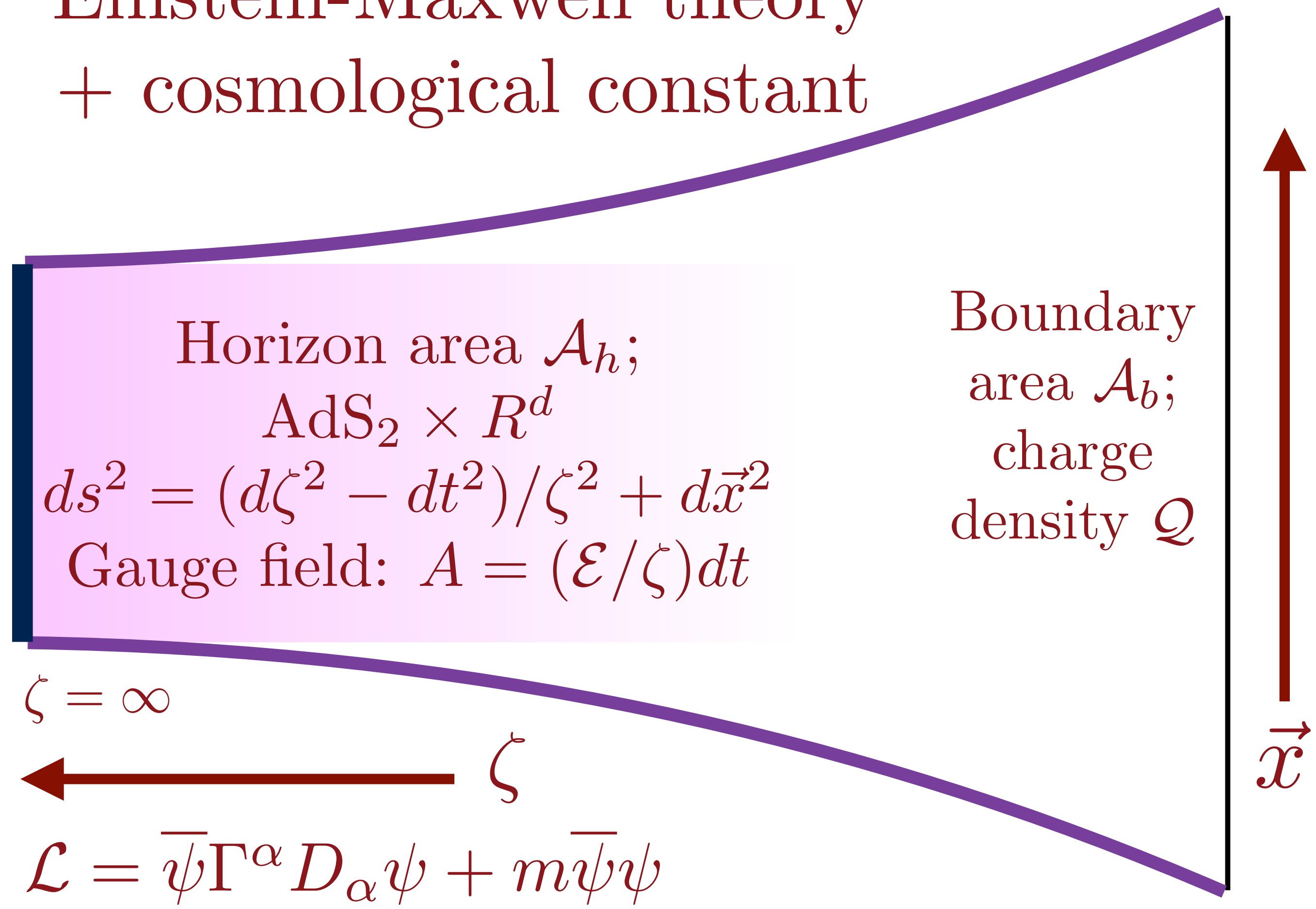


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'Equation of state' relating $\mathcal{E}$ and $\mathcal{Q}$ depends upon the geometry of spacetime far from the $AdS_2$

Eliminate $r_0$ between

$$\mathcal{Q} = \frac{r_0^{d-1}\sqrt{2d\,[(d-1)R^2 + (d+1)r_0^2]}}{\kappa^2 g_F}$$

$$\mathcal{E} = \frac{g_F r_0 \sqrt{2d\,[(d-1)R^2 + (d+1)r_0^2]}}{2\,[(d-1)^2 R^2 + d(d+1)r_0^2]}$$

S. Sachdev, arXiv:1506.05111

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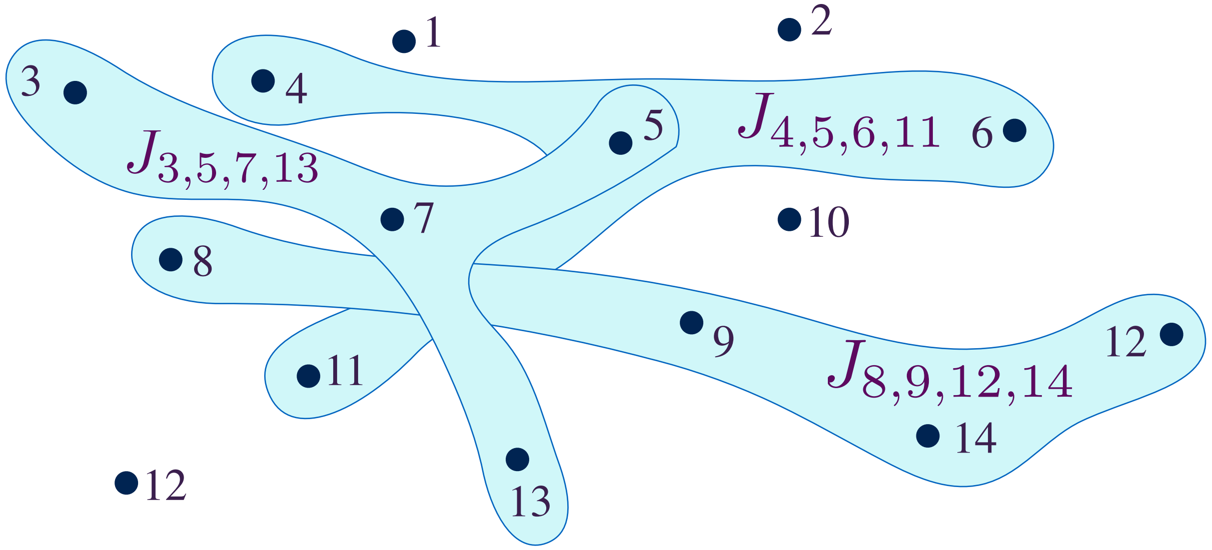


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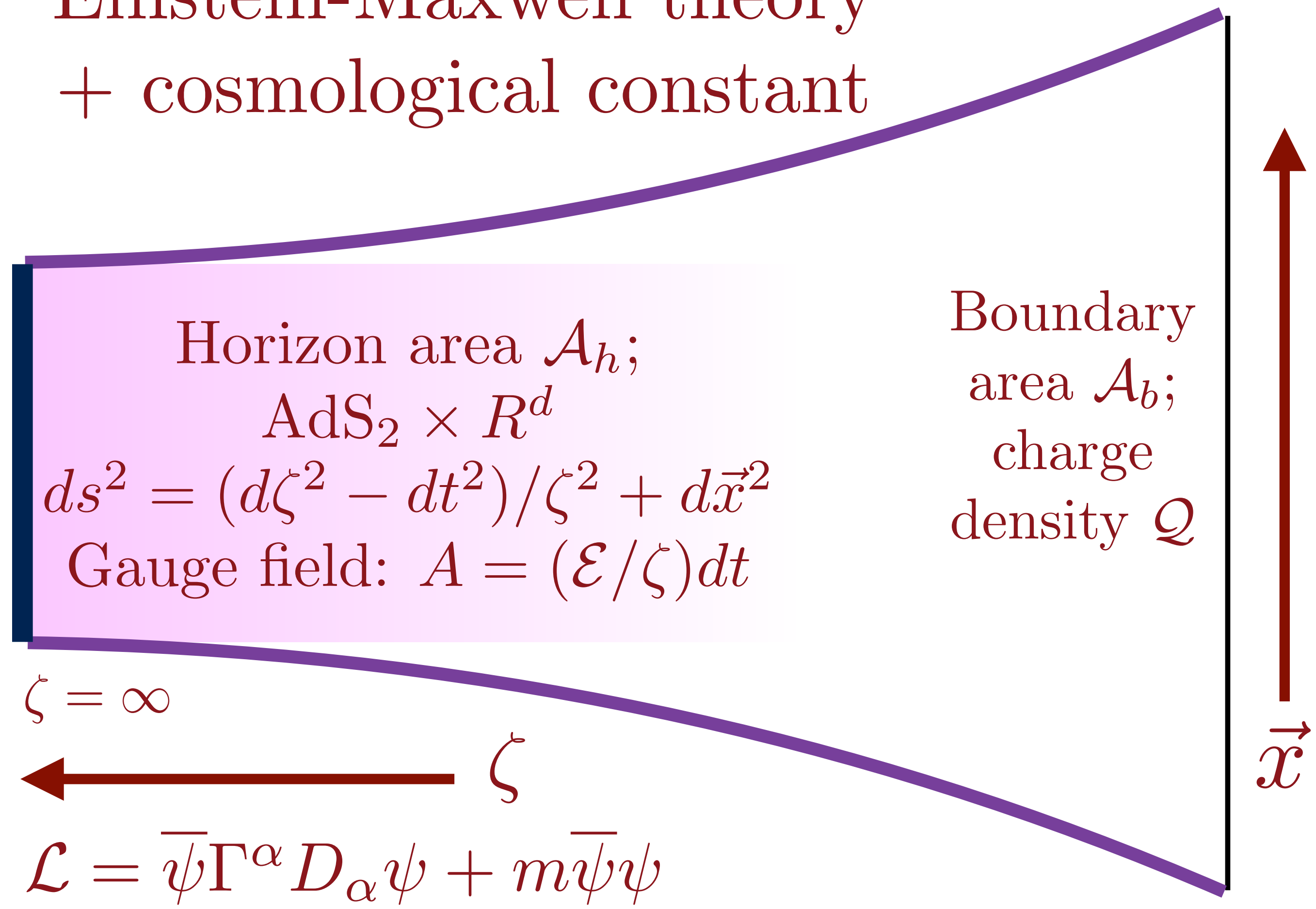


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Black hole thermodynamics (classical GR) yields

$$\frac{1}{\mathcal{A}_b} \frac{\partial \mathcal{A}_h}{\partial \mathcal{Q}} = 8\pi G_N \mathcal{E}$$

S. Sachdev, arXiv:1506.05111

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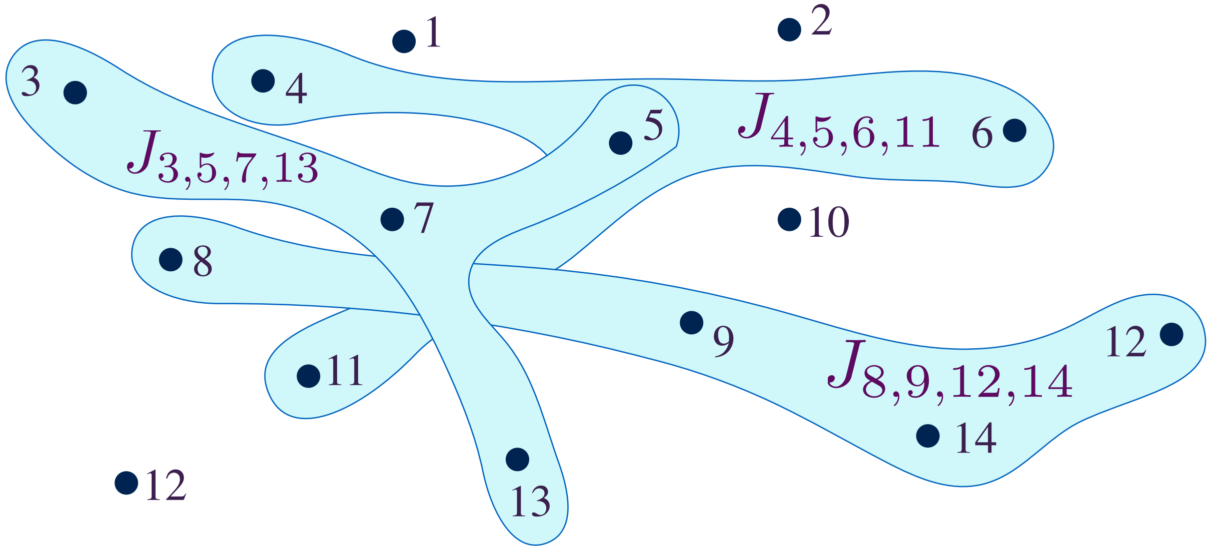


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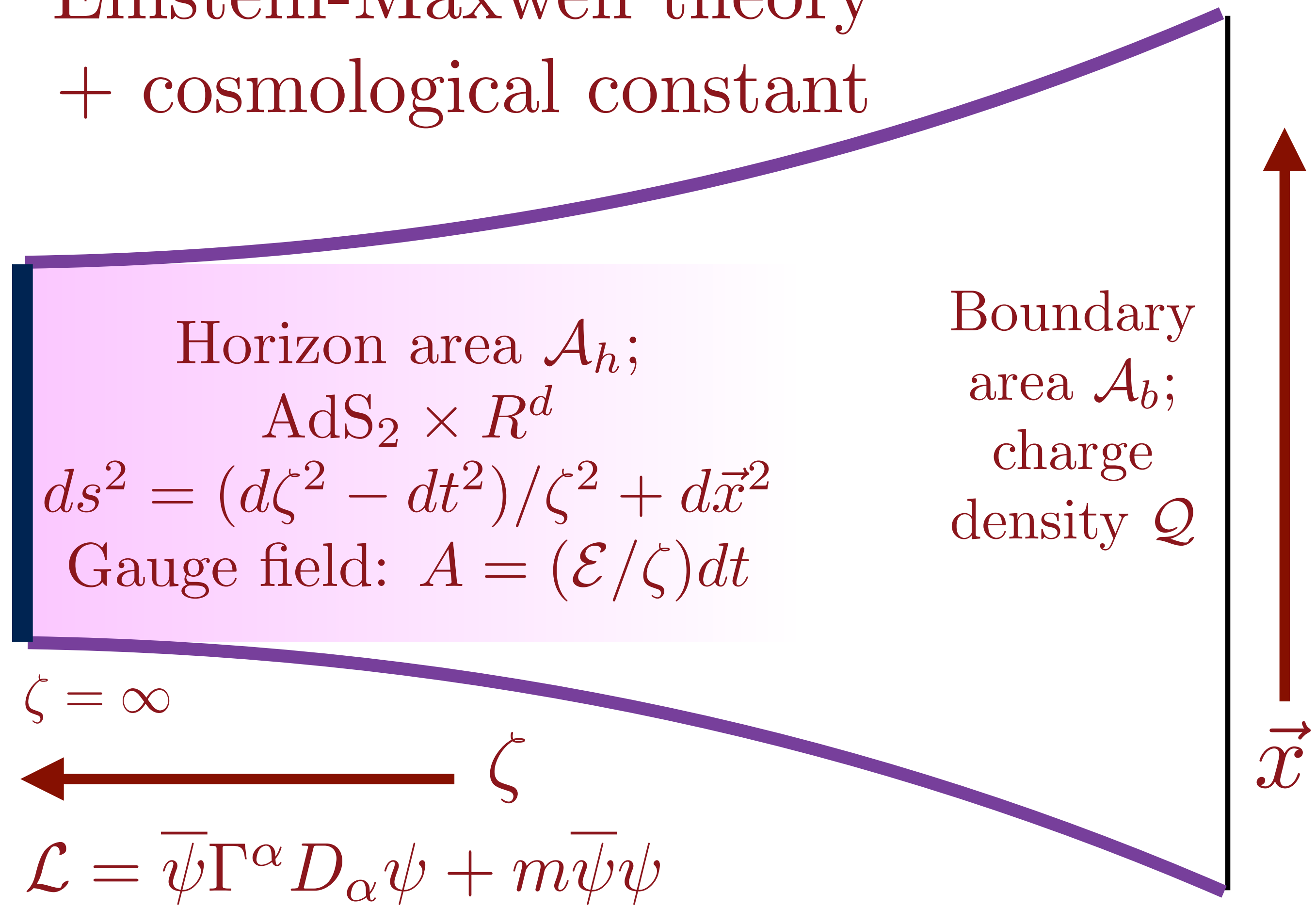


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Combination:

$$\mathcal{S} = \frac{\mathcal{A}_h}{4G_N \mathcal{A}_b}$$

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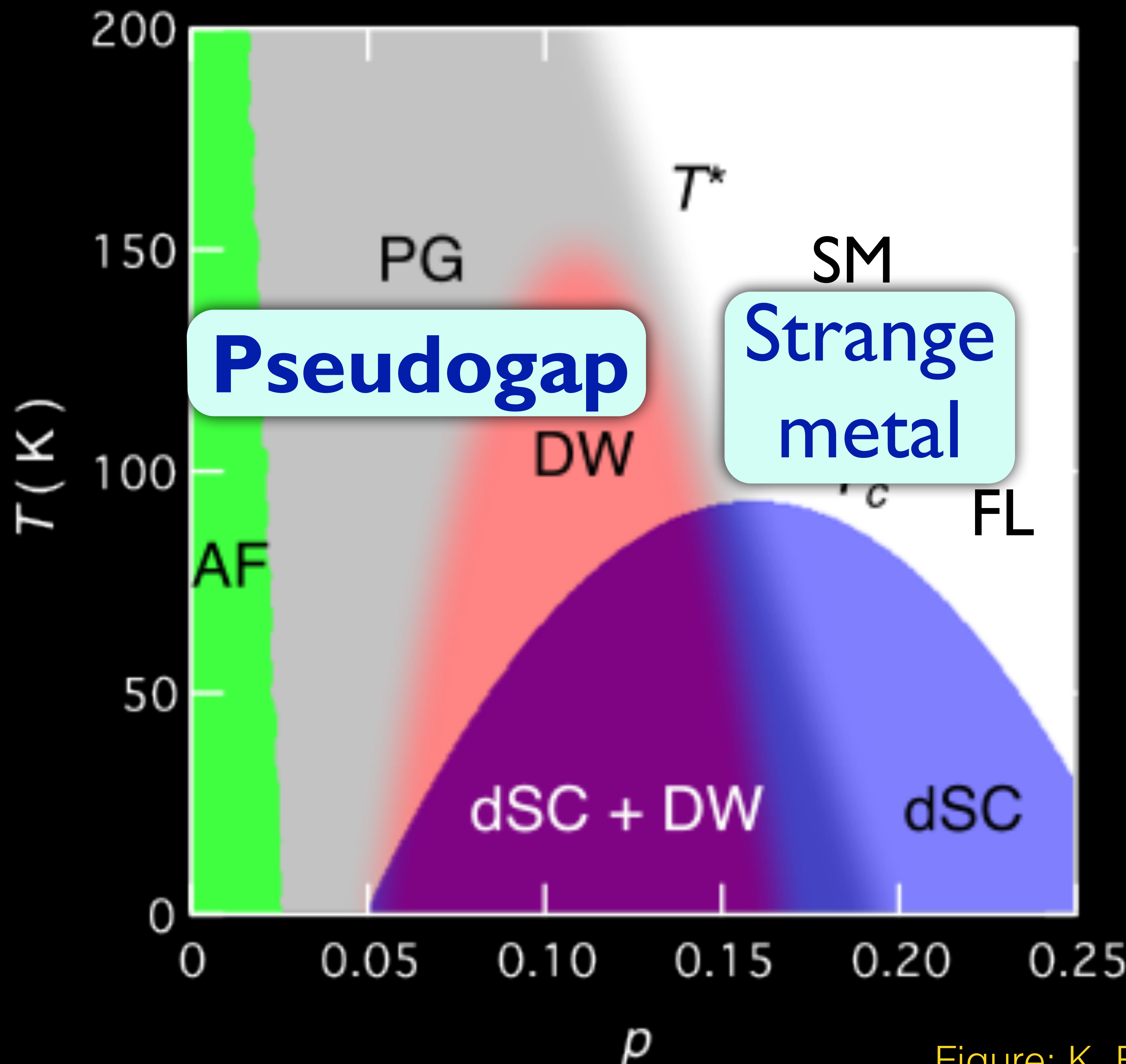


Figure: K. Fujita and J. C. Seamus Davis

1. The pseudogap metal

*Fermi liquid co-existening with topological order*

2. The strange metal

*Metal without quasiparticles*

*Infinite-range model: dual to extremal charged black holes and yields Bekenstein-Hawking entropy*