Antiferromagnetism and high temperature superconductivity

Basic Research Needs Workshop
on
Quantum Materials for Energy Relevant Technology,
Department of Energy
Gaithersburg Maryland Washingtonian Center, February 8, 2016

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

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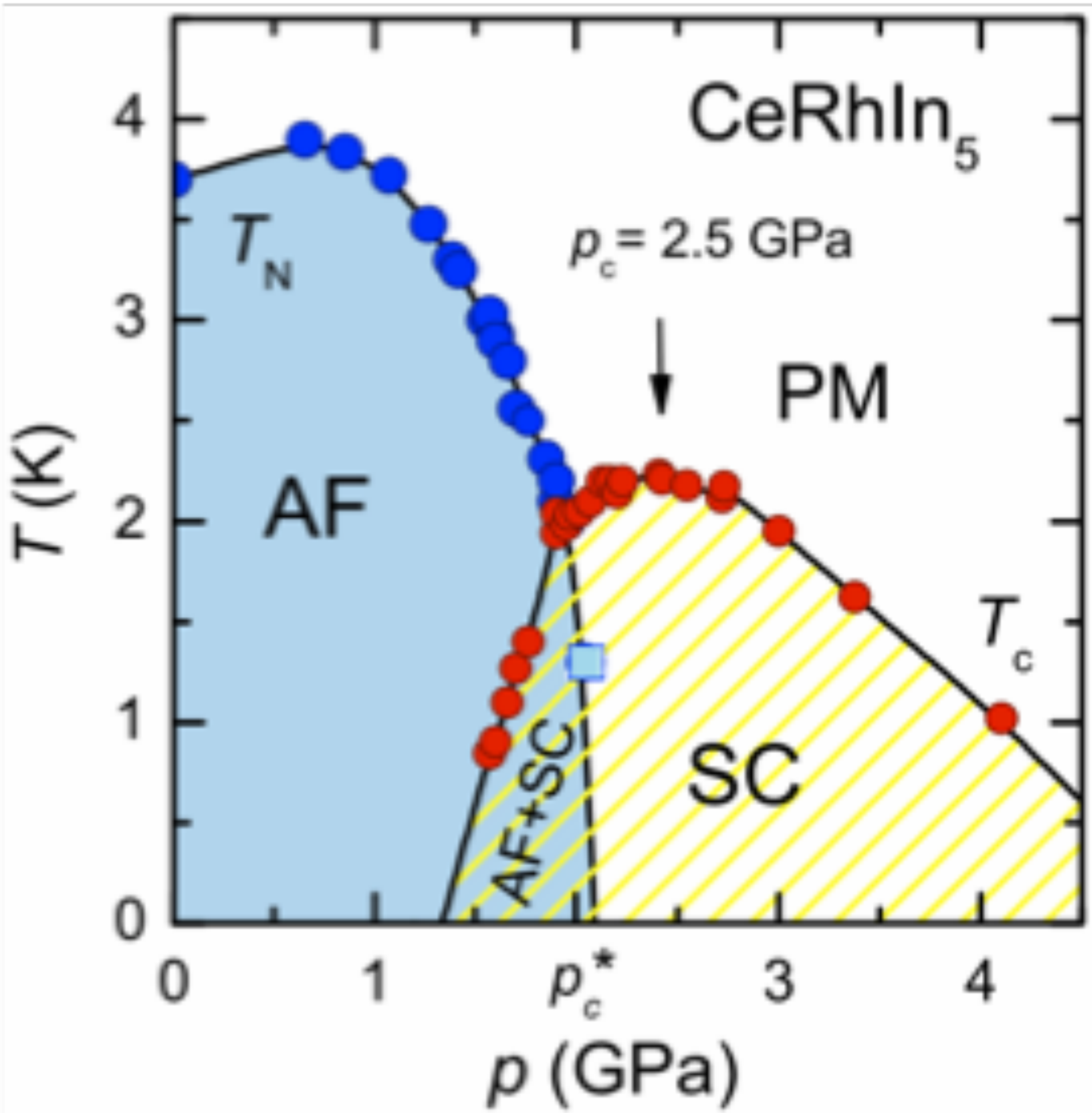
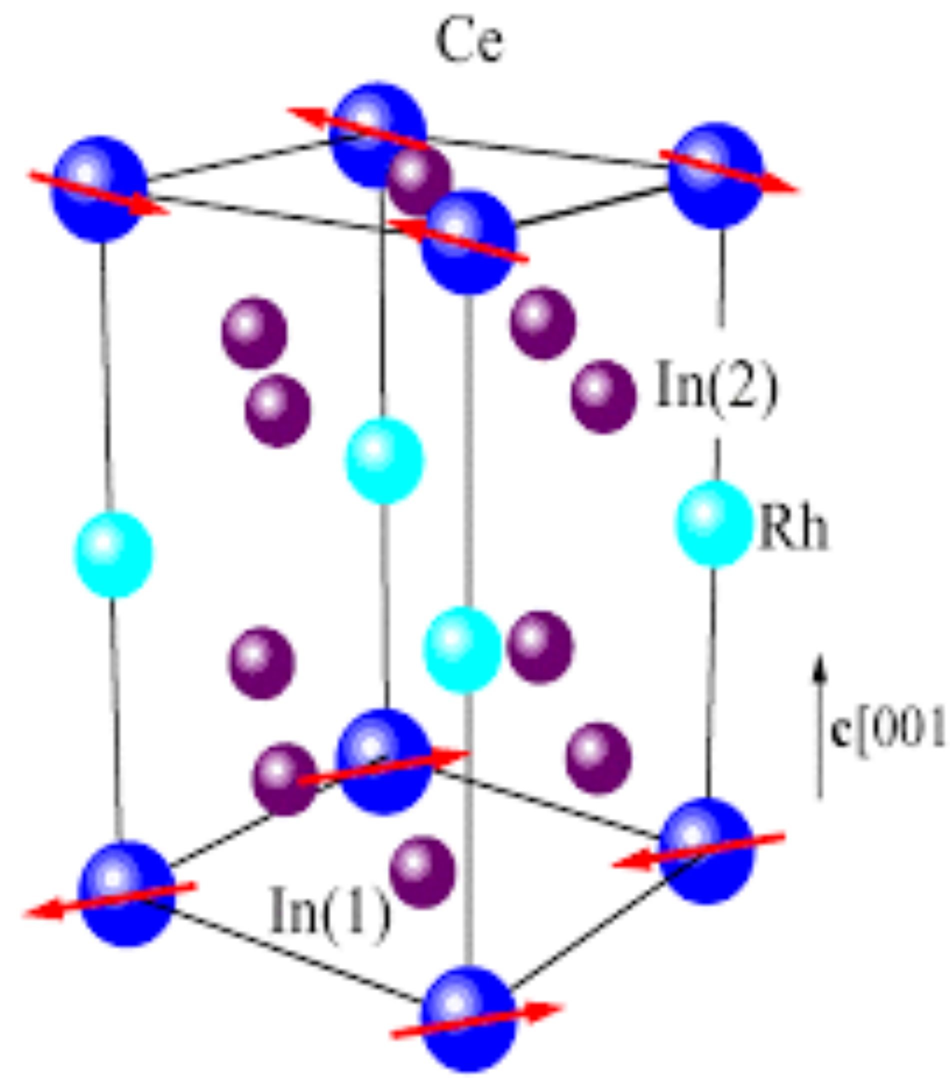
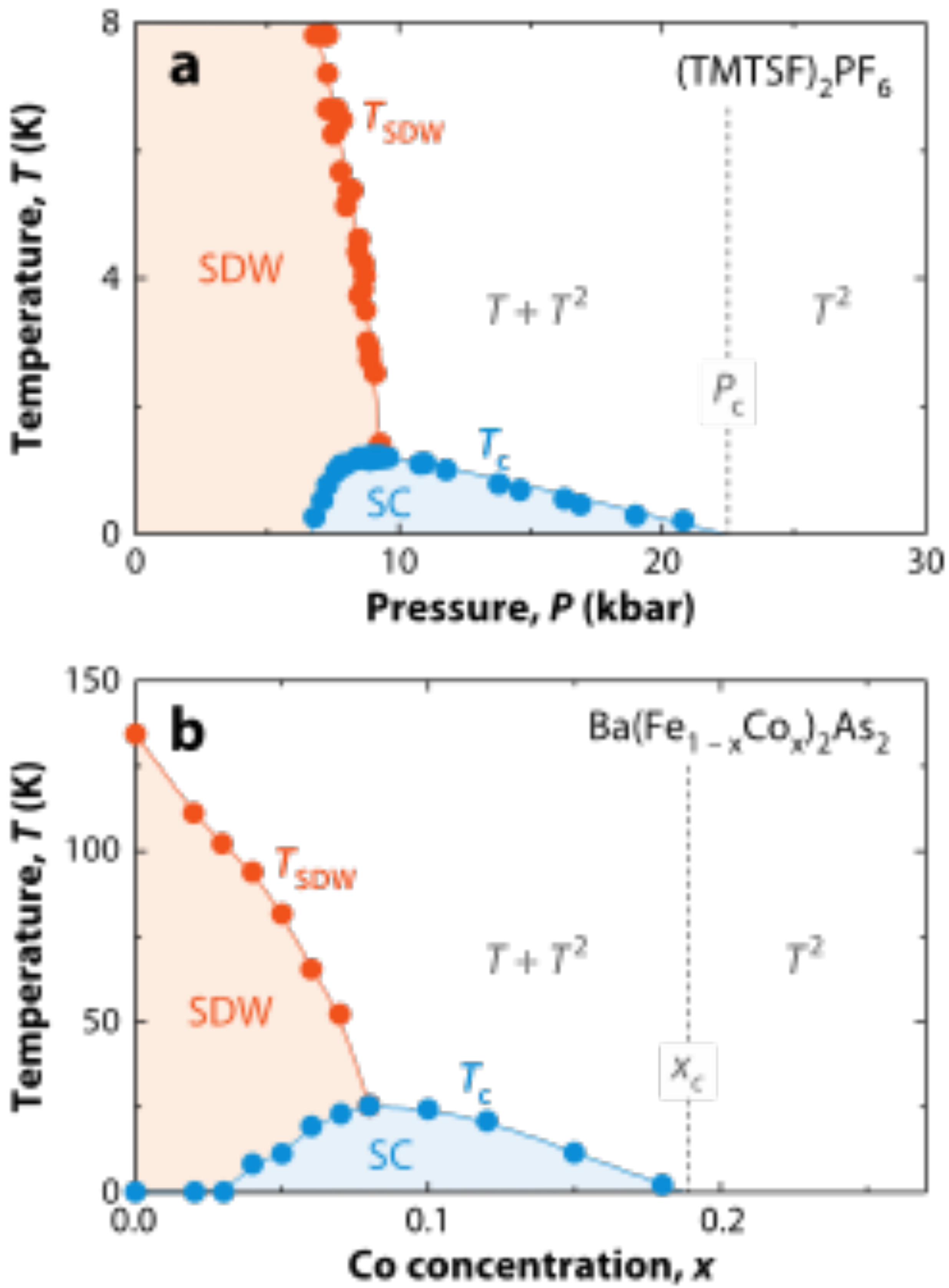
Antiferromagnetism and superconductivity



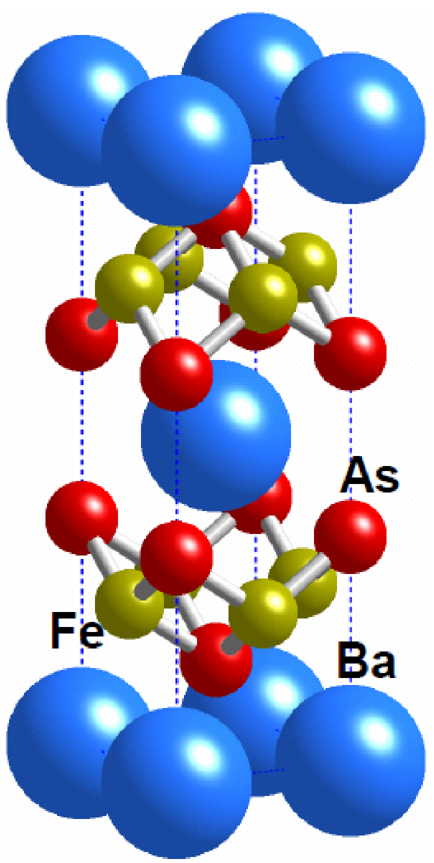


Knebel, 2010

Antiferromagnetism and superconductivity



Taillefer, ARCMP 2010

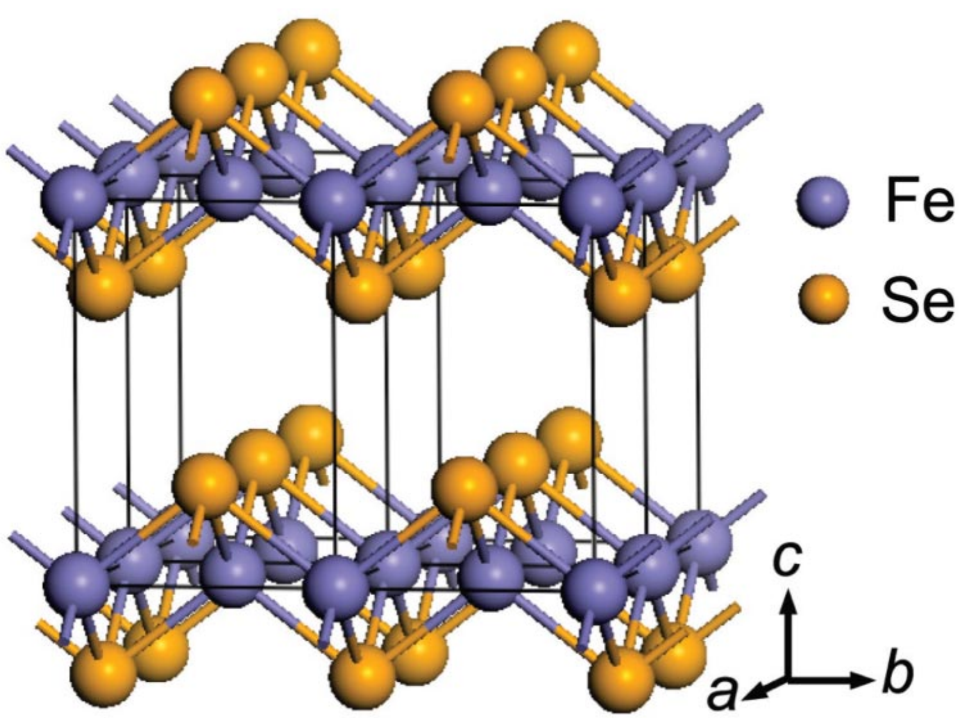


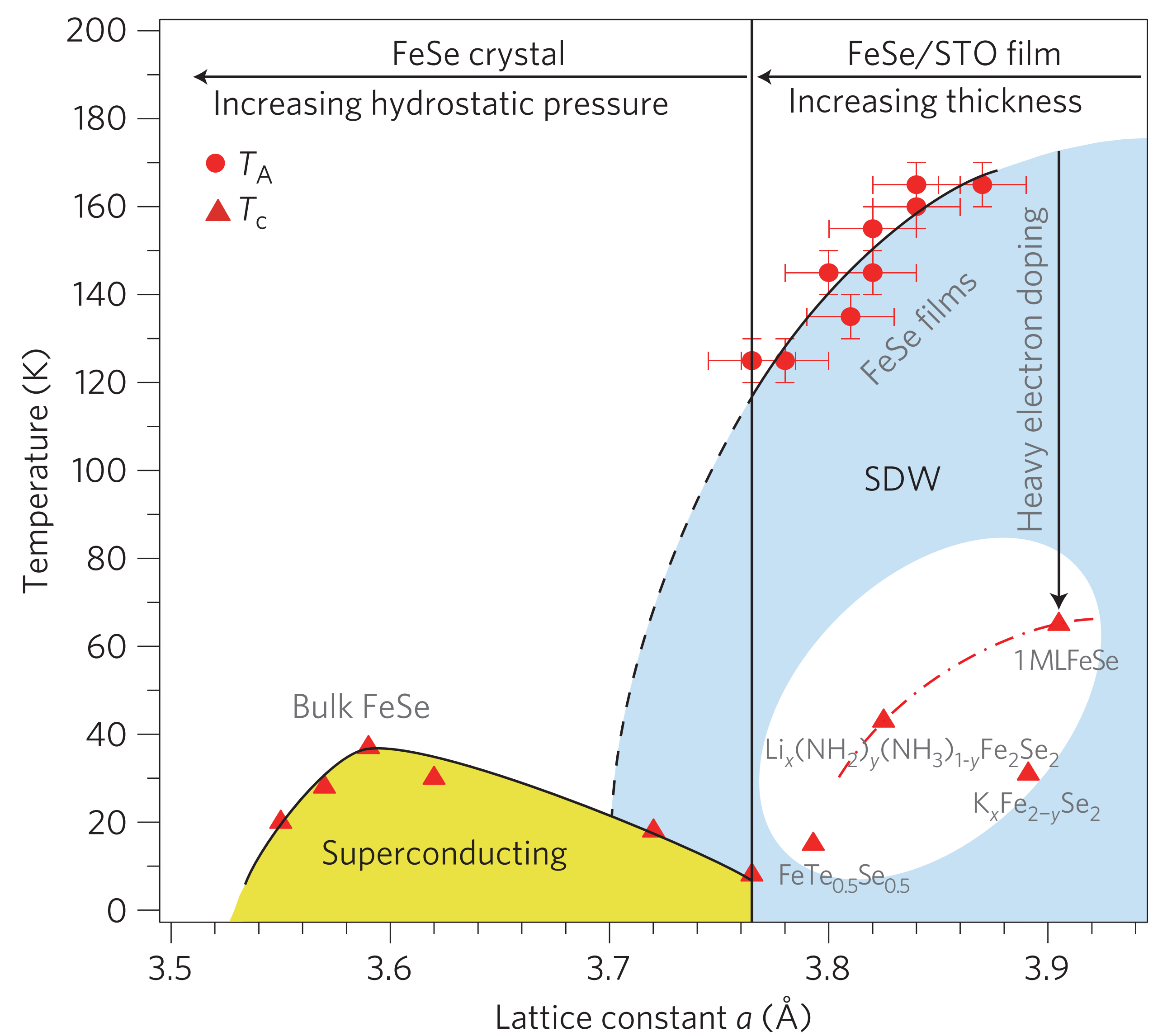
Antiferromagnetism and superconductivity

Superconductivity above 100 K in single-layer FeSe films on doped $SrTiO_3$

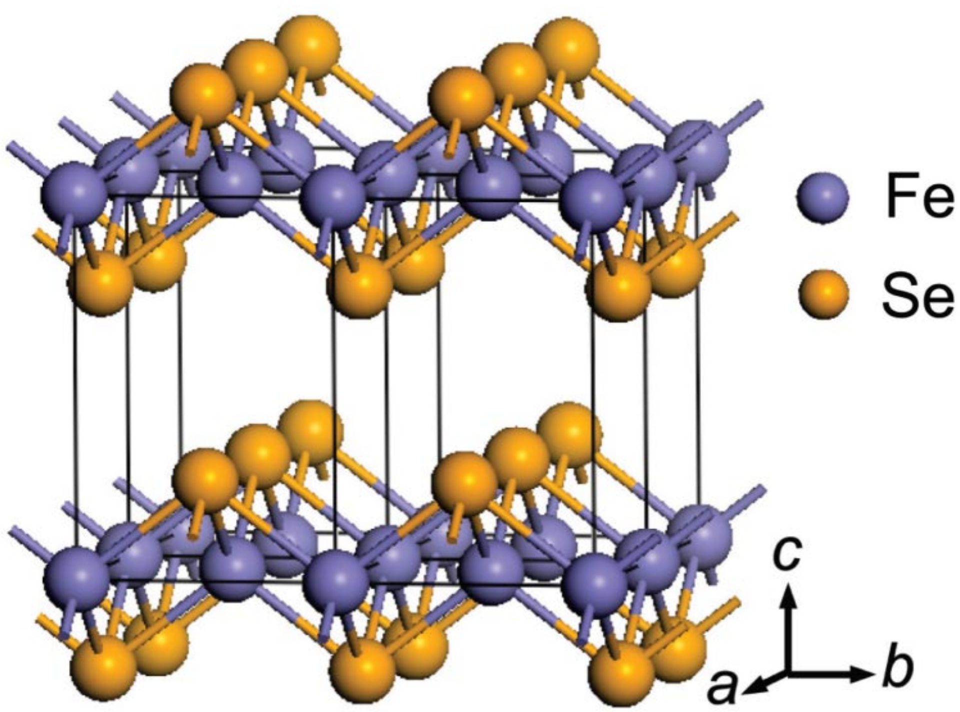
Jian-Feng Ge[1], Zhi-Long Liu[1], Canhua Liu[1,2★], Chun-Lei Gao[1,2], Dong Qian[1,2], Qi-Kun Xue[3★], Ying Liu[1,2,4] and Jin-Feng Jia[1,2★]

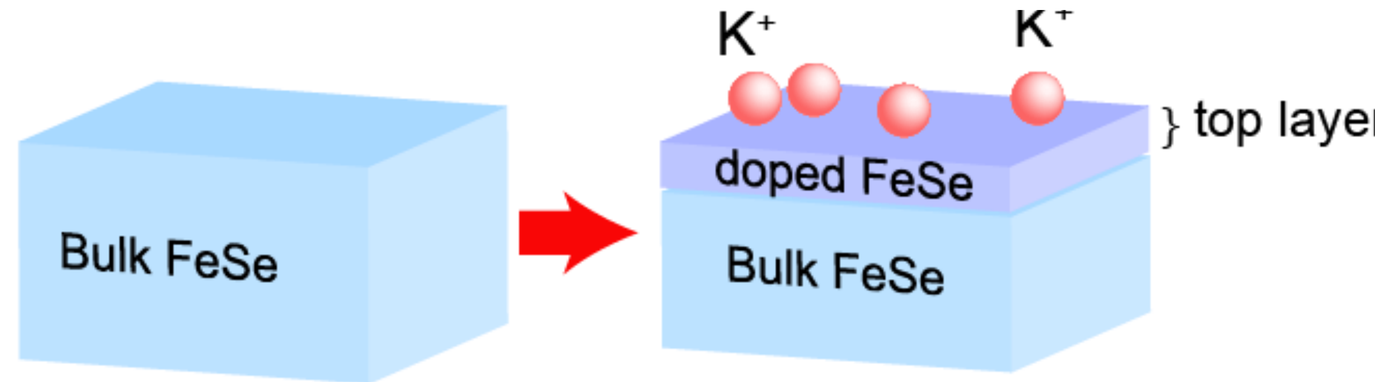
NATURE MATERIALS | VOL 14 | MARCH 2015

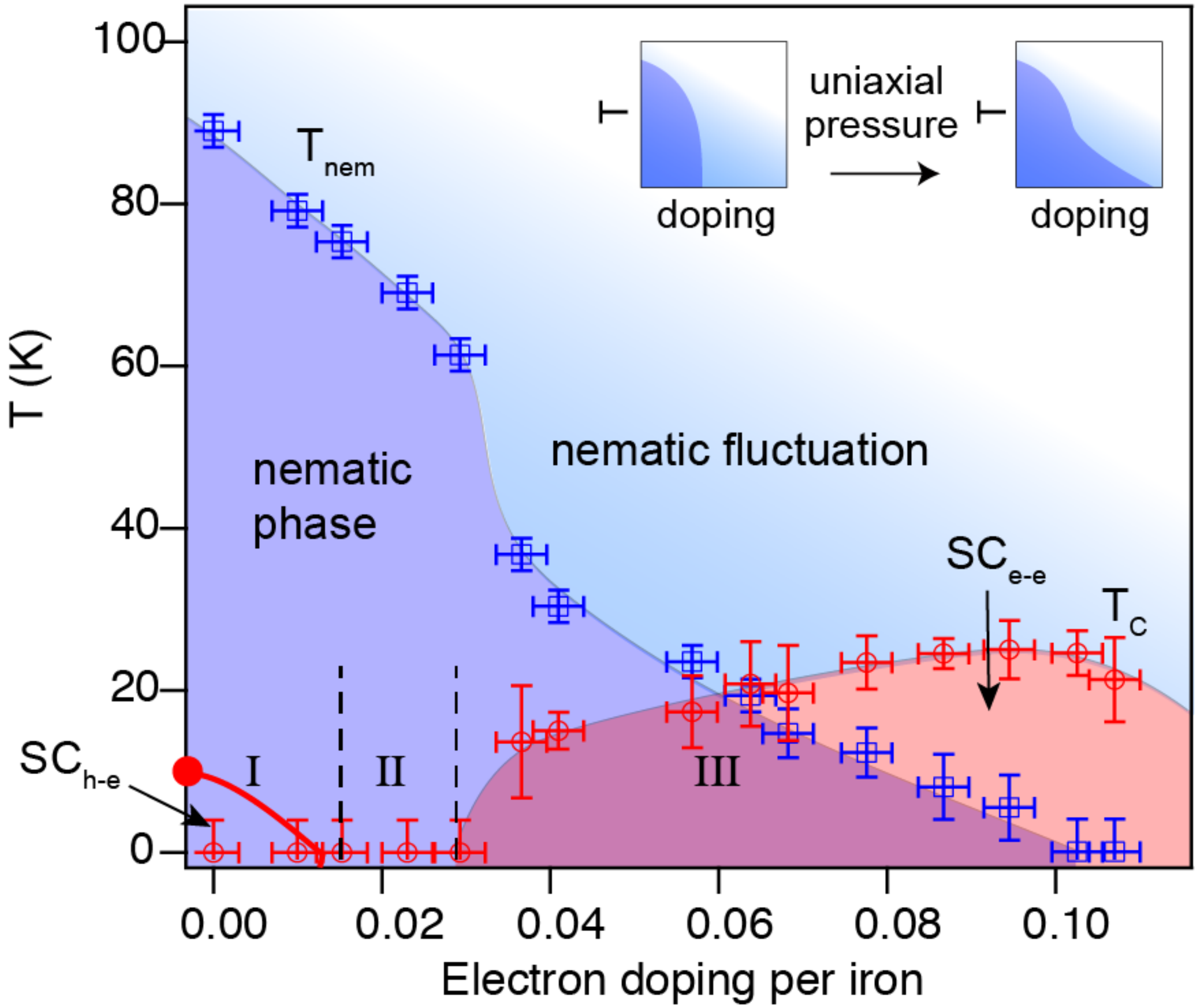




Tan et al, Nature Materials, 2013



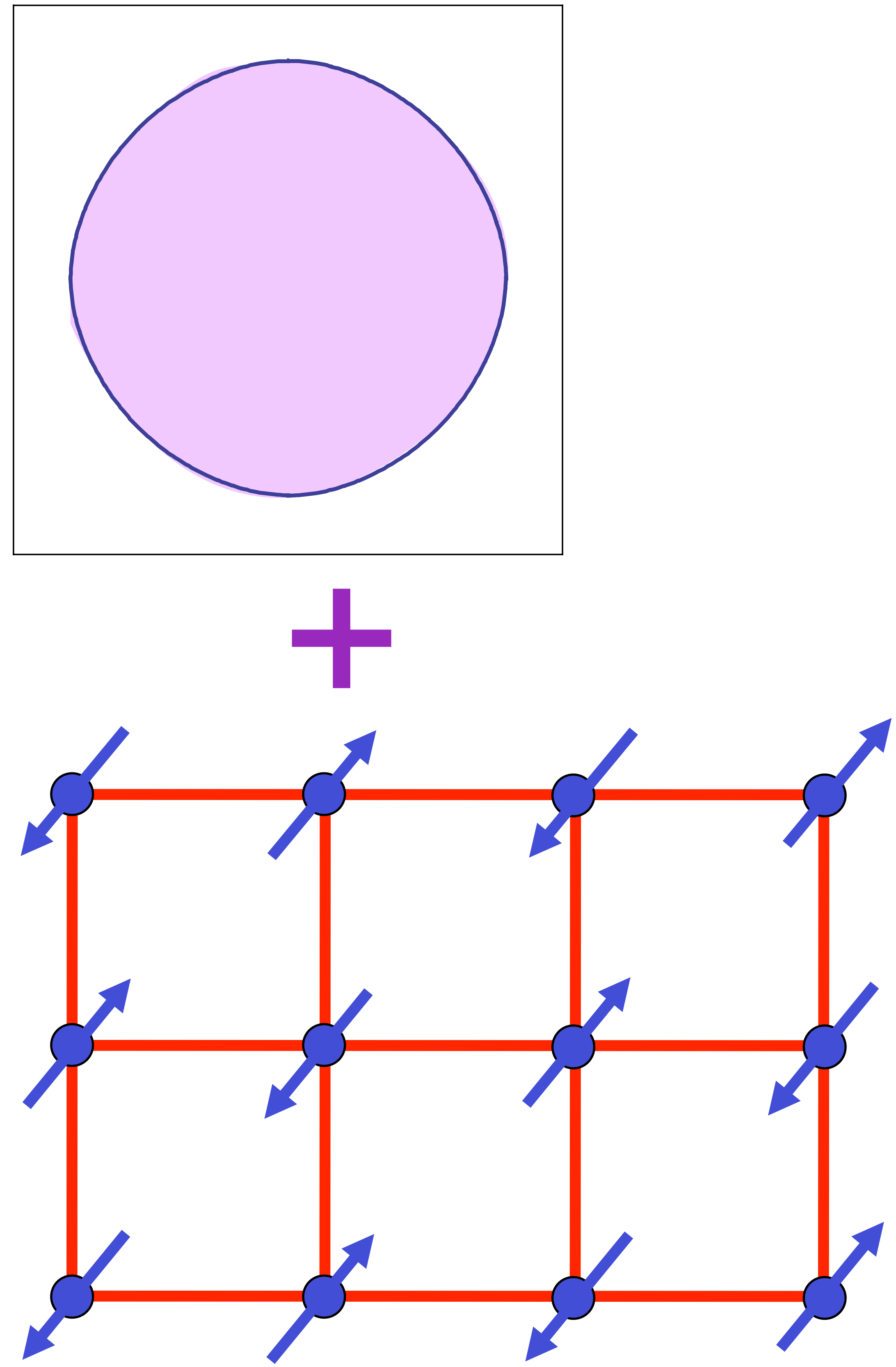




Z. R. Ye, C. F. Zhang, H. L. Ning, W. Li, L. Chen, T. Jia, M. Hashimoto,
D. H. Lu, Z.-X. Shen, and Y. Zhang, arXiv:1512.02526

Fermi surface+antiferromagnetism

Metal with "large" Fermi surface

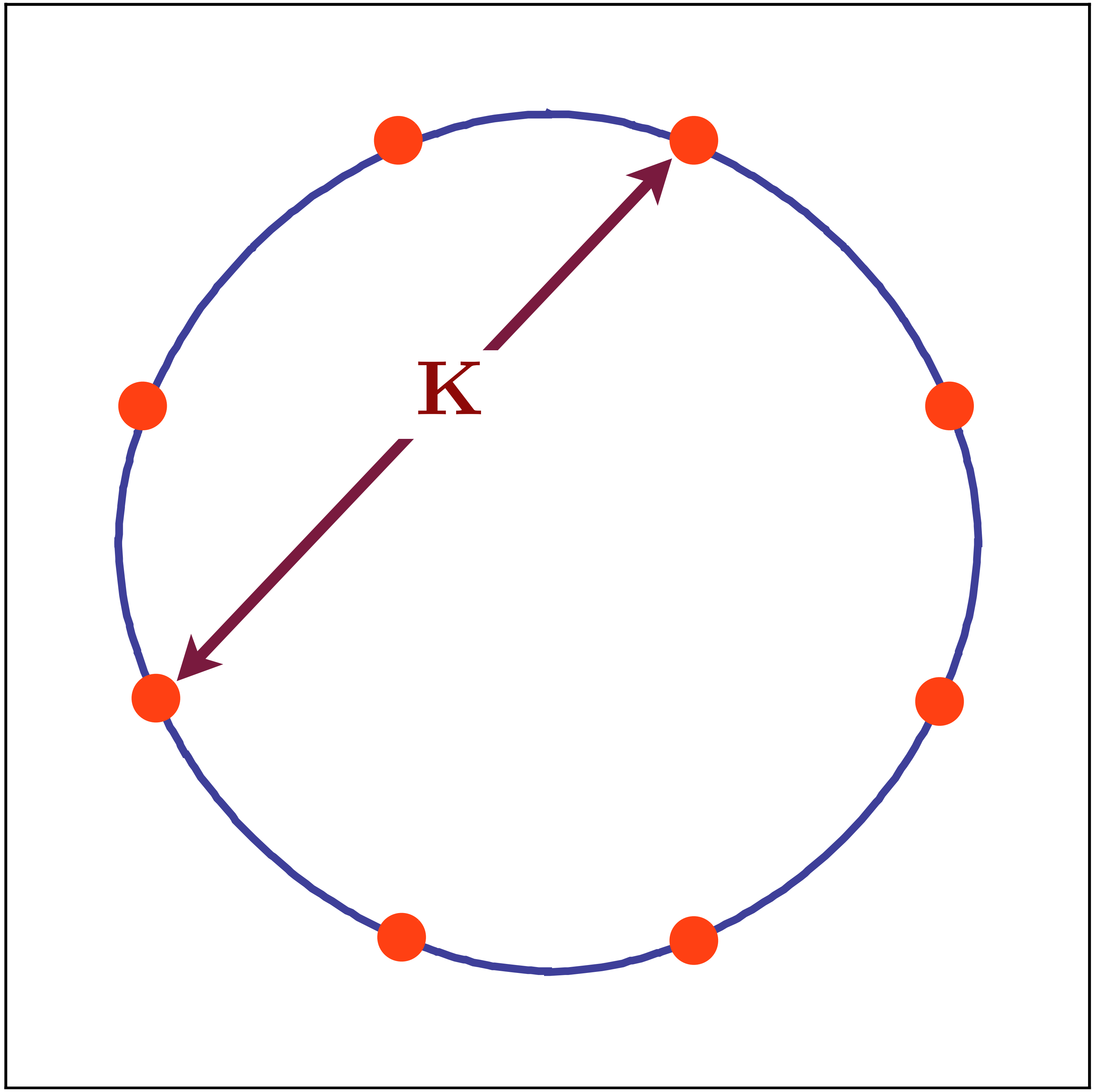


The electron spin polarization obeys

$$\left\langle \vec{S}(\mathbf{r},\tau) \right\rangle = \vec{\varphi}(\mathbf{r},\tau) e^{i\mathbf{K}\cdot\mathbf{r}}$$

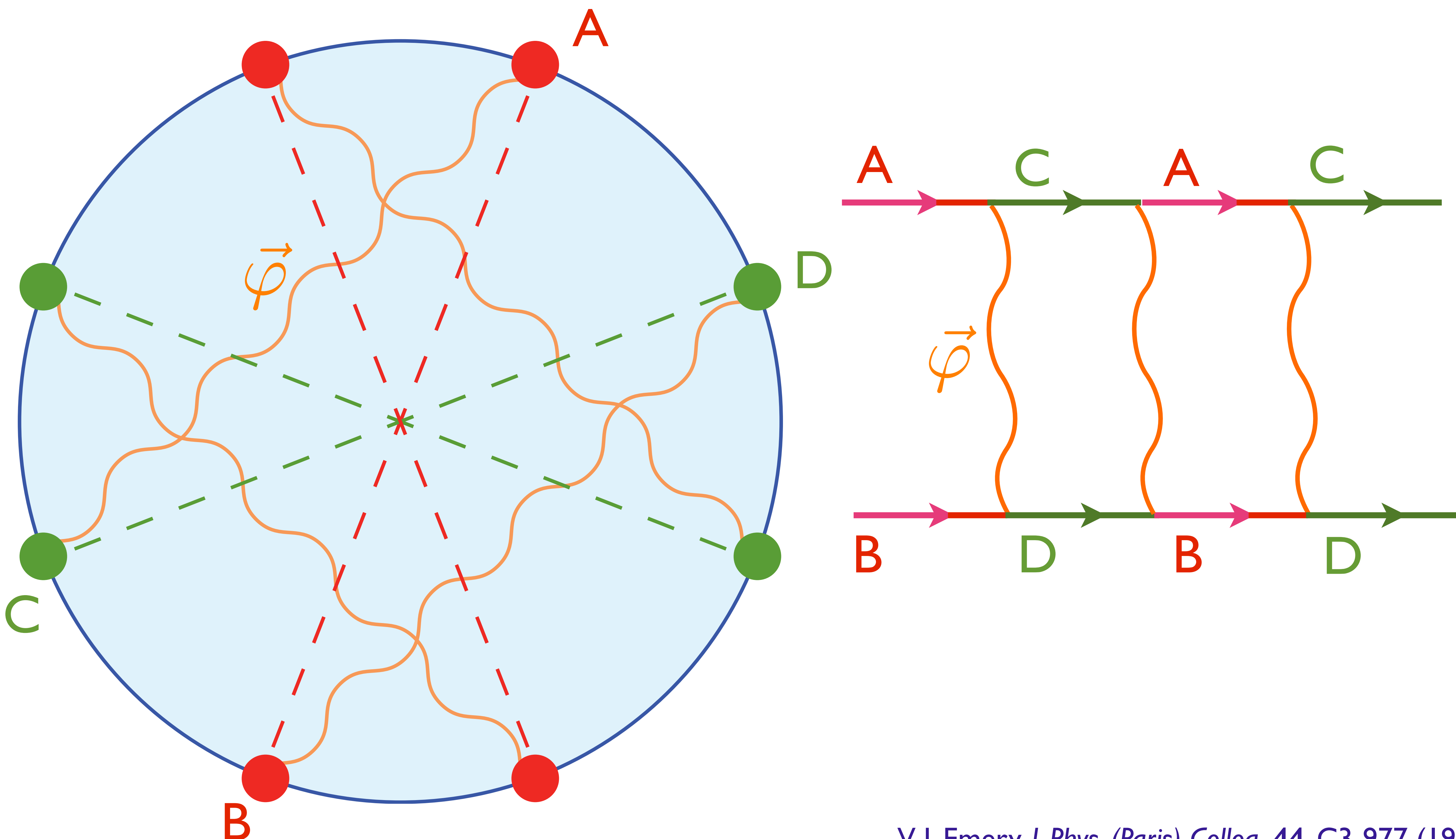
where $\mathbf{K}$ is the ordering wavevector.

Fermi surface+antiferromagnetism



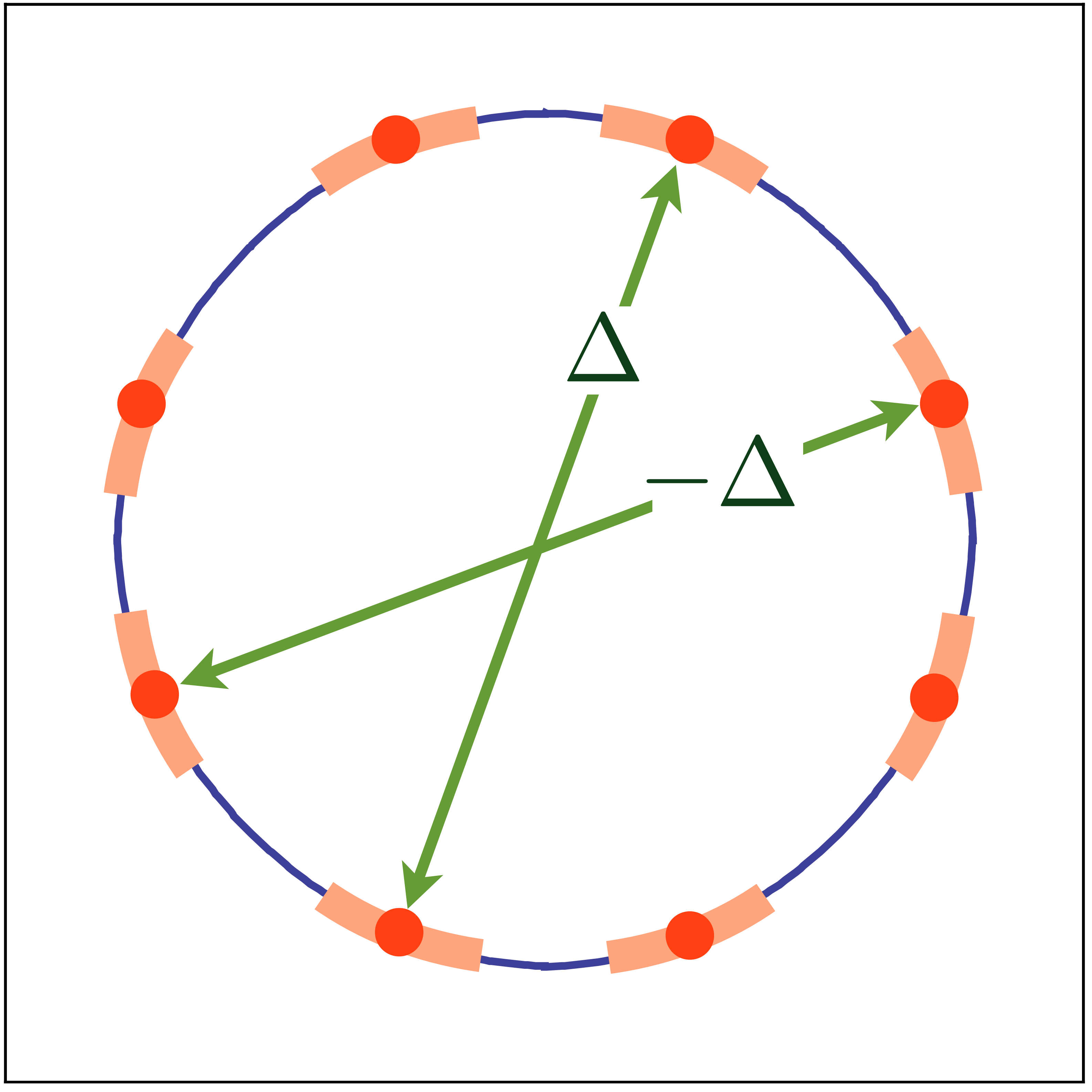
Hot spots in a single band model

Pairing "glue" from antiferromagnetic fluctuations



V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
D.J. Scalapino, E. Loh, and J.E. Hirsch, *Phys. Rev. B* **34**, 8190 (1986)
K. Miyake, S. Schmitt-Rink, and C. M.Varma, *Phys. Rev. B* **34**, 6554 (1986)
S. Raghu, S.A. Kivelson, and D.J. Scalapino, *Phys. Rev. B* **81**, 224505 (2010)

$$\left\langle c_{\mathbf{k}\alpha}^{\dagger} c_{-\mathbf{k}\beta}^{\dagger} \right\rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$$



Unconventional pairing at *and near* hot spots

The theory for the onset of antiferromagnetism in a metal flows to strong coupling in d=2

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- Pairing glue becomes stronger.

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- Other instabilities can appear: to charge and bond density waves, to nematic order, and to "topological" order and emergent gauge fields

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1. Sign-problem-free quantum Monte Carlo for the onset of anti ferromagnetism in metals.

2. Mott insulators: "intertwined orders", long-range entanglement, and emergent gauge fields

3. Quantum matter without quasiparticles:

   strange metals in superconductors and graphene,
   the quark-gluon plasma, and
   the superfluid-insulator transition of ultra-cold atoms, and
   the dynamics of charged black holes horizons

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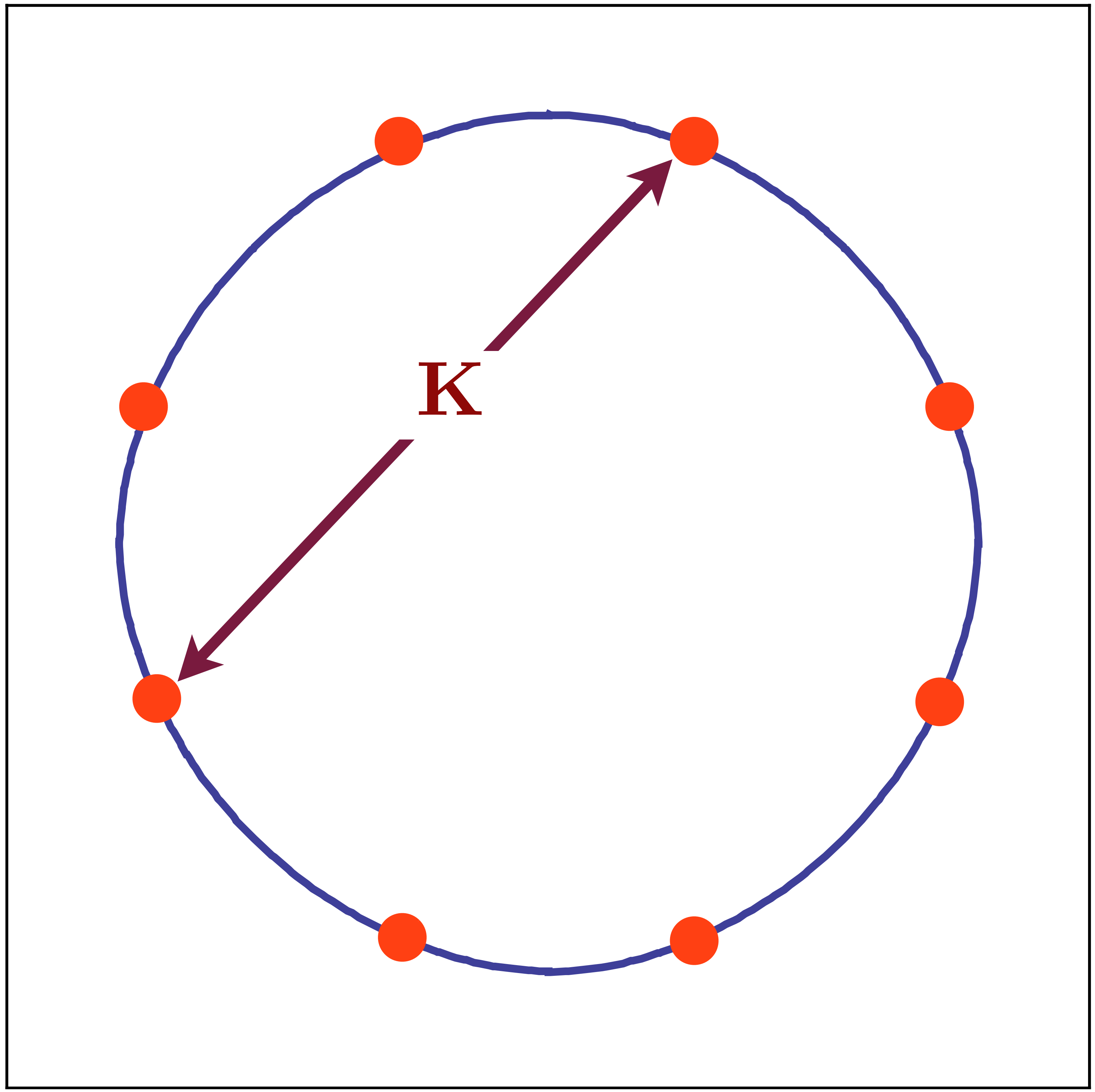
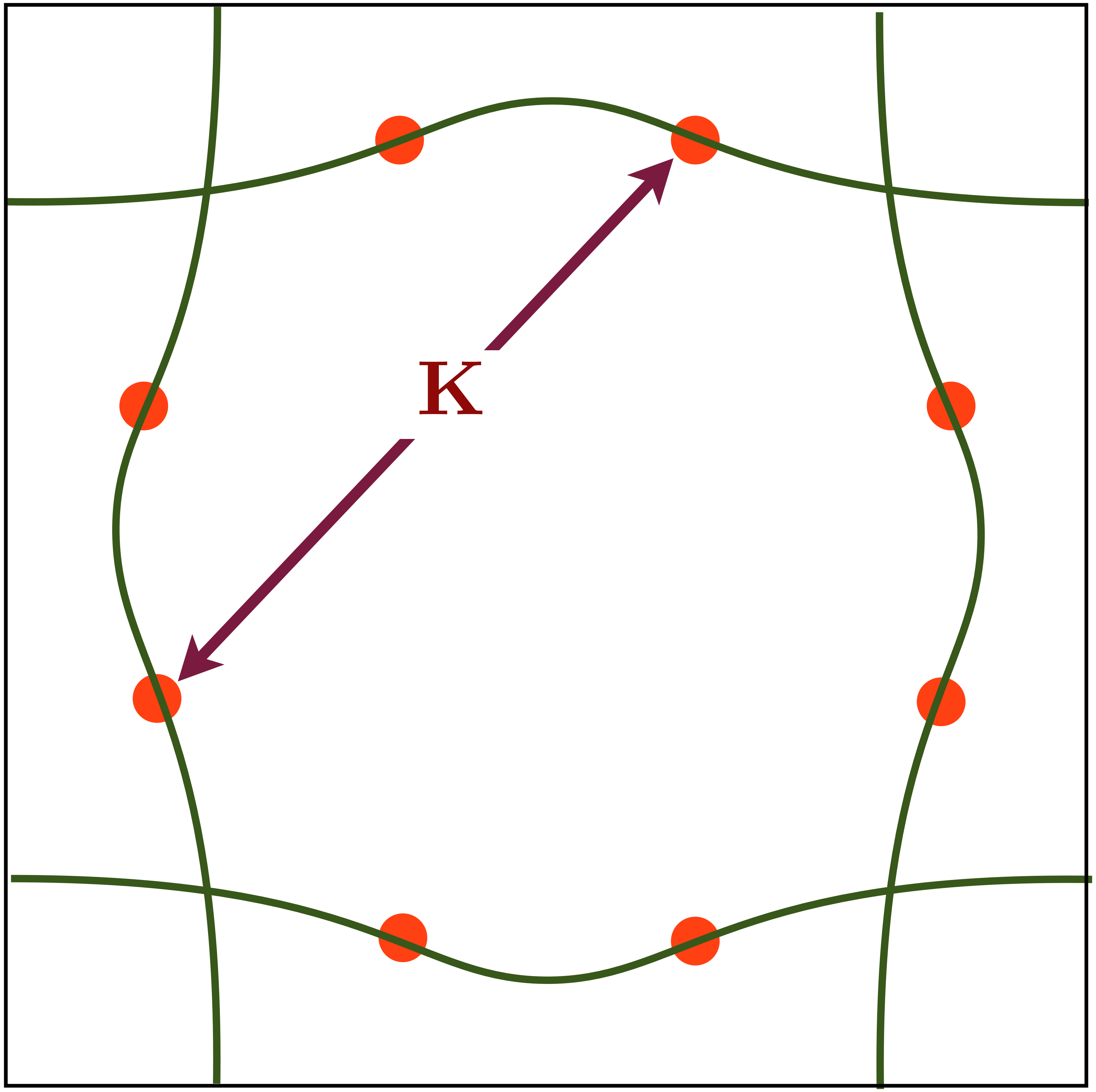


Hot spots in a single band model

QMC for the onset of antiferromagnetism

Faithful realization of the *generic* universal low energy theory for the onset of antiferromagnetism.

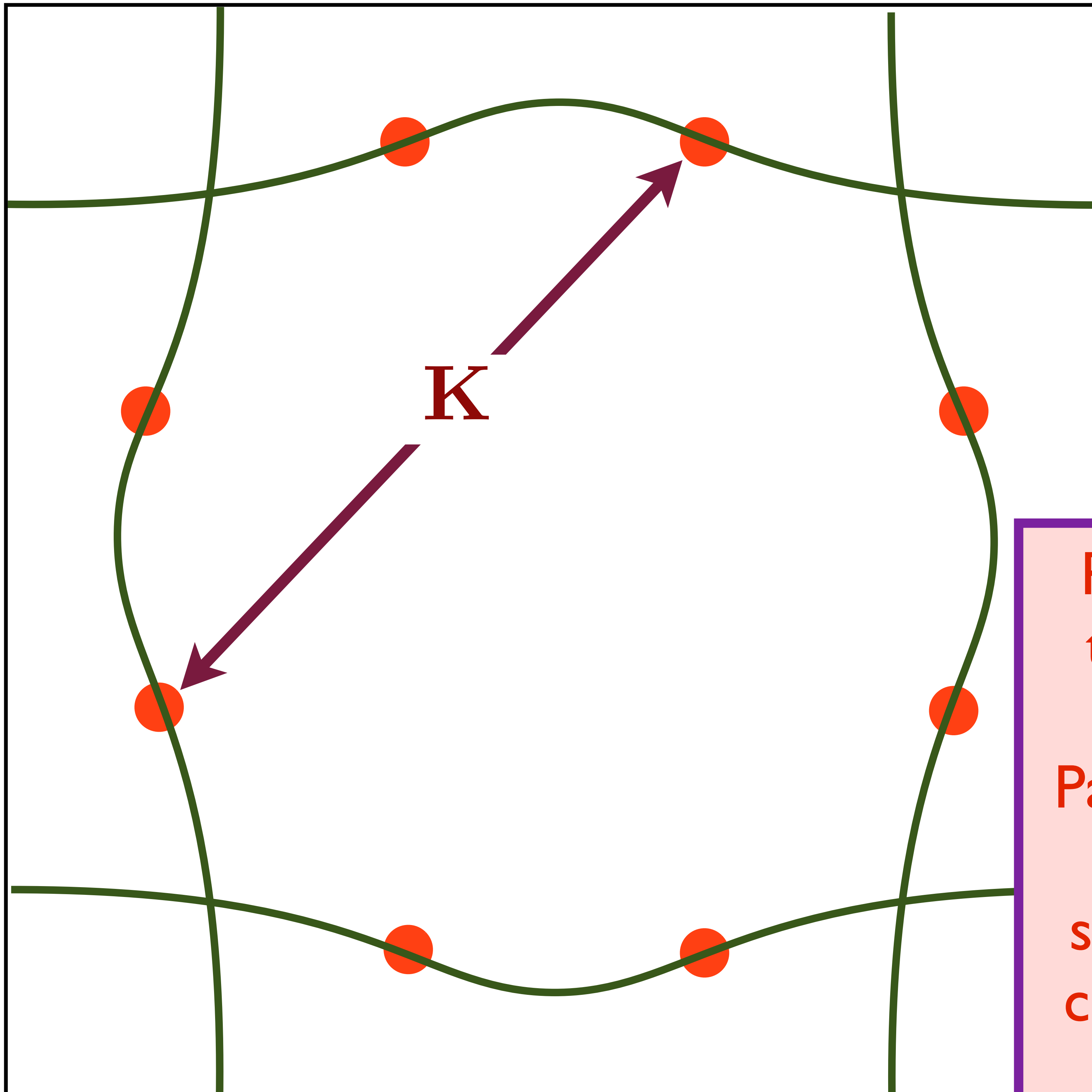


Hot spots in a two band model

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

QMC for the onset of antiferromagnetism

Sign problem is absent as long as *K* connects hotspots in distinct bands

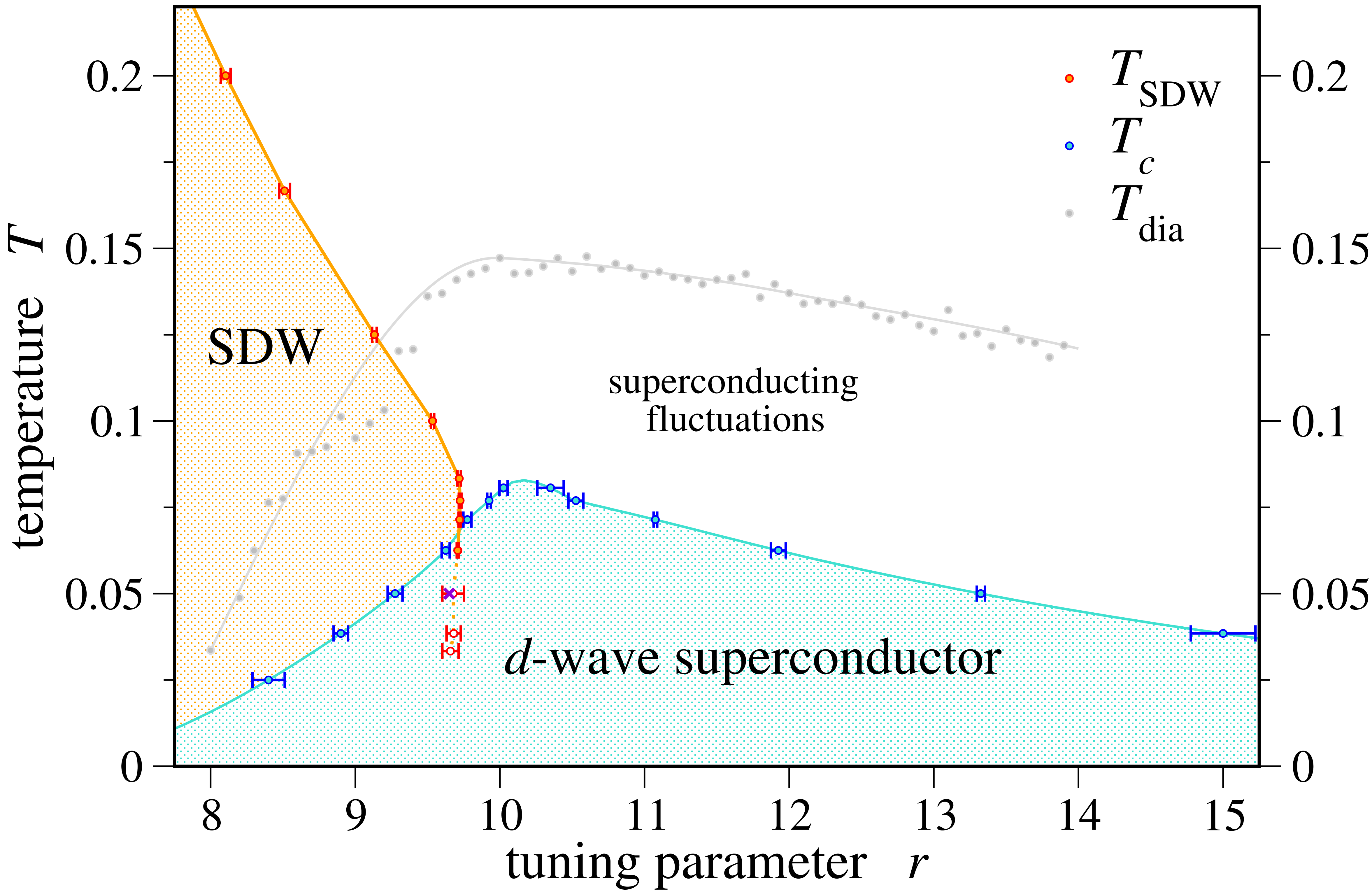


Hot spots in a two band model

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Requires only time-reversal symmetry. Particle-hole or point-group symmetries or commensurate densities ***not*** required !

QMC for the onset of antiferromagnetism

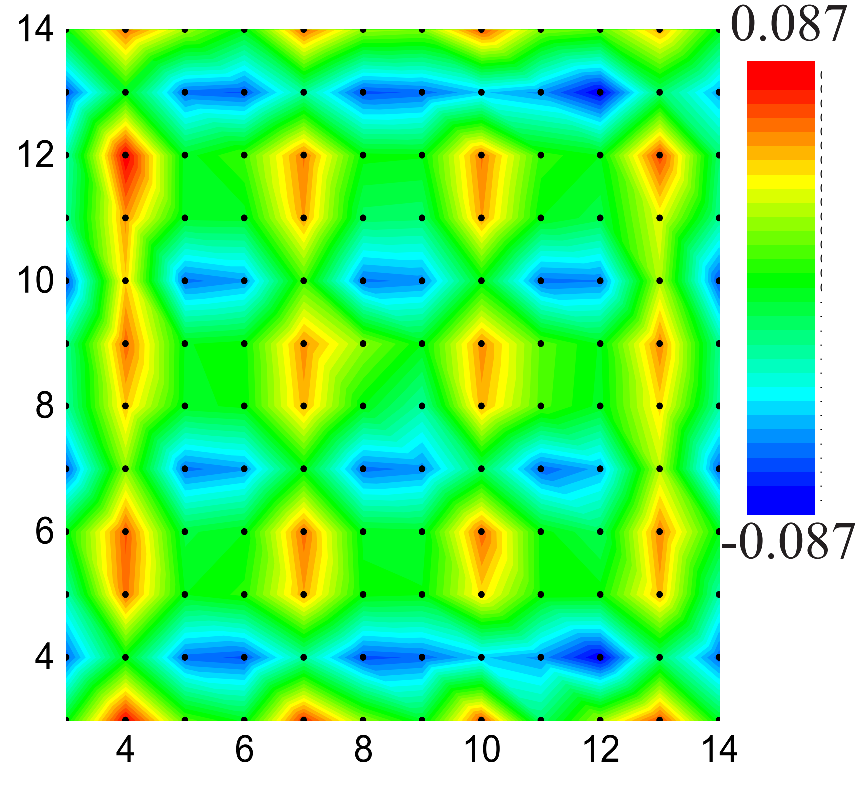


Yoni Schattner, Max H. Gerlach, Simon Trebst, and Erez Berg, arXiv:1512.07257

The nature of effective interaction in cuprate superconductors: a sign-problem-free quantum Monte-Carlo study

Zi-Xiang Li, Fa Wang, Hong Yao, and Dung-Hai Lee, arXiv:1512.04541

Here we perform large-scale sign-problem-free quantum Monte-Carlo simulations on an effective theory, featured with antiferromagnetic and nematic fluctuations, to study the intertwined antiferromagnetic, superconducting, and charge density wave instabilities of the cuprates. Our results suggest the inclusion of nematic fluctuations is essential in order to produce the observed type of charge density wave ordering. Interestingly we find that the d-wave Cooper pairing is enhanced by nematic fluctuations.



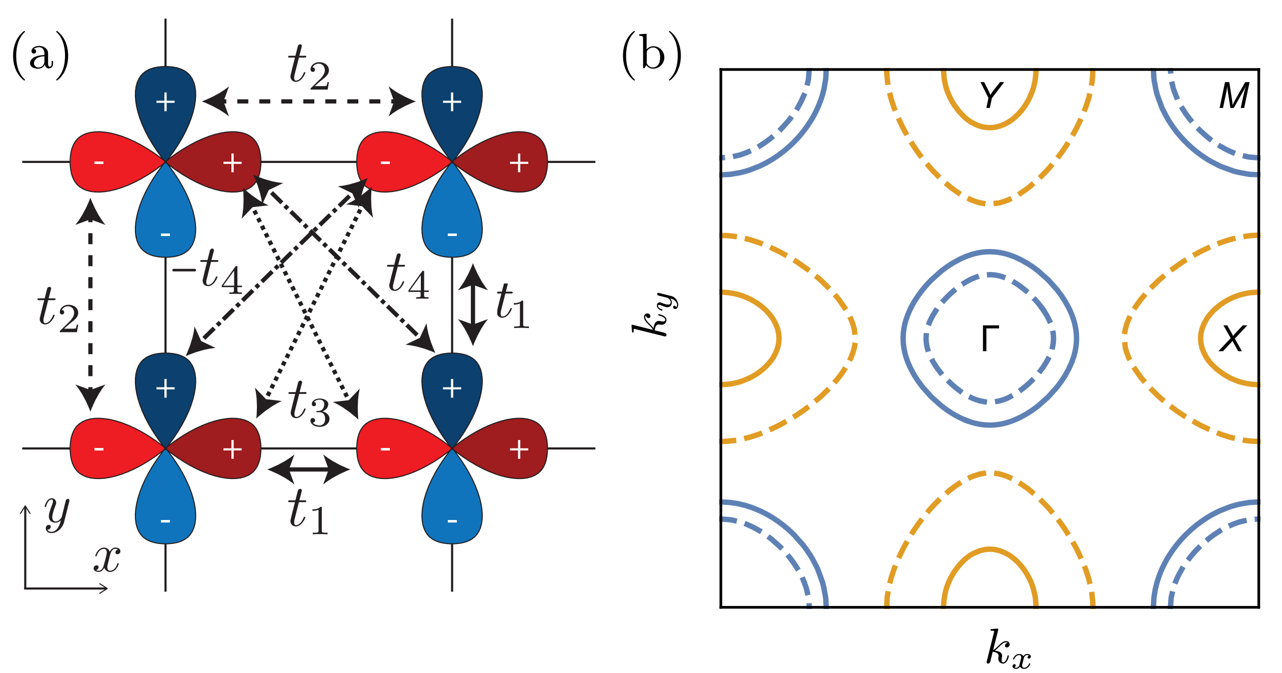
Quantum Monte Carlo study of the T_c enhancement mechanism in FeSe on $SrTiO_3$

Zi-Xiang Li, Fa Wang, Hong Yao, and Dung-Hai Lee, arXiv:1512.06179

Here we study the cooperation between electron-phonon and pure electron mechanisms of pairing by unbiased sign-problem-free quantum Monte Carlo computation on effective models capturing the low energy physics of $(FeSe)_1$/STO. Our results clearly indicate that irrespective to the pure electronic driving force of Cooper pairing and the resulting pairing symmetry, nematic fluctuations and especially forward-focusing electron-phonon couplings significantly enhance the superconductivity.

Superconductivity and Nematic Fluctuations in a model of FeSe monolayers: A Determinant Quantum Monte Carlo Study

Philipp T. Dumitrescu, Maksym Serbyn, Richard T. Scalettar, and Ashvin Vishwanath, arXiv:1512.08523



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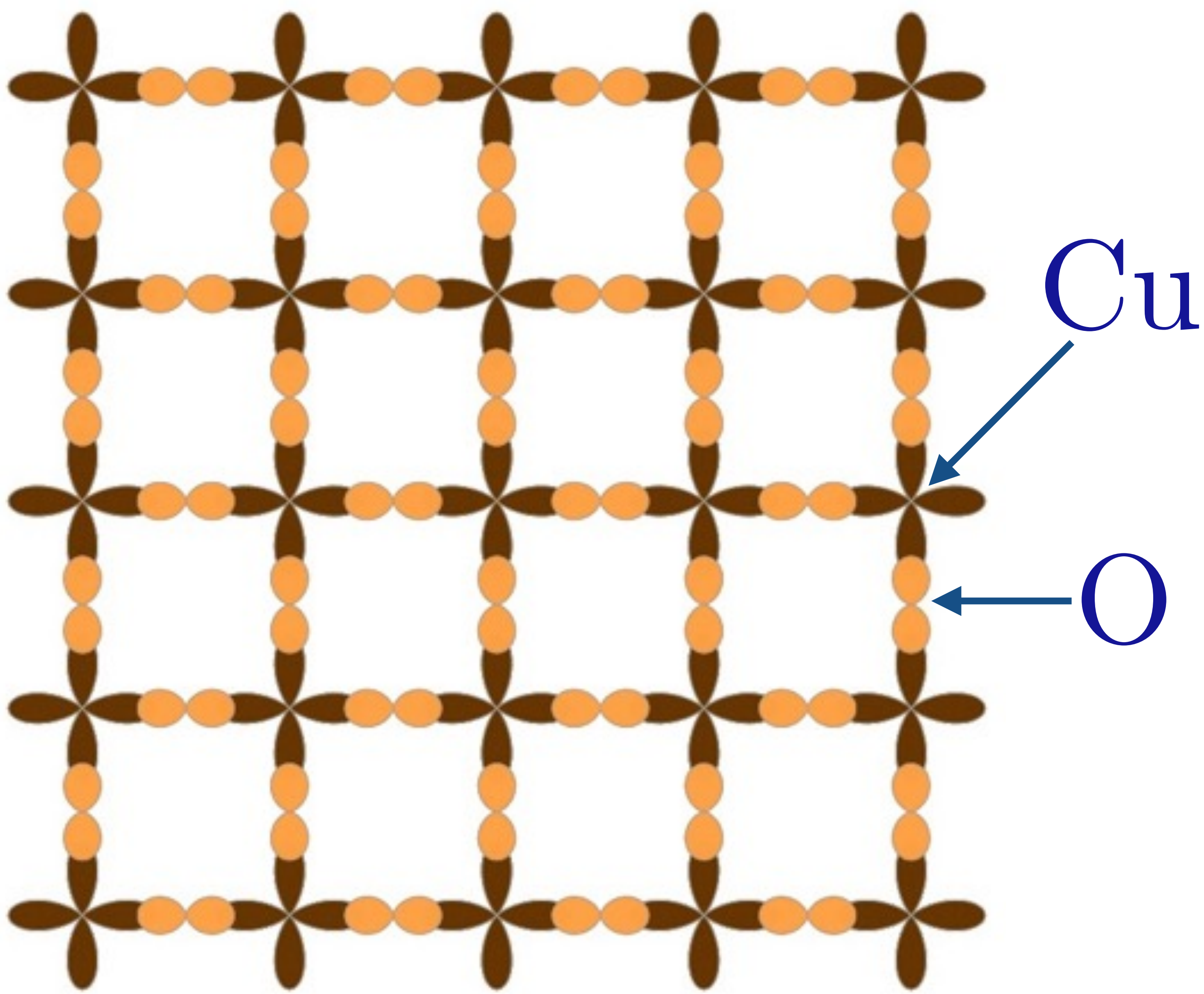
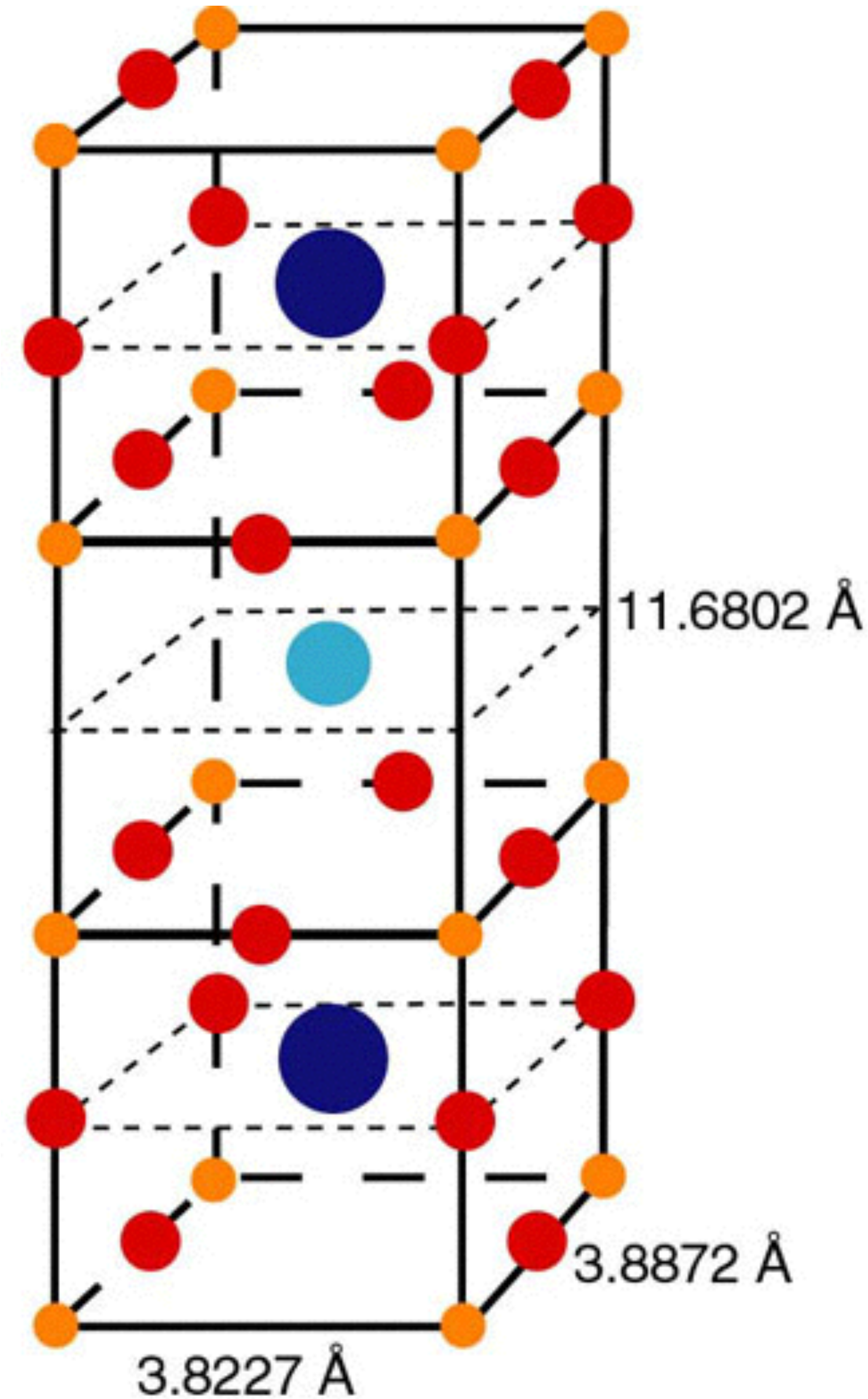
High temperature superconductors



CuO_2 plane

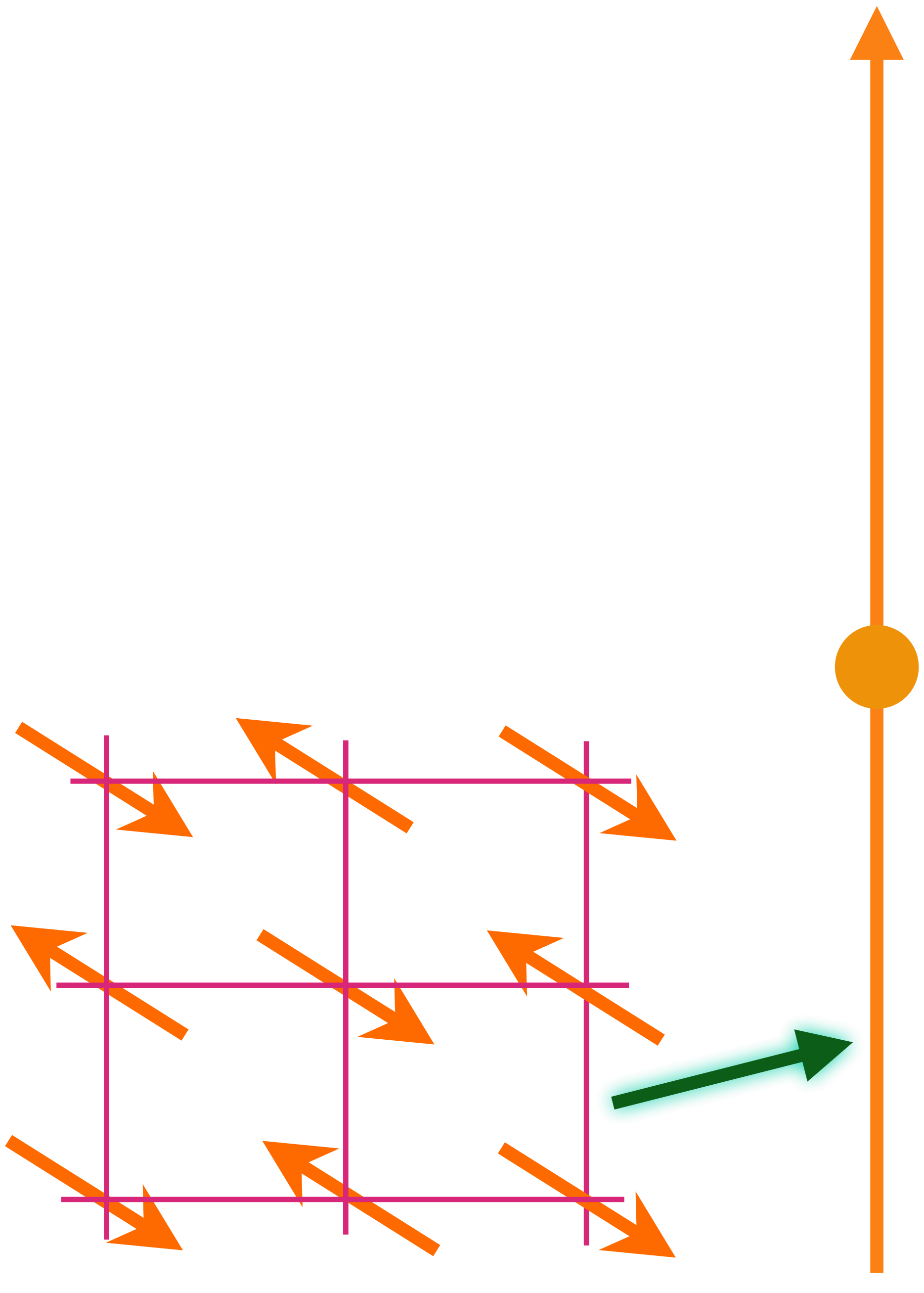
Mott insulator at a density of 1 electron per site.



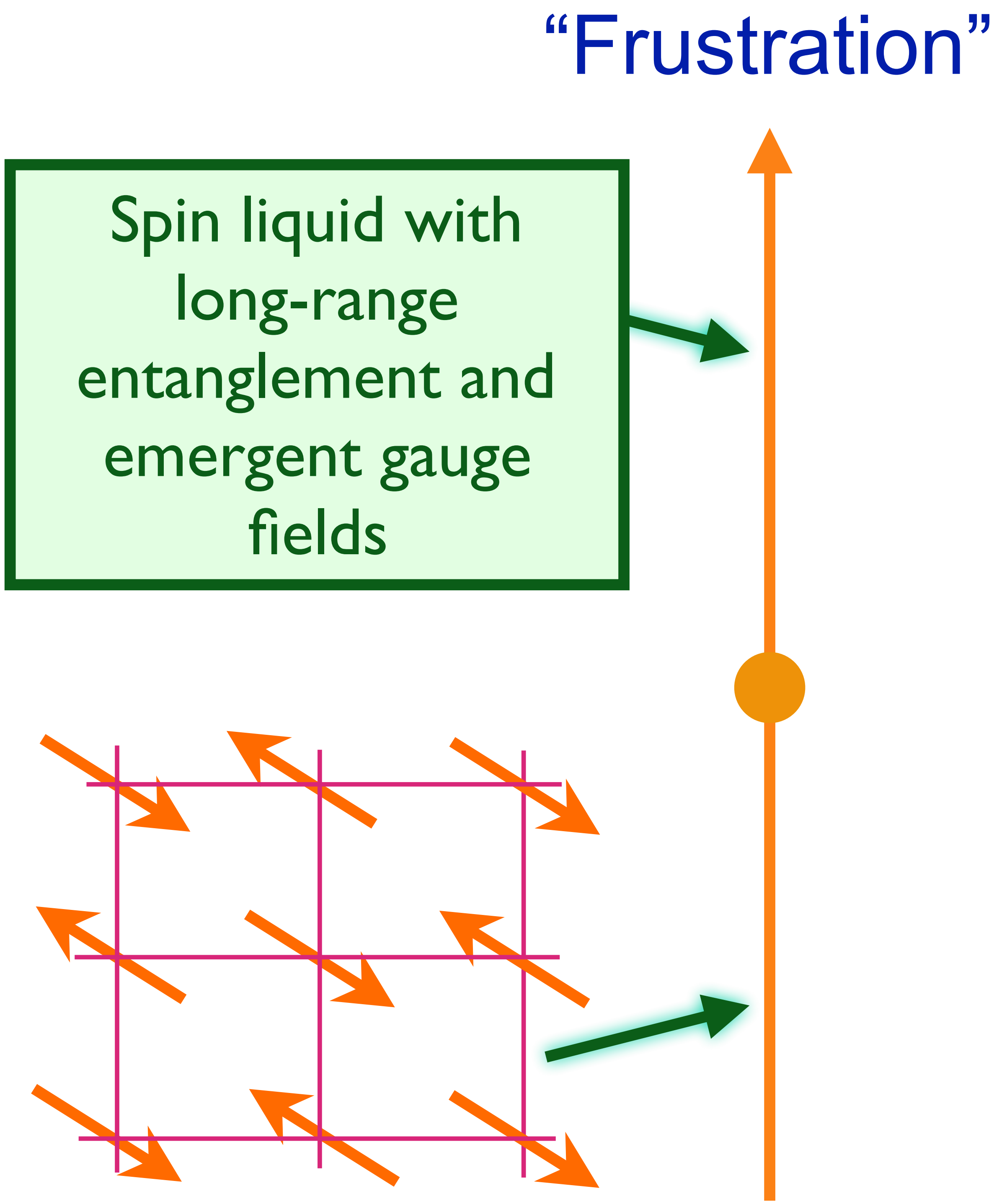
$YBa_2Cu_3O_{6+x}$

Mott insulators

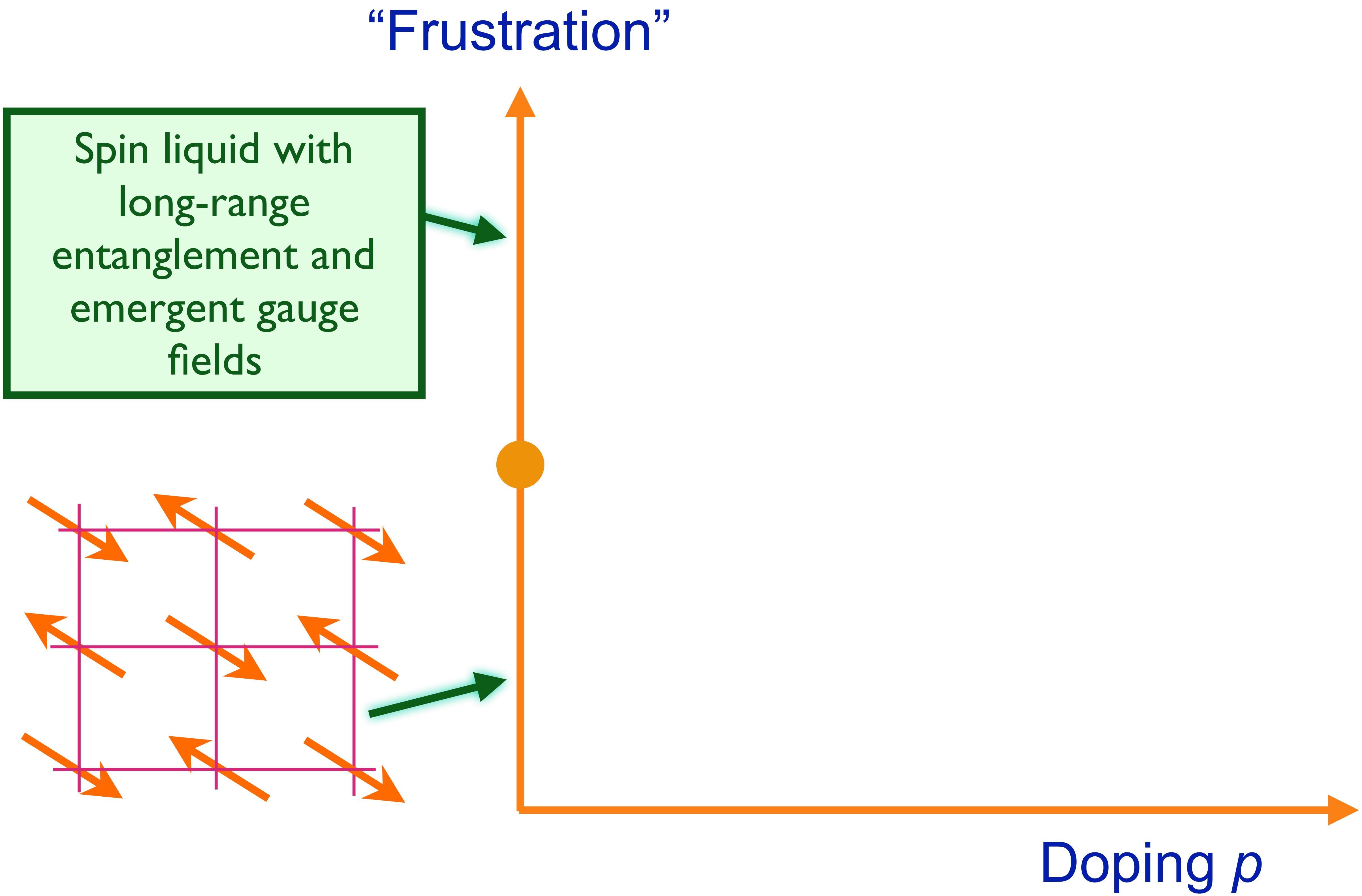
"Frustration"



Mott insulators



Doped Mott insulators



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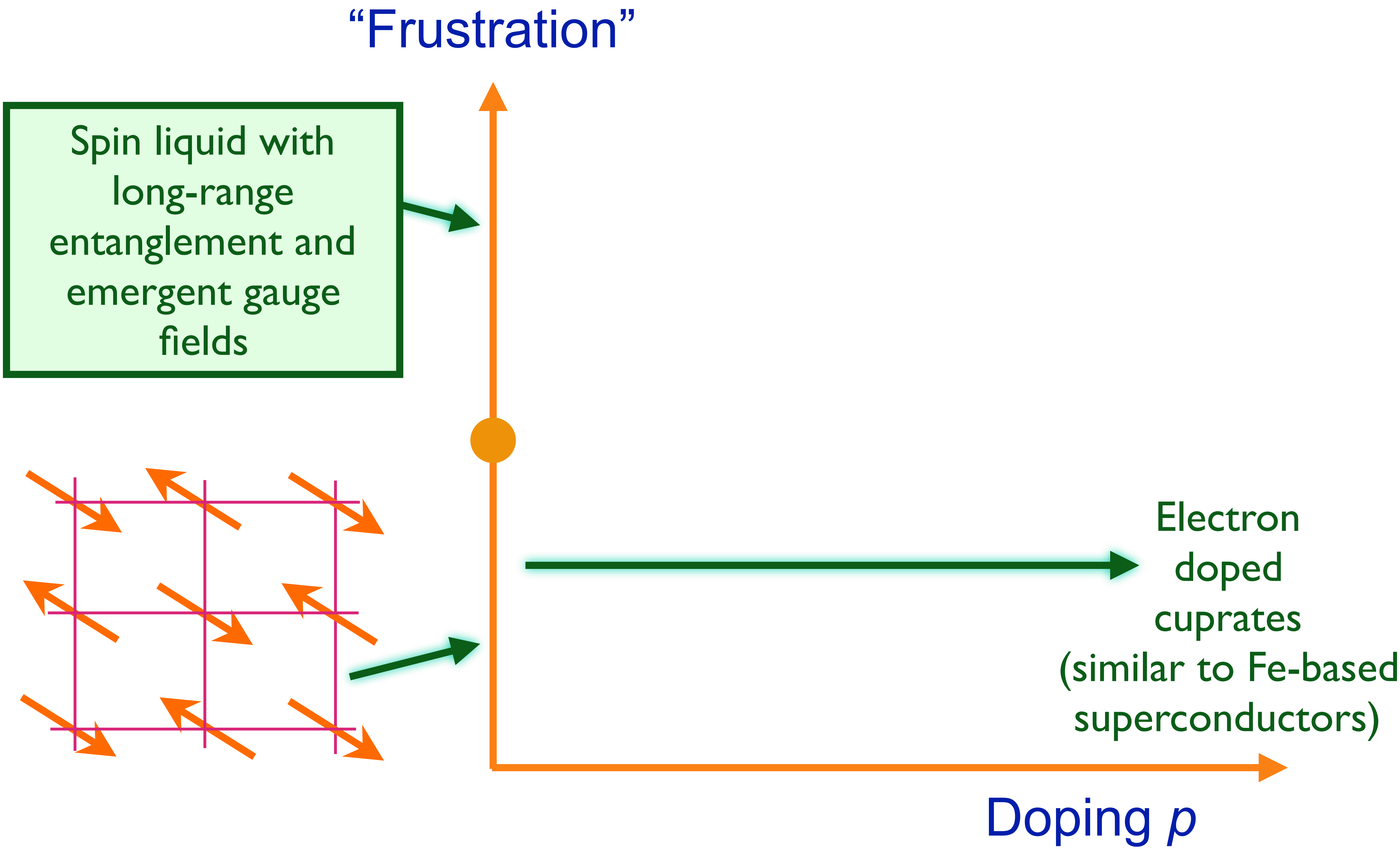
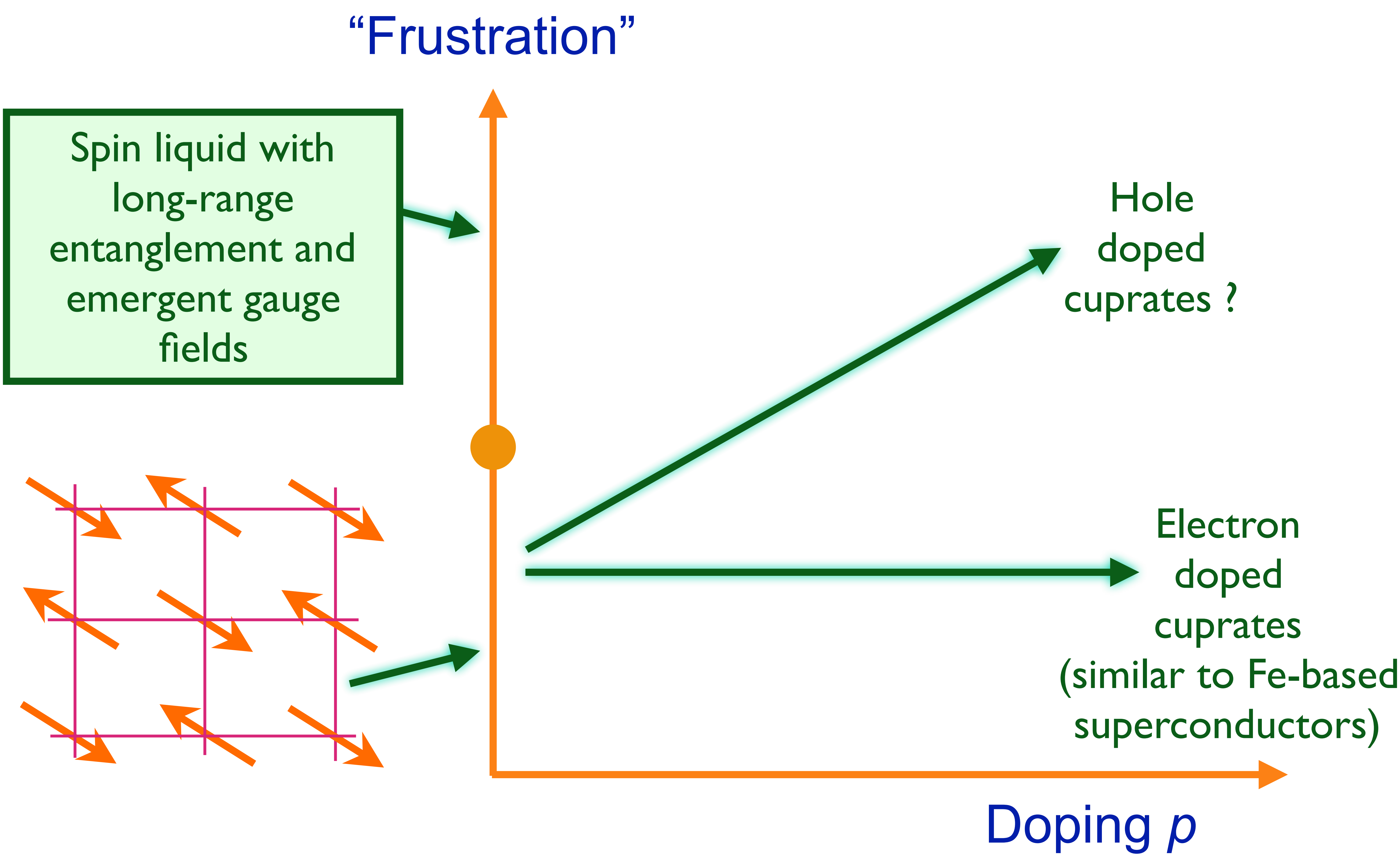
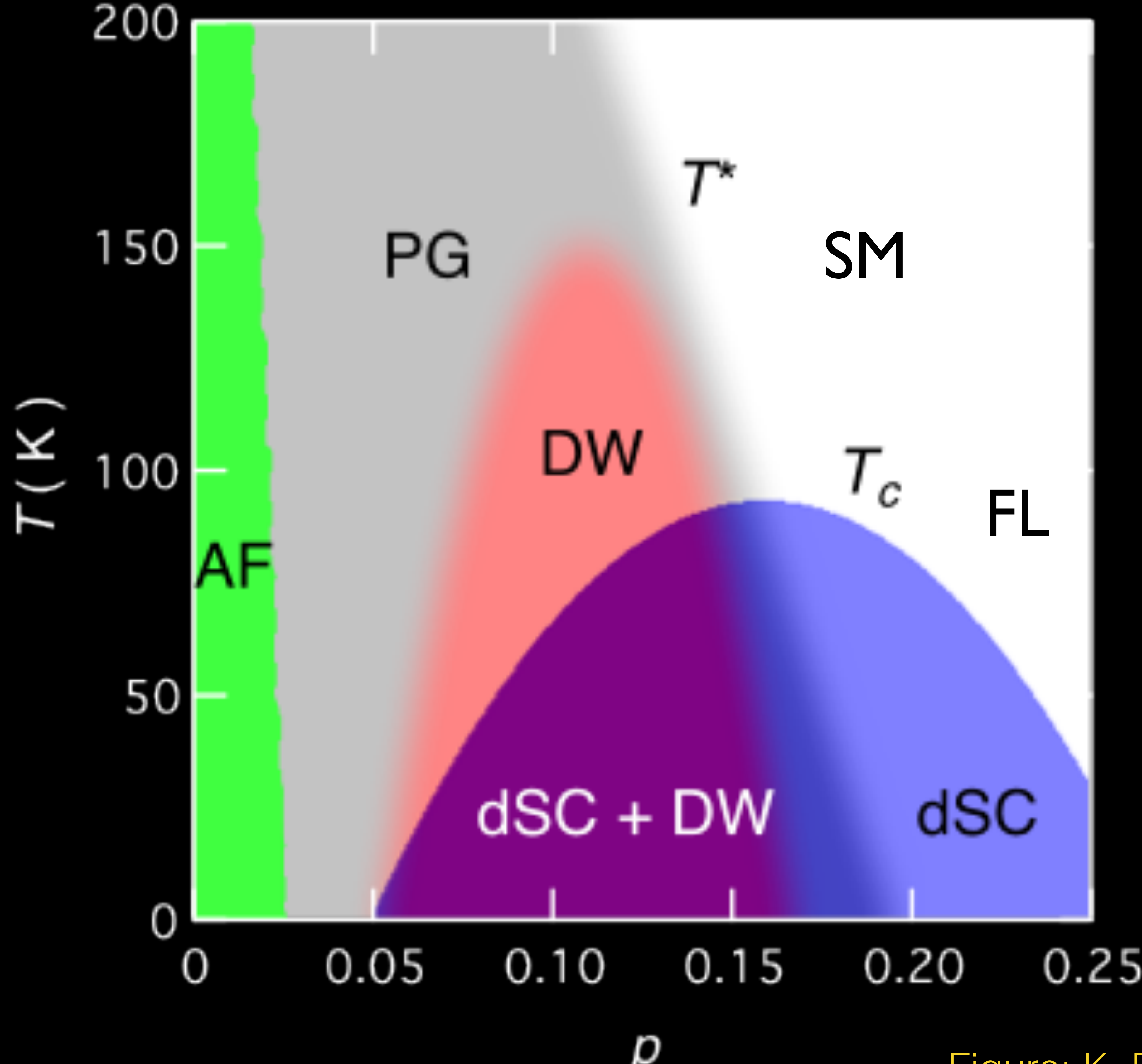
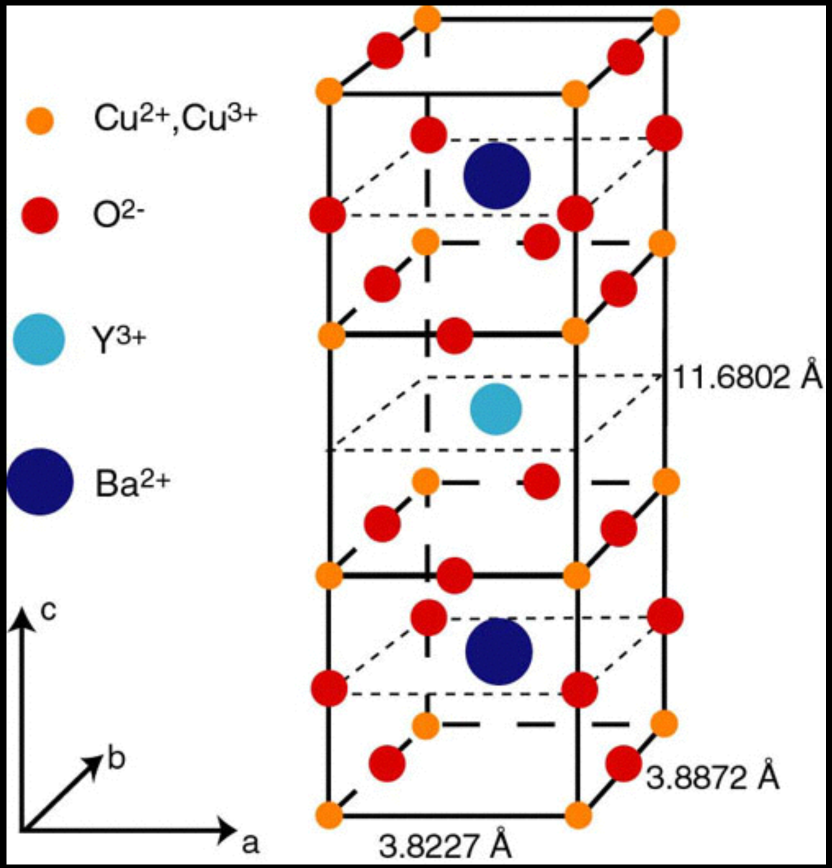


Doped Mott insulators







$YBa_2Cu_3O_{6+x}$

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

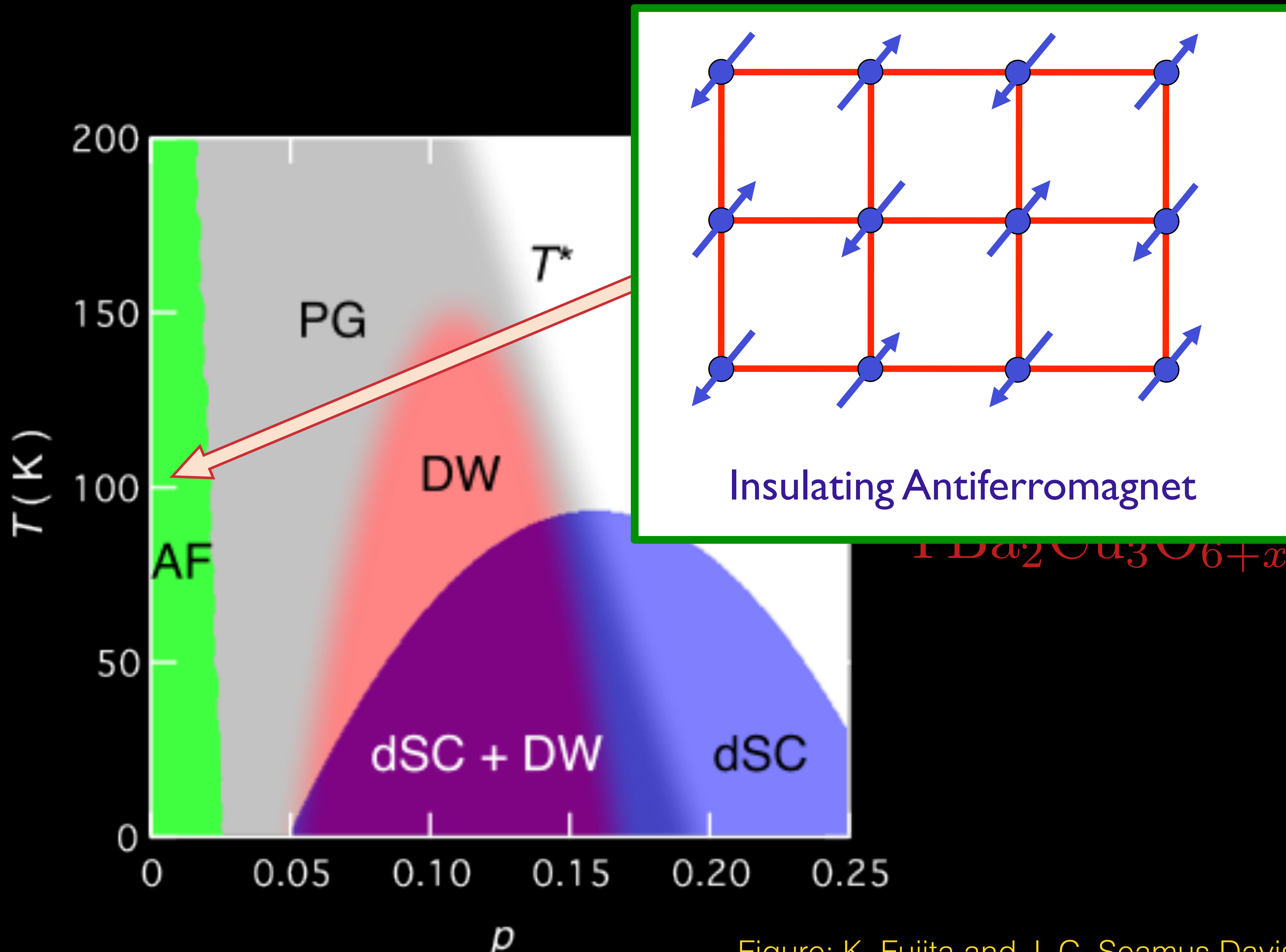
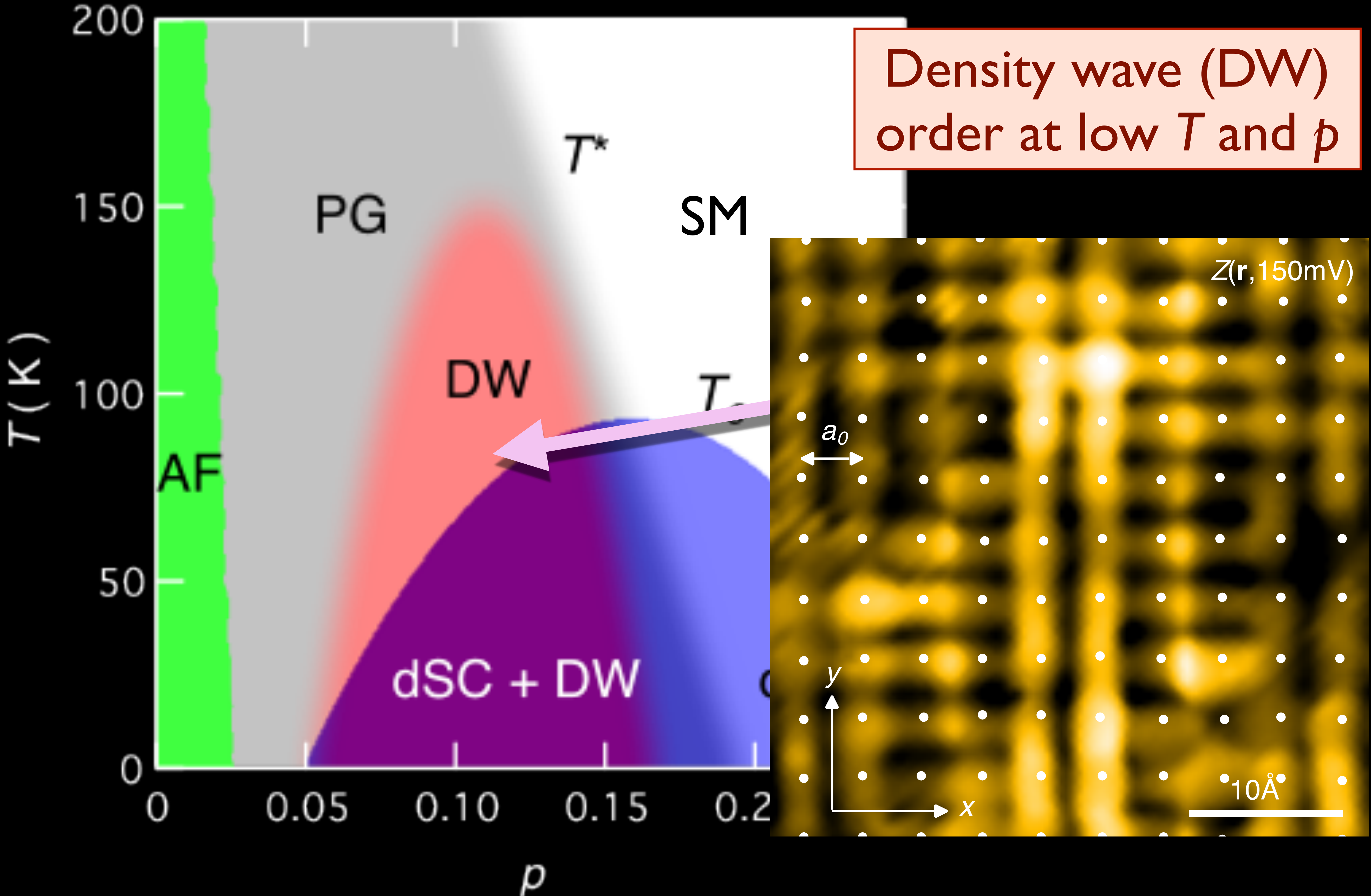


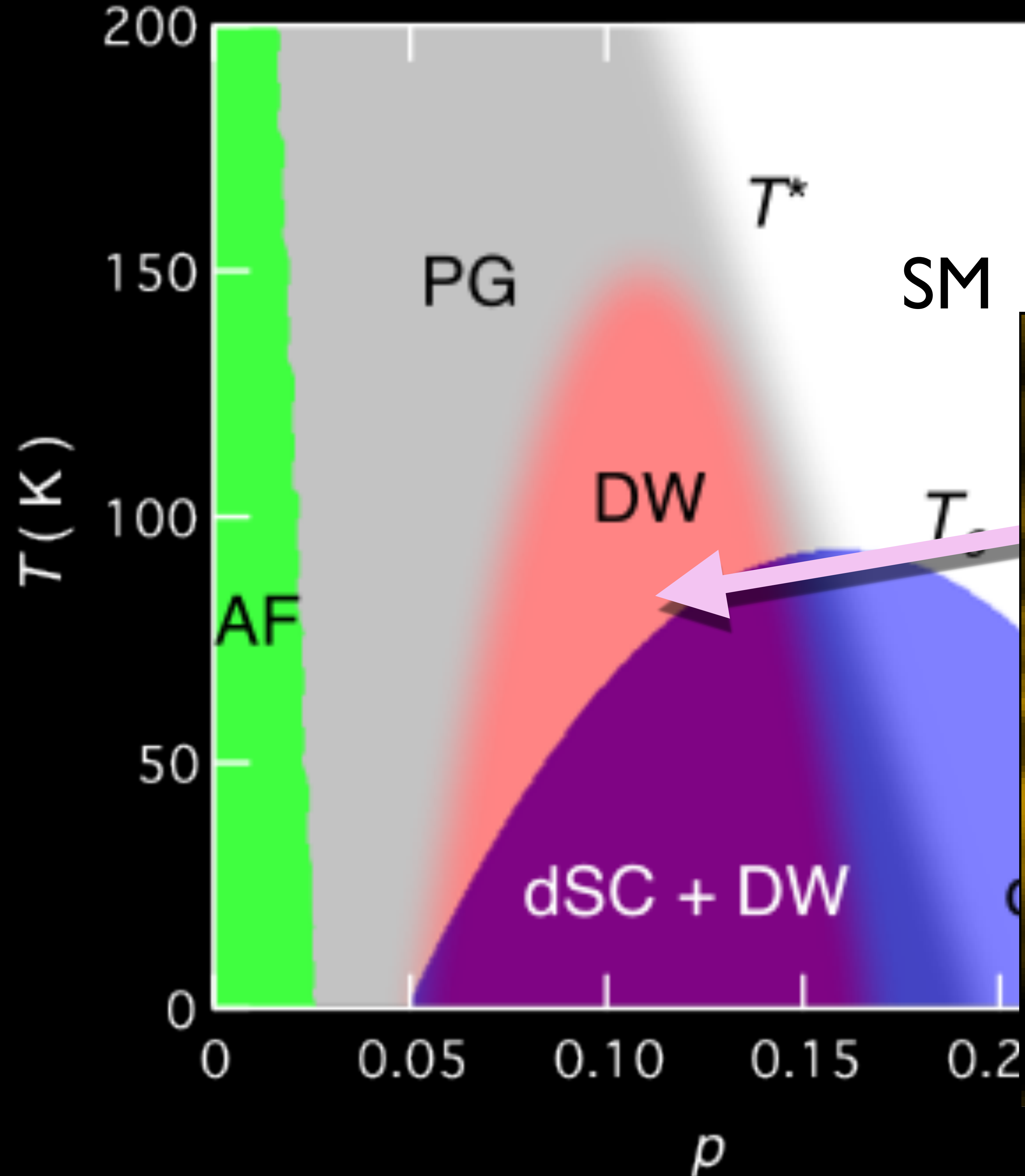
Figure: K. Fujita and J. C. Seamus Davis

Y. Kohsaka *et al.*, Science **315**, 1380 (2007)
M. H. Hamidian *et al.*, Nature Physics **12**, 150 (2016)

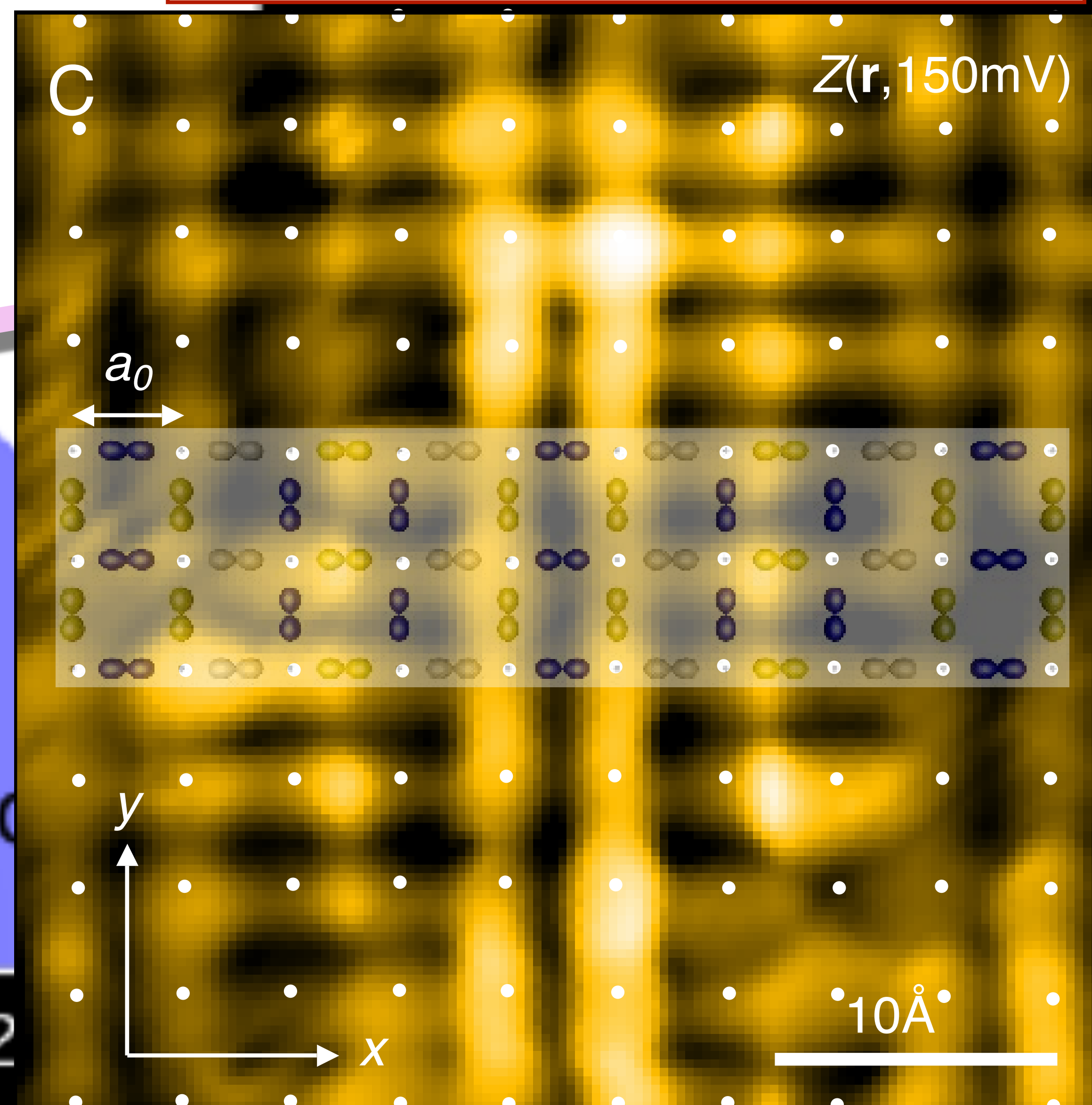


Density wave (DW) order at low T and p

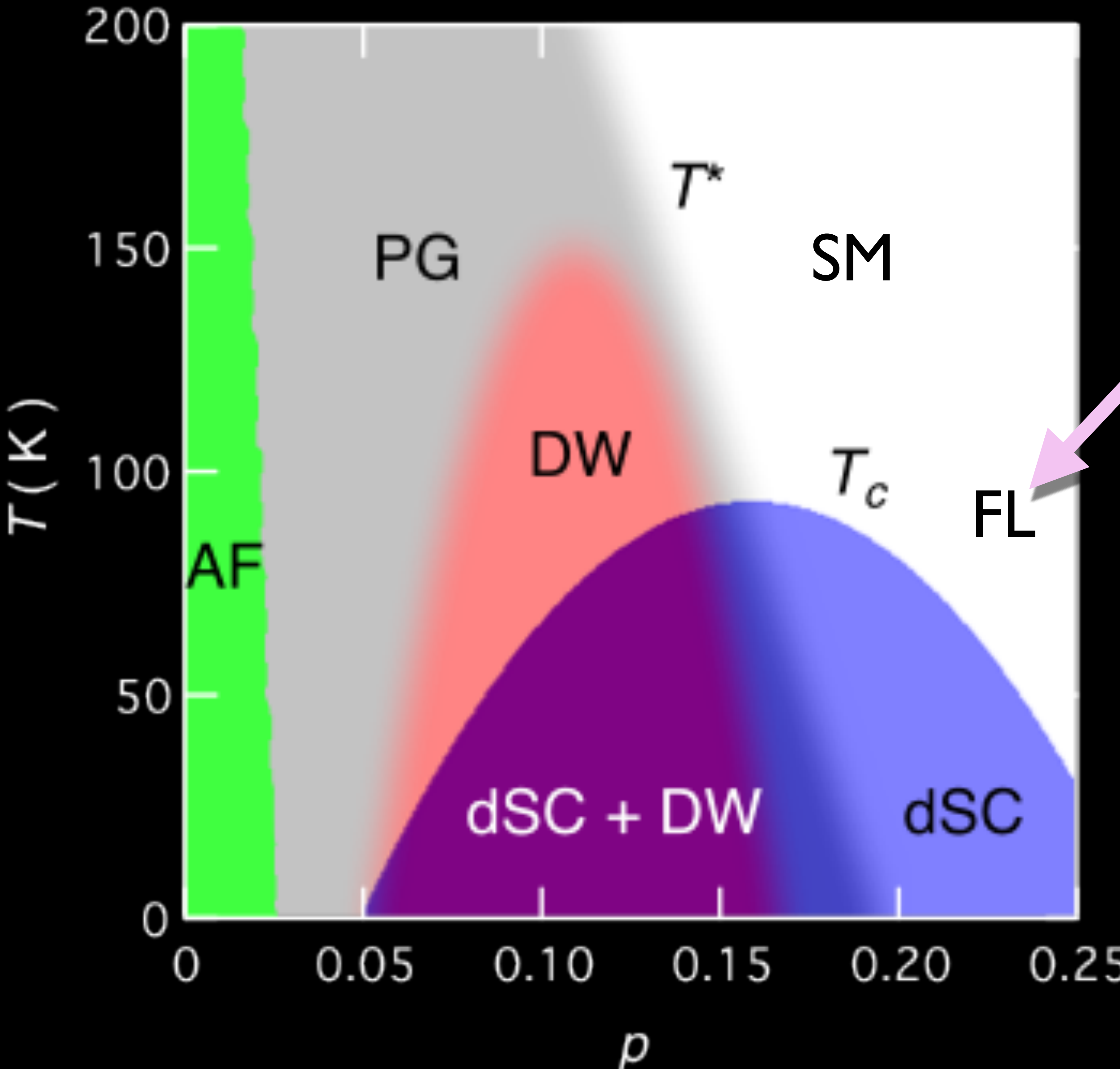
M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS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

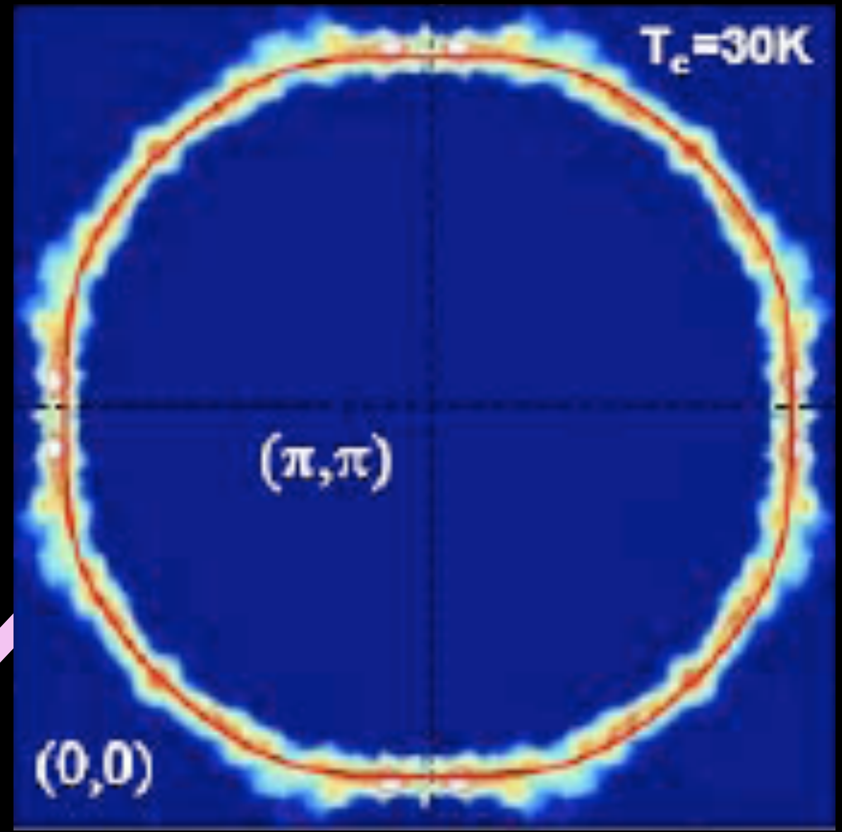


Identified as a predicted "*d*-form factor density wave"



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)

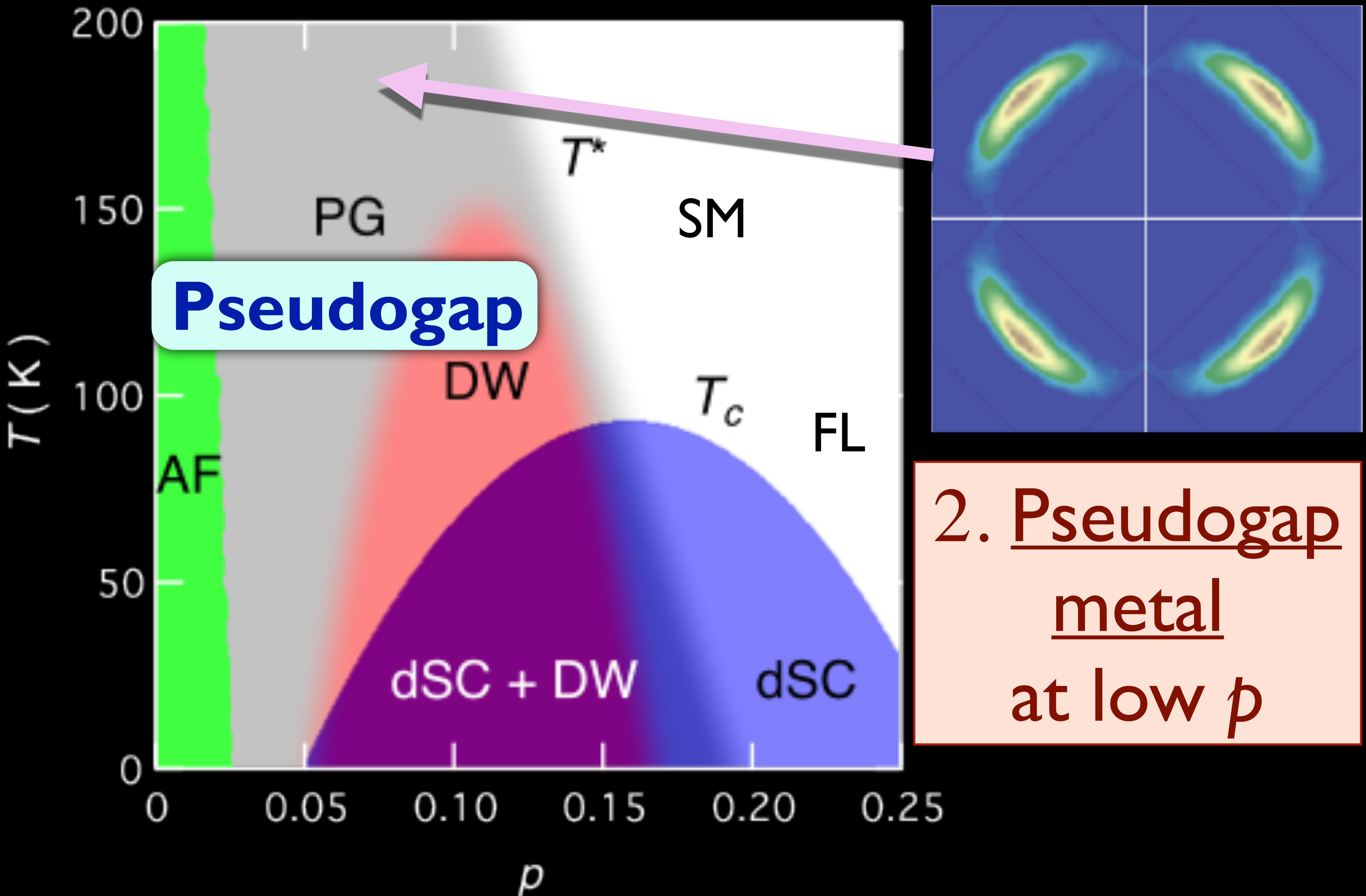




Fermi liquid

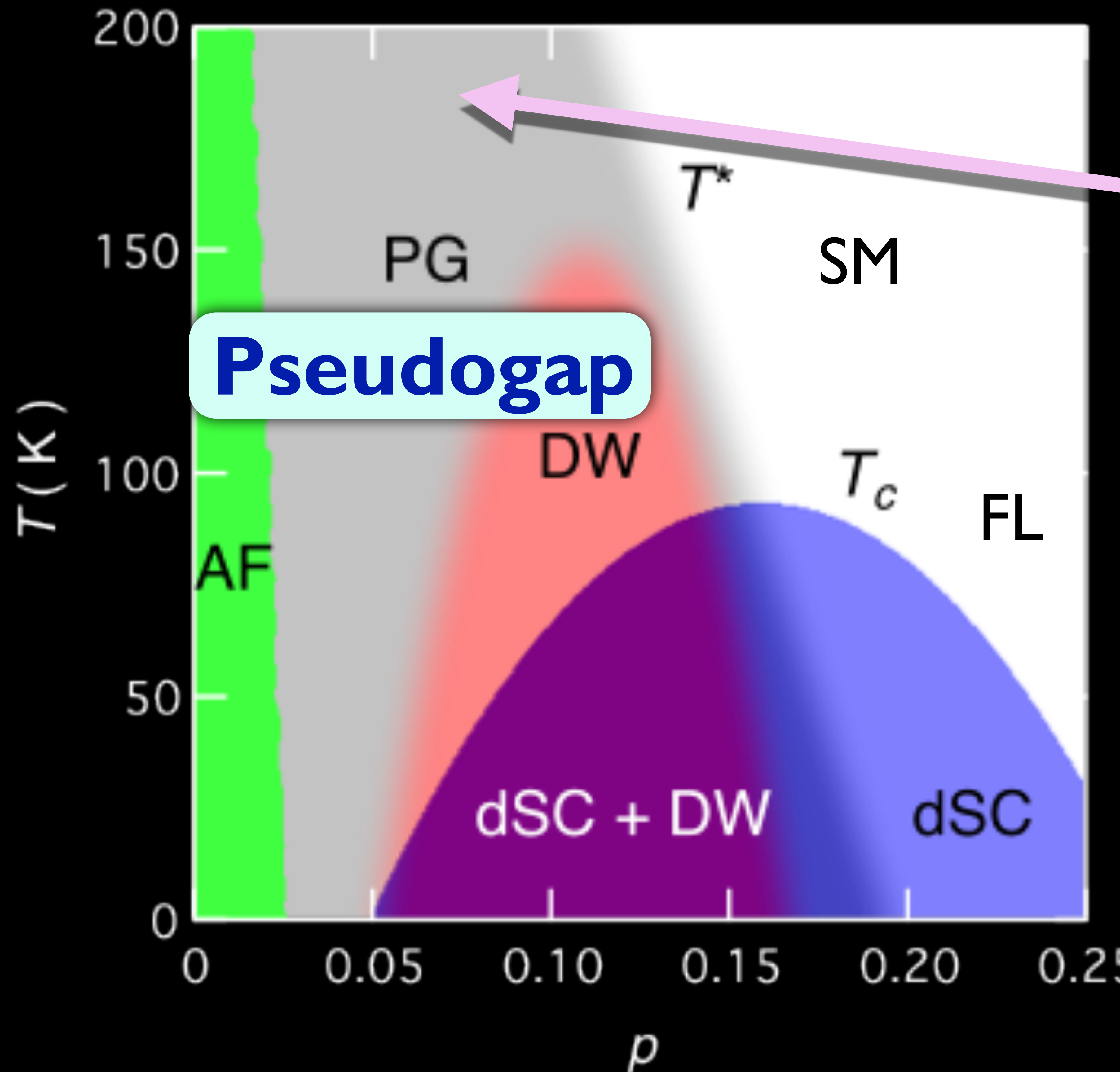
Area enclosed by Fermi surface =1+p

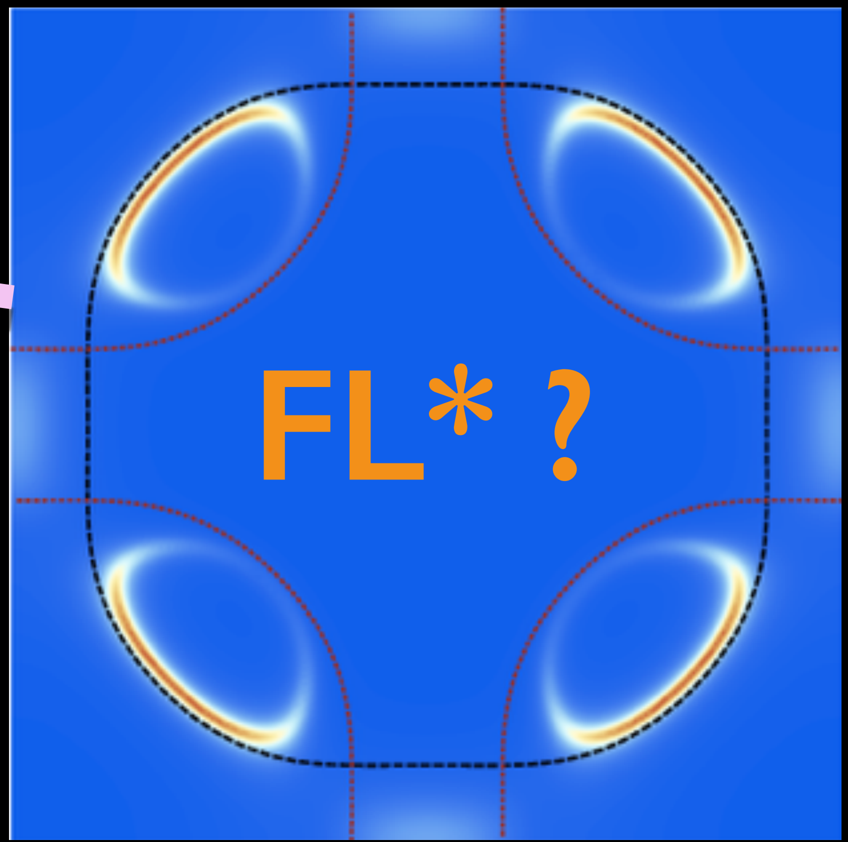
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)



2. Pseudogap metal at low p

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





A metal with long-range entanglement and emergent gauge fields — with electron-like quasiparticles on a Fermi surface of size p

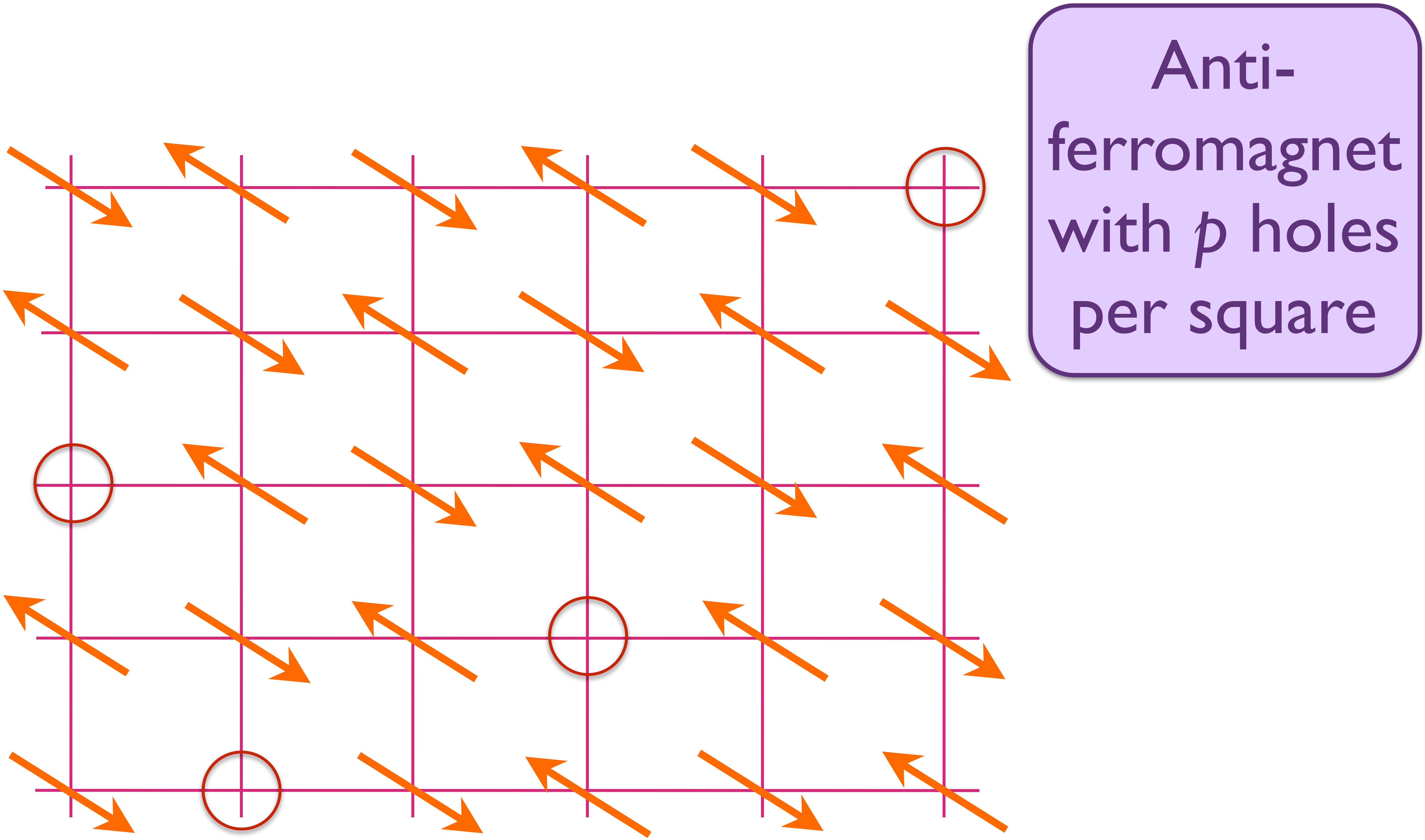
FL*

This a metal with:

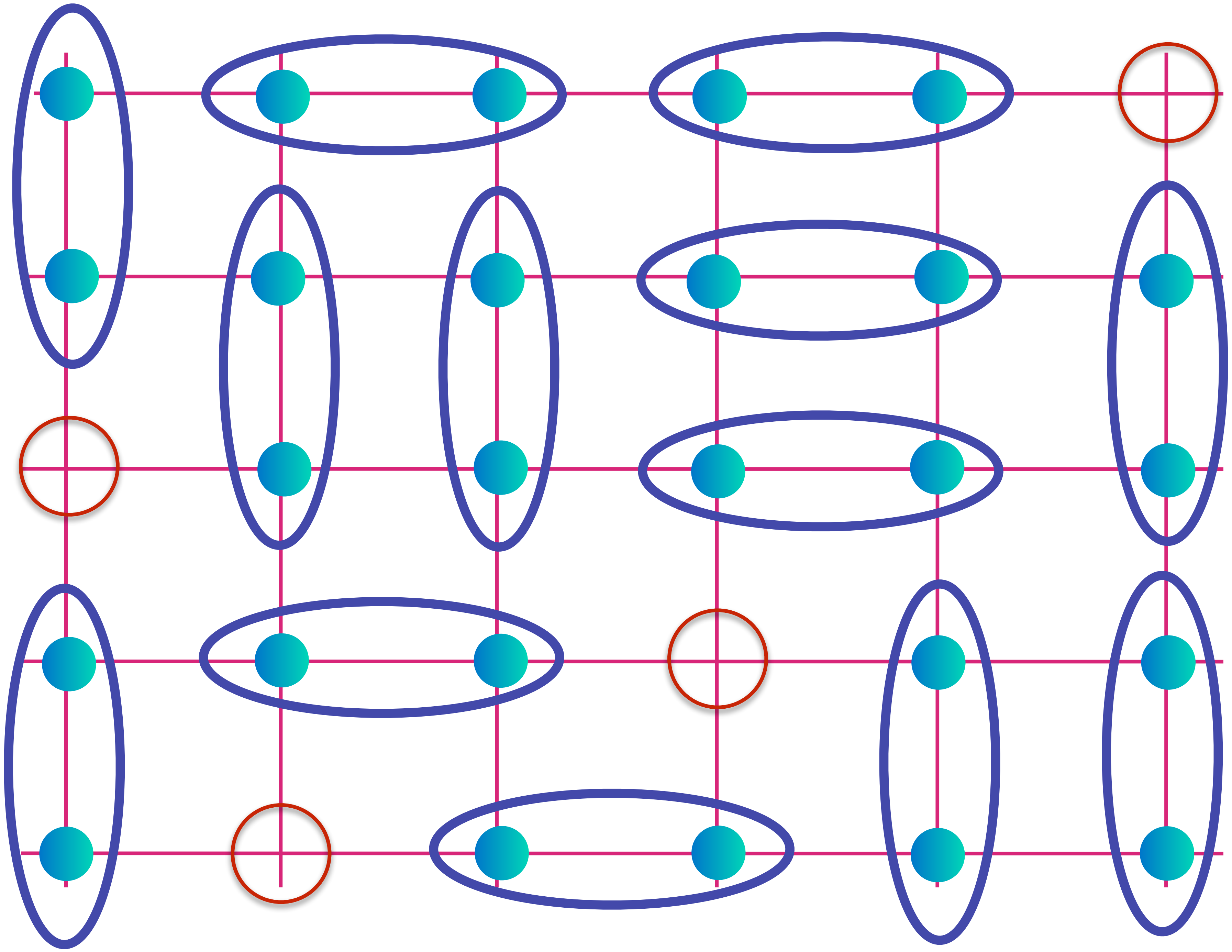
- A Fermi surface of electrons enclosing volume p, and not the Luttinger volume of $1+p$
- Additional low energy excitations, not associated with quasiparticles, described by emergent gauge fields

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

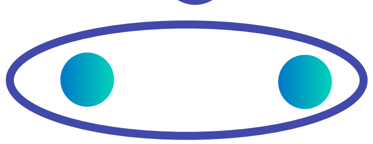
M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)


Anti-ferromagnet with p holes per square

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



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



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

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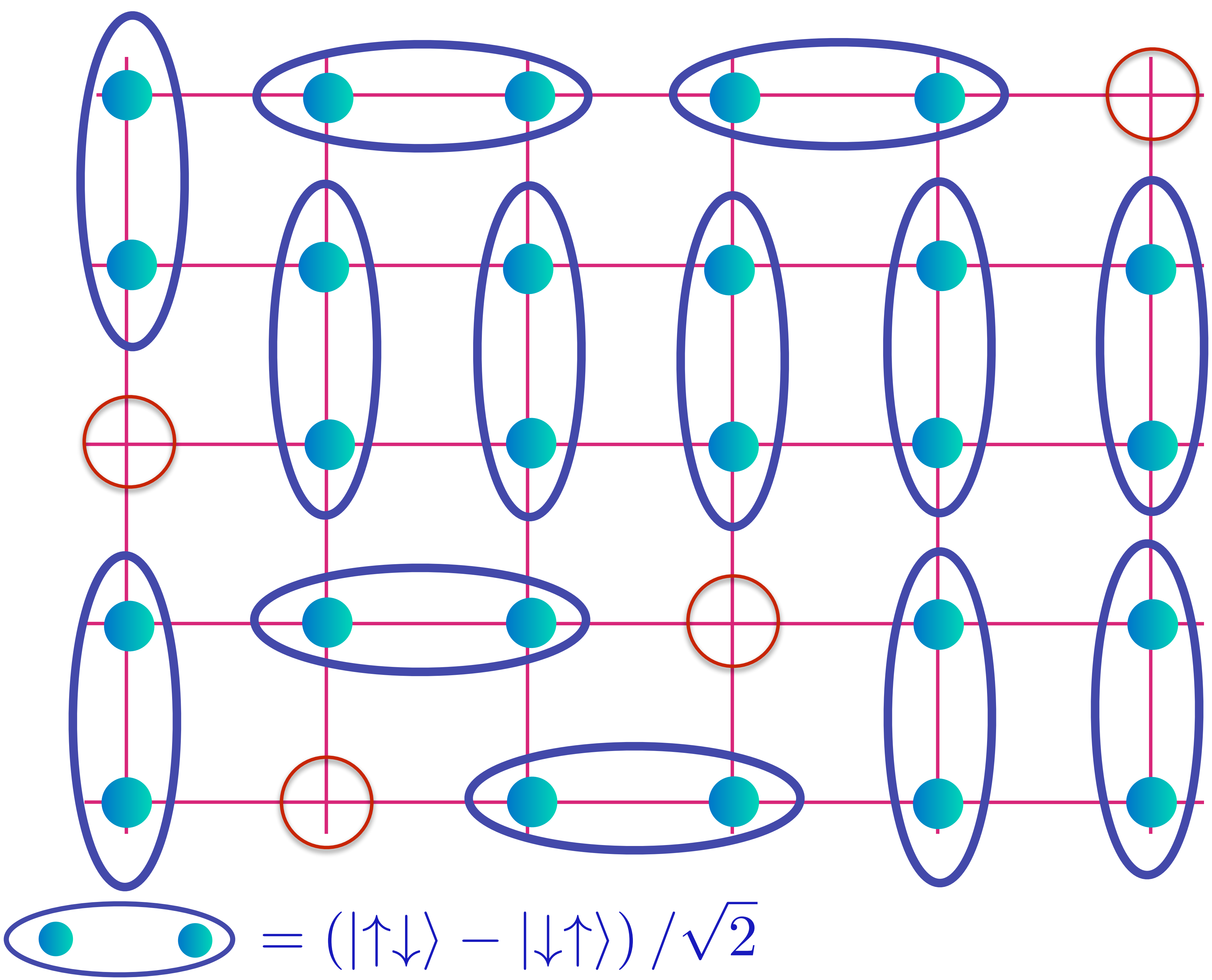

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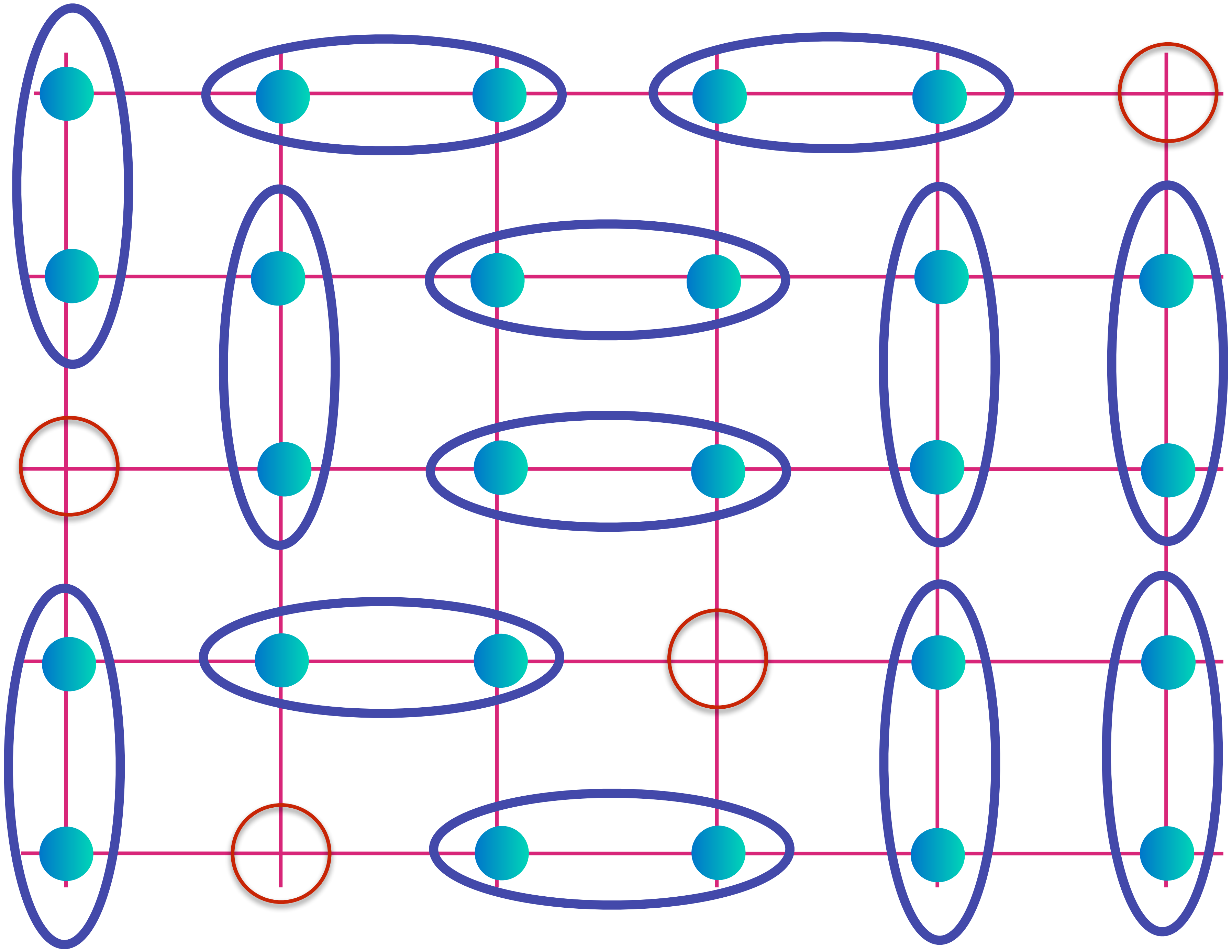

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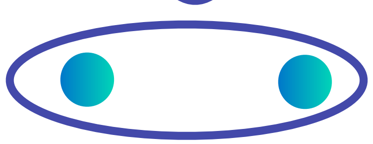 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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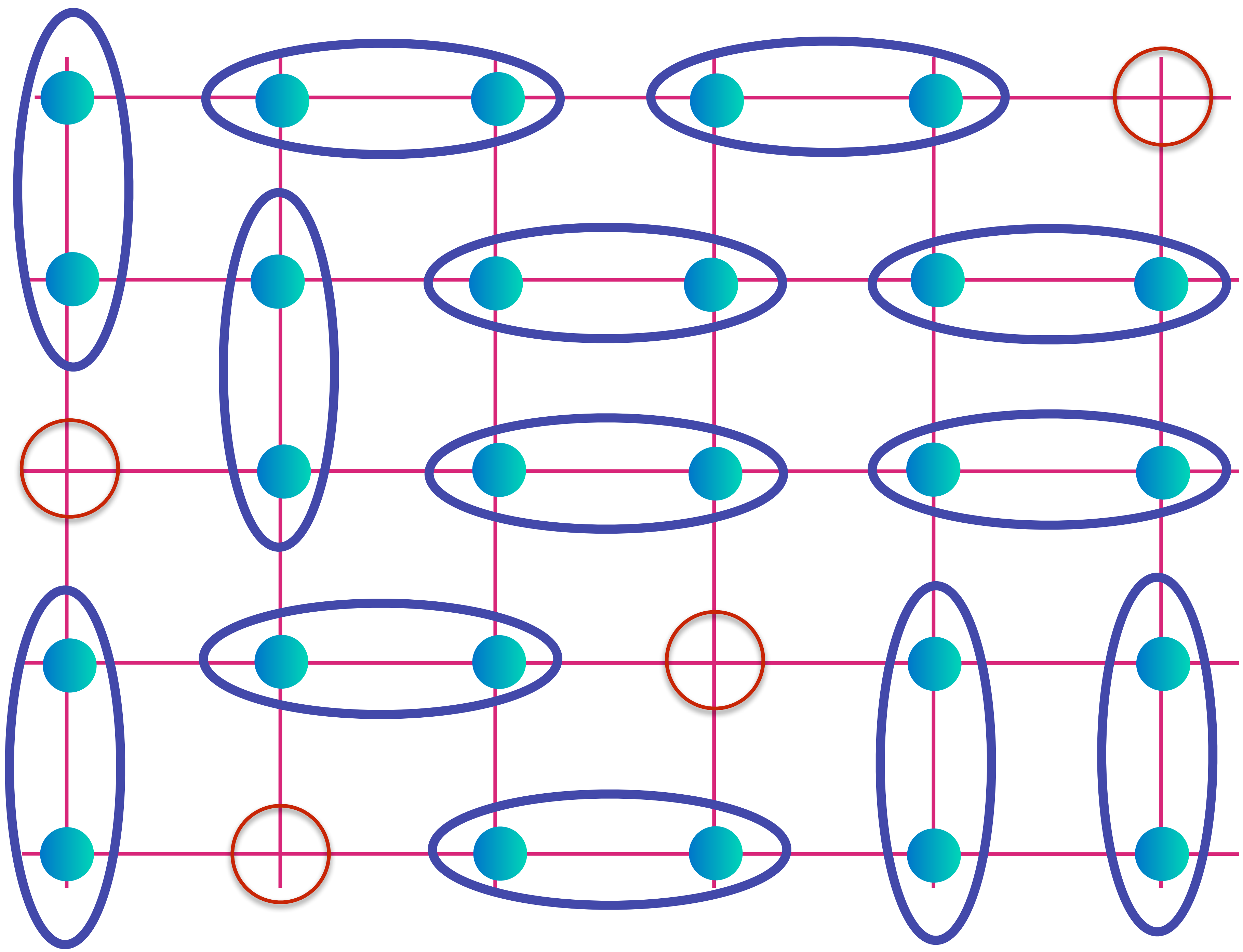

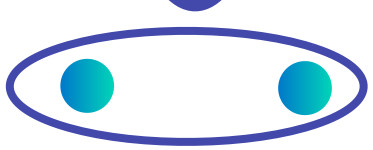
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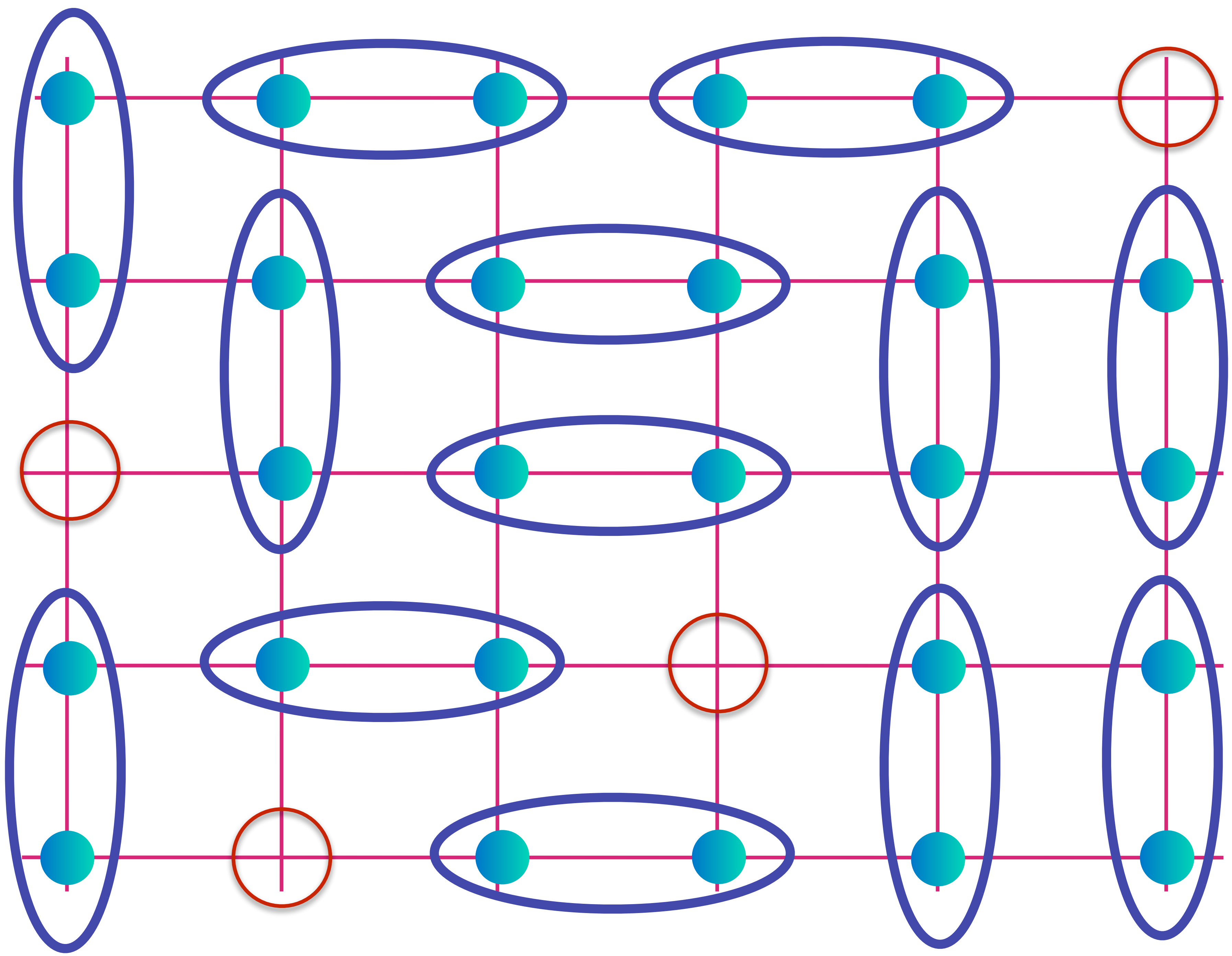

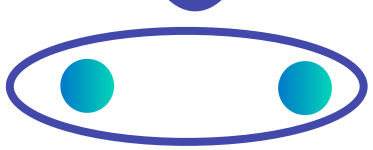 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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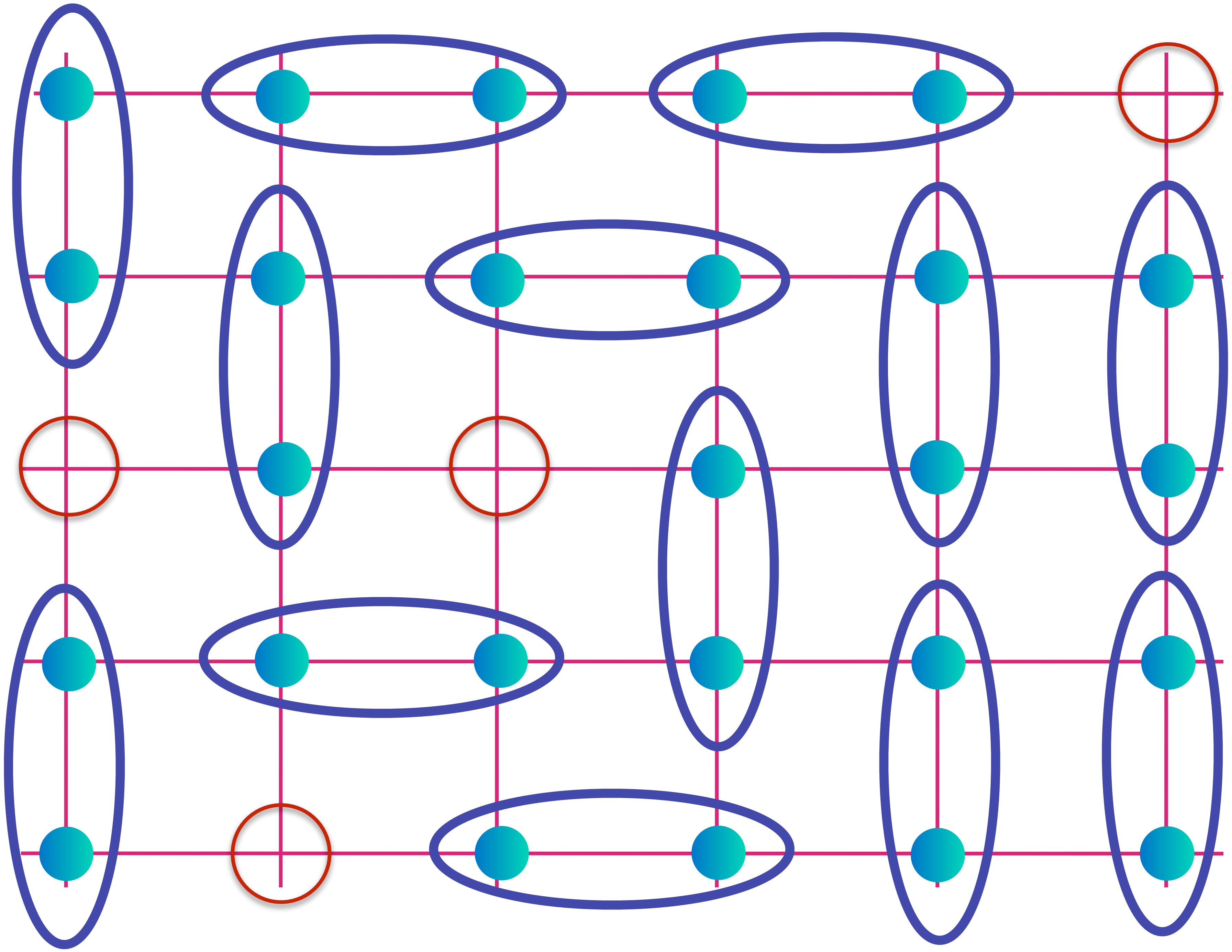

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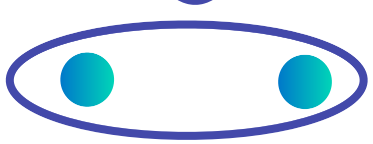
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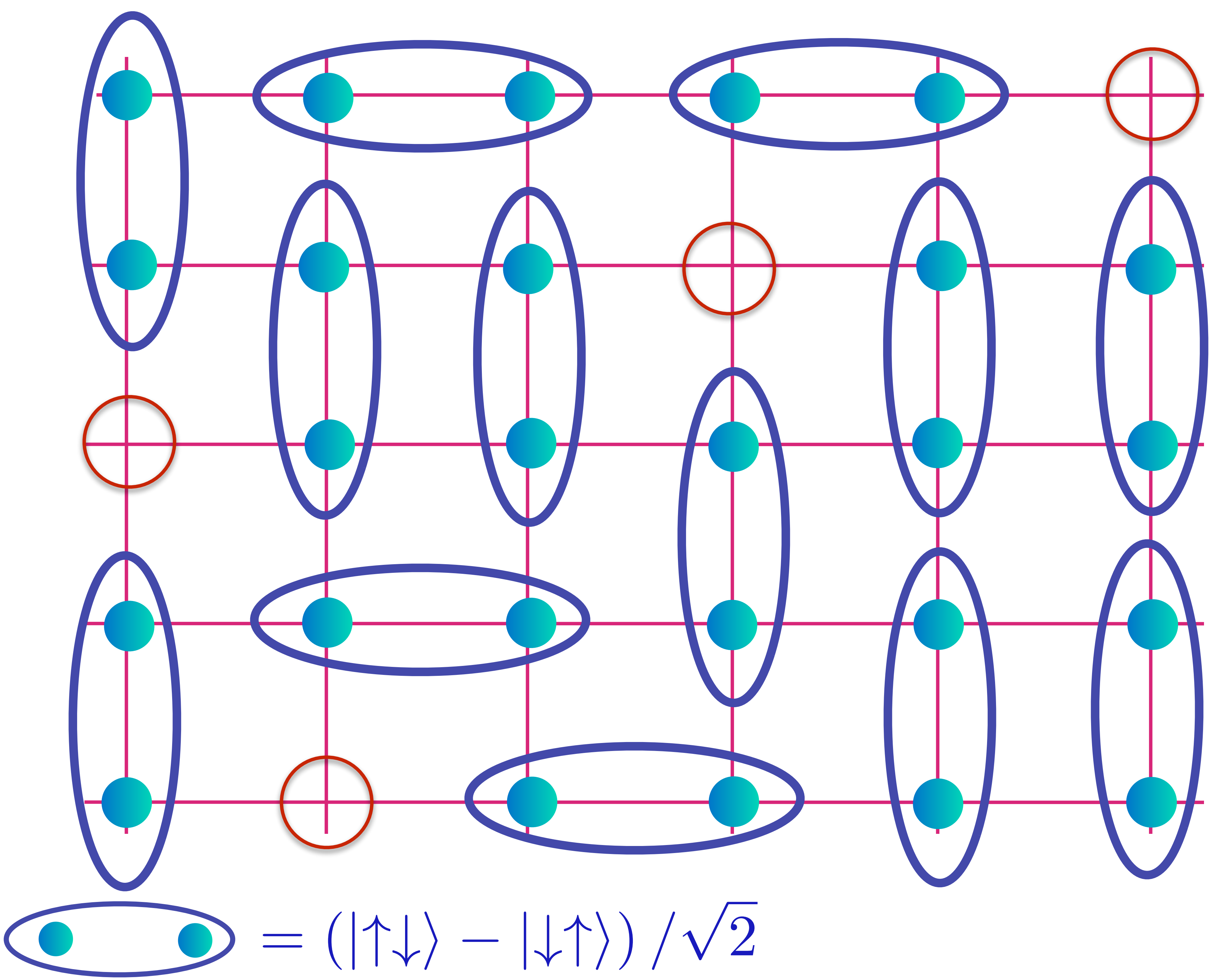

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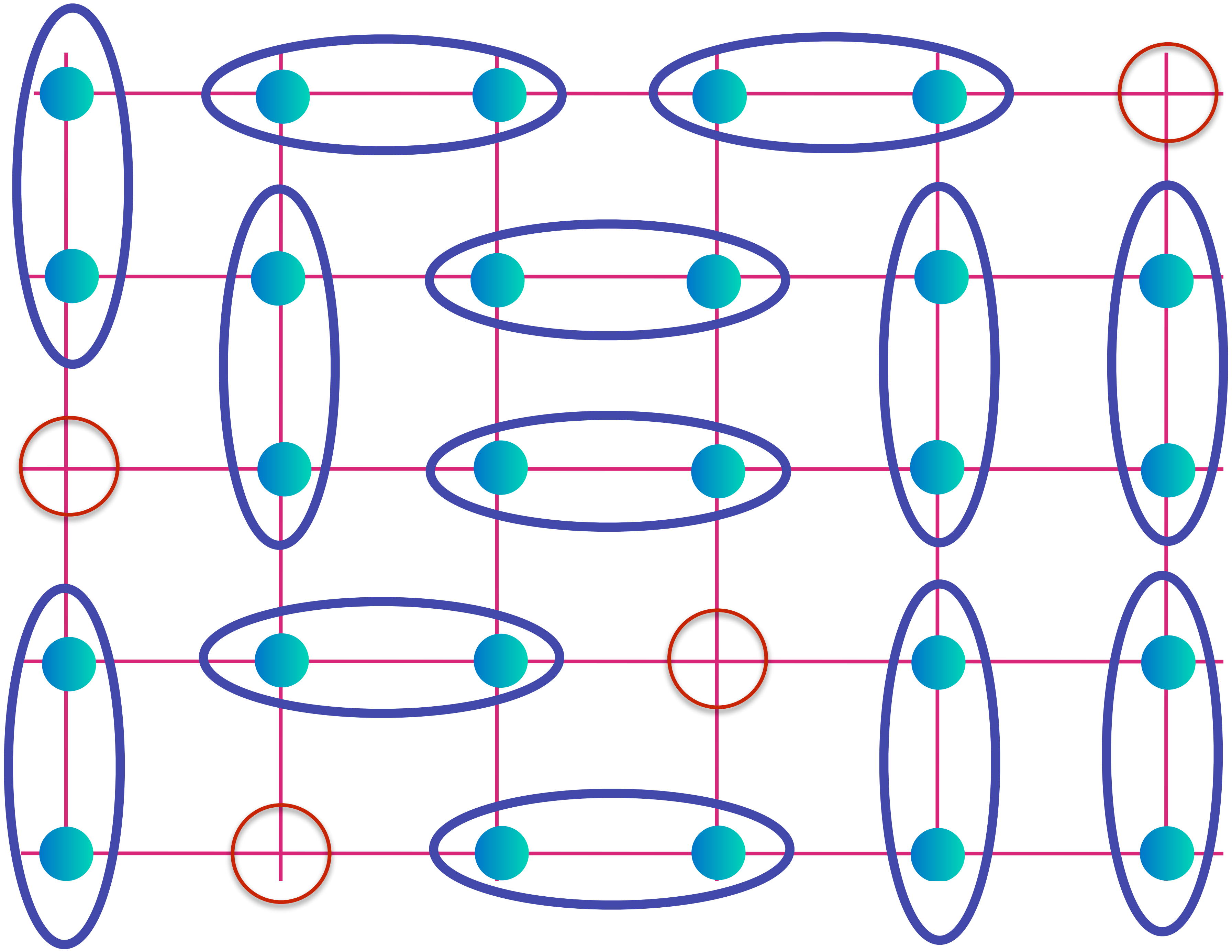

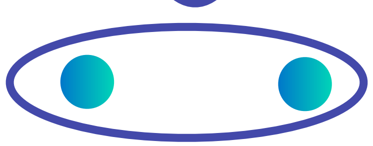

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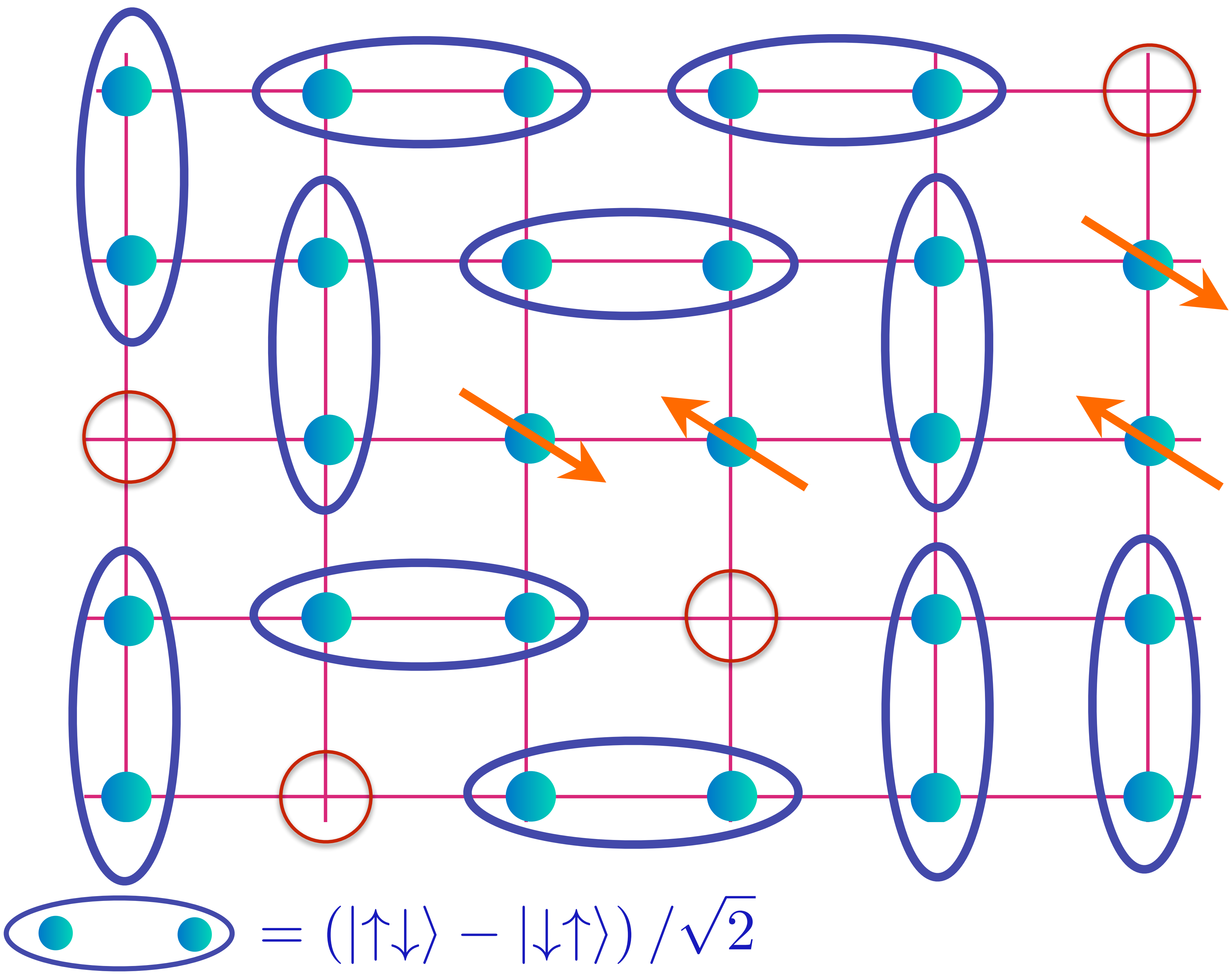
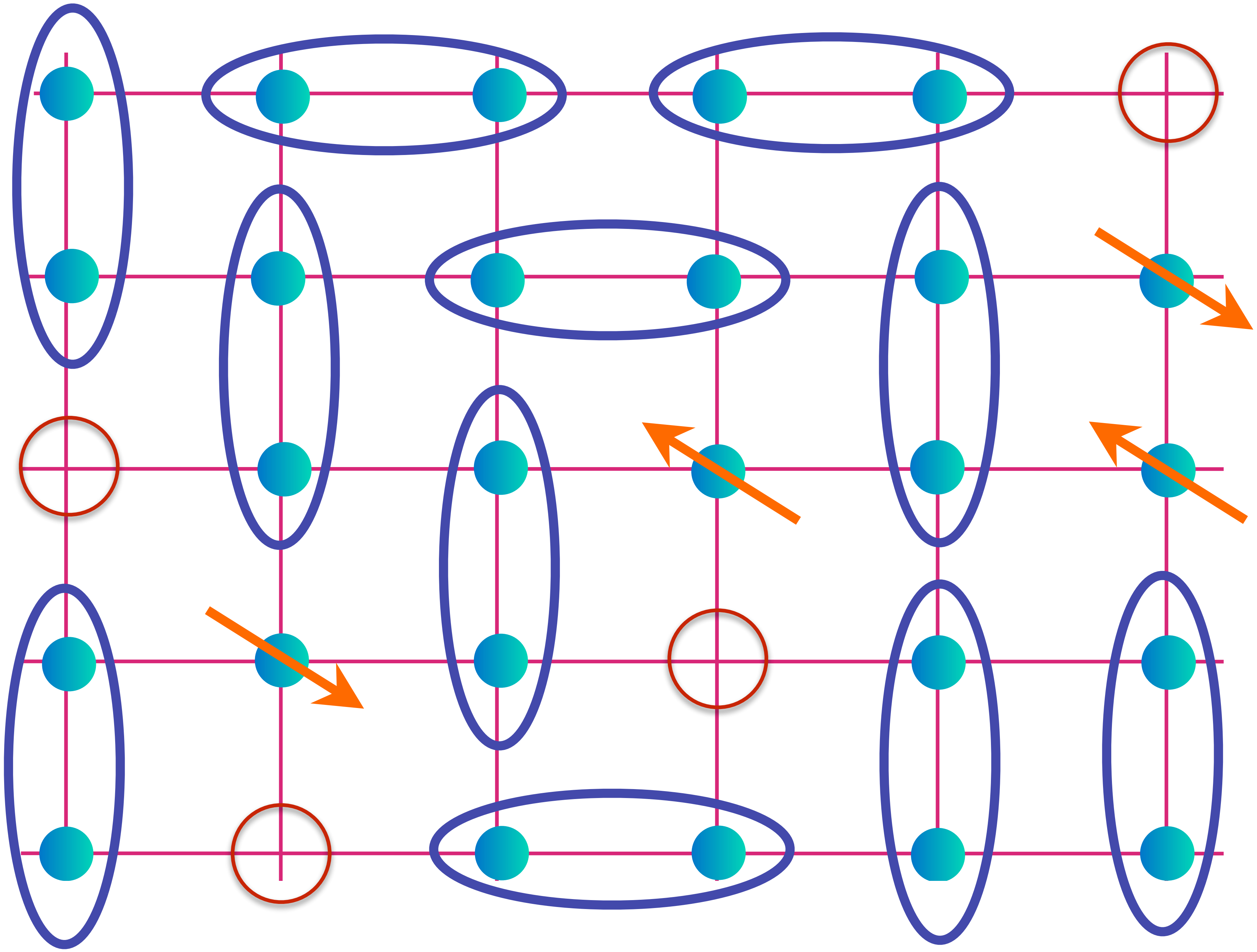
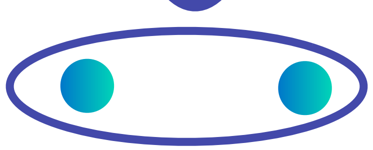

$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$





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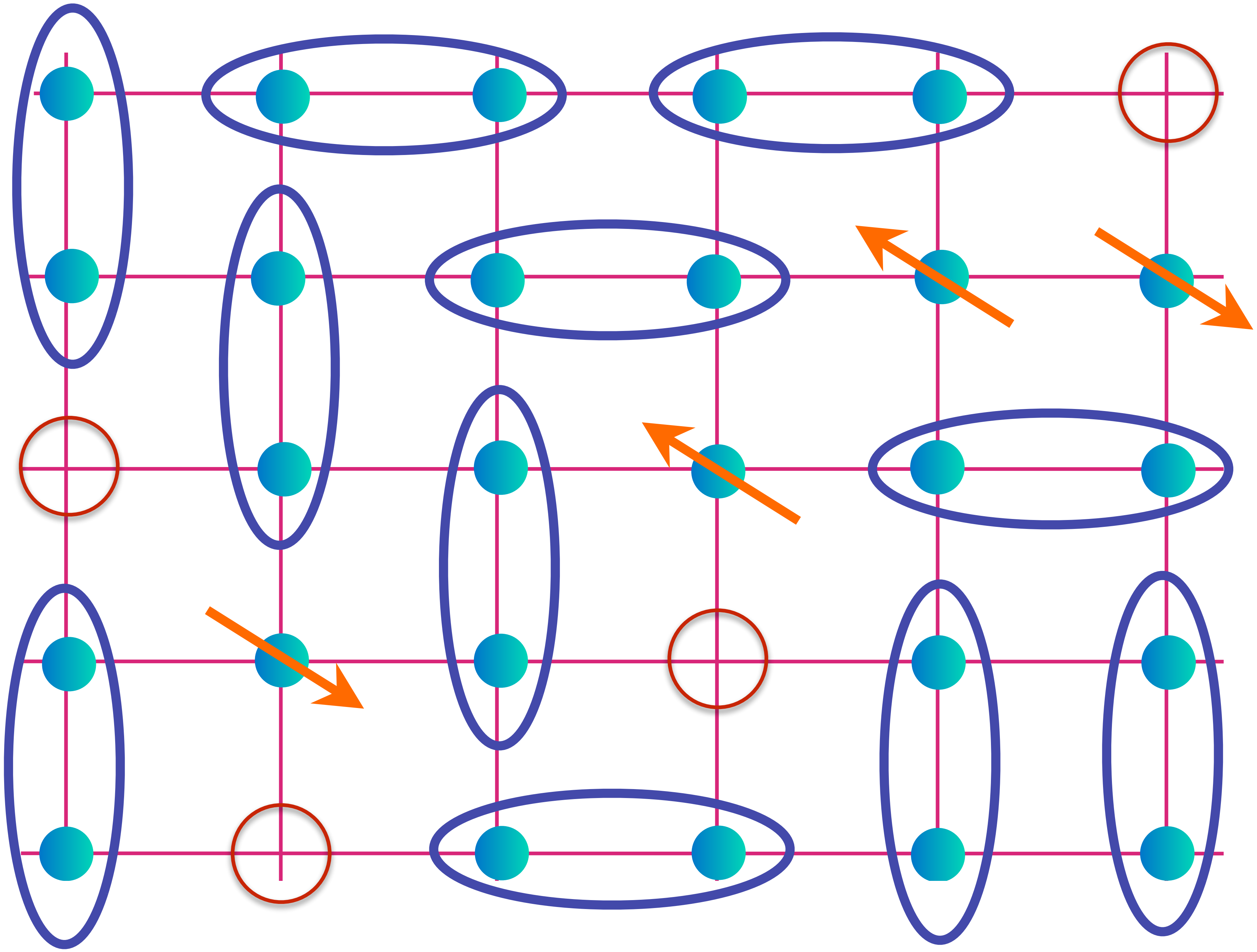
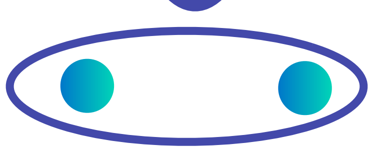
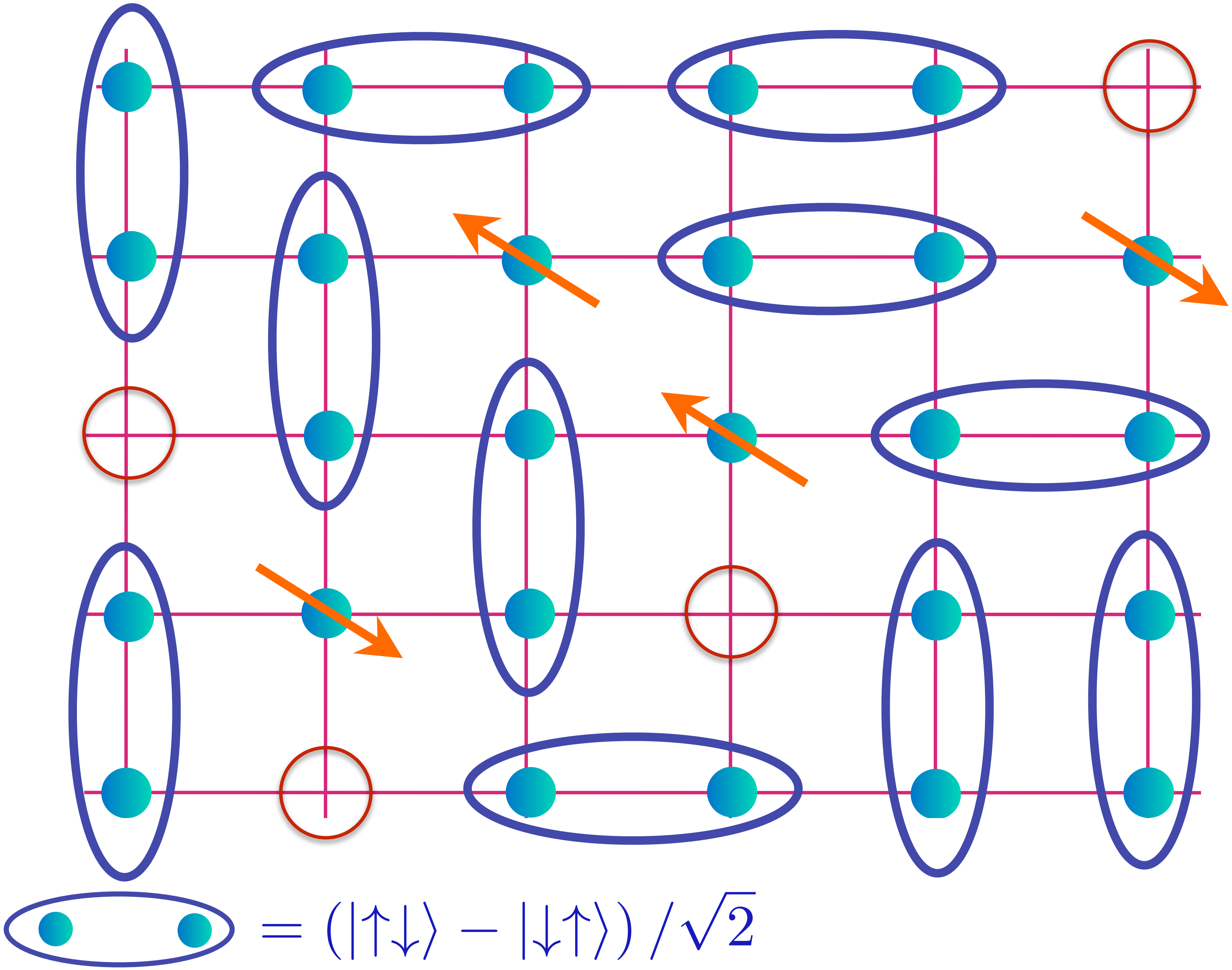


 $$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$



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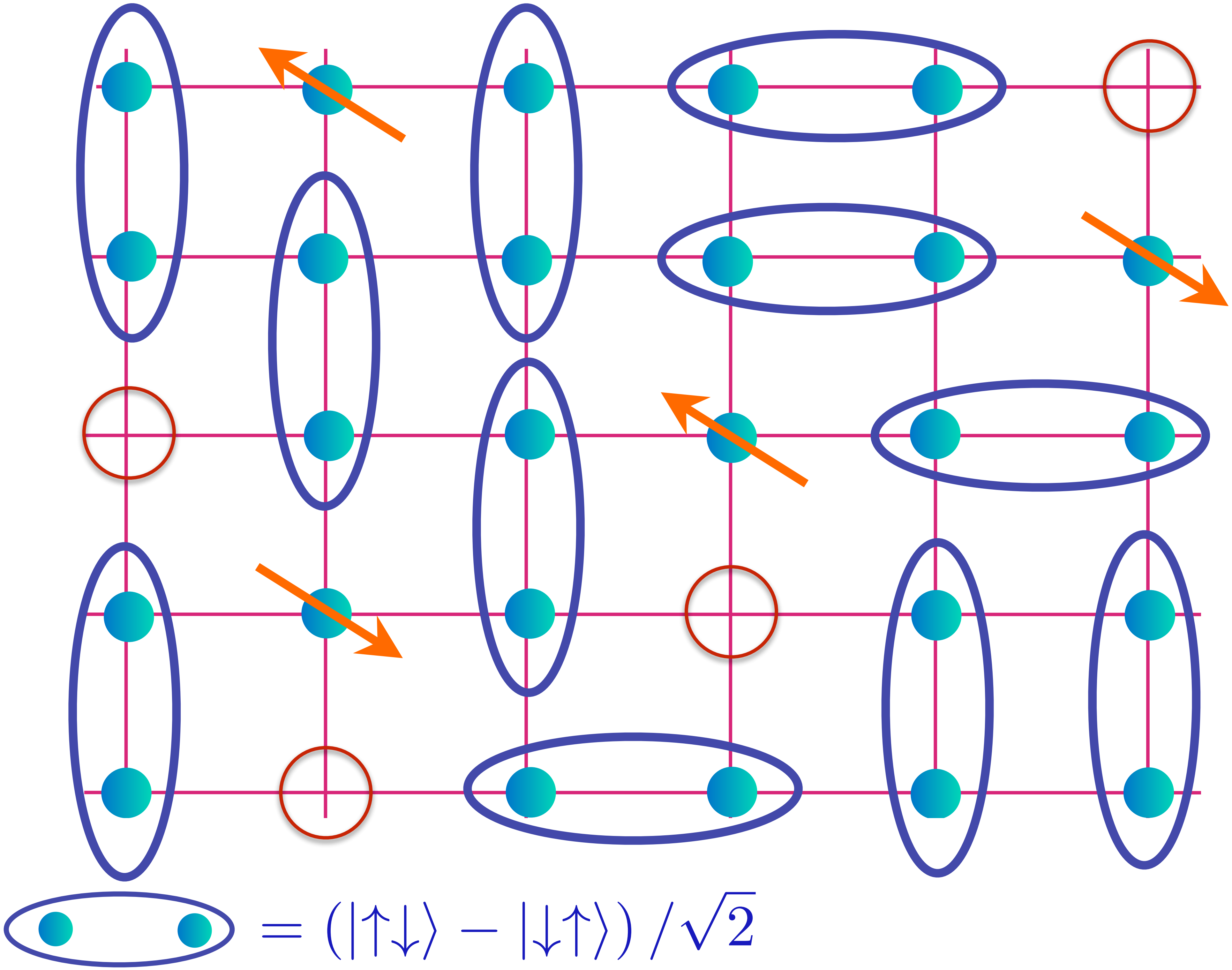
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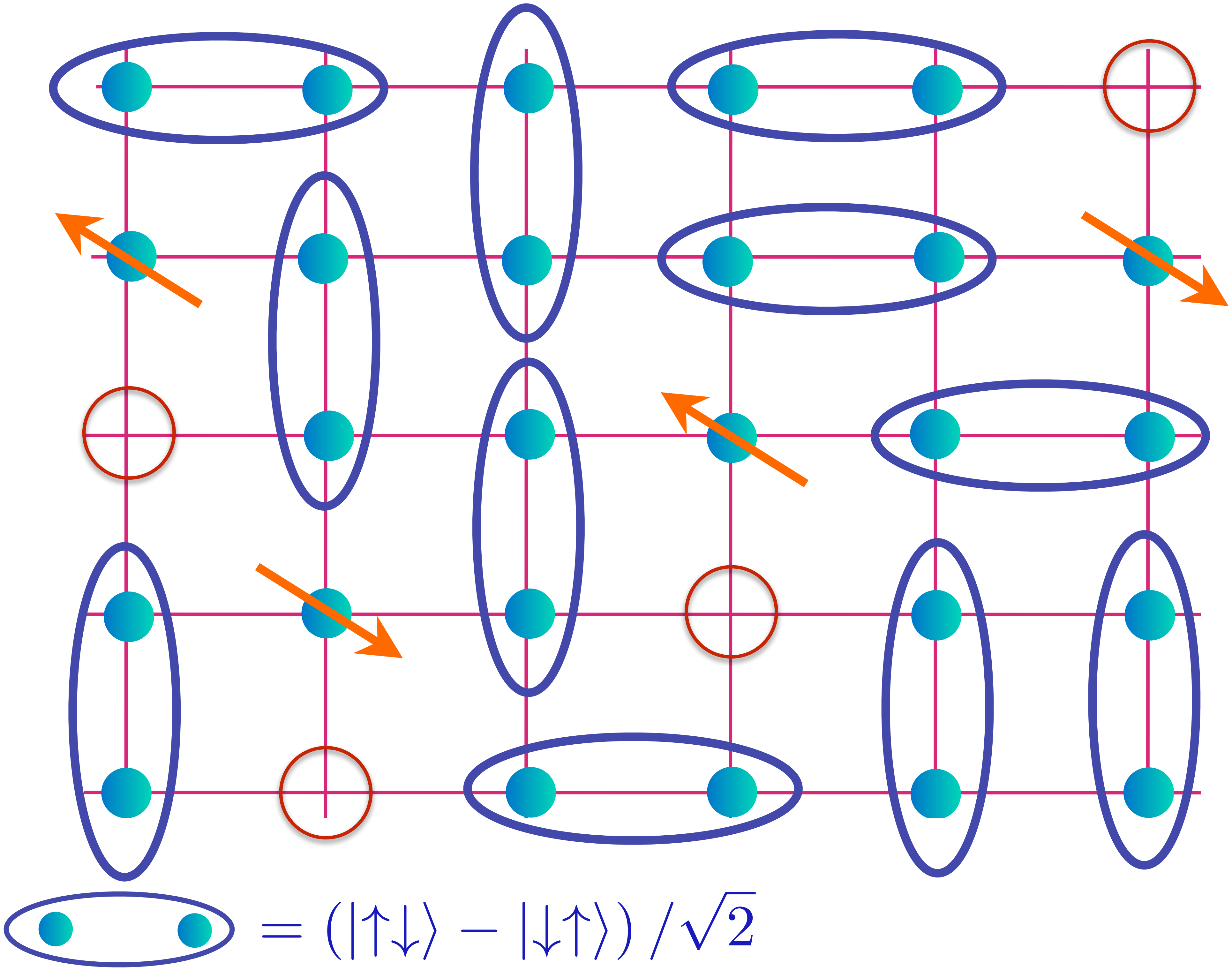
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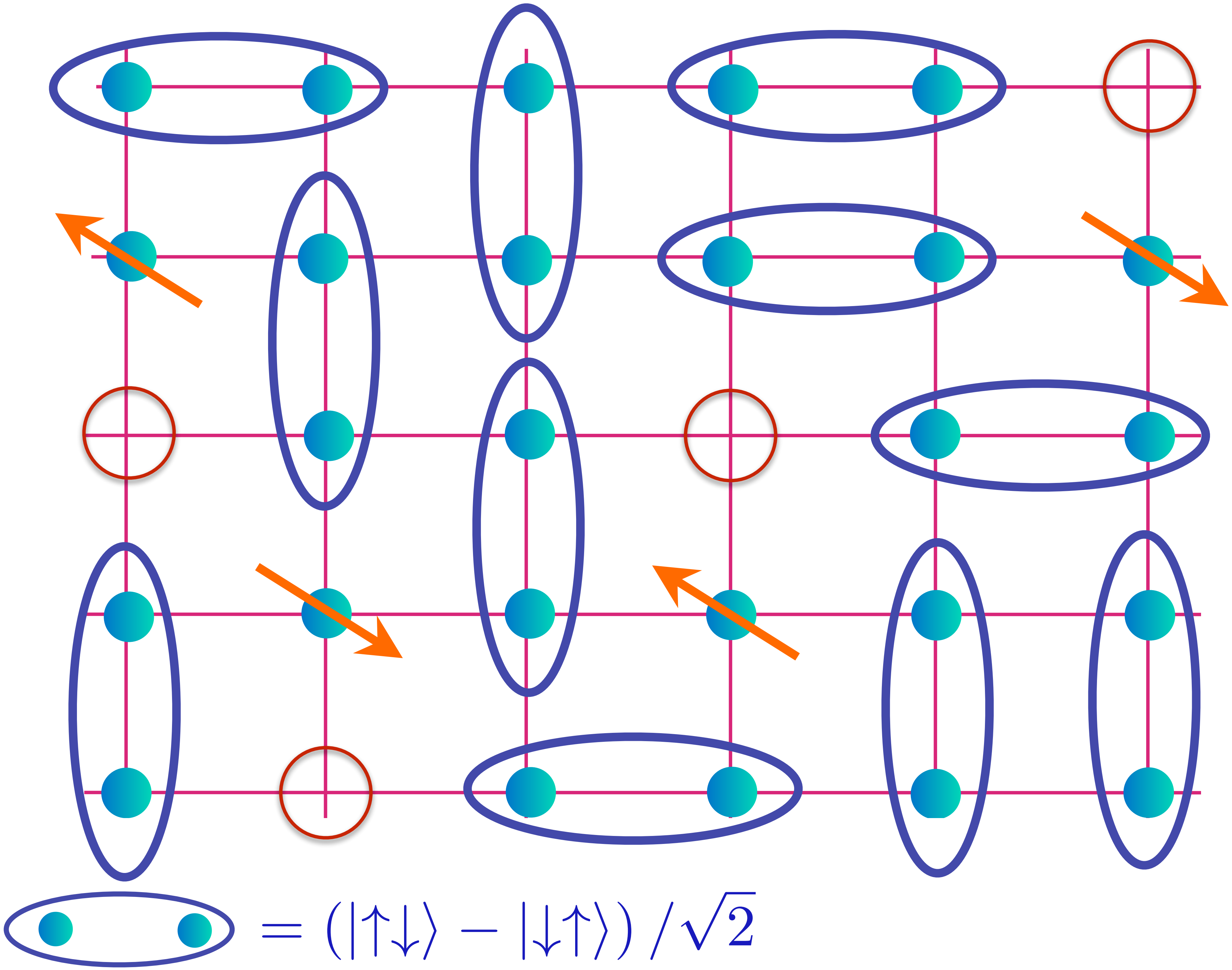

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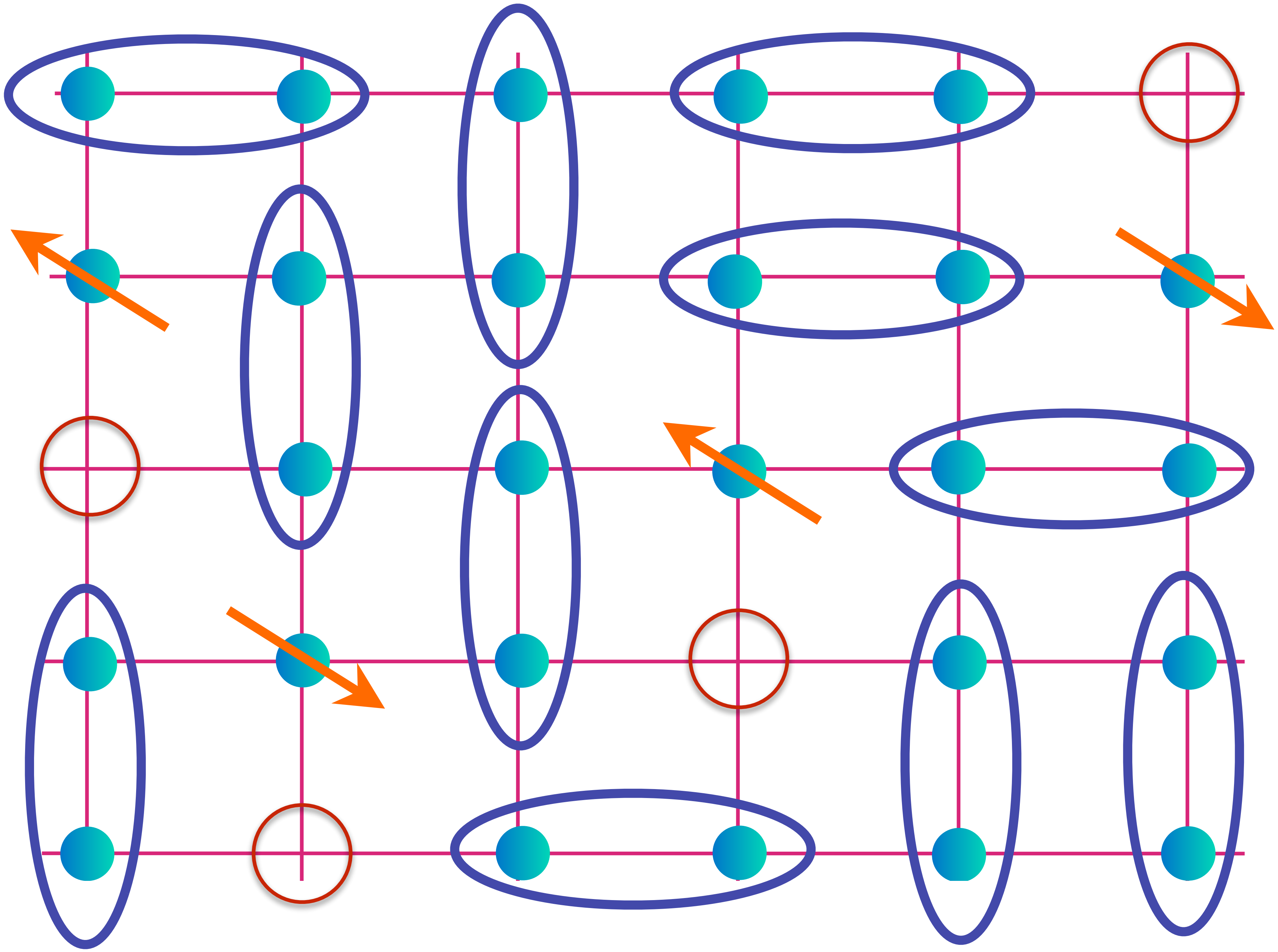

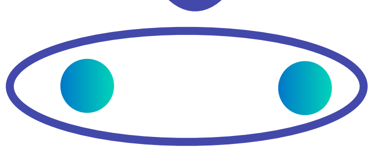 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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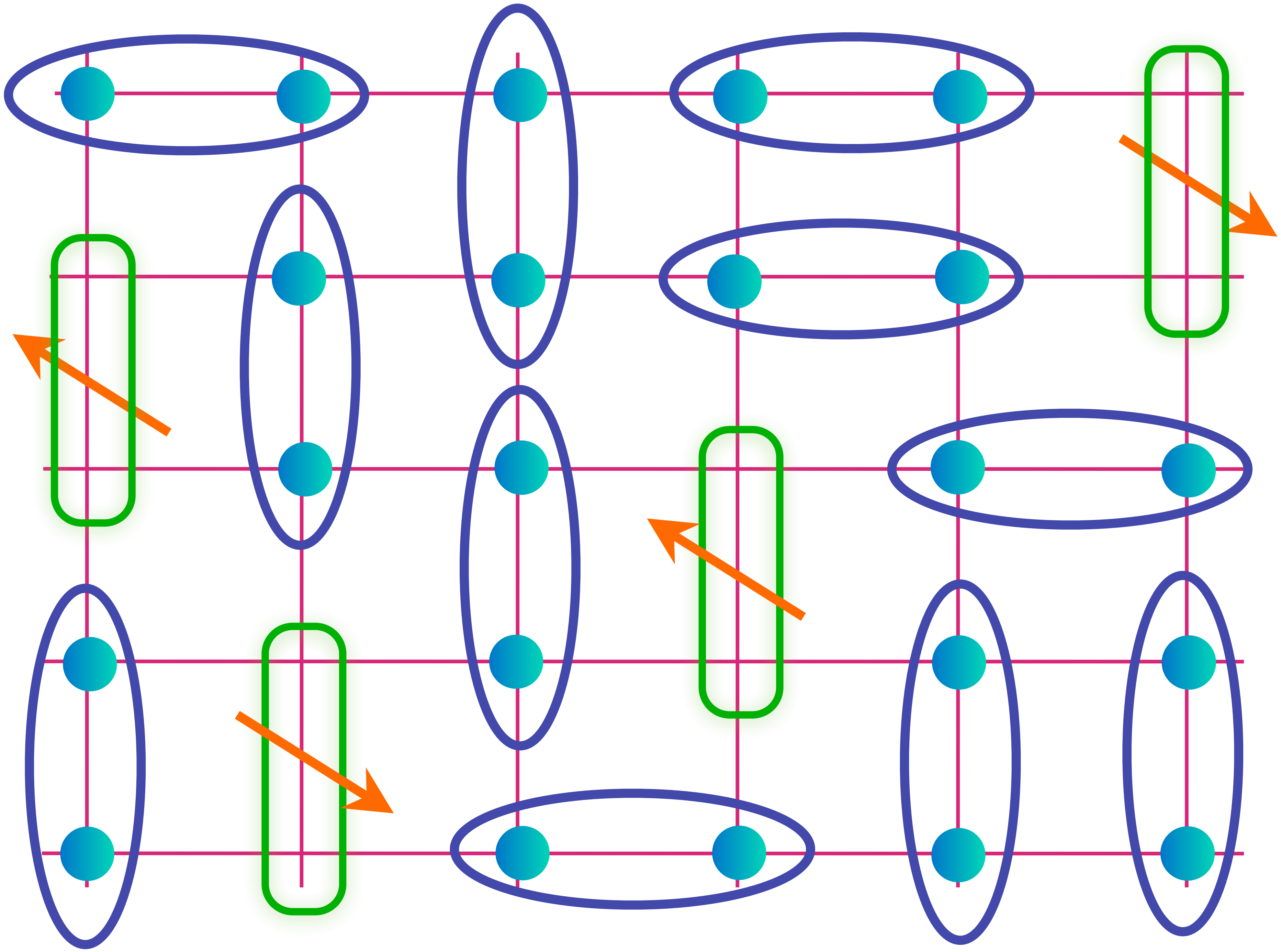
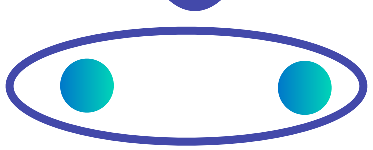
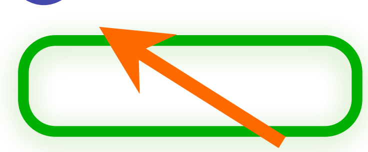
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Metal with emergent gauge fields — detectable by violation of Luttinger theorem by Fermi surface of size p

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

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

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

FL*

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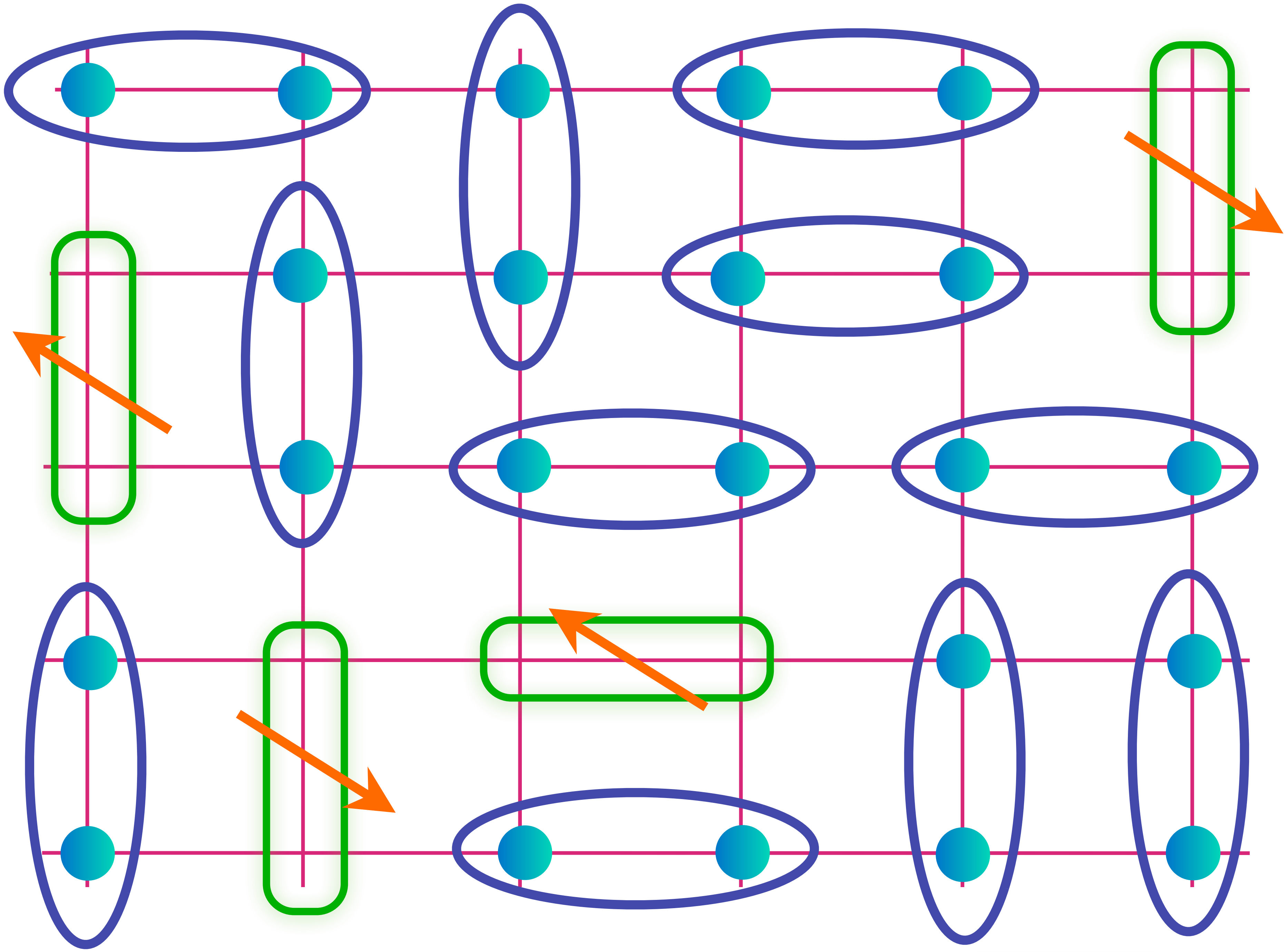
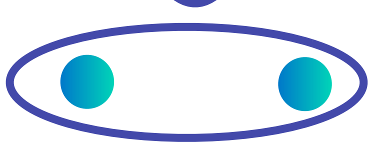
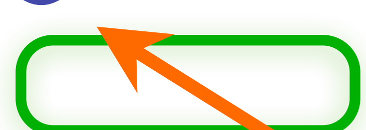


Metal with emergent gauge fields — detectable by violation of Luttinger theorem by Fermi surface of size p

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

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

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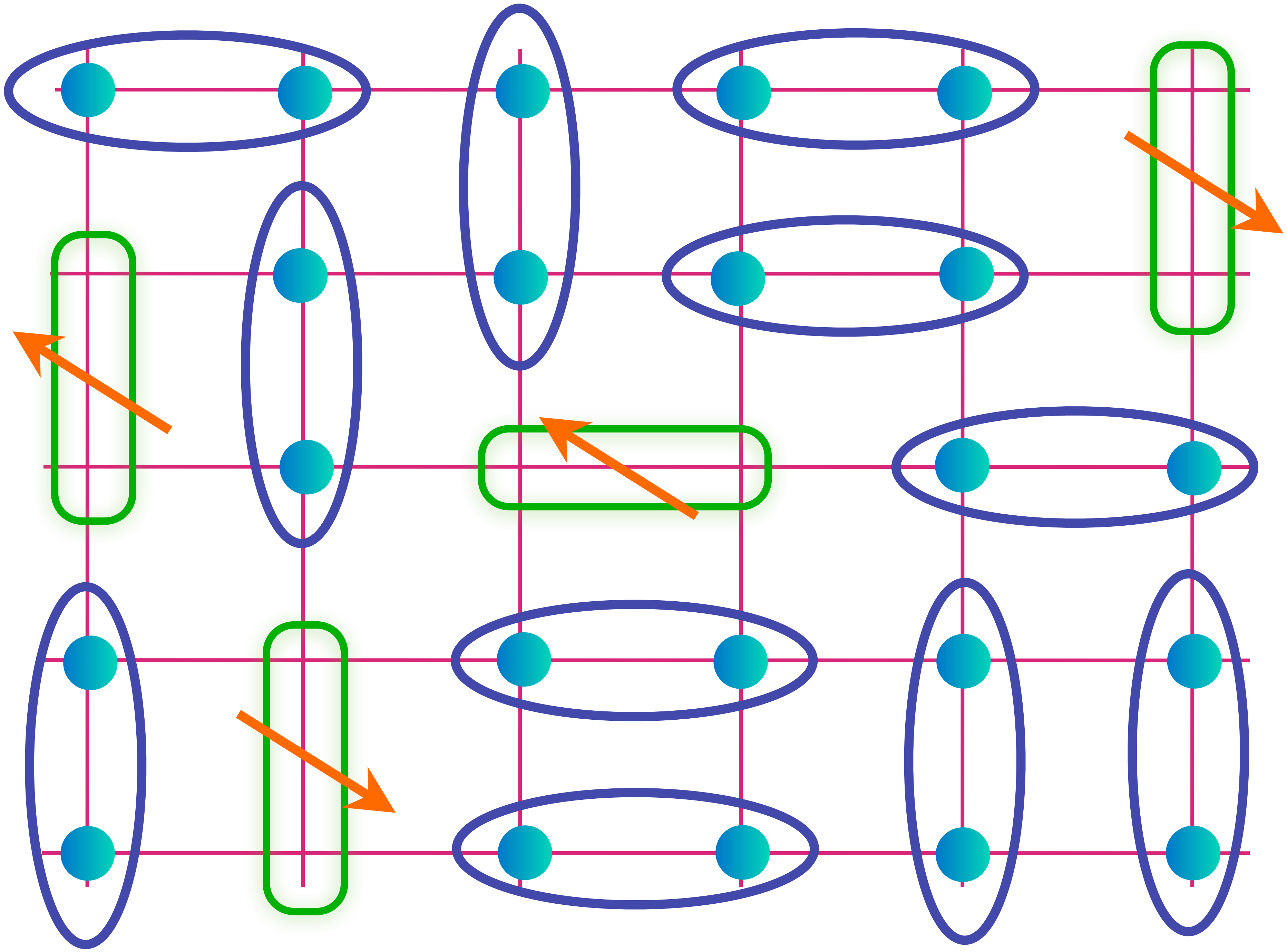

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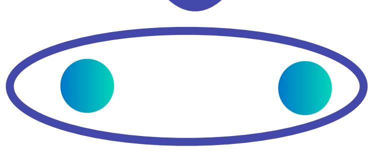
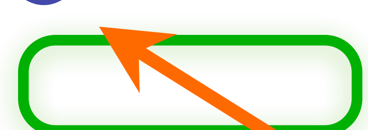
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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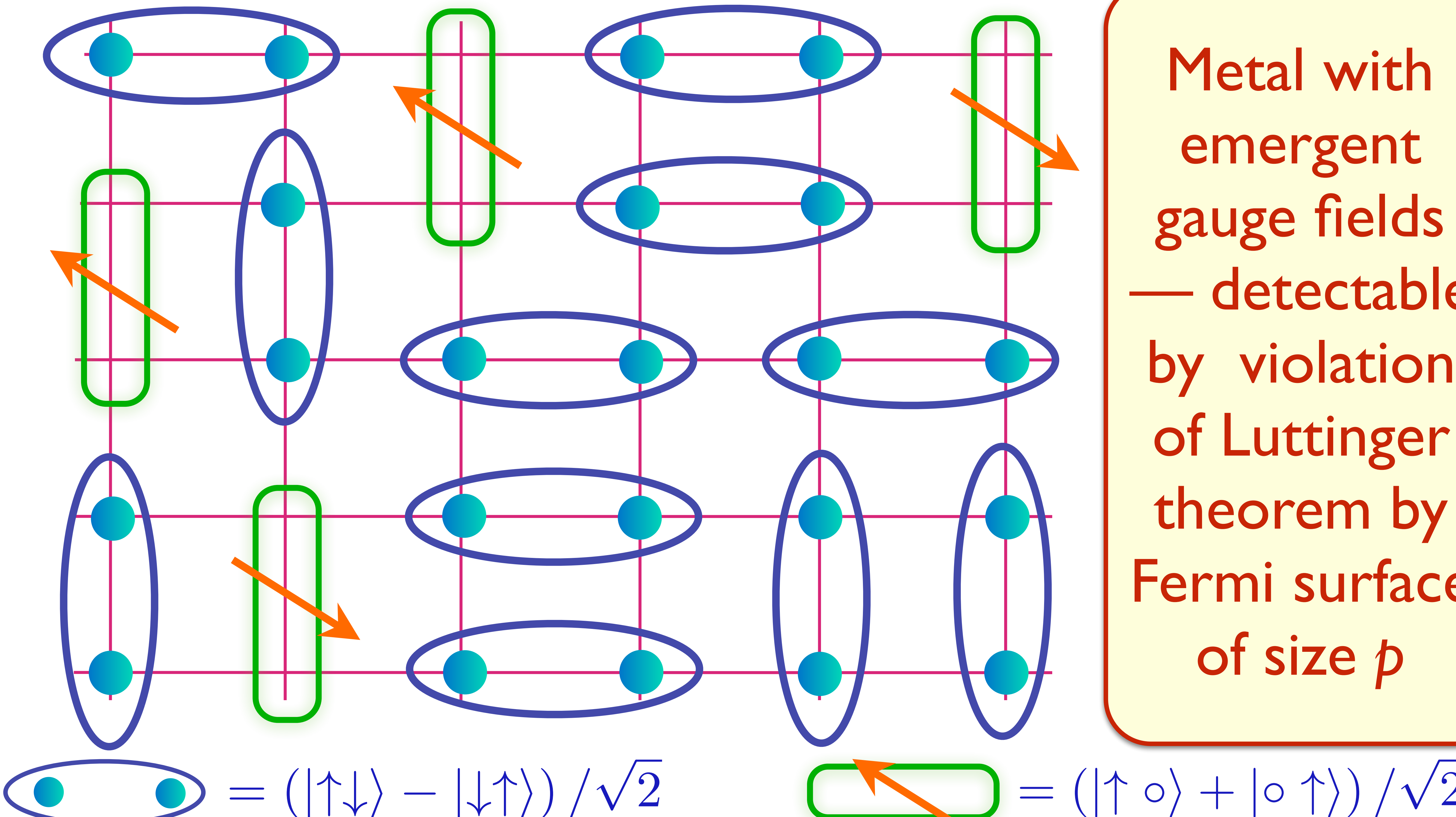

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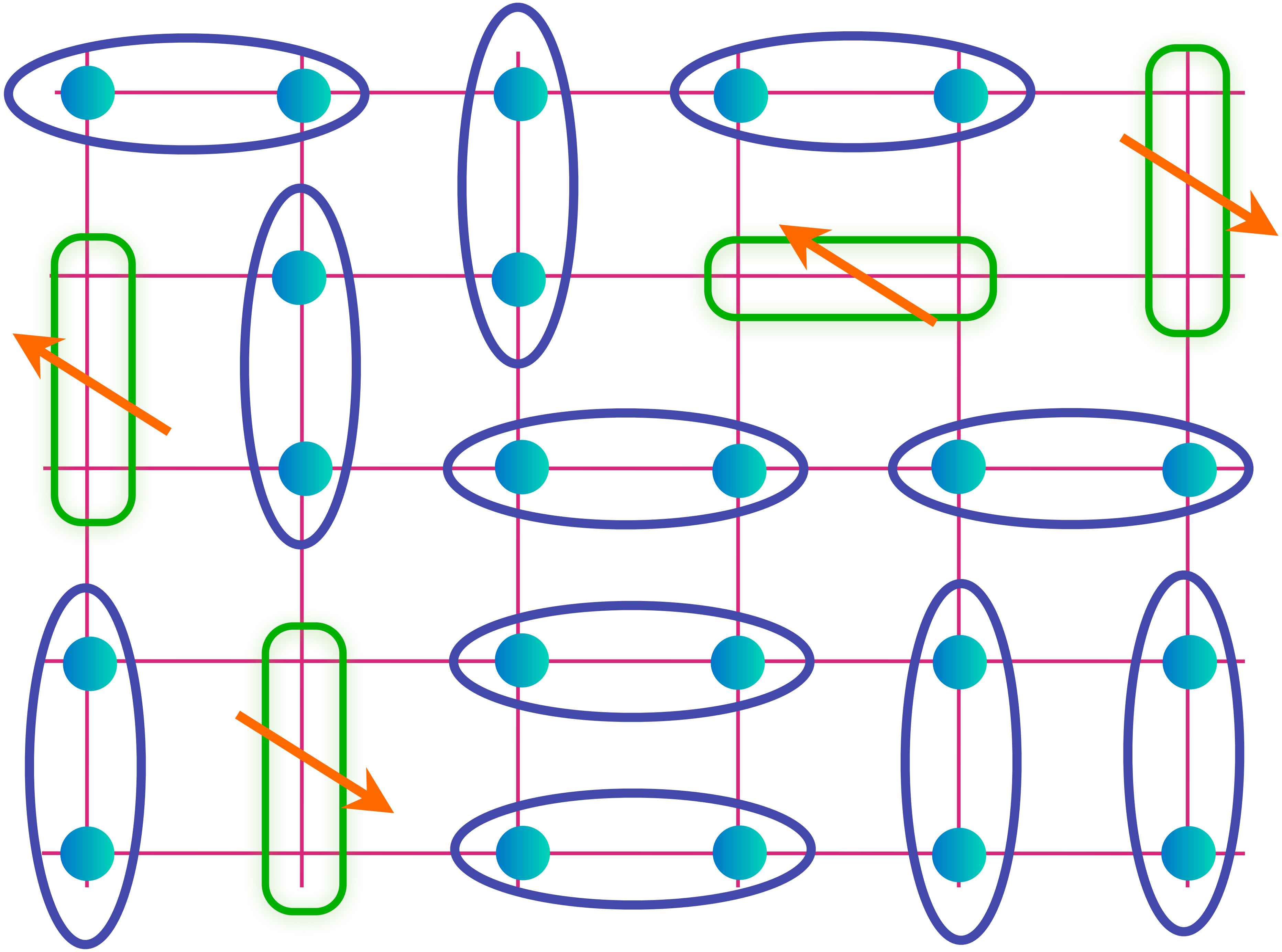
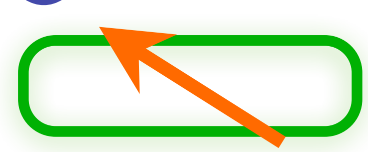


Metal with emergent gauge fields — detectable by violation of Luttinger theorem by Fermi surface of size p

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

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

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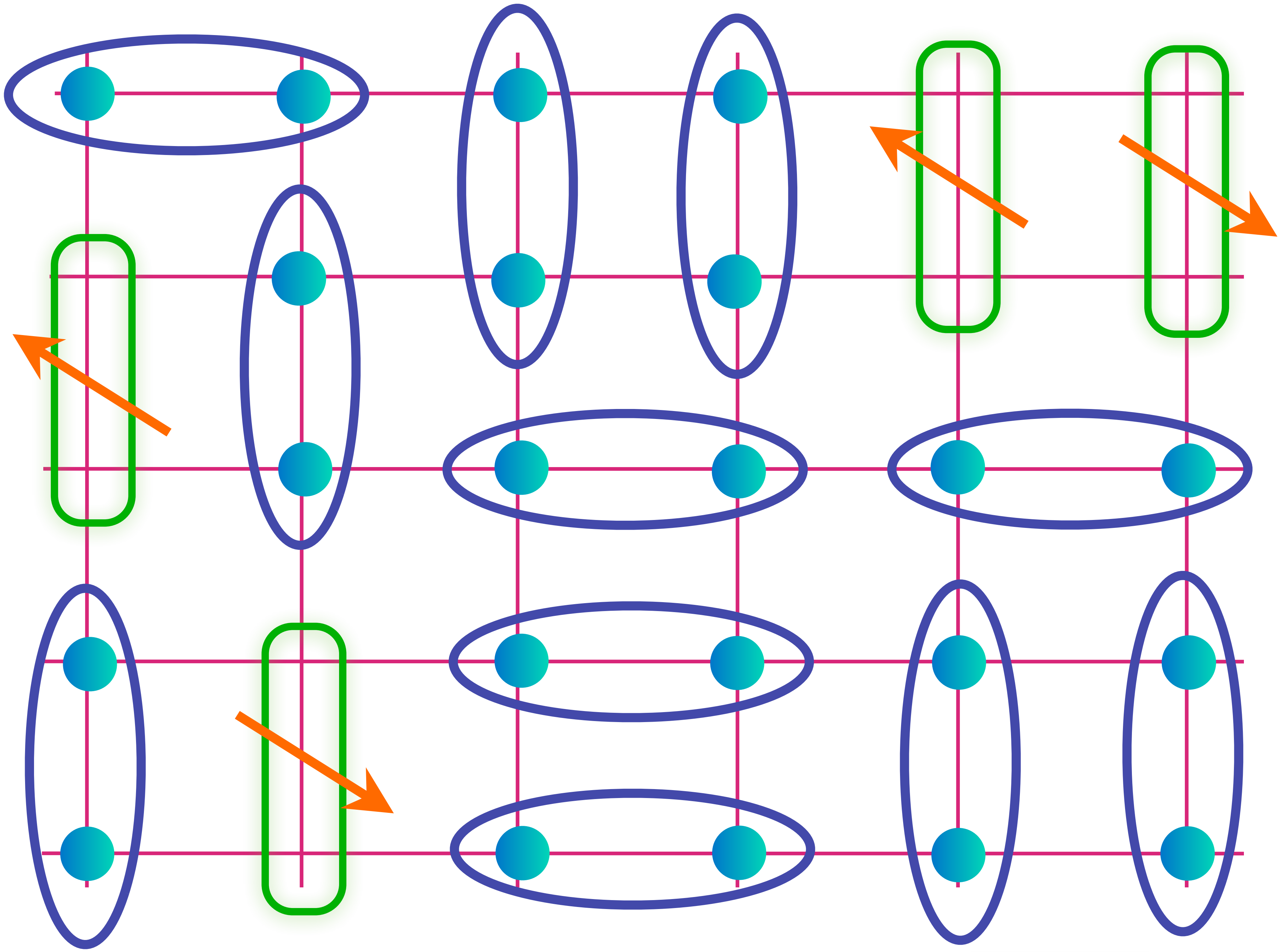

Metal with emergent gauge fields — detectable by violation of Luttinger theorem by Fermi surface of size p

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

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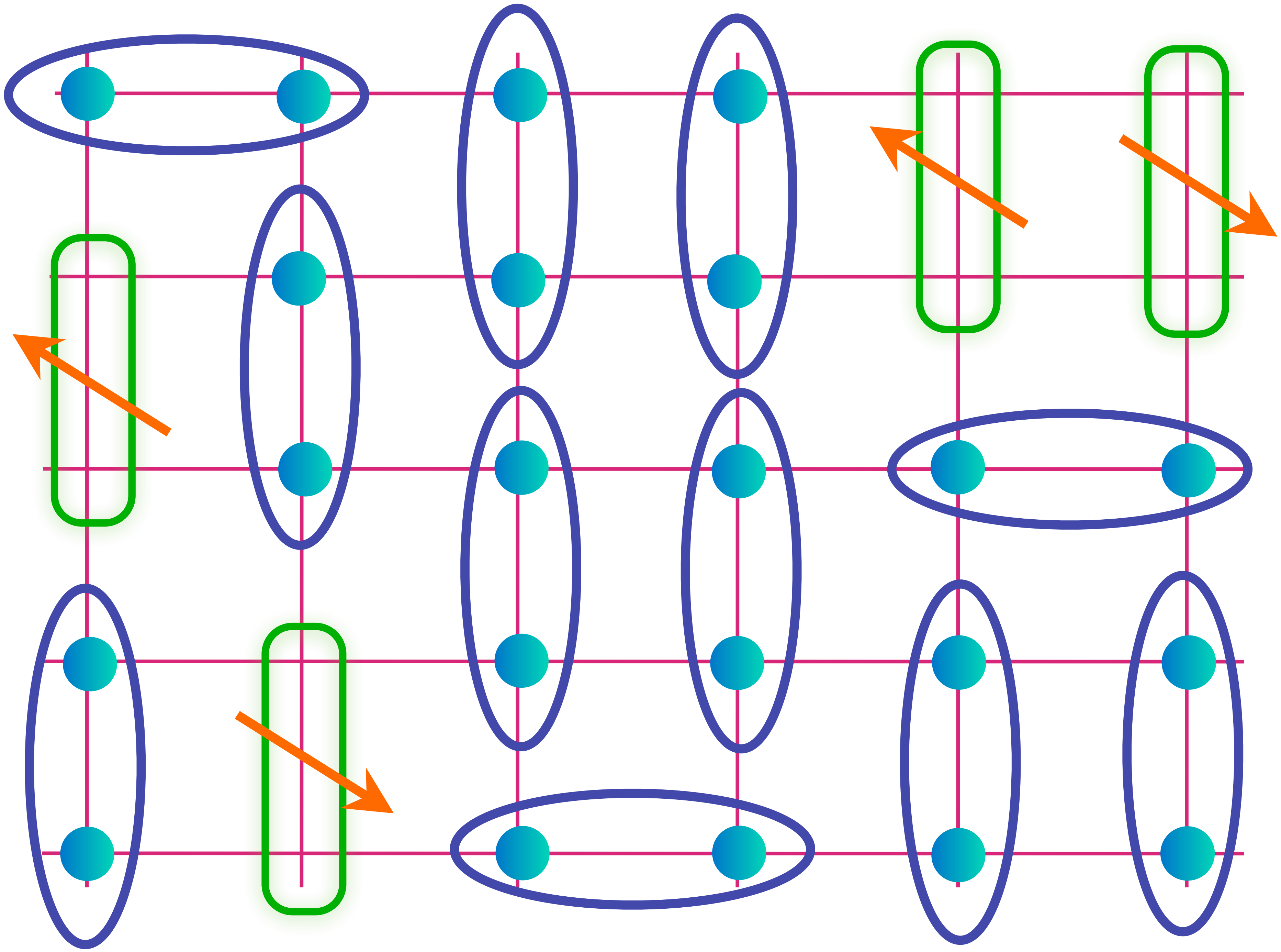

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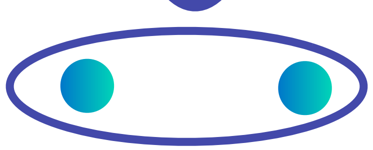
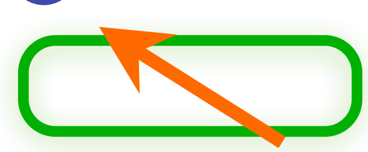
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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

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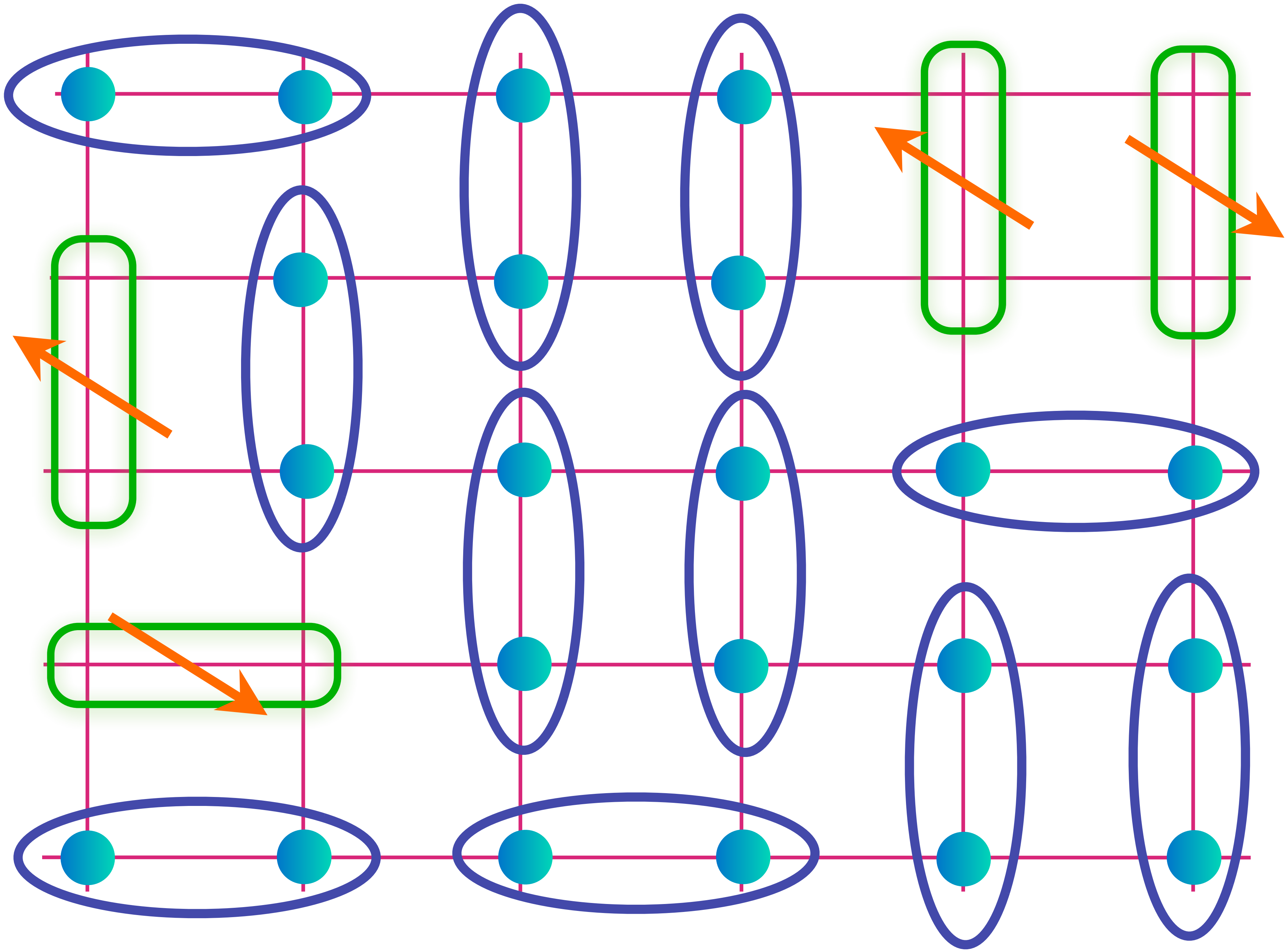

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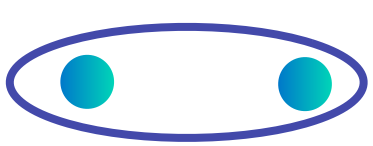
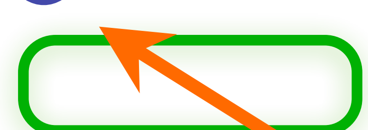
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

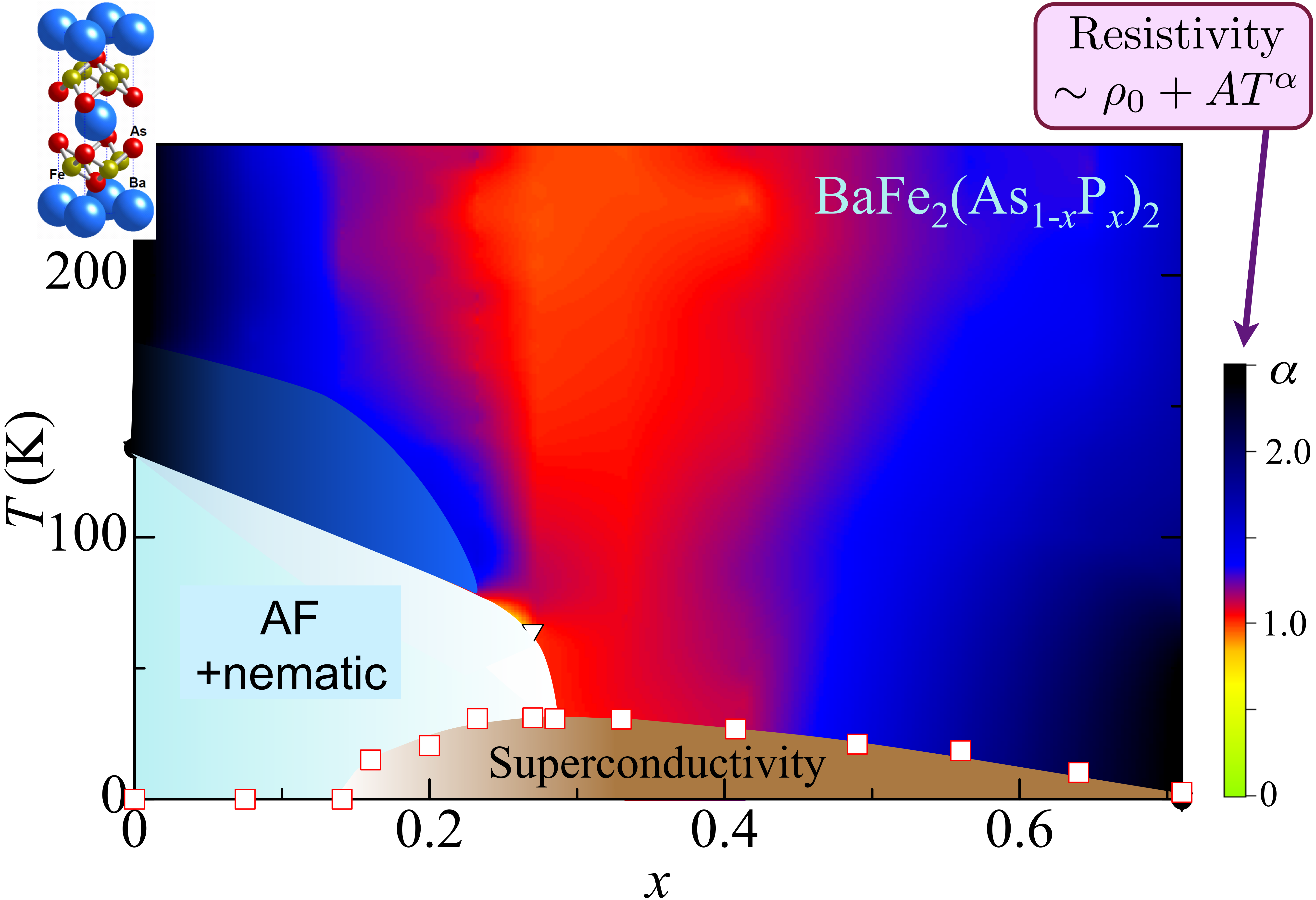
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

1. Sign-problem-free quantum Monte Carlo for the onset of anti ferromagnetism in metals.

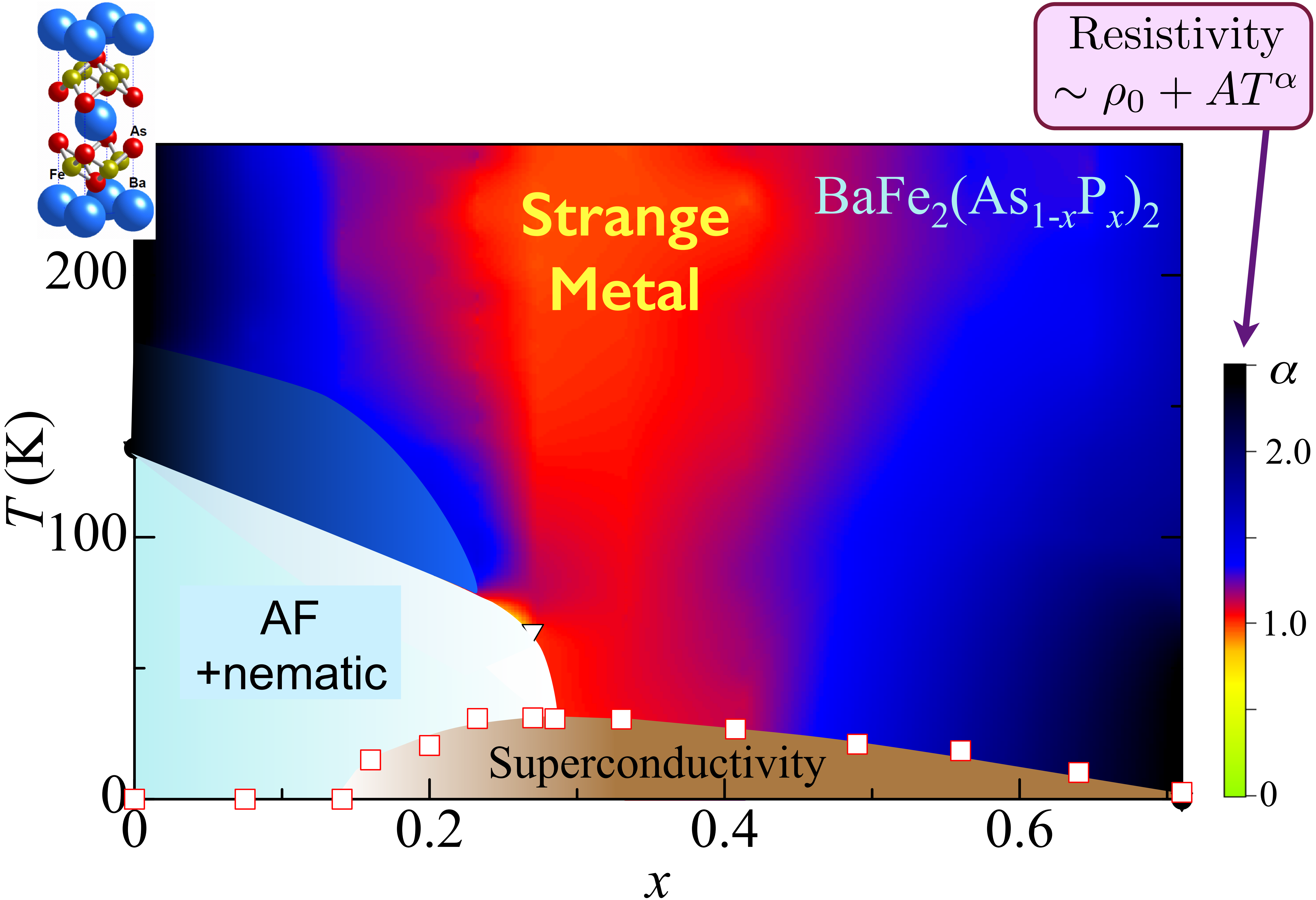
2. Mott insulators: "intertwined orders", long-range entanglement, and emergent gauge fields

3. Quantum matter without quasiparticles:

   strange metals in superconductors and graphene,
   the quark-gluon plasma, and
   the superfluid-insulator transition of ultra-cold atoms, and
   the dynamics of charged black holes horizons



S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)



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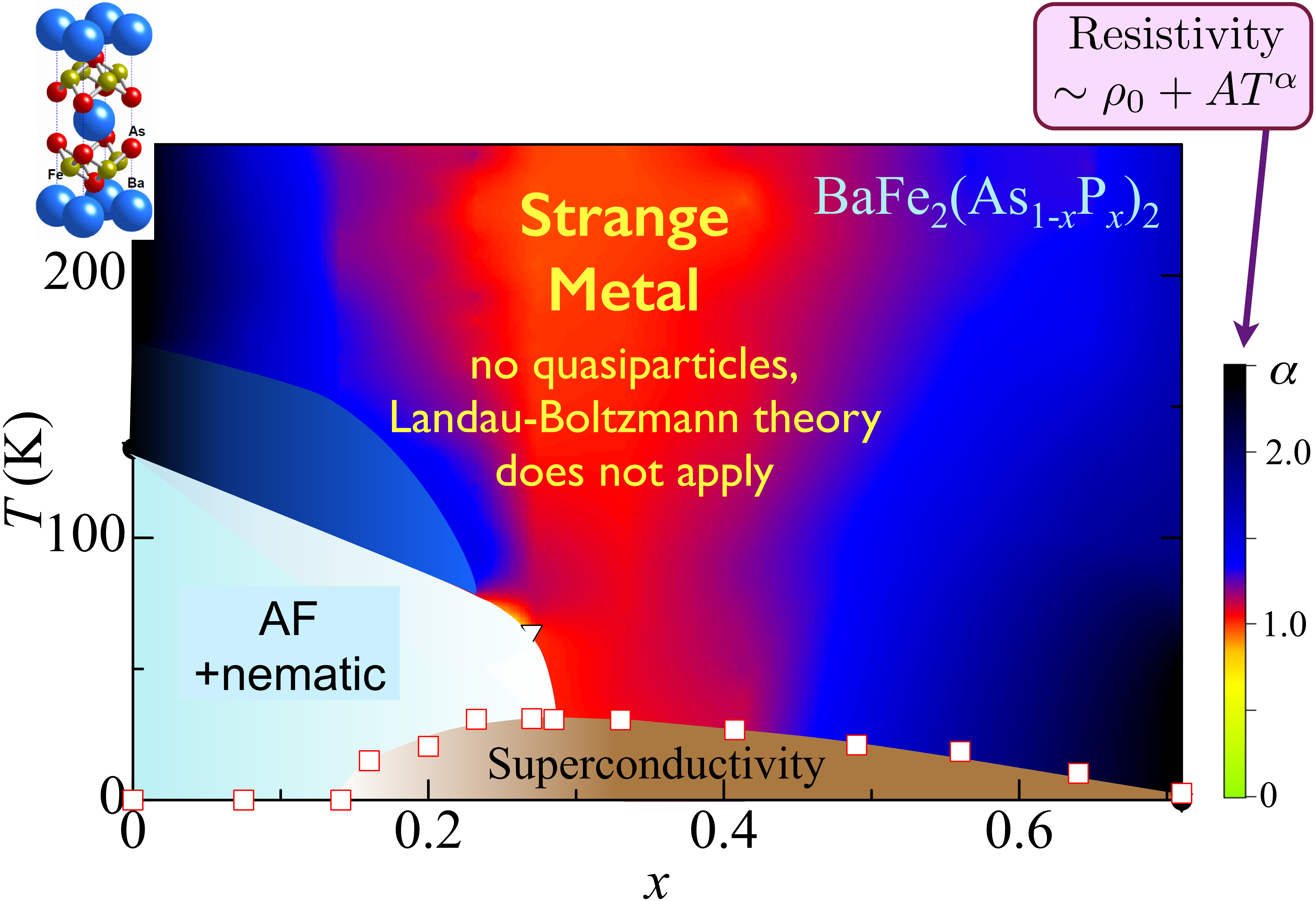

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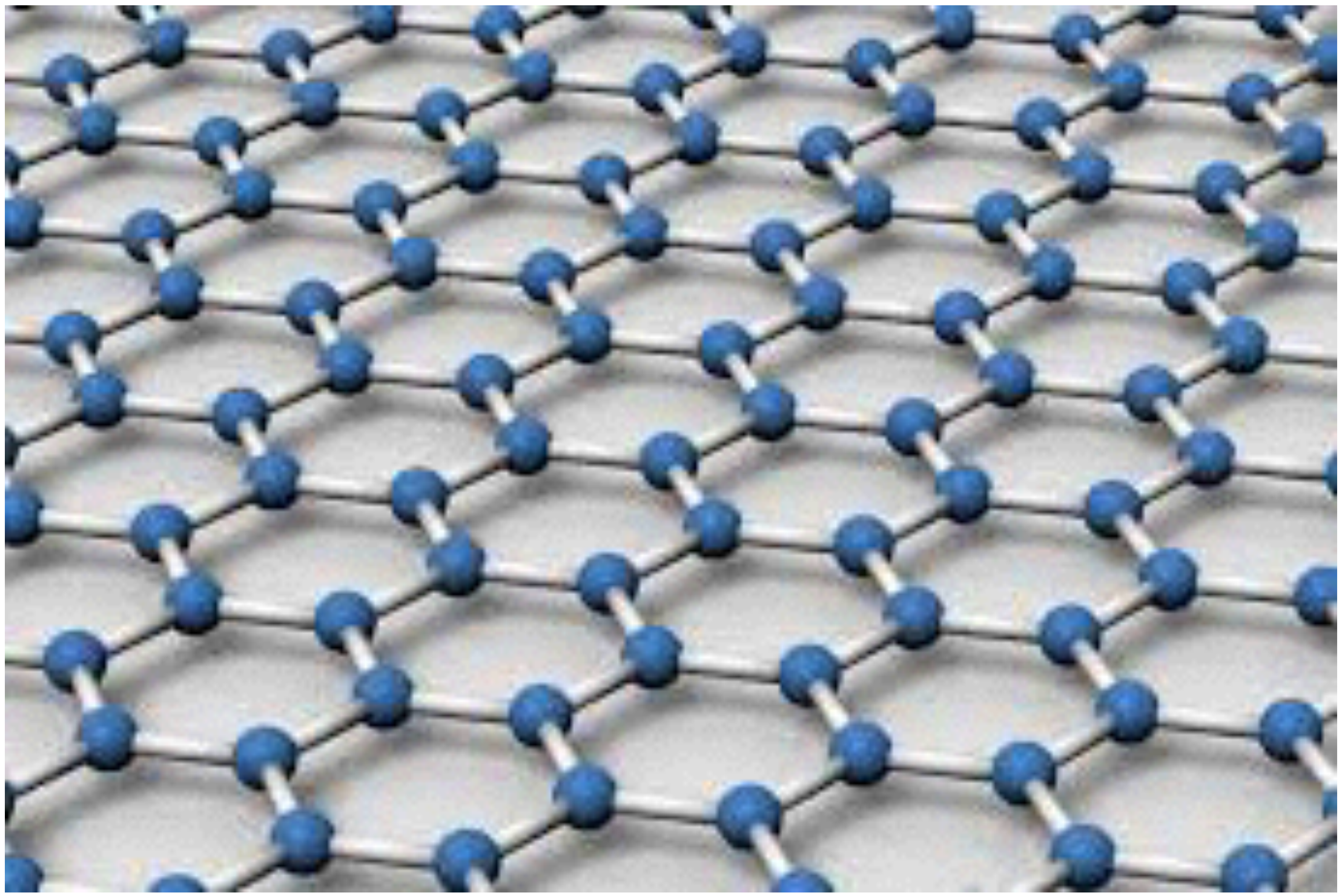
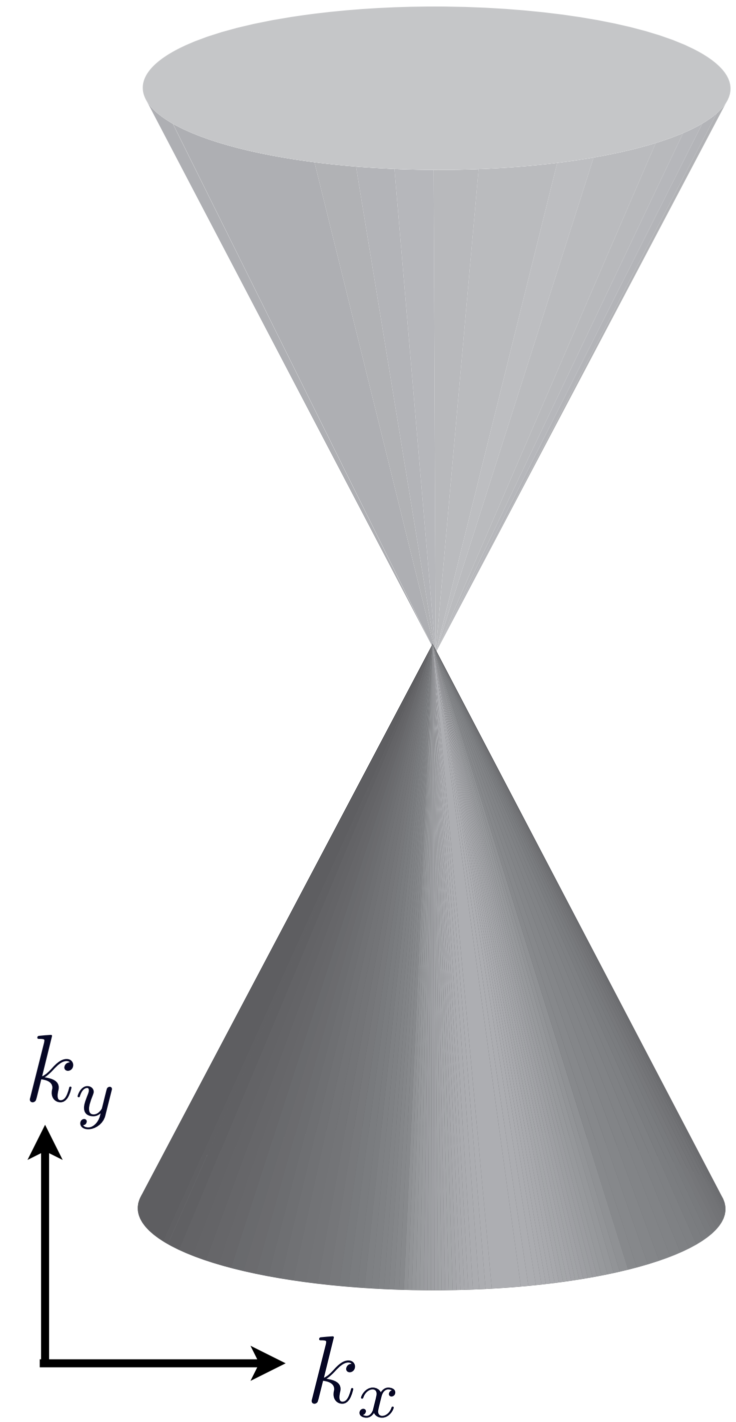
Quantum matter without quasiparticles:

- Strange metals in high temperature superconductors
- Graphene
- Superfluid-insulator transition of ultracold atoms in an optical lattice
- Quark-gluon plasma
- *Charged black hole horizons in anti-de Sitter space*

Graphene

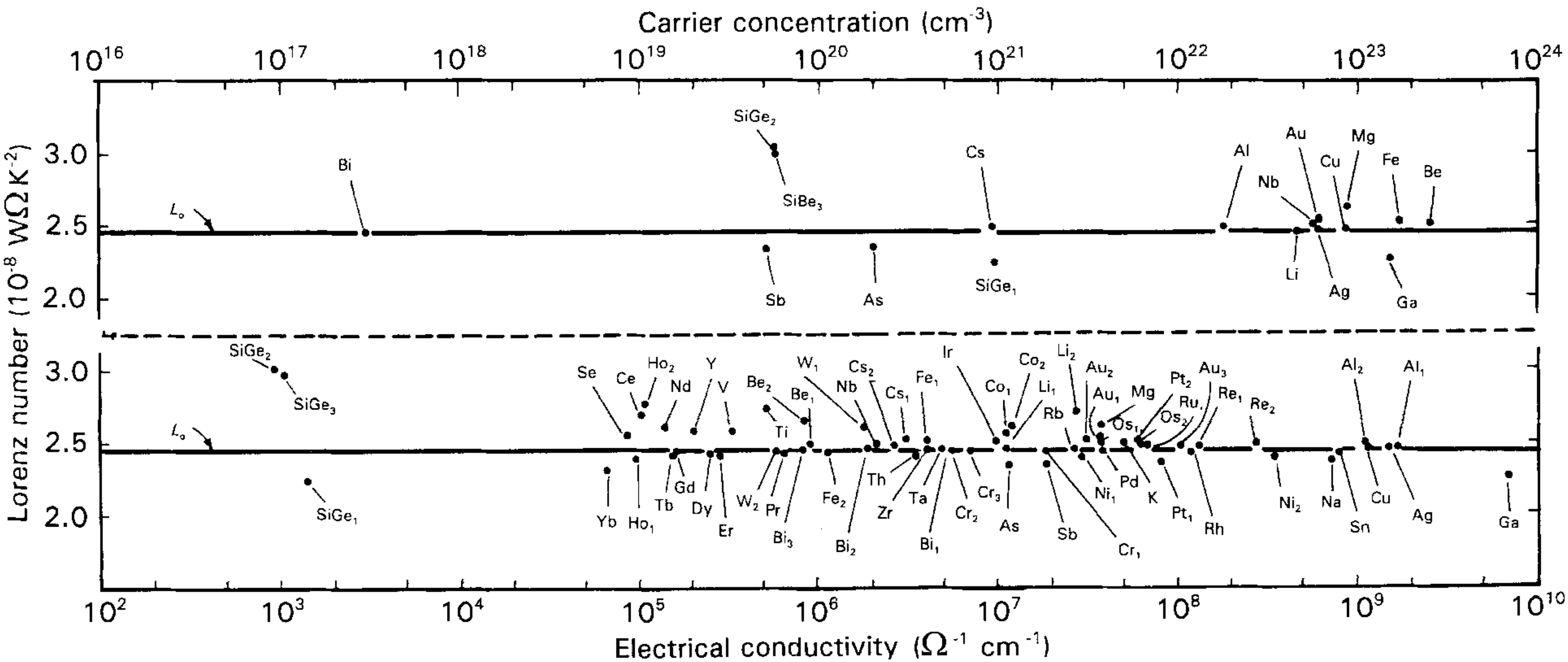




Transport with quasiparticles

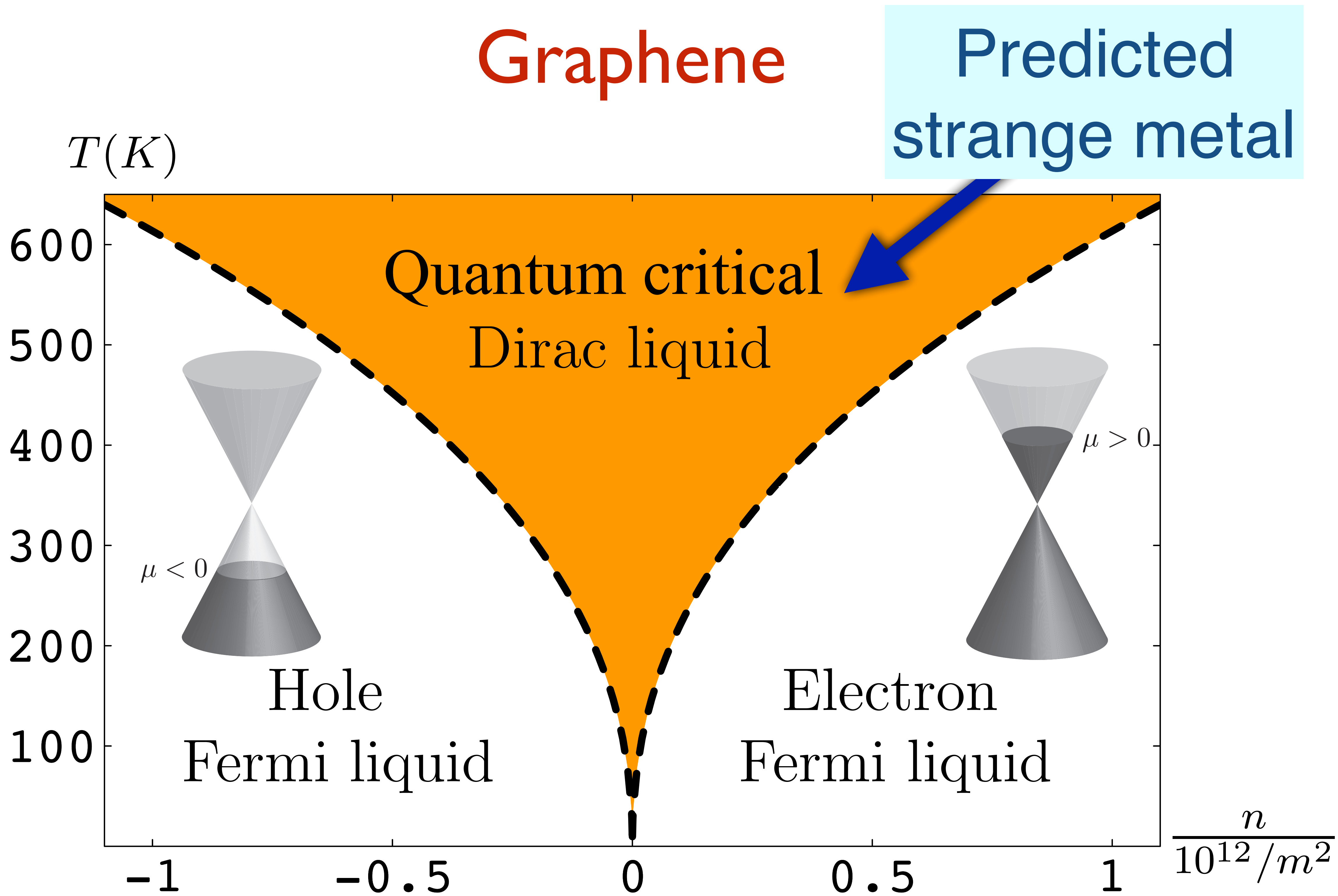
- Wiedemann-Franz law in a Fermi liquid:

$$L_0 = \frac{\kappa}{\sigma T} \approx \frac{\pi^2 k_B^2}{3e^2} \approx 2.45 \times 10^{-8}\ \frac{\mathrm{W}\cdot\Omega}{\mathrm{K}^2}.$$



G. S. Kumar, G. Prasad, and R.O. Pohl, J. Mat. Sci. **28**, 4261 (1993)

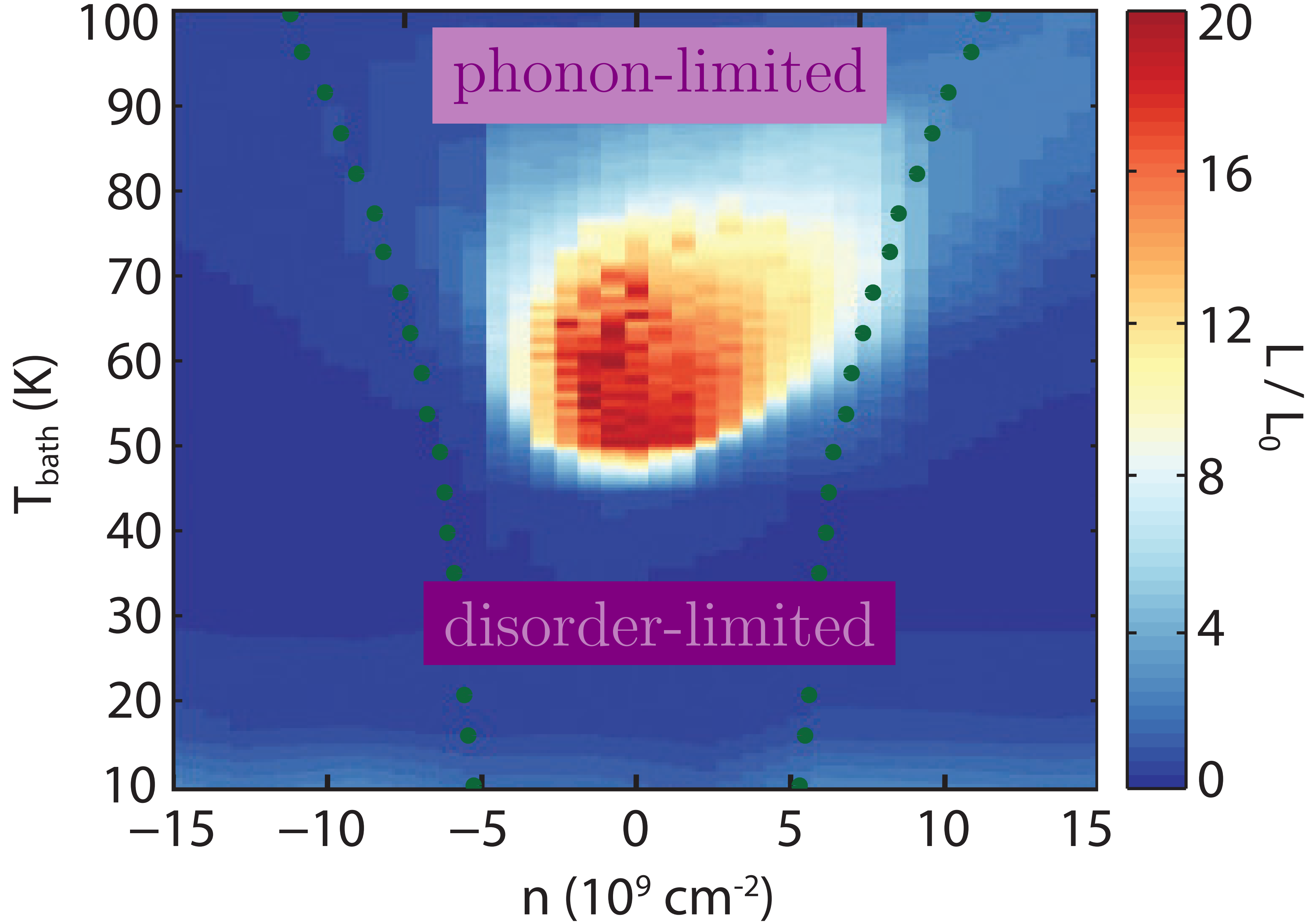
Graphene



M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim,
Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, arXiv:1509.04713; Science, to appear

Strange metal in graphene



$$L = \frac{(\text{Thermal conductivity})}{T\,(\text{Electrical conductivity})}; \quad L_0 \equiv \frac{\pi^2 k_B^2}{3e^2}$$

J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim,
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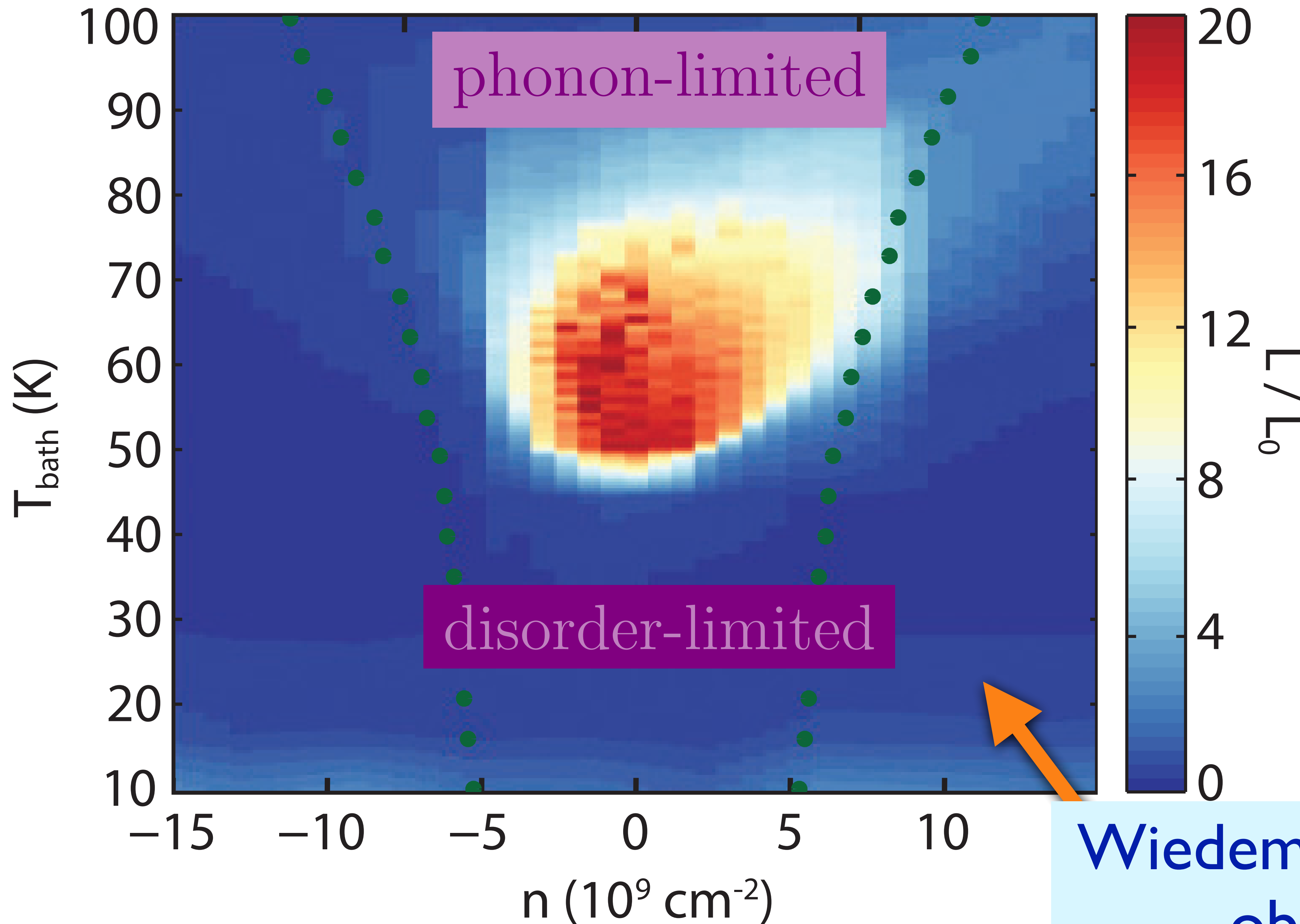
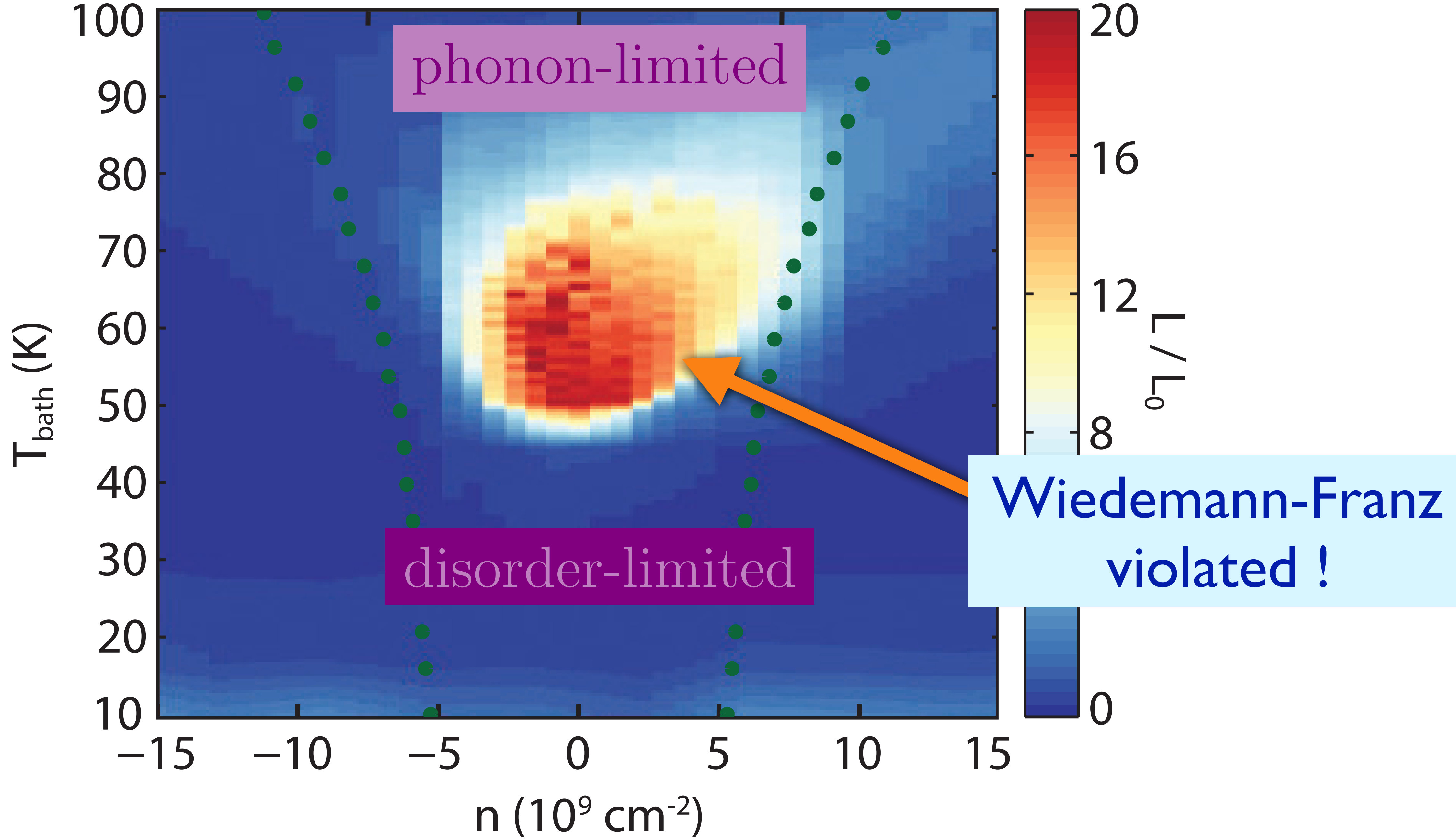


Wiedemann-Franz obeyed

$$L = \frac{\text{(Thermal conductivity)}}{T\,\text{(Electrical conductivity)}}; \quad L_0 \equiv \frac{\pi^2 k_B^2}{3e^2}$$

J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, arXiv:1509.04713; Science, to appear

Strange metal in graphene



$$L = \frac{(\text{Thermal conductivity})}{T\,(\text{Electrical conductivity})}; \qquad L_0 \equiv \frac{\pi^2 k_B^2}{3e^2}$$

Transport in Strange Metals

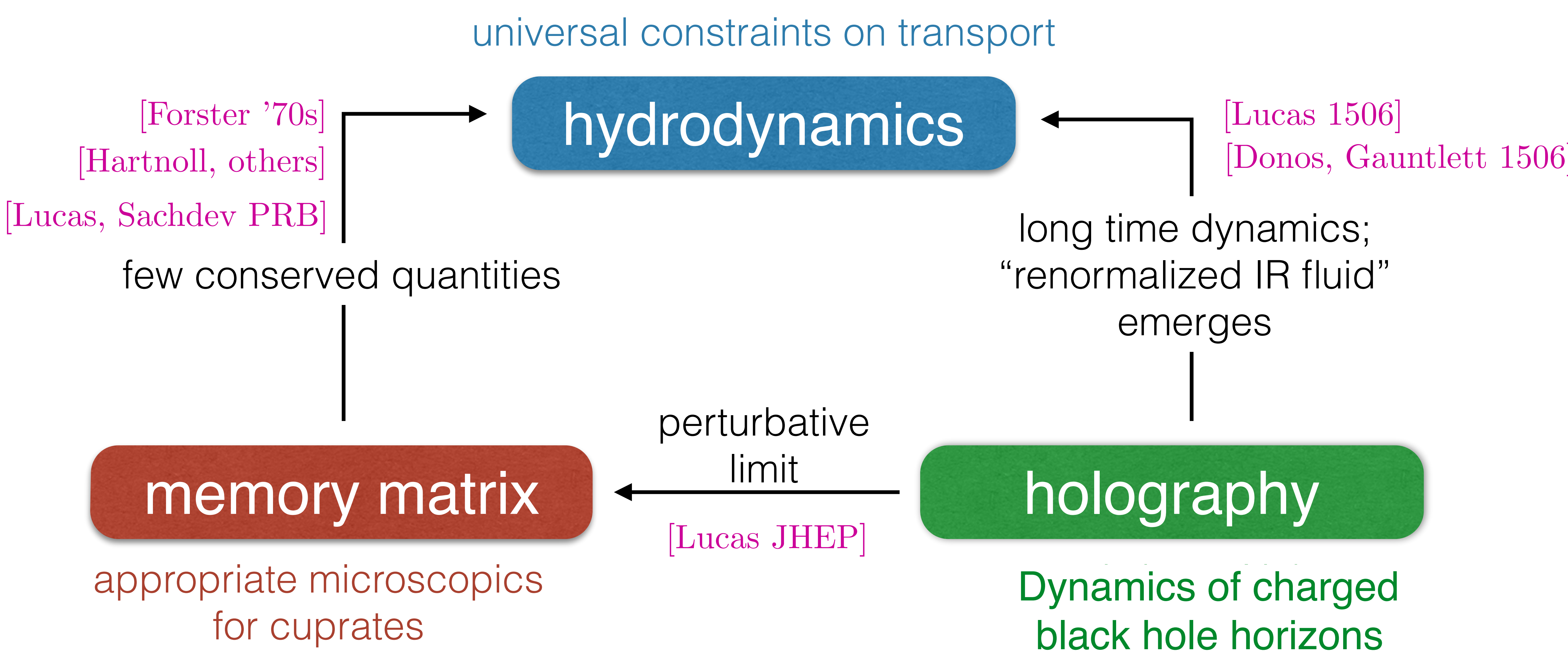
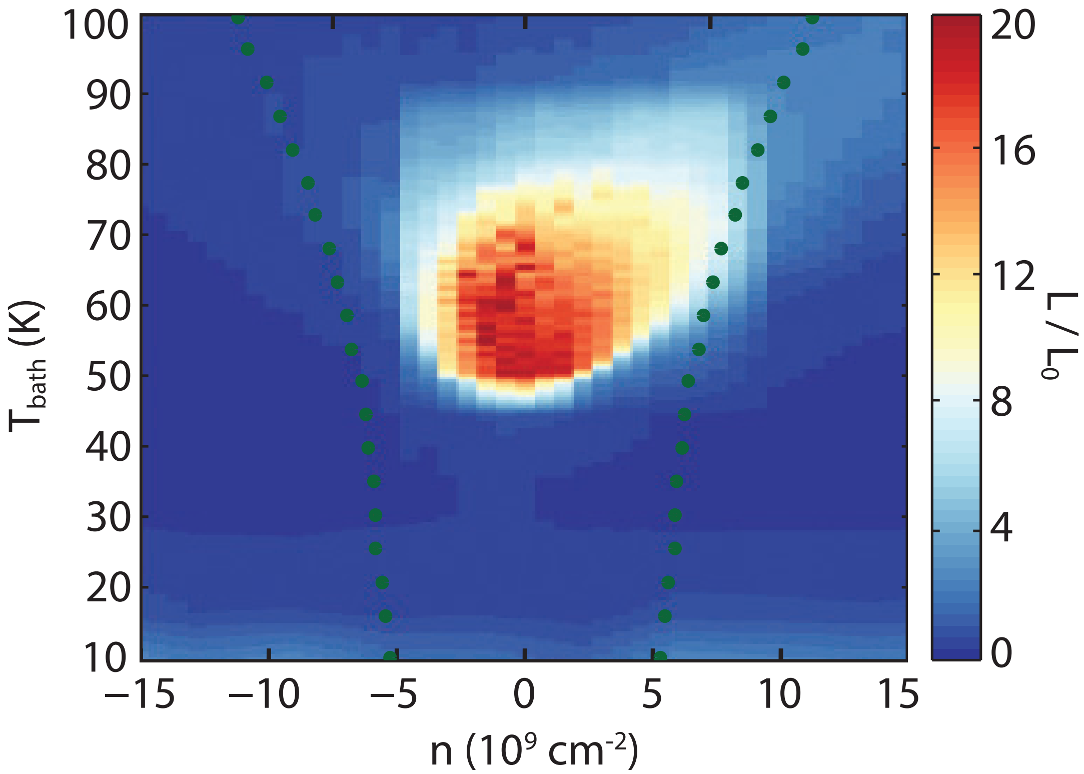
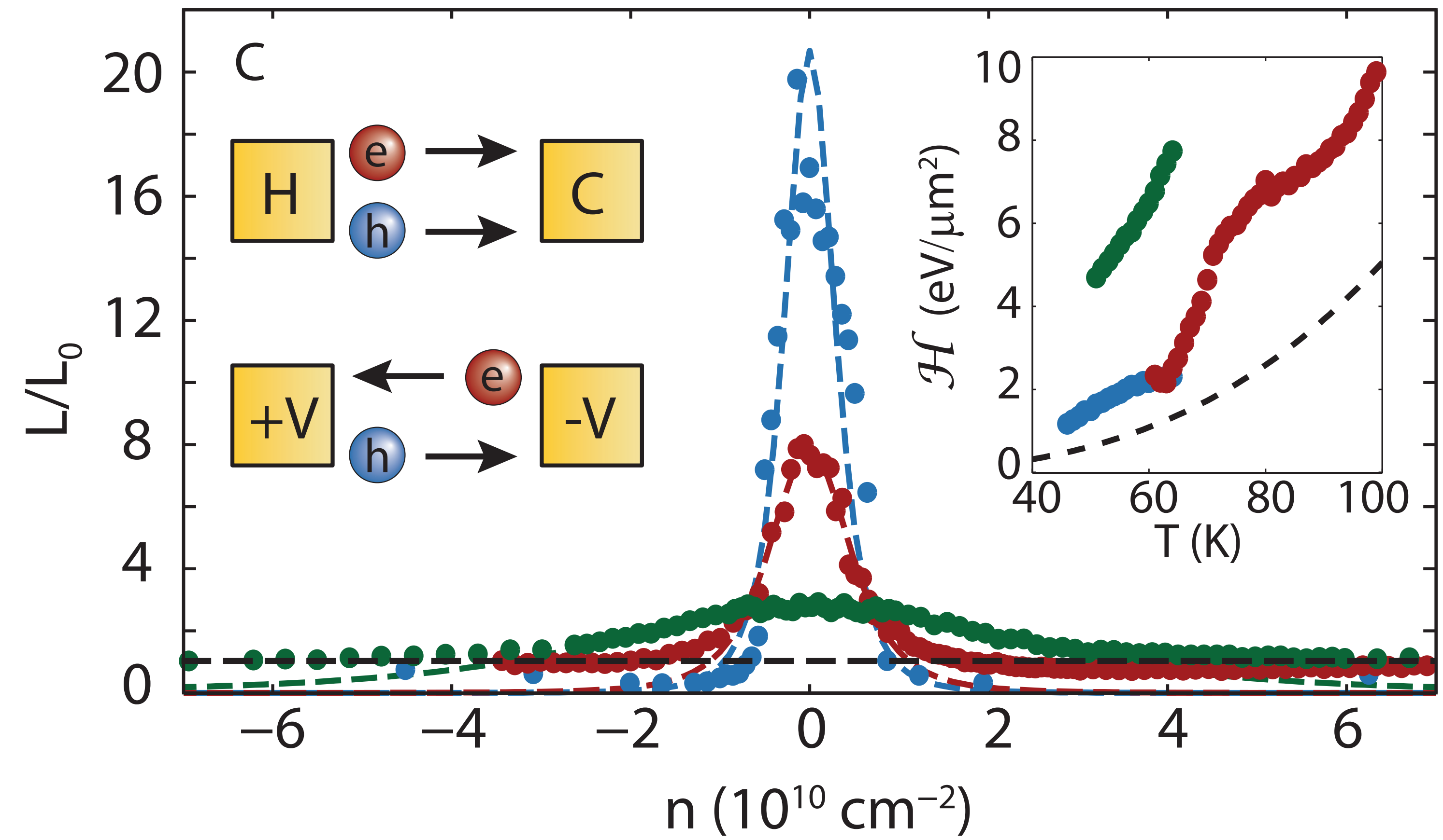


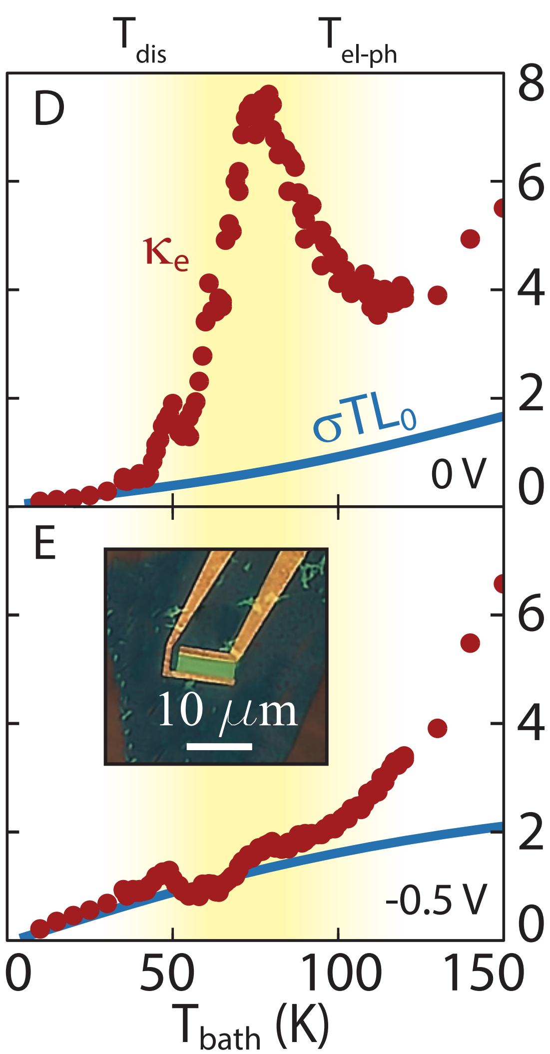
figure from [Lucas, Sachdev, *Physical Review* **B91** 195122 (2015)]

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

Strange metal in graphene







Lorentz ratio $L = \kappa/(T\sigma)$

$$= \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T^2 \sigma_Q} \frac{1}{\left(1 + e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}/(\mathcal{H}\sigma_Q)\right)^2}$$

J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, arXiv:1509.04713; Science, to appear

Strange metal in graphene

arXiv:1509.04165

Negative local resistance due to viscous electron backflow in graphene

D. A. Bandurin[1], I. Torre[2,3], R. Krishna Kumar[1,4], M. Ben Shalom[1,5], A. Tomadin[6], A. Principi[7], G. H. Auton[5], E. Khestanova[1,5], K. S. Novoselov[5], I. V. Grigorieva[1], L. A. Ponomarenko[1,4], A. K. Geim[1], M. Polini[3,6]

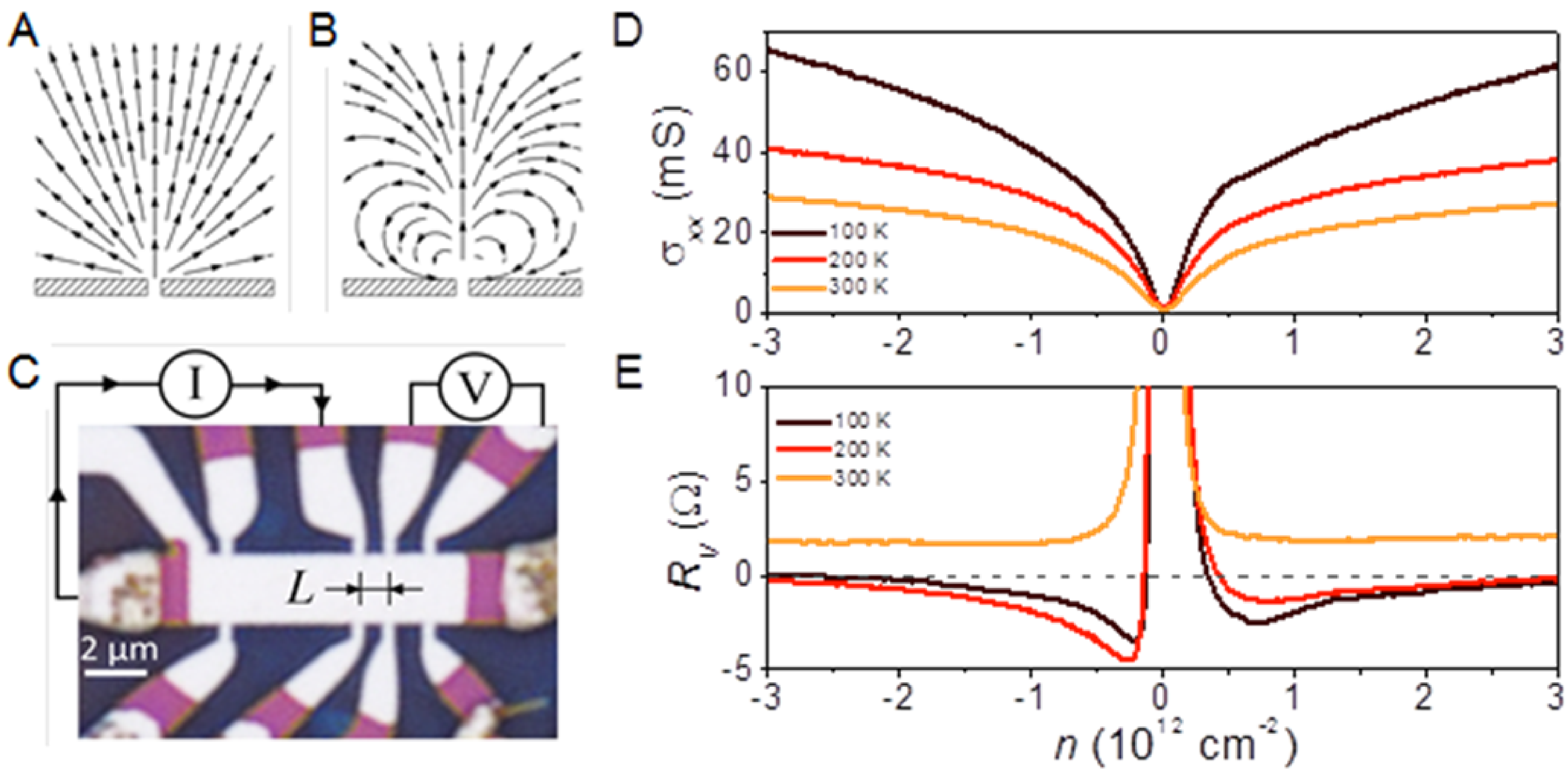
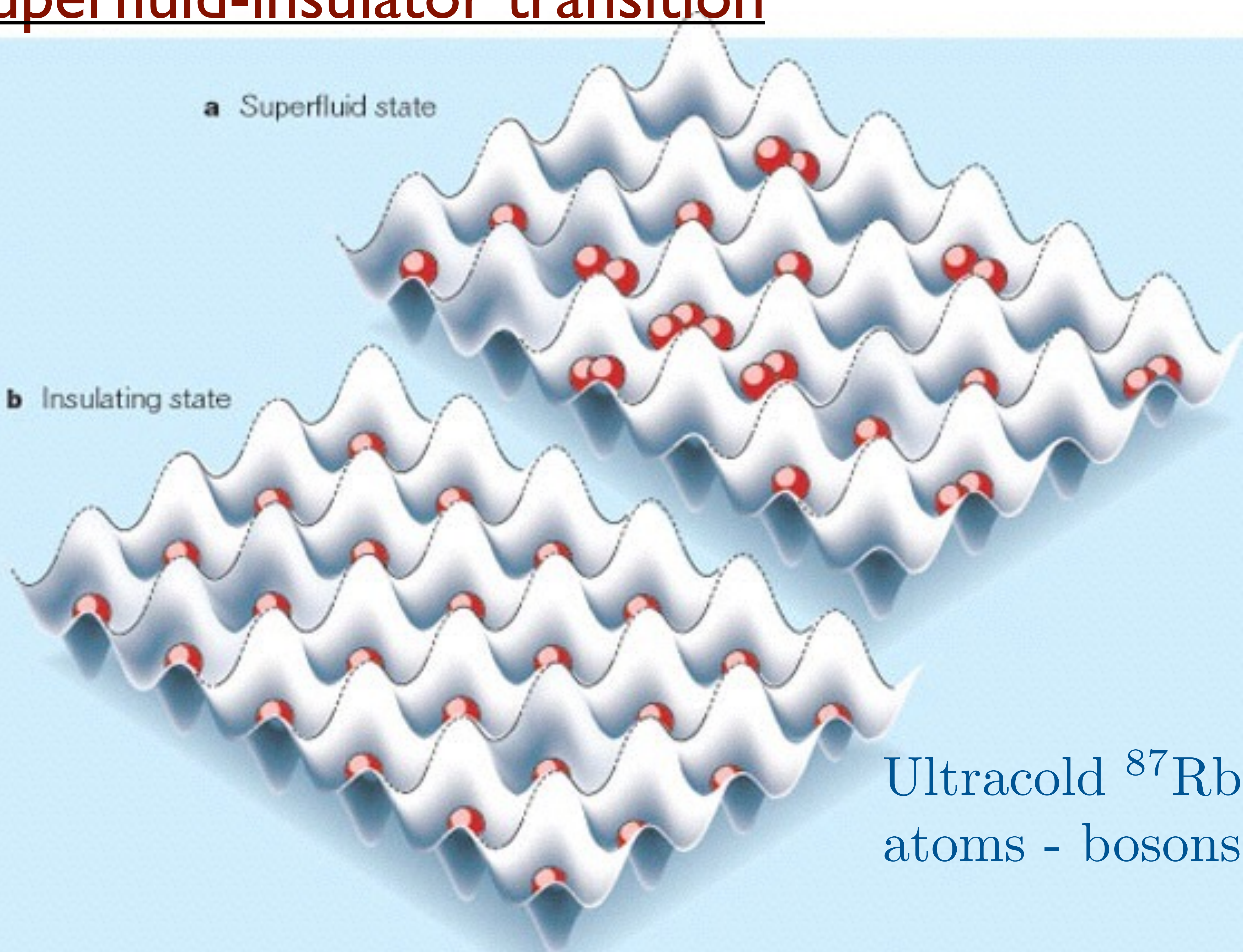


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (**d,e**) Longitudinal conductivity σ_{xx} and $R_{\rm V}$ for this device as a function of n induced by applying gate voltage. $I = 0.3$ µA; $L = 1$ µm. For more detail, see Supplementary Information.

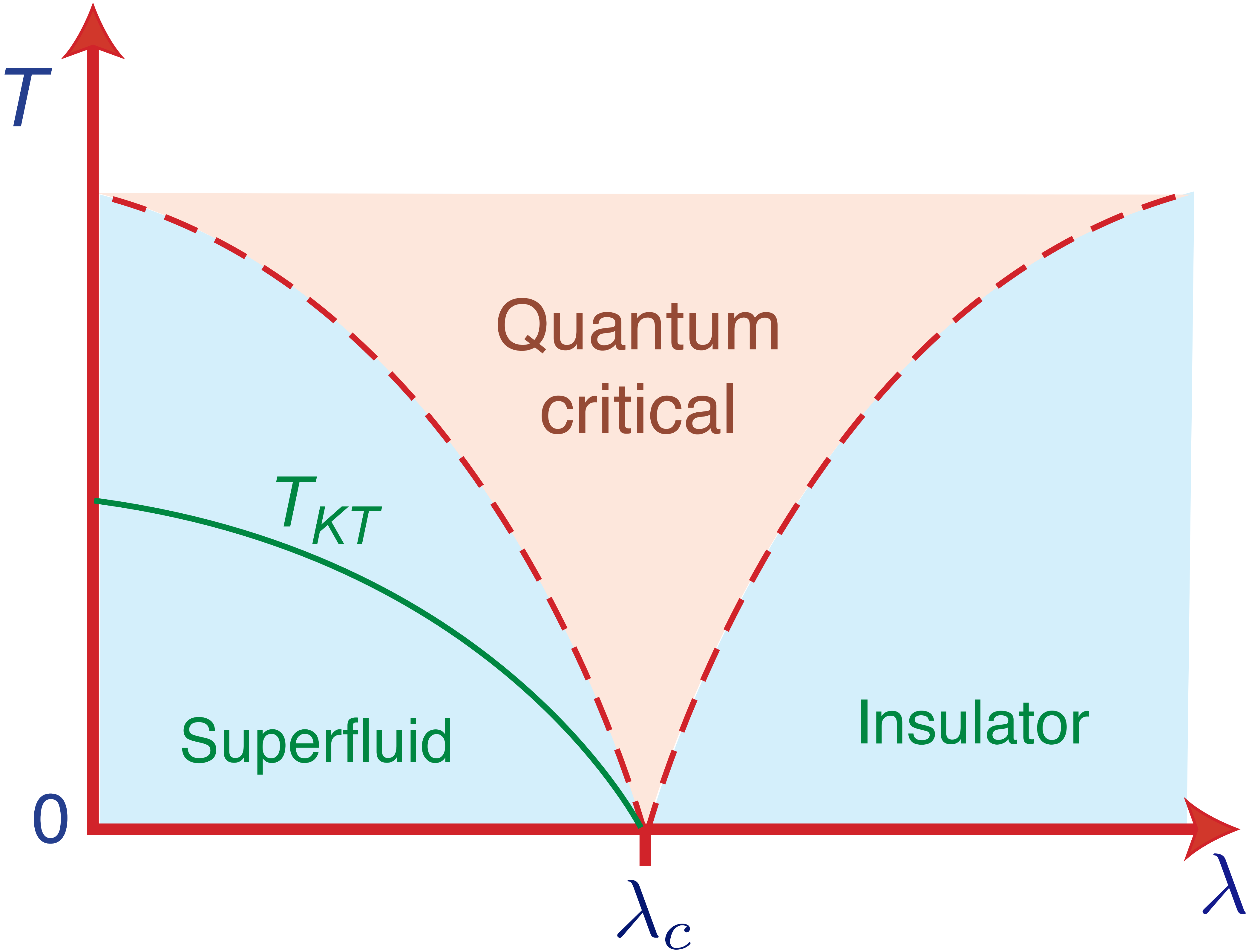
Superfluid-insulator transition



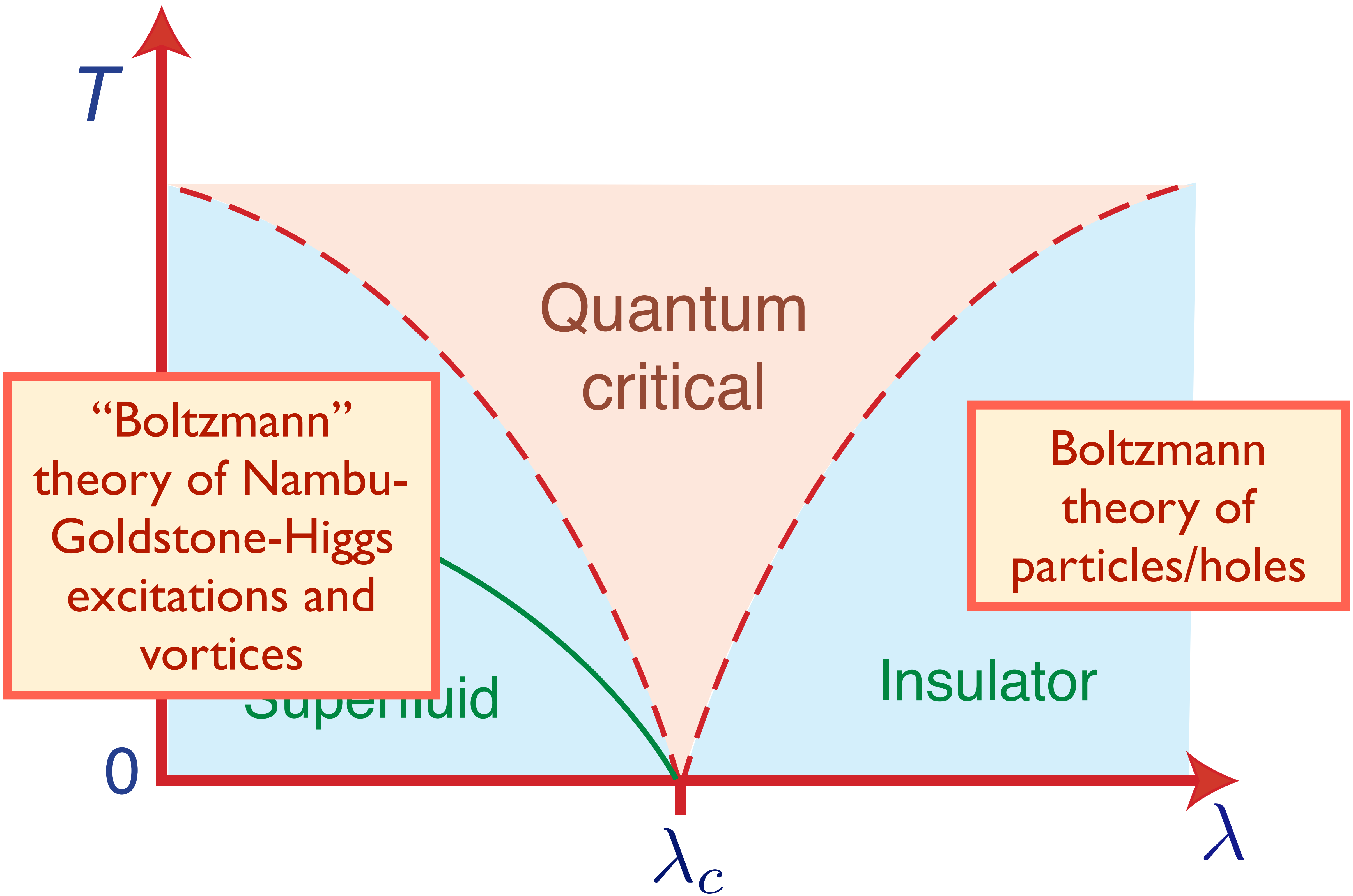
Ultracold ^{87}Rb
atoms - bosons

M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

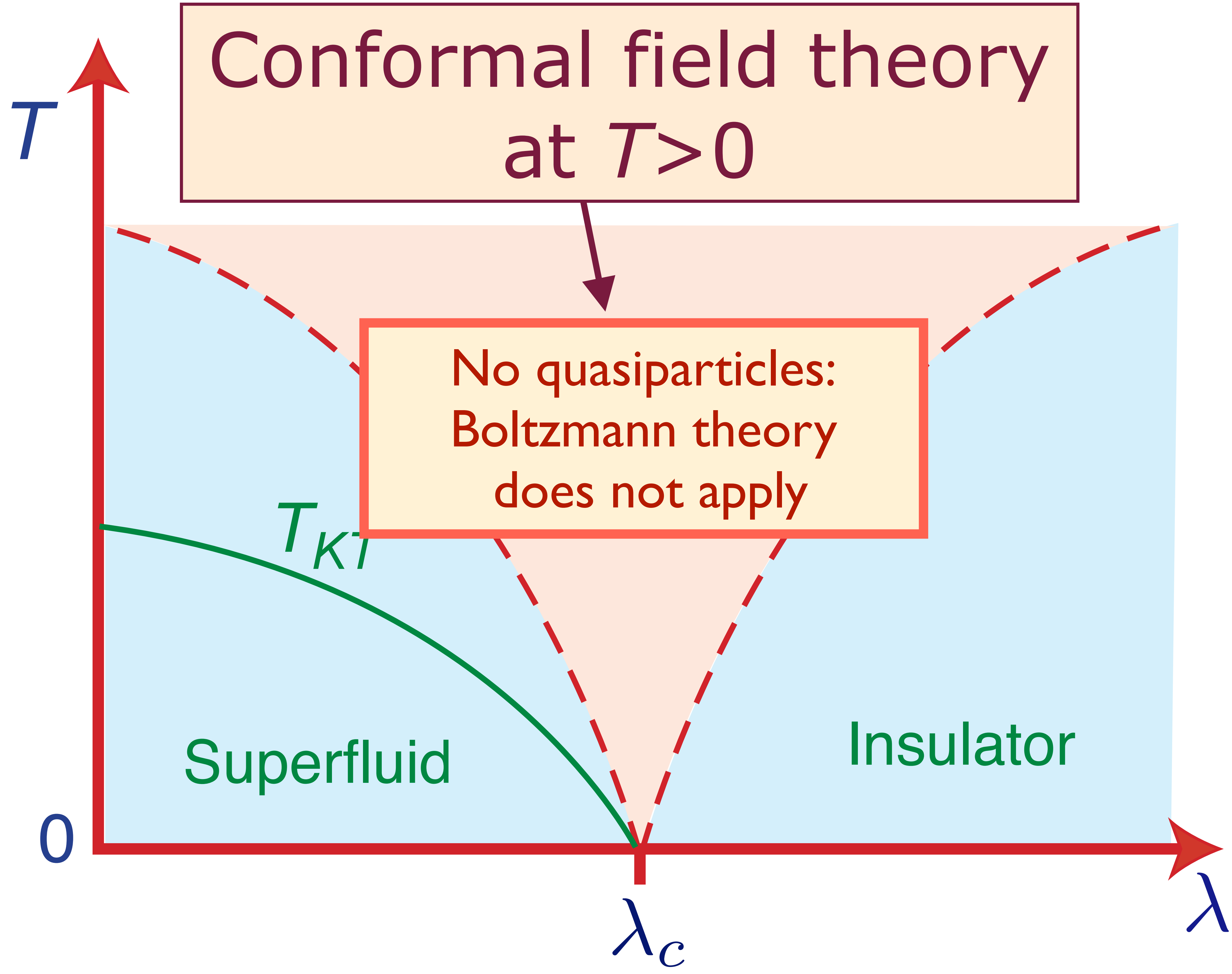
Superfluid-insulator transition



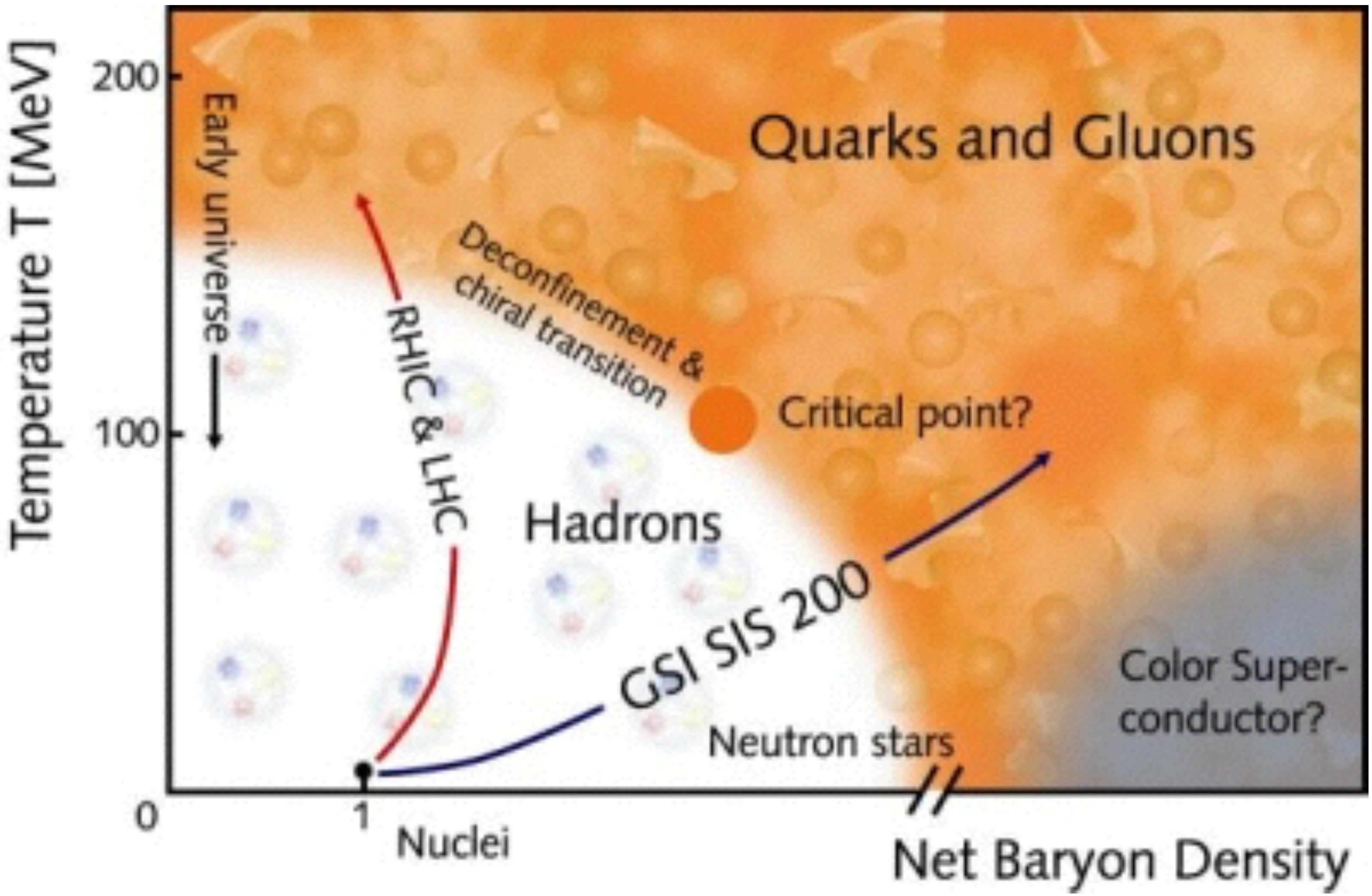
Superfluid-insulator transition



Superfluid-insulator transition



Quark-gluon plasma



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2. Mott insulators: "intertwined orders", long-range entanglement, and emergent gauge fields

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   the quark-gluon plasma, and
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   the dynamics of charged black holes horizons