Antiferromagnetism, high temperature superconductivity, and quantum criticality

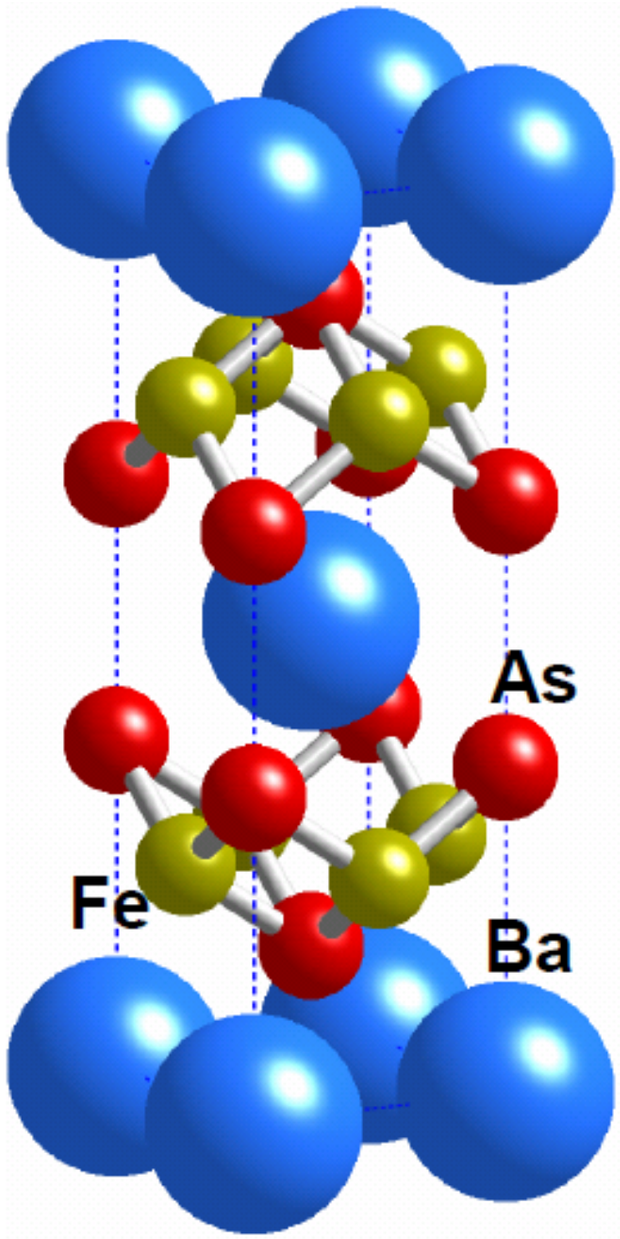
Frontiers of Quantum Matter,
NYU Provost Retreat,
February 8, 2016

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

Iron pnictides:

a new class of high temperature superconductors



Resistivity
$\sim \rho_0 + AT^\alpha$

$BaFe_2(As_{1-x}P_x)_2$

200

100

0

T (K)

AF
+nematic

Superconductivity

0

0.2

0.4

0.6

x

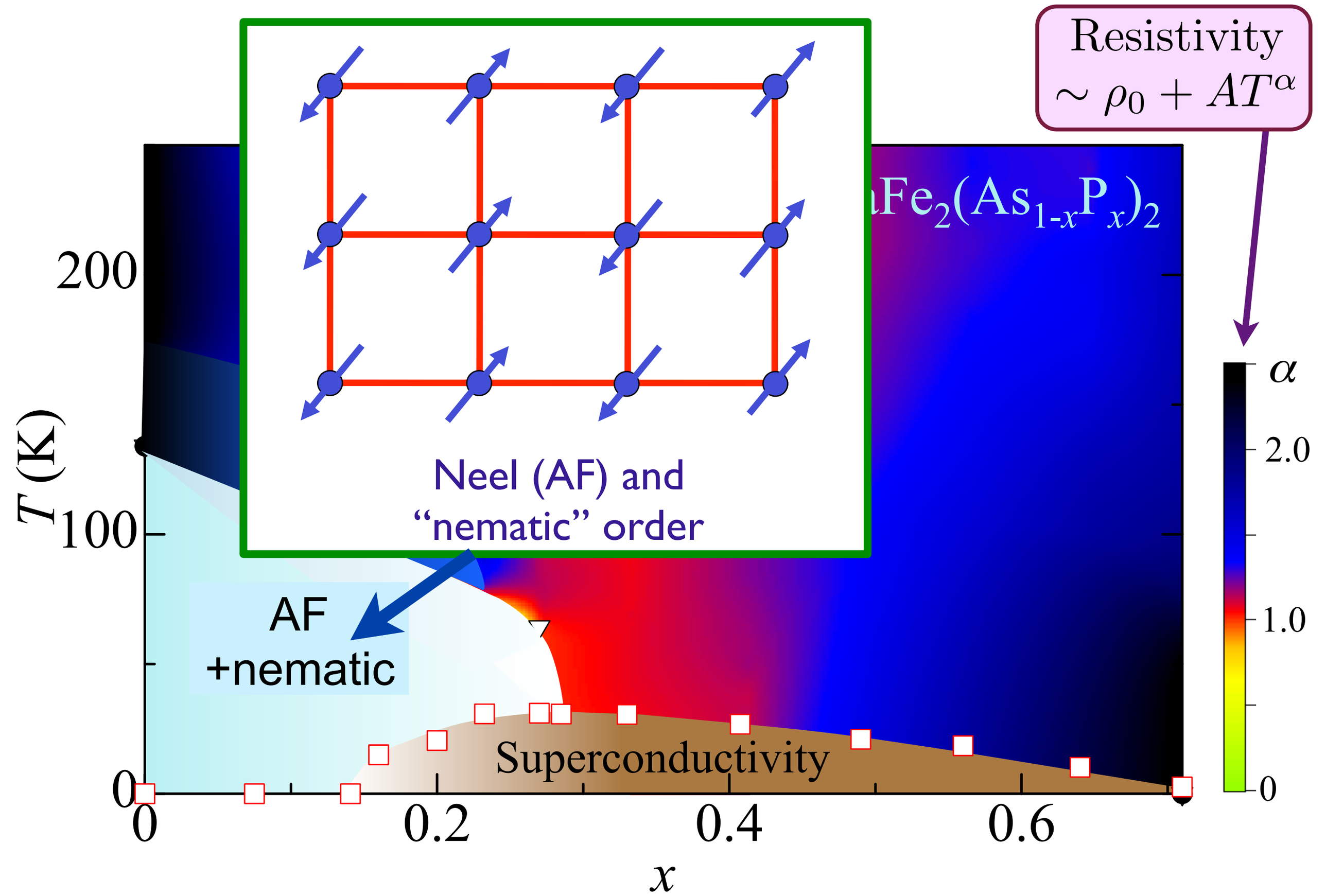
α

2.0

1.0

0

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)



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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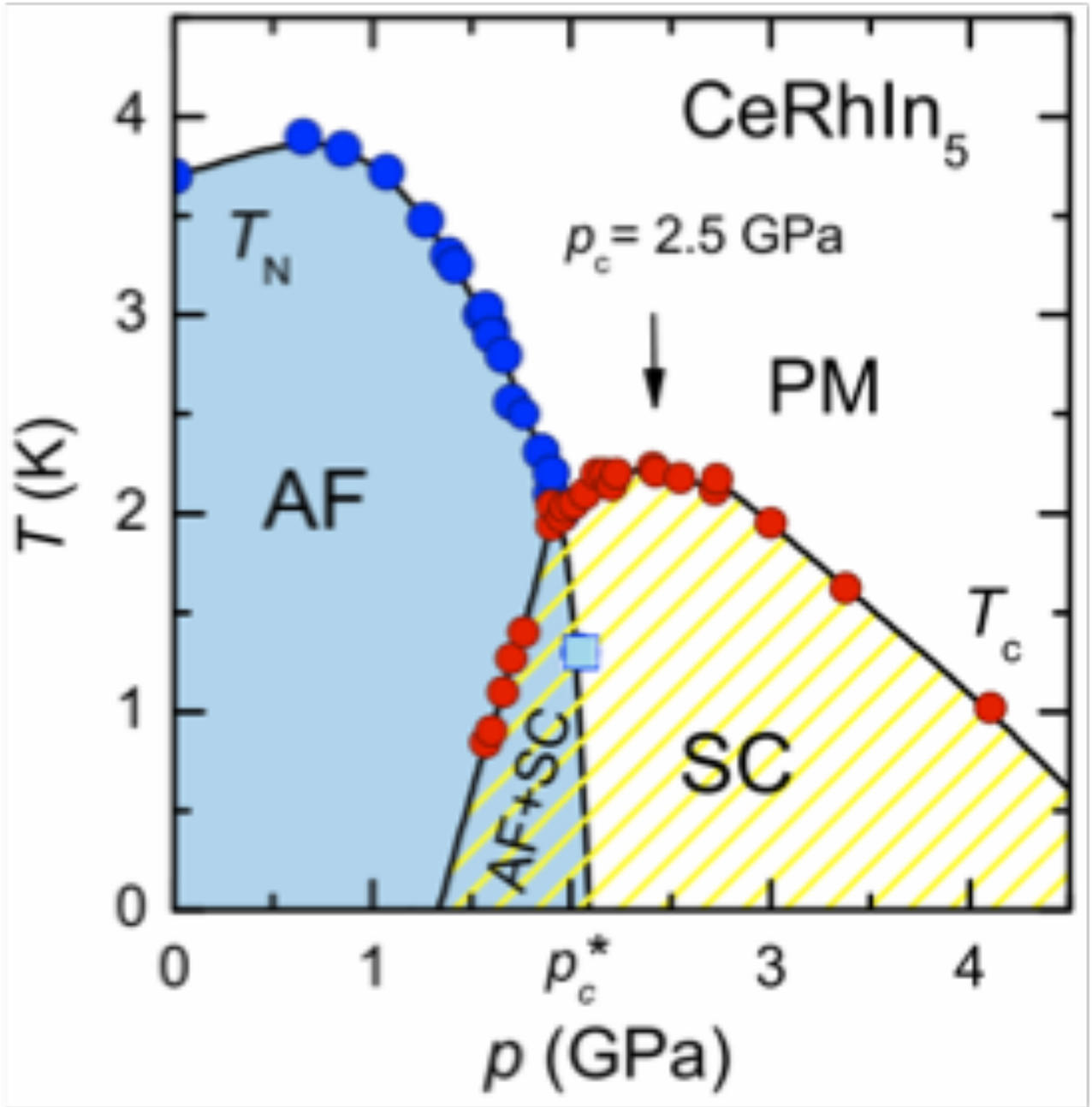
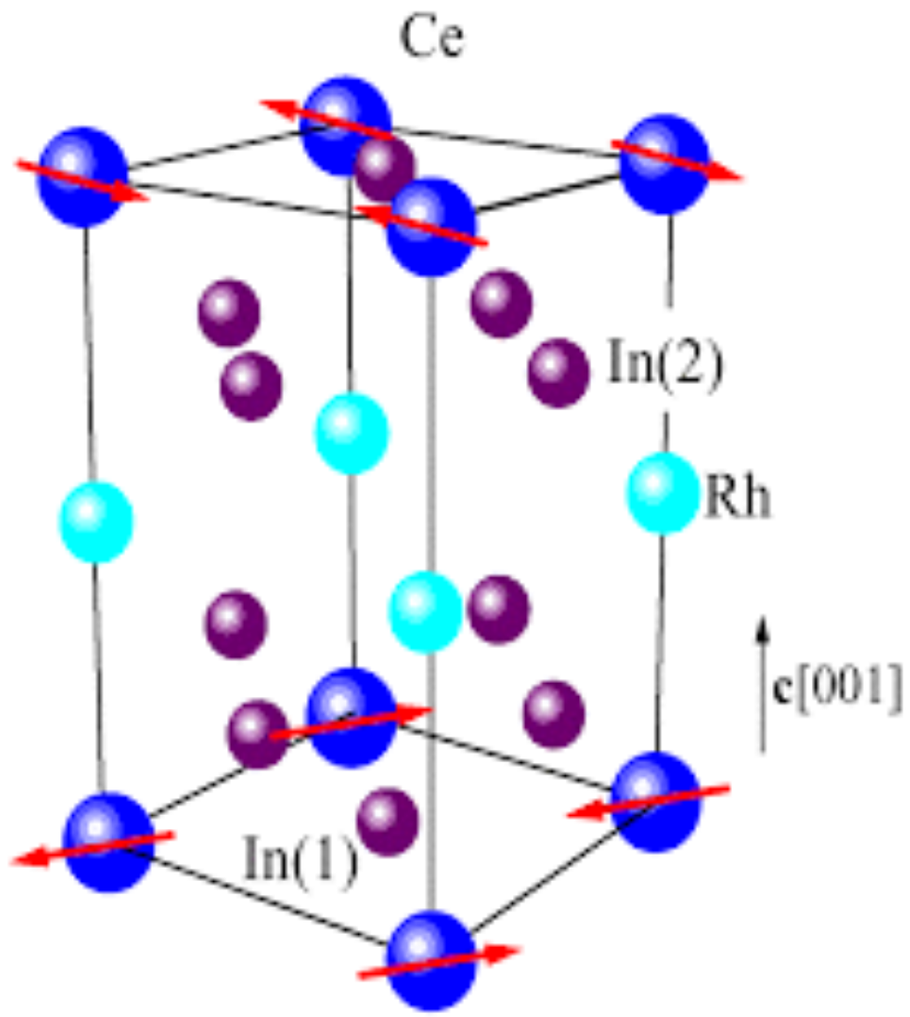
Superconductor
Bose condensate of pairs of electrons

S. Kasahara, T. Shiba
H. Ike

Antiferromagnetism and superconductivity





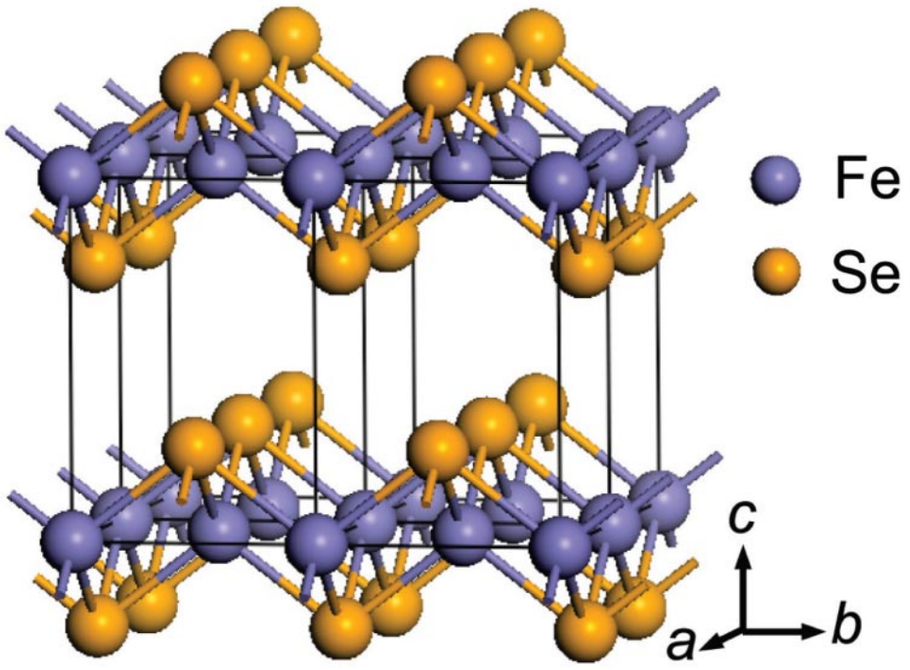
Knebel, 2010

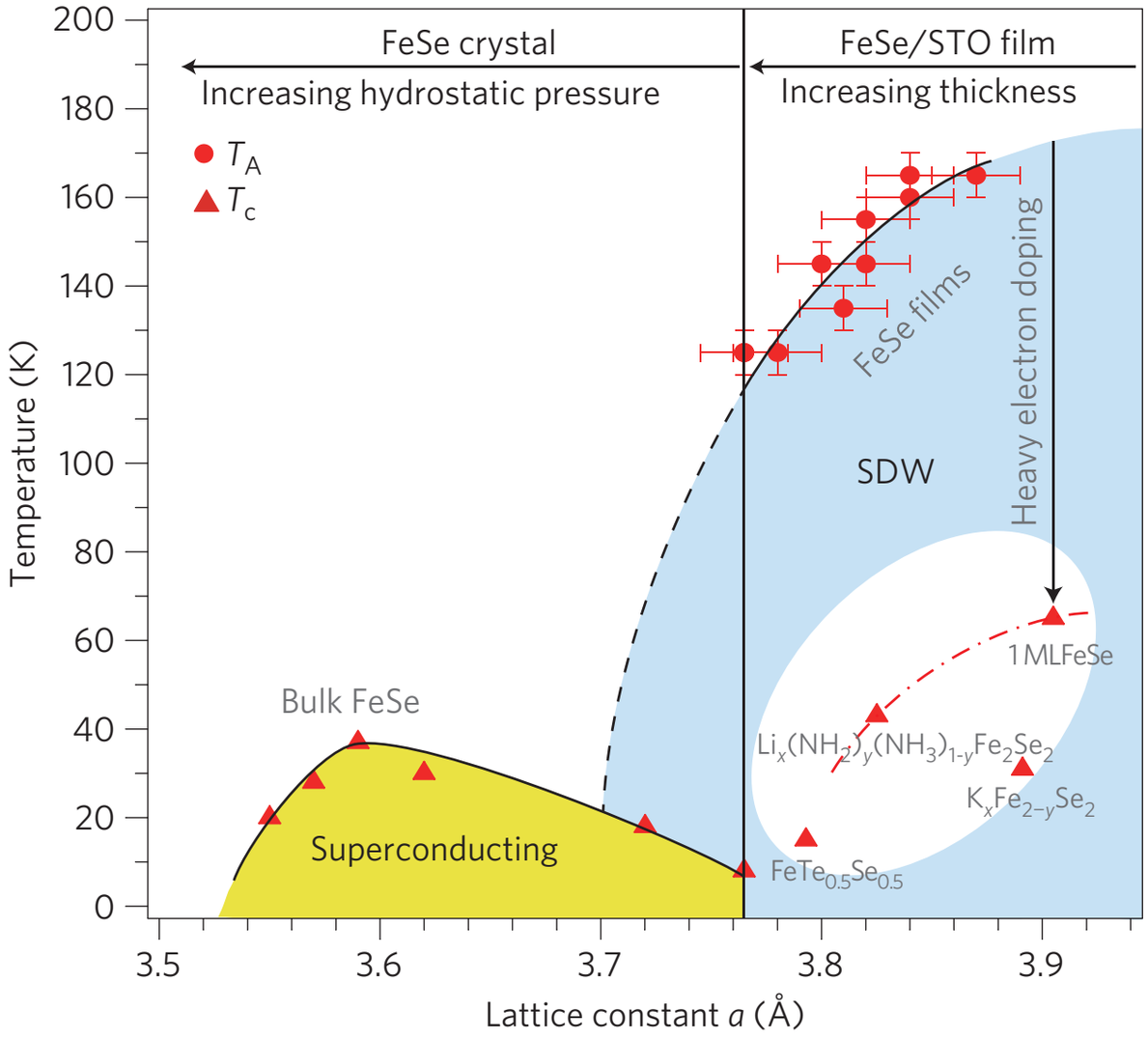
Antiferromagnetism and superconductivity

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

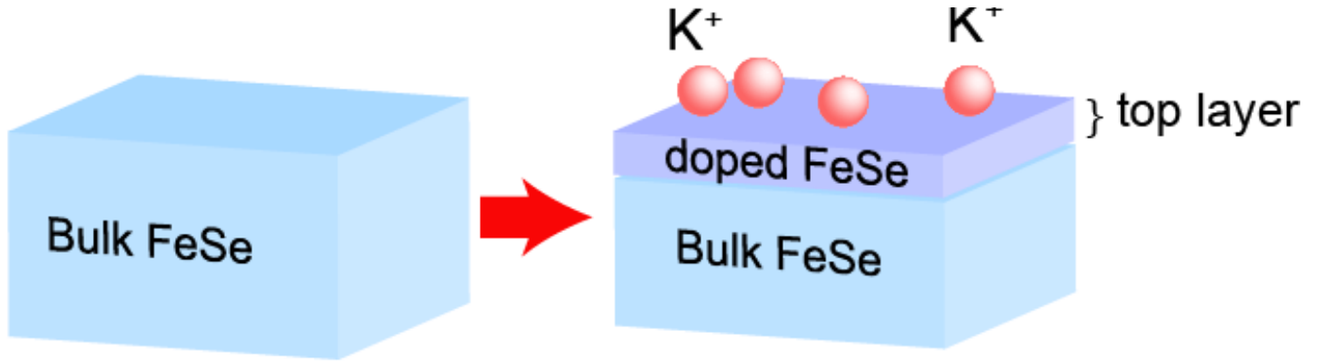
Jian-Feng Ge[1], Zhi-Long Liu[1], Canhua Liu[1,2]*, Chun-Lei Gao[1,2], Dong Qian[1,2], Qi-Kun Xue[3]*, Ying Liu[1,2,4] and Jin-Feng Jia[1,2]*

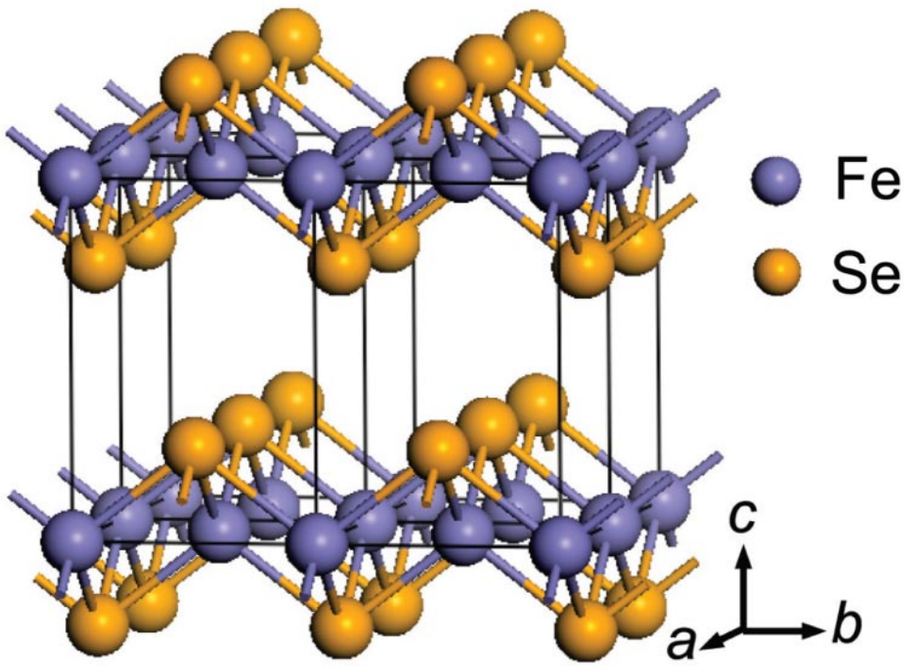
NATURE MATERIALS | VOL 14 | MARCH 2015

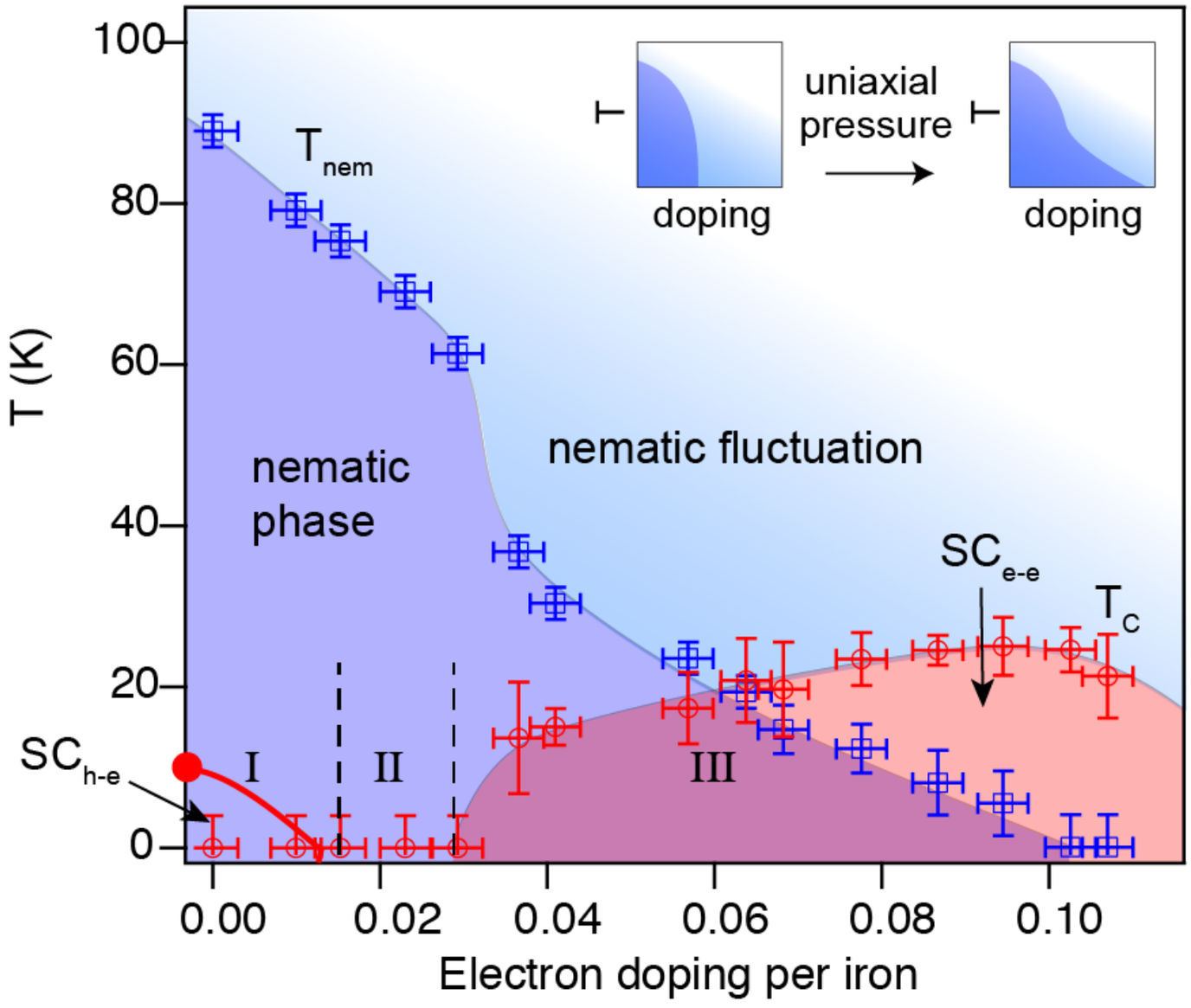




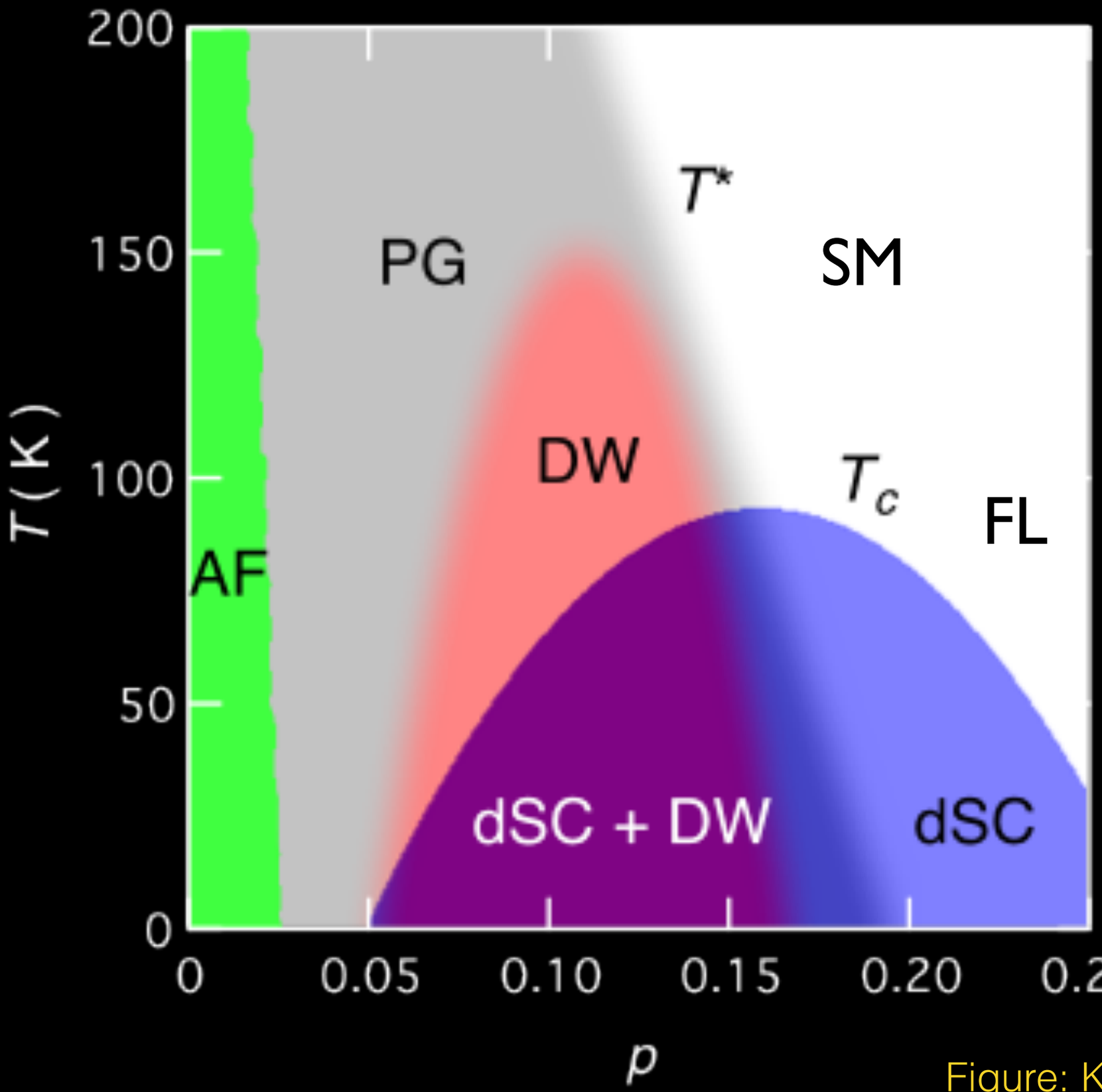
Tan et al, Nature Materials, 2013

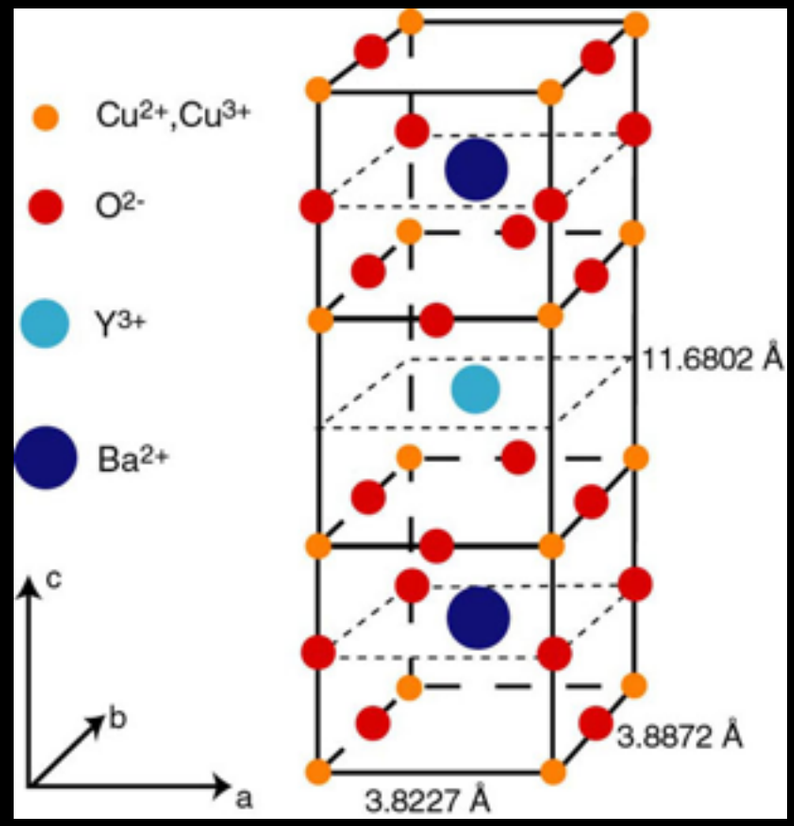






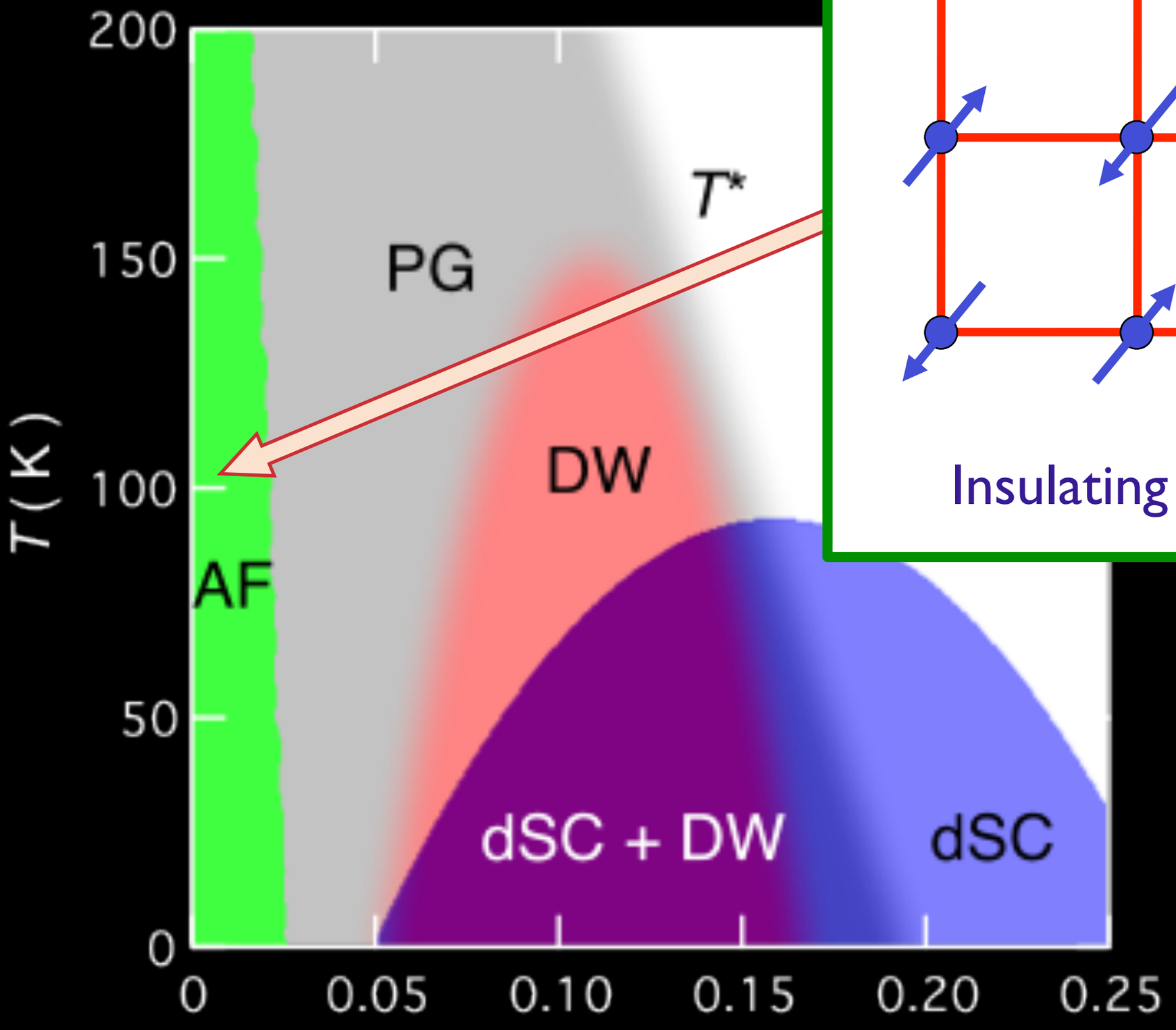
Z. R. Ye, C. F. Zhang, H. L. Ning, W. Li, L. Chen, T. Jia, M. Hashimoto, D. H. Lu, Z.-X. Shen, and Y. Zhang, arXiv:1512.02526

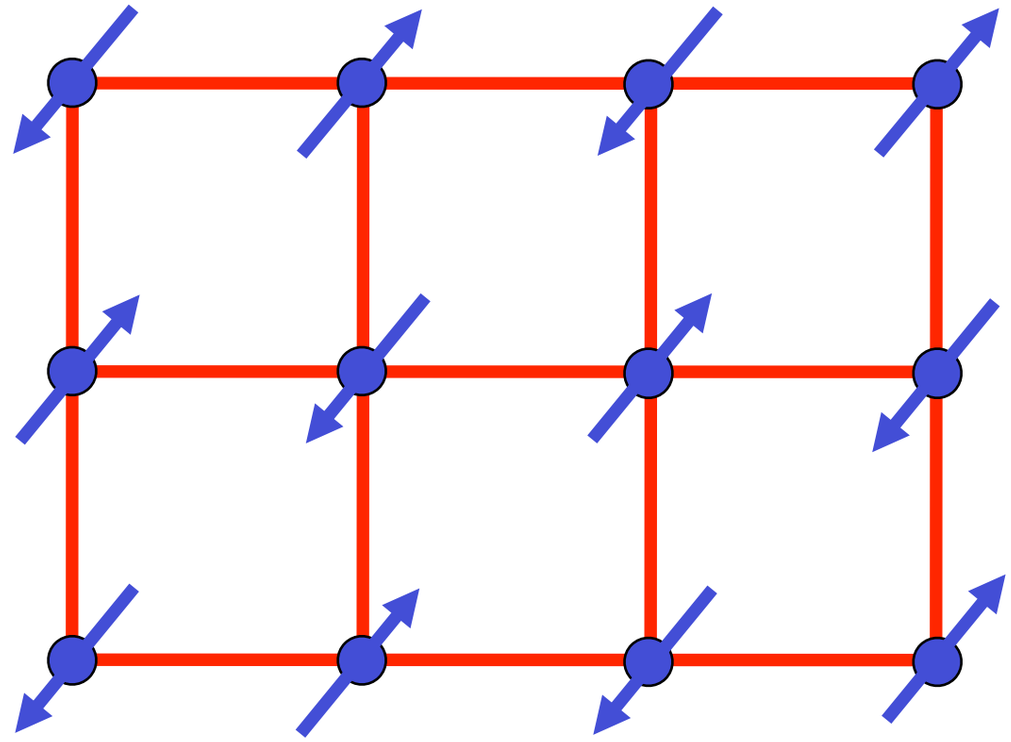




$YBa_2Cu_3O_{6+x}$

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





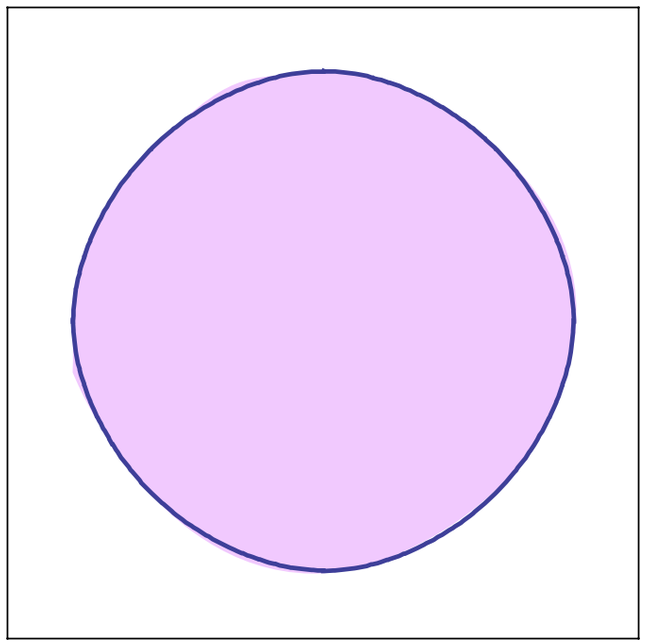
Insulating Antiferromagnet

$YBa_2Cu_3O_{6+x}$

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

Fermi surface+antiferromagnetism

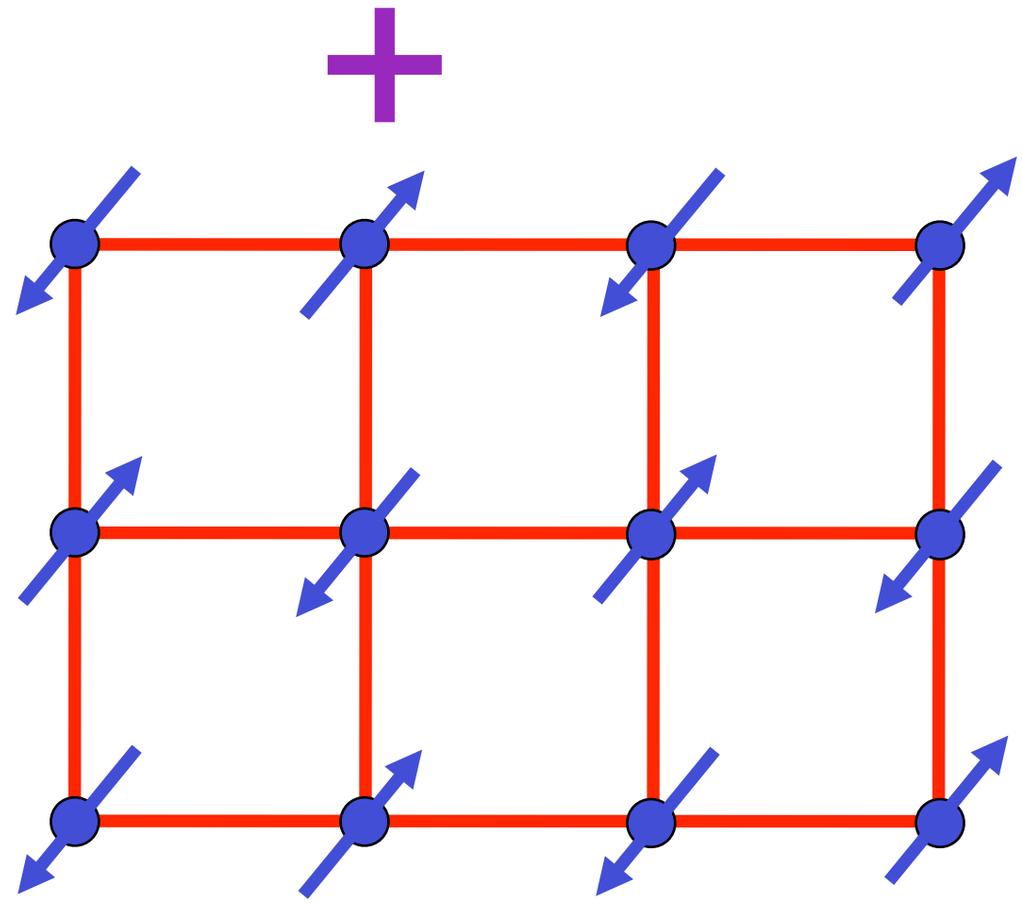
Metal with "large"
Fermi surface



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.



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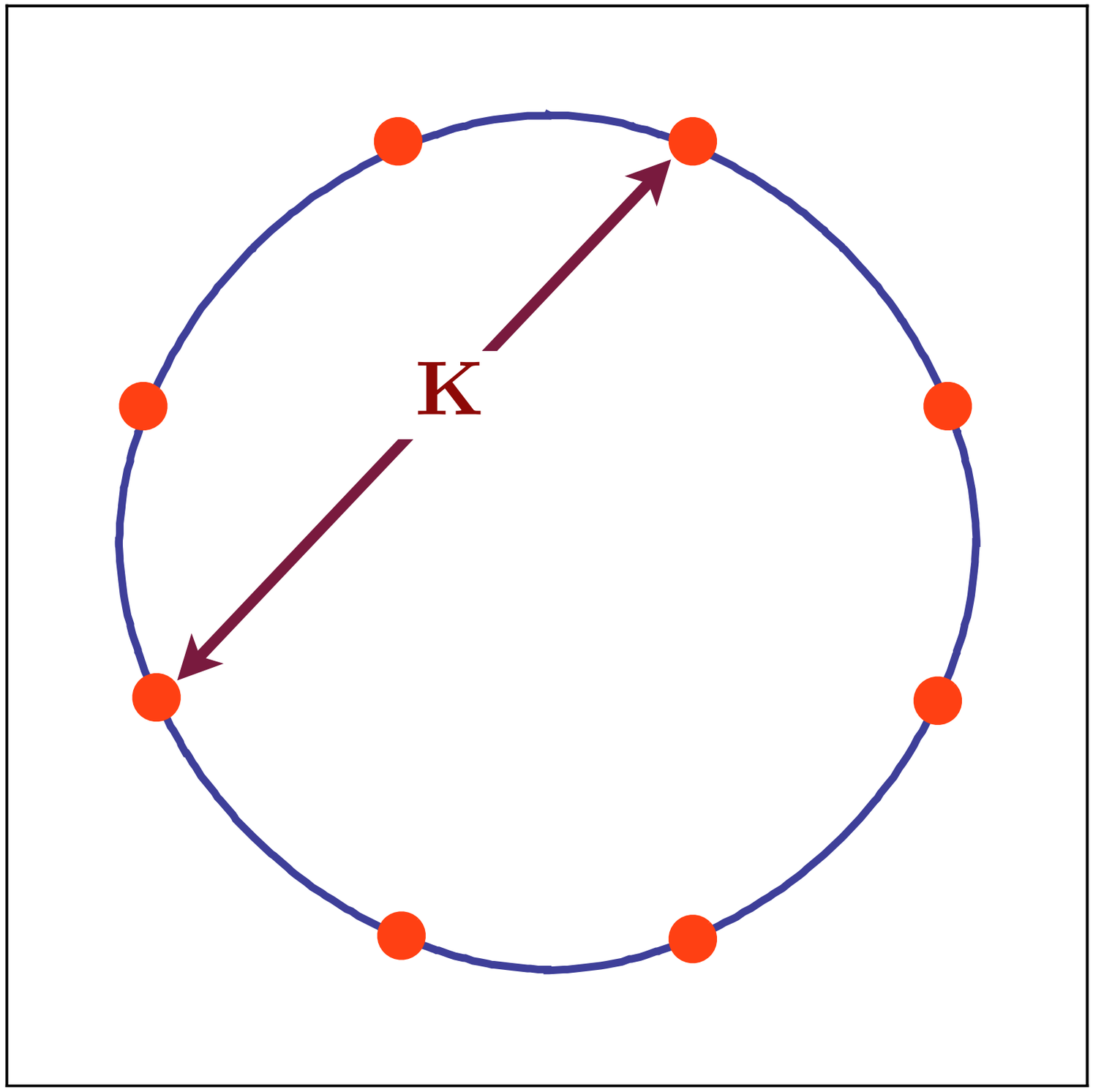
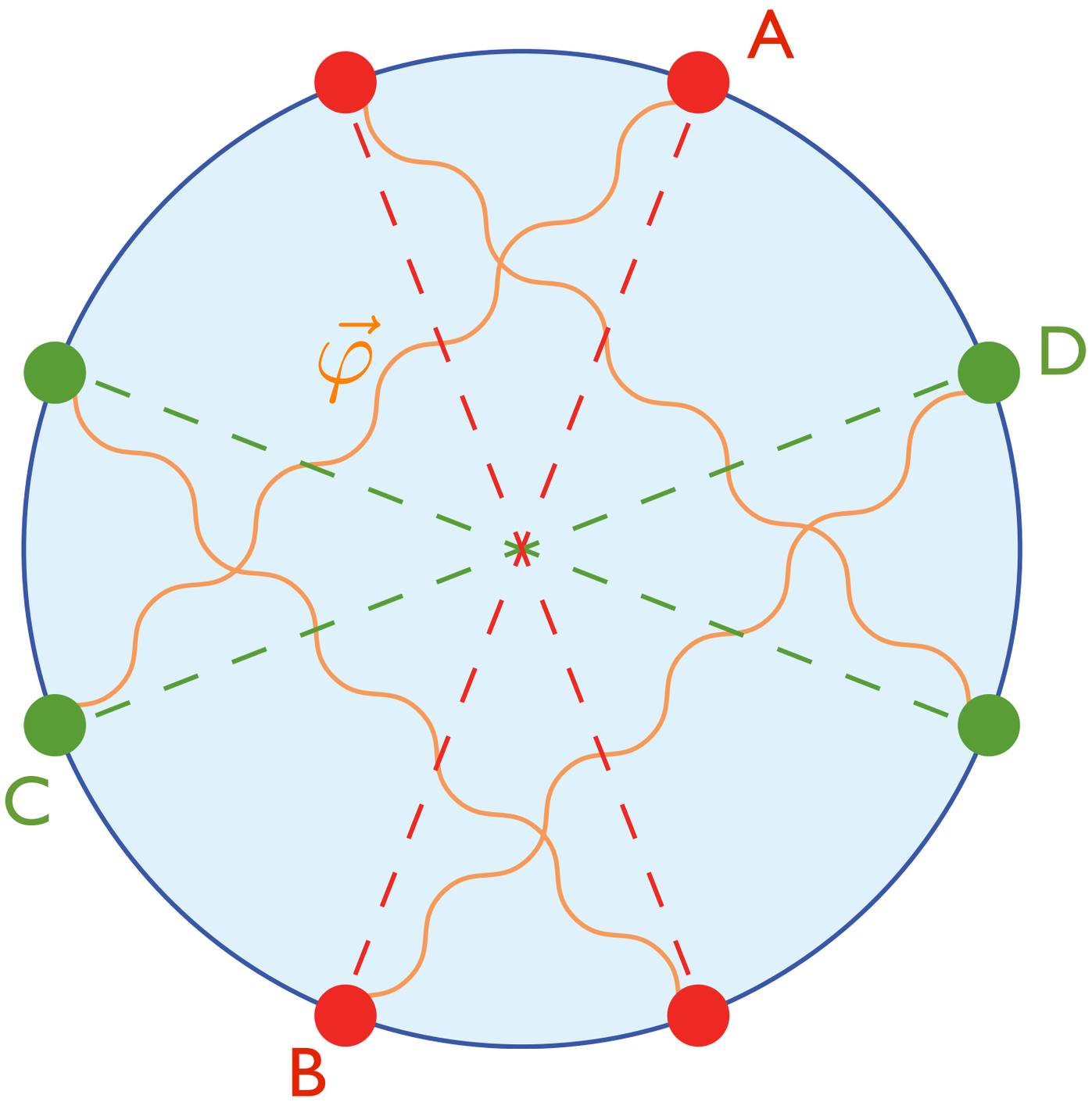
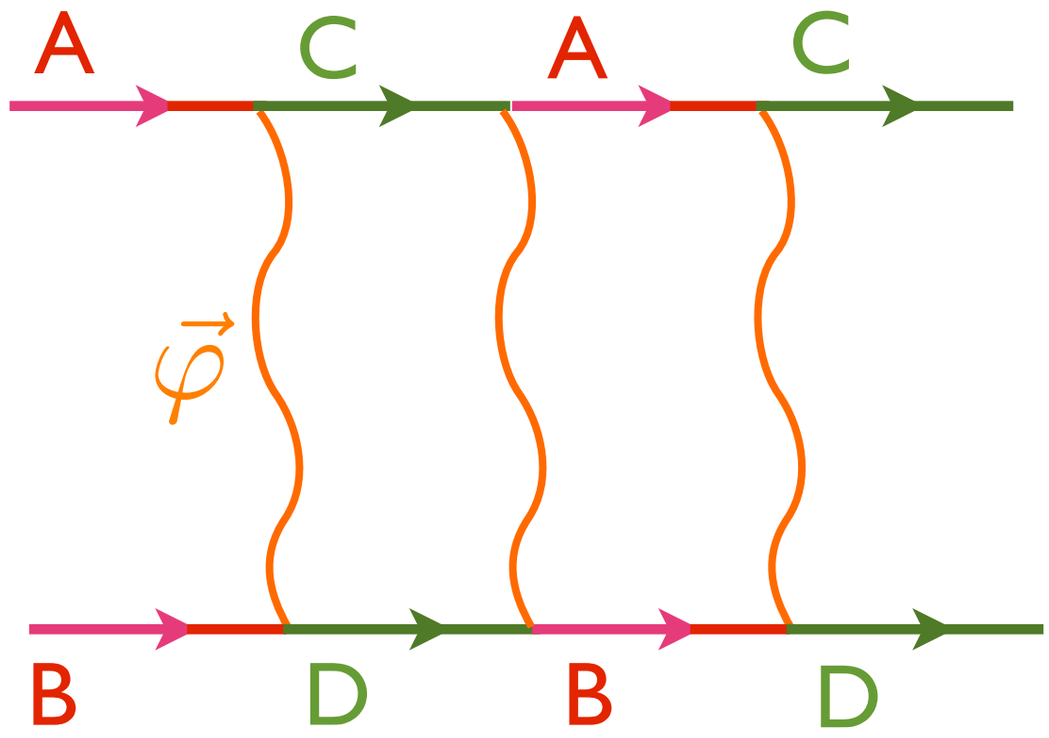


Hot spots in a single band model

Pairing "glue" from antiferromagnetic fluctuations





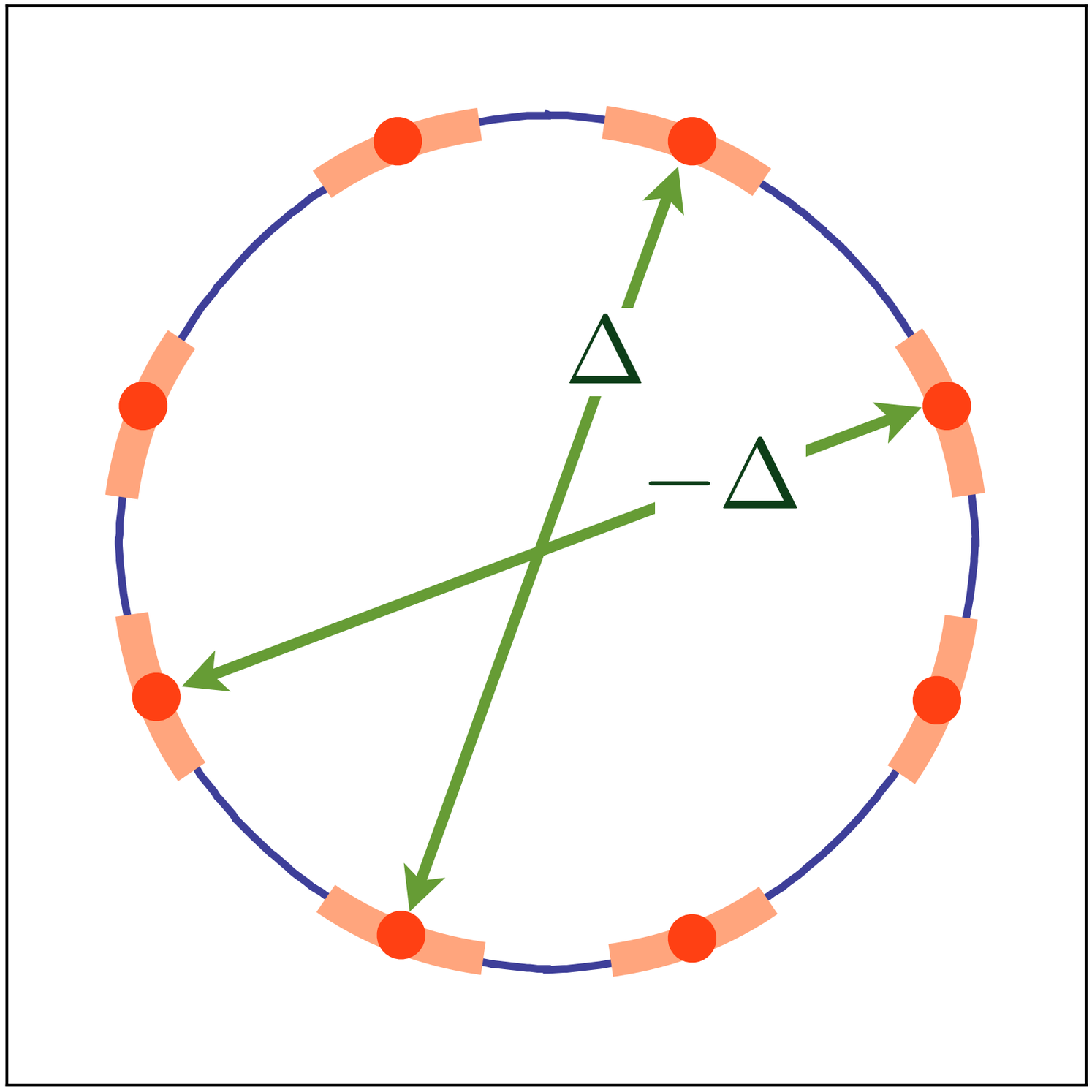
V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)

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)

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



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

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

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

2. Quantum matter without quasiparticles:

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

3. Long range quantum entanglement and emergent gauge fields in the cuprates

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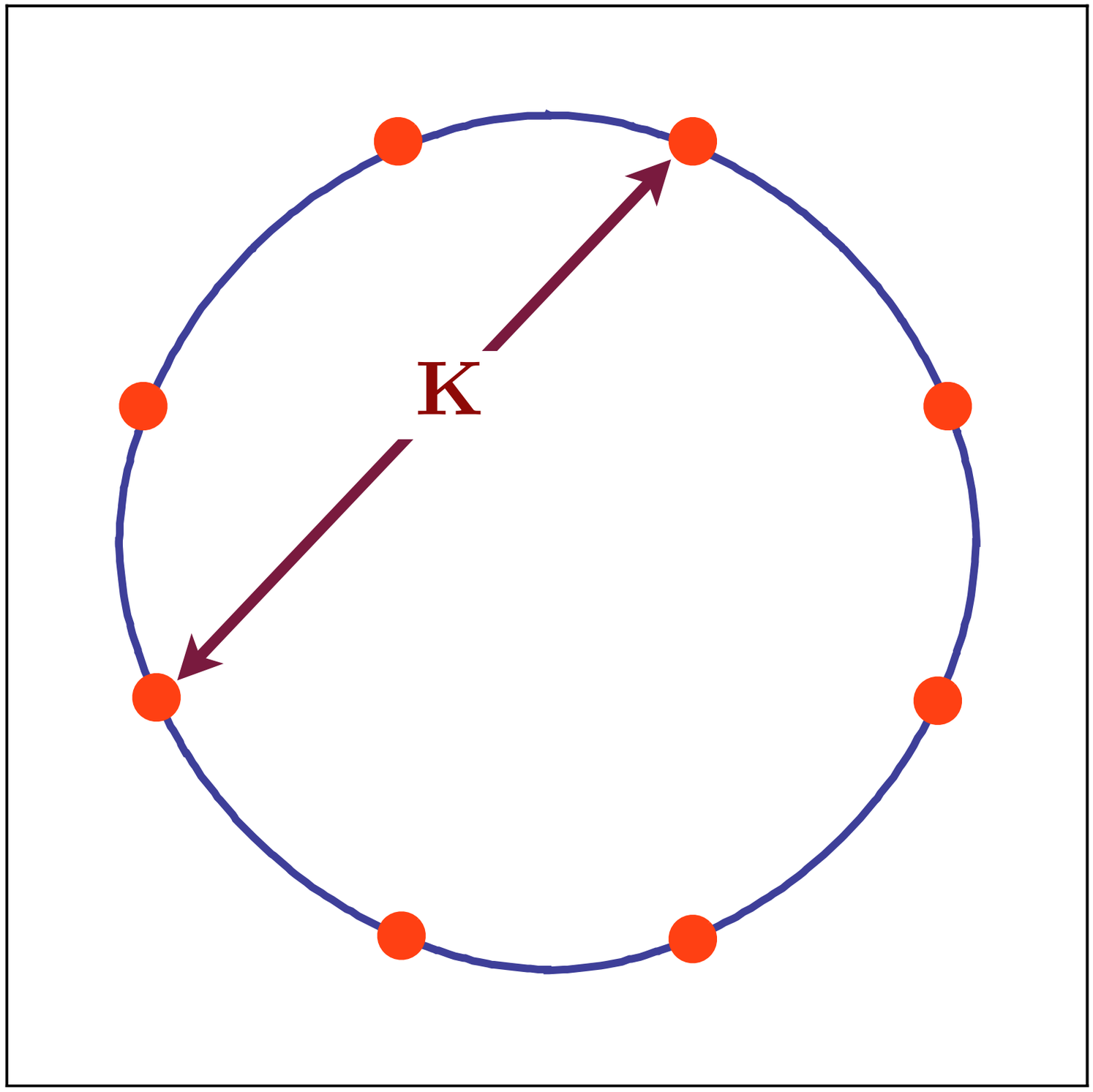
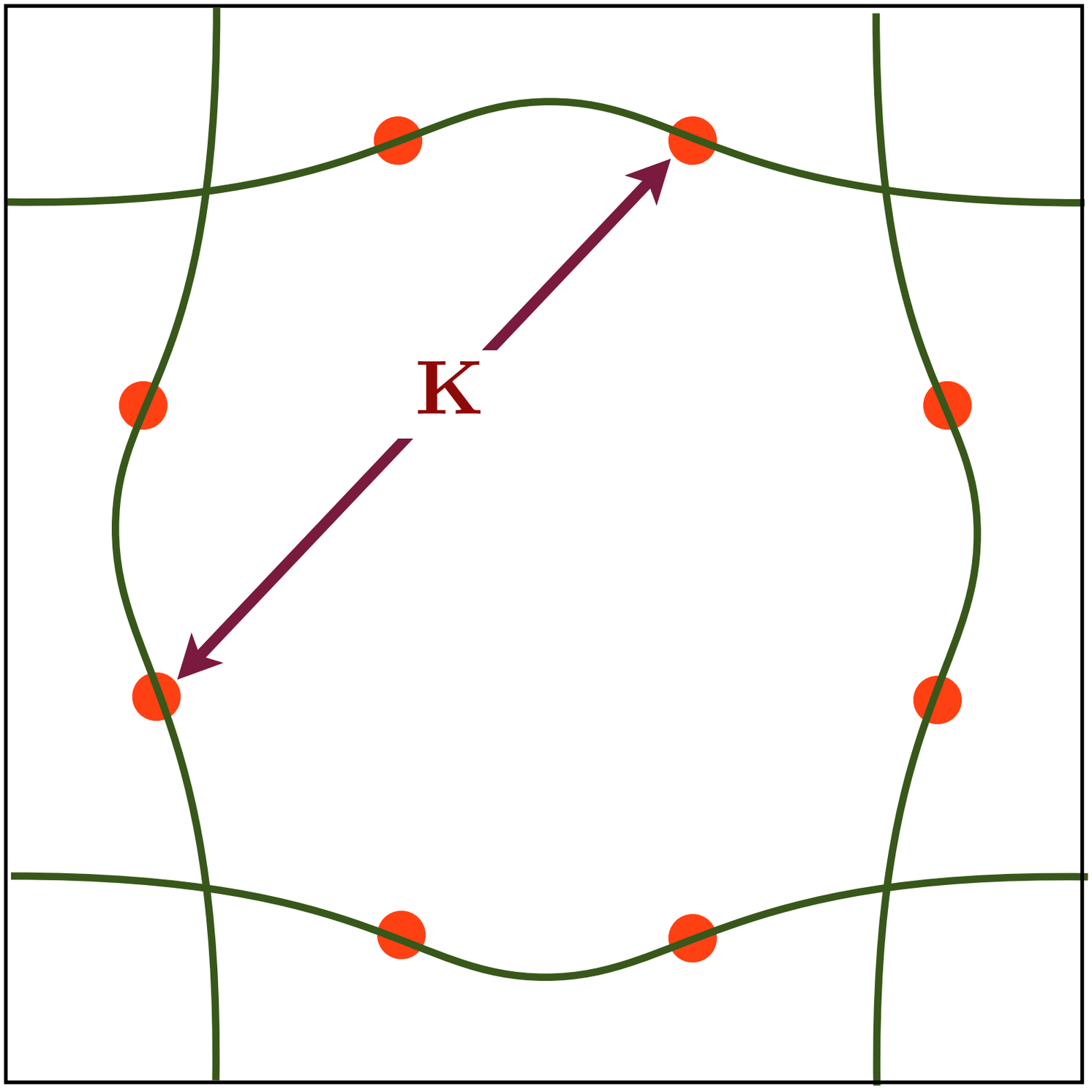


Hot spots in a single band model

QMC for the onset of antiferromagnetism

Faithful realization of the *generic* universal low energy theory for the onset of antiferro-magnetism.

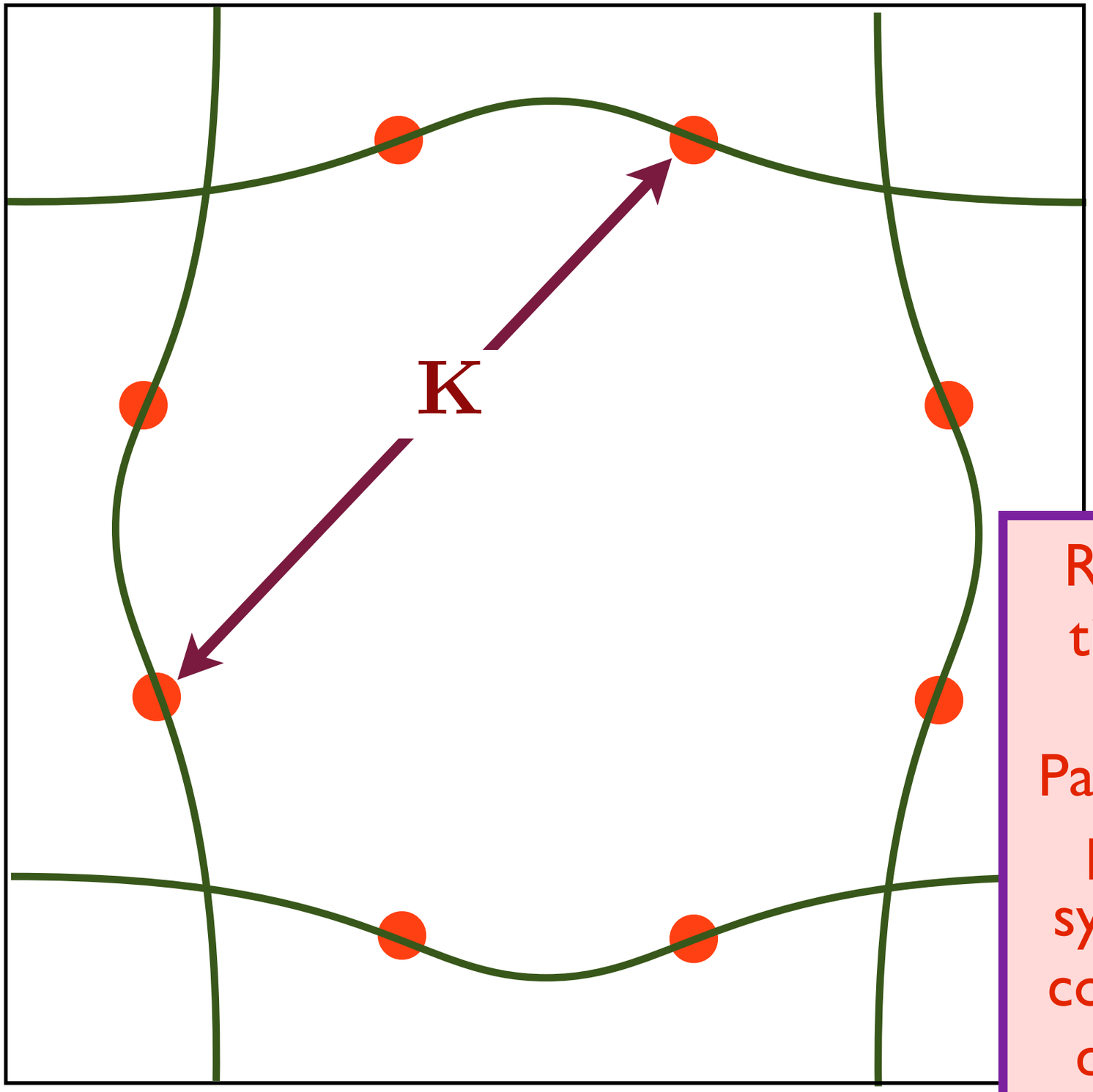


Hot spots in a two band model

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 mod

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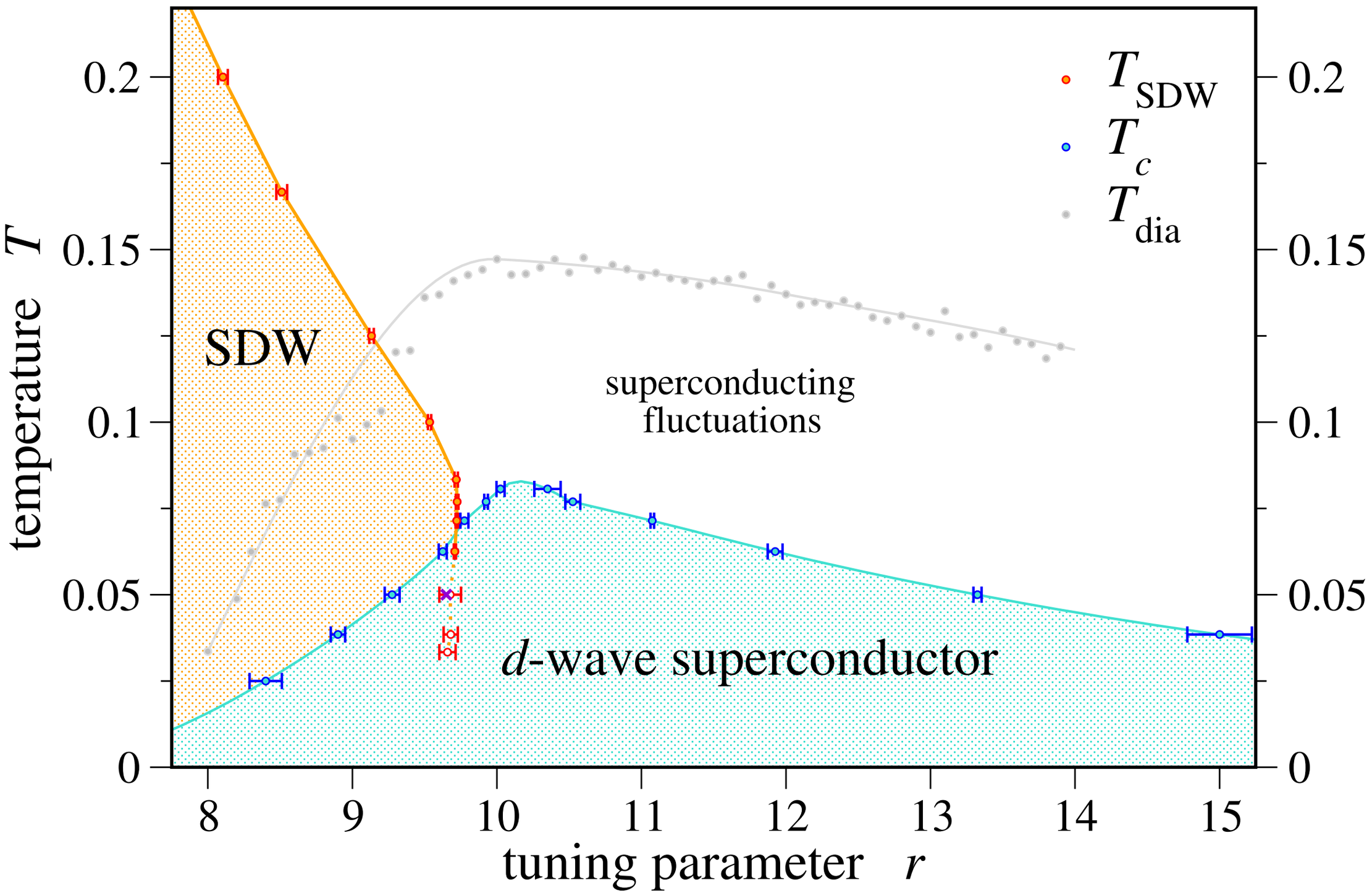
Requires only time-reversal symmetry. Particle-hole or point-group symmetries or commensurate densities ***not*** required !

QMC for the onset of antiferromagnetism

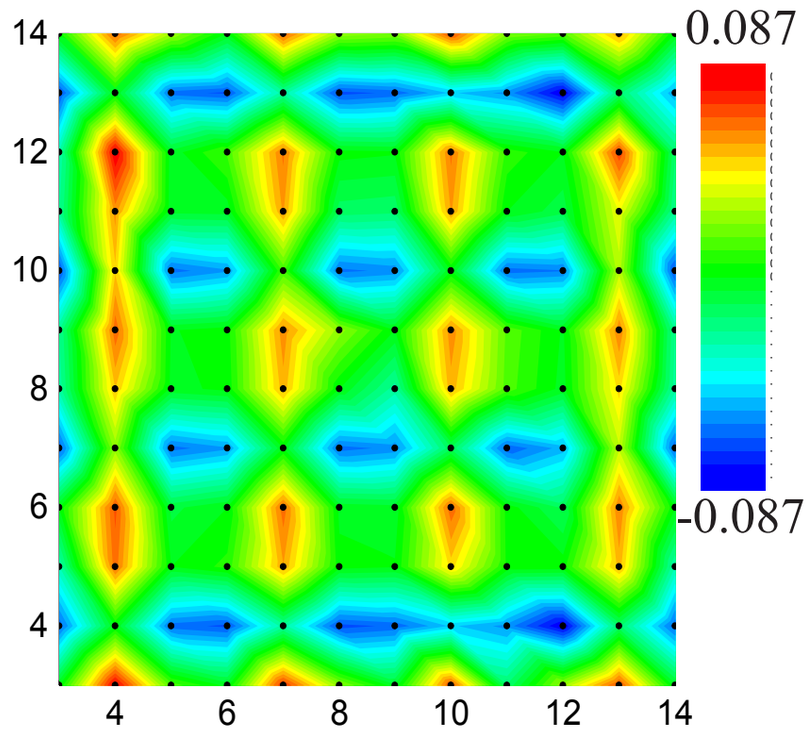


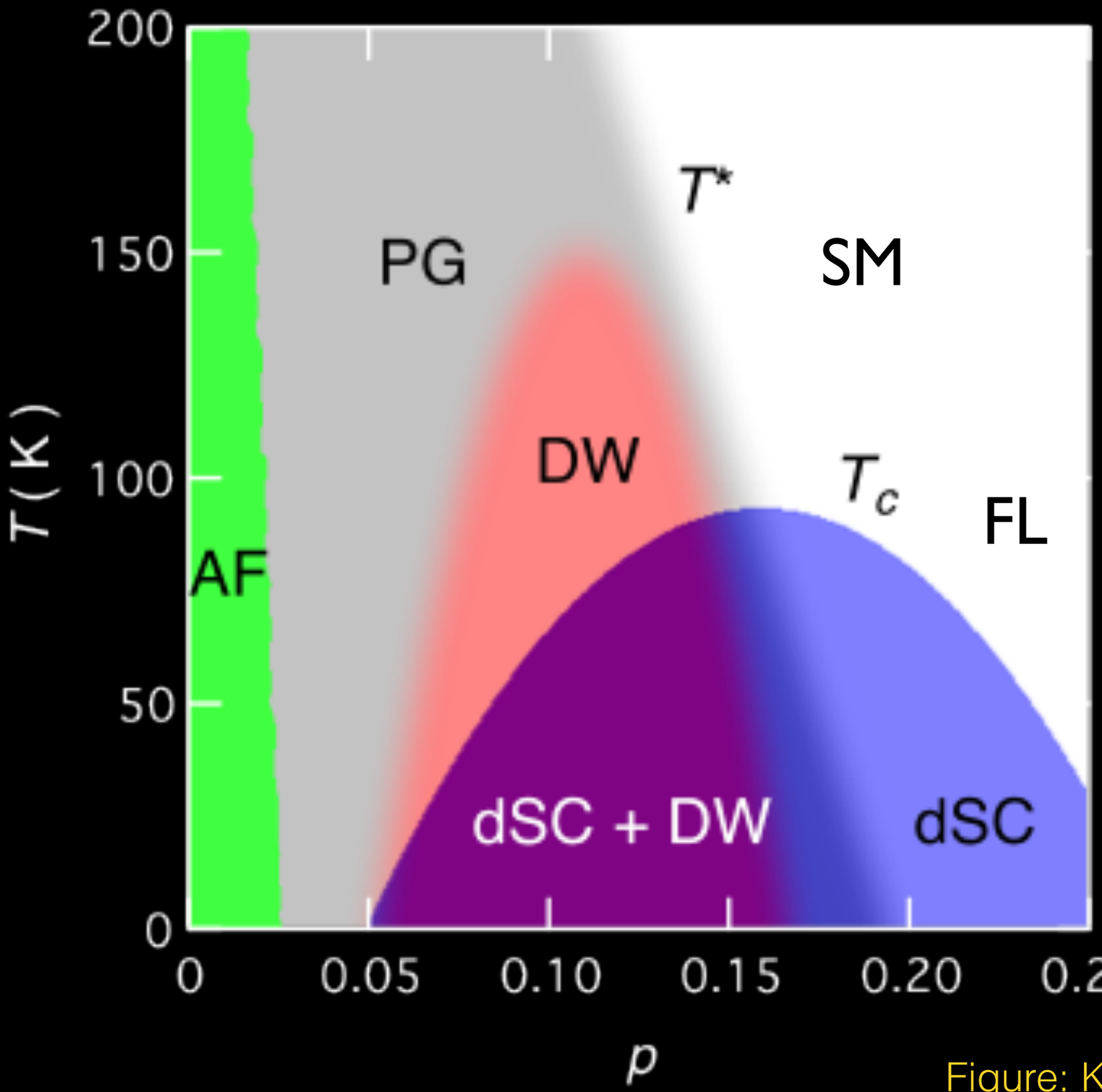
Yoni Schattner, Max H. Gerlach, Simon Trebst, and Erez Berg, arXiv:1512.07257

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.





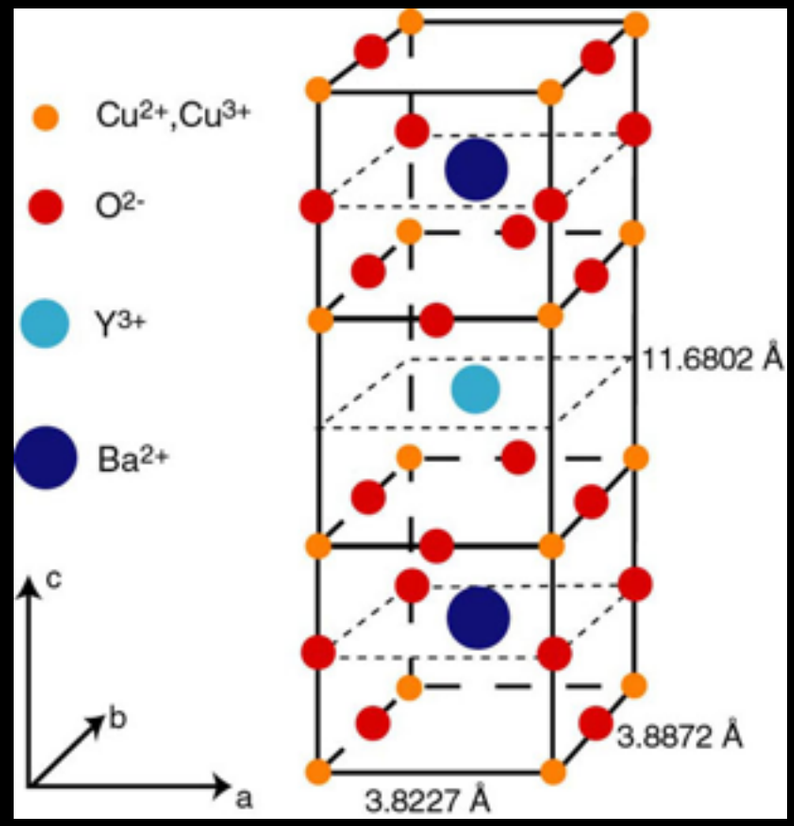


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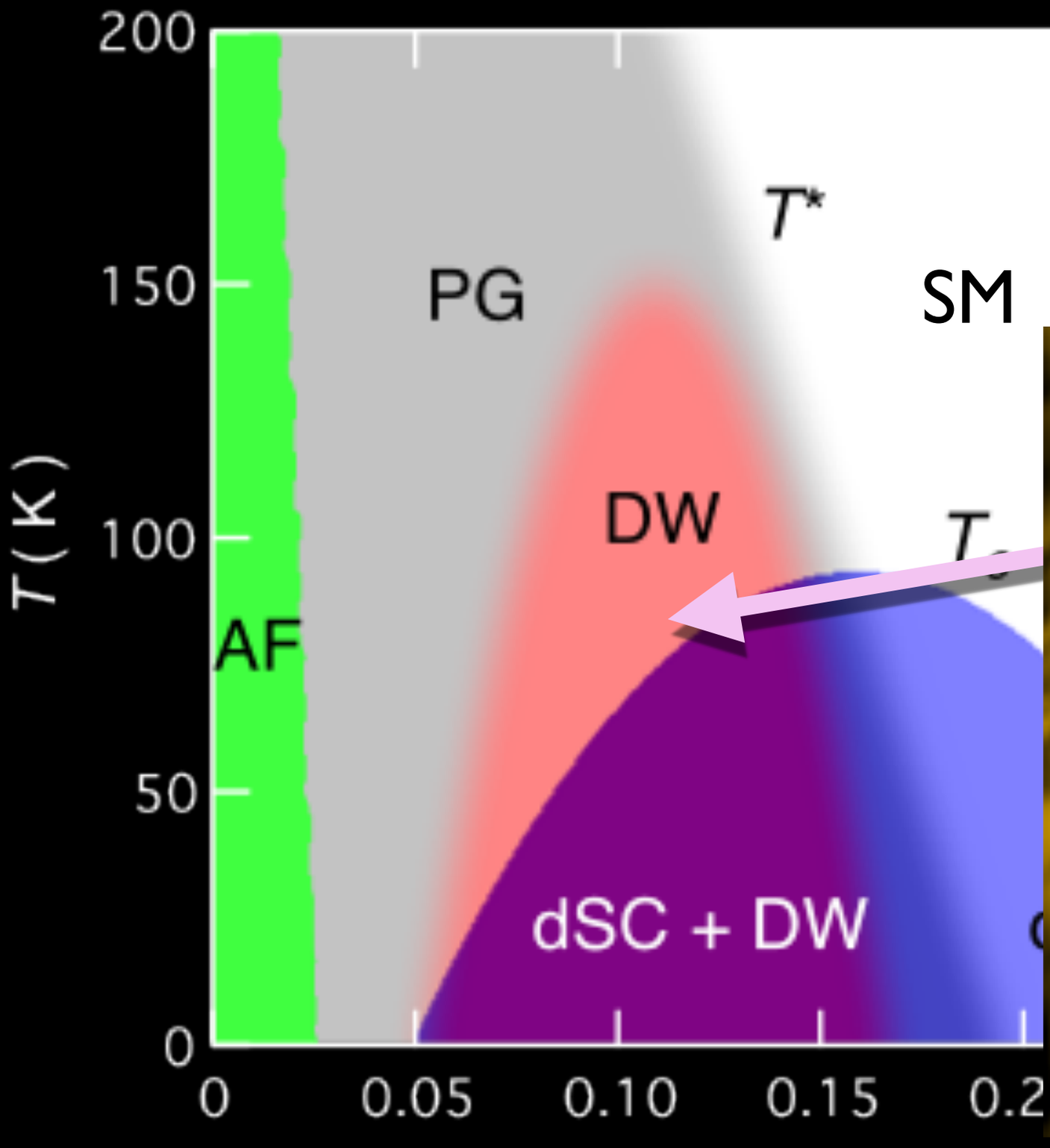
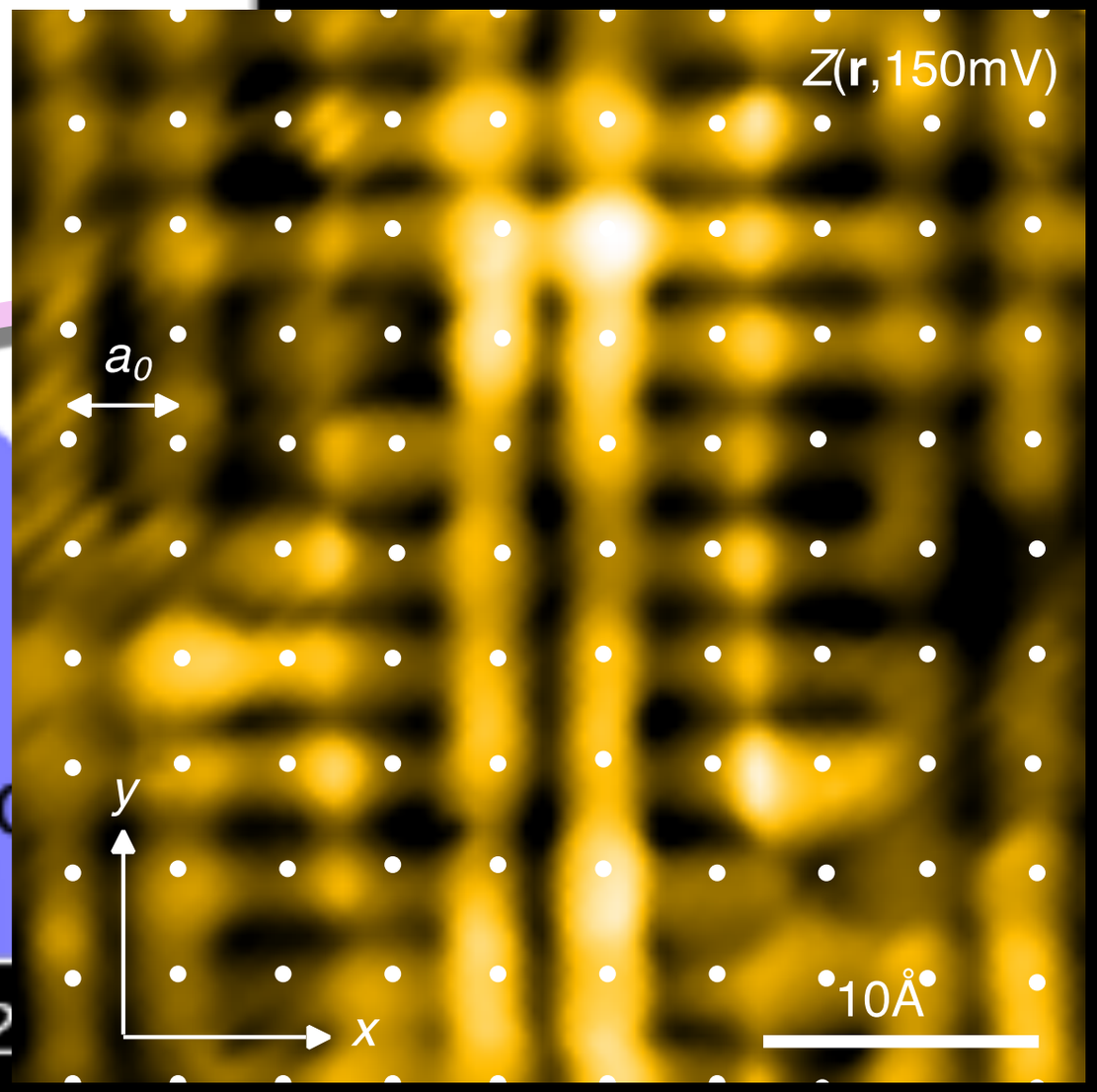
Figure: K. Fujita and J. C. Seamus Davis

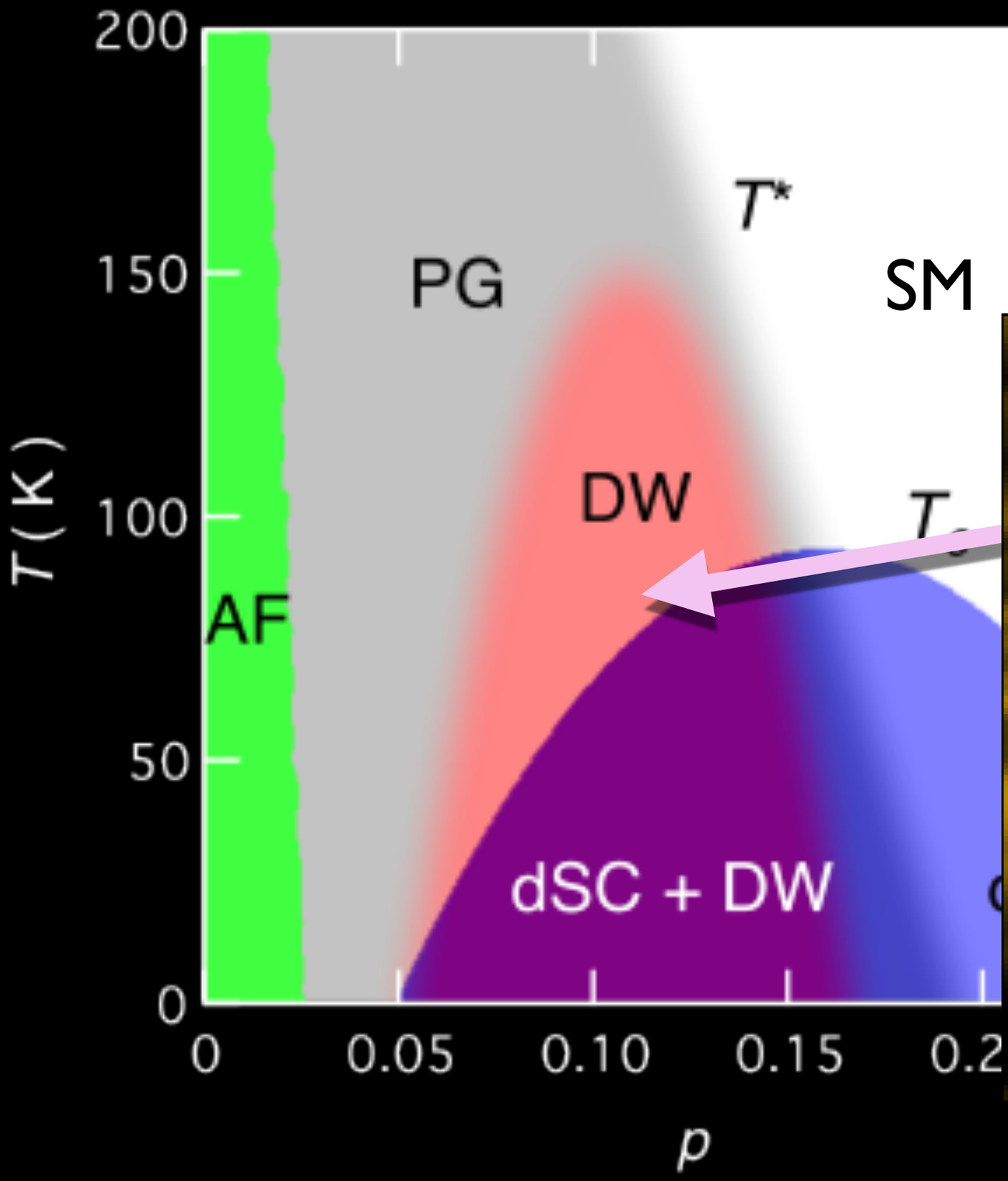
Y. Kohsaka *et al.*, Science **315**, 1380 (2007)
M. H. Hamidian *et al.*, Nature Physics **12**, 150 (2016)

Density wave (DW) order at low T and p

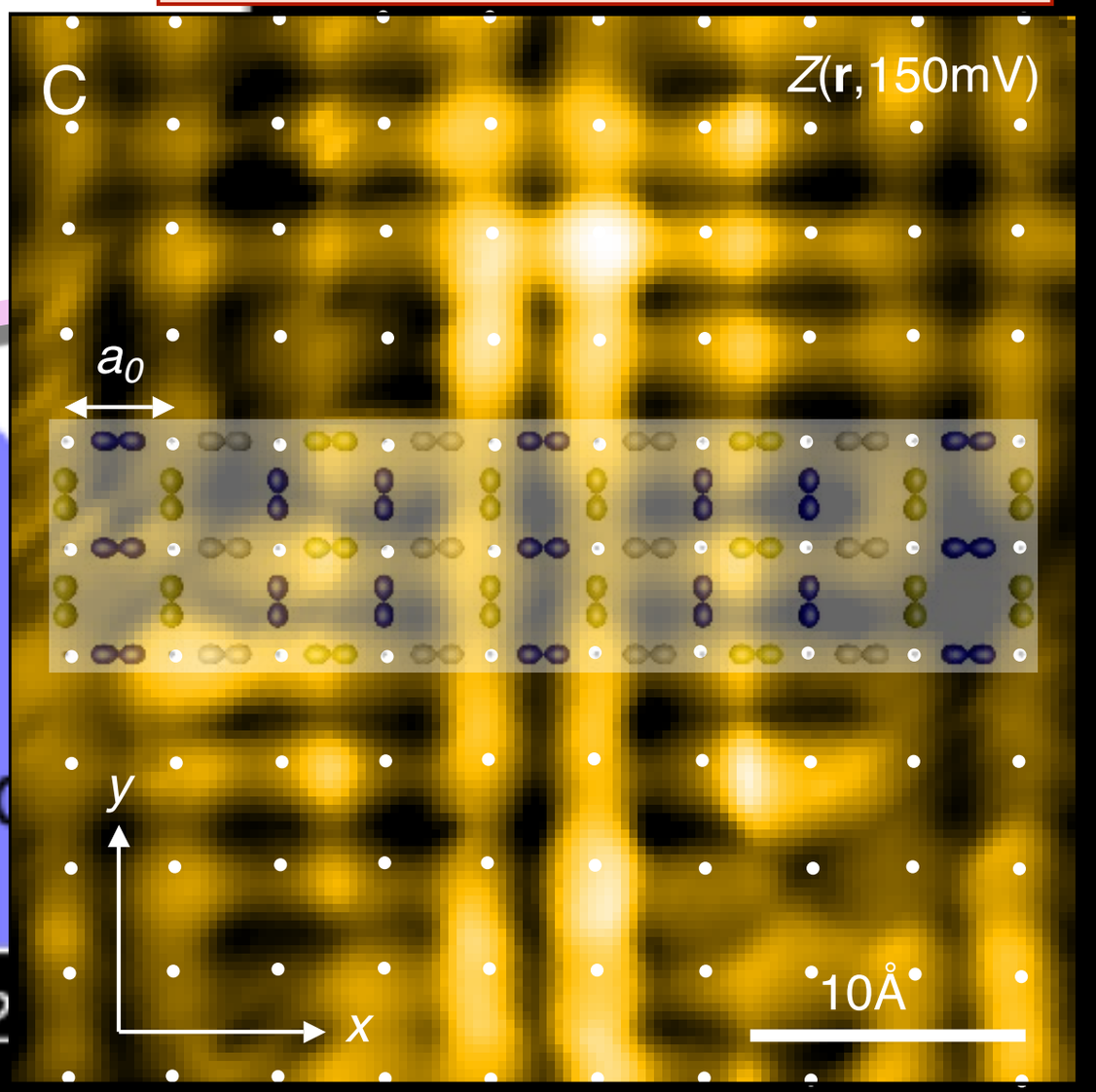




M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS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



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



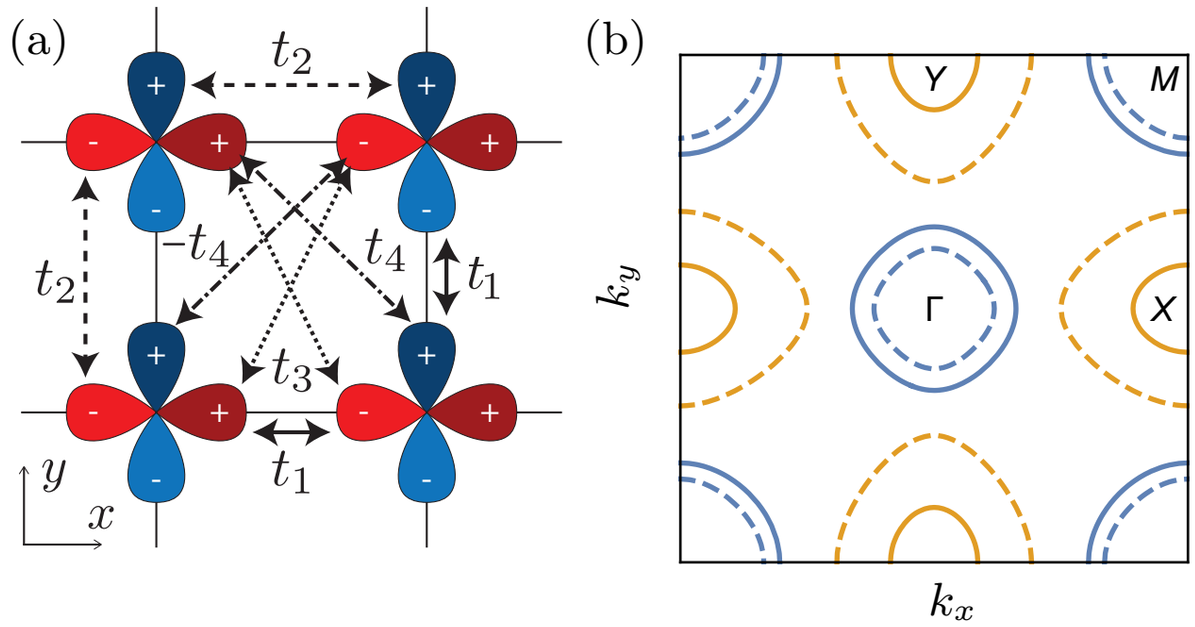
Quantum Monte Carlo study of the T_c enhancement mechanism in FeSe on $SrTiO_3$

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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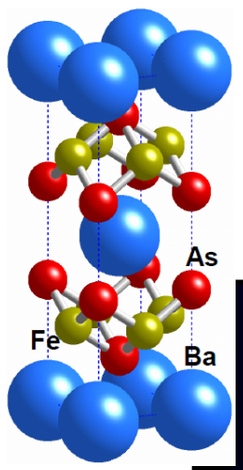

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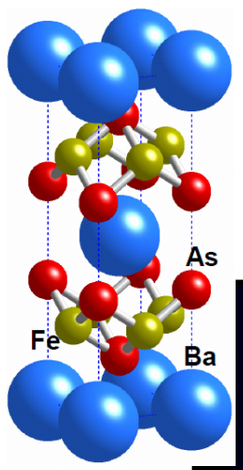

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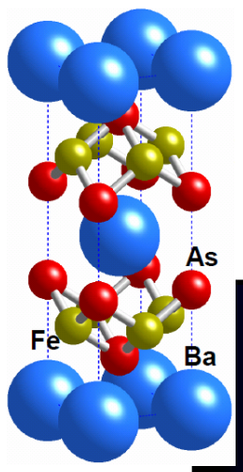

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Strange Metal

no quasiparticles,
Landau-Boltzmann theory
does not apply

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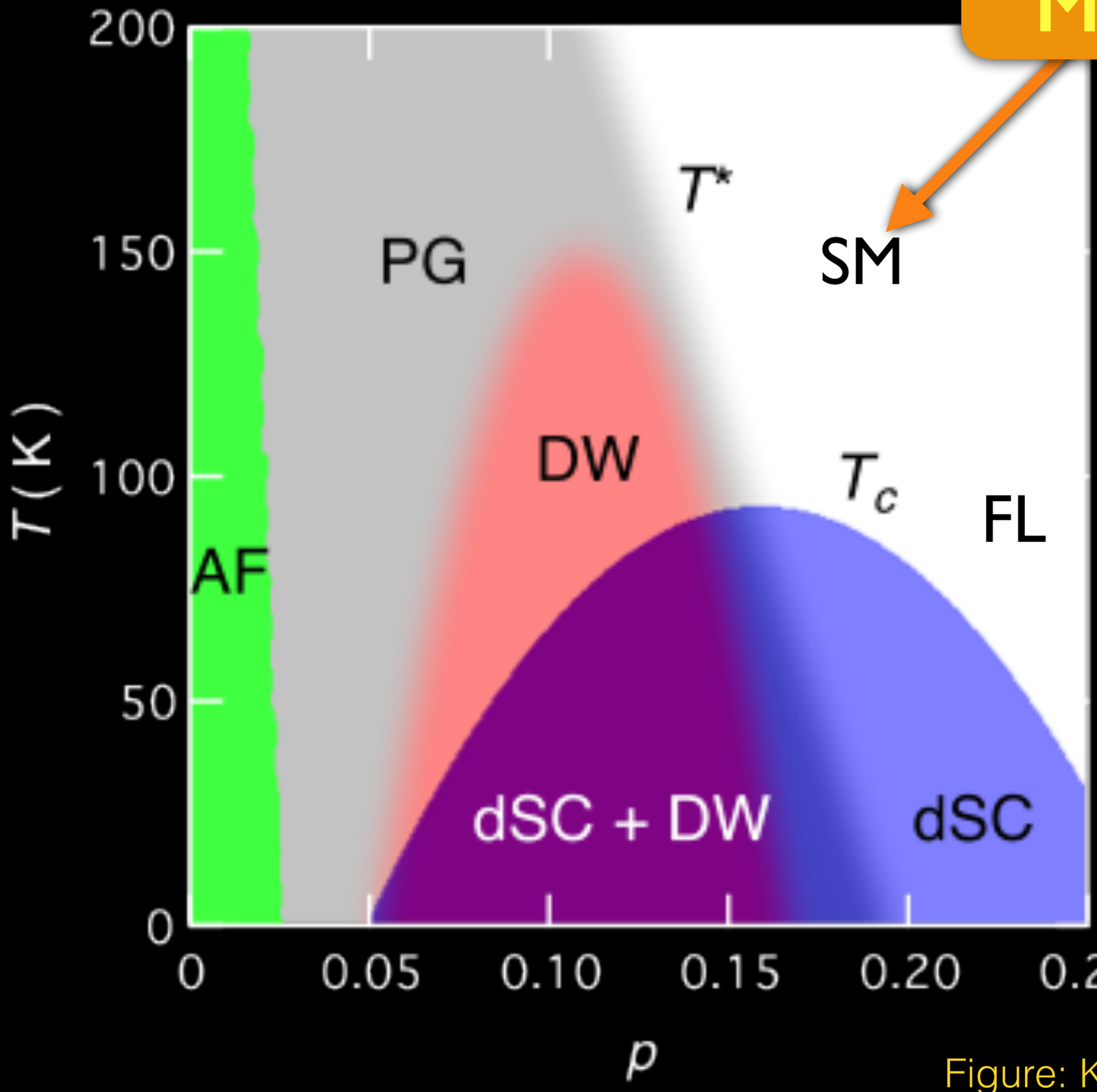
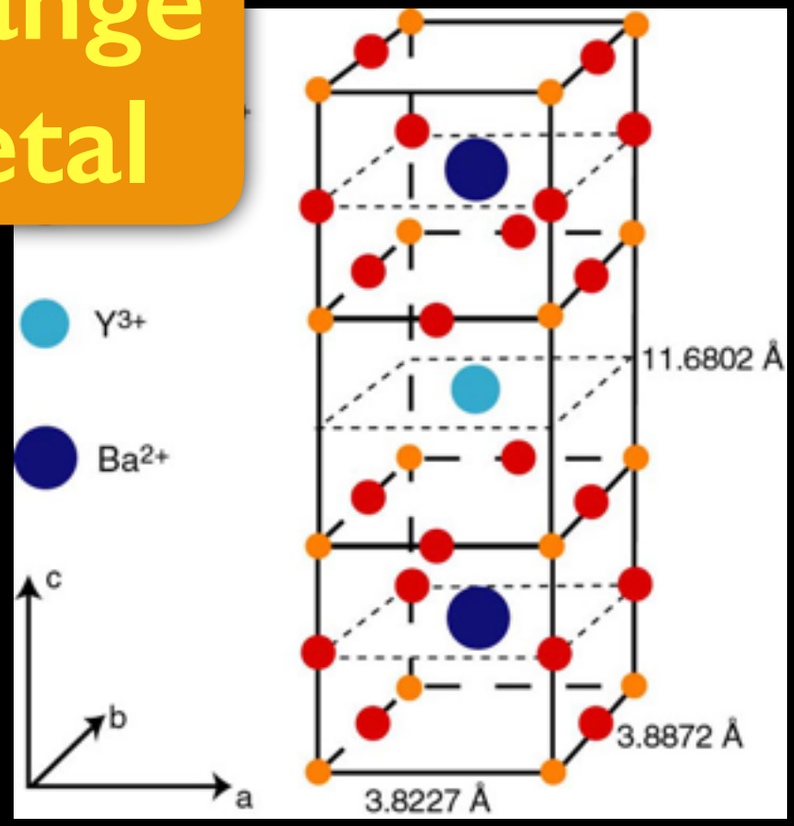
Strange Metal



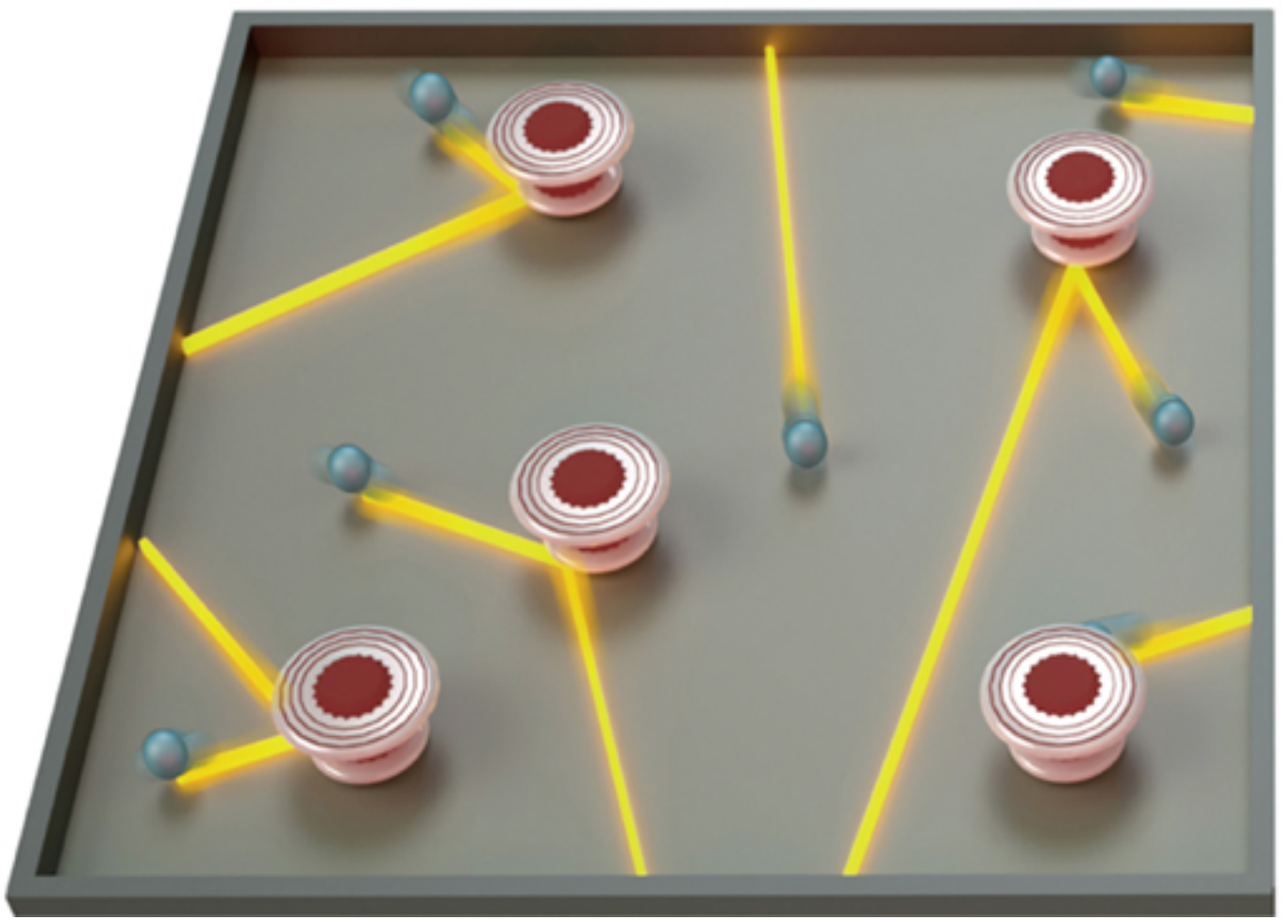


$YBa_2Cu_3O_{6+x}$

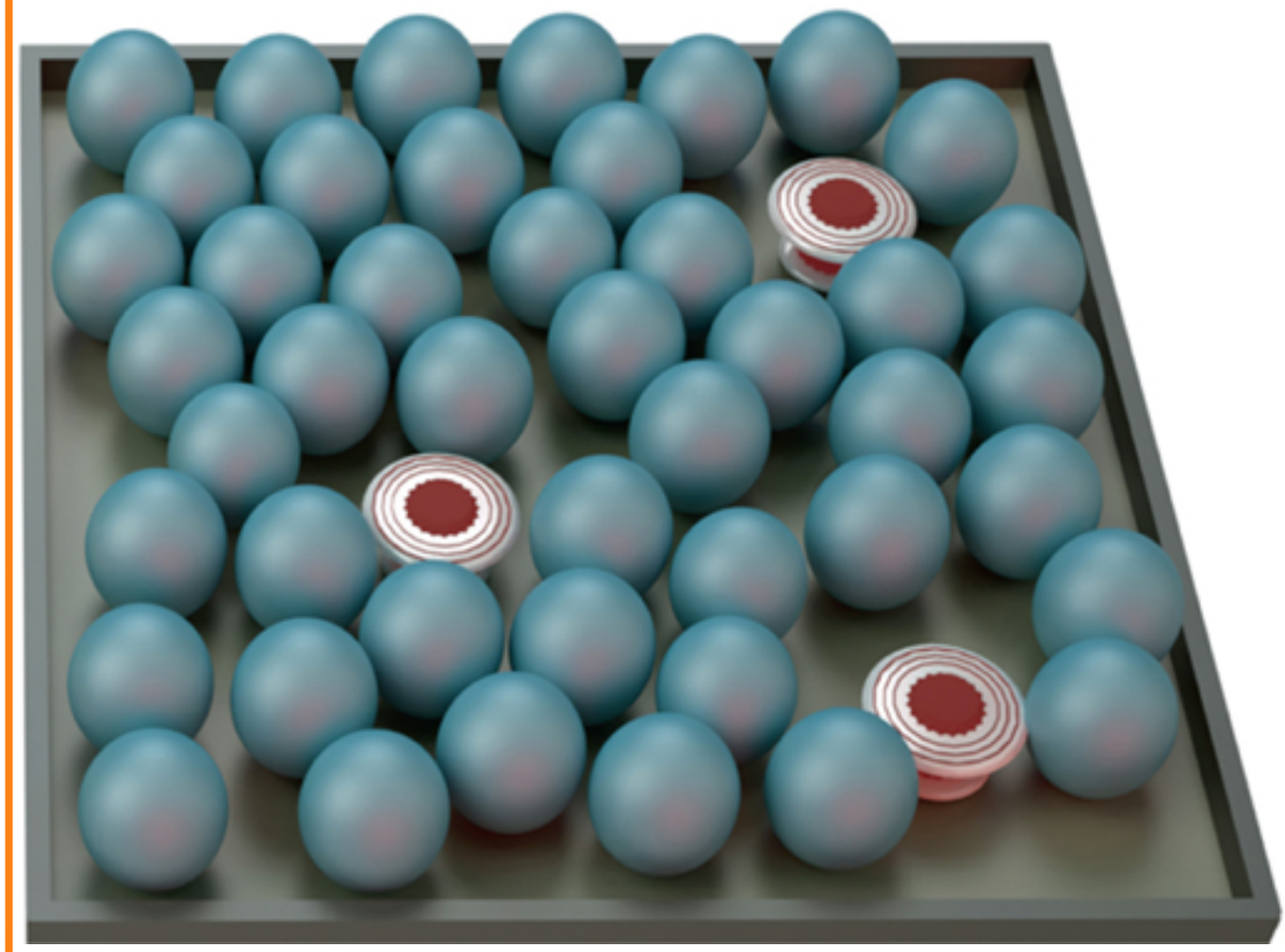
Figure: K. Fujita and J. C. Seamus Davis

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*

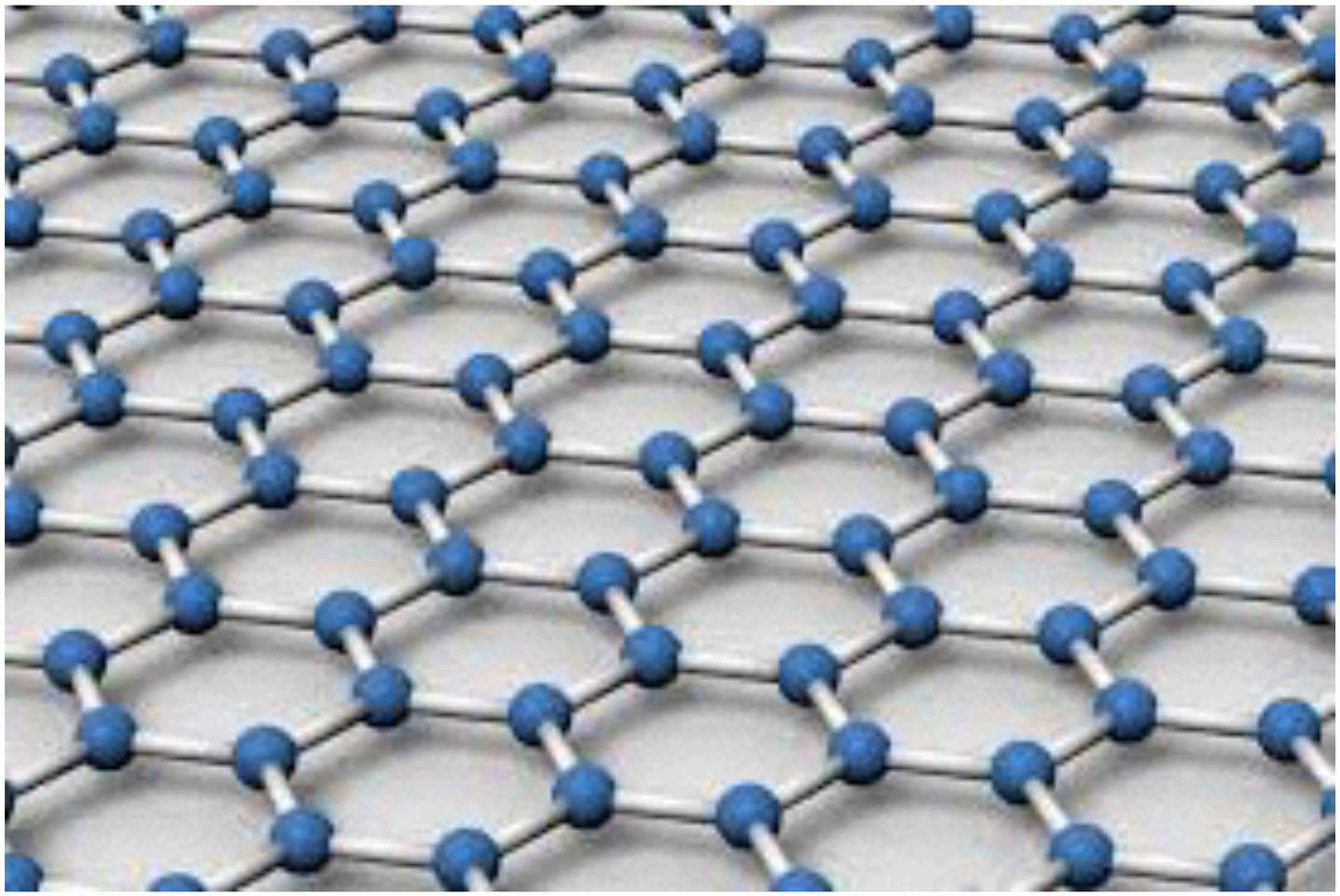


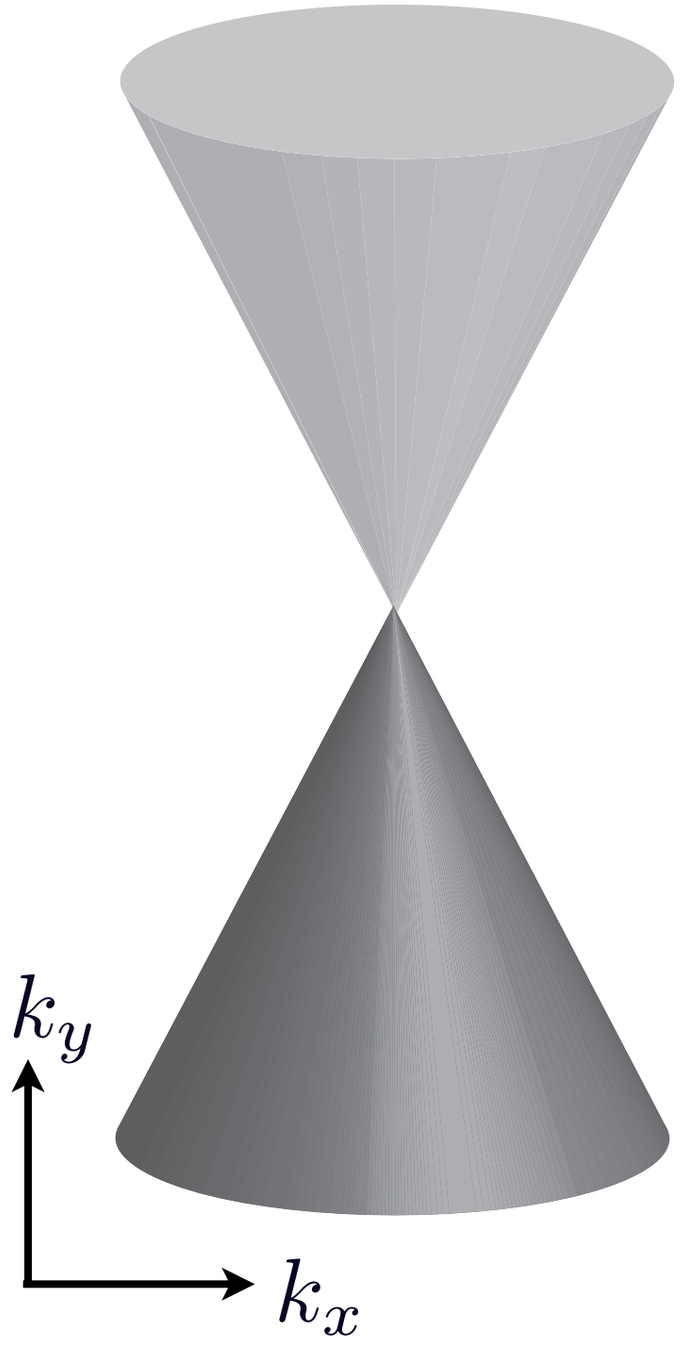
Fermi liquids: quasiparticles moving ballistically between impurity (red circles) scattering events



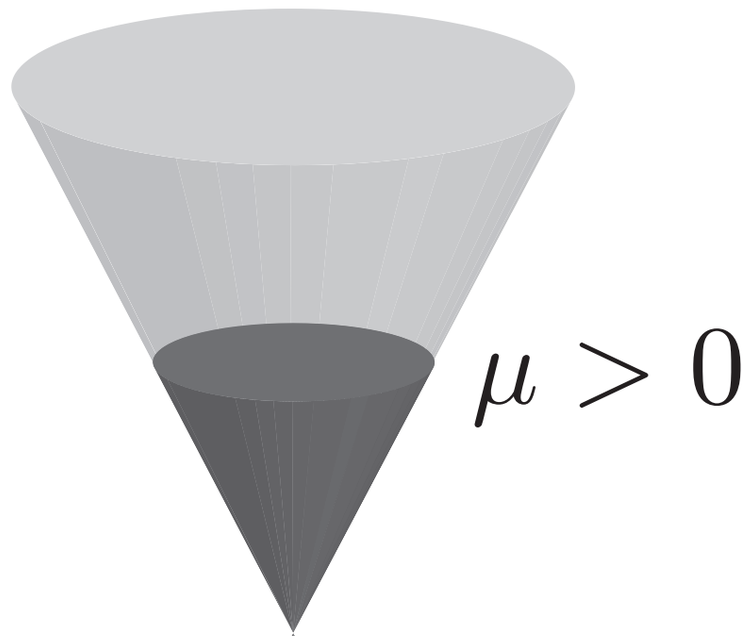
Strange metals: electrons scatter frequently off each other, so there is no regime of ballistic quasiparticle motion. The electron "liquid" then "flows" around impurities

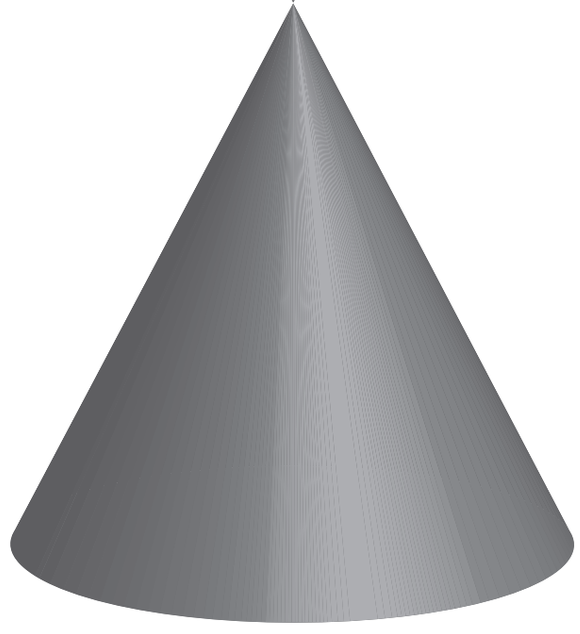
Graphene

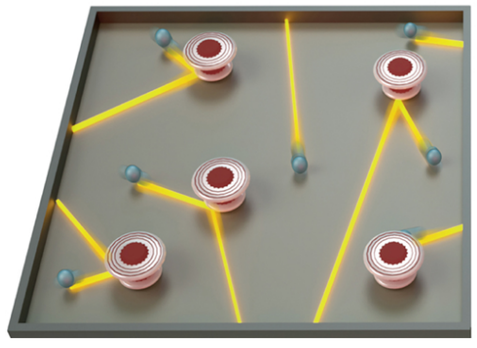




Graphene

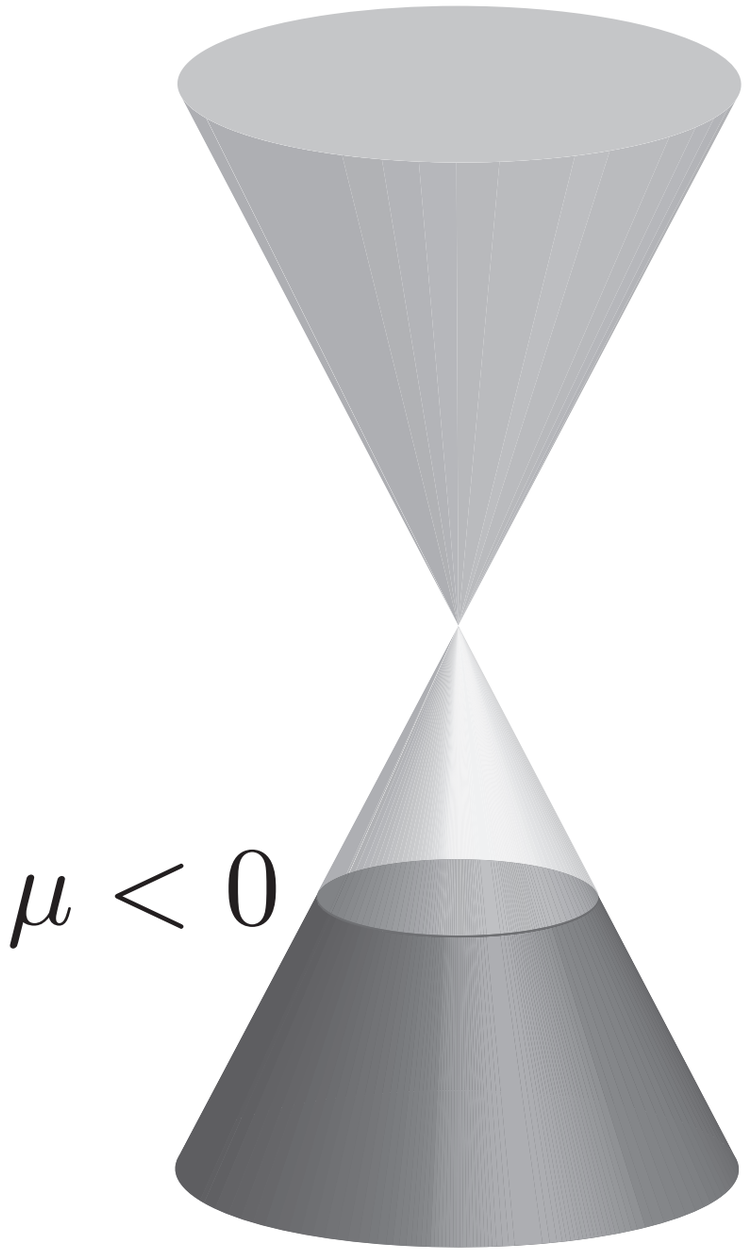




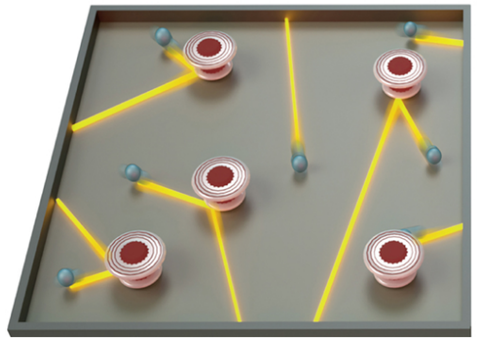


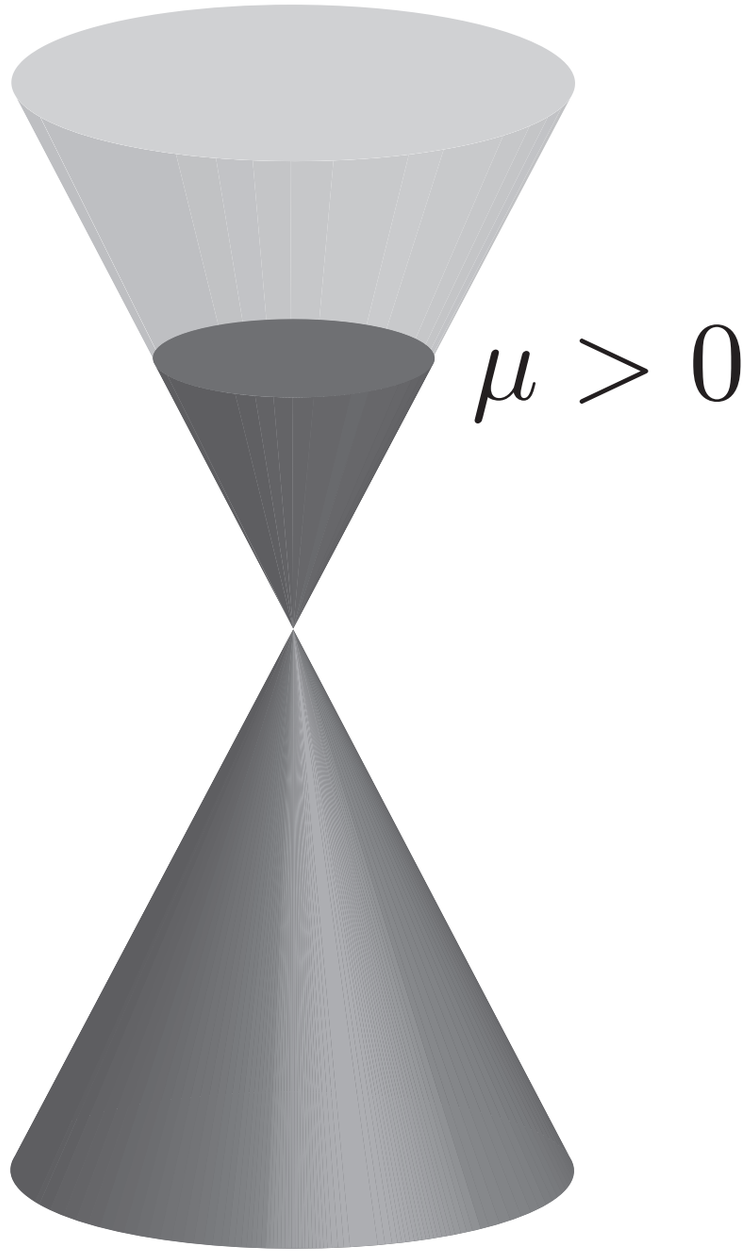
Electron
Fermi surface

Graphene



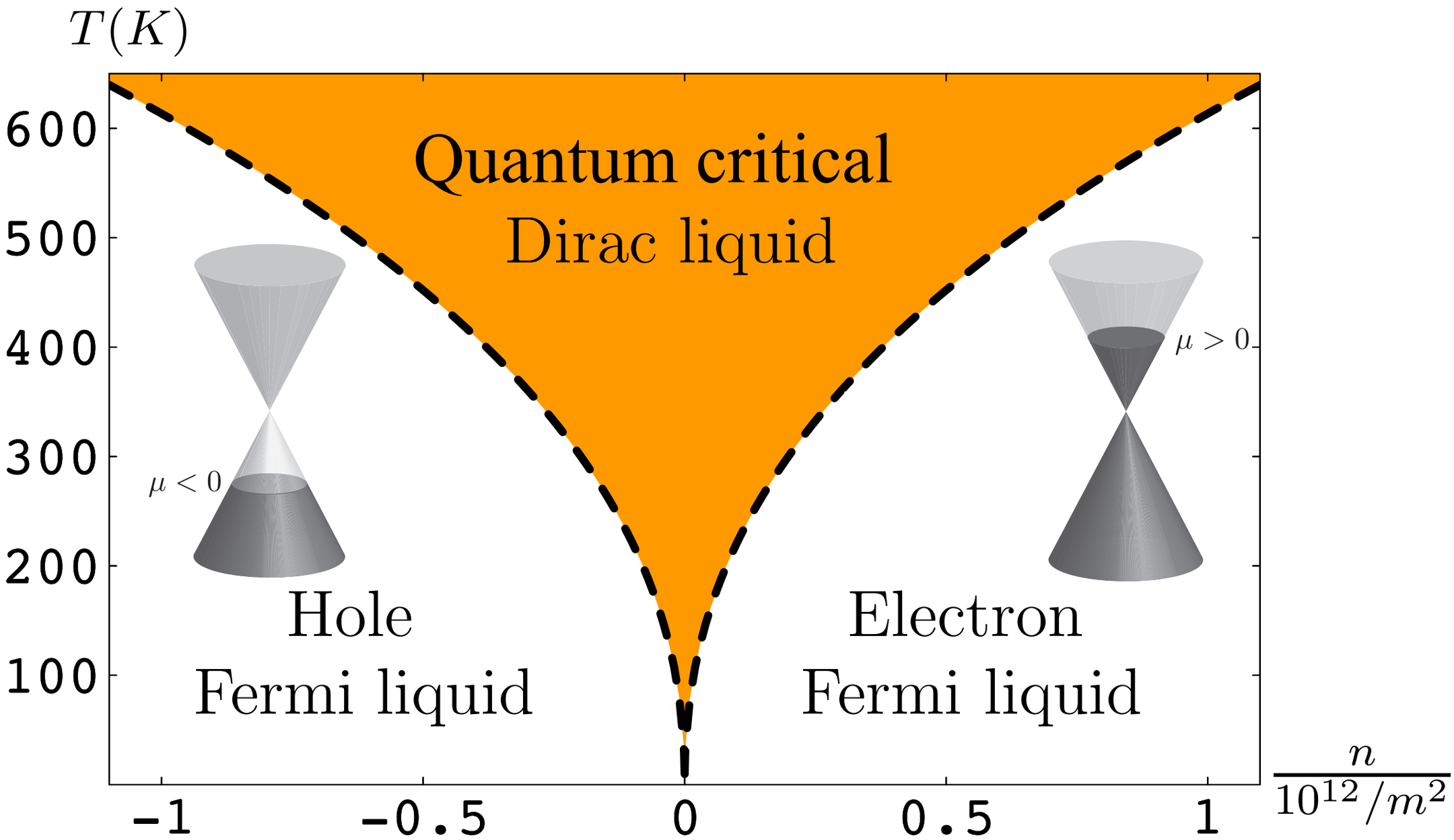
Hole
Fermi surface





Electron
Fermi surface

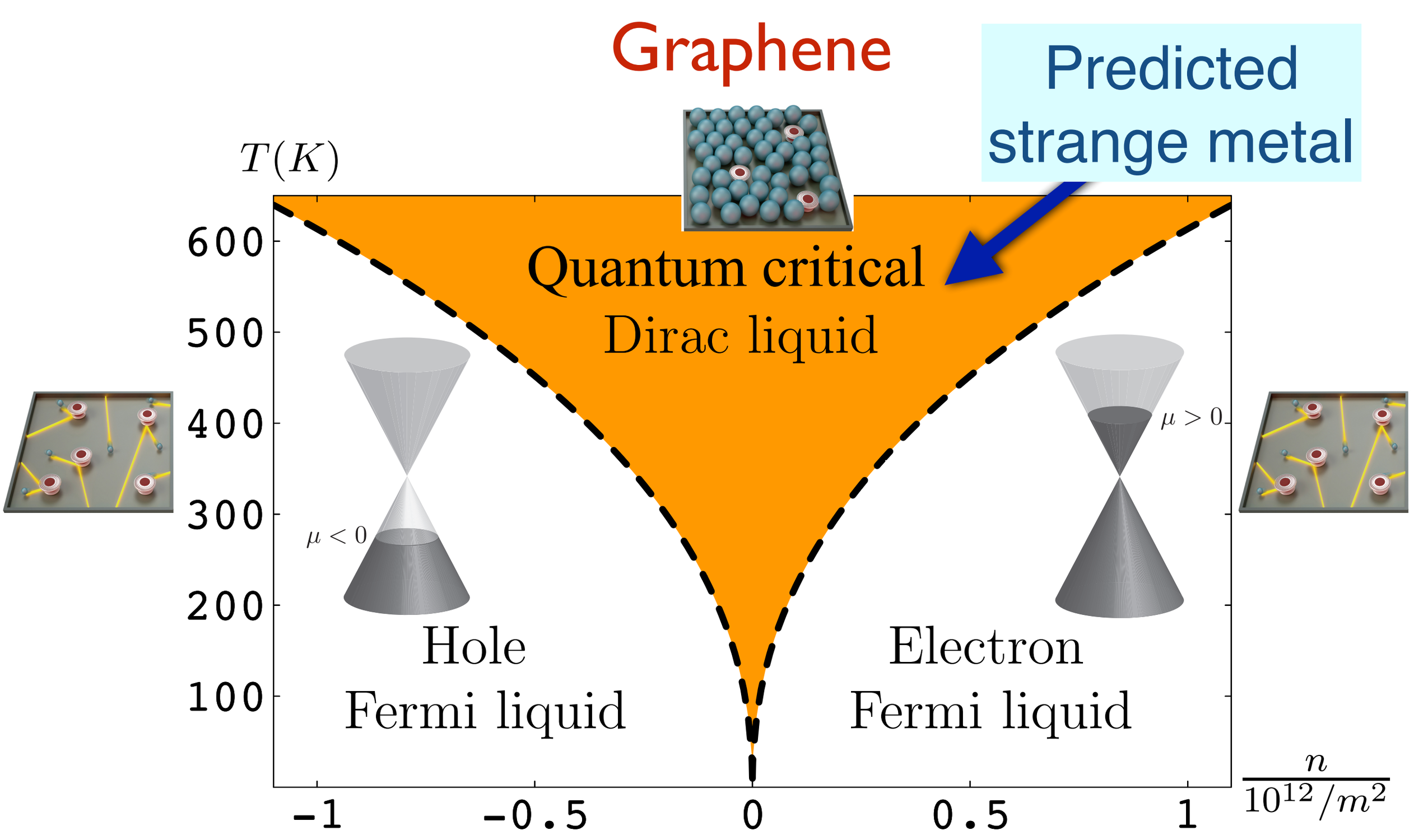
Graphene



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

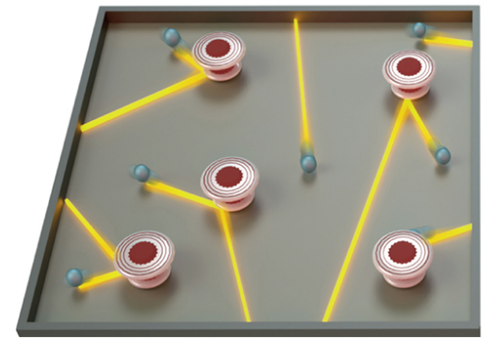
Graphene

Predicted strange metal



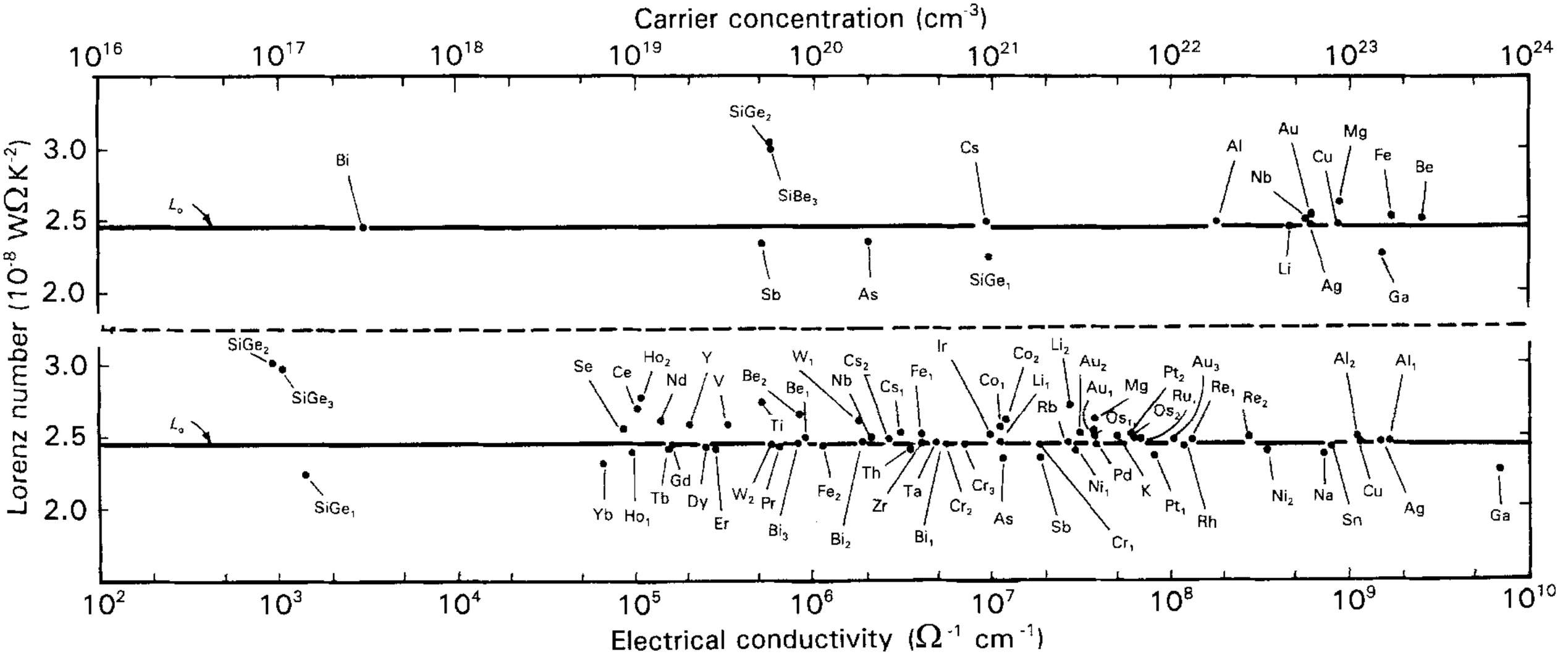
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Thermal and electrical conductivity with quasiparticles



- Wiedemann-Franz law in a Fermi liquid:

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



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

Graphene

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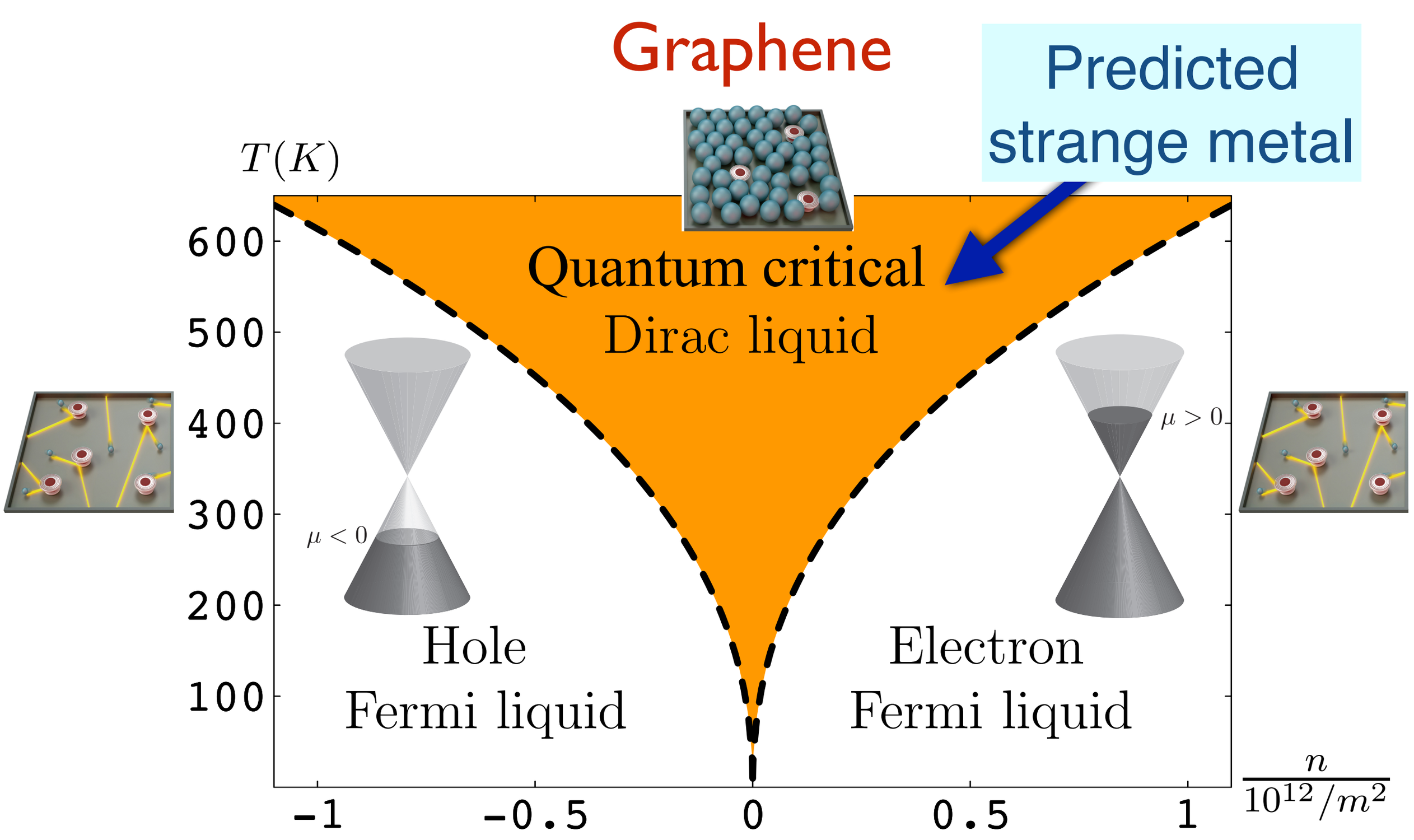

M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
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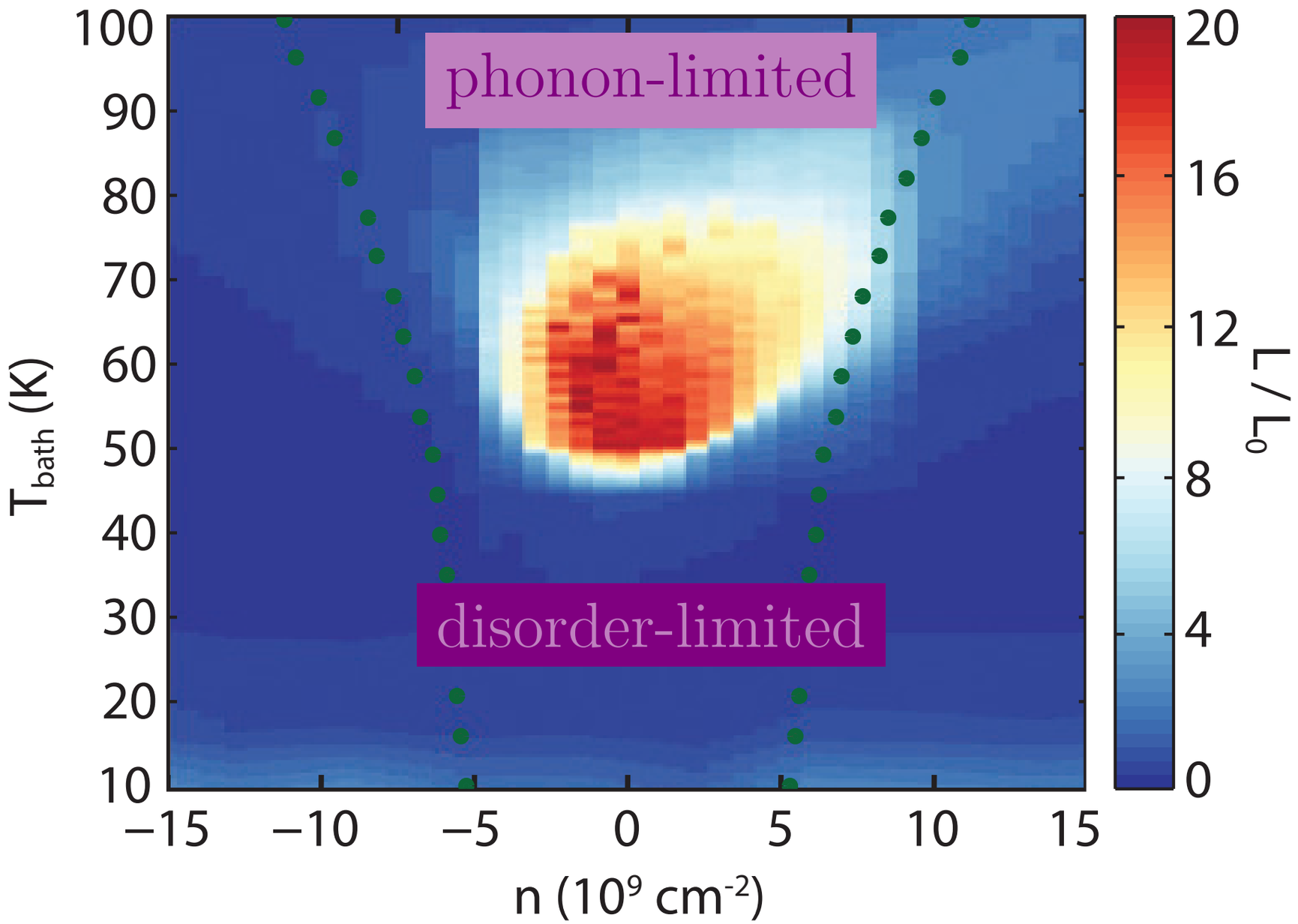
J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016)

Strange metal in graphene

$$L = \frac{\kappa}{T\sigma}$$

$$L_0 = \frac{\pi^2 k_B^2}{3e^2}$$



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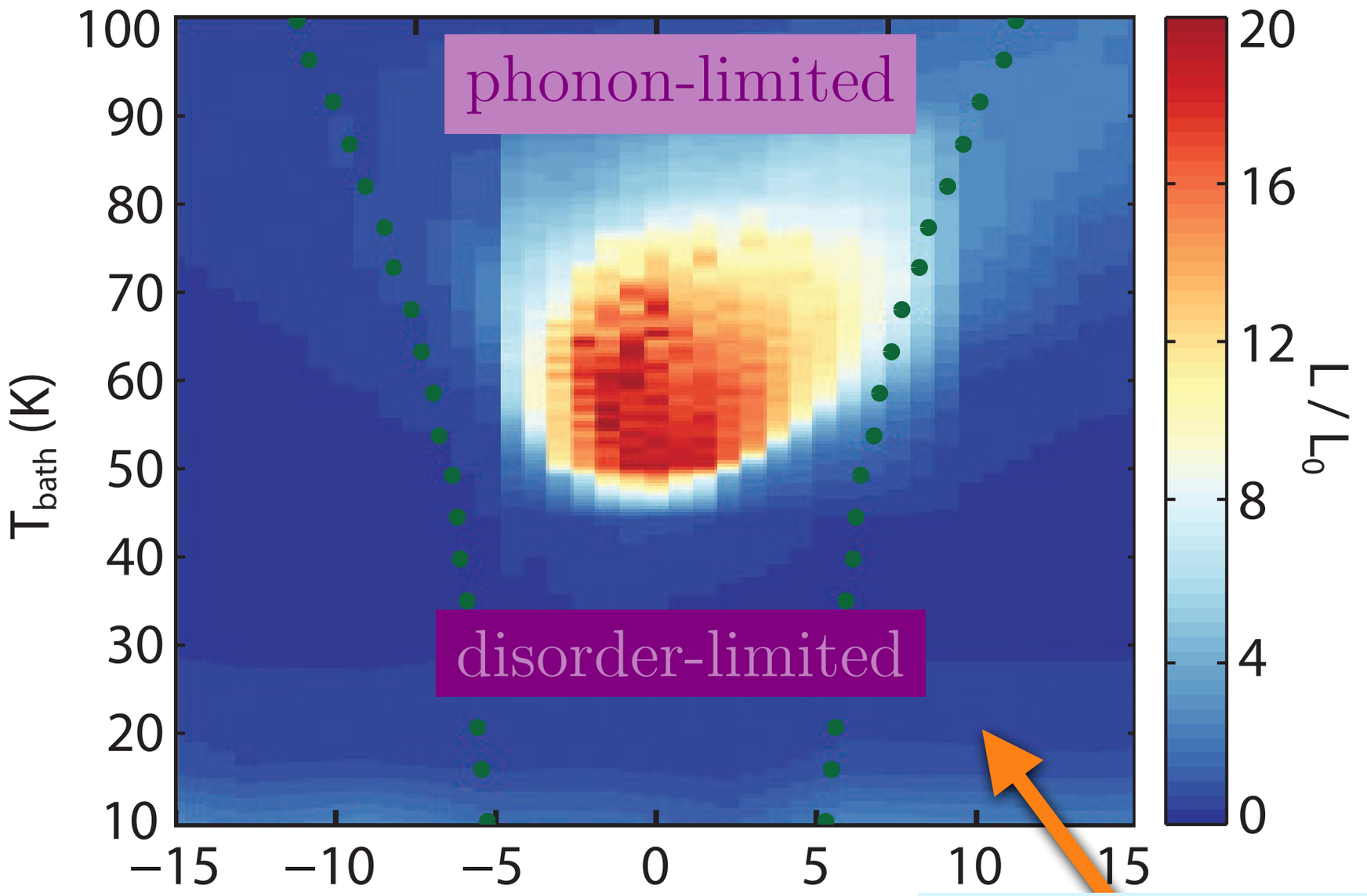

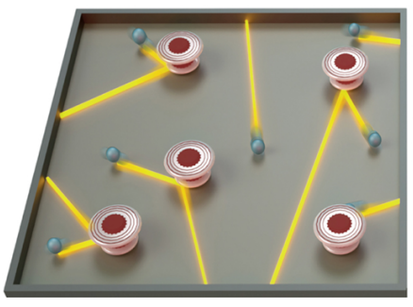

Wiedemann-Franz obeyed

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, Science **351**, 1058 (2016)

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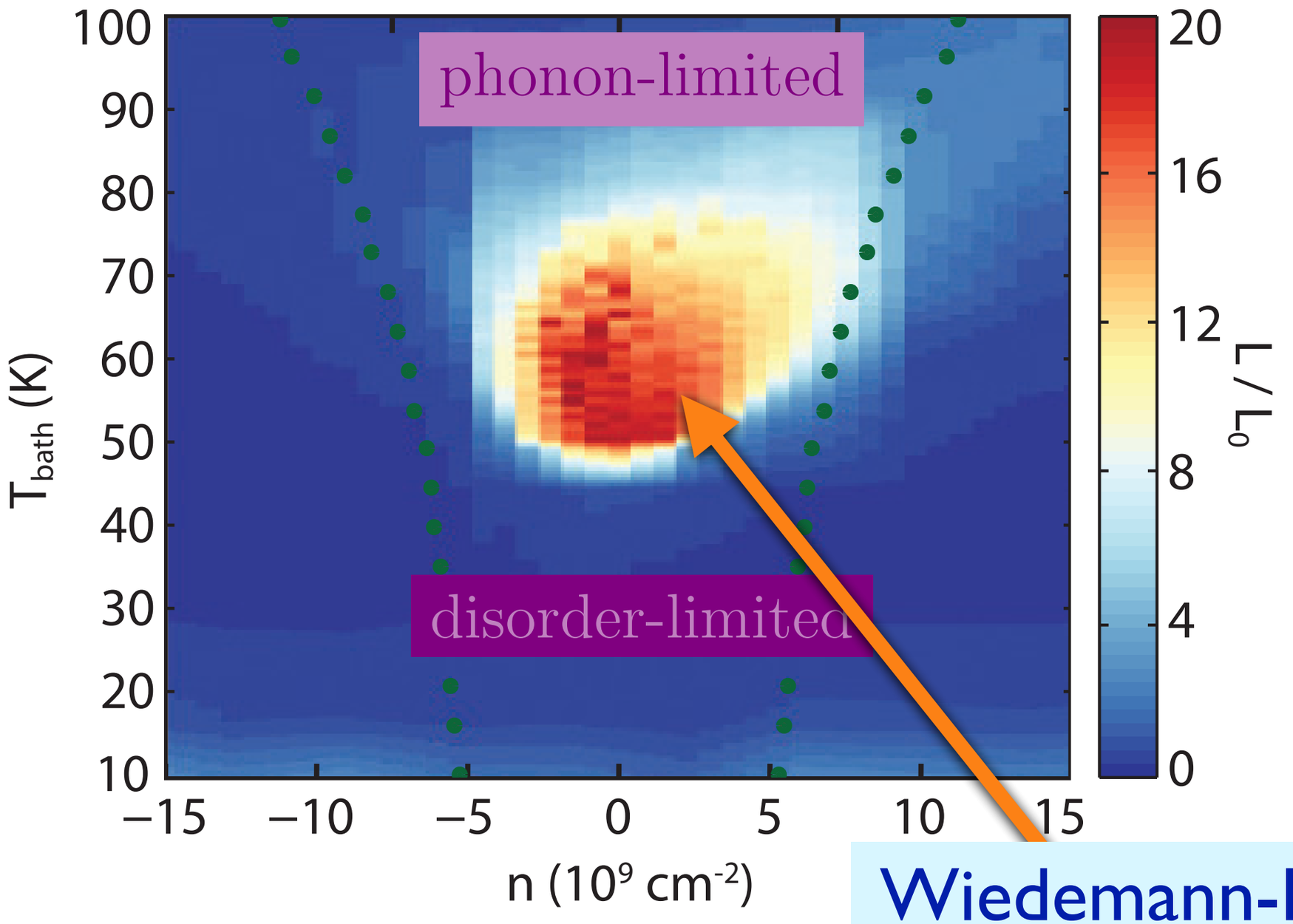
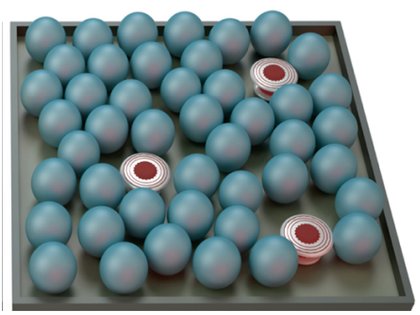
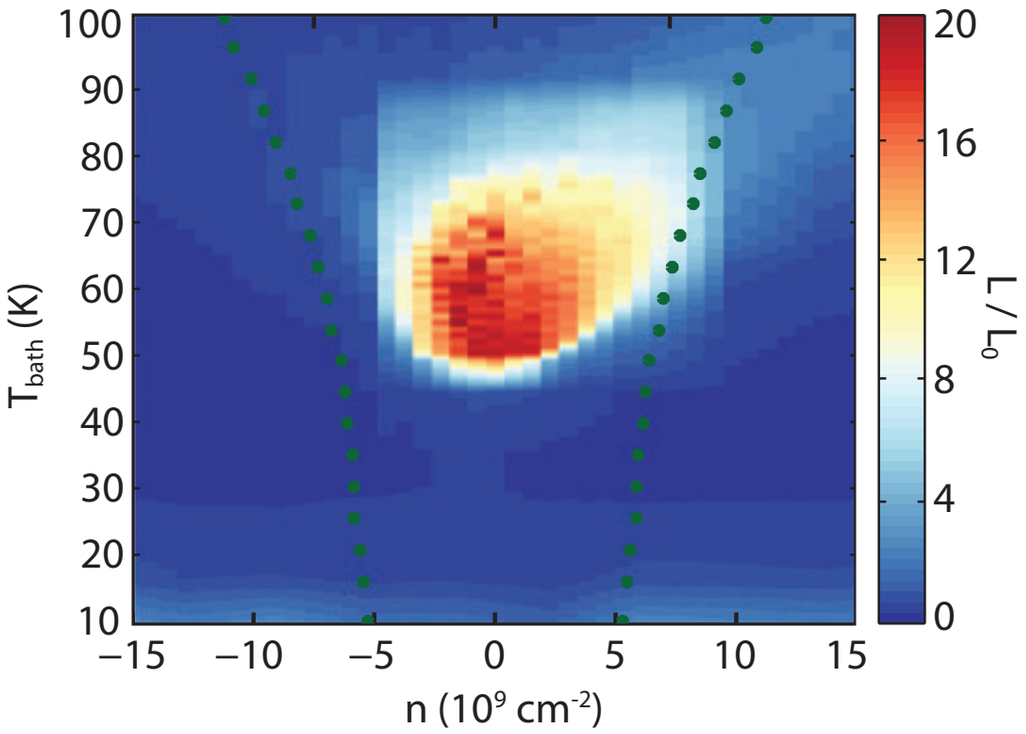
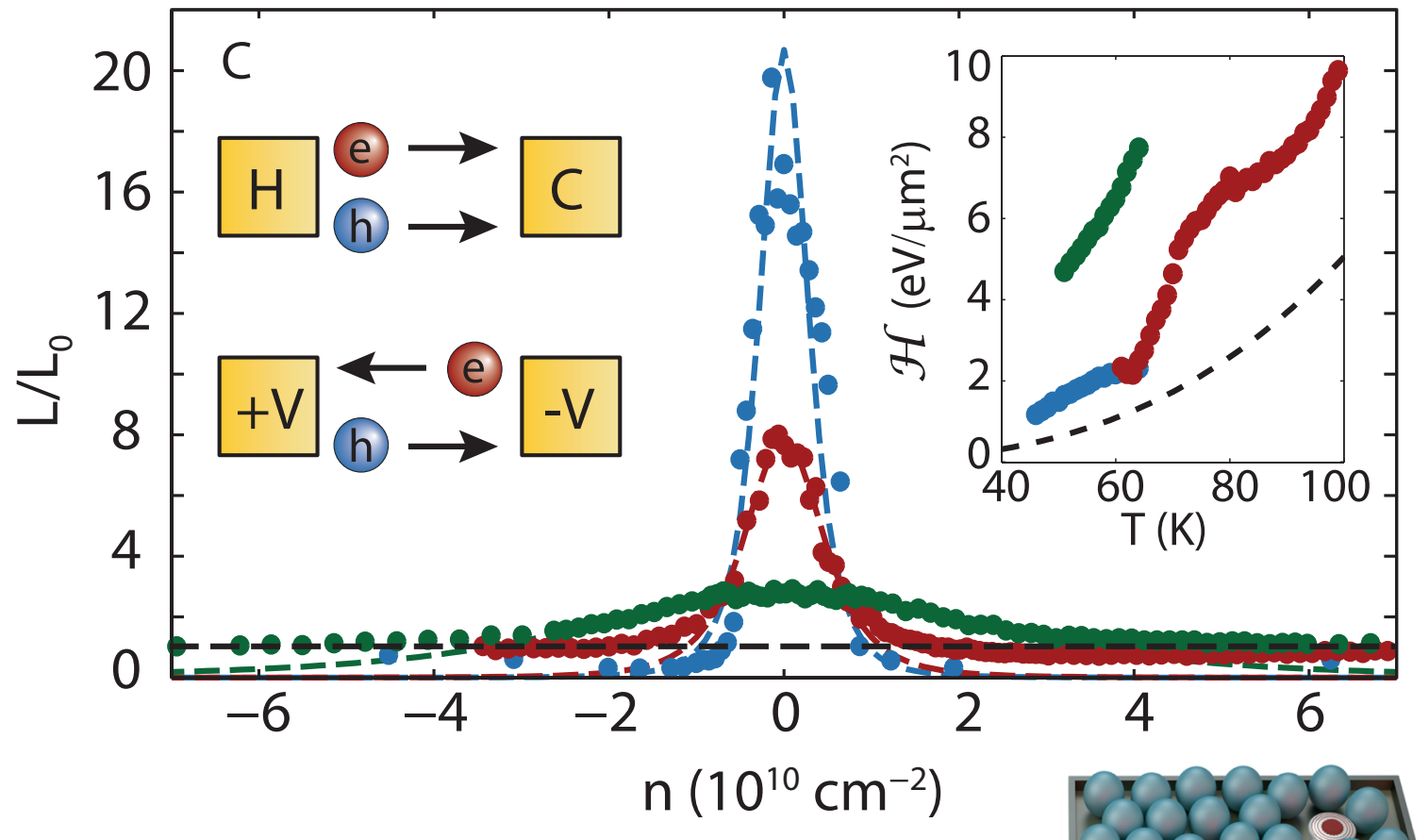
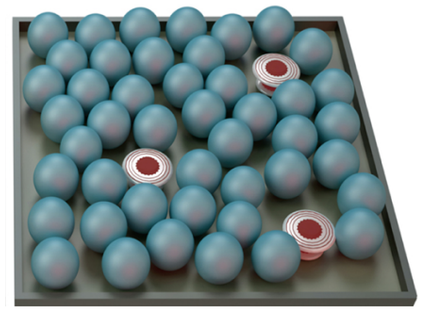


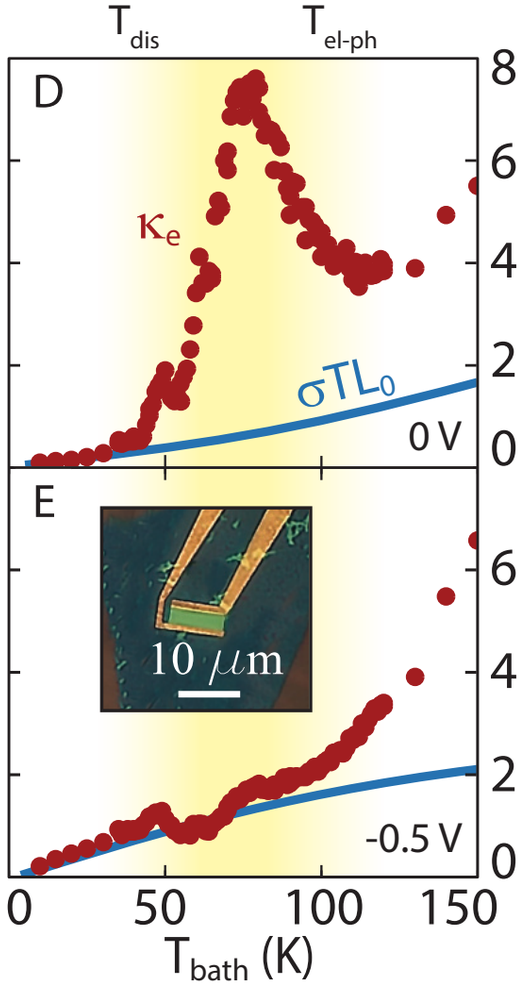


Wiedemann-Franz violated !









$$\text{Lorentz ratio } L = \kappa/(T\sigma)$$
$$= \frac{v_F^2 \mathcal{H} \tau_{\text{imp}}}{T^2 \sigma_Q} \frac{1}{\left(1 + e^2 v_F^2 \mathcal{Q}^2 \tau_{\text{imp}}/(\mathcal{H}\sigma_Q)\right)^2}$$

$\mathcal{Q} \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density

$\sigma_Q \rightarrow$ quantum critical conductivity

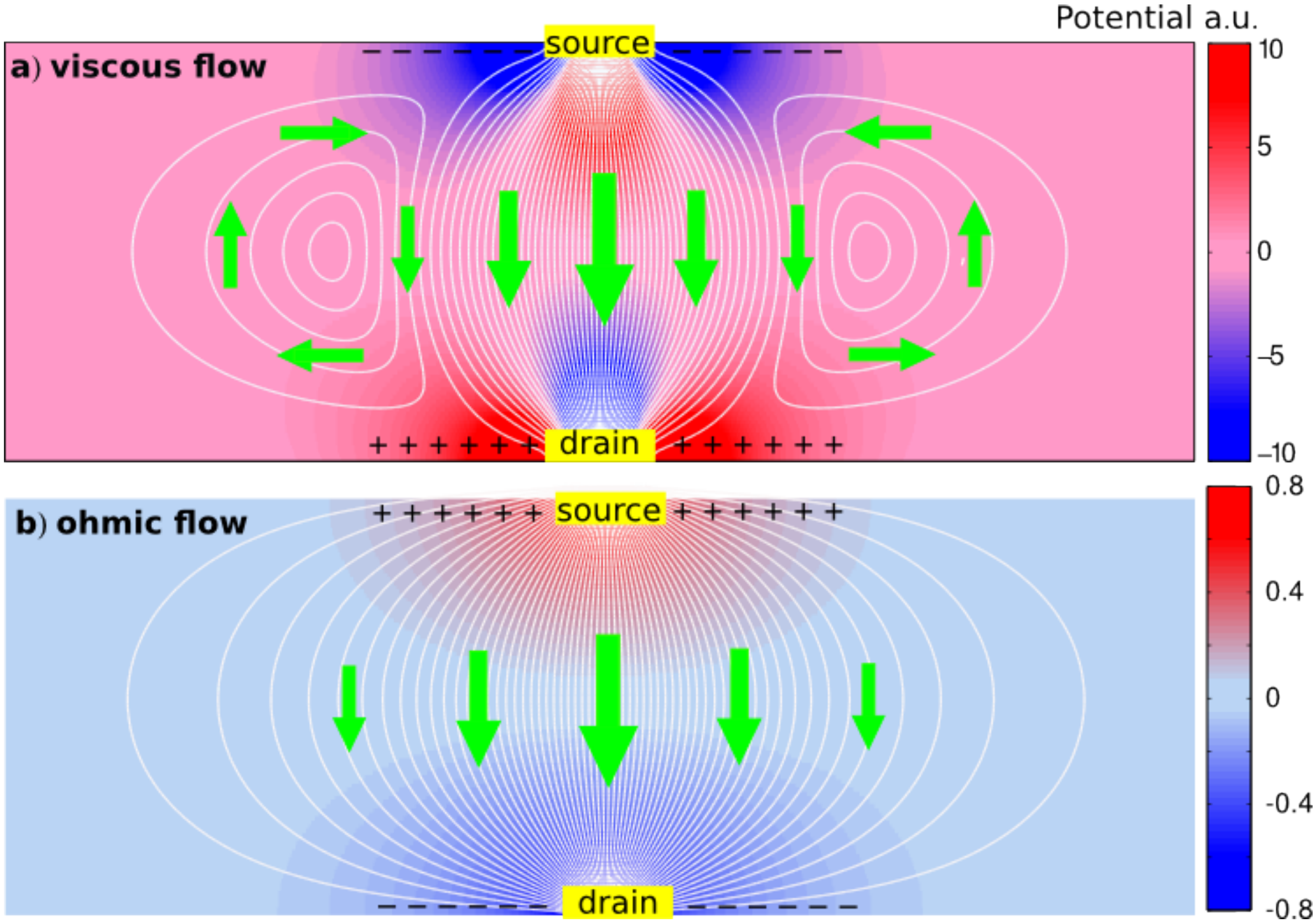
$\tau_{\text{imp}} \rightarrow$ momentum relaxation time from impurities

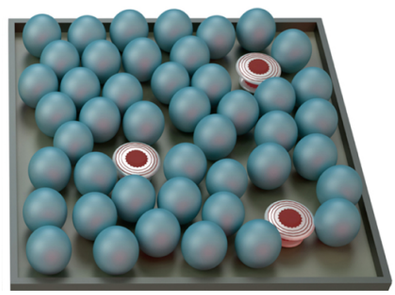
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

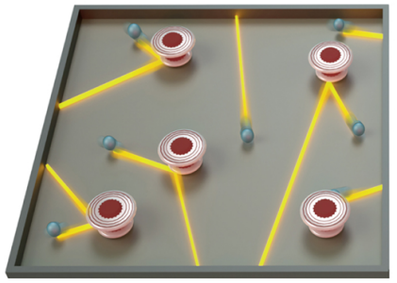
J. Crossno et al., Science **351**, 1058 (2016)

Strange metal in graphene

Negative local resistance due to viscous electron backflow in graphene







L. Levitov and G. Falkovich, arXiv:1508.00836, *Nature Physics online*

Strange metal in graphene

Science **351**, 1055 (2016)

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]

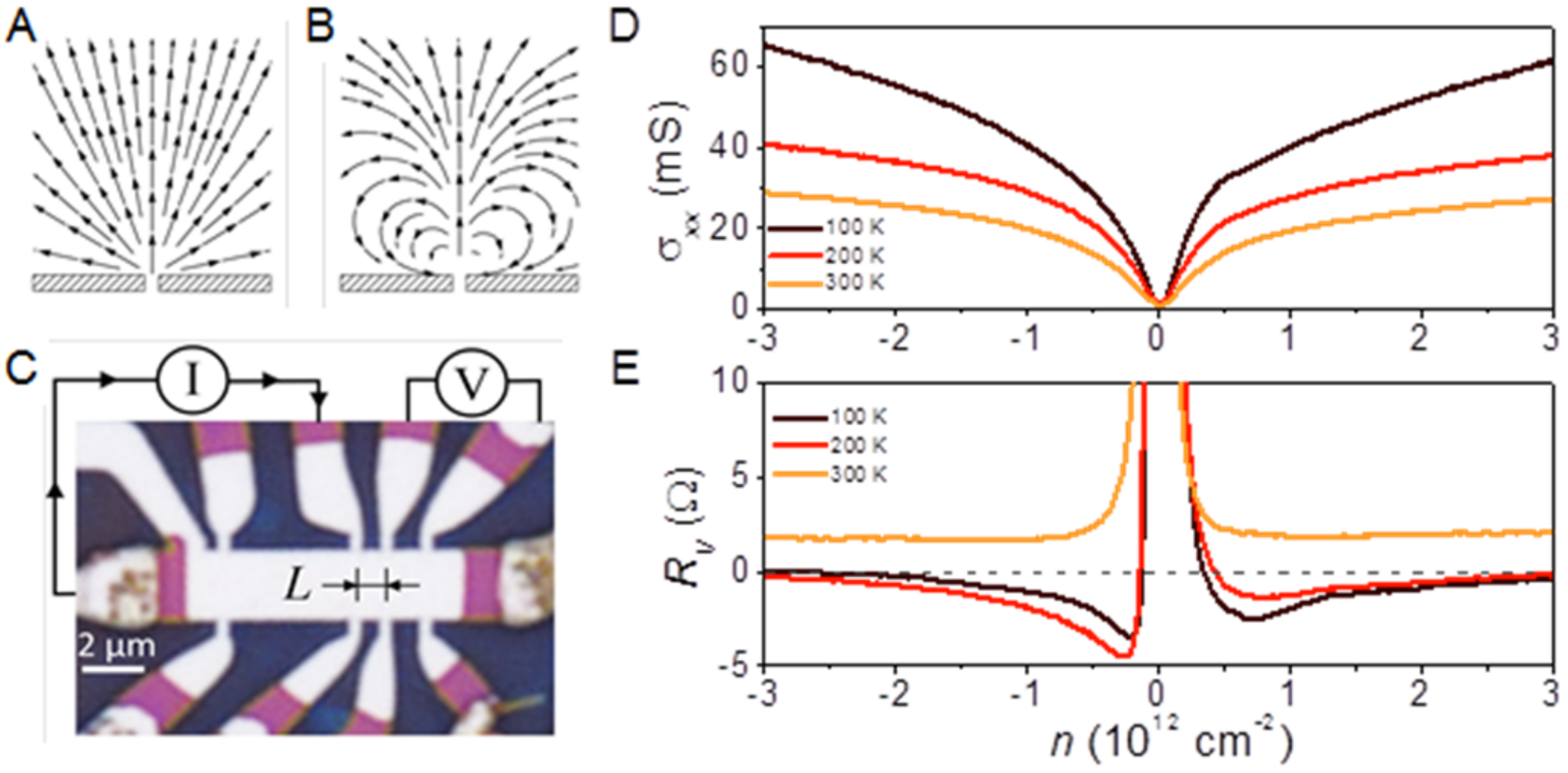
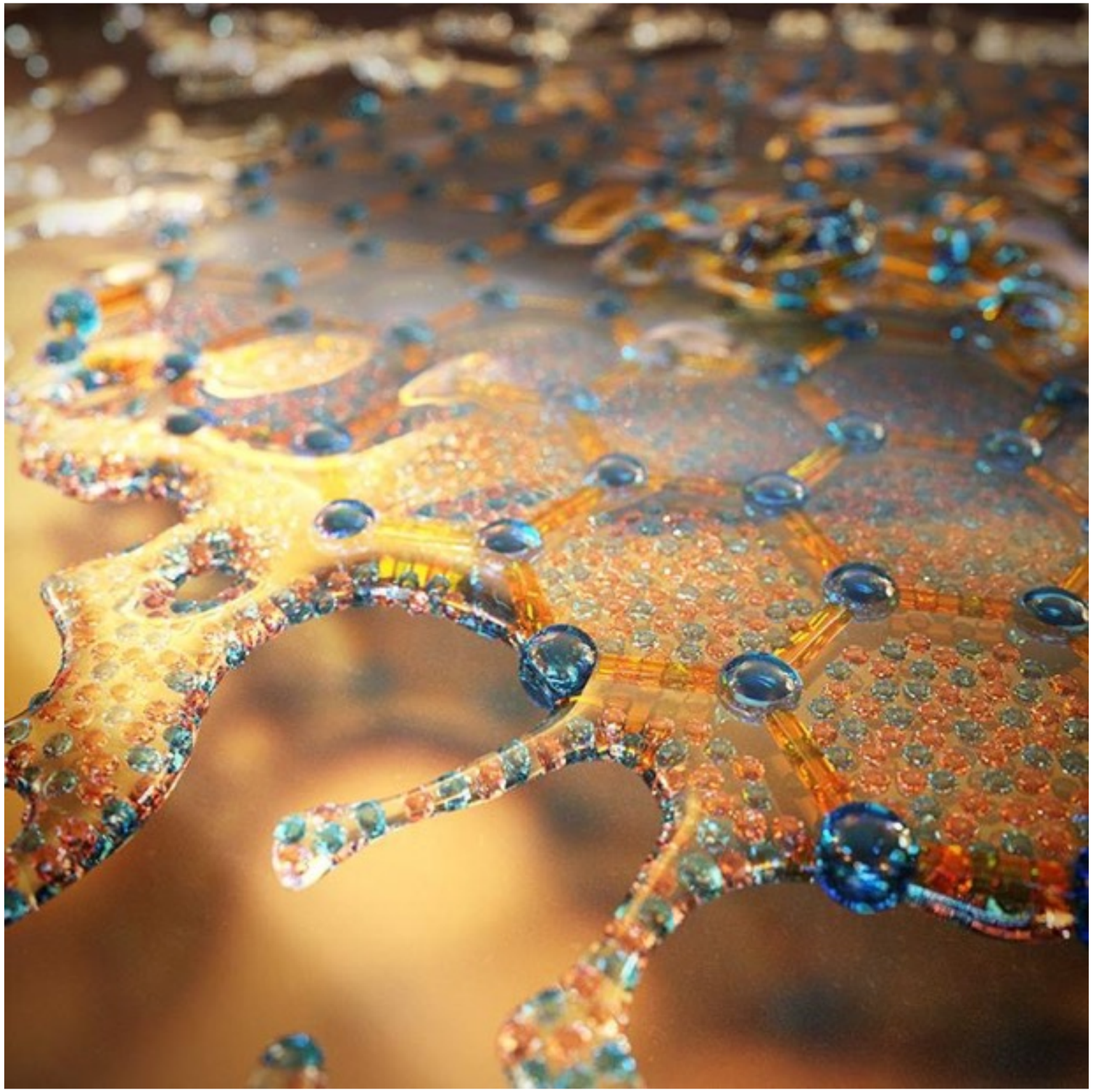
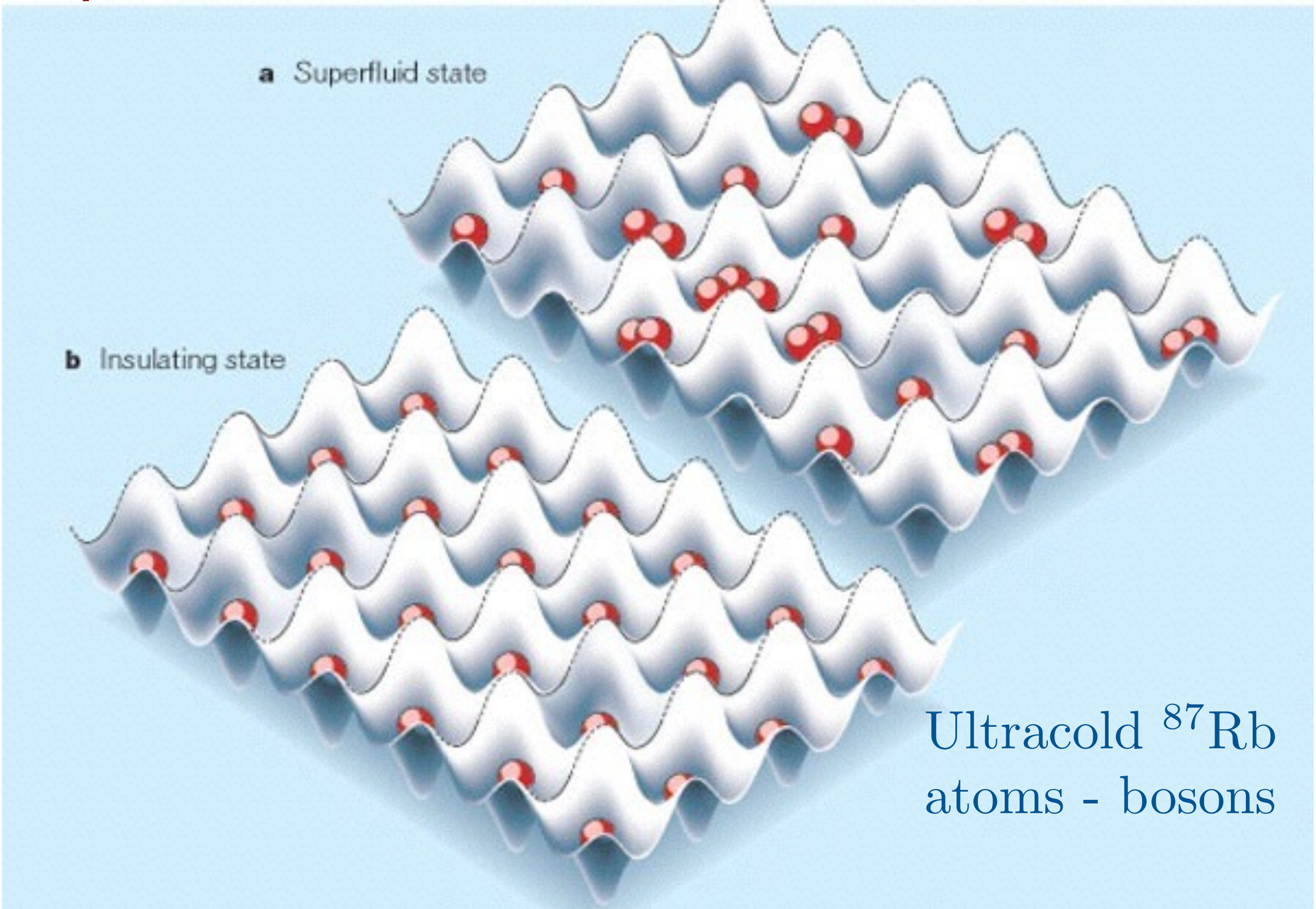


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (**d,e**) Longitudinal conductivity σ_{xx} and R_{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.

Graphene: "a metal that behaves like water"

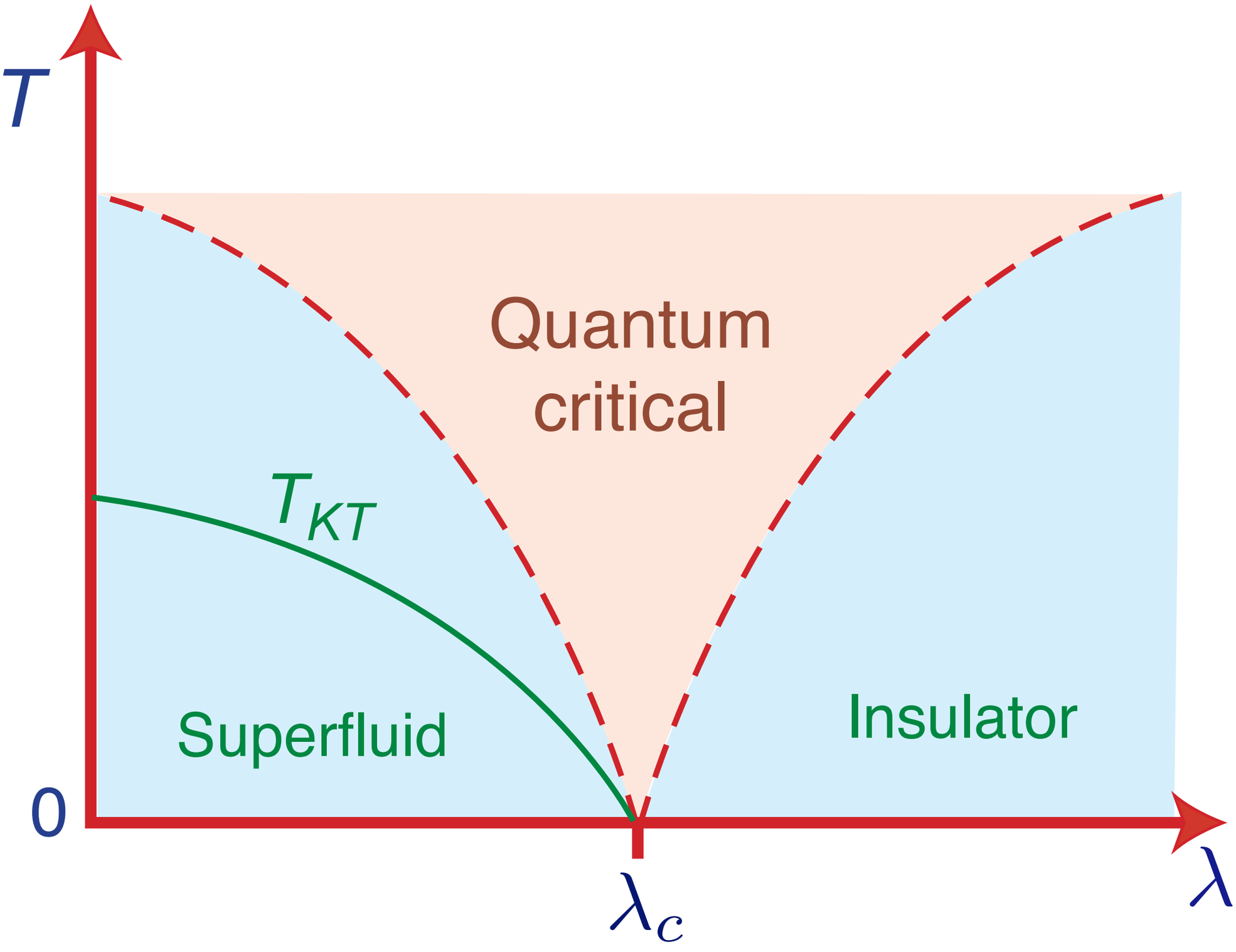


Superfluid-insulator transition



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

Superfluid-insulator transition



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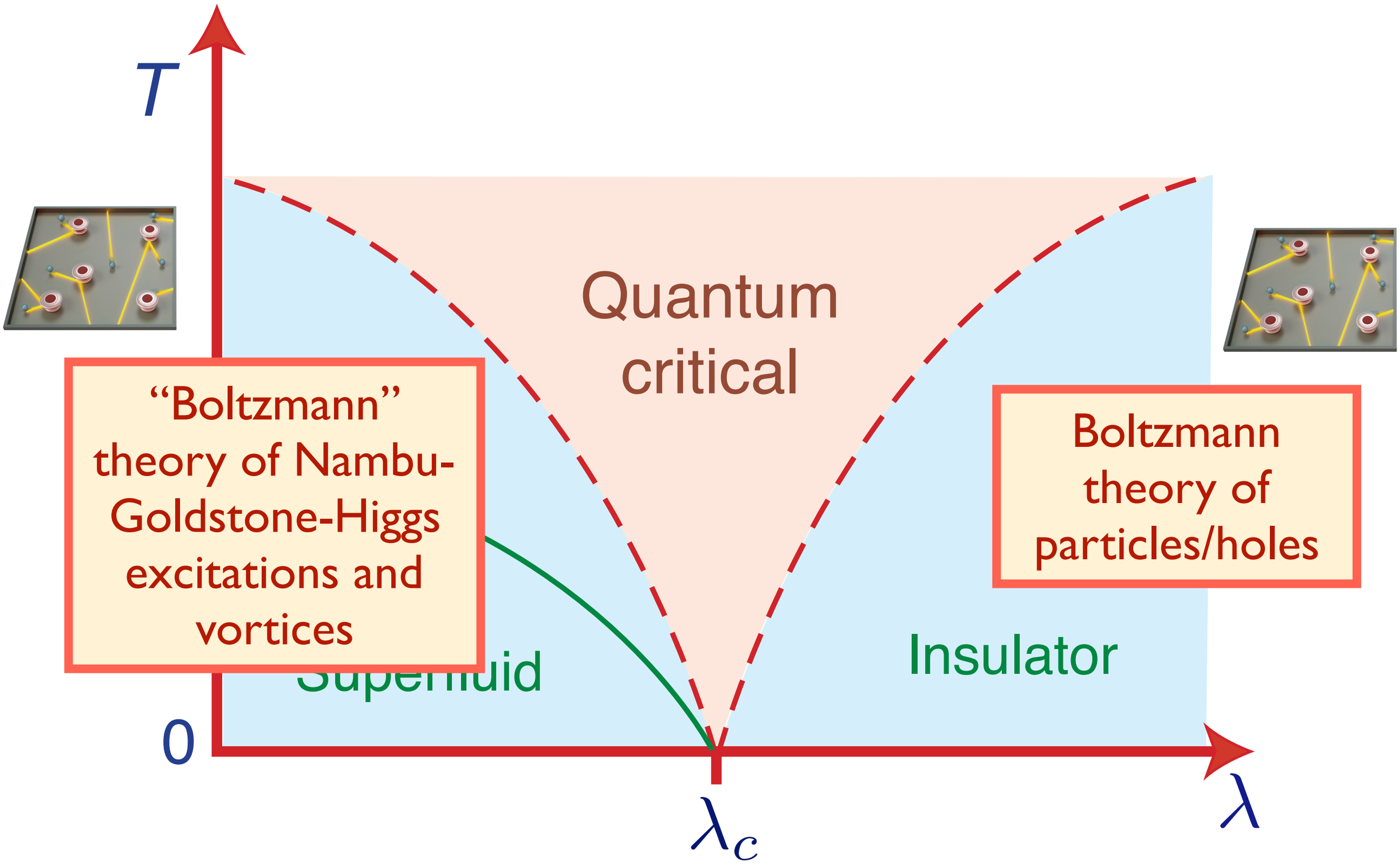

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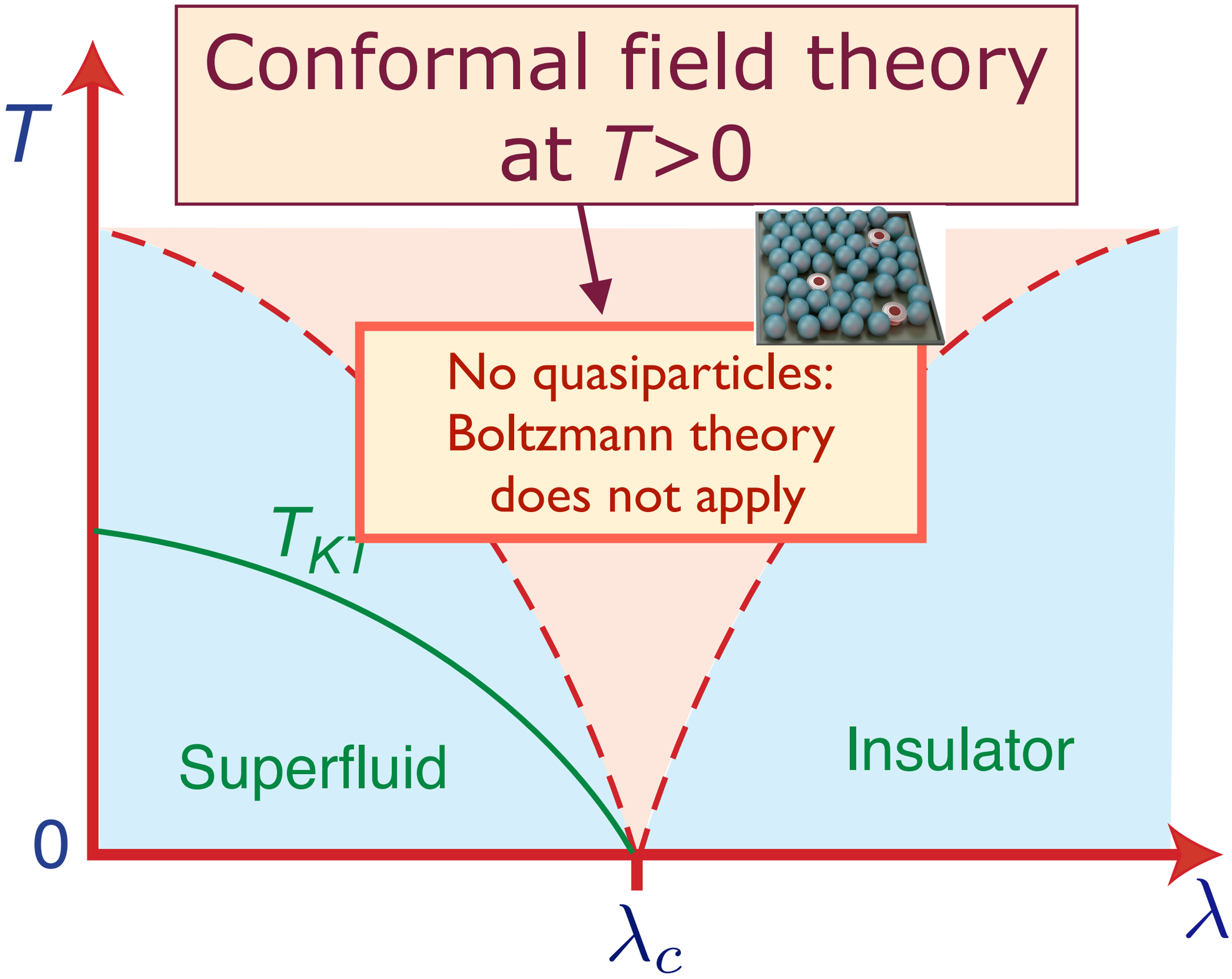
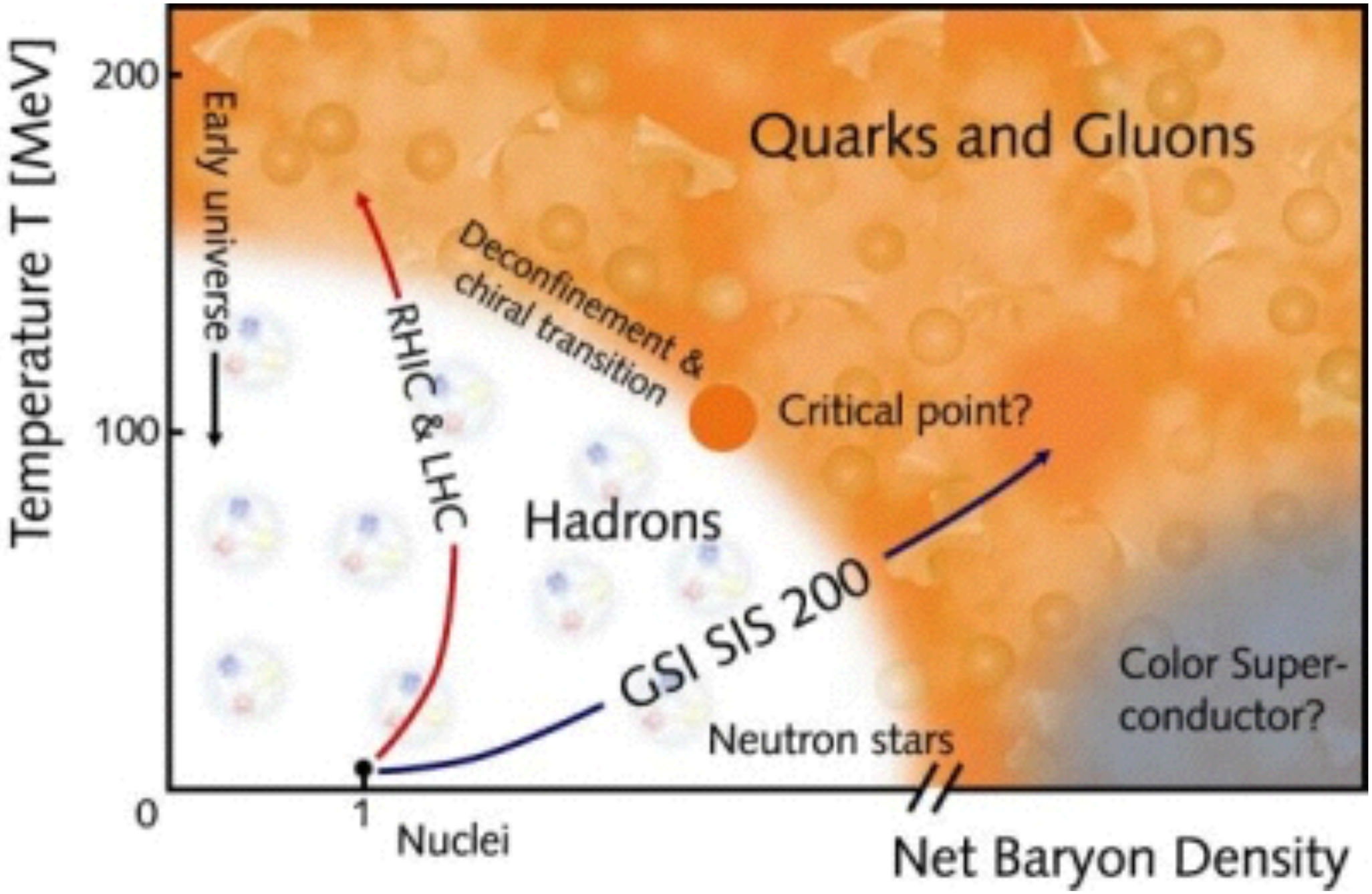


Quark-gluon plasma



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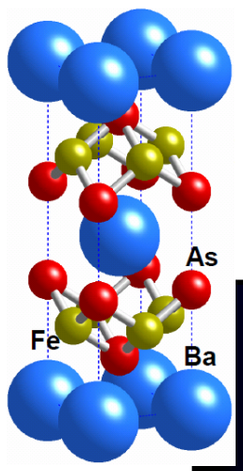

Resistivity
$\sim \rho_0 + AT^\alpha$

$BaFe_2(As_{1-x}P_x)_2$

In progress:
theory of "hydrodynamic"
electron flow in strange
metals of correlated
electron compounds

AF
+nematic

Superconductivity

T (K)

200

100

0

0

0.2

0.4

0.6

x

α

2.0

1.0

0

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)

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

2. Quantum matter without quasiparticles:

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

3. Long range quantum entanglement and emergent gauge fields in the cuprates

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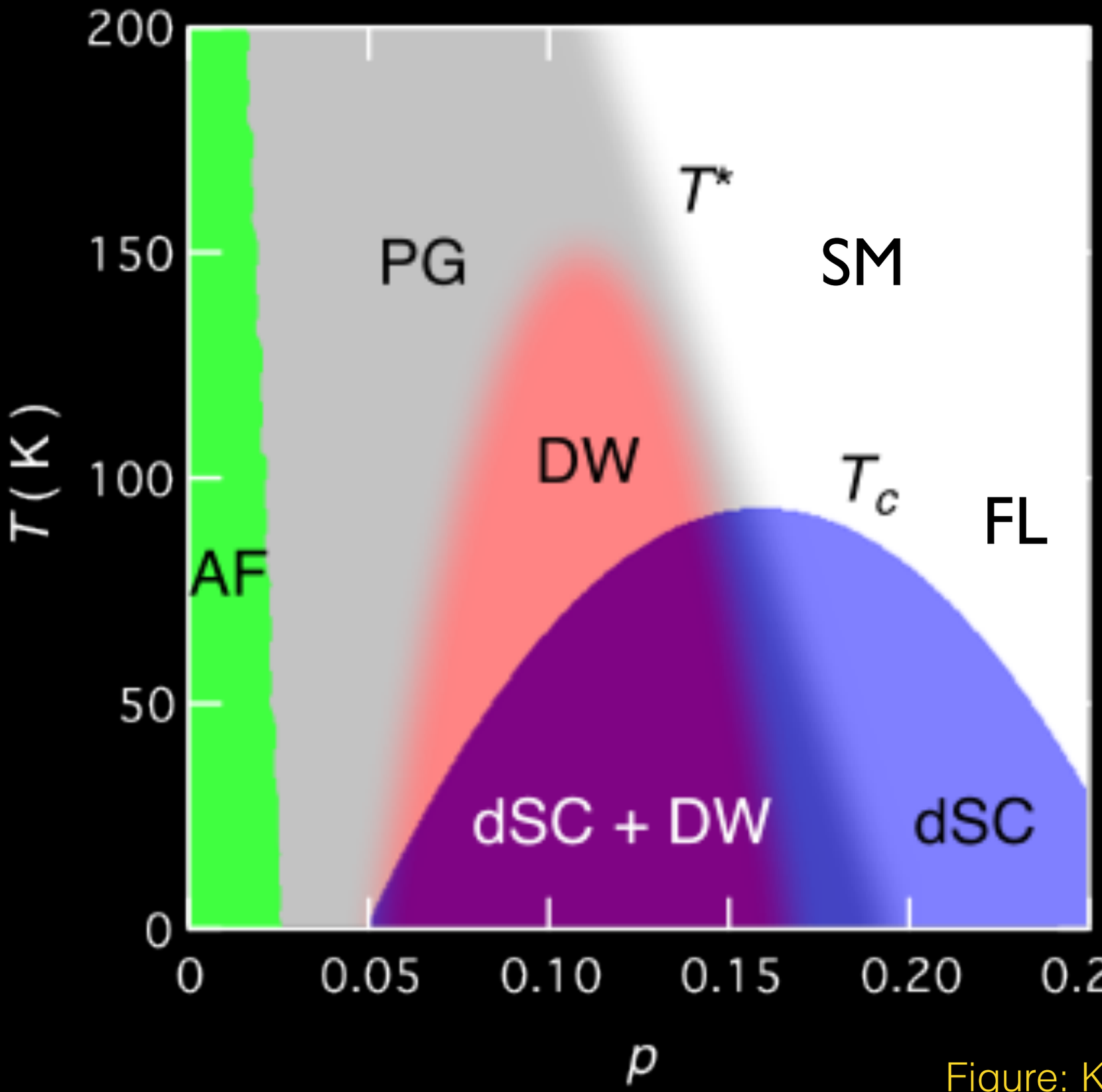
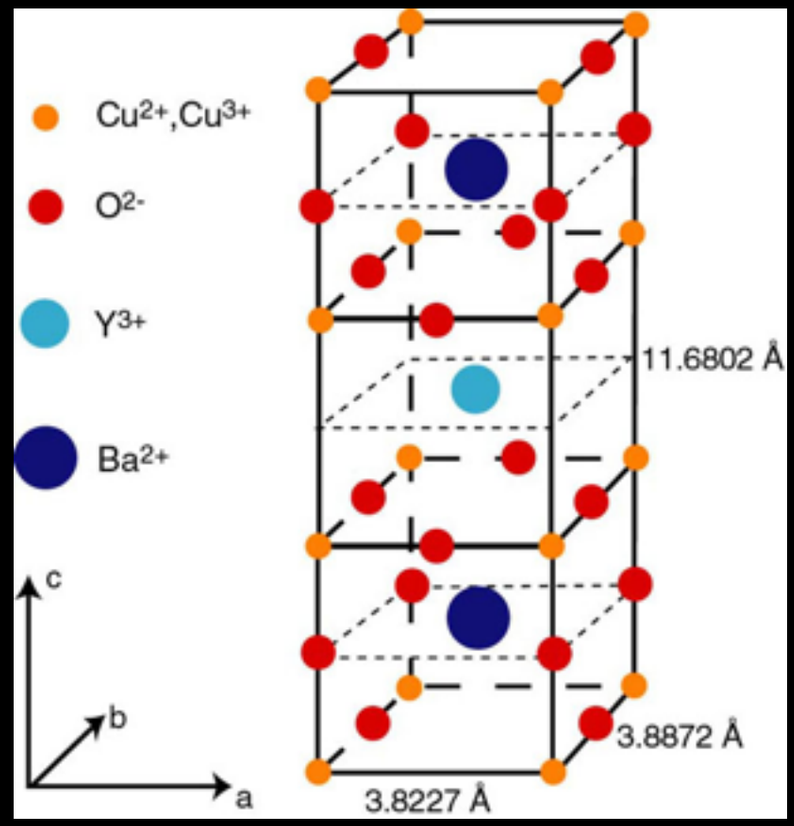
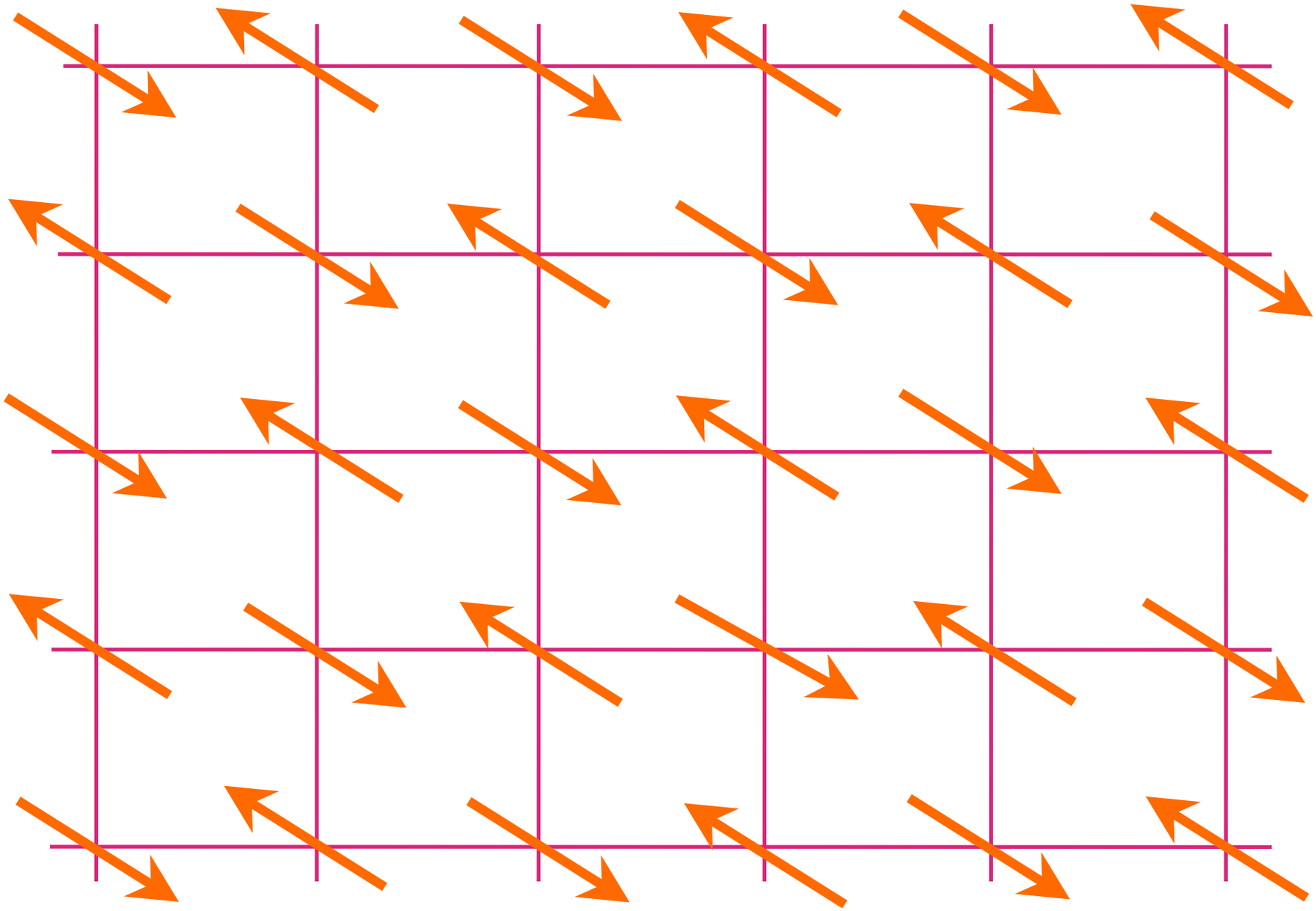


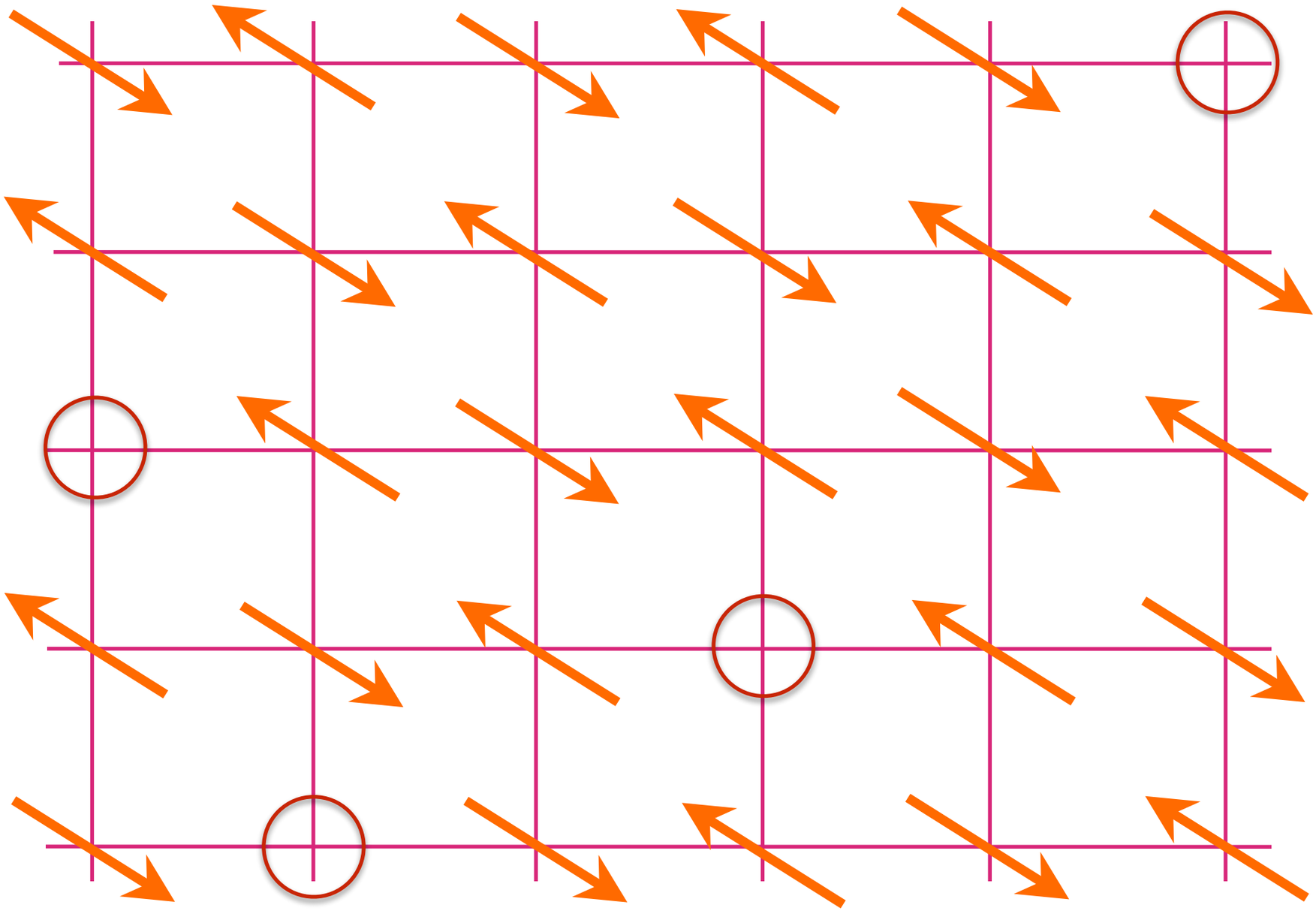


$YBa_2Cu_3O_{6+x}$

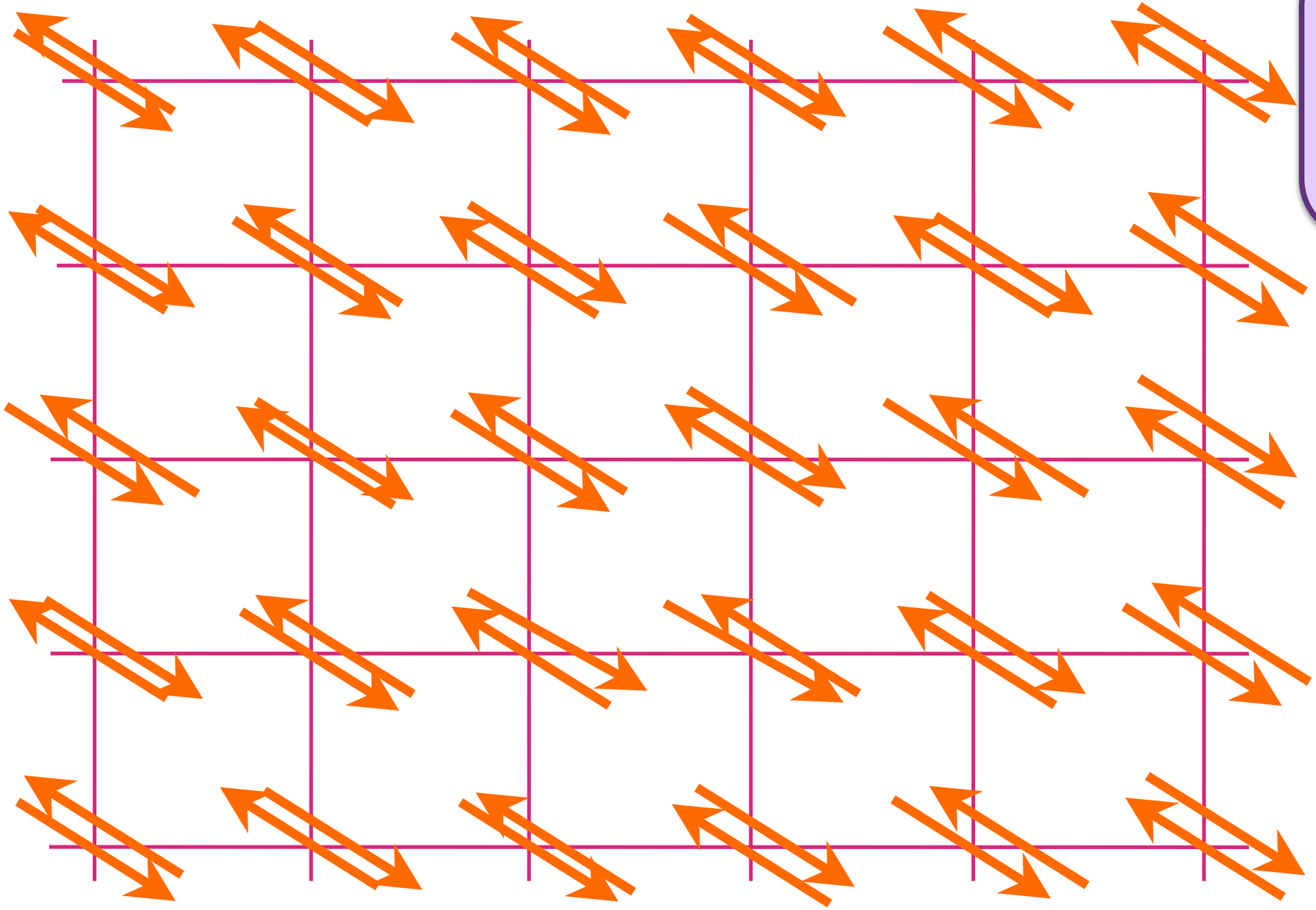
Figure: K. Fujita and J. C. Seamus Davis



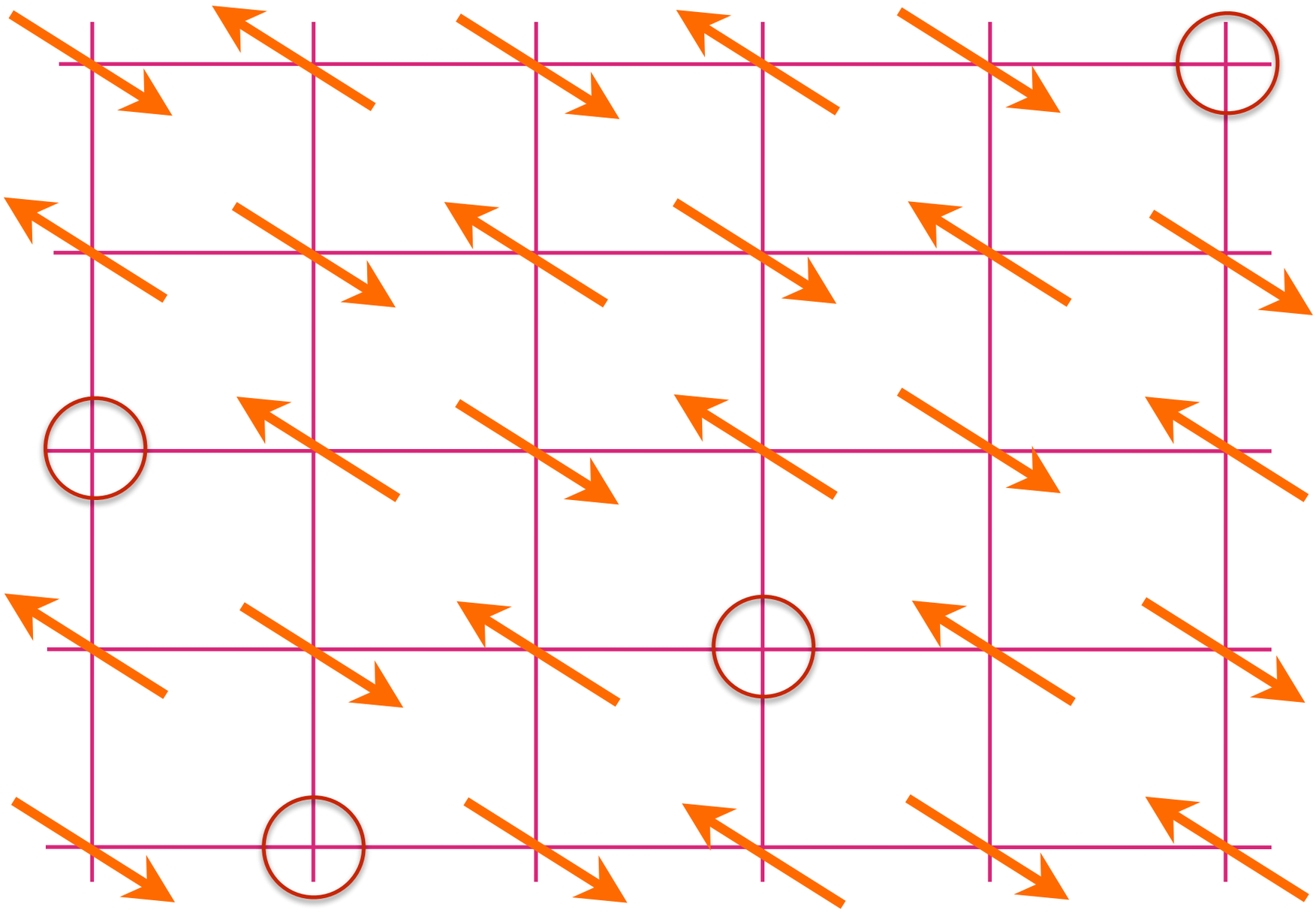
"Undoped" Anti-ferromagnet



Anti-ferromagnet with p holes per square



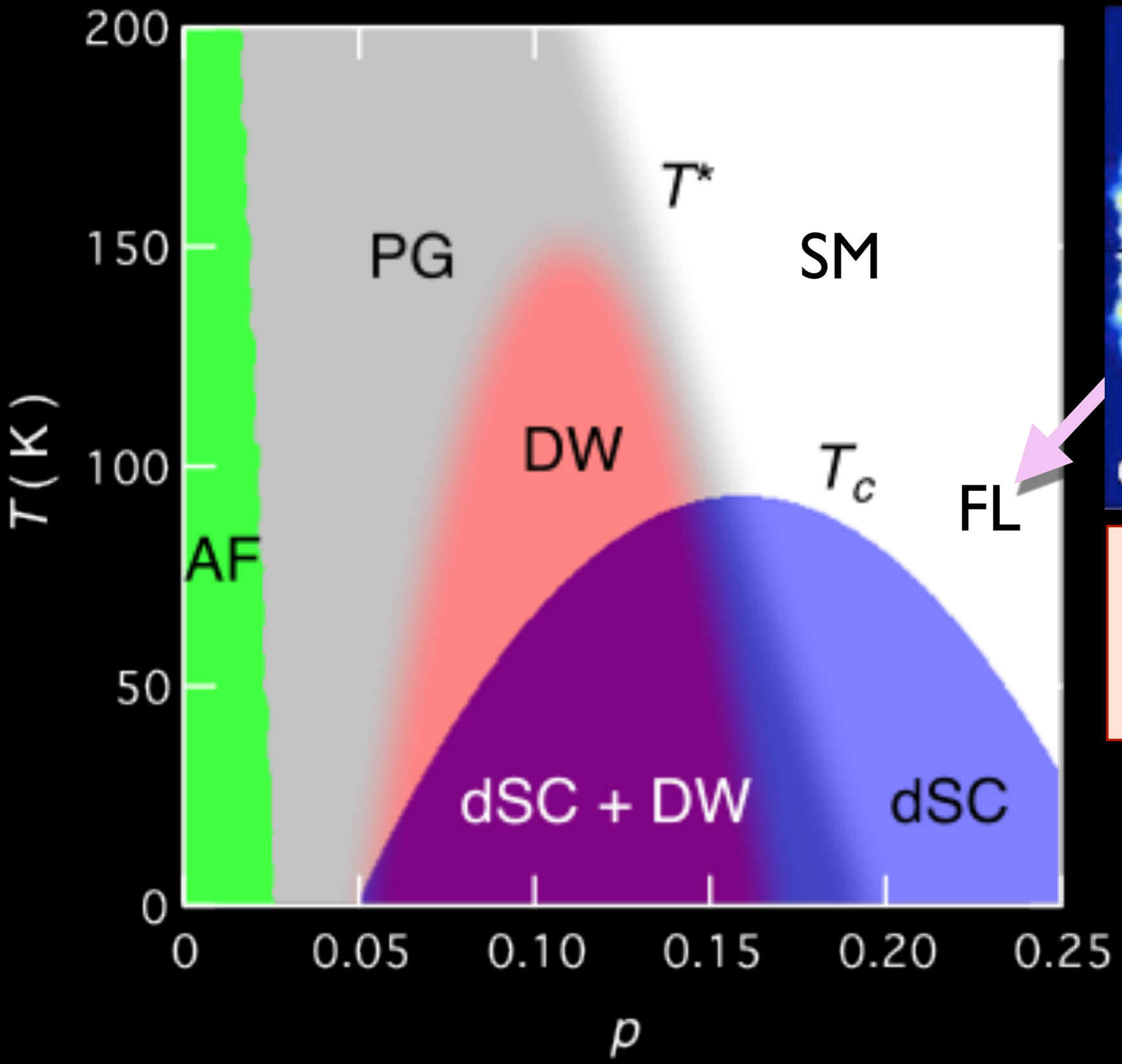
Filled
Band

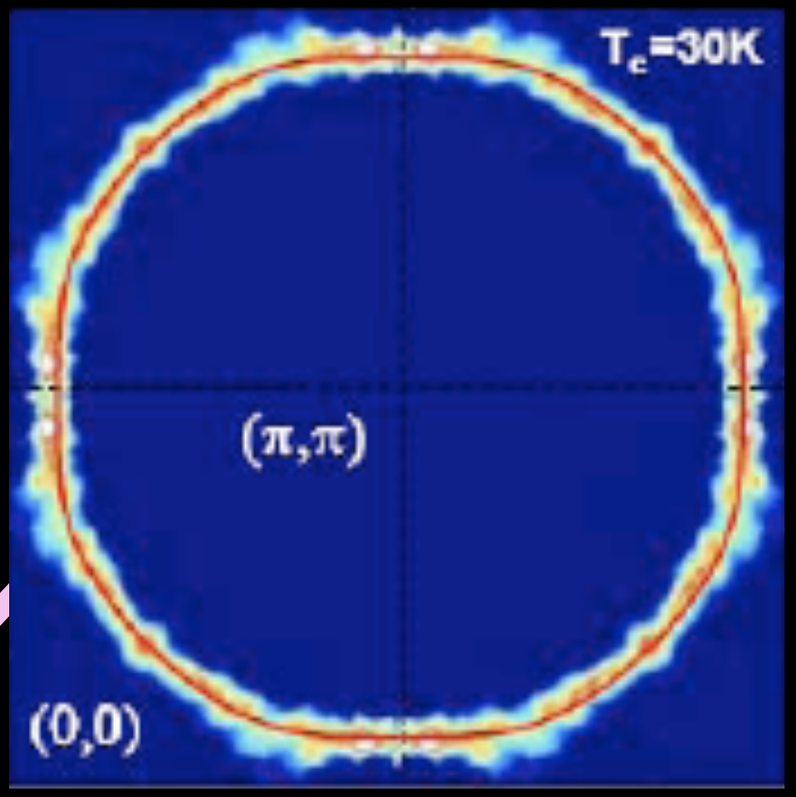


Anti-ferromagnet with p holes per square

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

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)

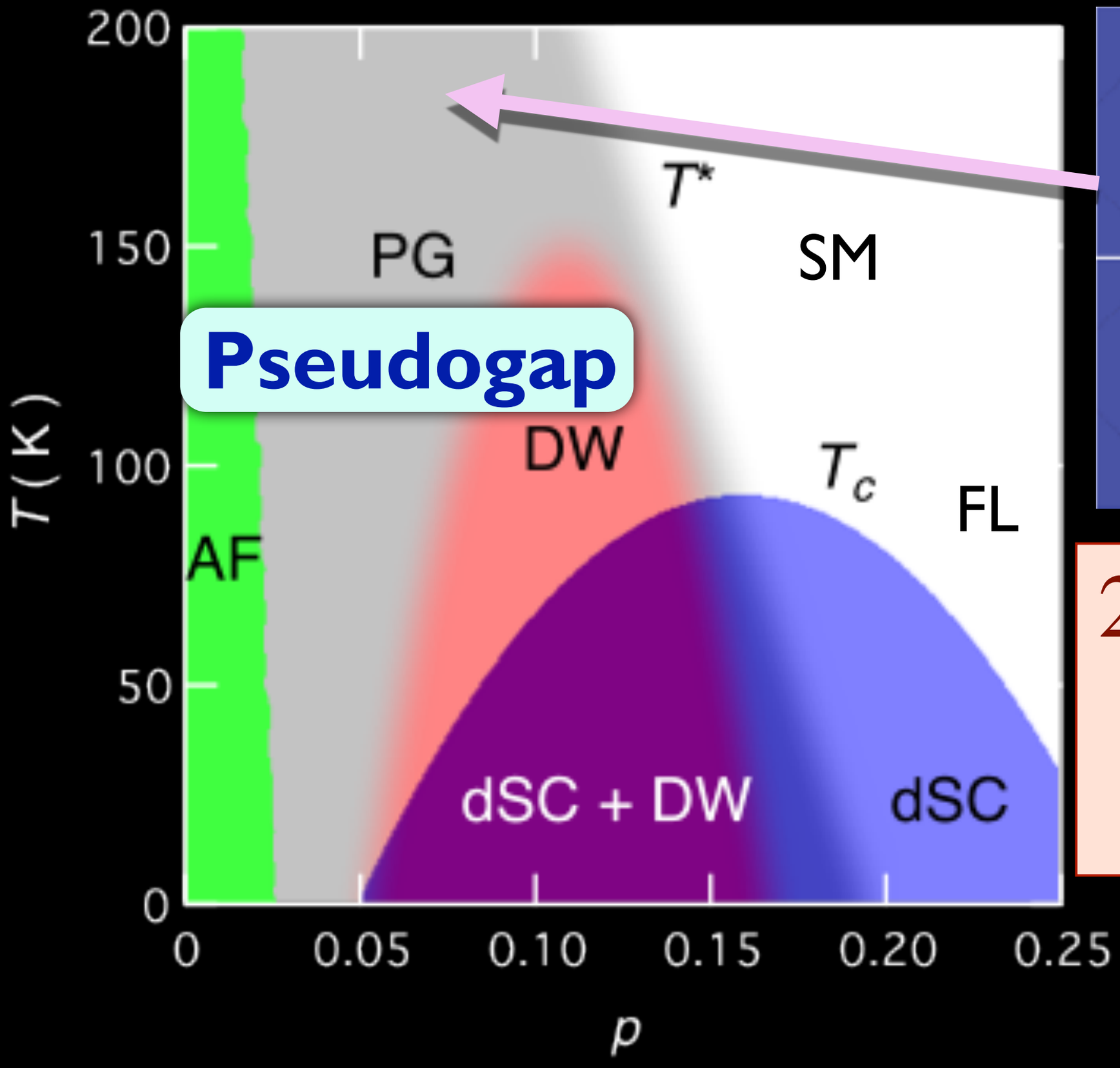


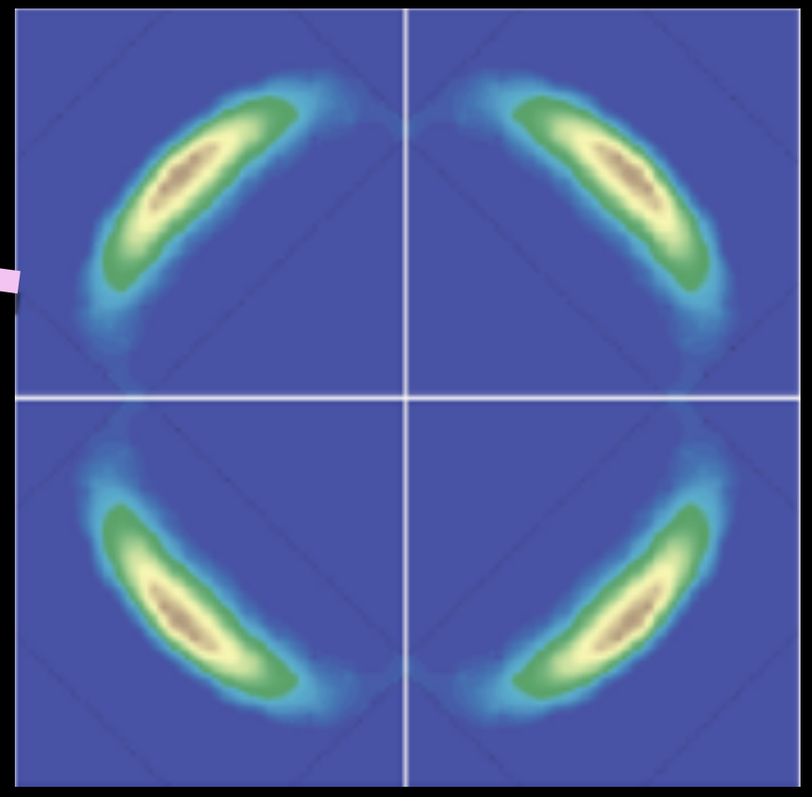


Fermi liquid

Area enclosed by Fermi surface = 1+p

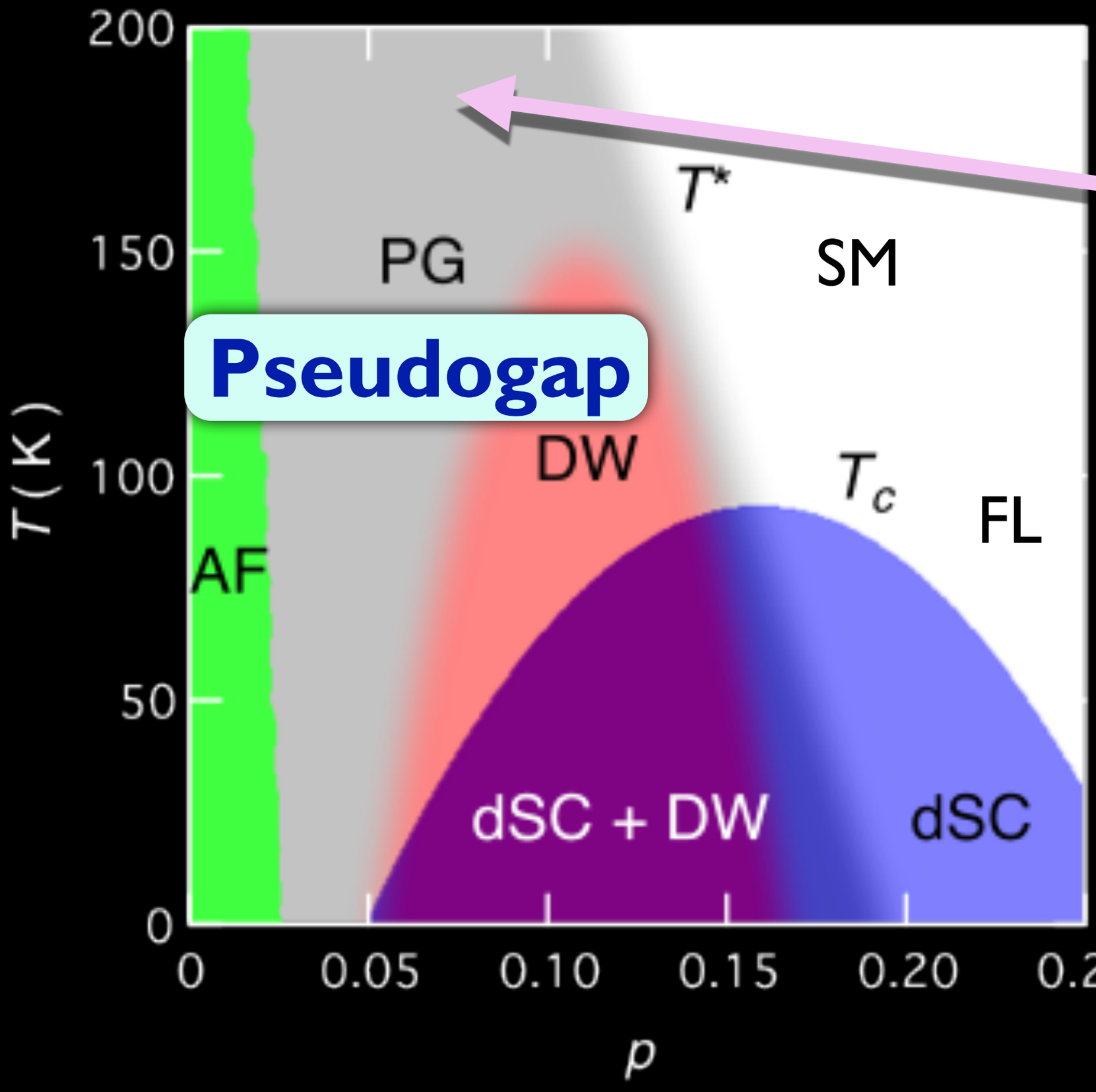
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

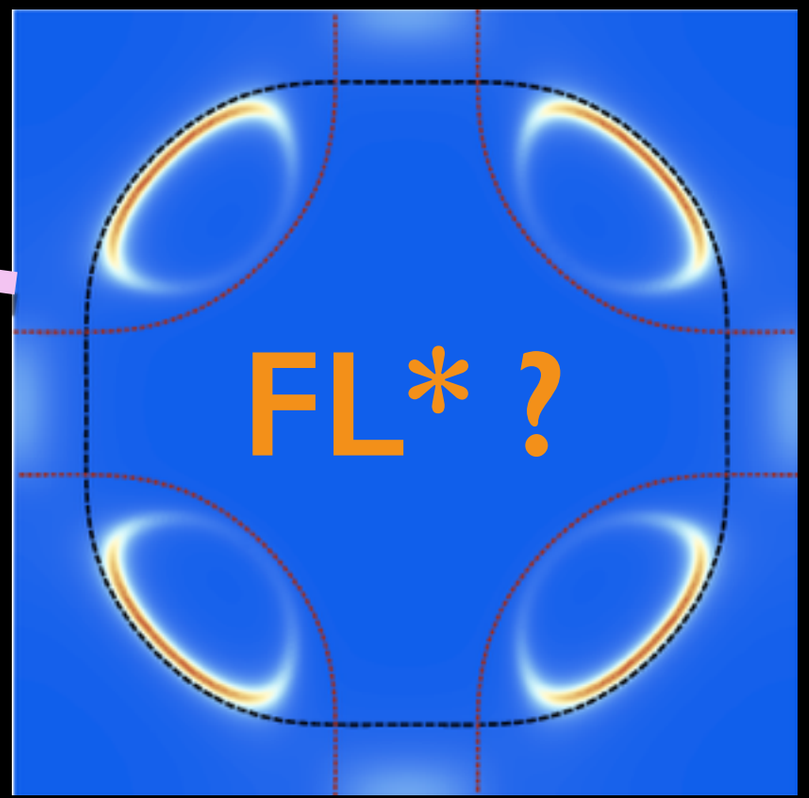




2. <u>Pseudogap metal</u> at low p

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

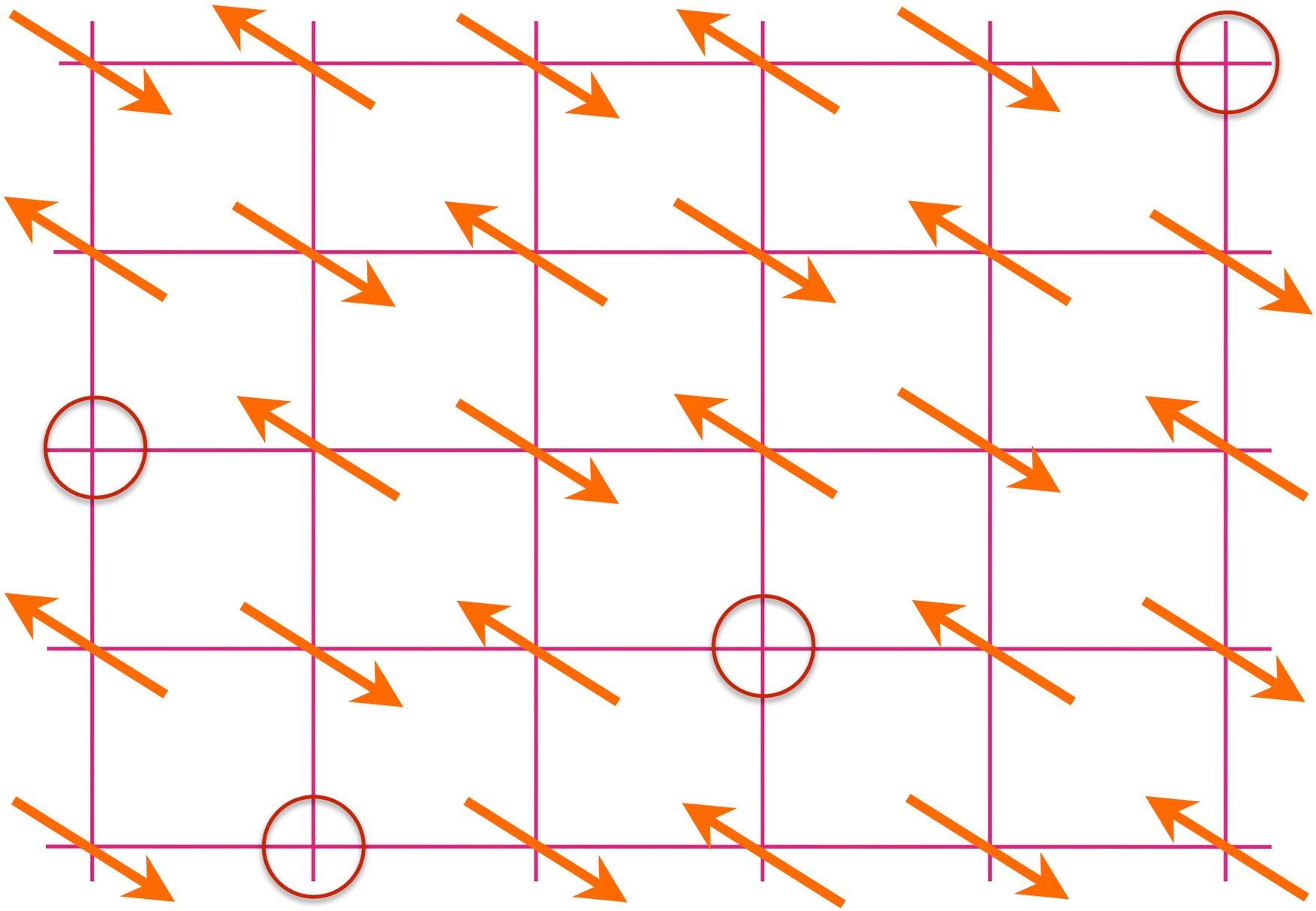
FL*

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

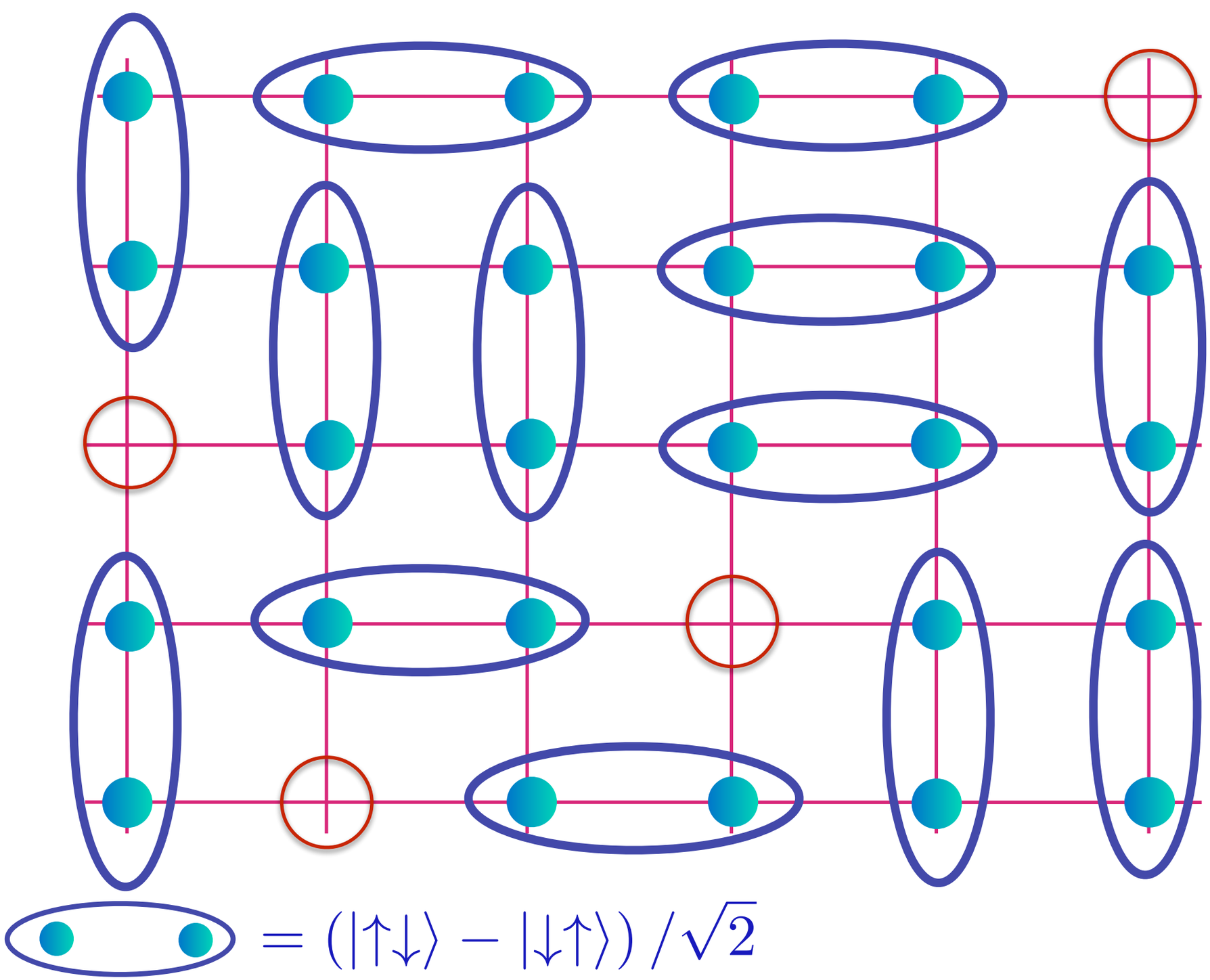
There is a general and fundamental relationship between these two characteristics.

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)



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

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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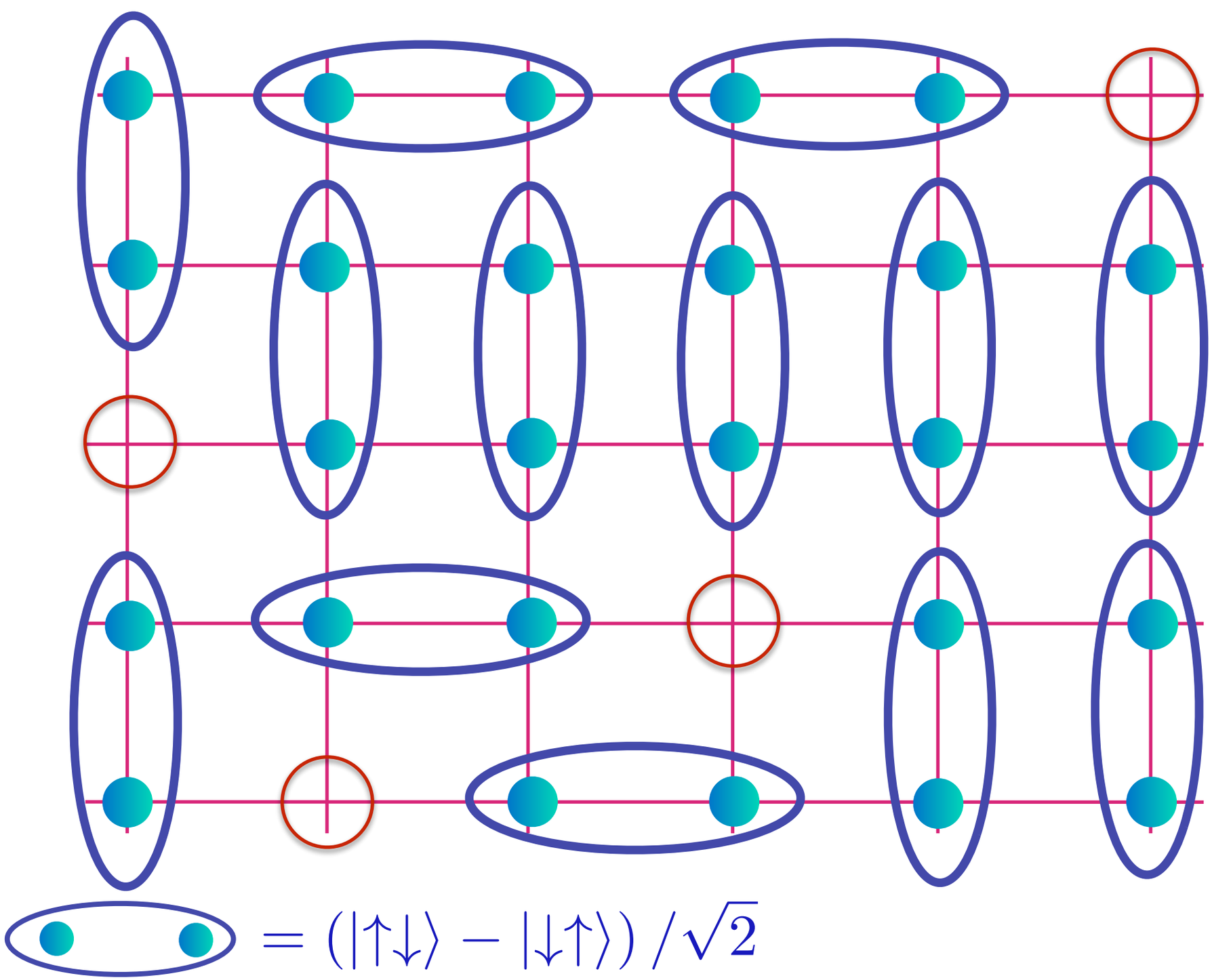

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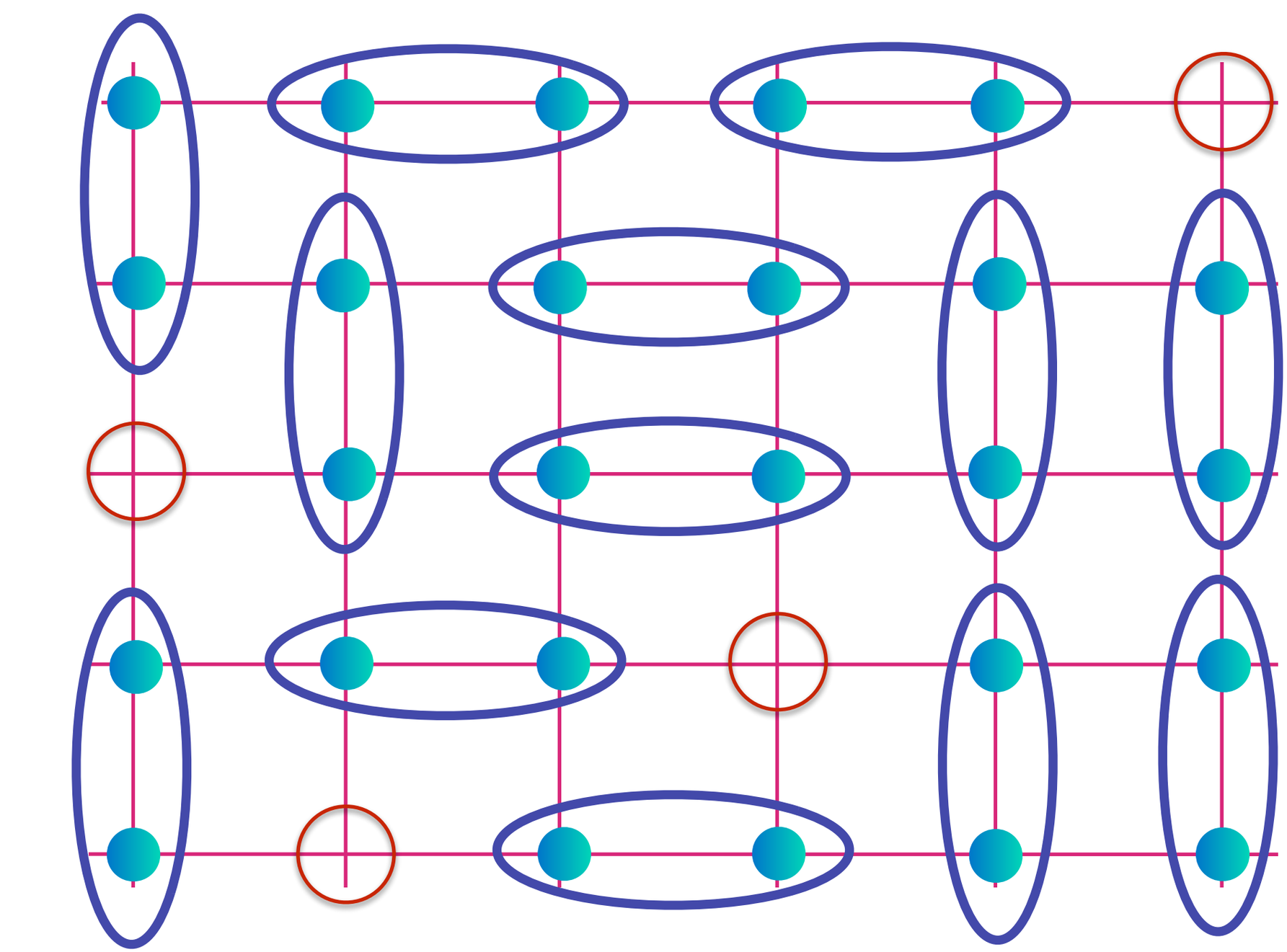

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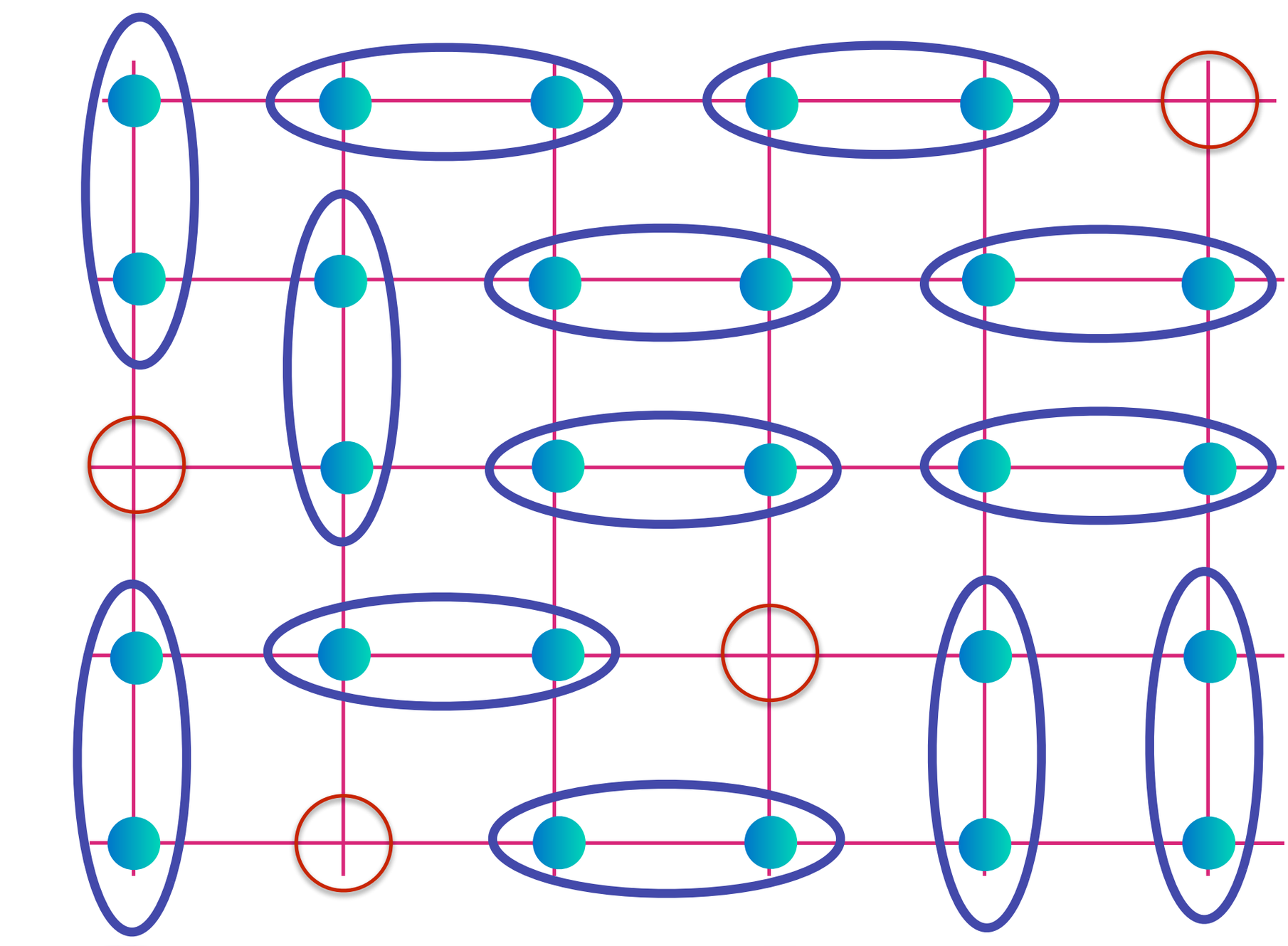

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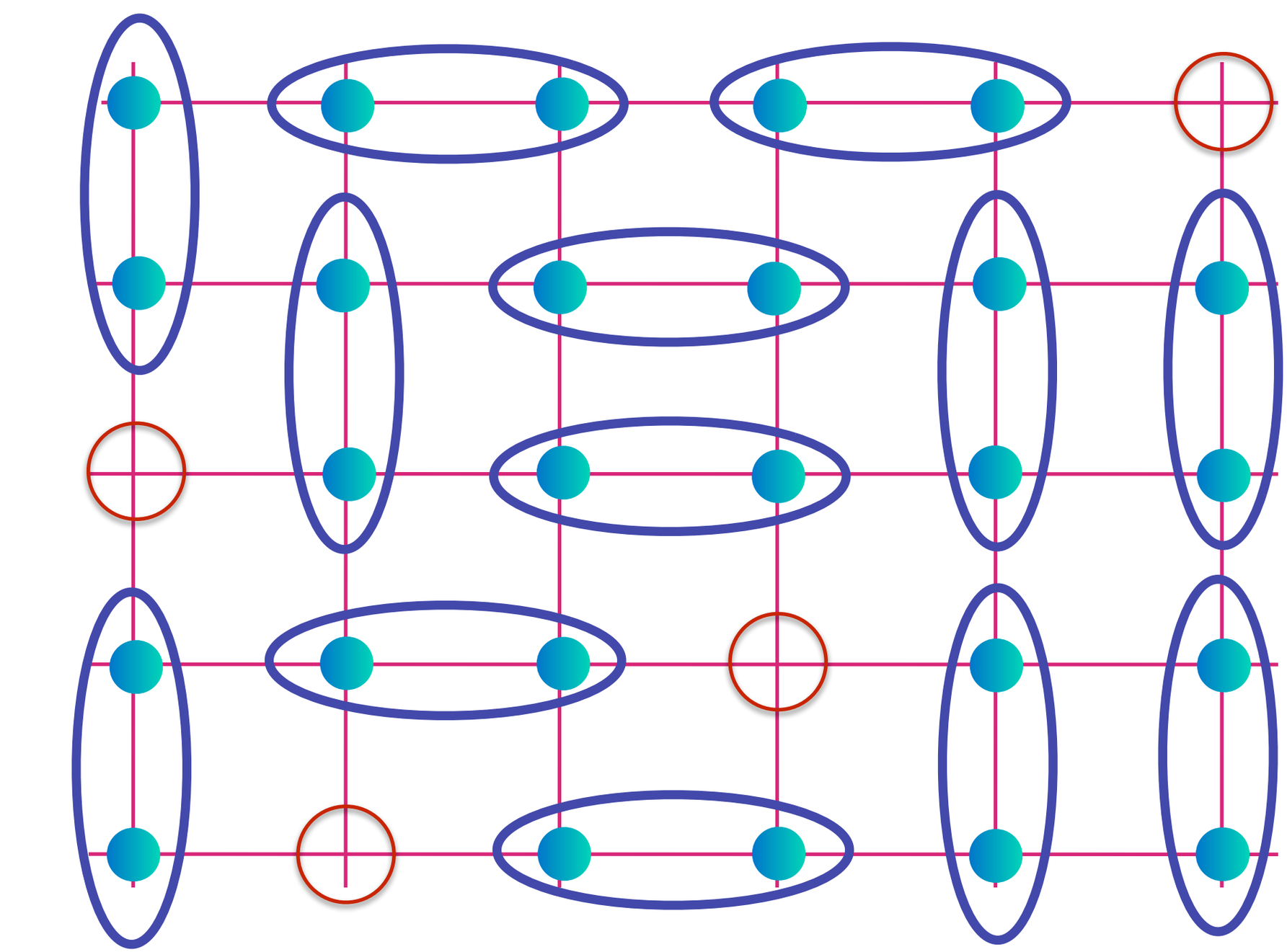

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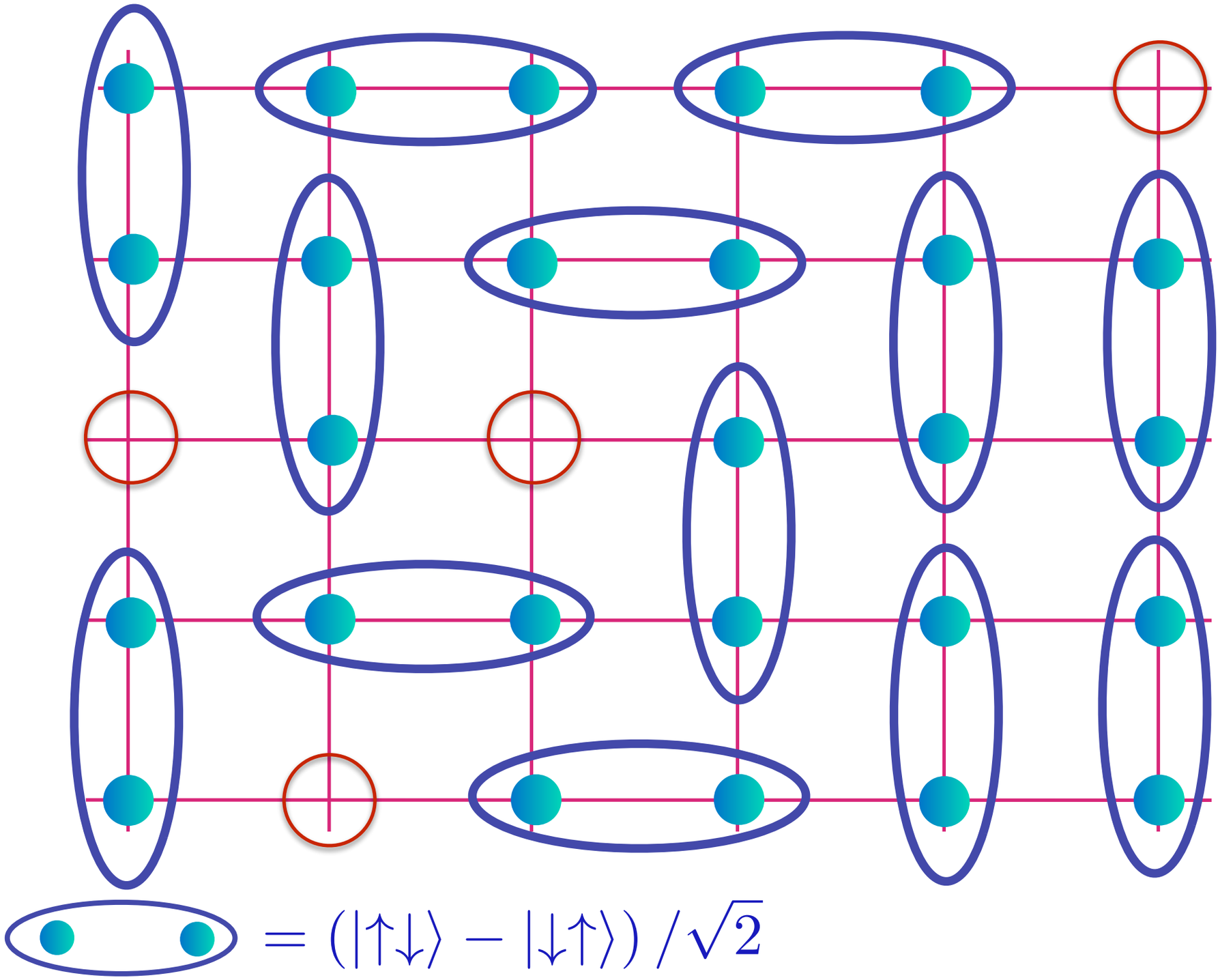

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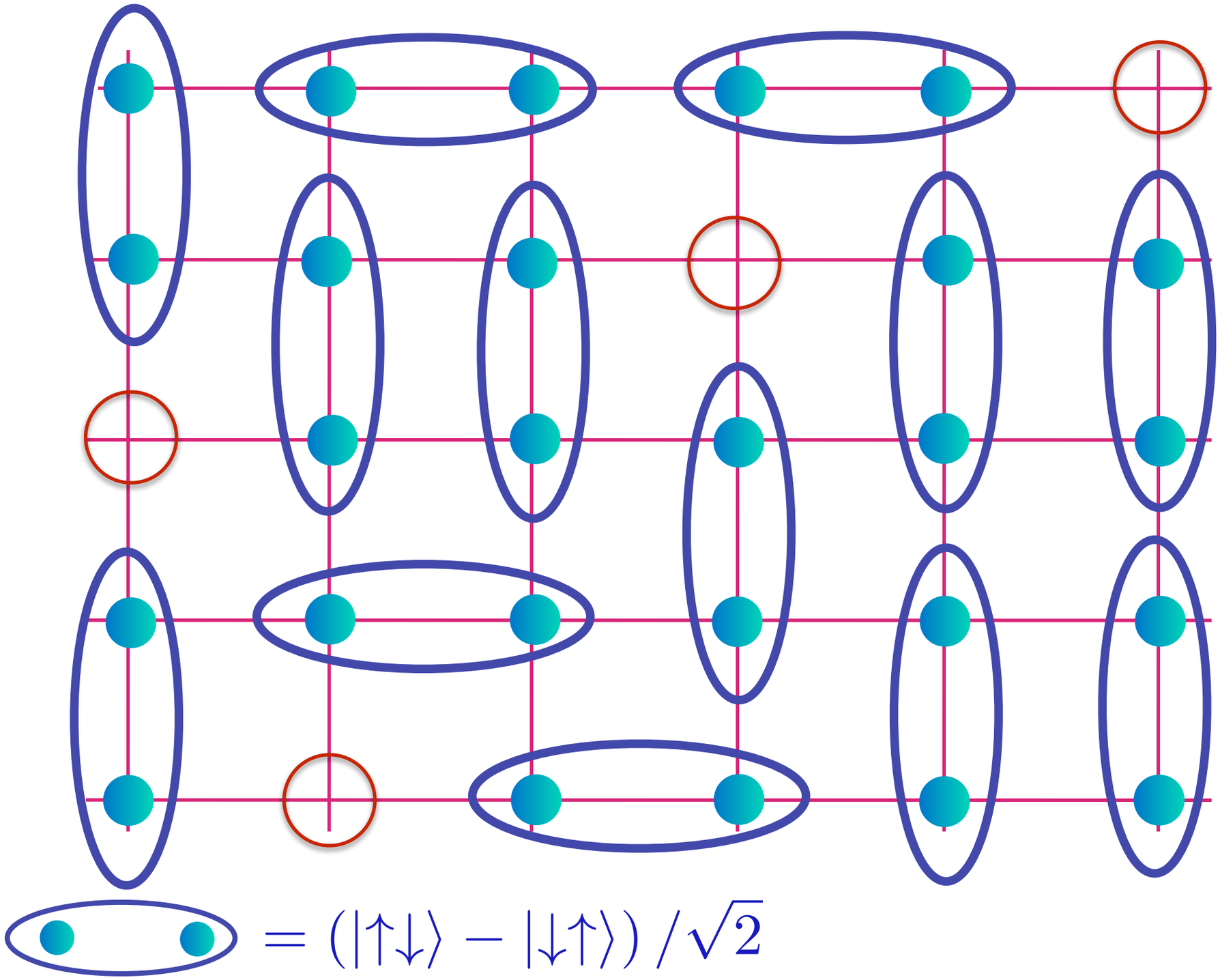

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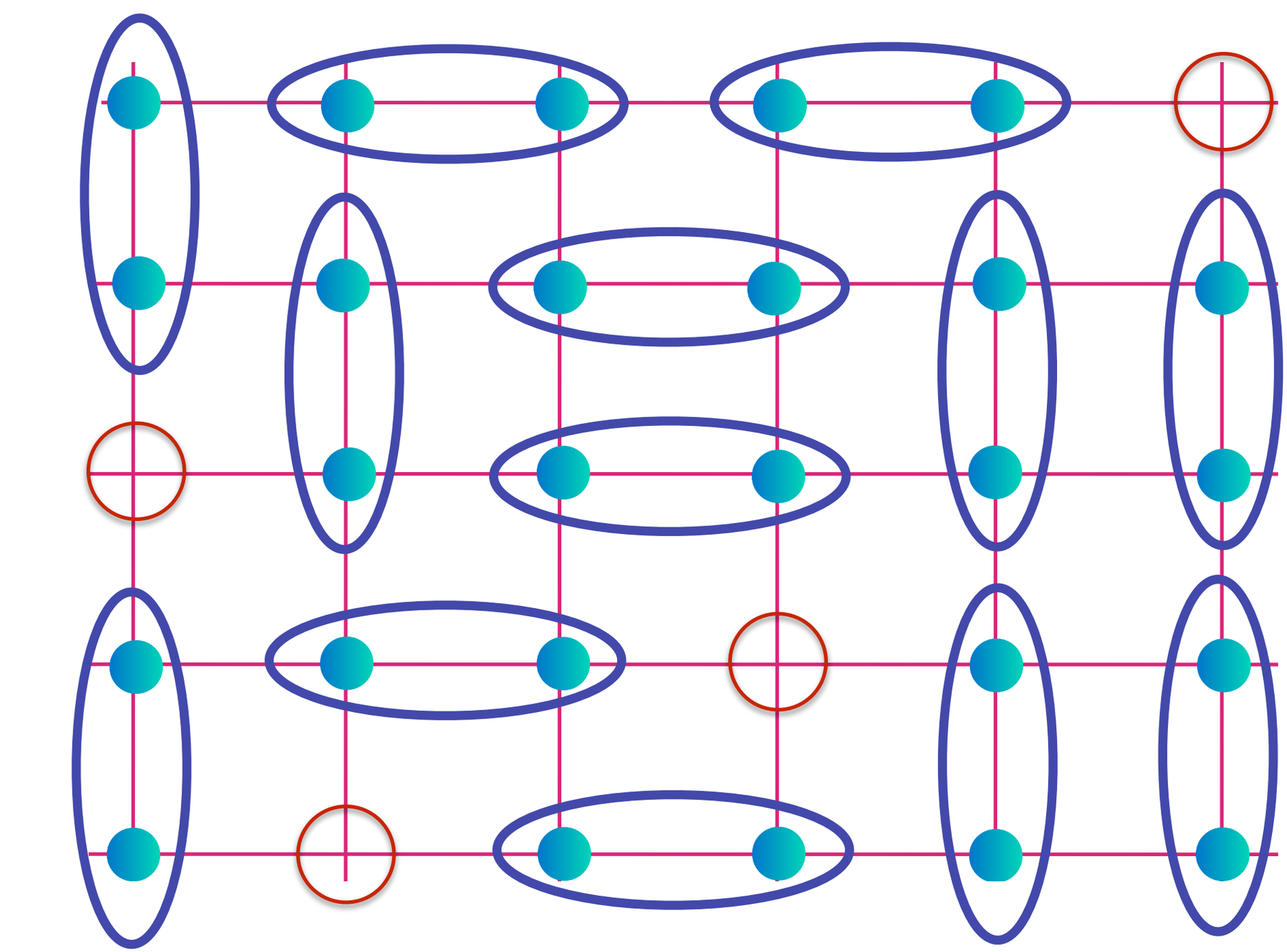

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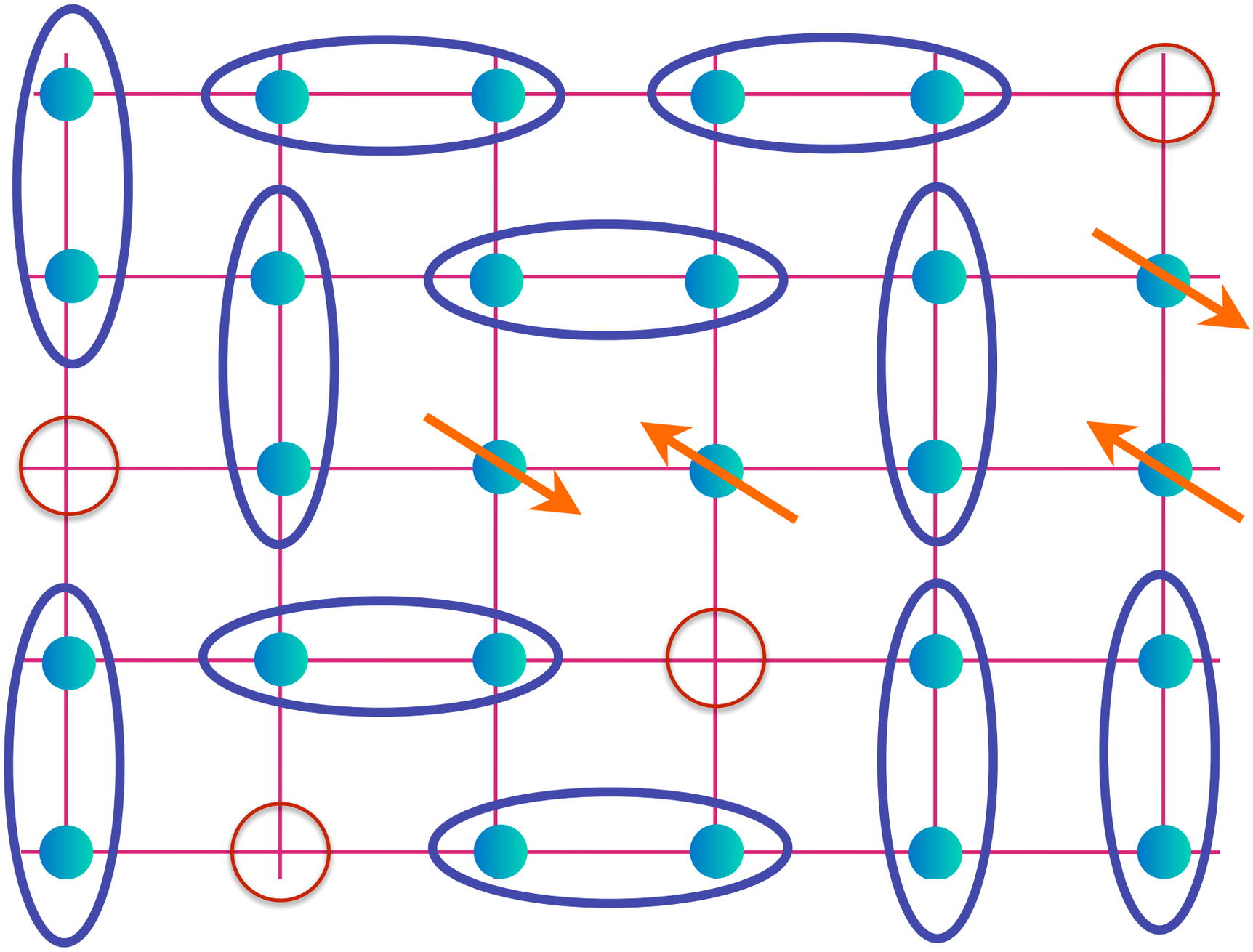

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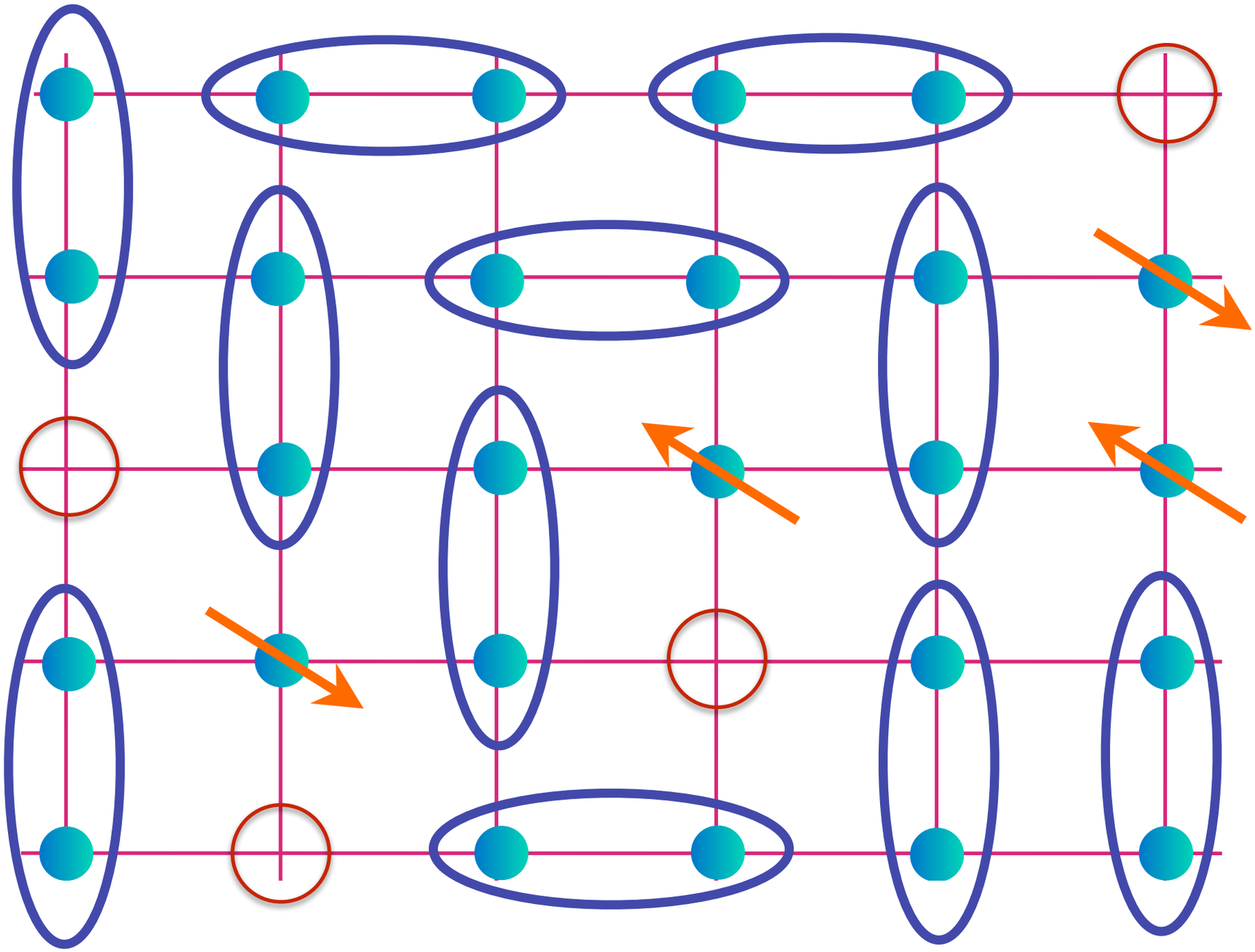

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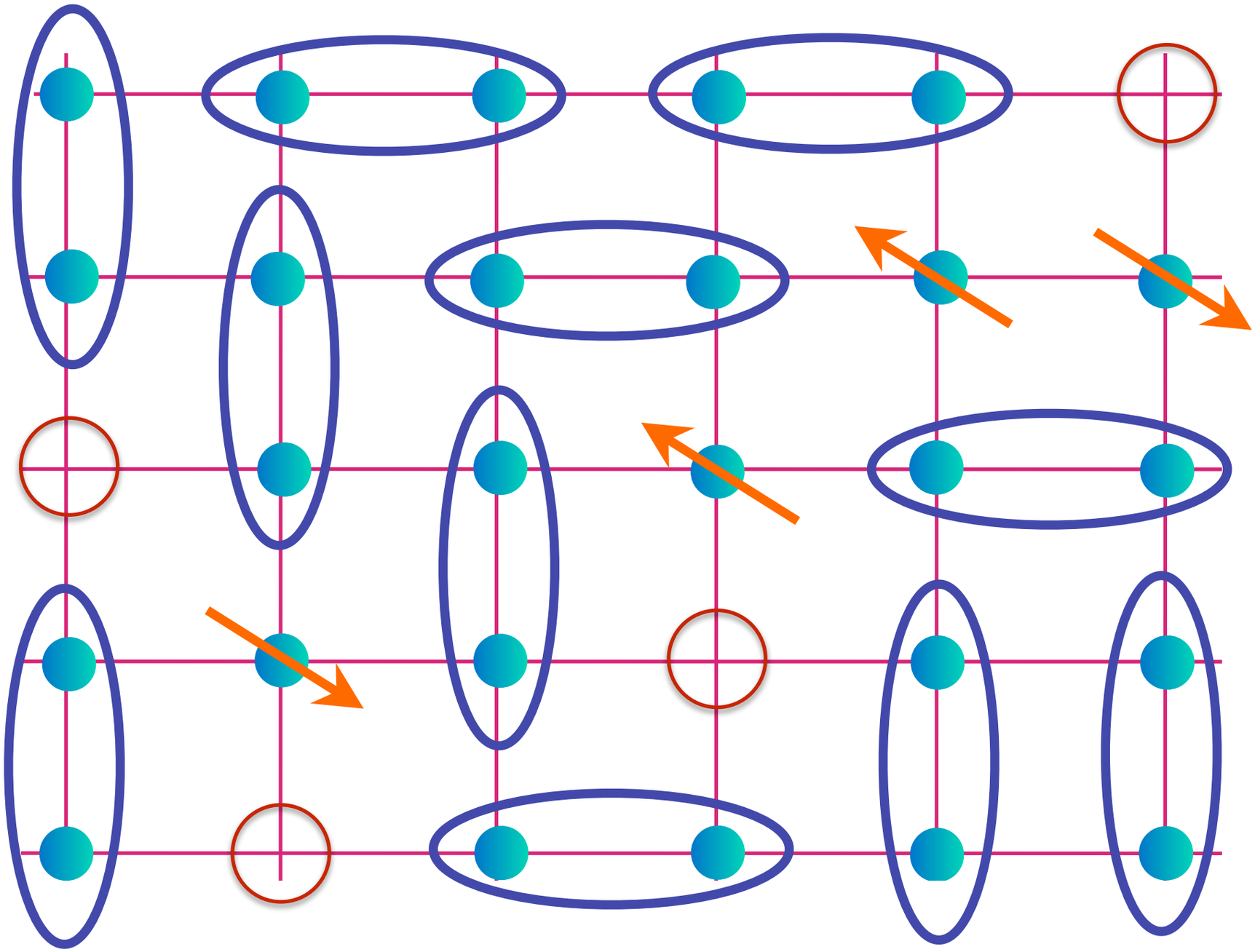

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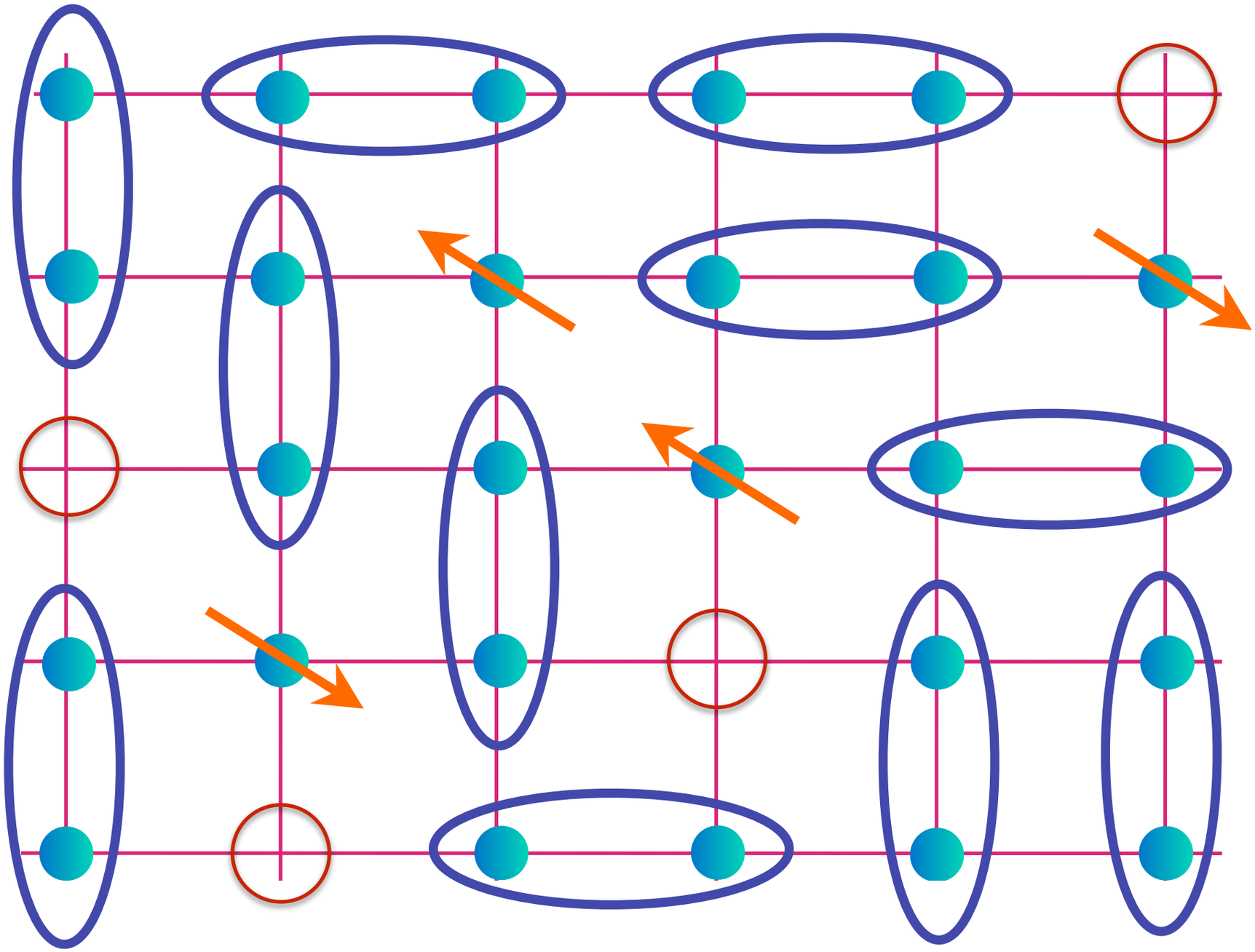

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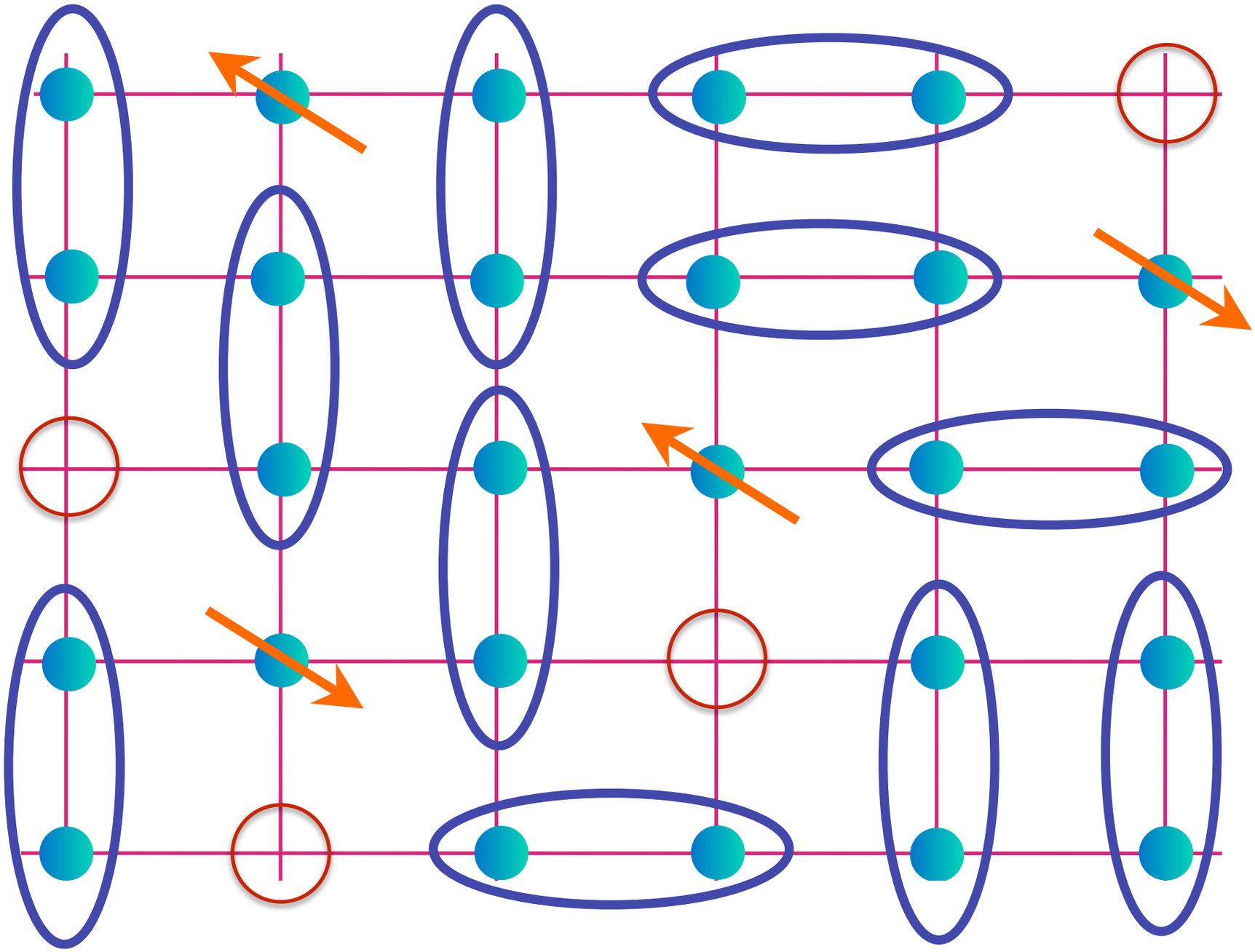

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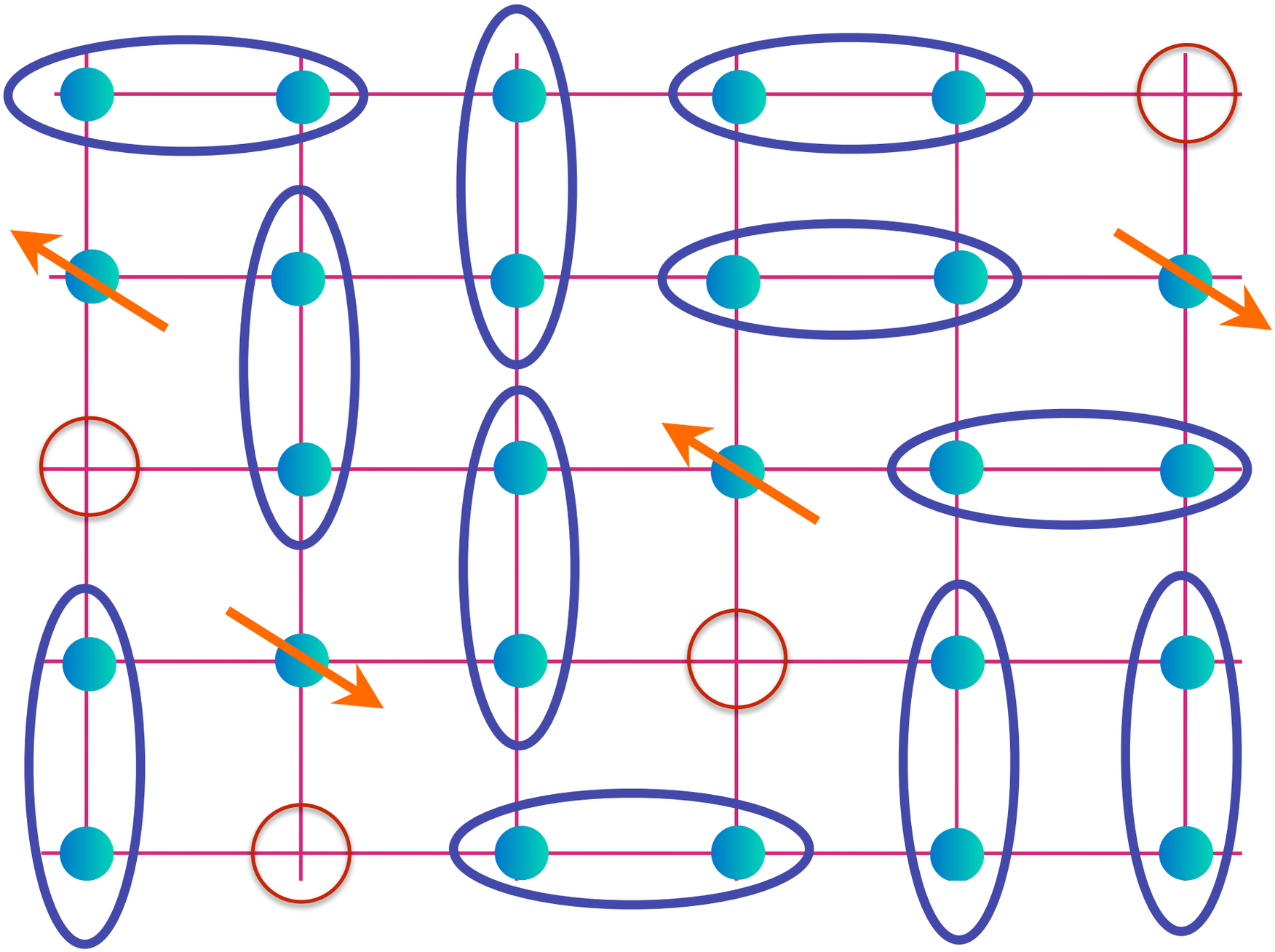

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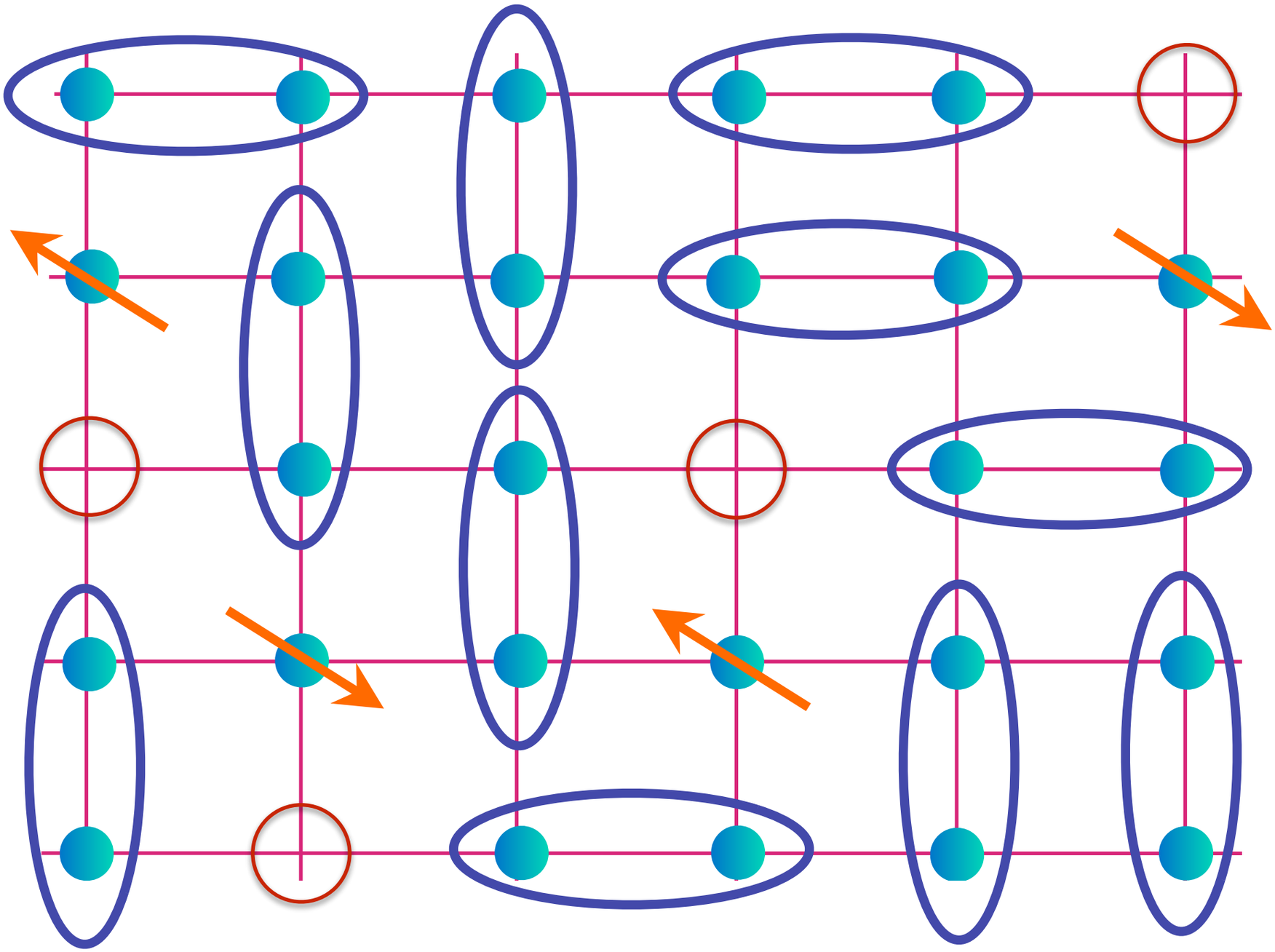

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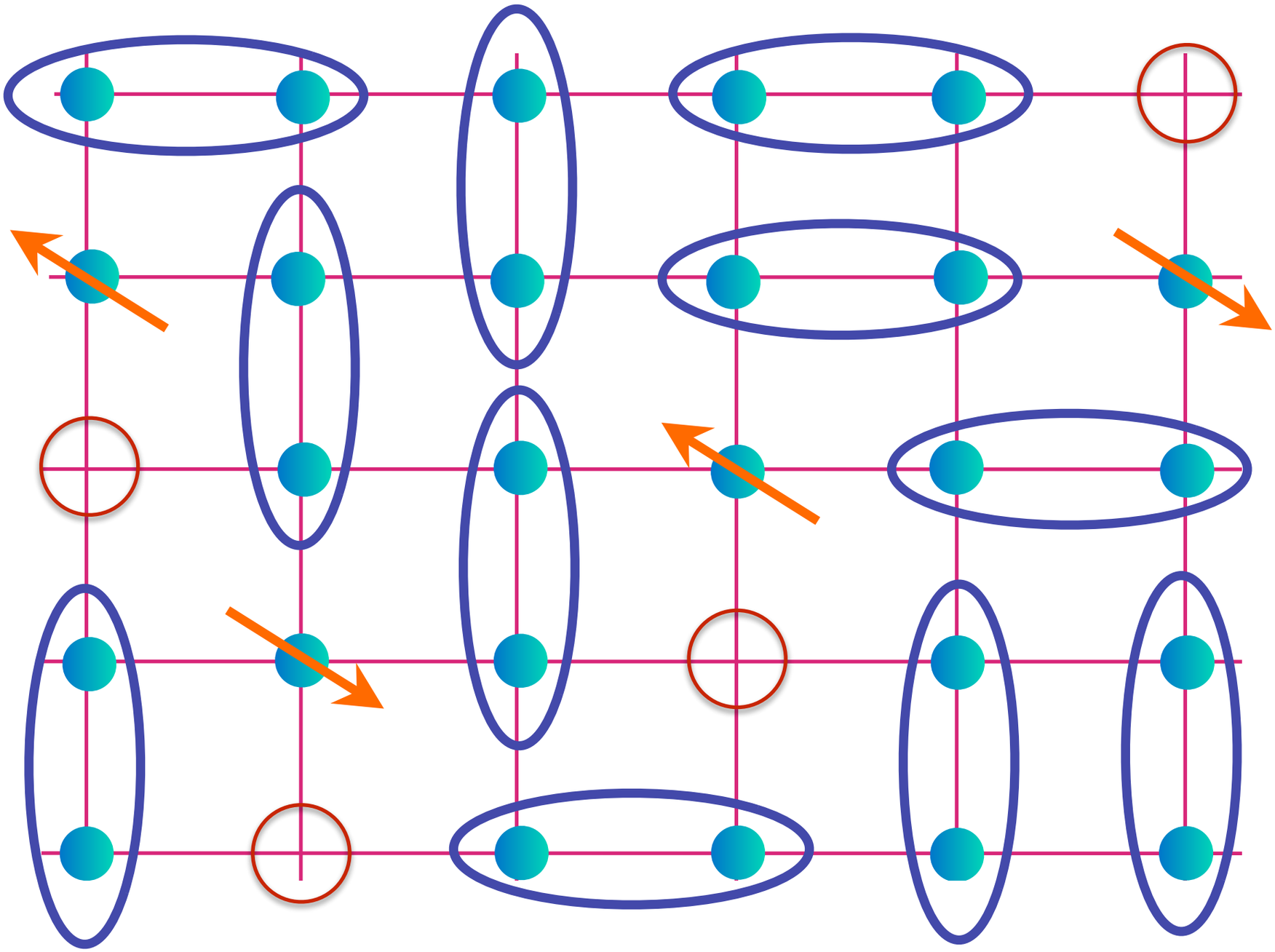

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FL*

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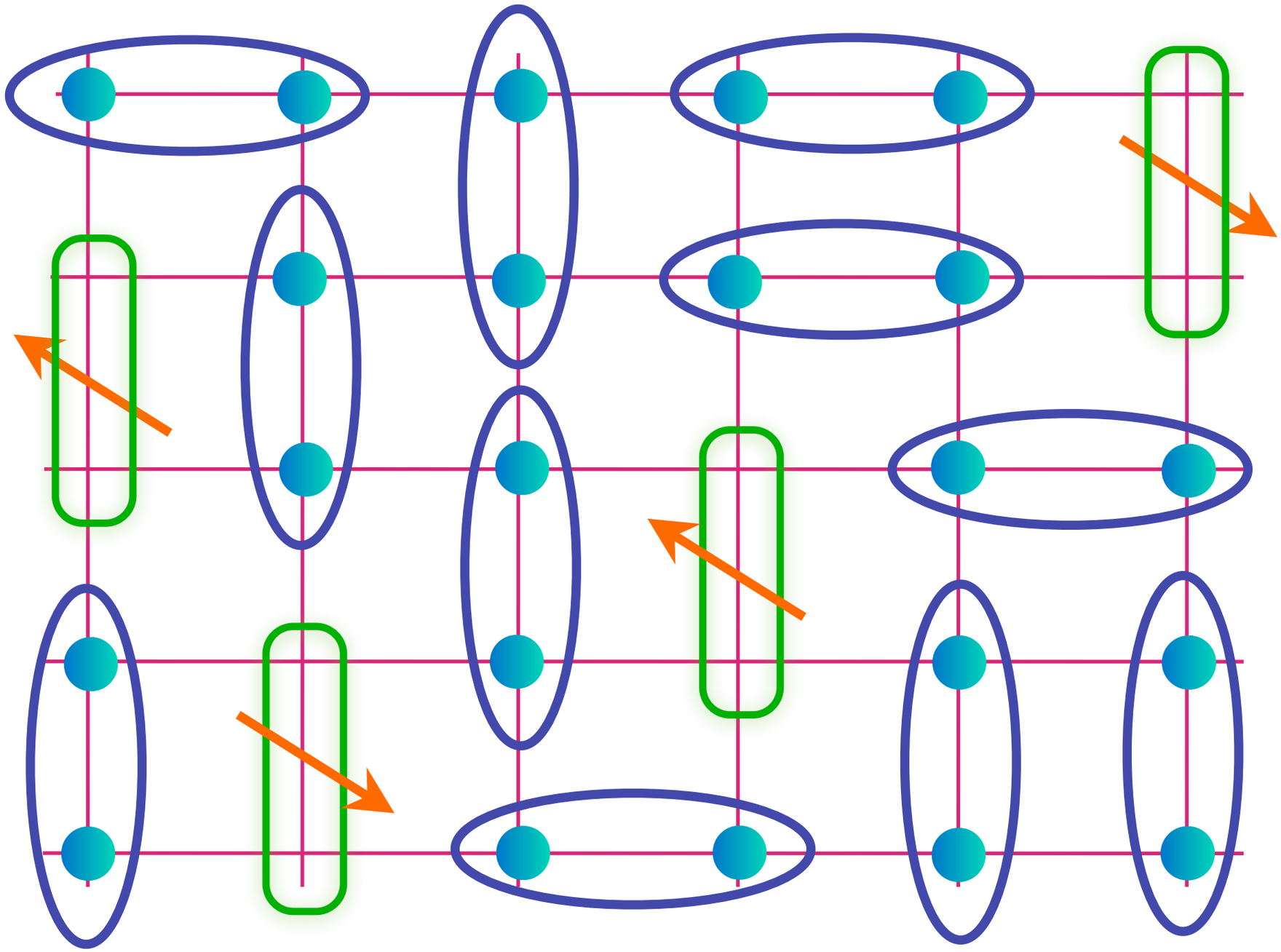
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



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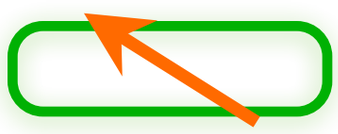

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M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

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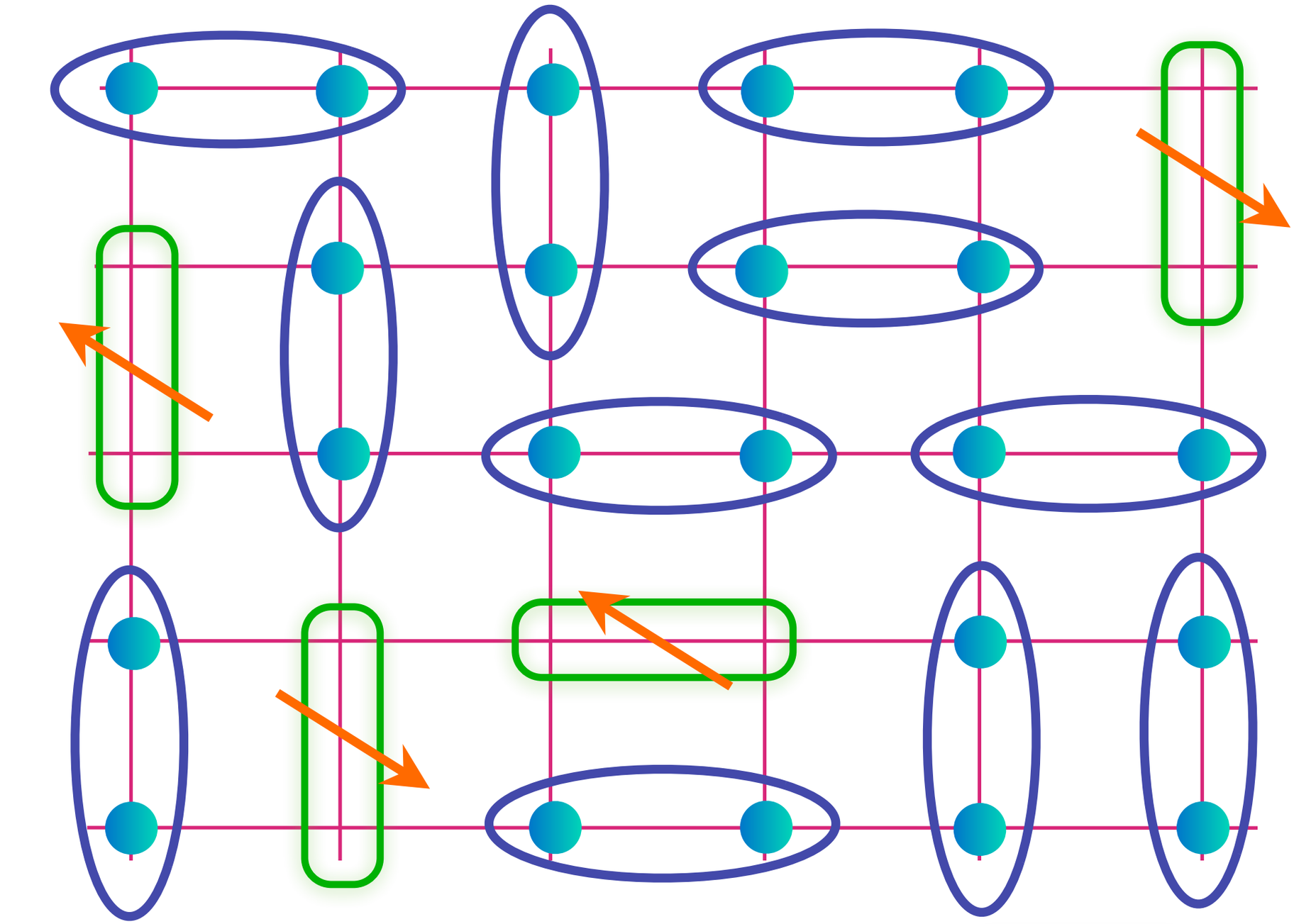

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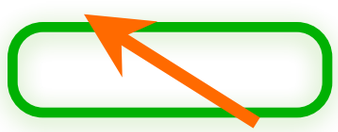

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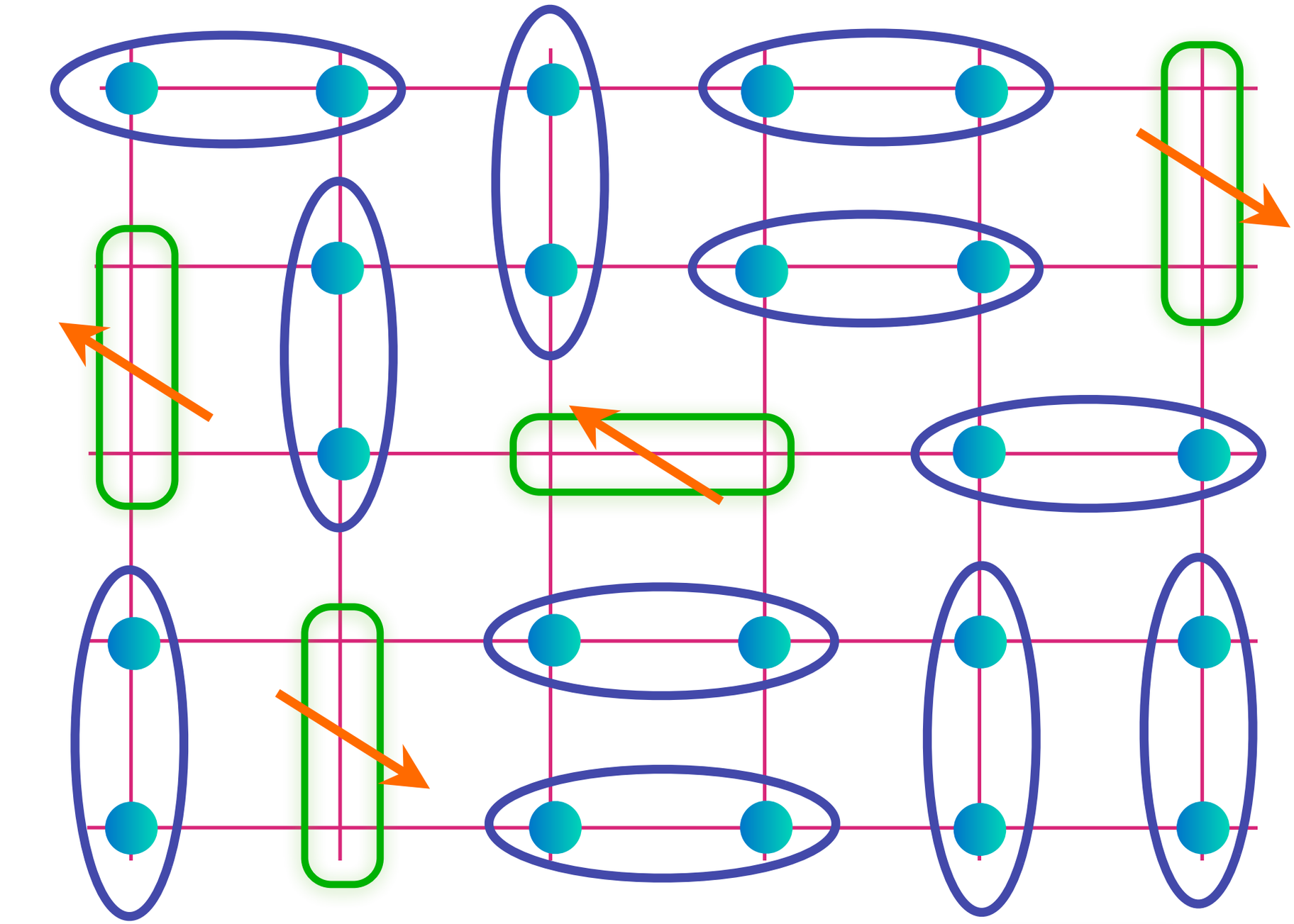

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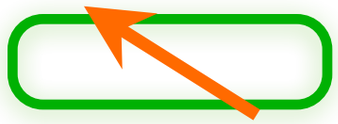

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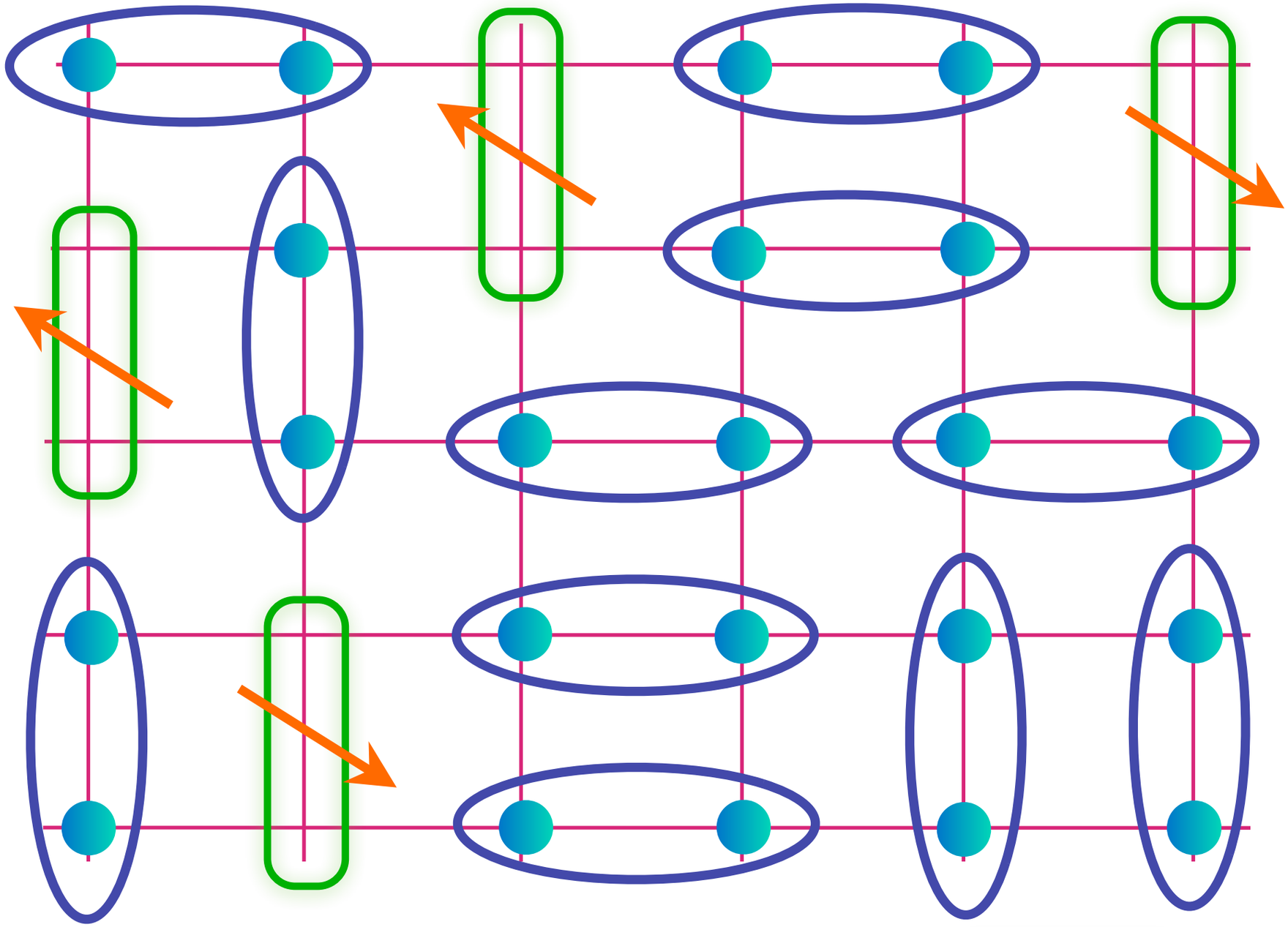

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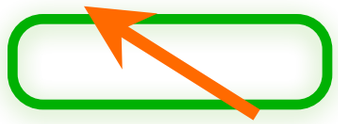

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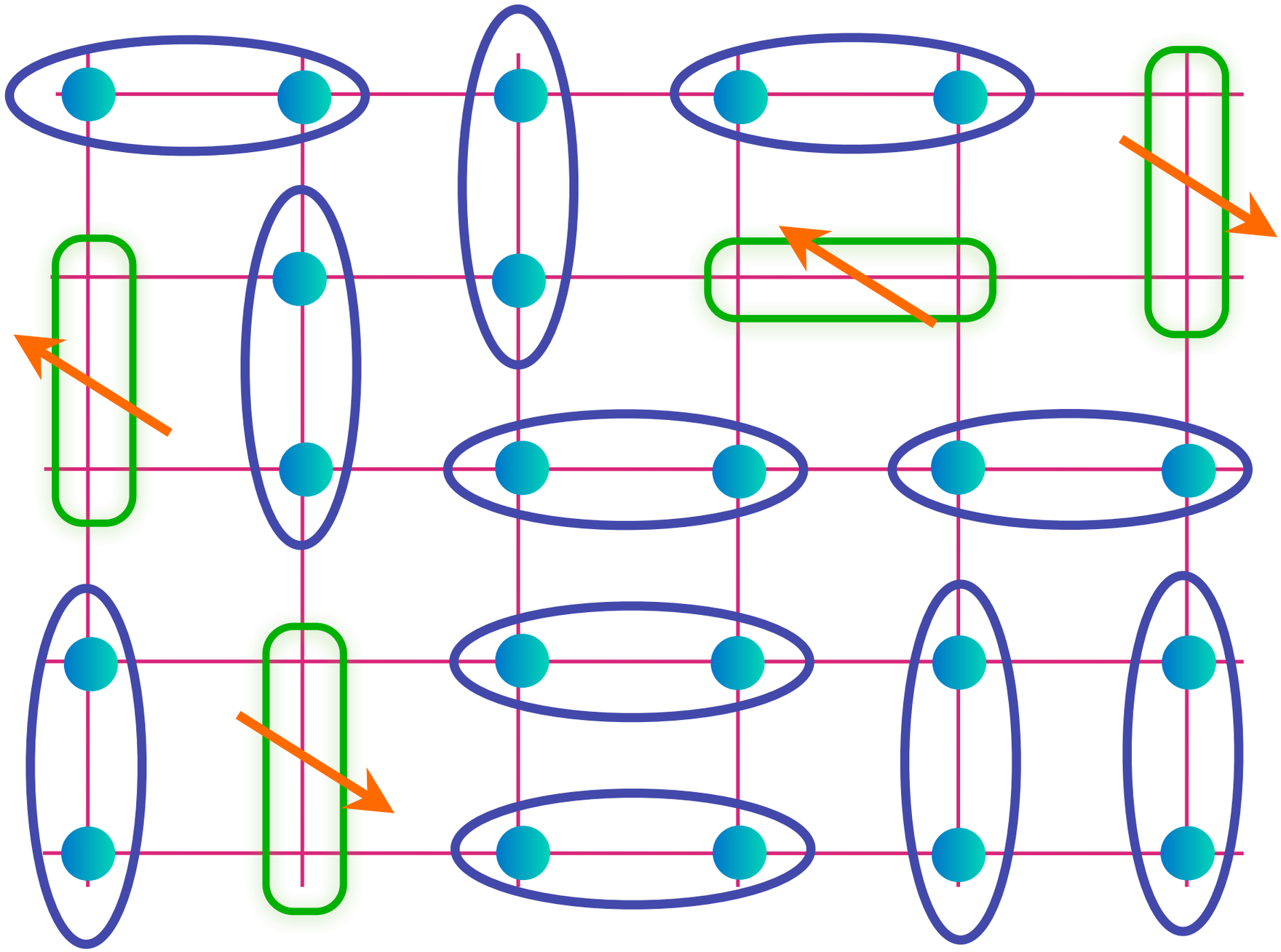

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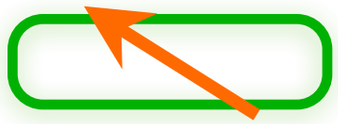

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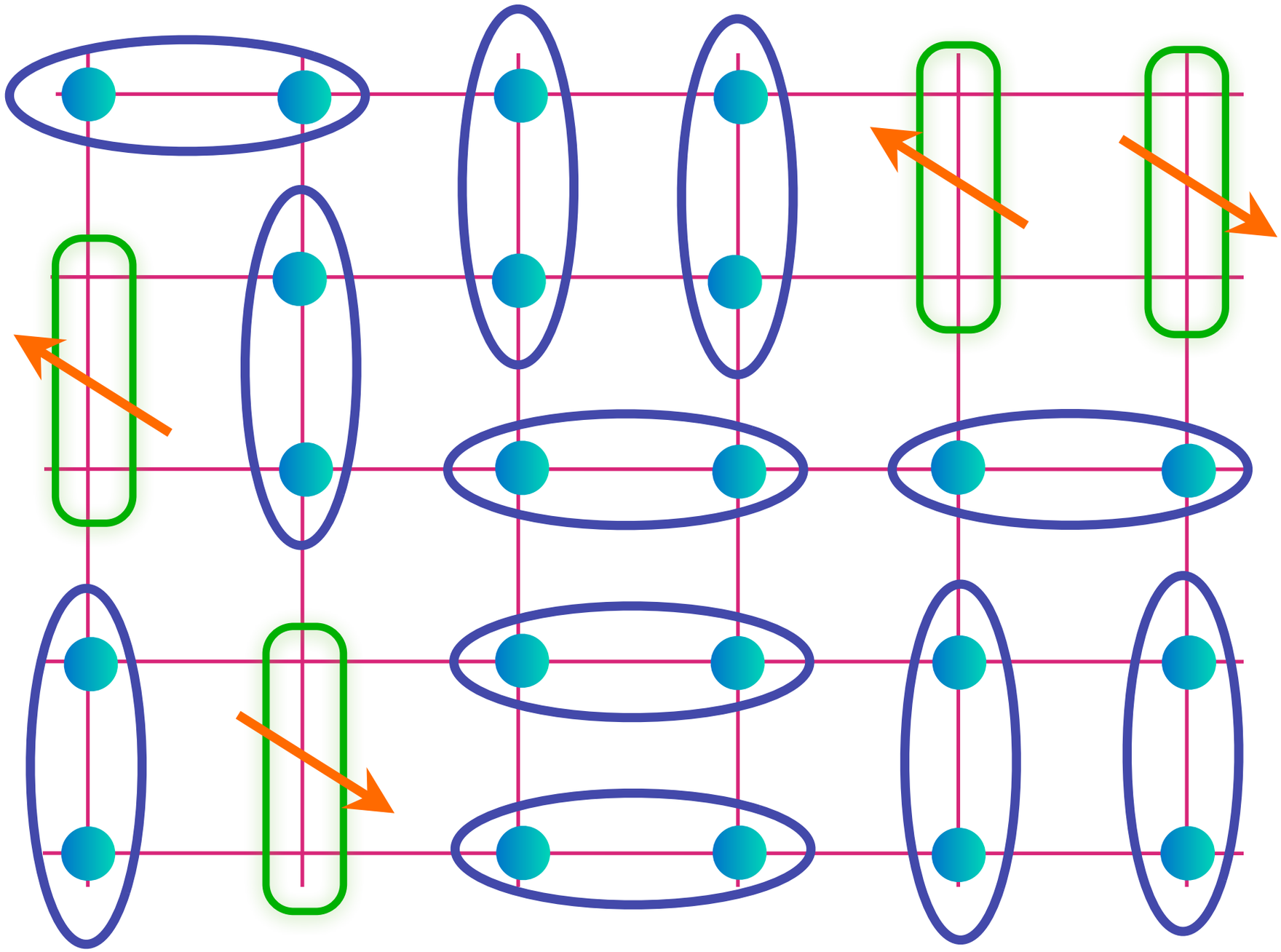

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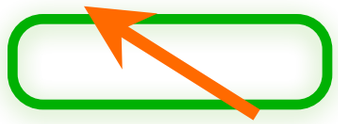

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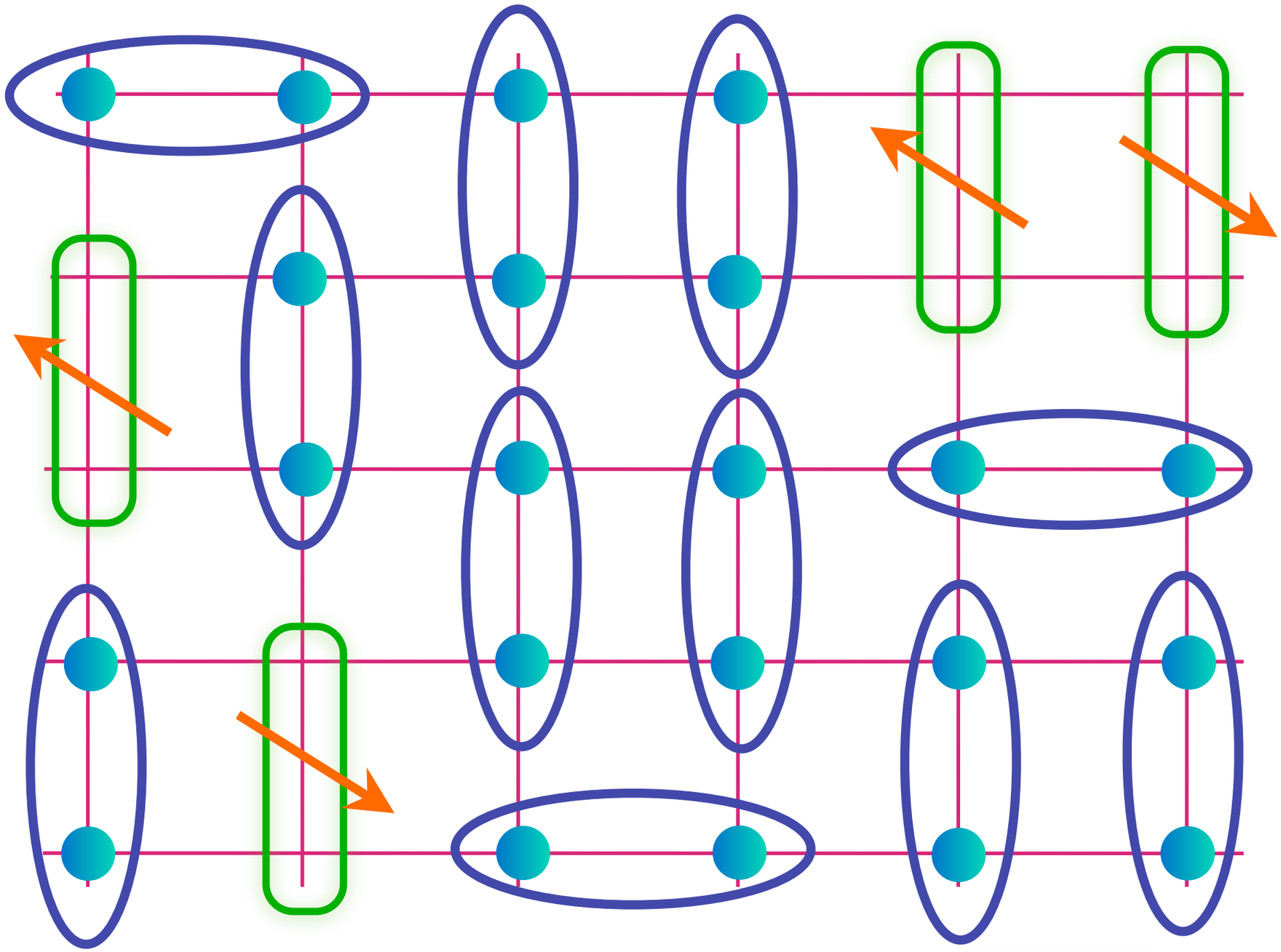
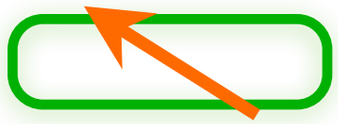


$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$



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

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

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

FL*

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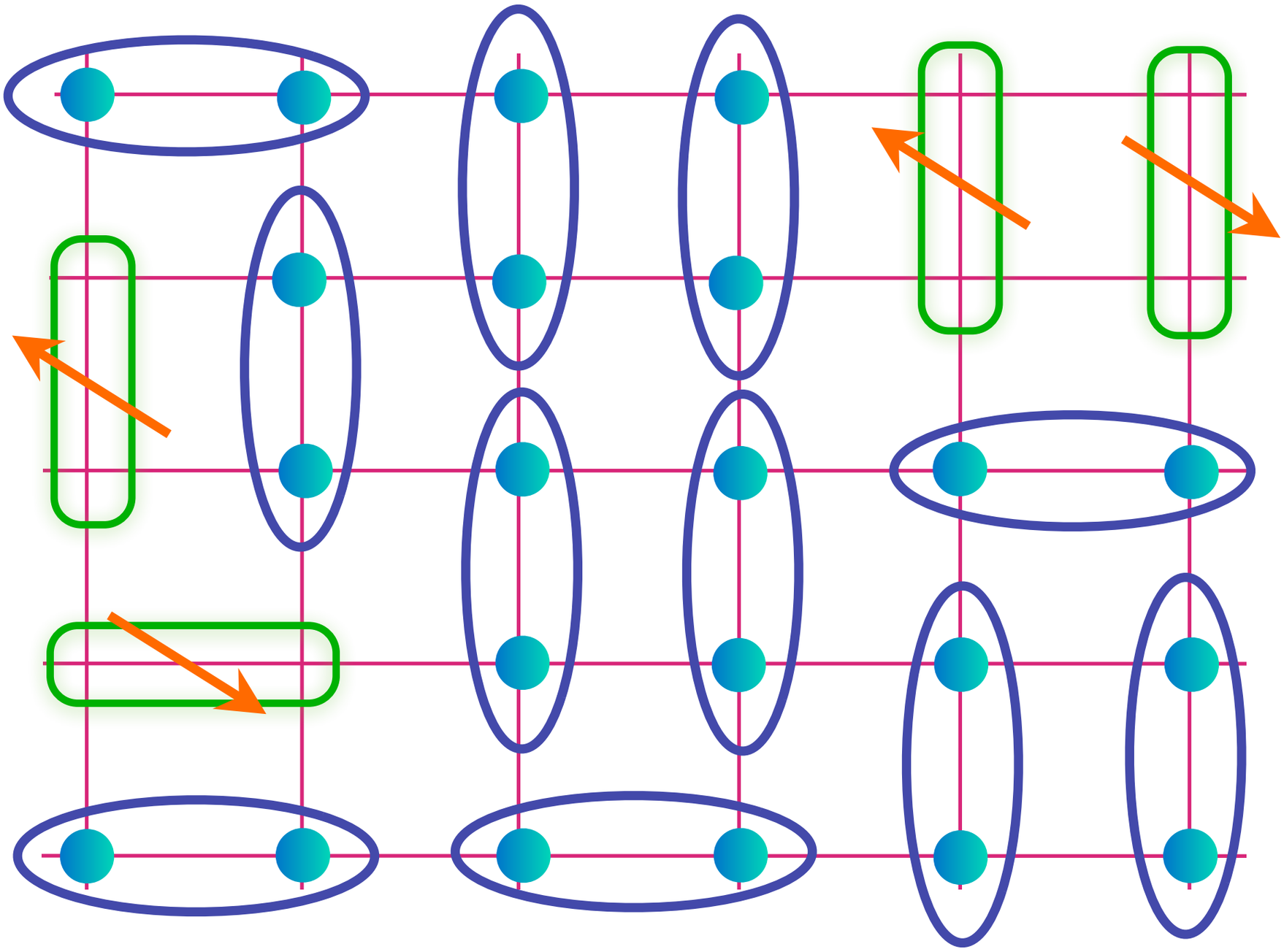

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$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

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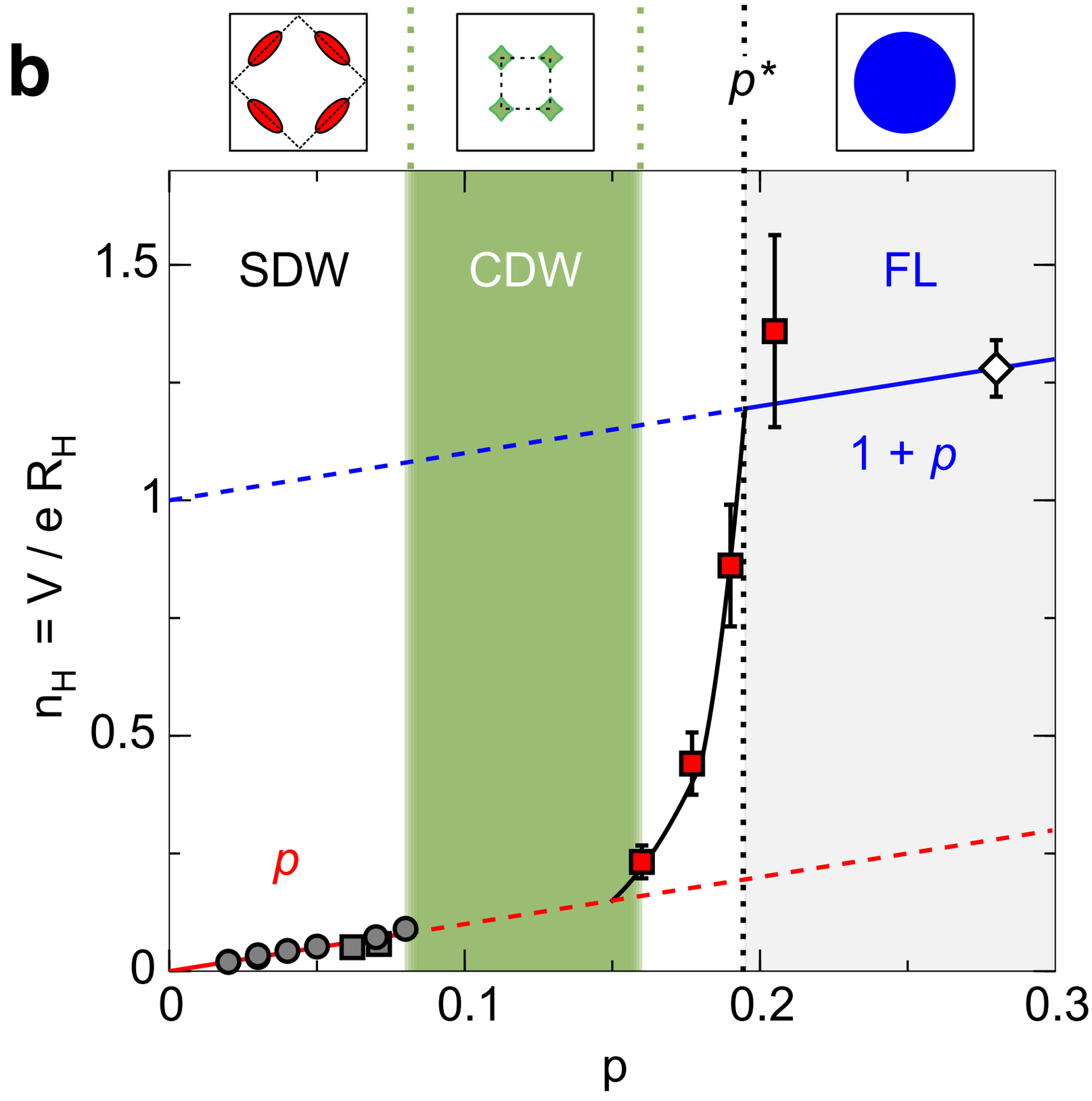
Recent experiment supporting FL* model for pseudogap metal



Badoux, Proust, Taillefer et al., arXiv:1511.08162, Nature online (2016)

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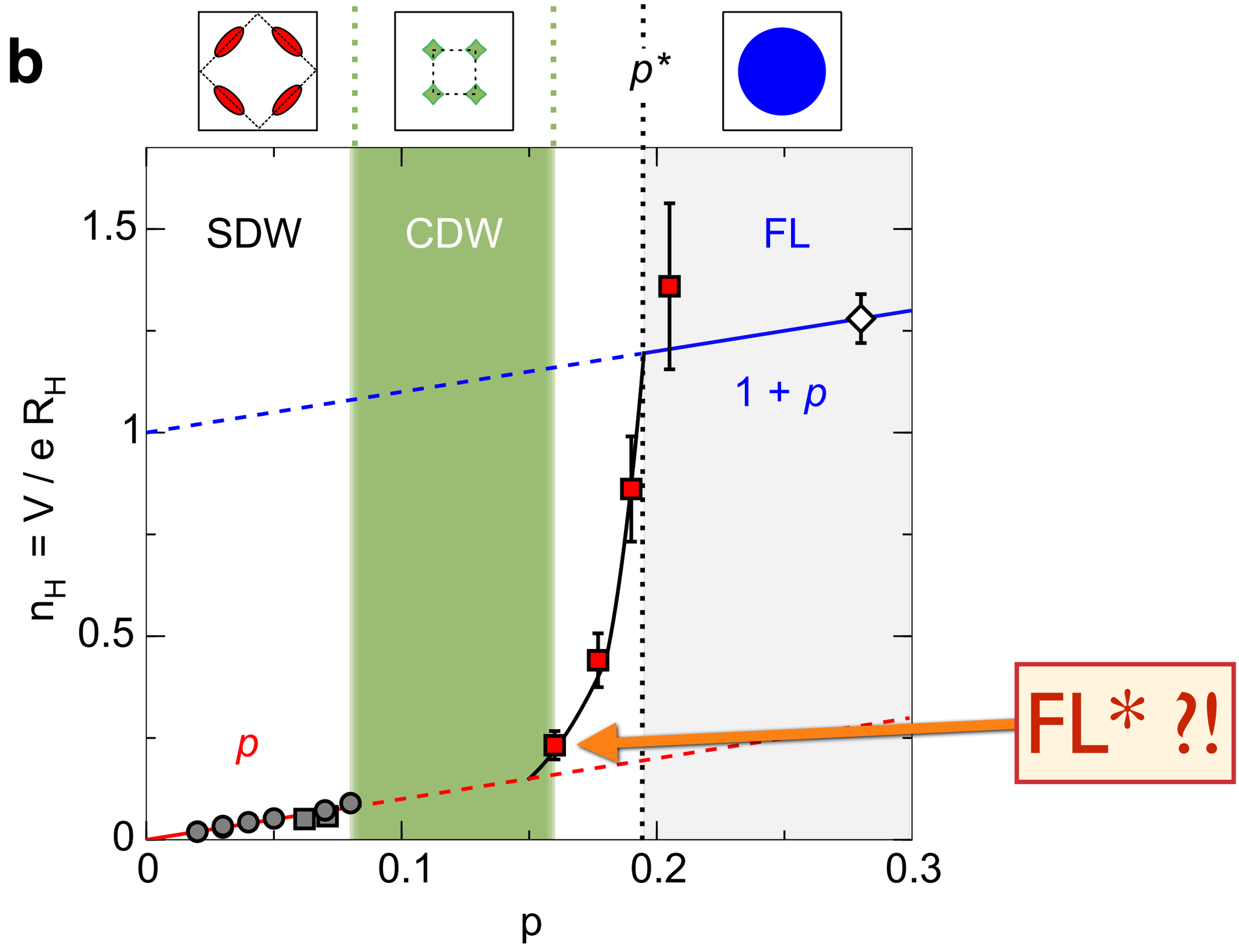

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