

Entangled states of quantum matter

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PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

PHYSICS

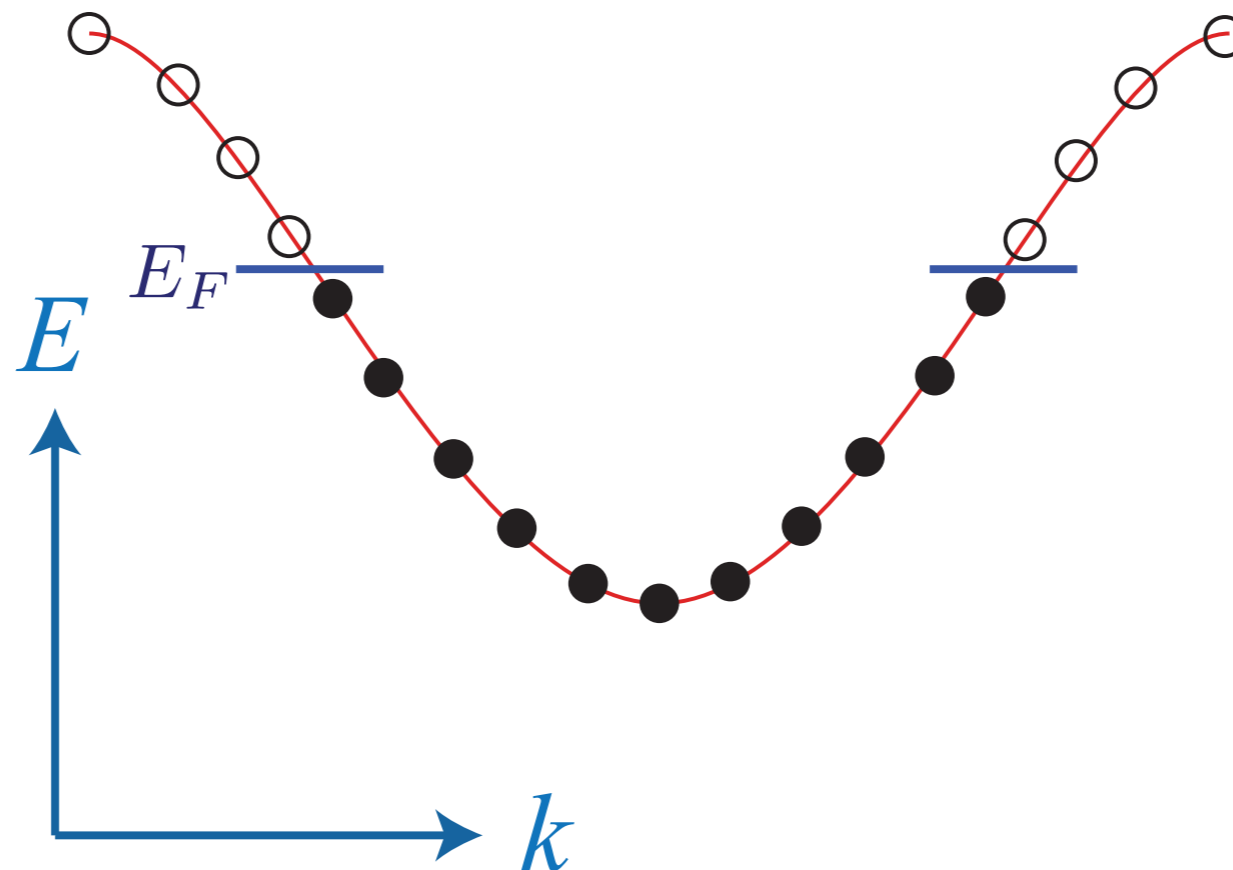


HARVARD

Foundations of quantum many body theory:

I. Ground states connected adiabatically to independent electron states

Metals

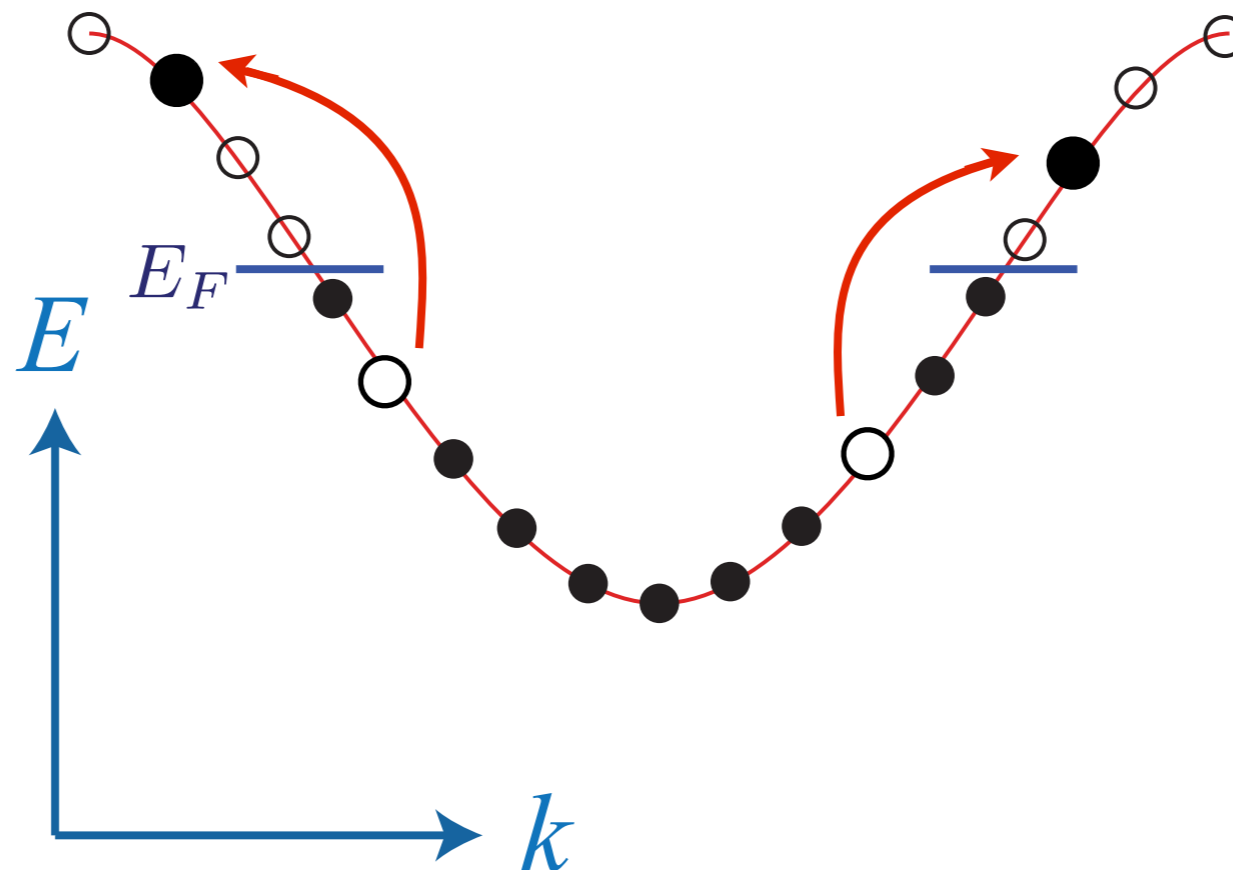


Foundations of quantum many body theory:

1. Ground states connected adiabatically to independent electron states

2. Boltzmann-Landau theory of quasiparticles

Metals



Modern phases of quantum matter:

I. Ground states disconnected from independent electron states: many-particle entanglement

Modern phases of quantum matter:

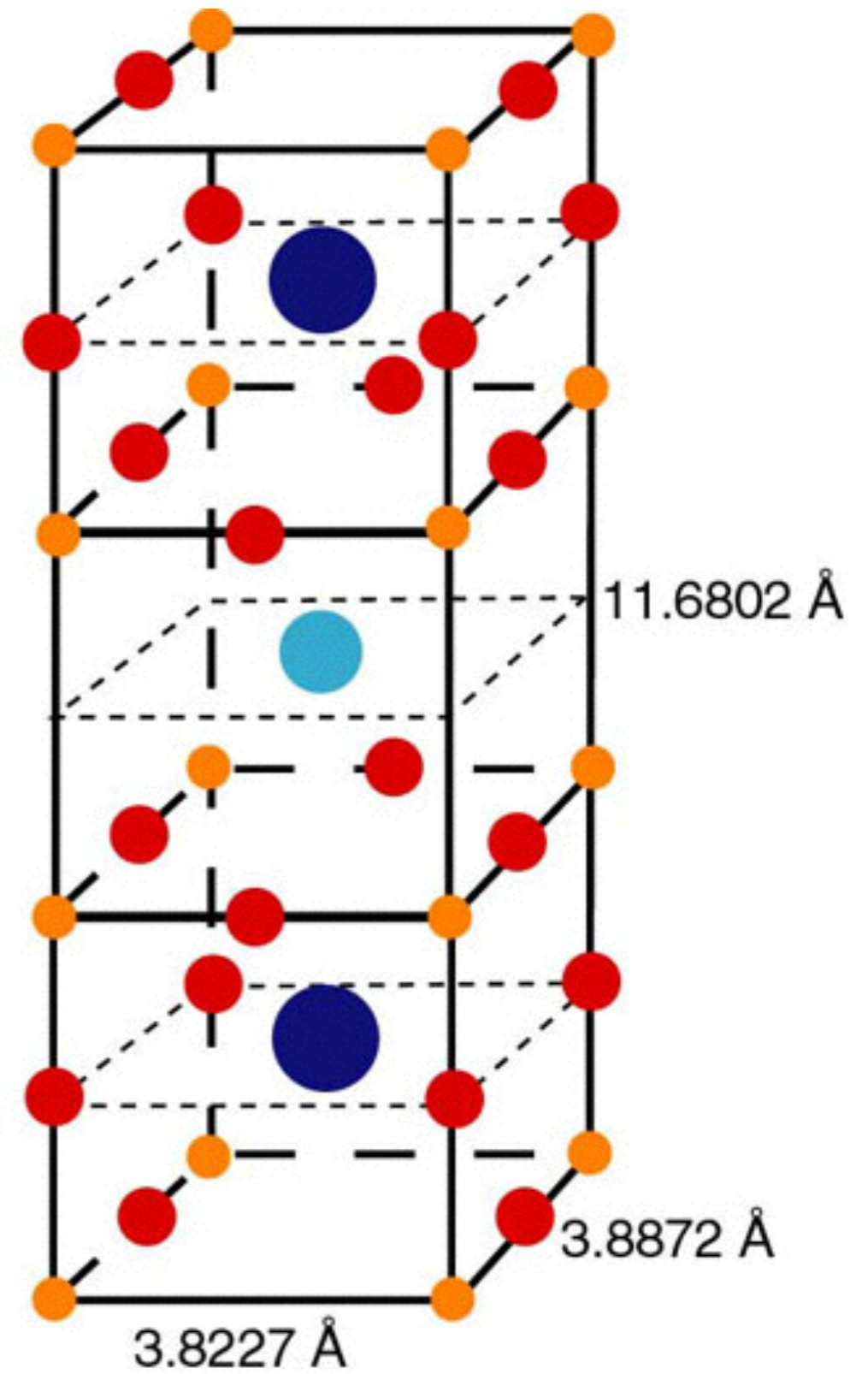
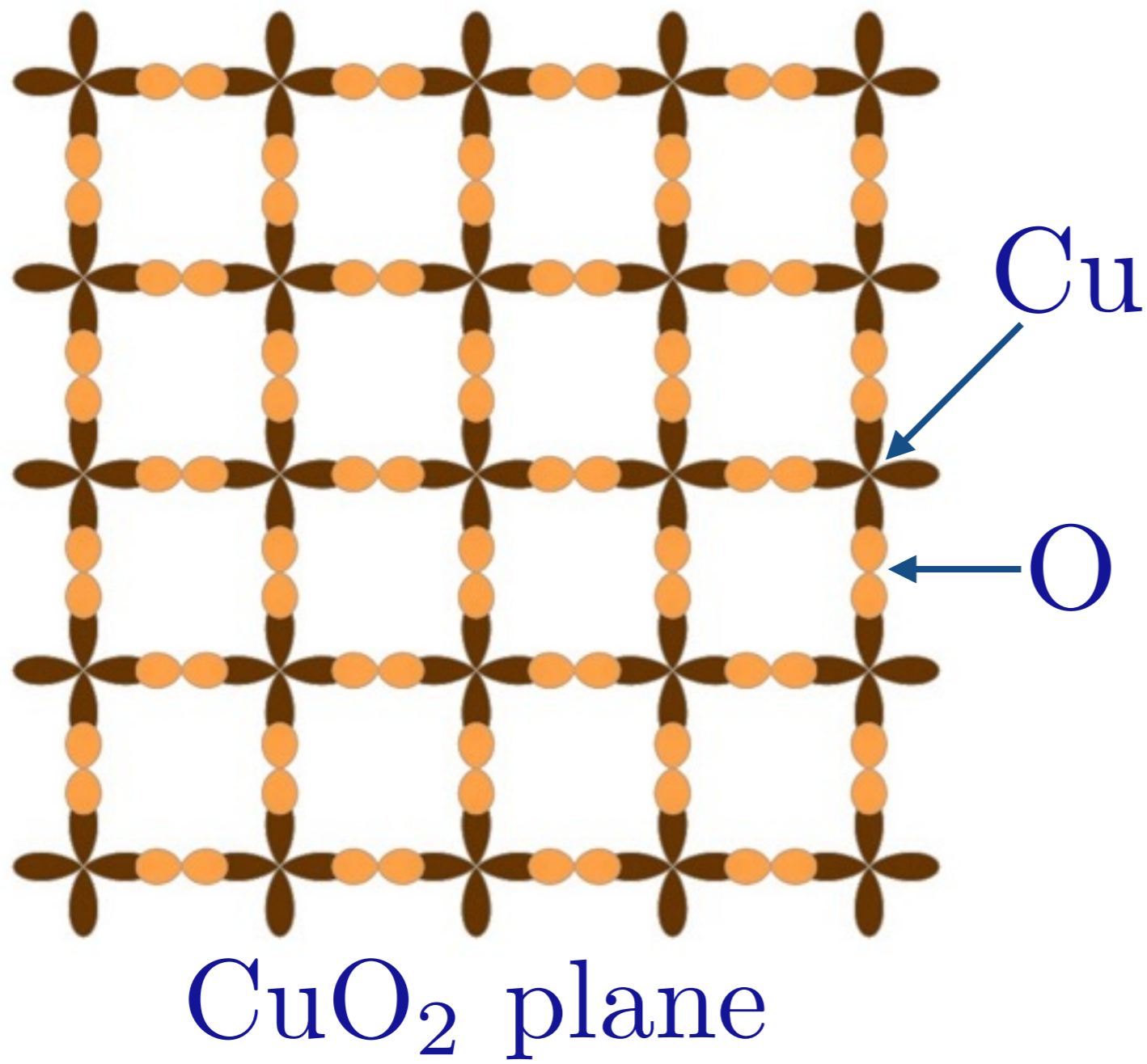
1. Ground states disconnected from independent electron states: many-particle entanglement
2. (A) Topological order and quasiparticles with fractional quantum numbers

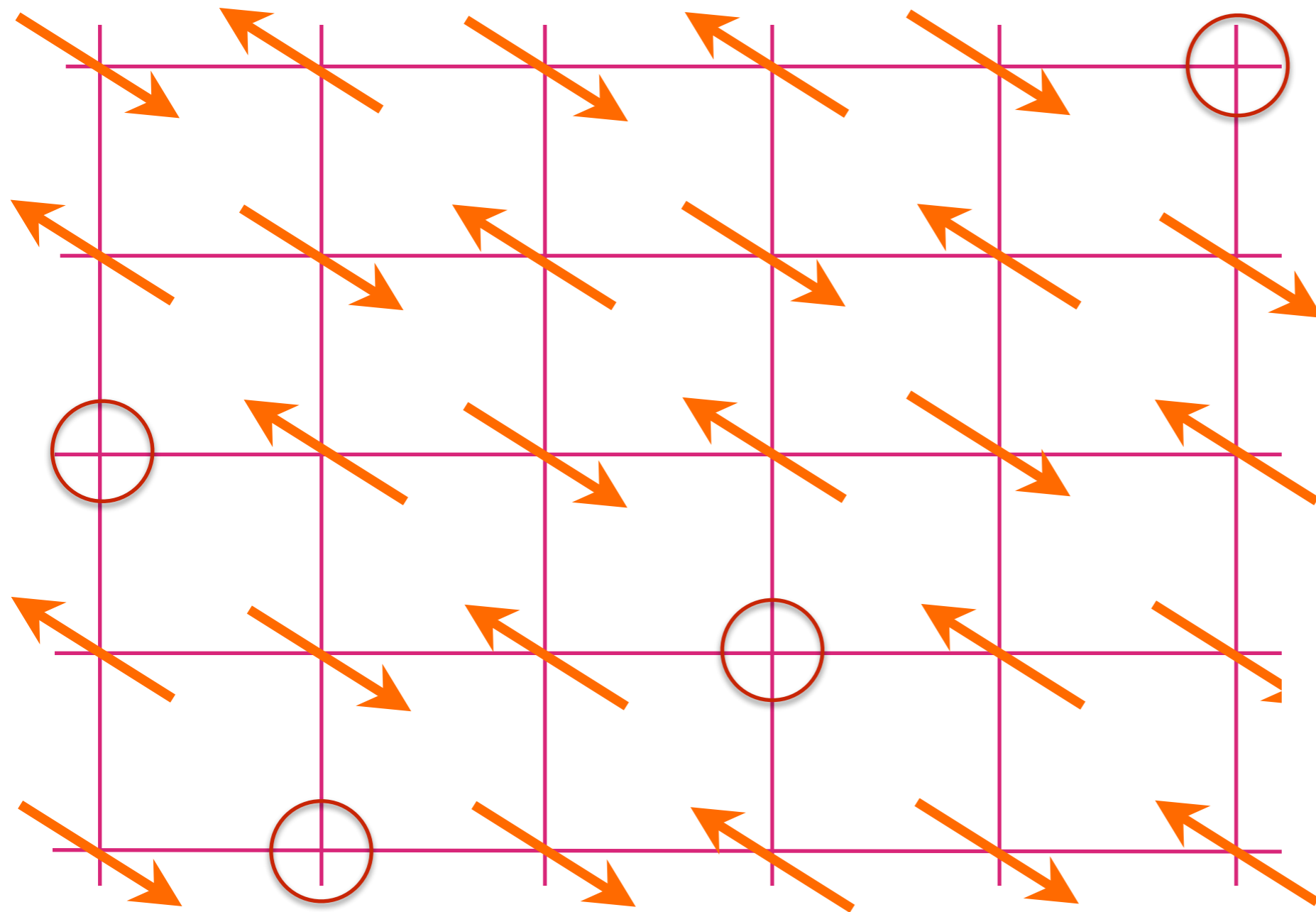
Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. (A) Topological order and quasiparticles with fractional quantum numbers
(B) Gapless states with no quasiparticles

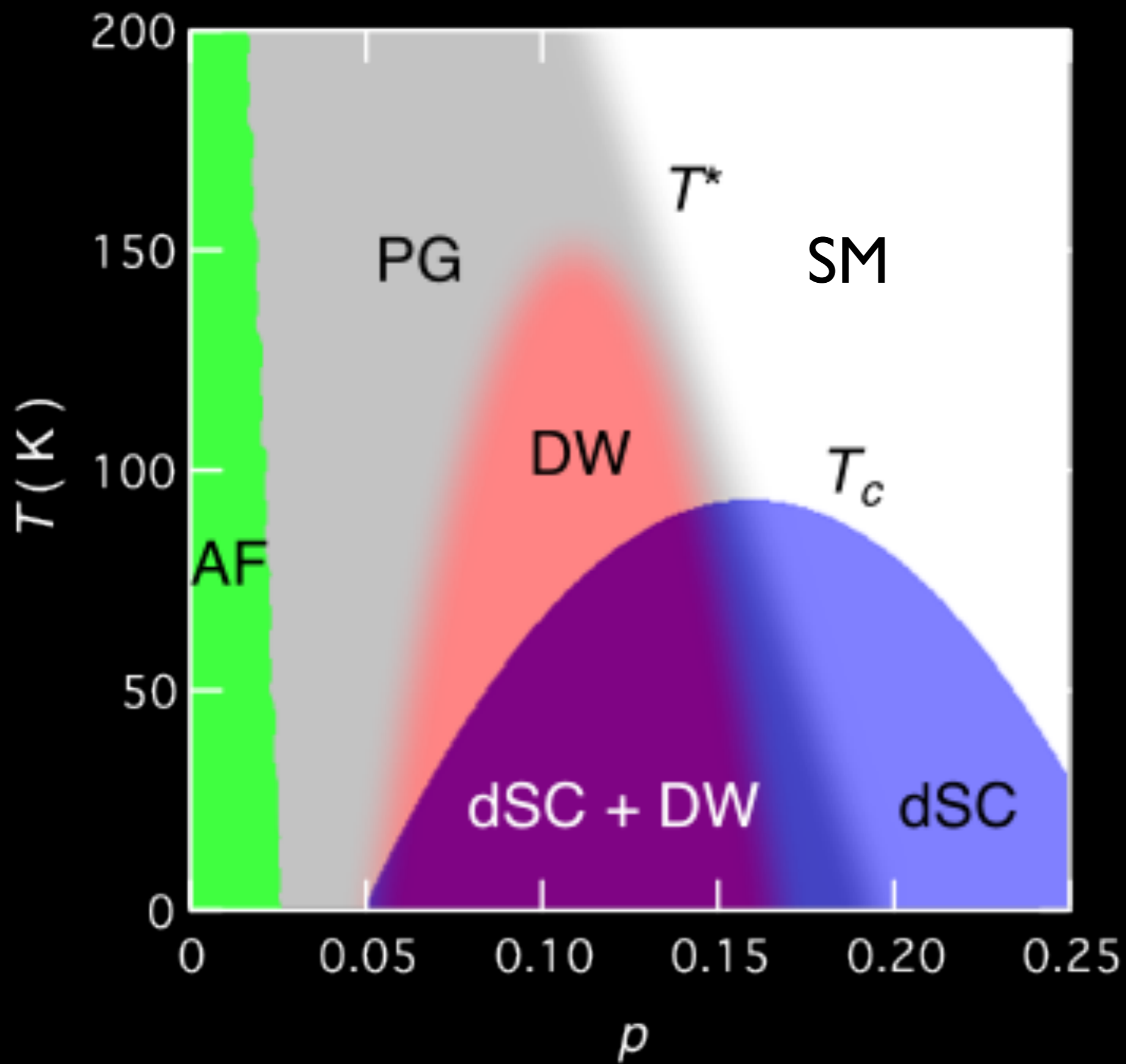
High temperature superconductors

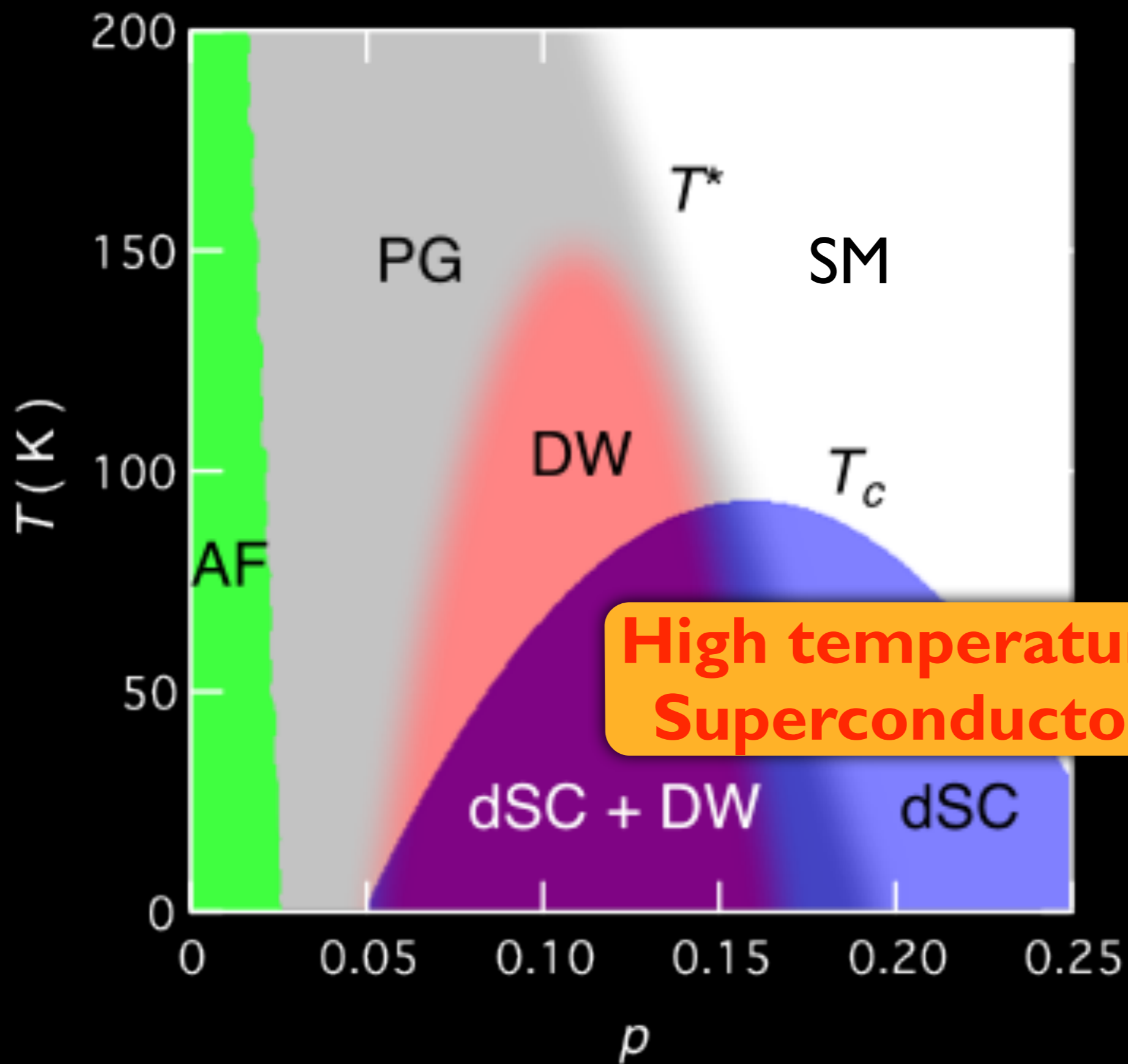




Anti-ferromagnet
with p holes
per square

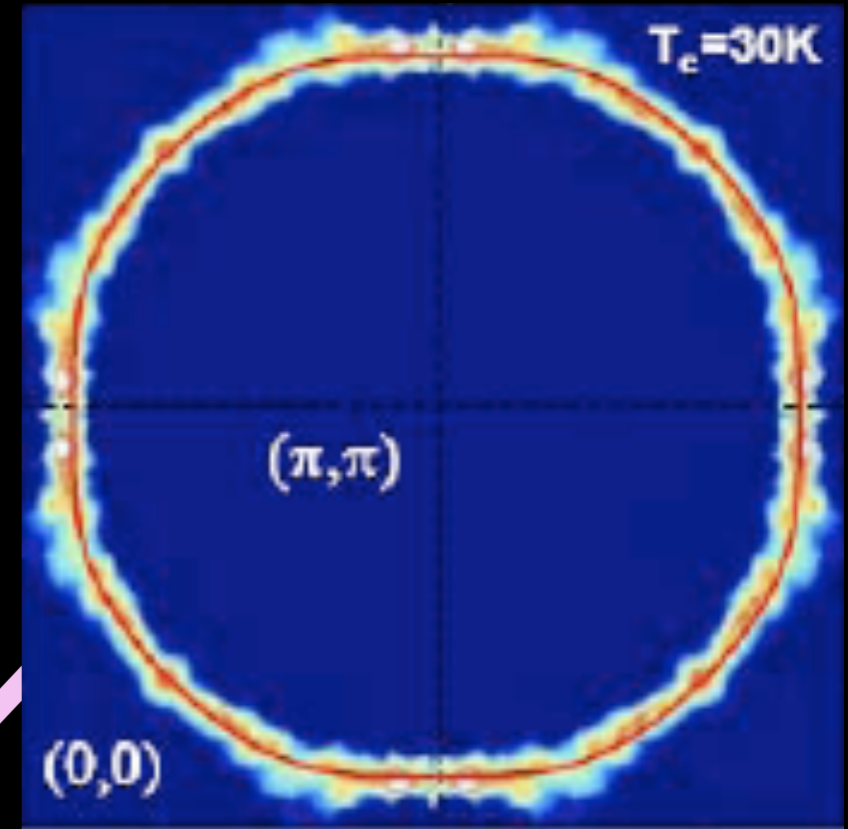
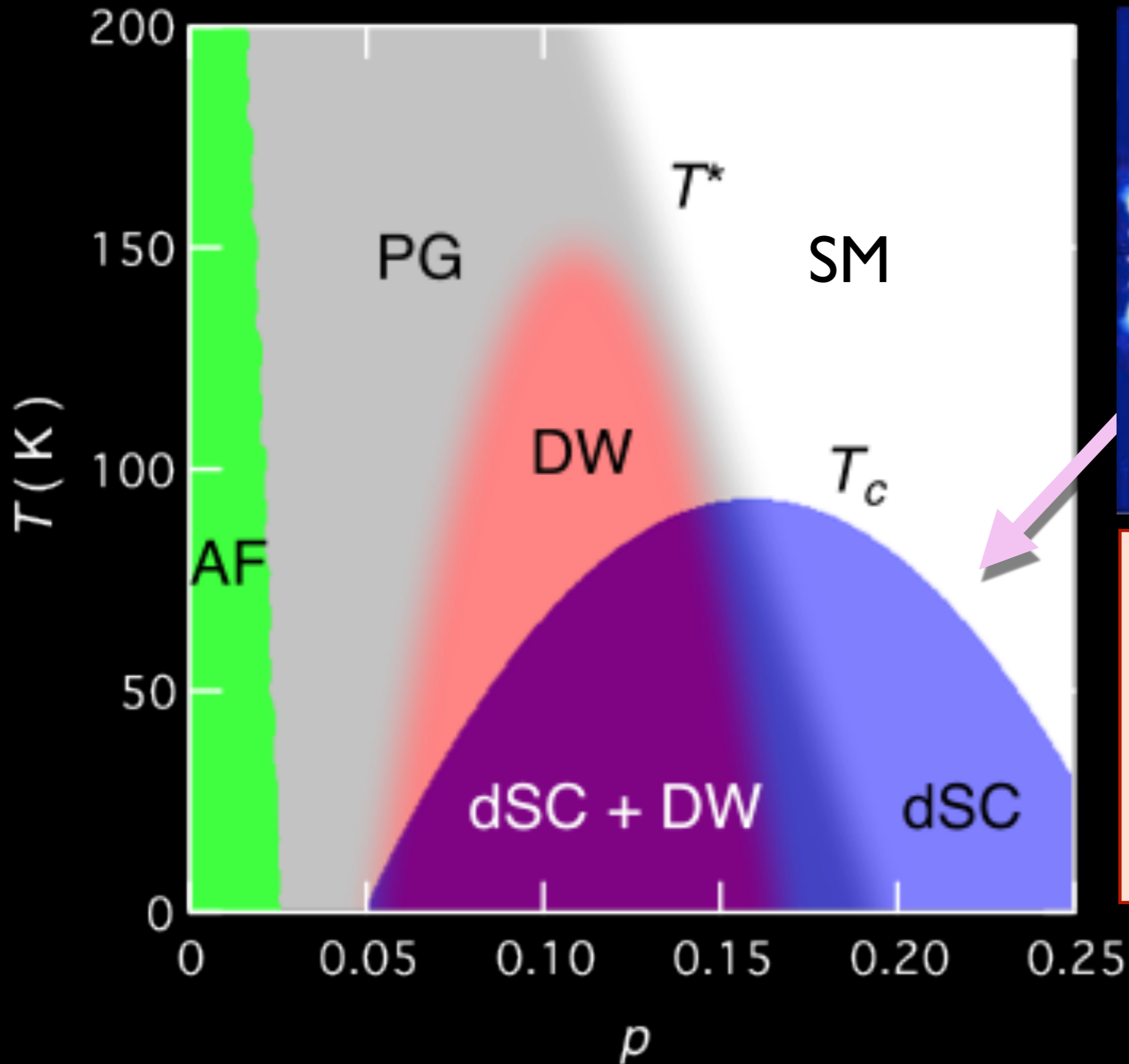
But relative
to the band
insulator,
there are
 $1 + p$ holes
per square





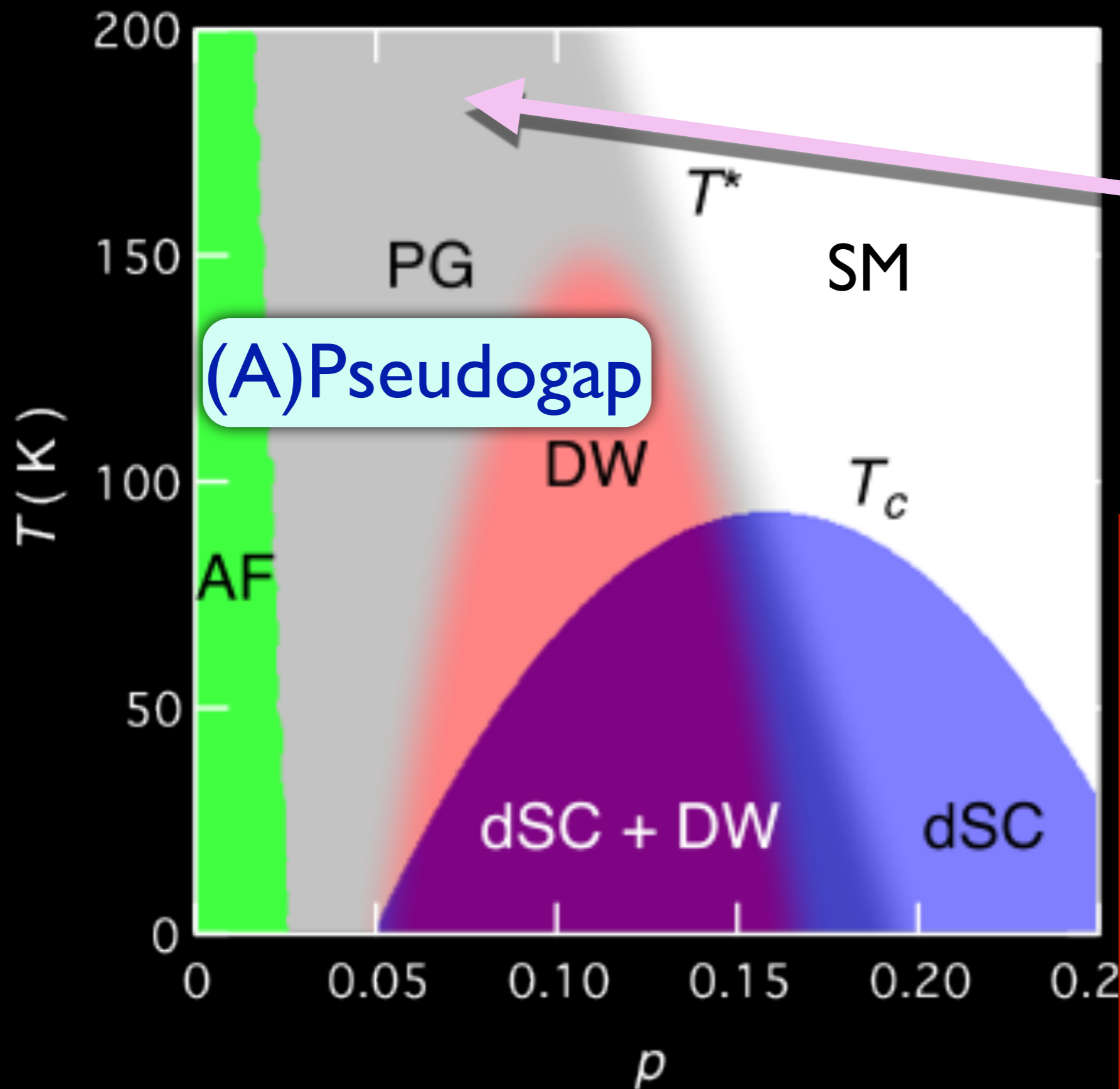
High temperature Superconductor

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)

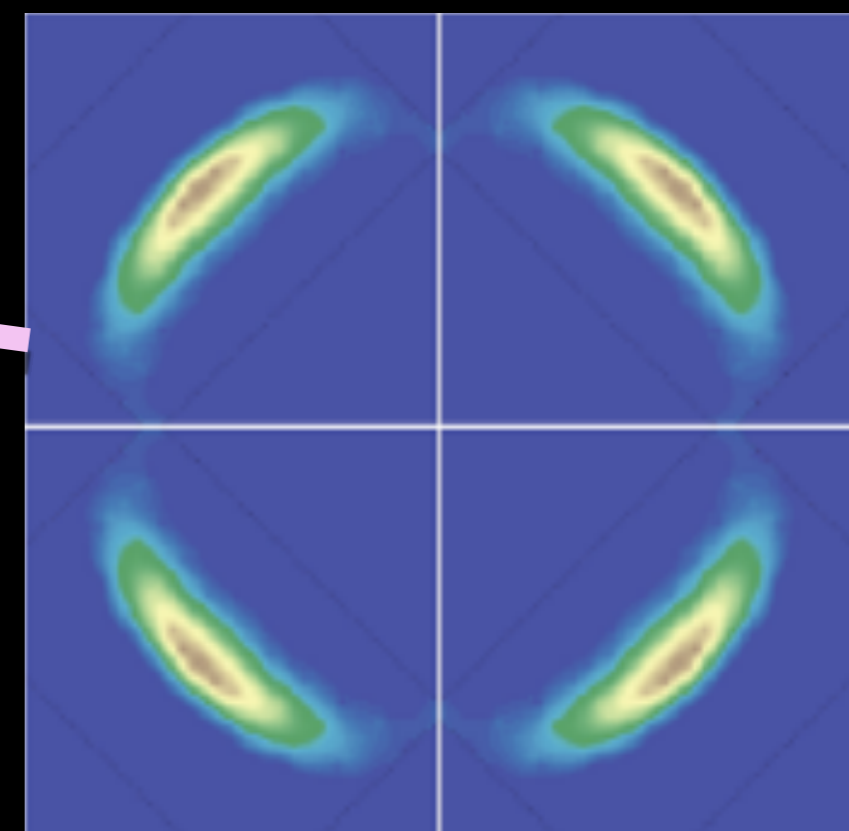


Conventional (unentangled) metal
Area enclosed by Fermi surface = $1+p$

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)



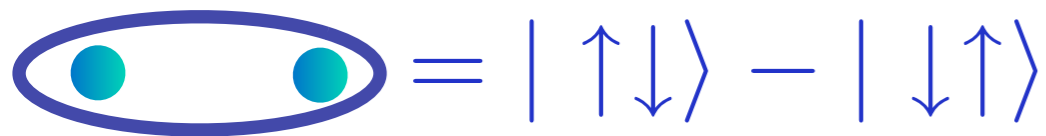
(A) Pseudogap

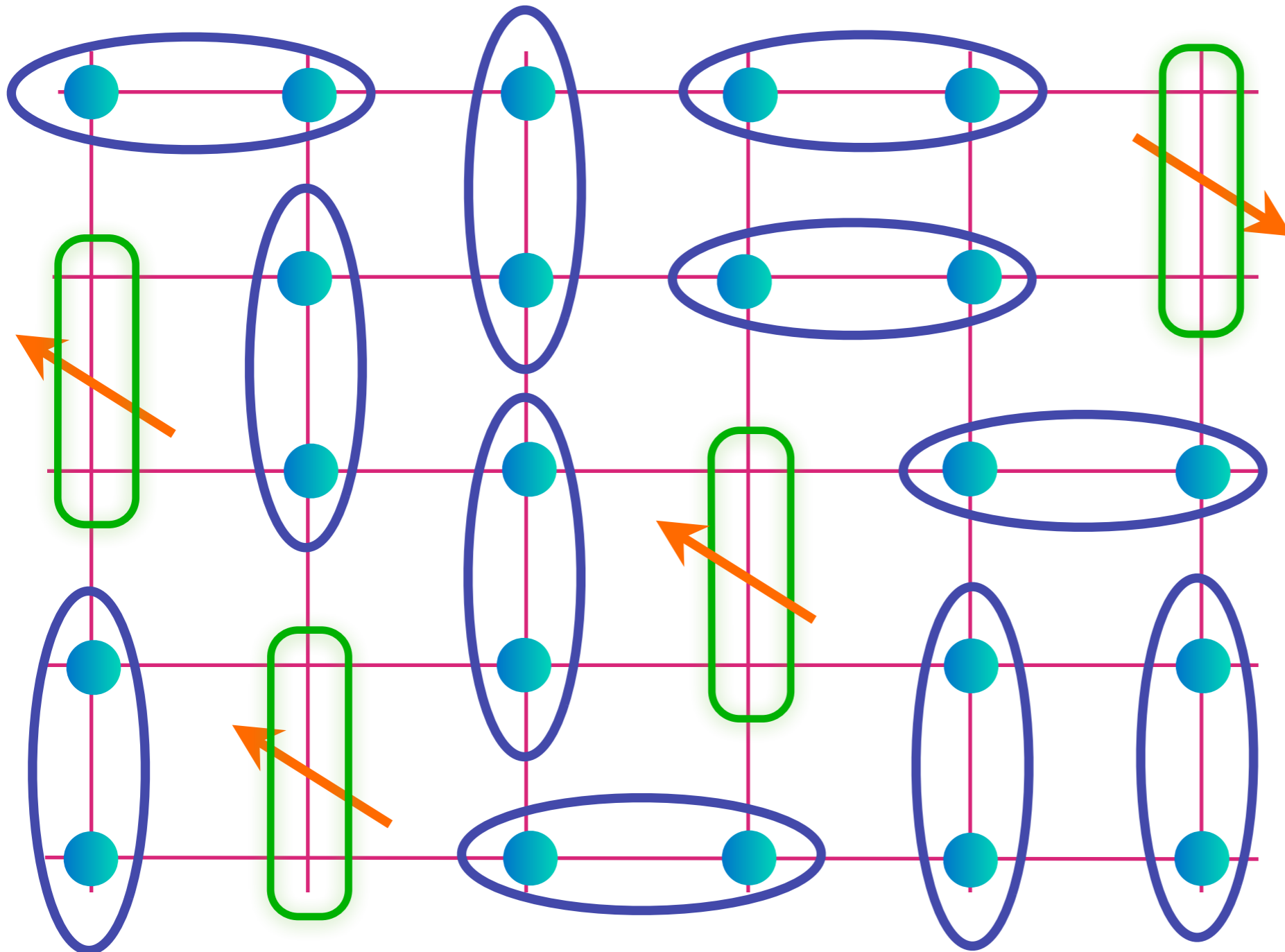


Entangled metal:

- (i) long-range entanglement described by emergent “gauge” fields
- (ii) electronic quasiparticles around a Fermi surface of size p

Entangled metal


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



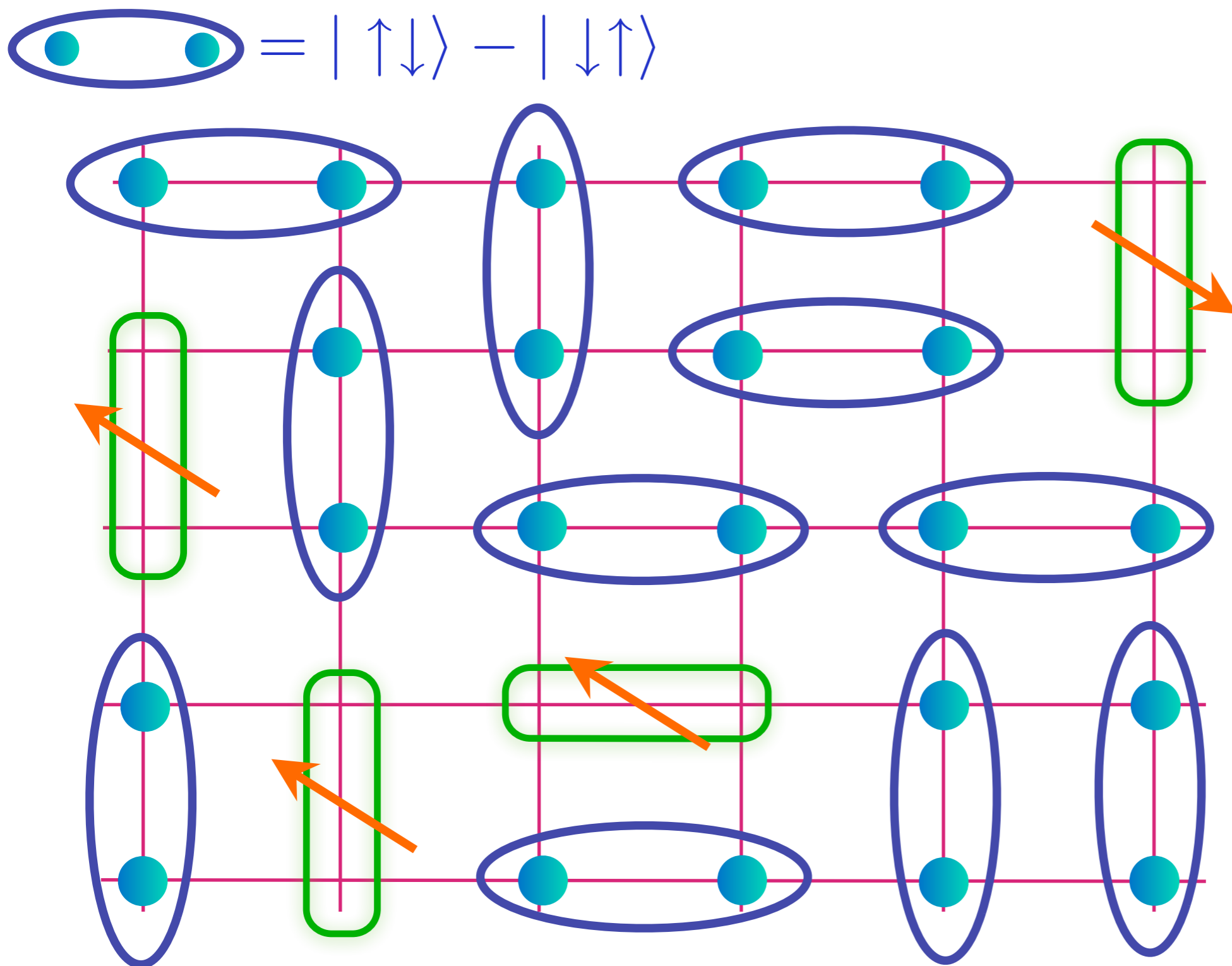
Emergent
gauge field
(blue dimers)
and
gauge-neutral,
spin $S=1/2$,
charge $+e$
fermions
(green dimers)
of density p

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)

E. G. Moon and S. S. *Phys. Rev. B* **83**, 224508 (2011); M. Punk, A. Allais, and S. S., arXiv:1501.00978.

Entangled metal



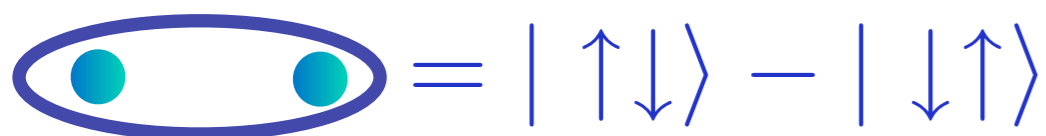
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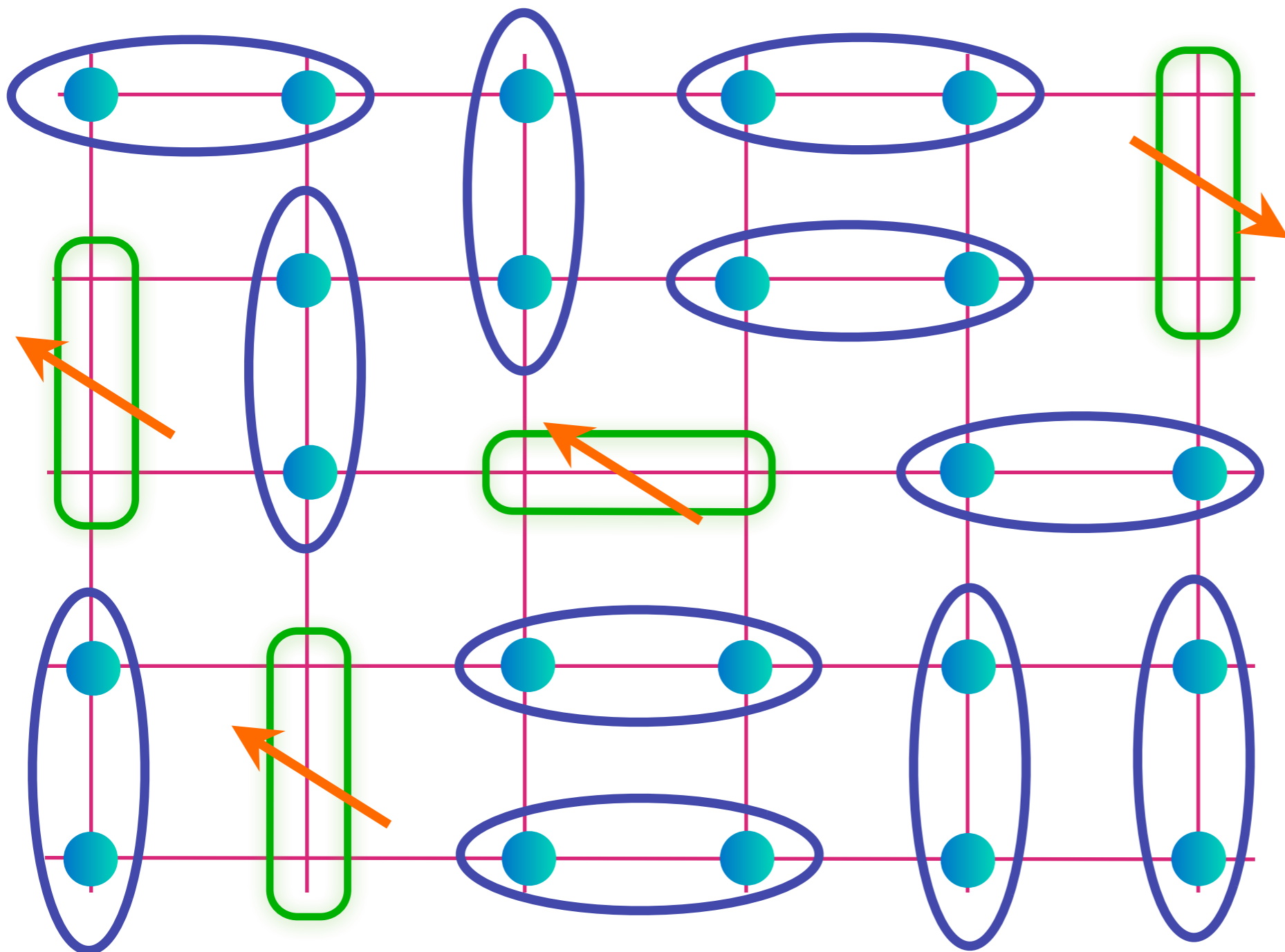
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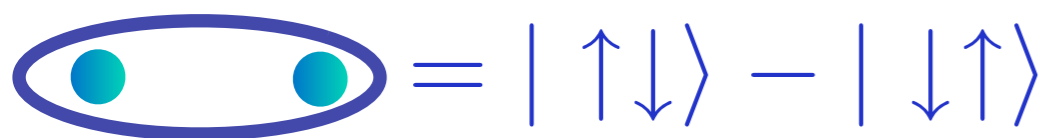
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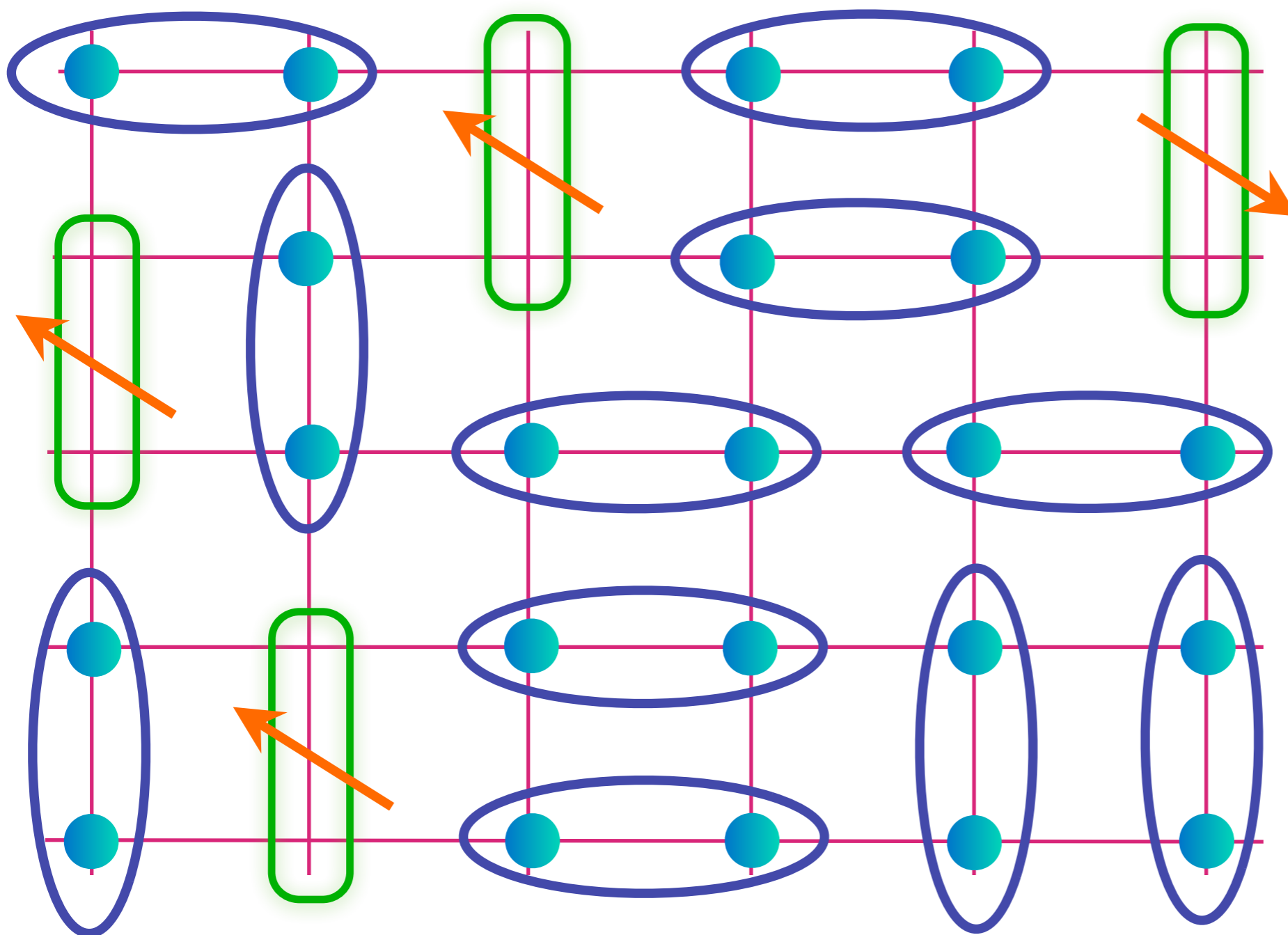
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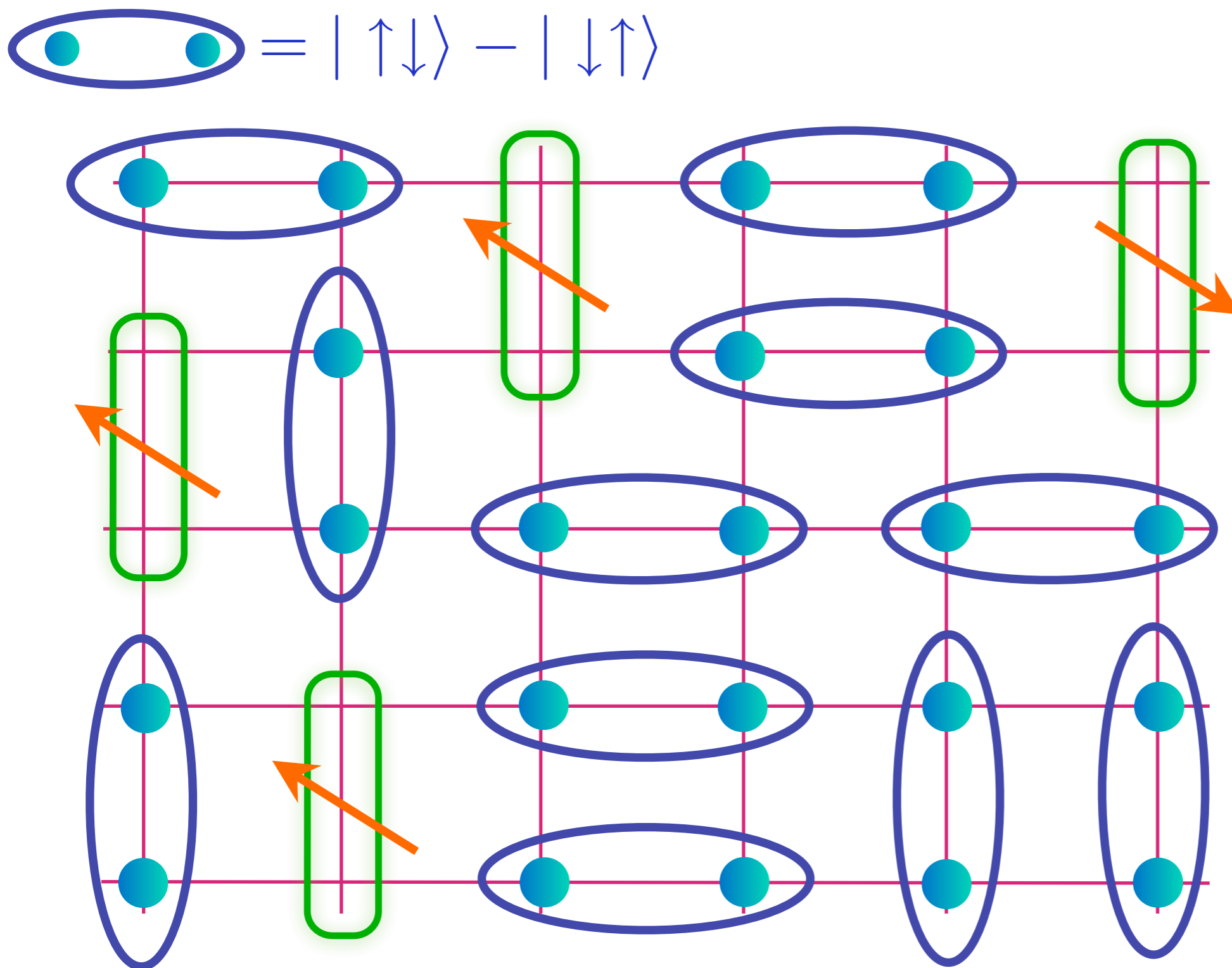
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Entangled metal



Motion of fermionic green dimers leads of Fermi surface of electron-like quasiparticles of size p , with anisotropic spectral weight; this co-exists with topological order (blue dimers)

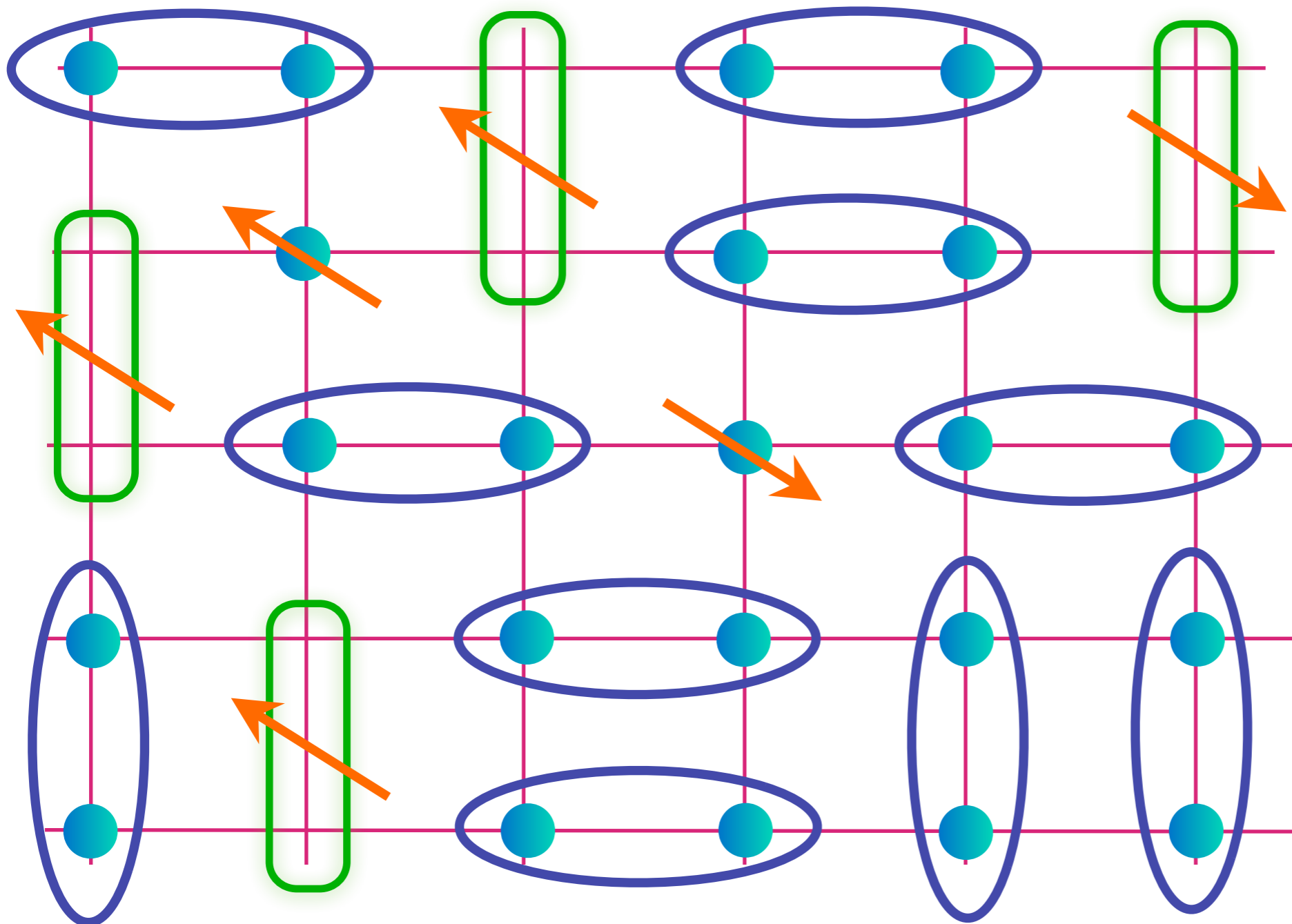
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Entangled metal

$$\text{[Diagram of two blue dots in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$



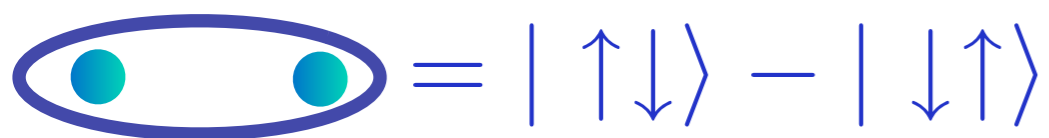
Also,
fractionalized
quasiparticles:
neutral, spin
 $S=1/2$,
“spinons”

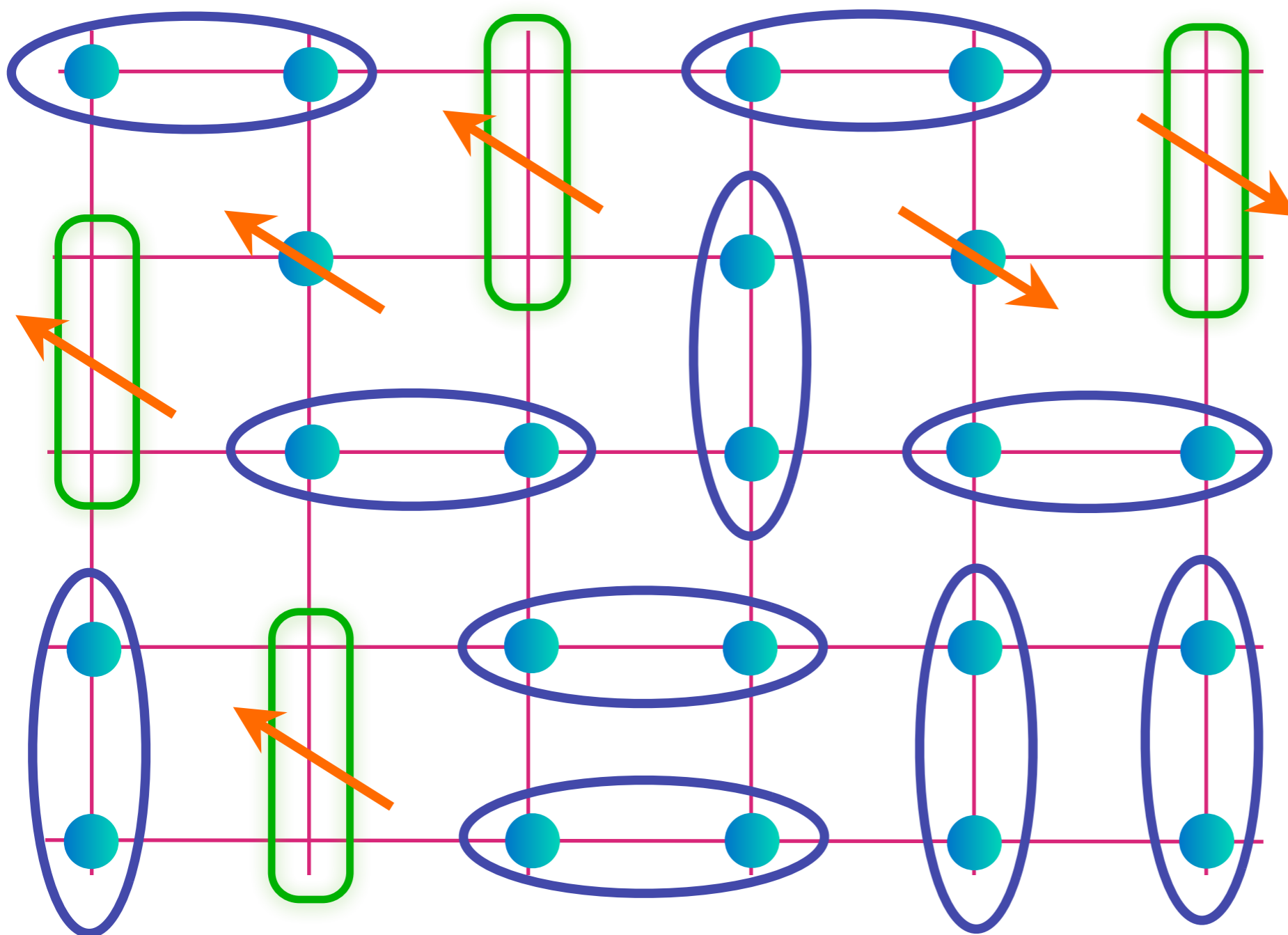
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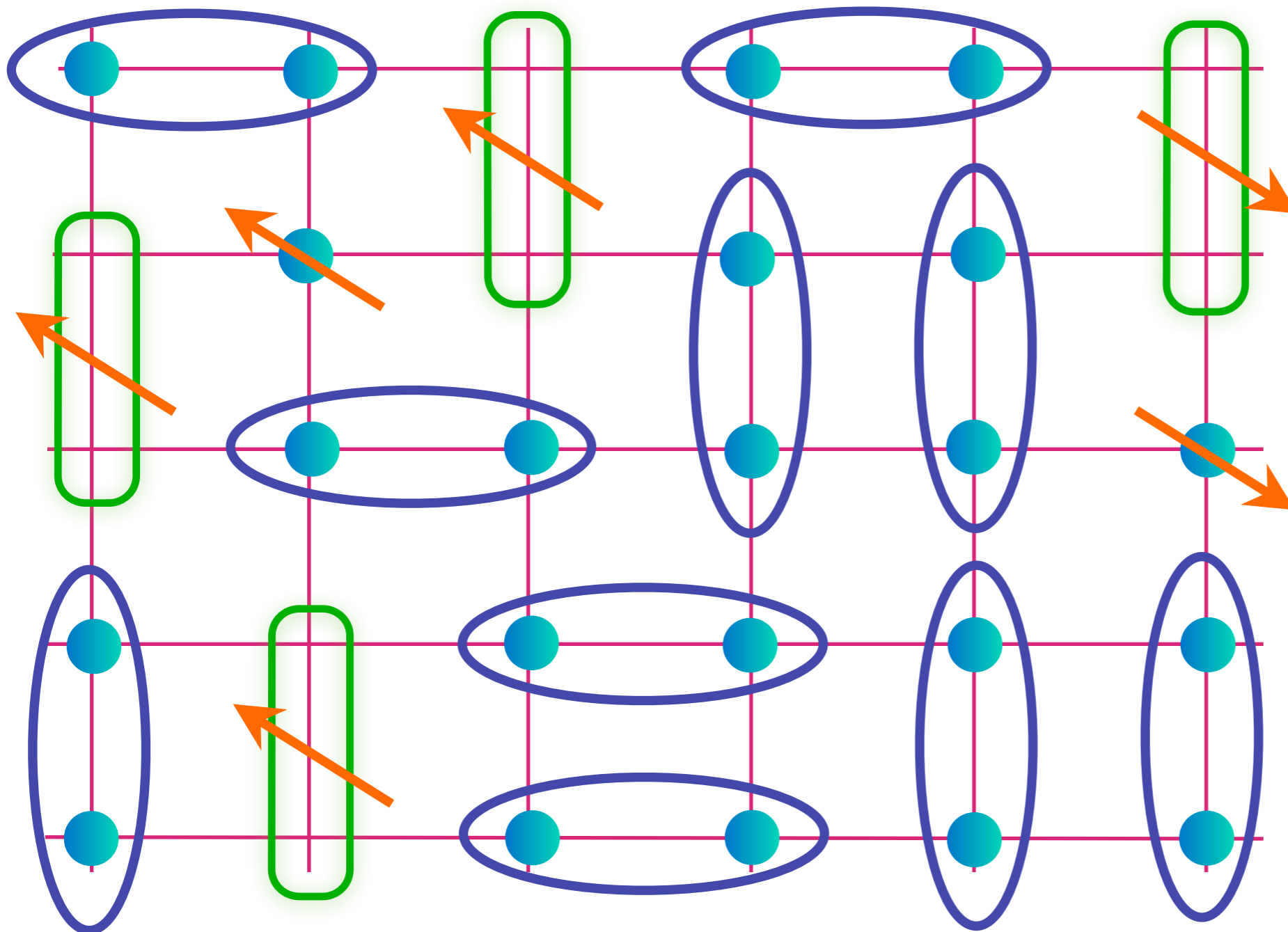
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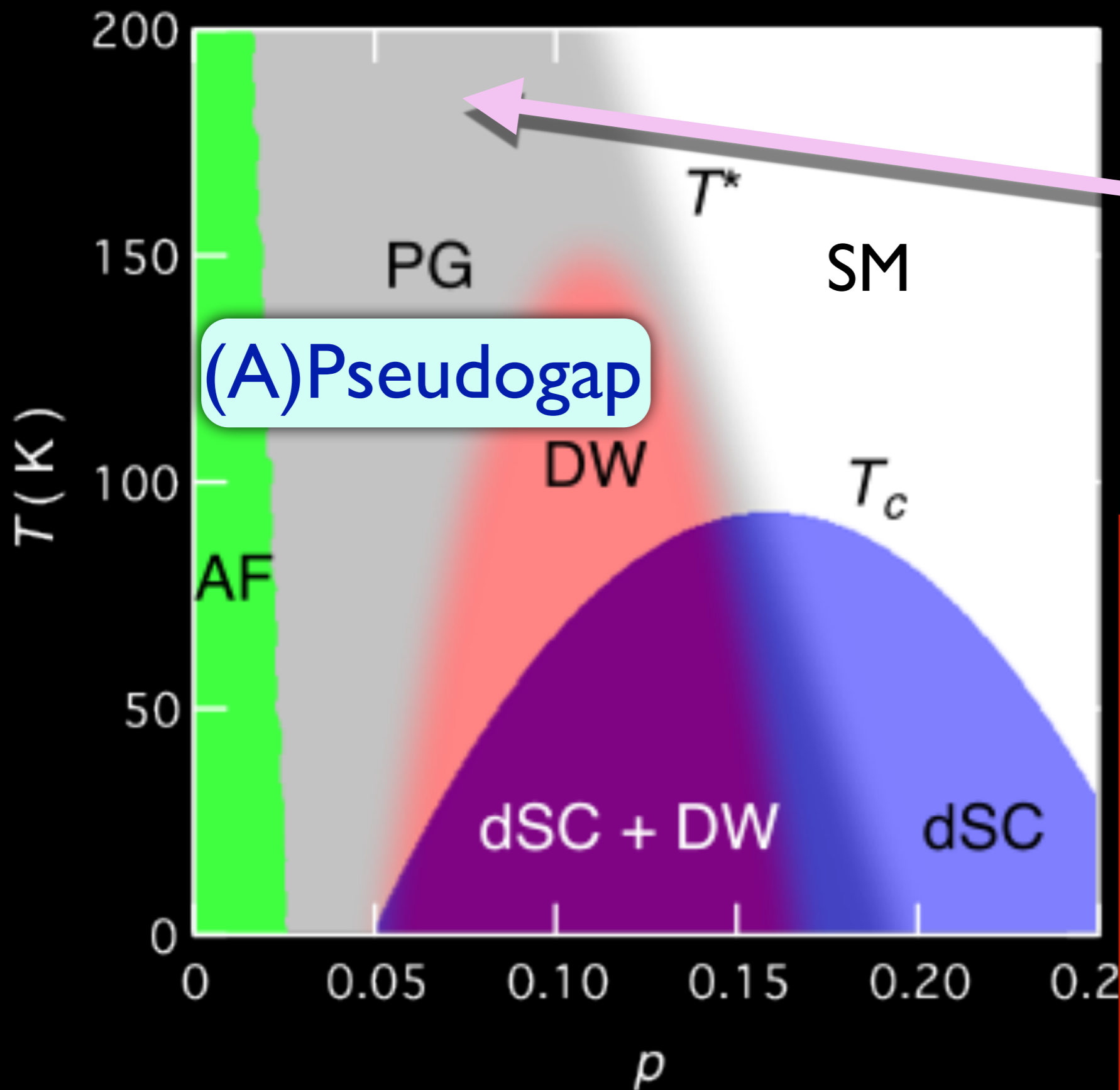
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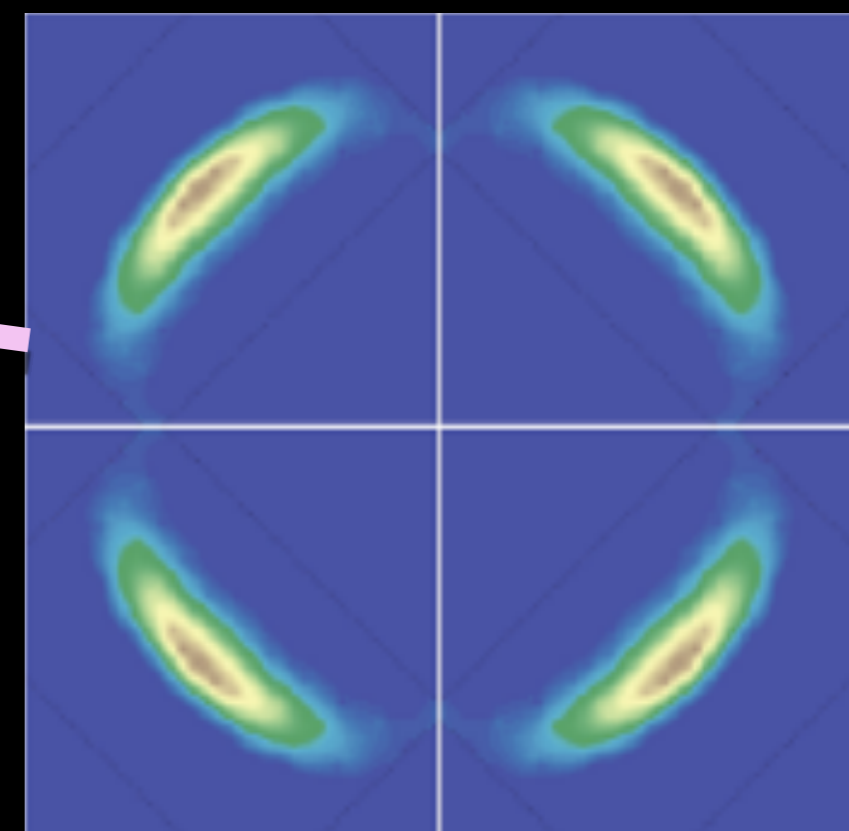
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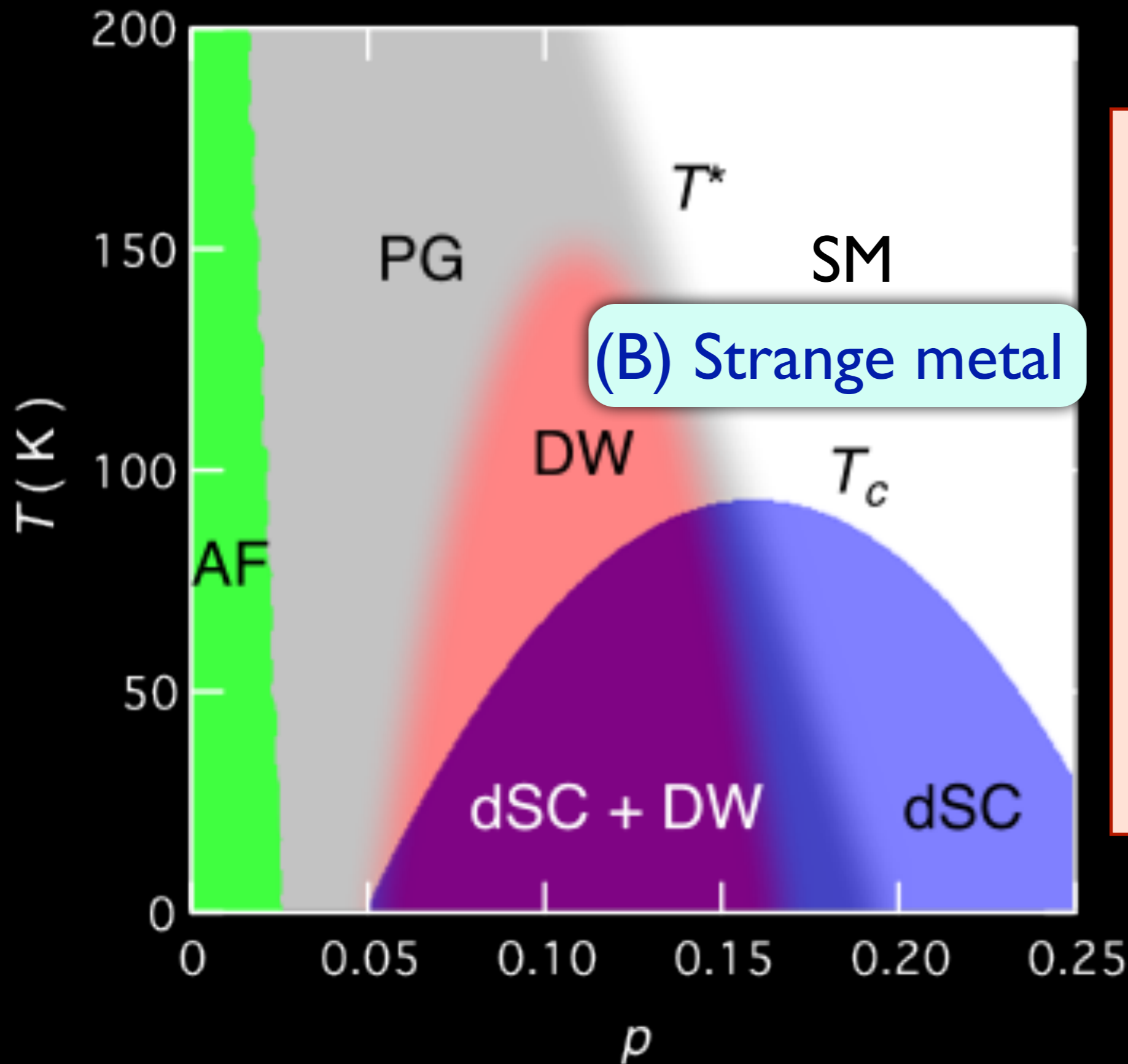


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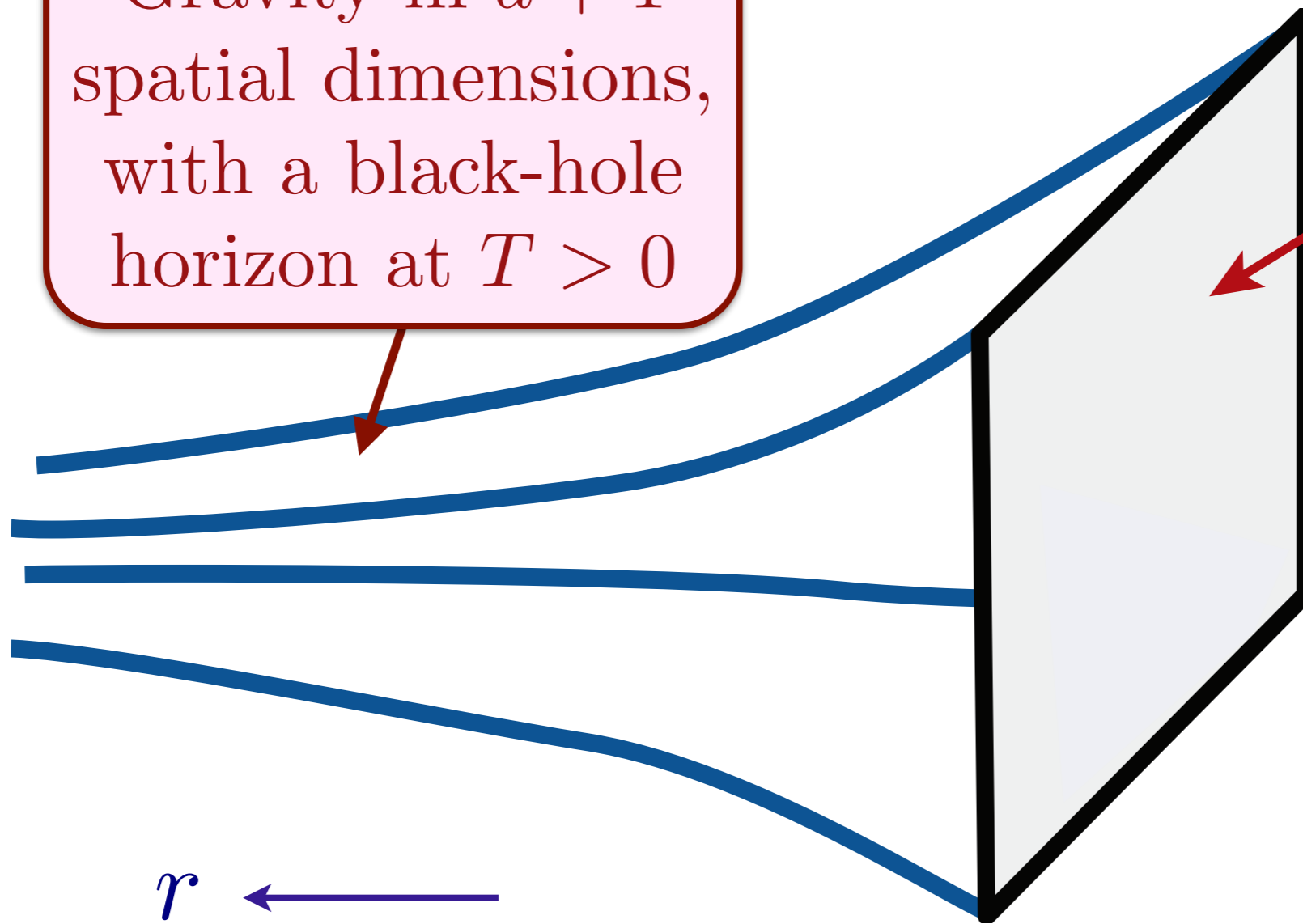
Strange metal:
Remarkable metallic state with long-range entanglement, and no quasiparticles.

Progress has been made by analogies to solvable models in string theory of the quantum dynamics of charged black holes

Holography conformal field theory: AdS/CFT

Gravity in $d + 1$ spatial dimensions, with a black-hole horizon at $T > 0$

A CFT in d spatial dimensions



r ←
Emergent
“holographic”
dimension

Solvable models which have led to new insights on the transport properties of quantum matter without quasiparticles

Holography of a strange metal: a charged black hole

Horizon of a charged black hole

A strange metal at density $\langle Q \rangle$

Electric flux

$\langle Q \rangle$
 $\neq 0$

$$\mathcal{E}_r = \langle Q \rangle$$

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Emergent
“holographic”
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$$\mathcal{E}_r = \langle Q \rangle$$

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