Observation of the Yamaji effect in a cuprate and FL* theory of the pseudogap

HQI-RIKEN 2nd Joint Workshop on Quantum Science
Harvard University
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Subir Sachdev

PHYSICS
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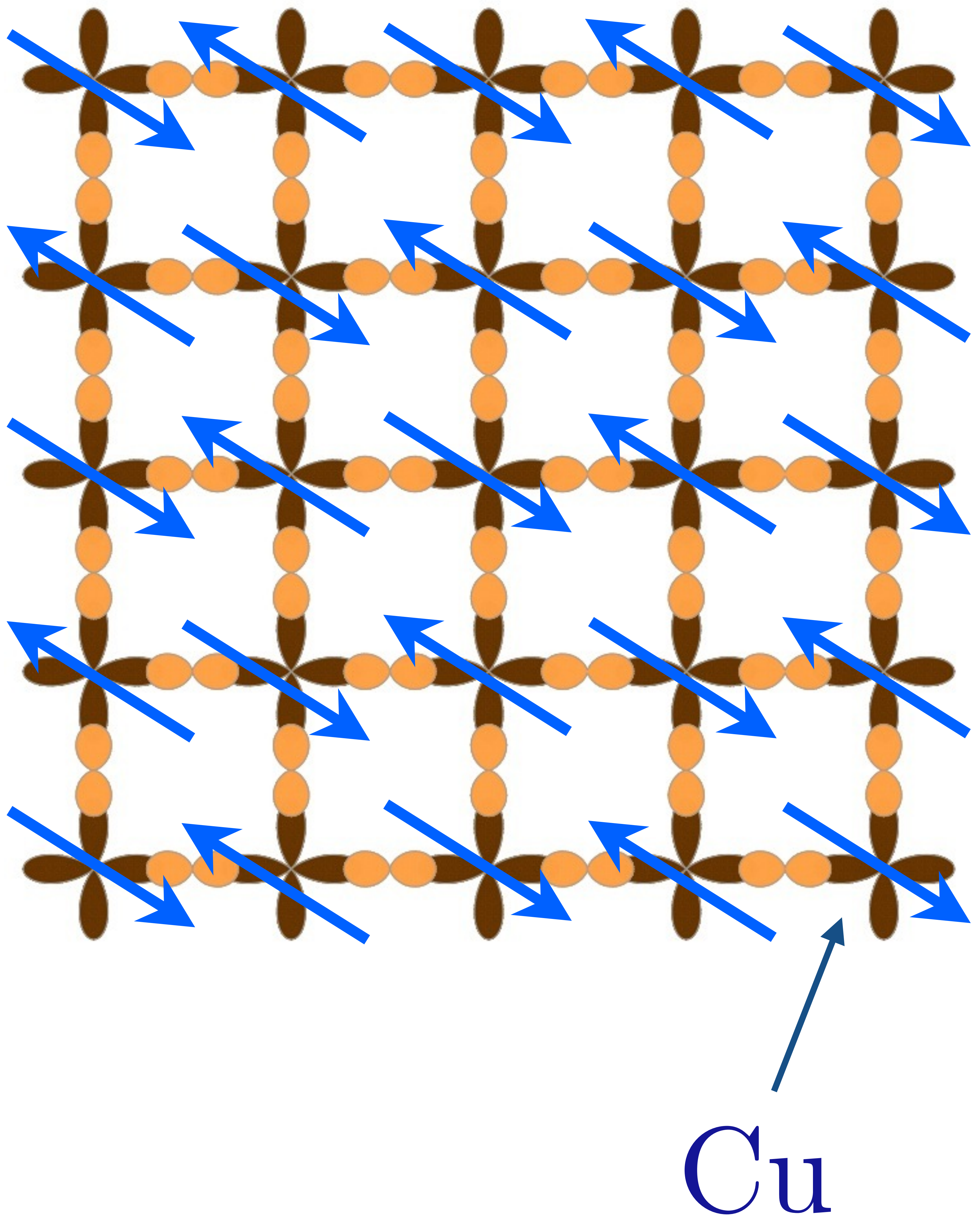
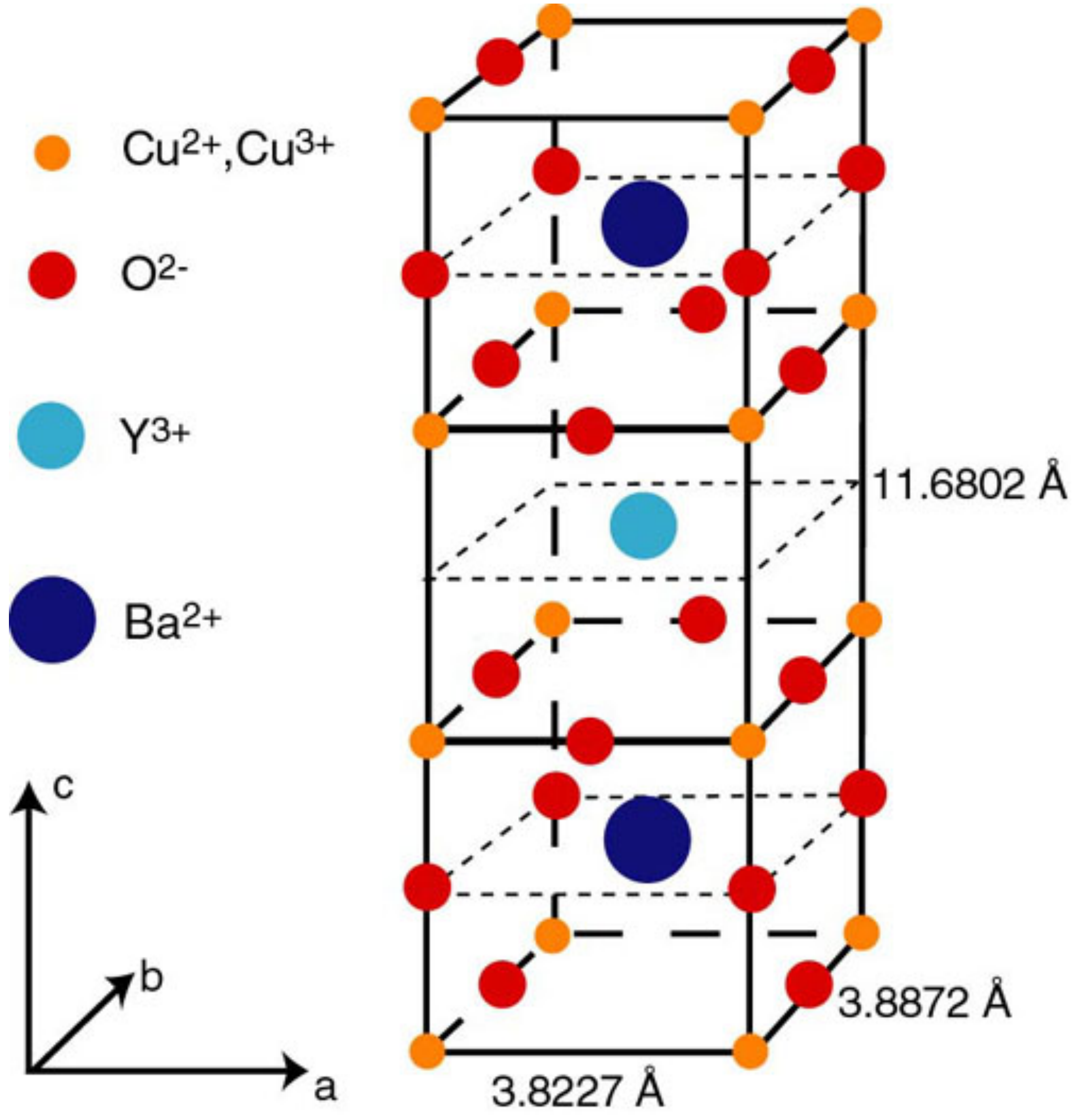
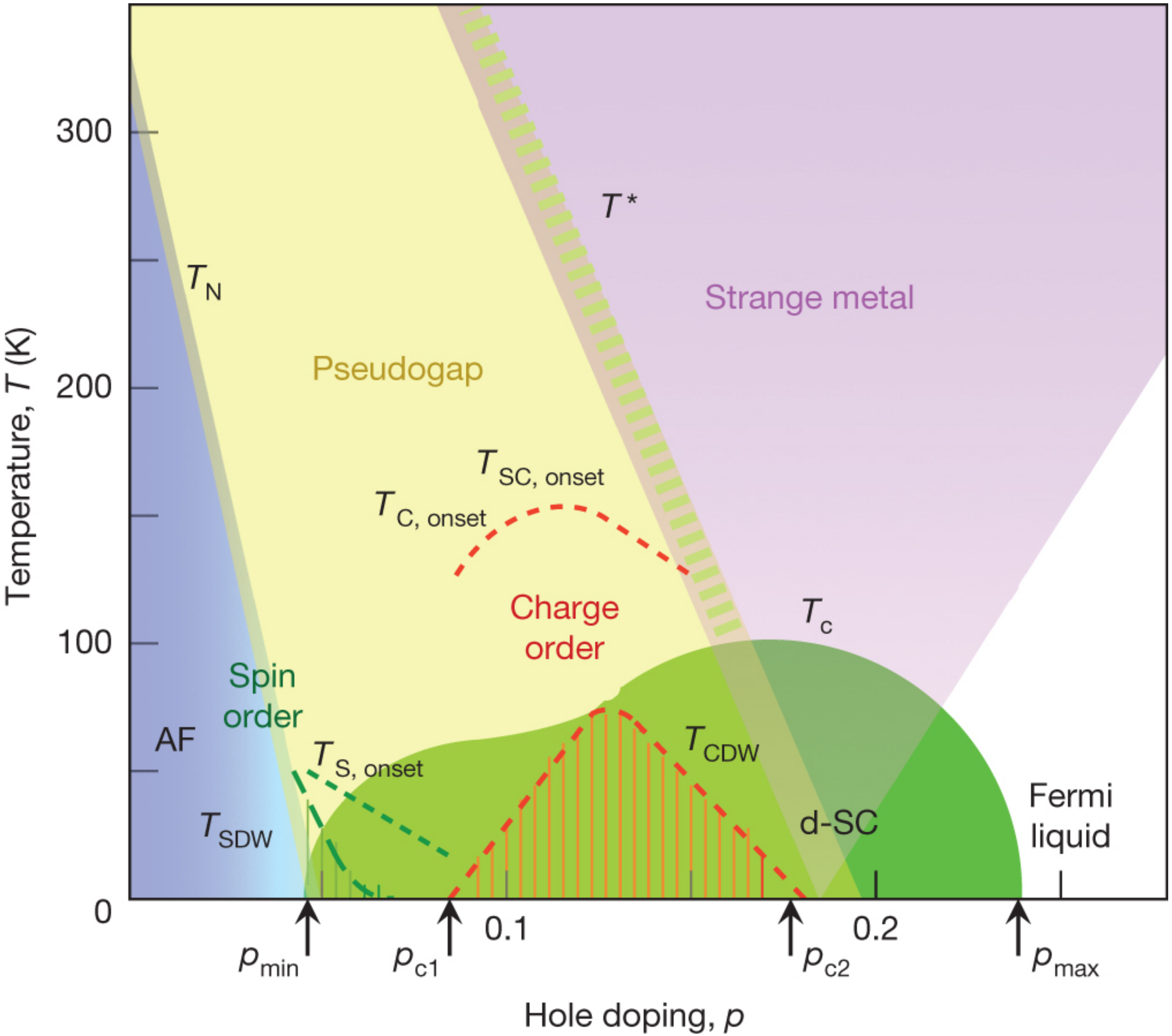
Antiferromagnetic insulator at a density of one electron per Cu

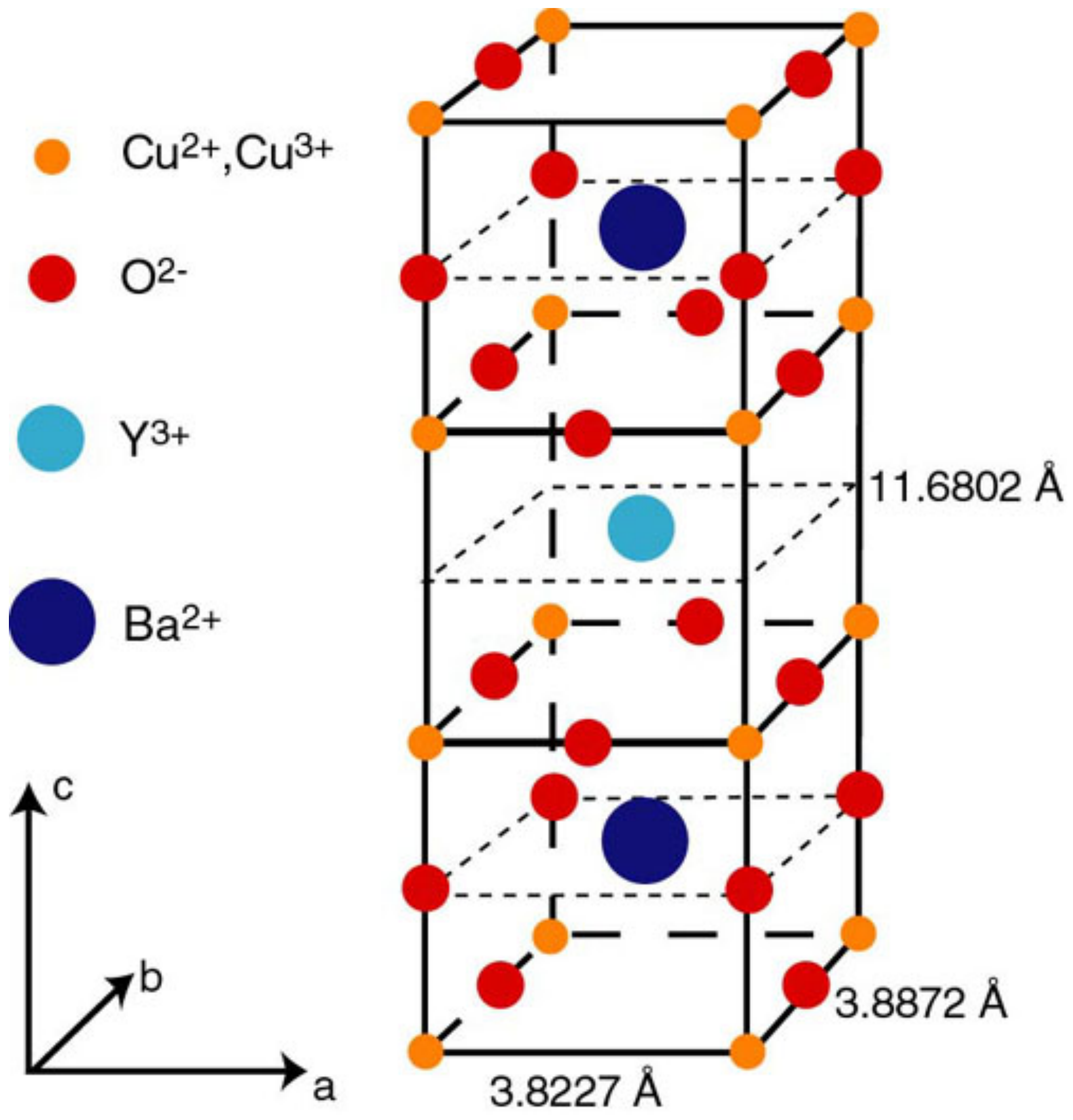




$YBa_2Cu_3O_{6+x}$

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)





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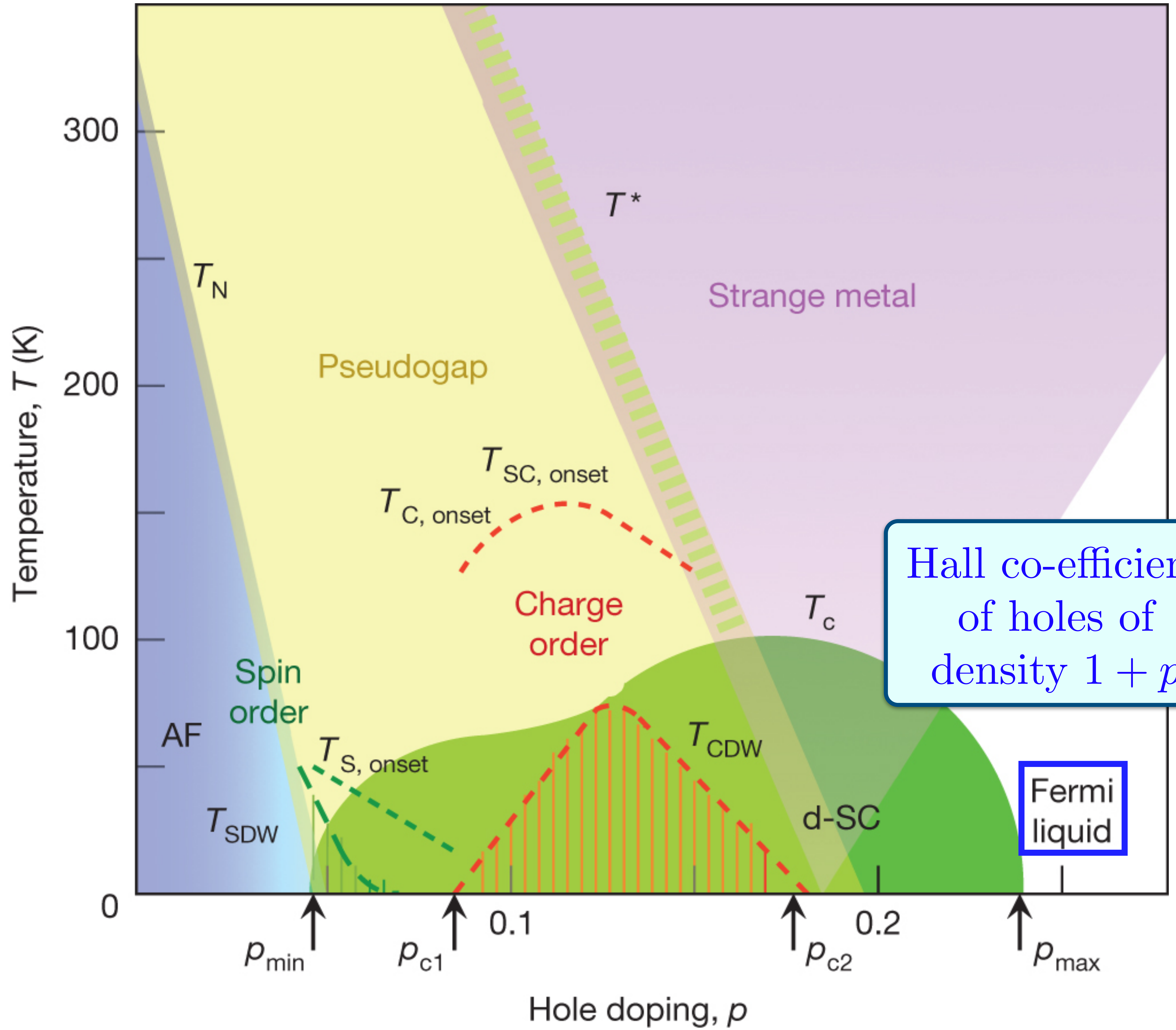
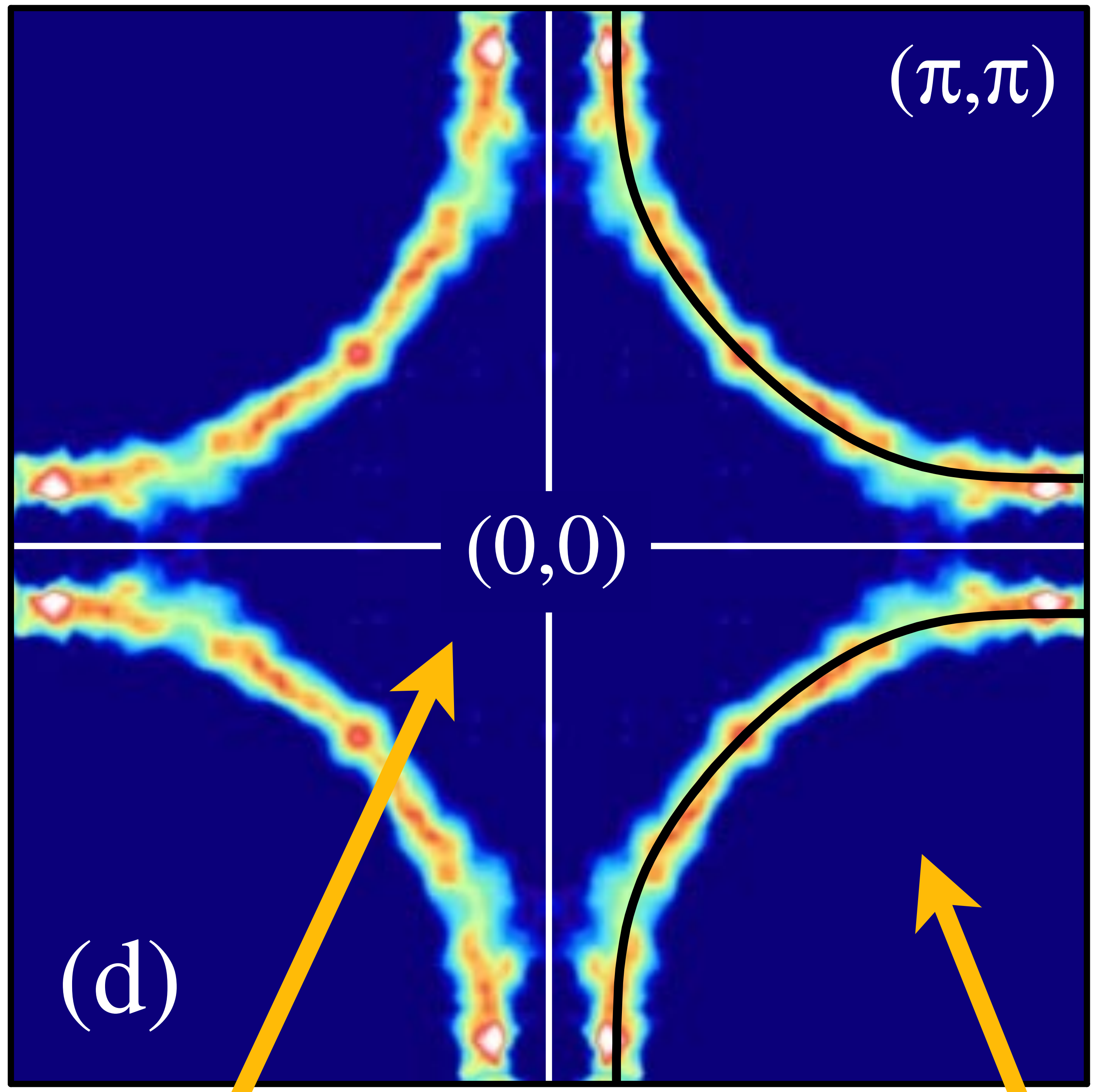


Hall co-efficient of holes of density $1+p$



1-p electrons

1+p holes

Luttinger, 1960: Area enclosed by the Fermi surface is the same as that for free fermions *with the same symmetry.*

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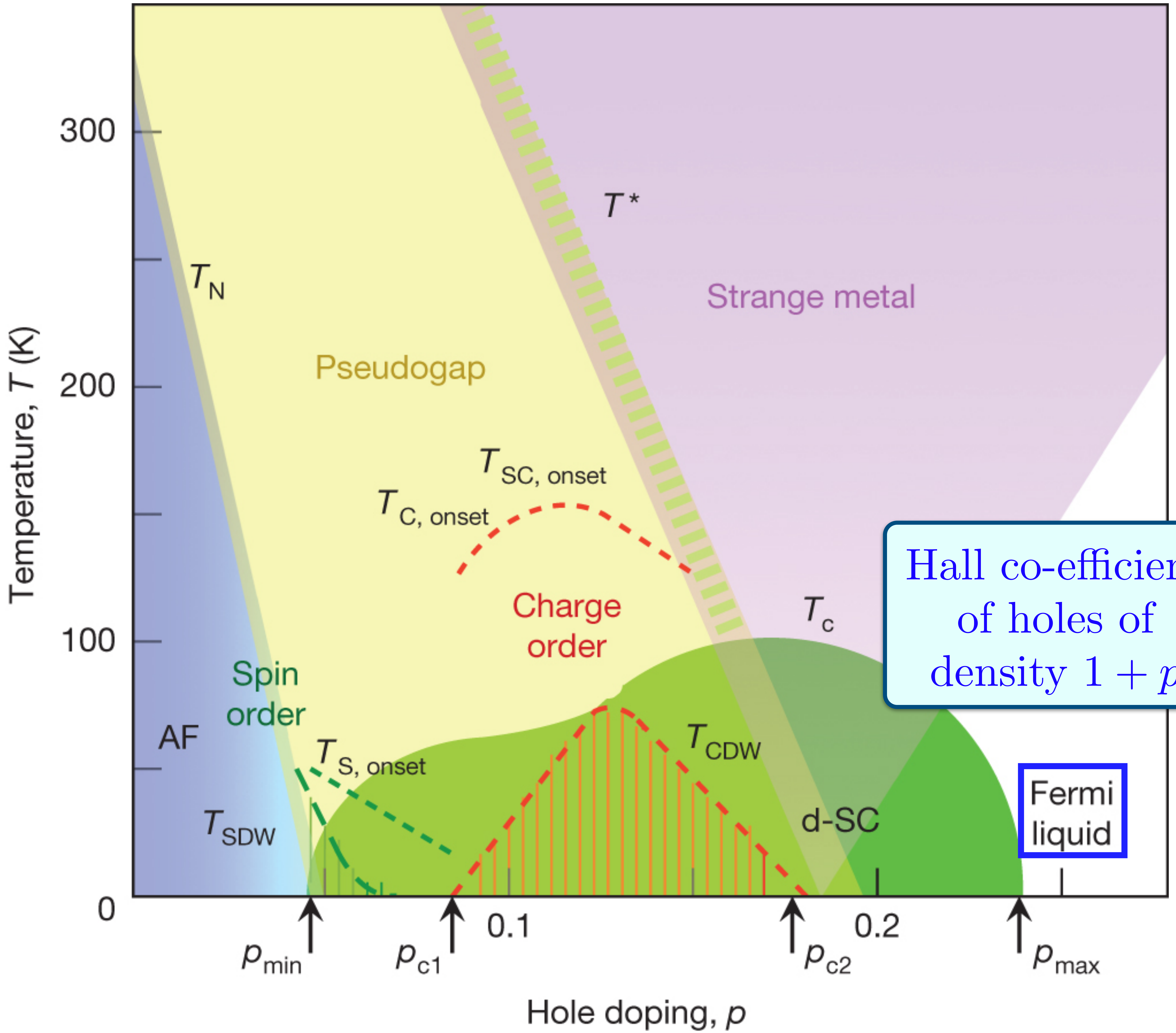

Hall co-efficient of holes of density $1 + p$

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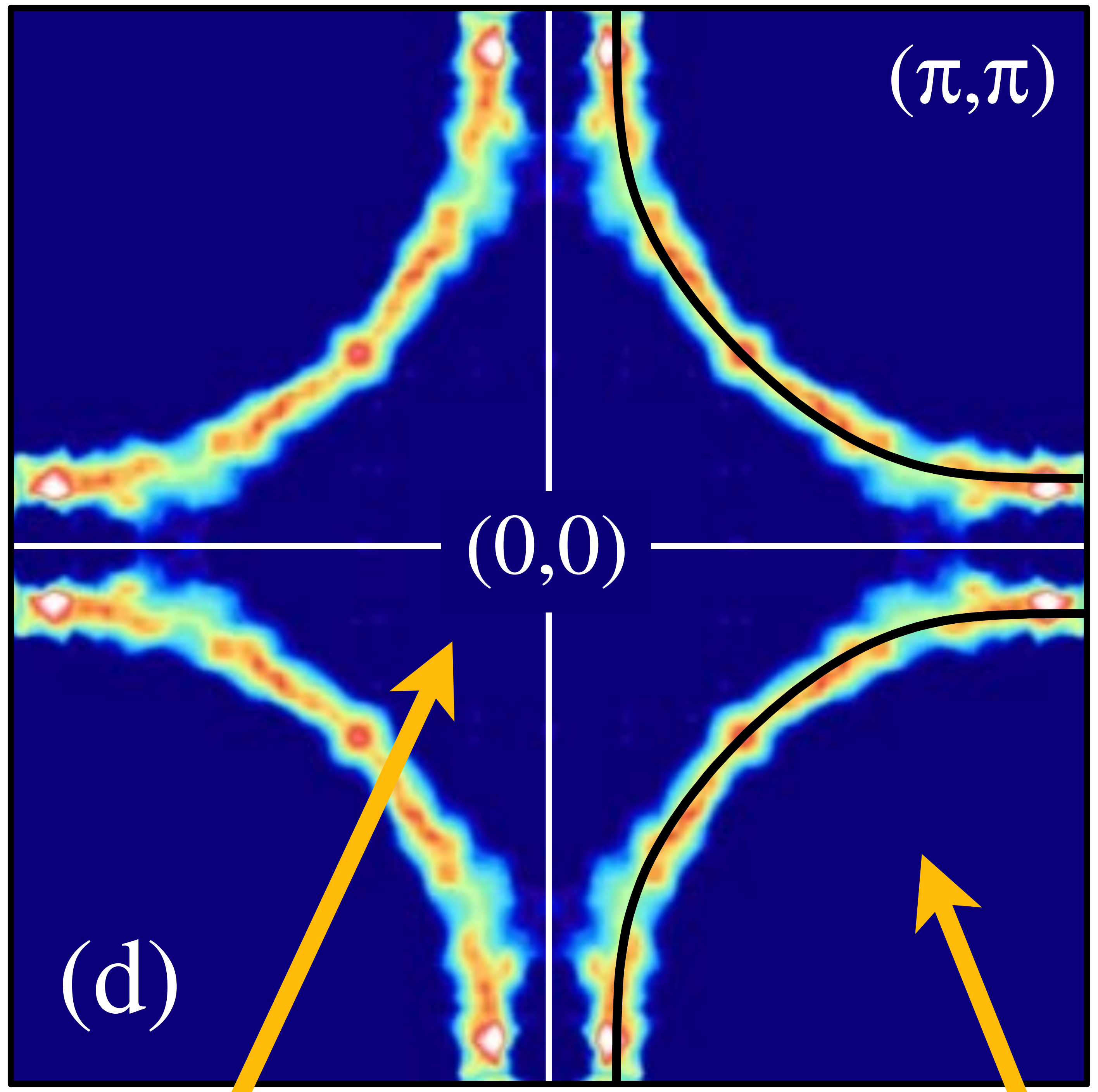

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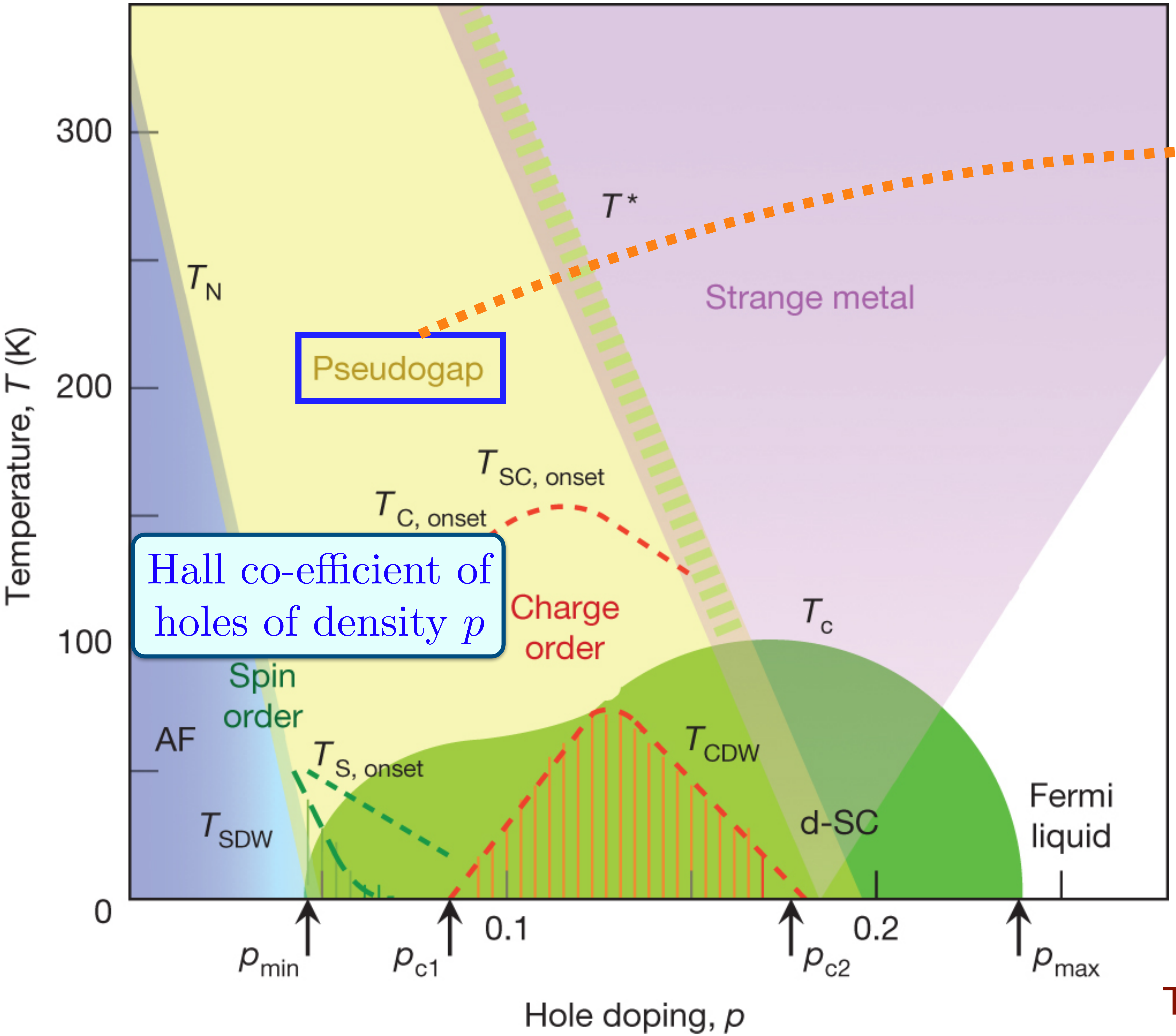
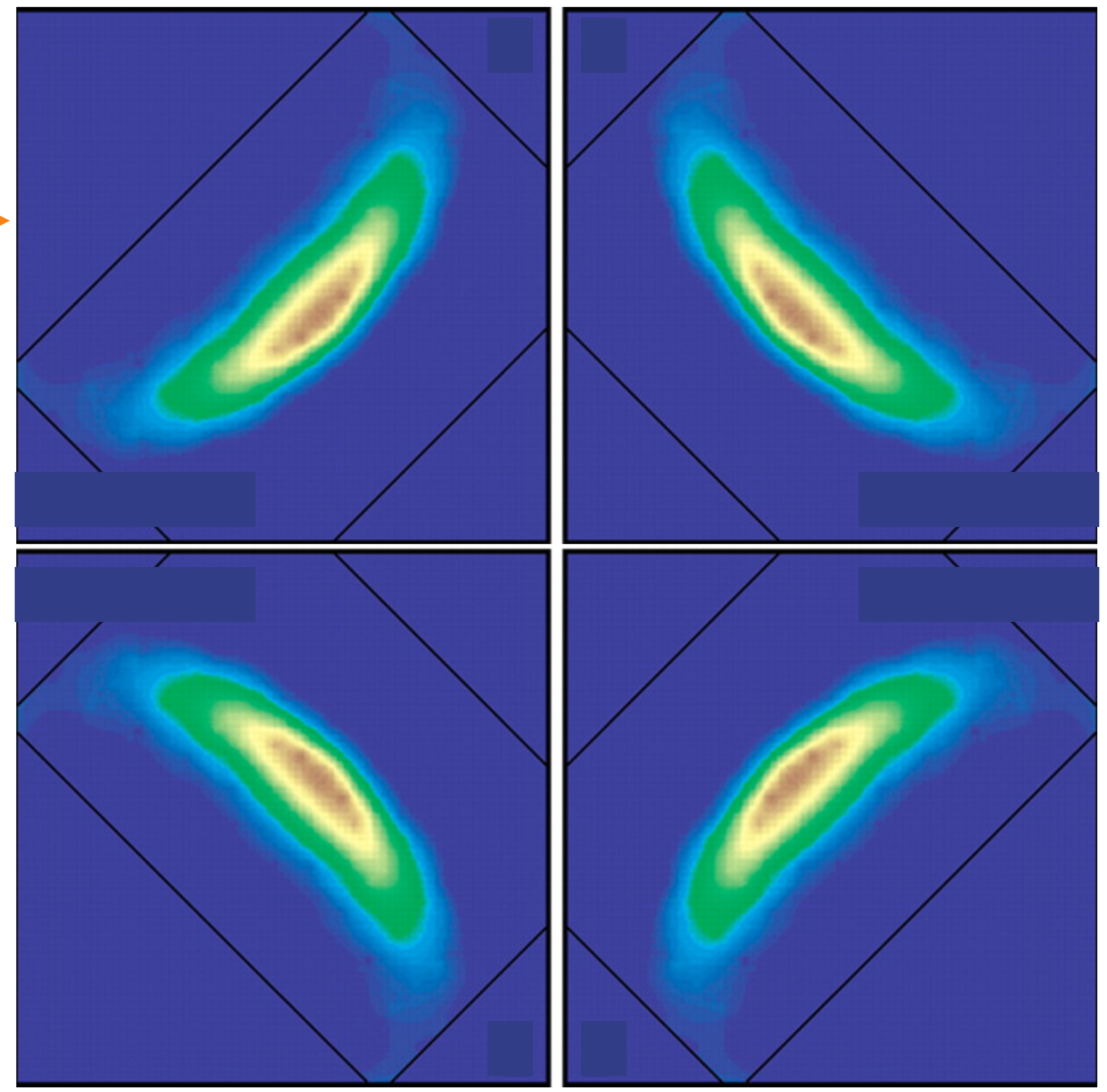
Luttinger, 1960: Area enclosed by the Fermi surface is the same as that for free fermions *with the same symmetry*.

Oshikawa, 2000: Area constrained by a 't Hooft anomaly of global U(1) and translations

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



Kyle M. Shen *et al.*, Science **307**, 901 (2005)



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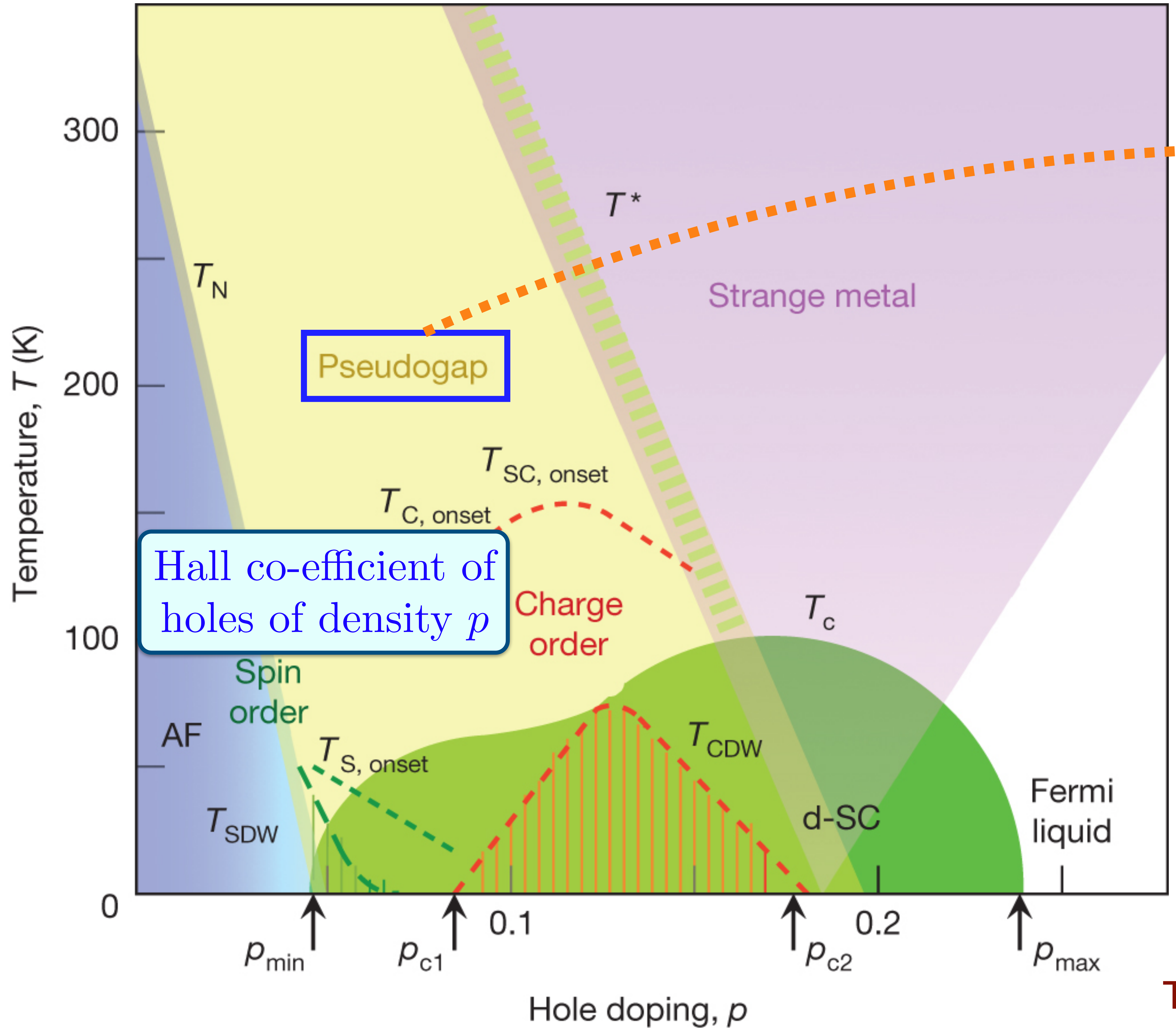
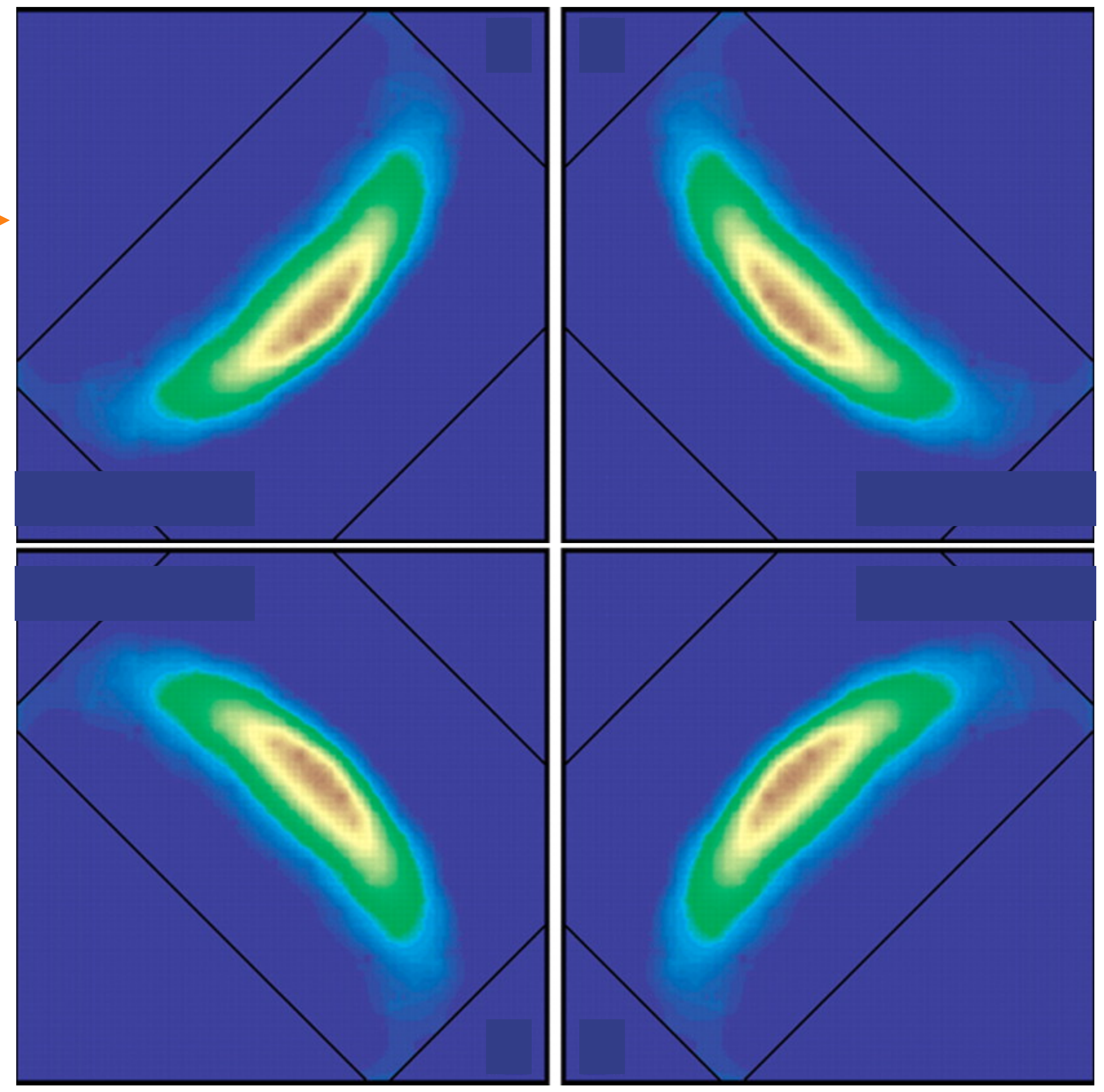




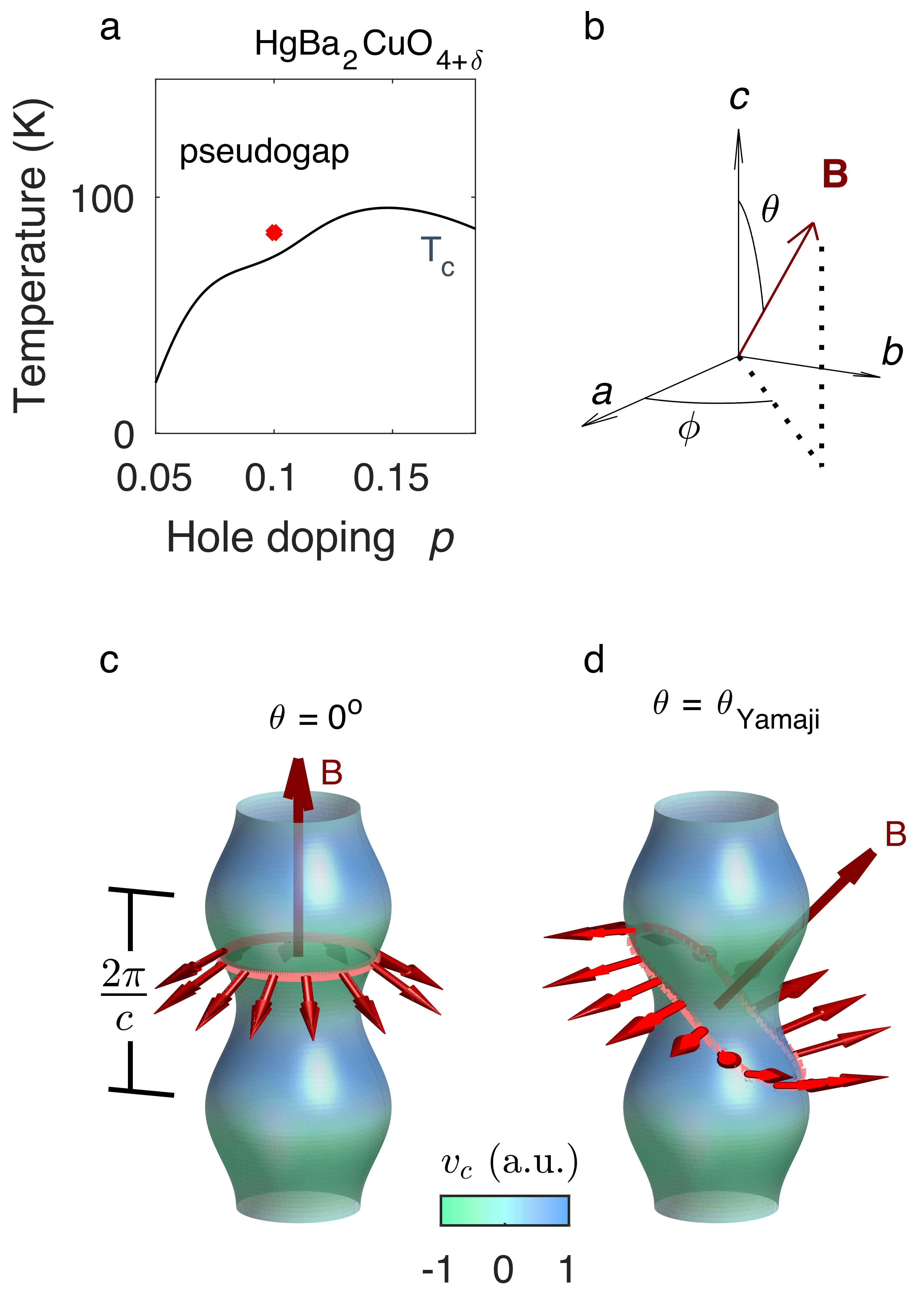
Will explain with a Fractionalized Fermi Liquid (FL*) which evades the Luttinger constraint by a *critical spin liquid*

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003)

Observation of the Yamaji effect in a cuprate superconductor

Mun K. Chan[1], Katherine A. Schreiber[1], Oscar E. Ayala-Valenzuela[1], Eric D. Bauer[2], Arkady Shekhter[1] & Neil Harrison[1]

nature physics
arXiv:2411.10631
Published online: 16 September 2025



At the Yamaji angle, the orbits in the plane orthogonal to $\boldsymbol{B}$ have an area which is independent of momentum in the c direction, to first order in the hopping along the c direction.

K. Yamaji JPSJ **58**, 1520 (1989)

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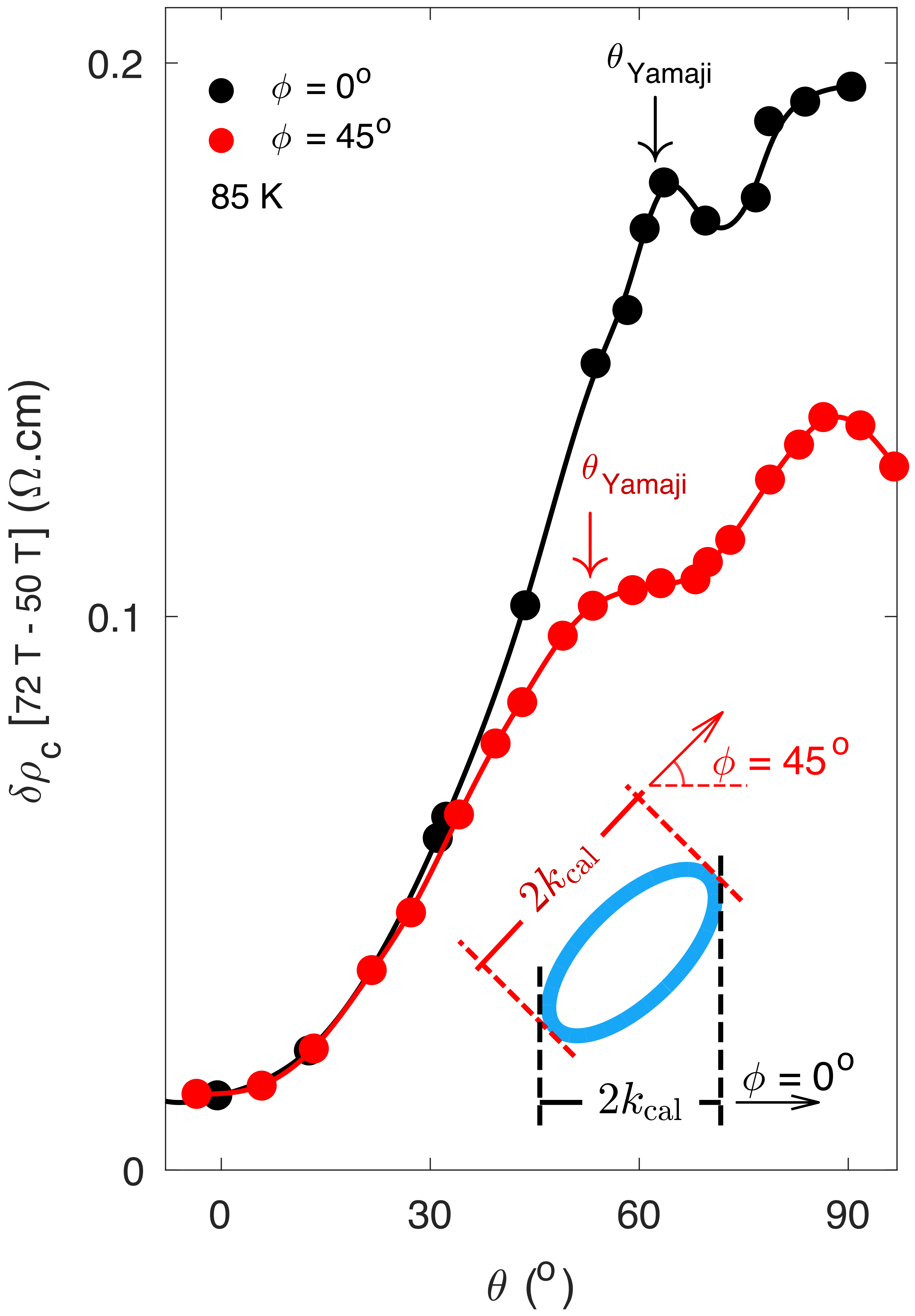
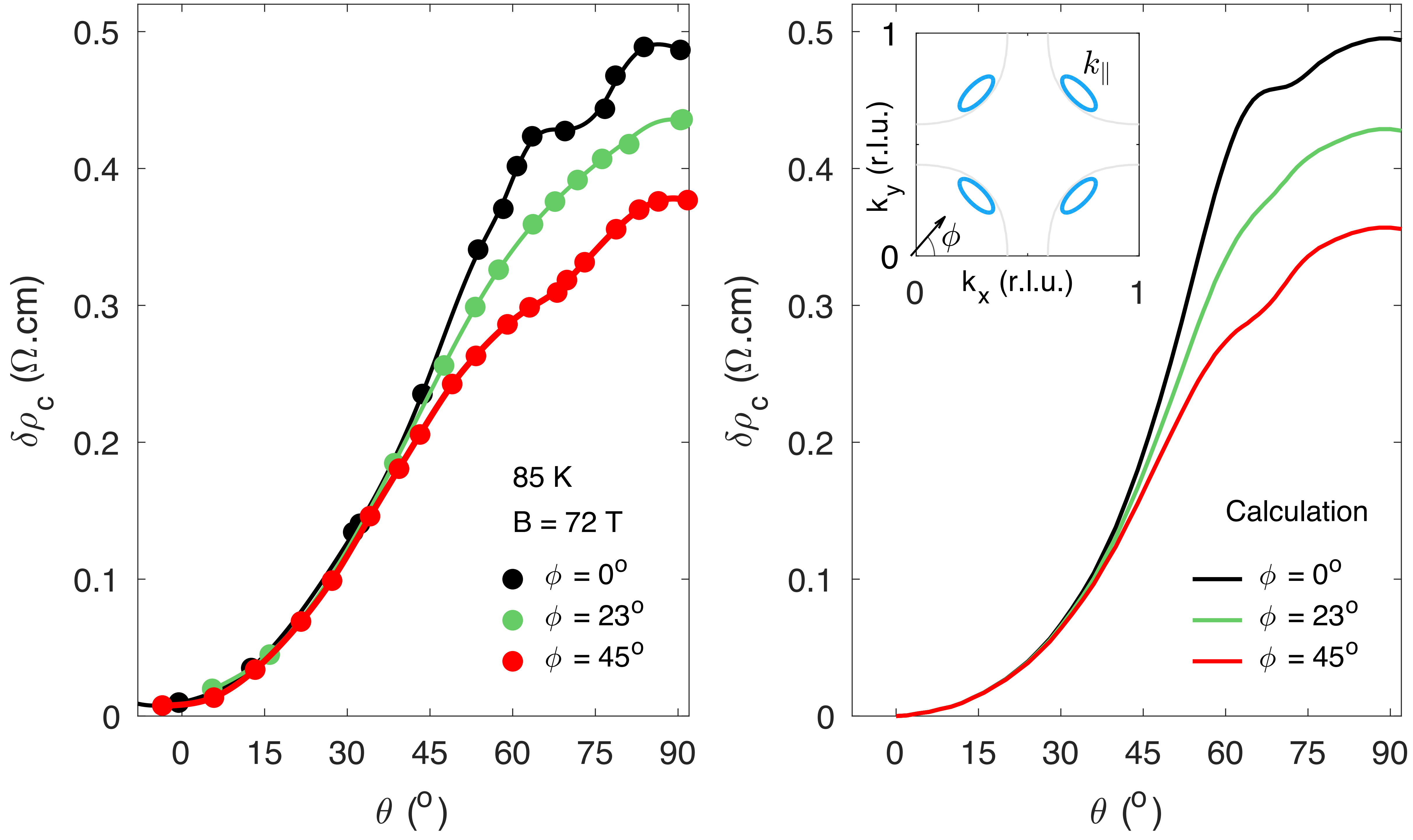


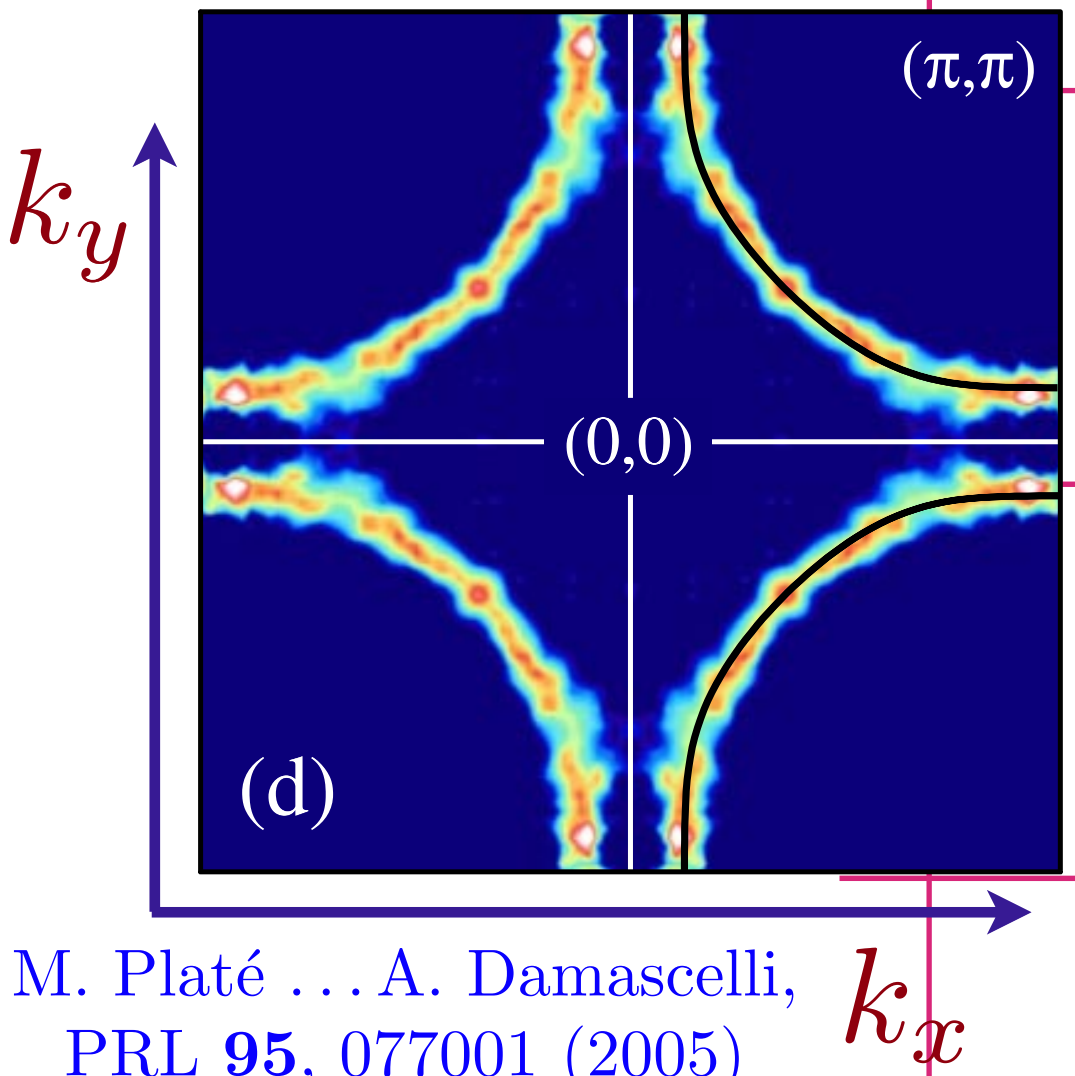


Doping
$p = 0.1$

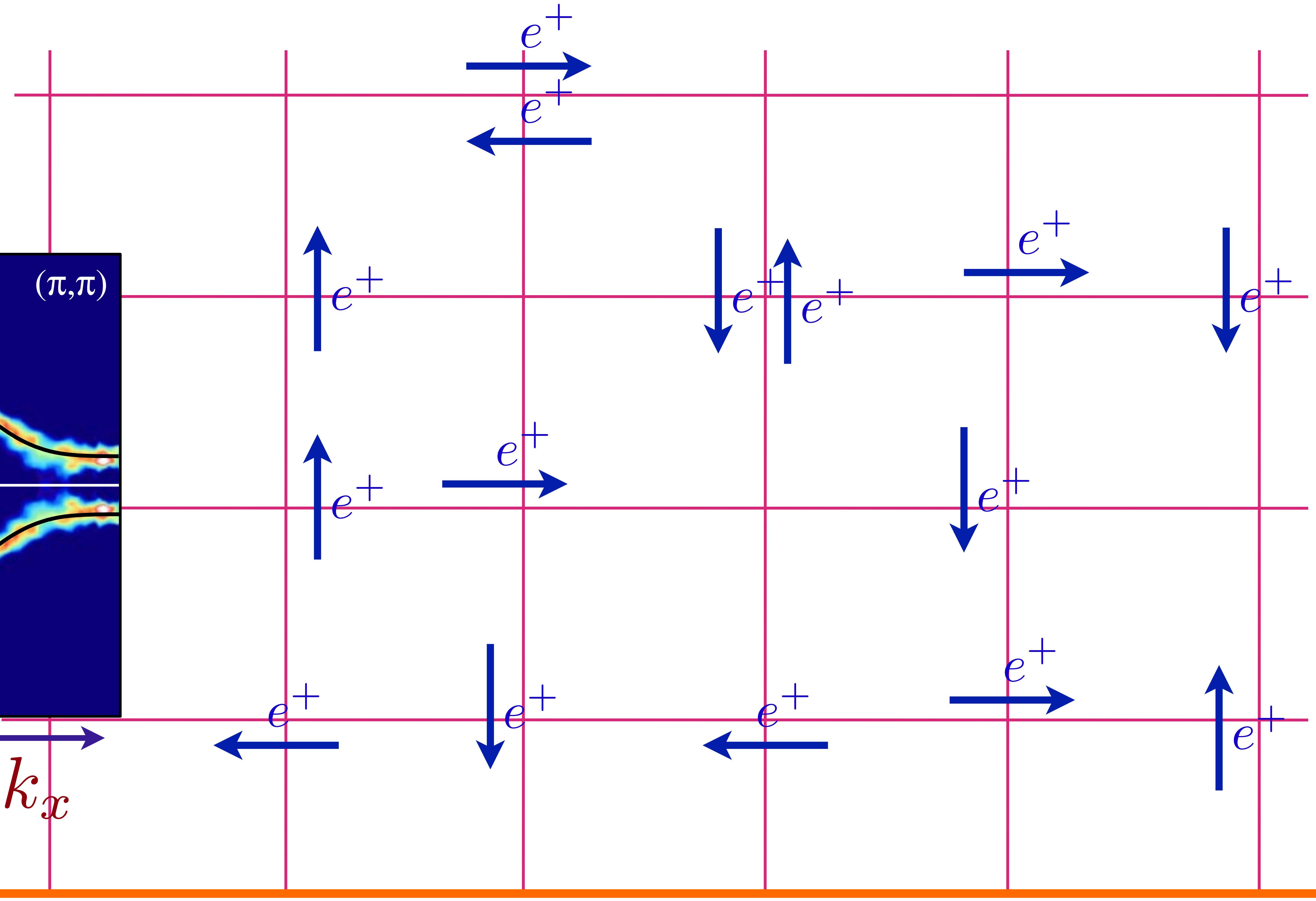
"The small size of the pockets determined from the Yamaji effect is … approximately 1.3% of the Brillouin zone area"

Metals obtained by doping Mott insulators

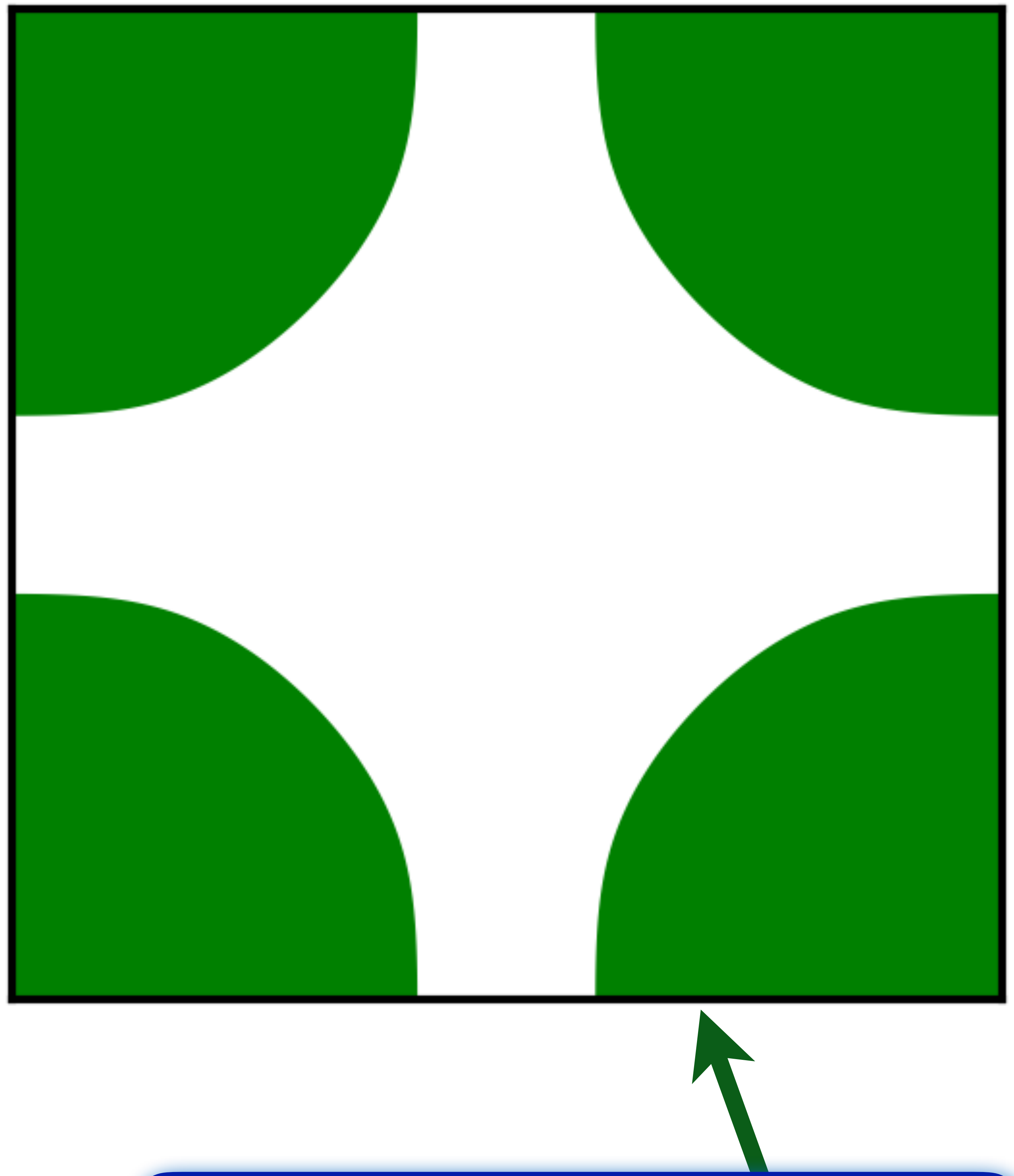
Ordinary metal



M. Platé ... A. Damascelli, PRL **95**, 077001 (2005)



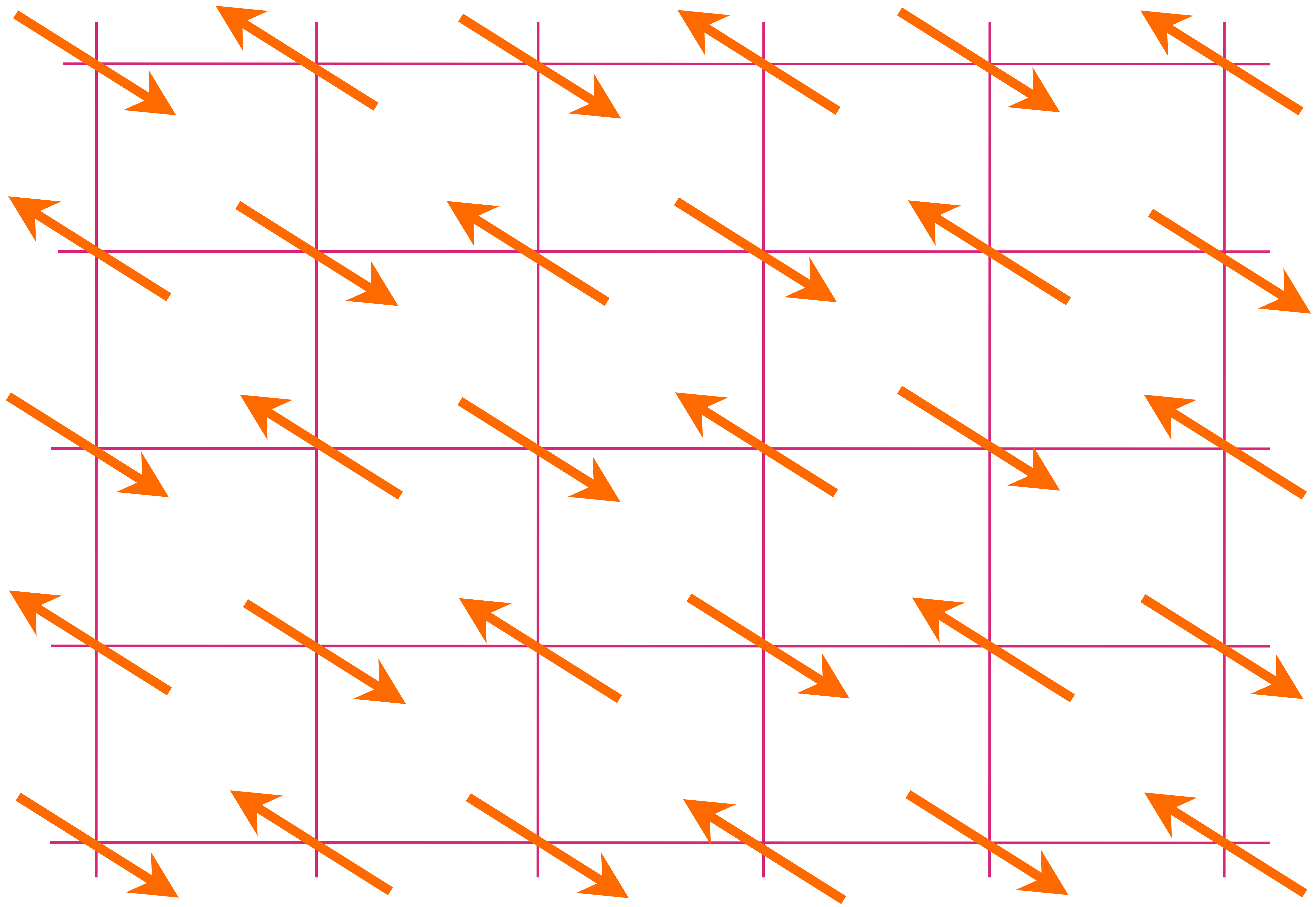
Luttinger area.
No broken symmetry



Area $(1+p)/2$

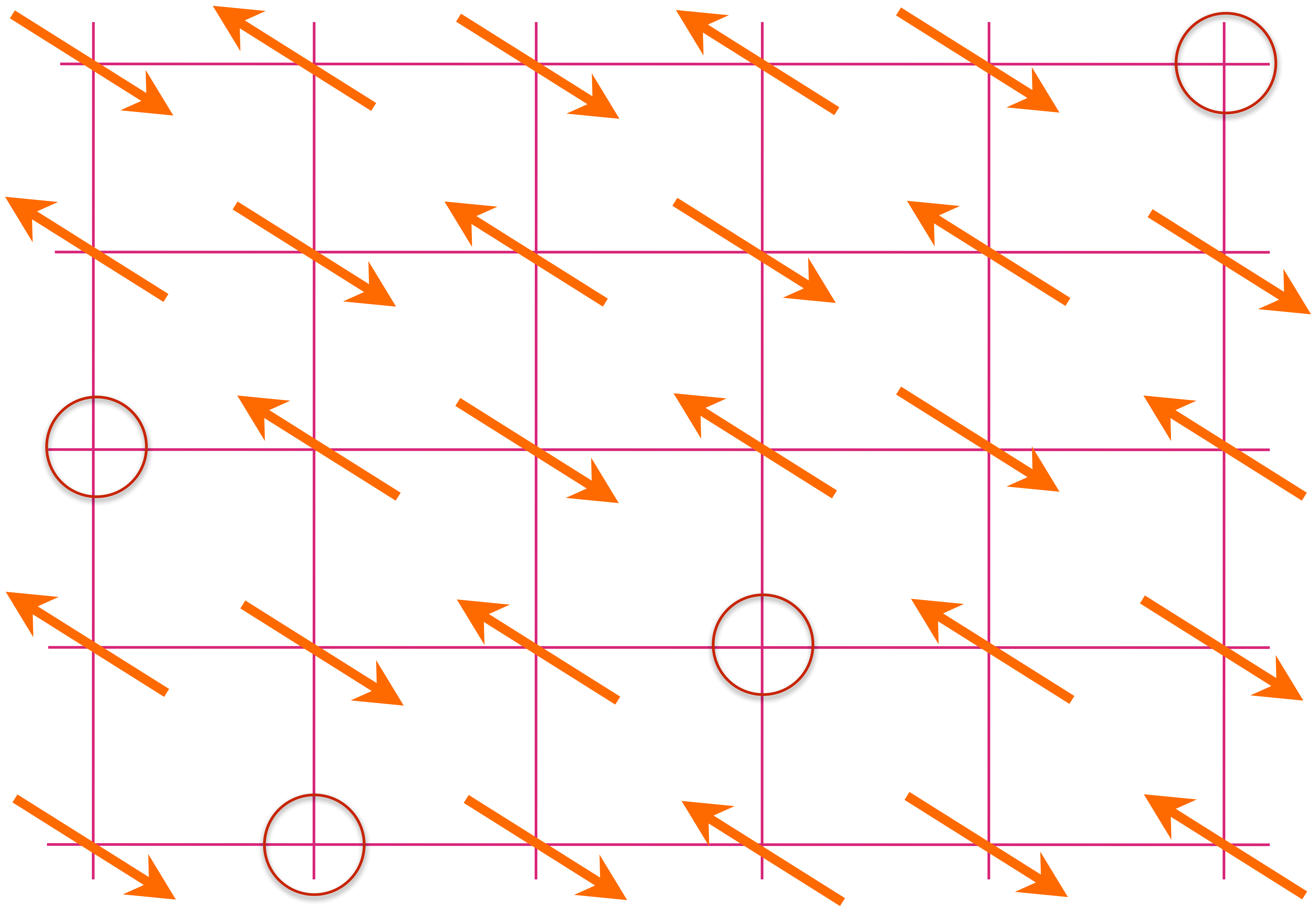
At large p, we obtain a gas of nearly free fermionic holes of density $1+p$ (relative to the filled band with 2 electrons per site)

Insulating antiferromagnet



Doping an insulating antiferromagnet with holes of density p

AF metal



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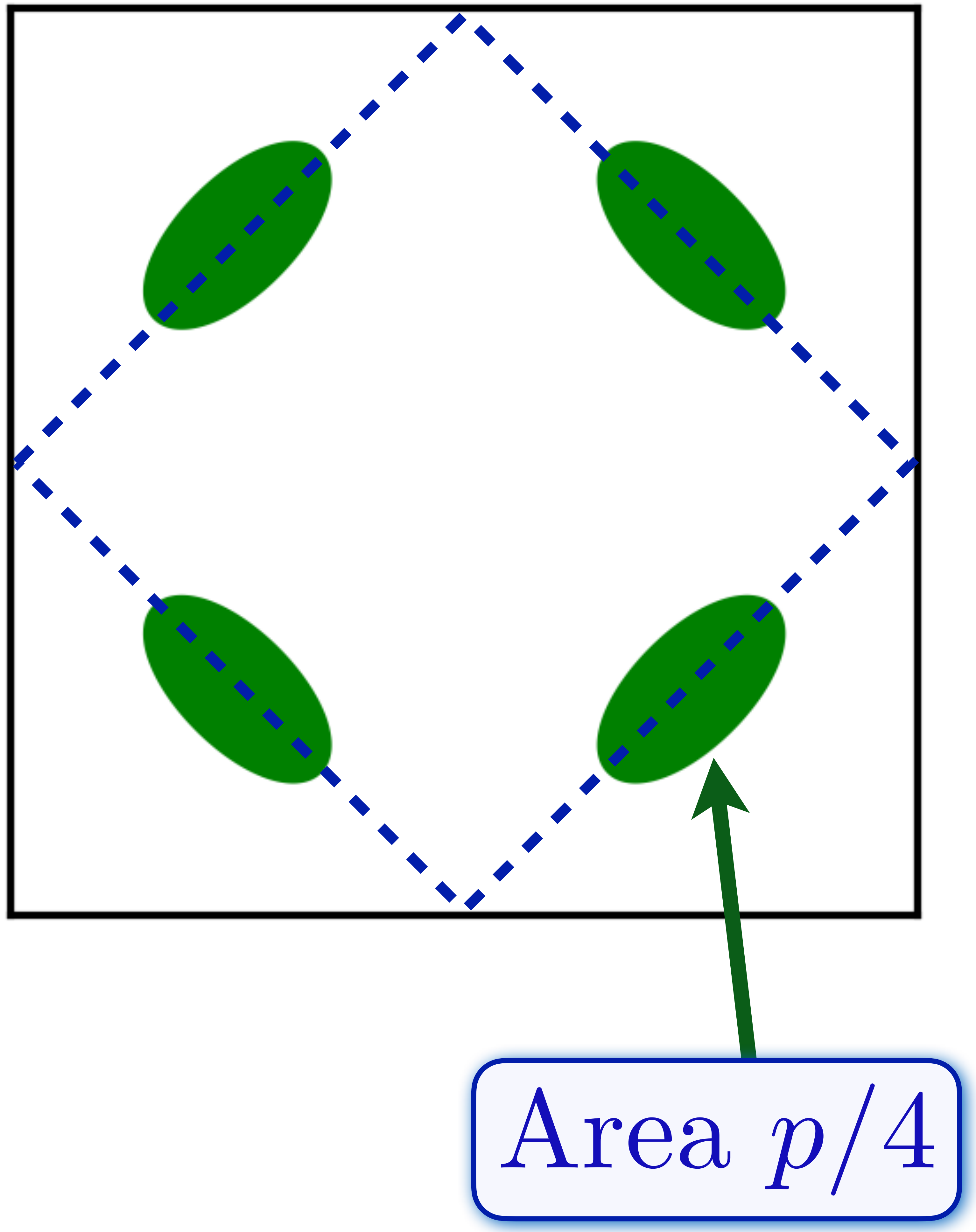
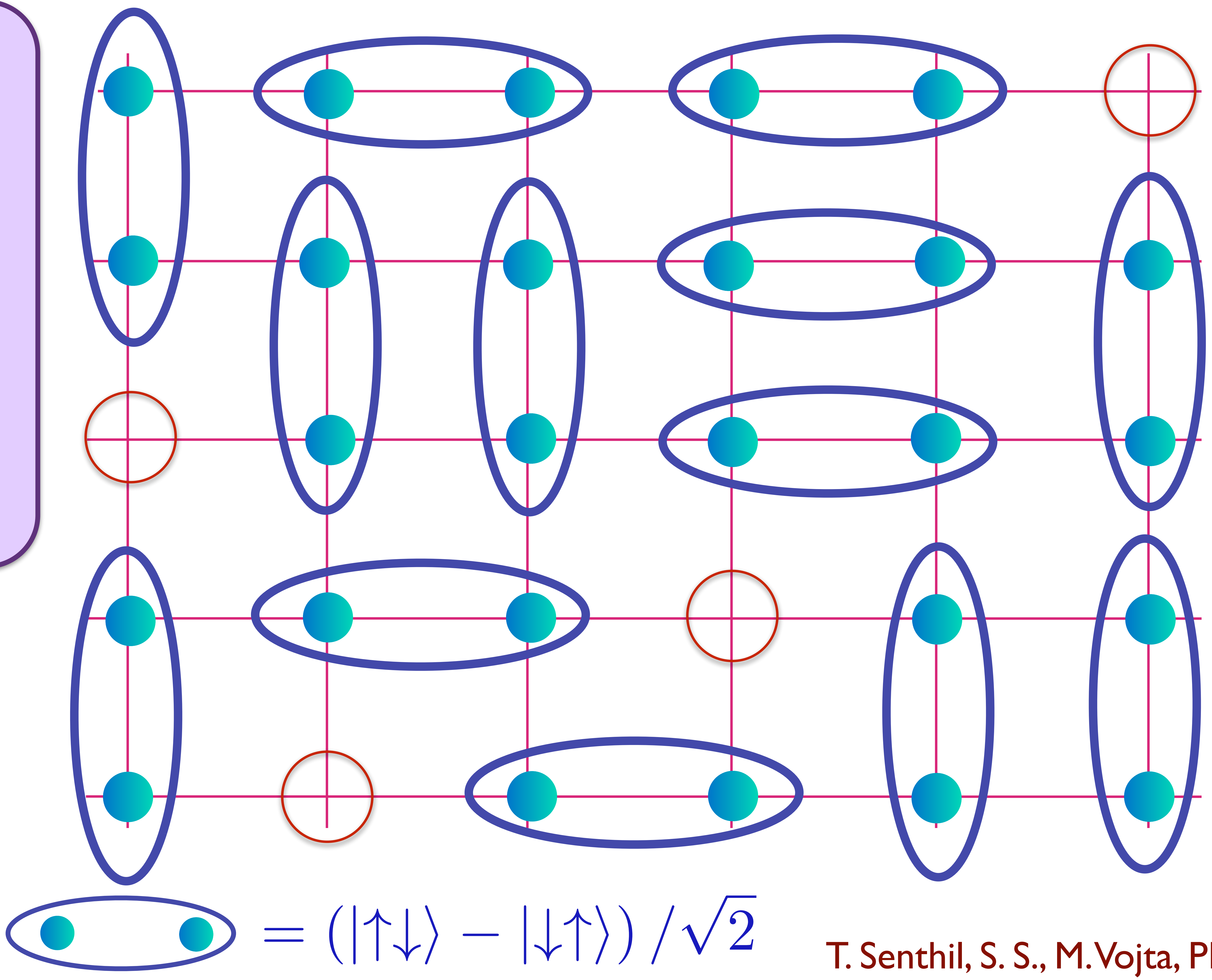


Doping an insulating antiferromagnet with holes of density p

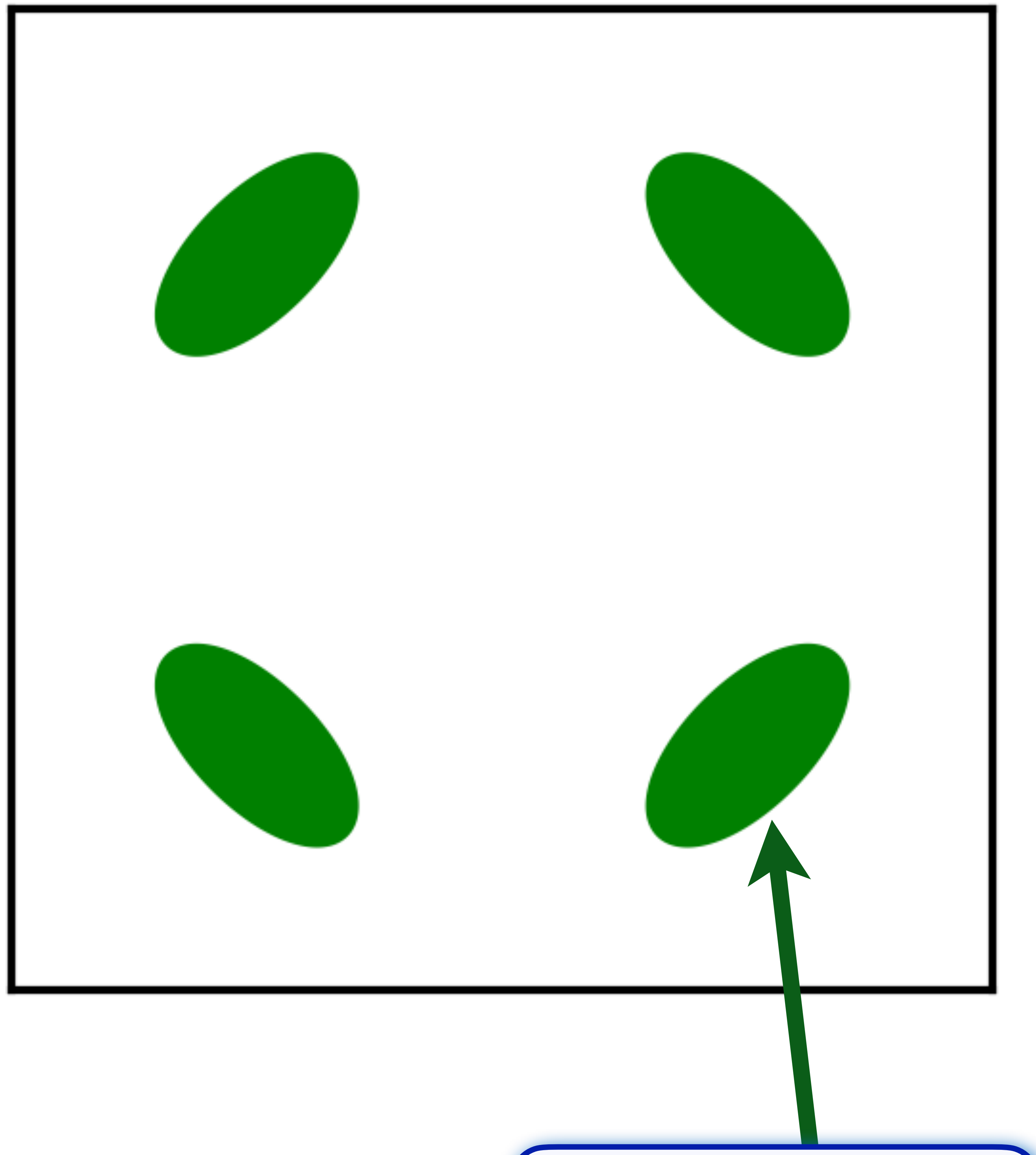
Holon metal

Spin liquid with density p of spinless, charge +e "holons".



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

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



Area $p/4$

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003);
R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007);
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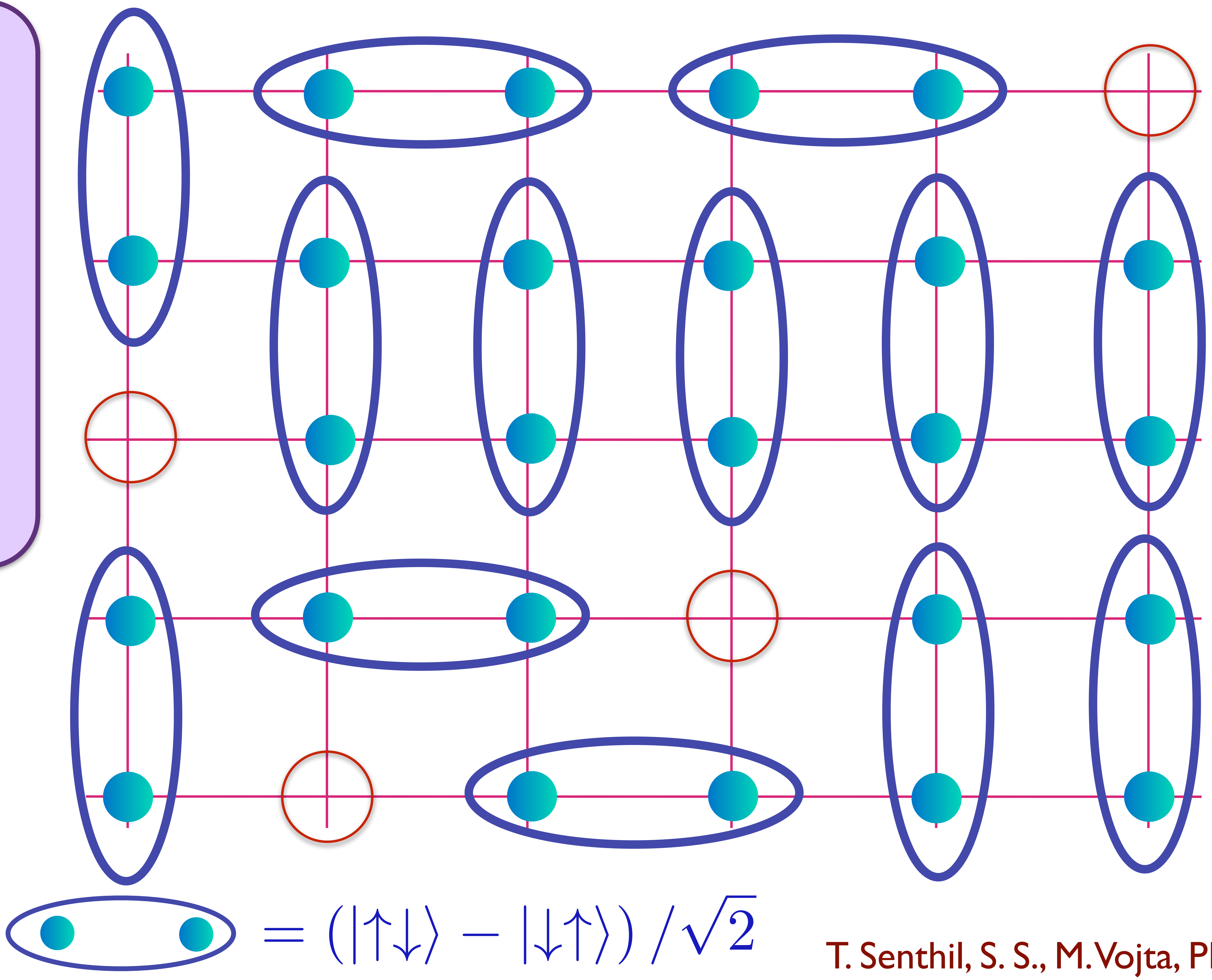

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

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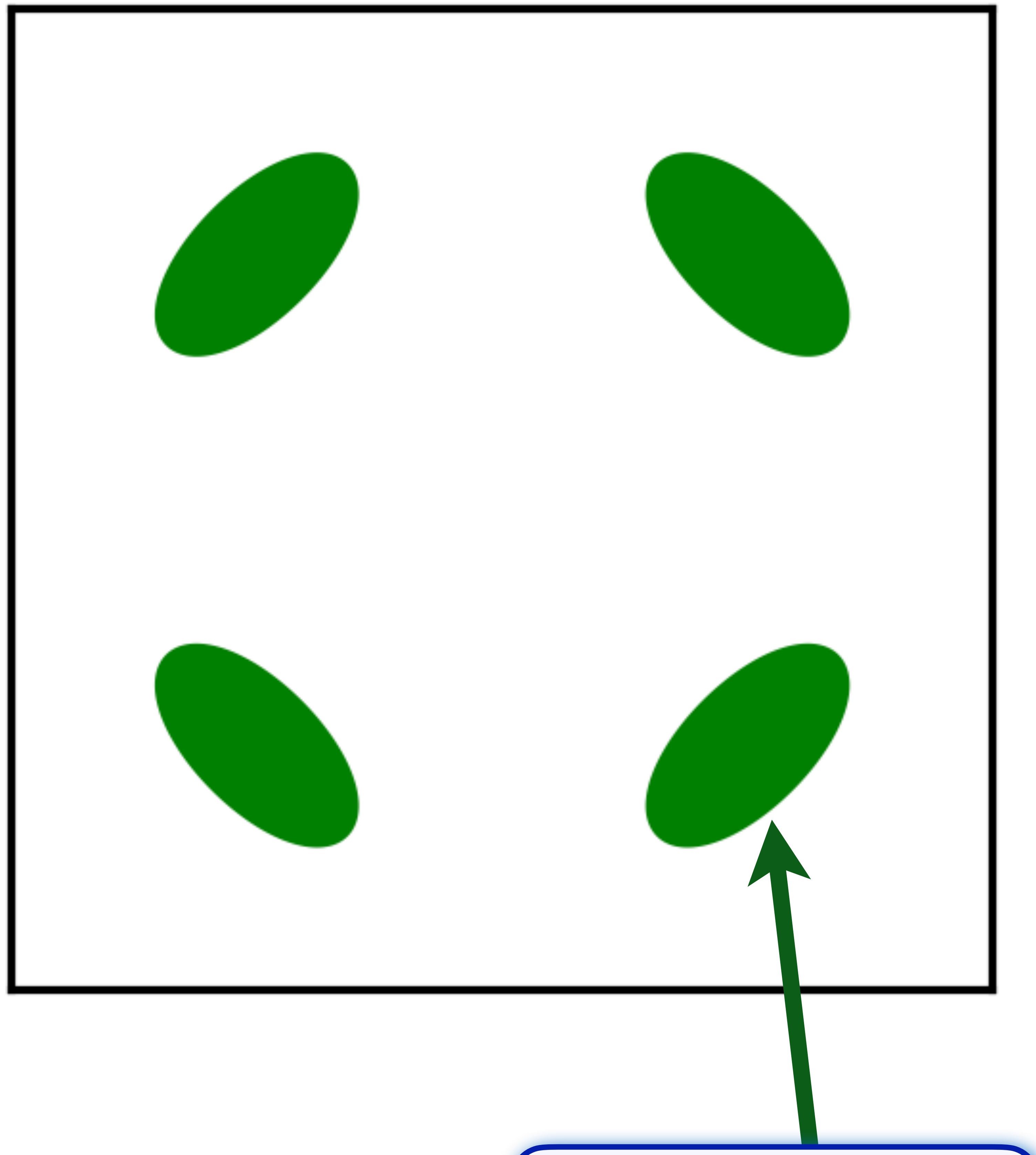

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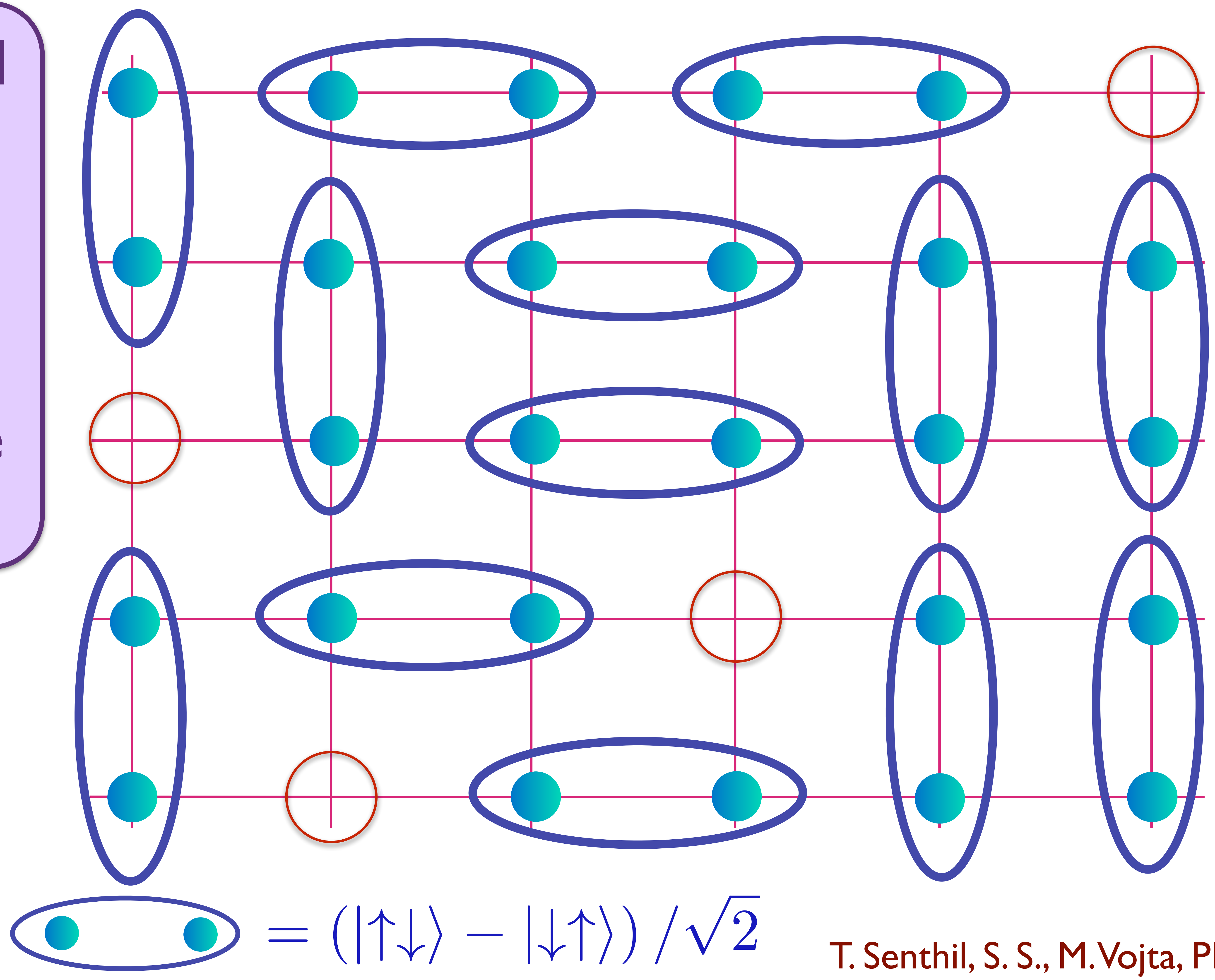

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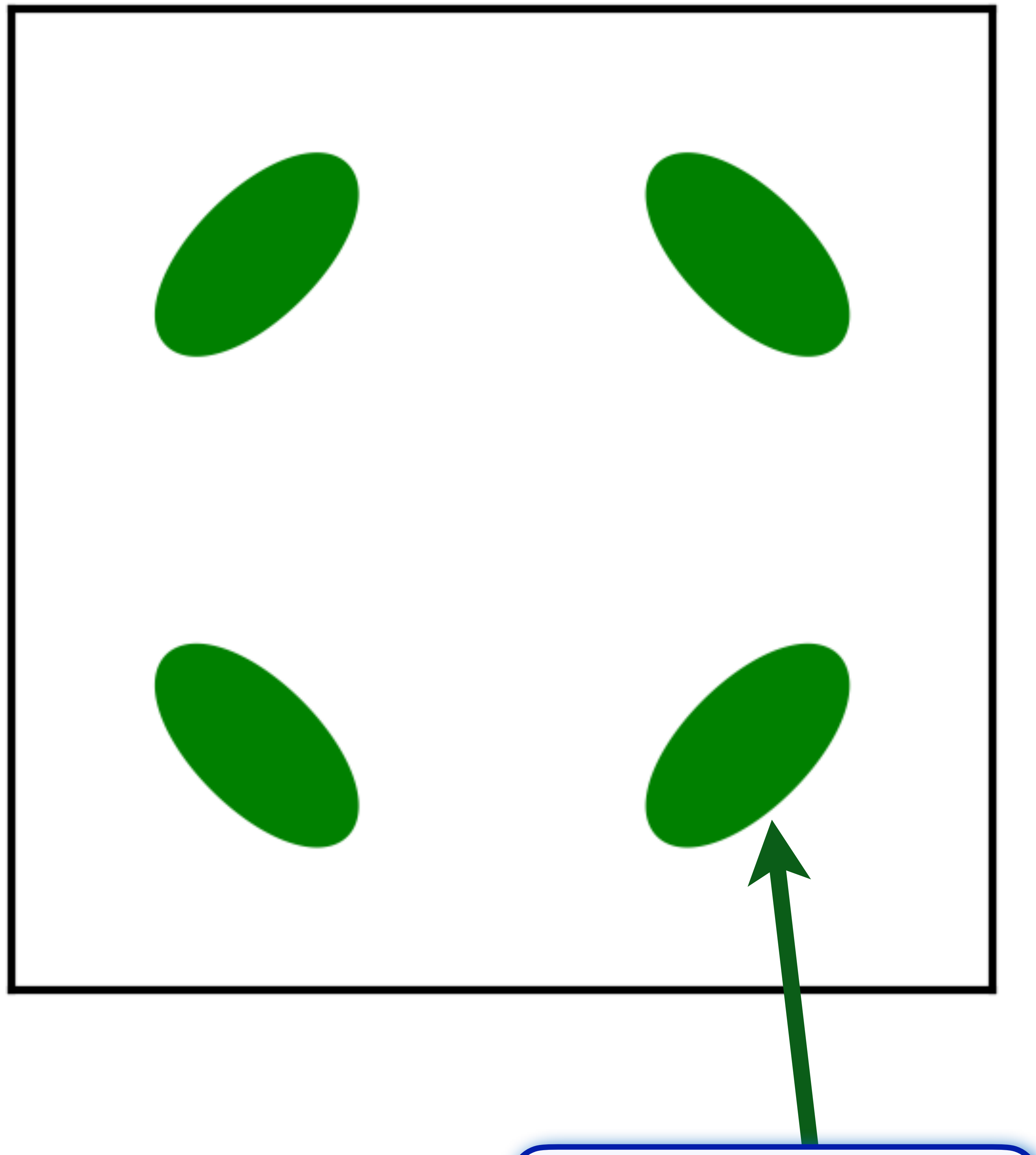

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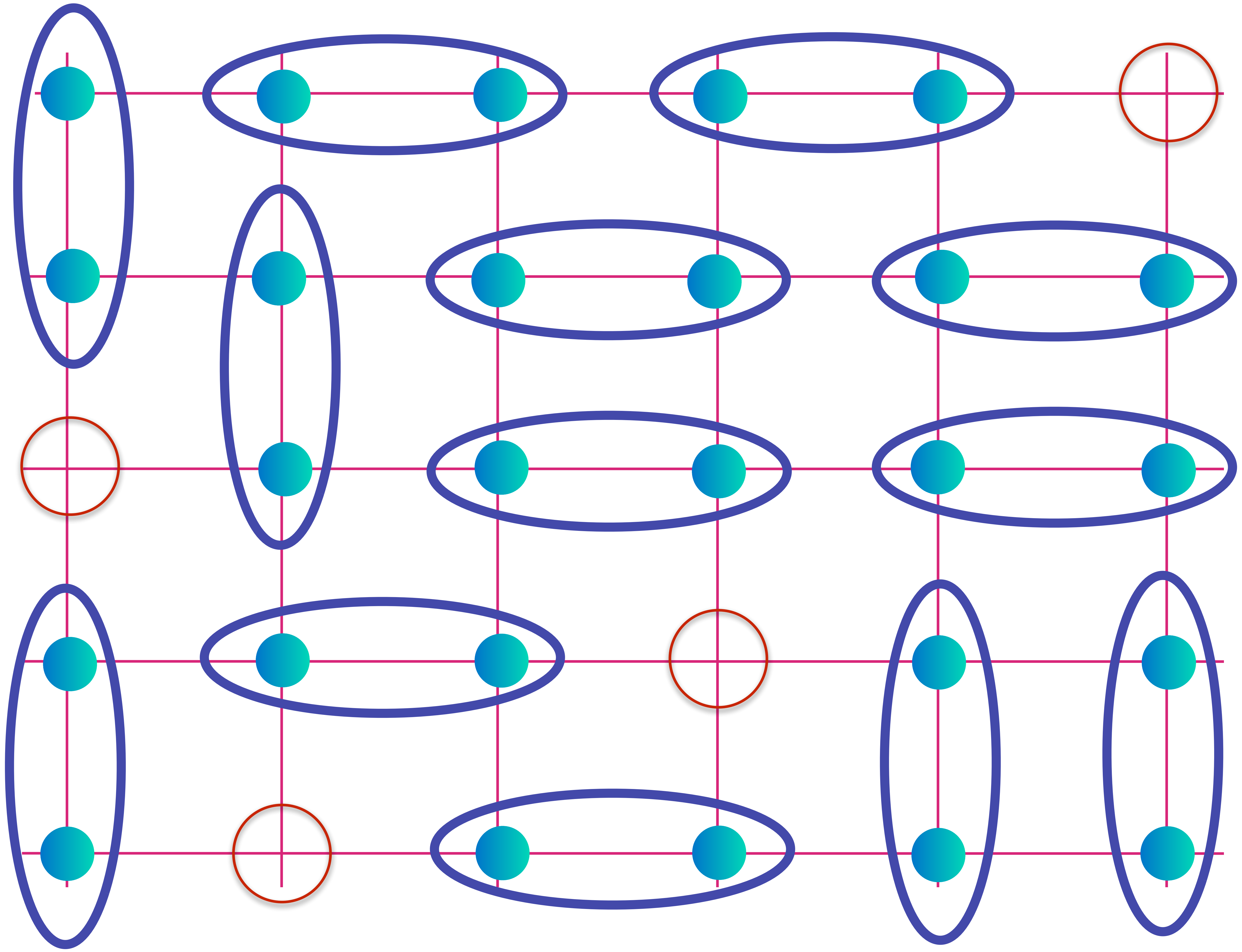

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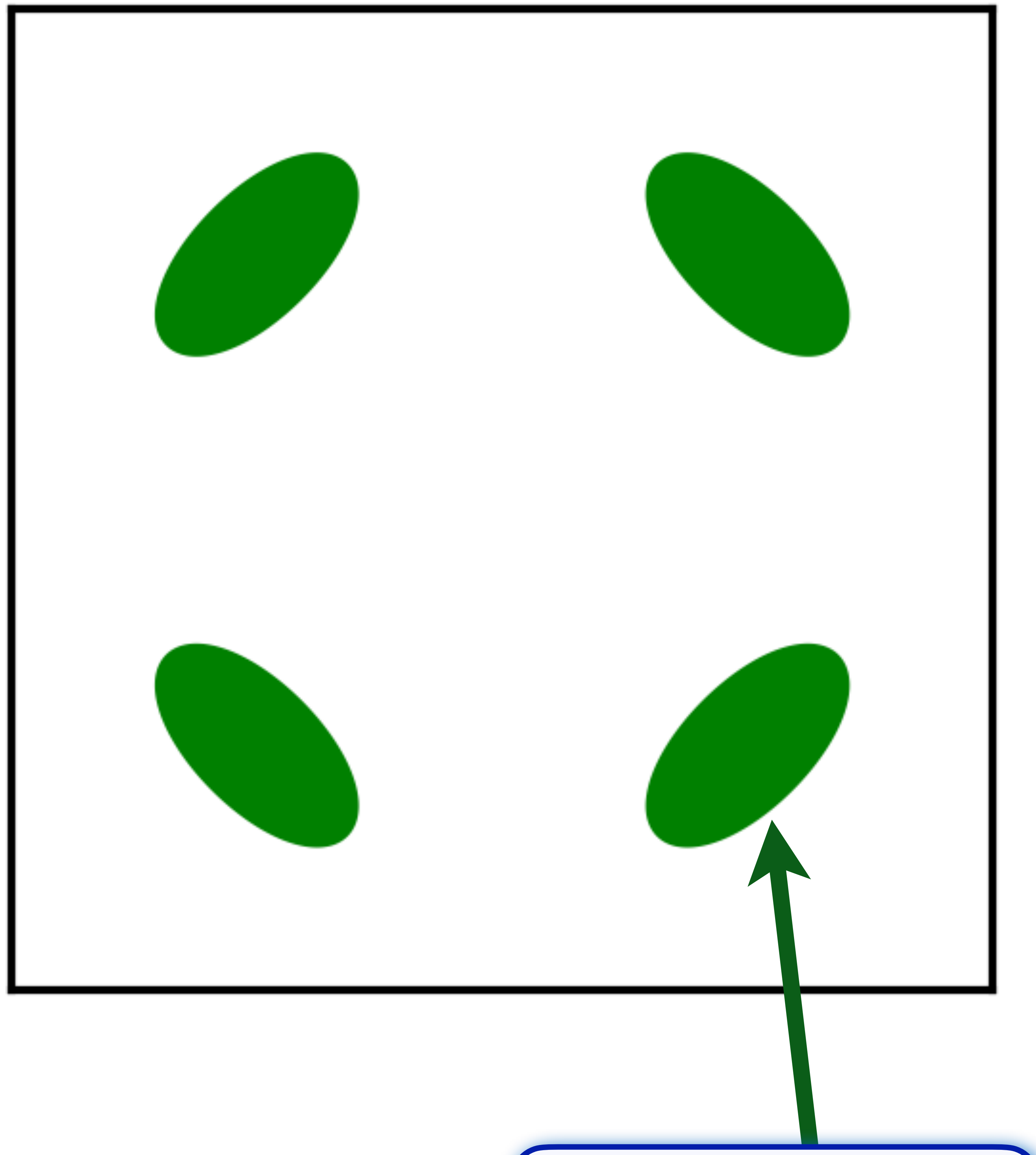

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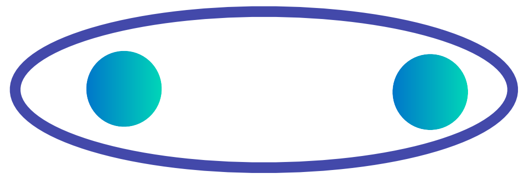 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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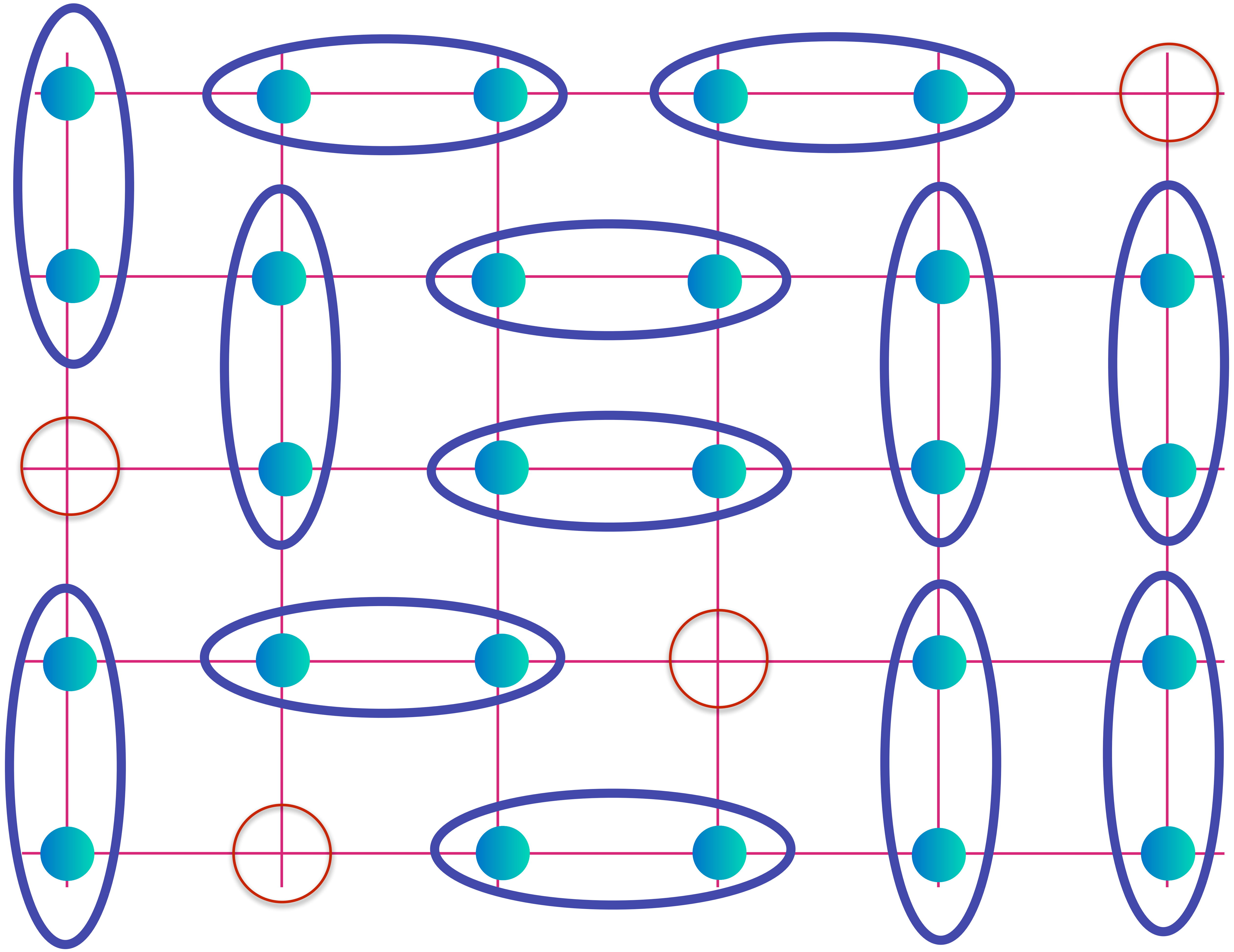

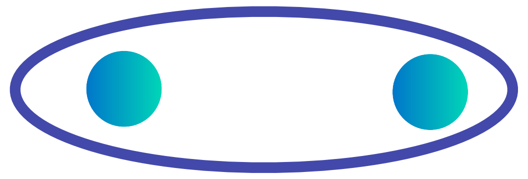 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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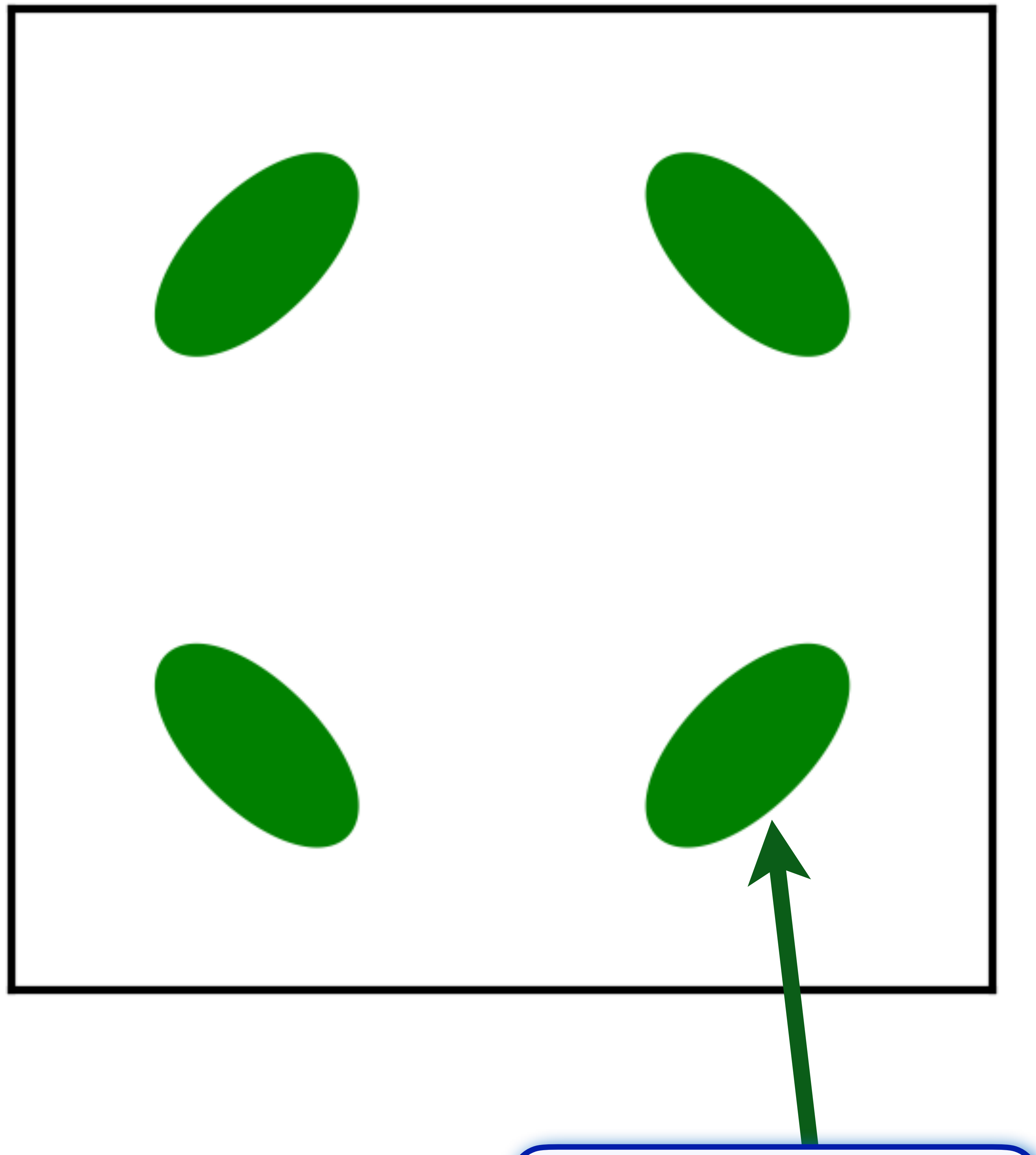

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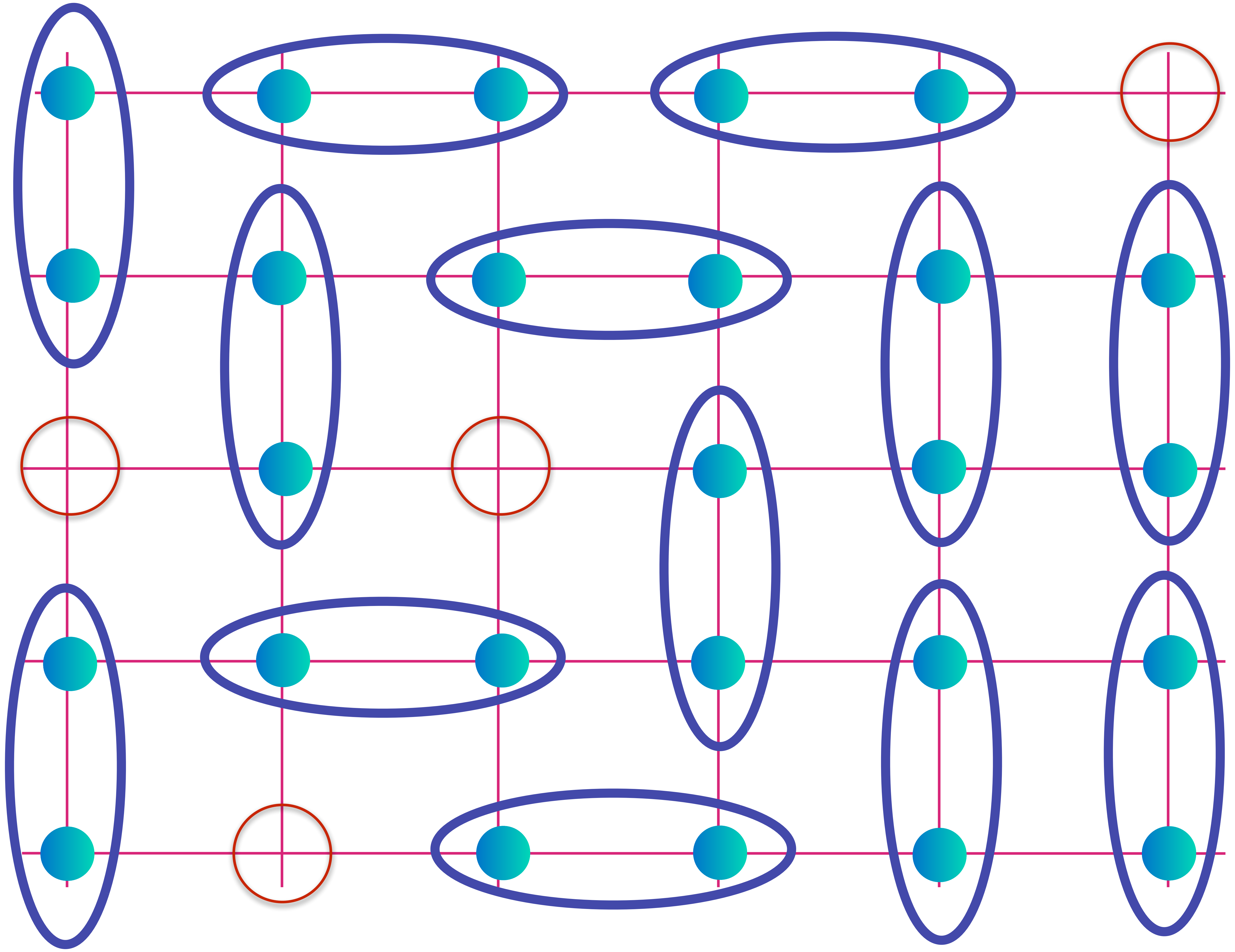

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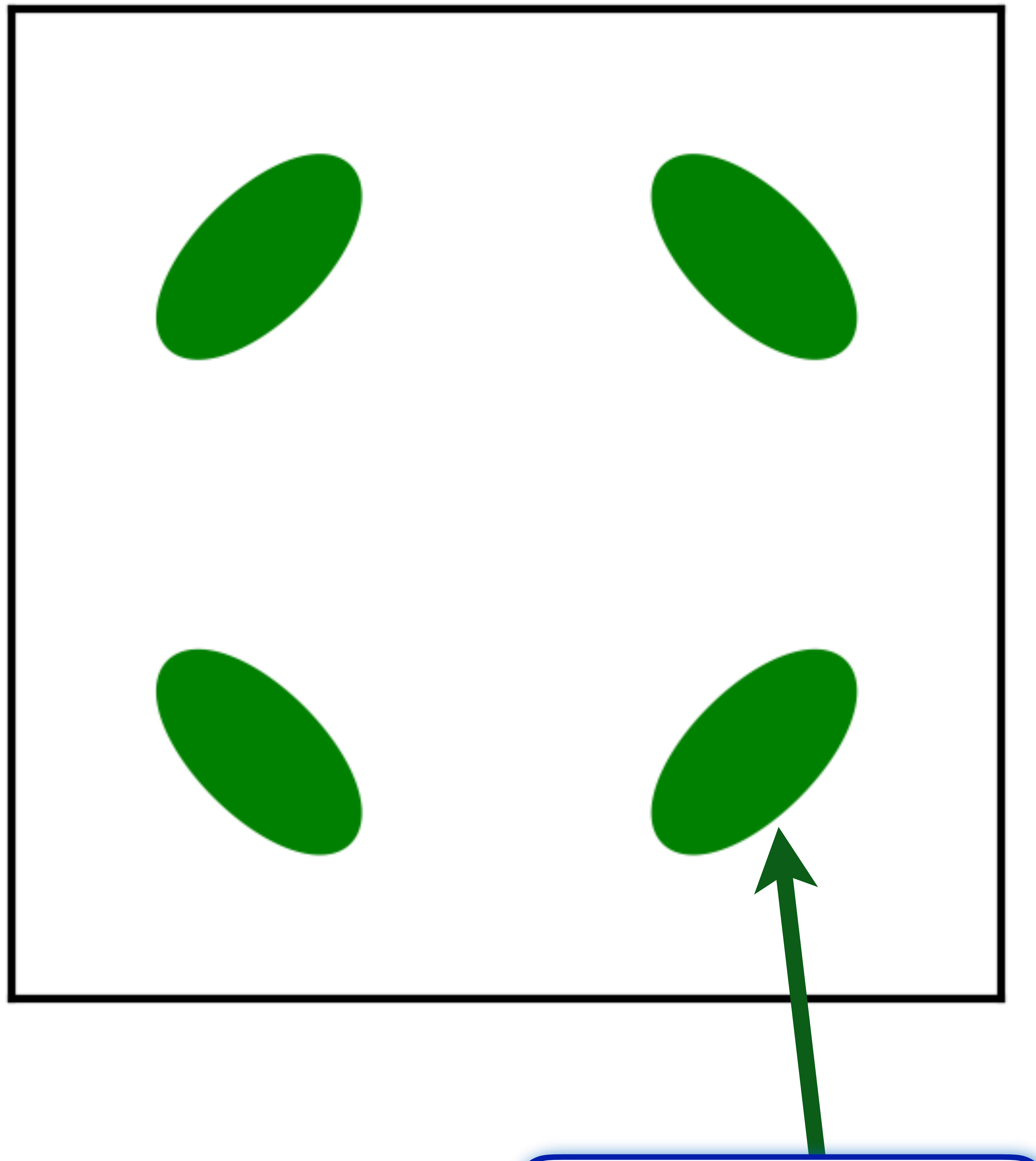

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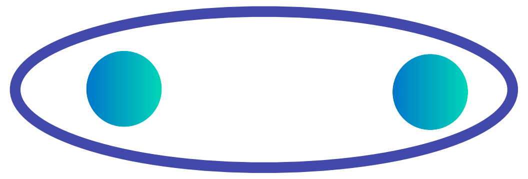 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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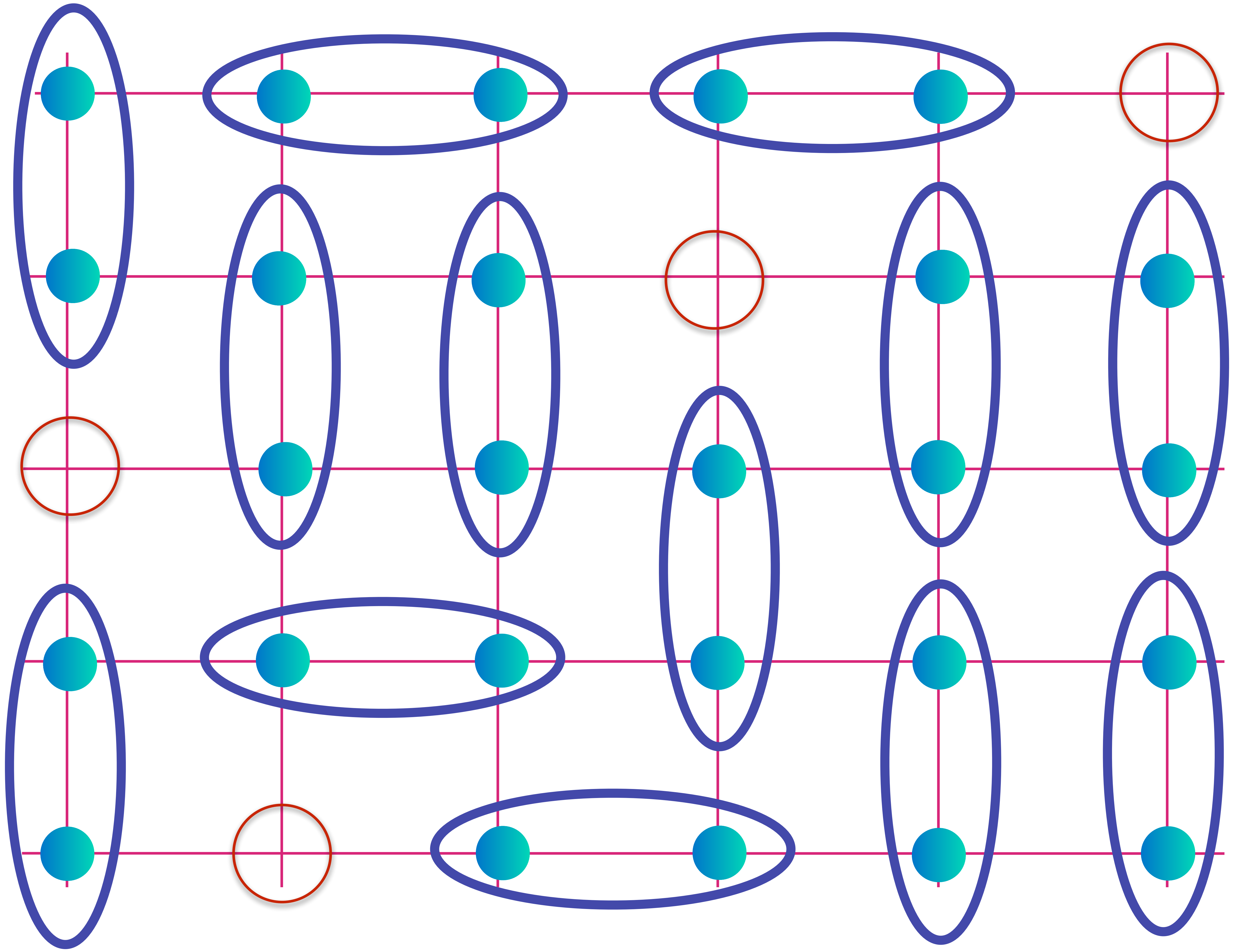

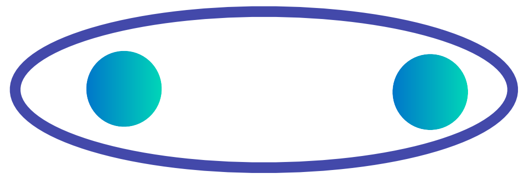 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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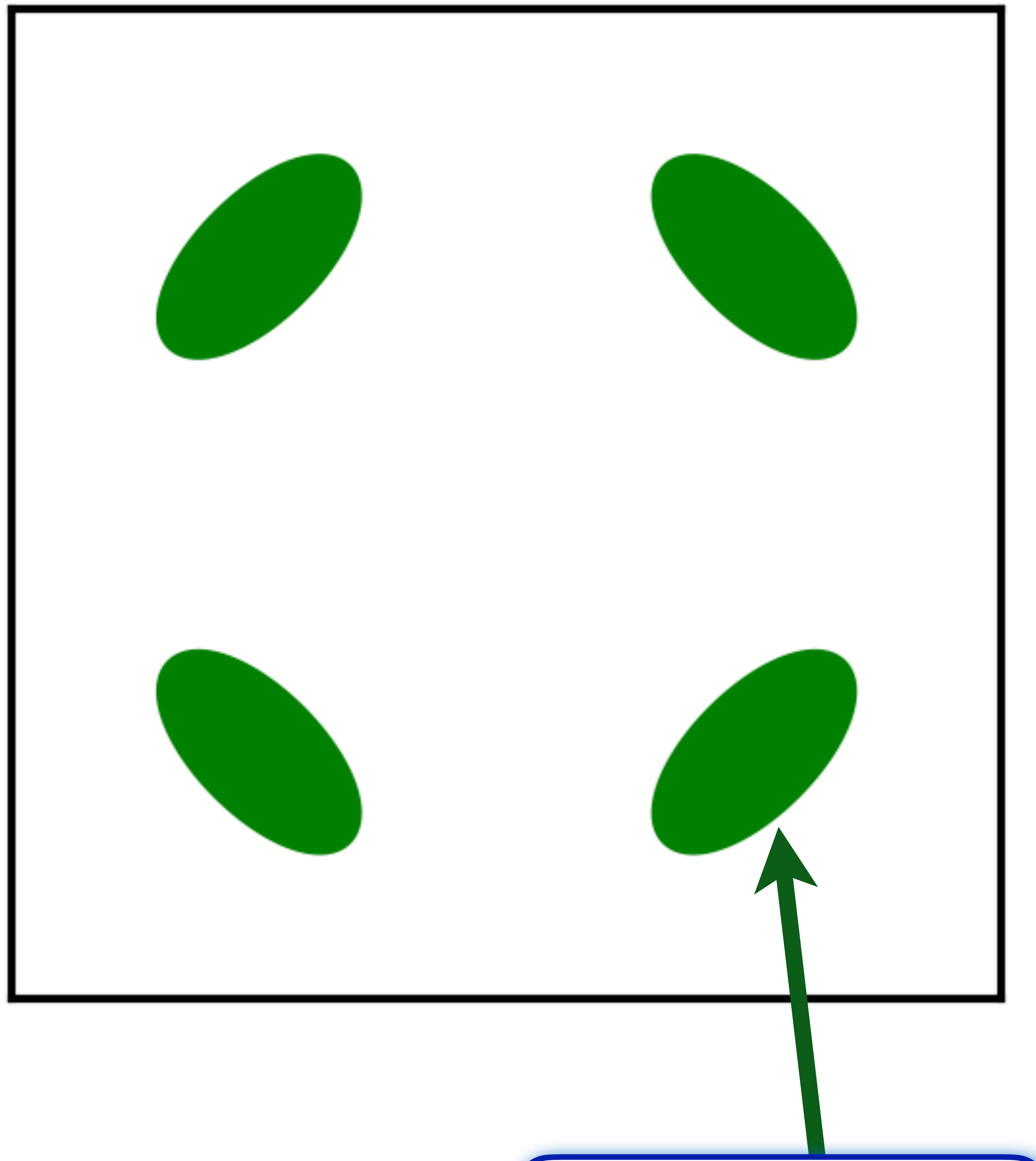

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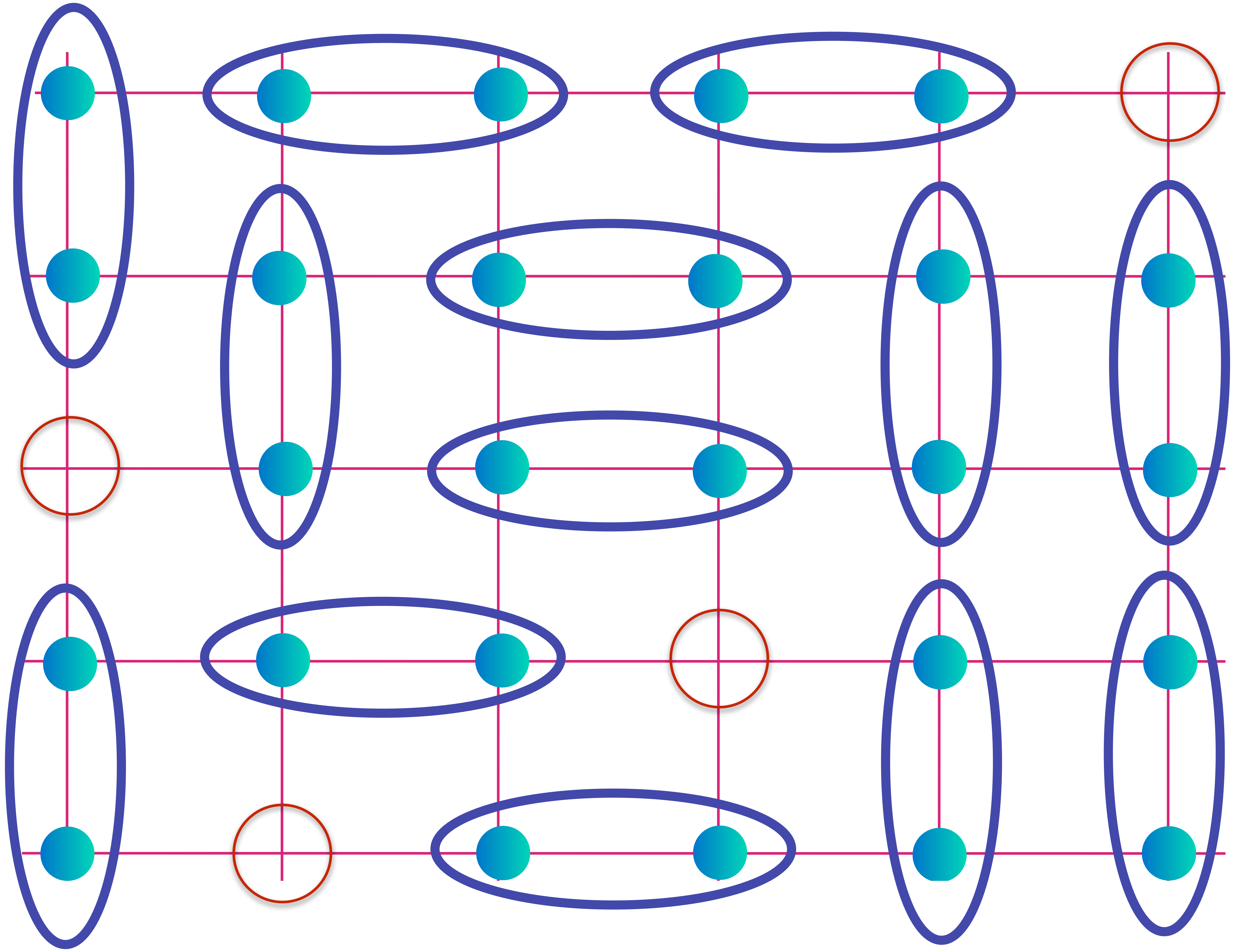

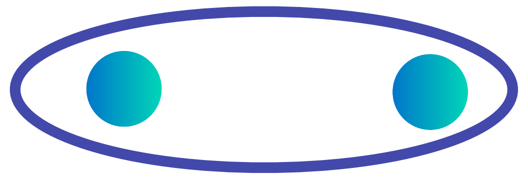 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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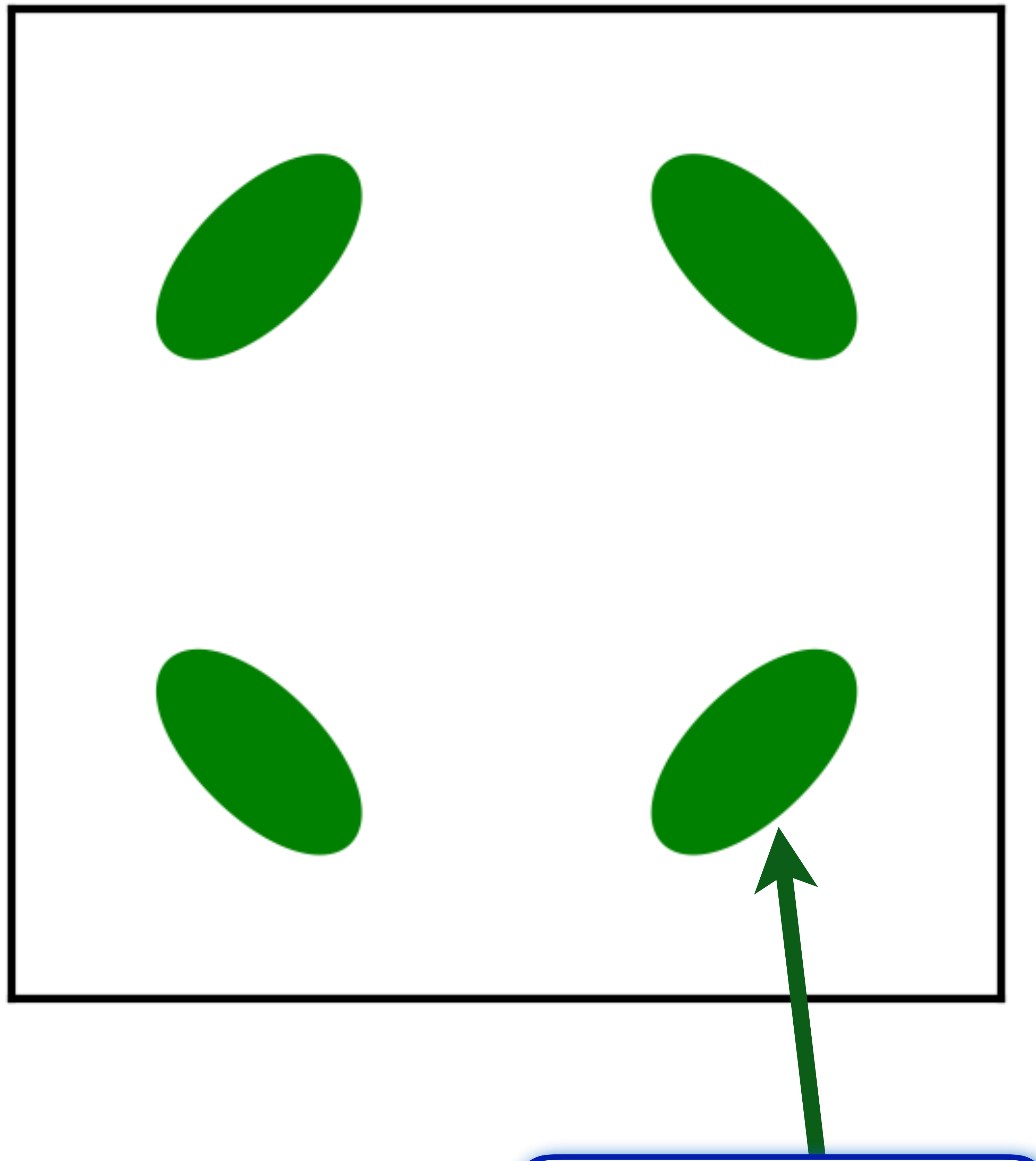

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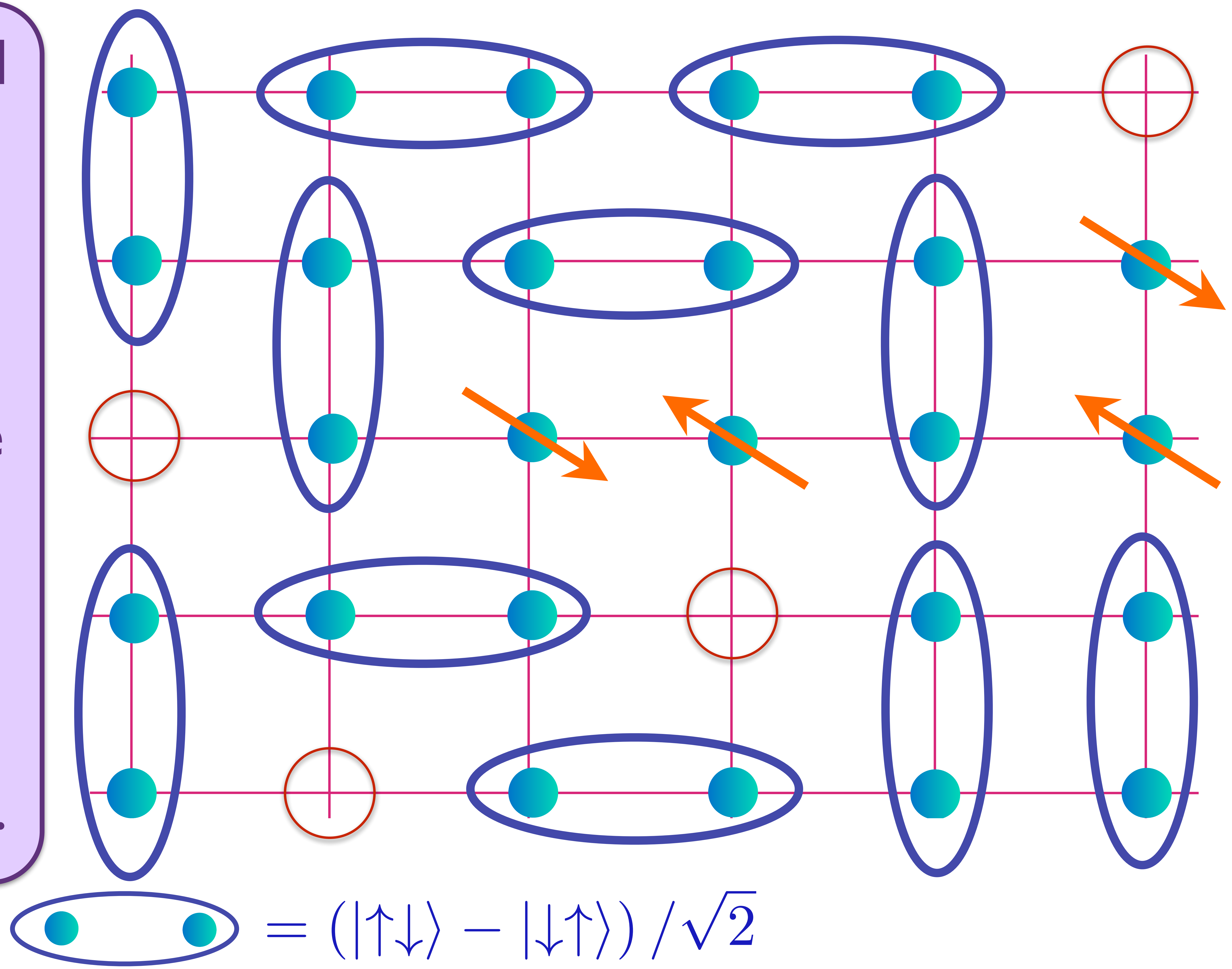

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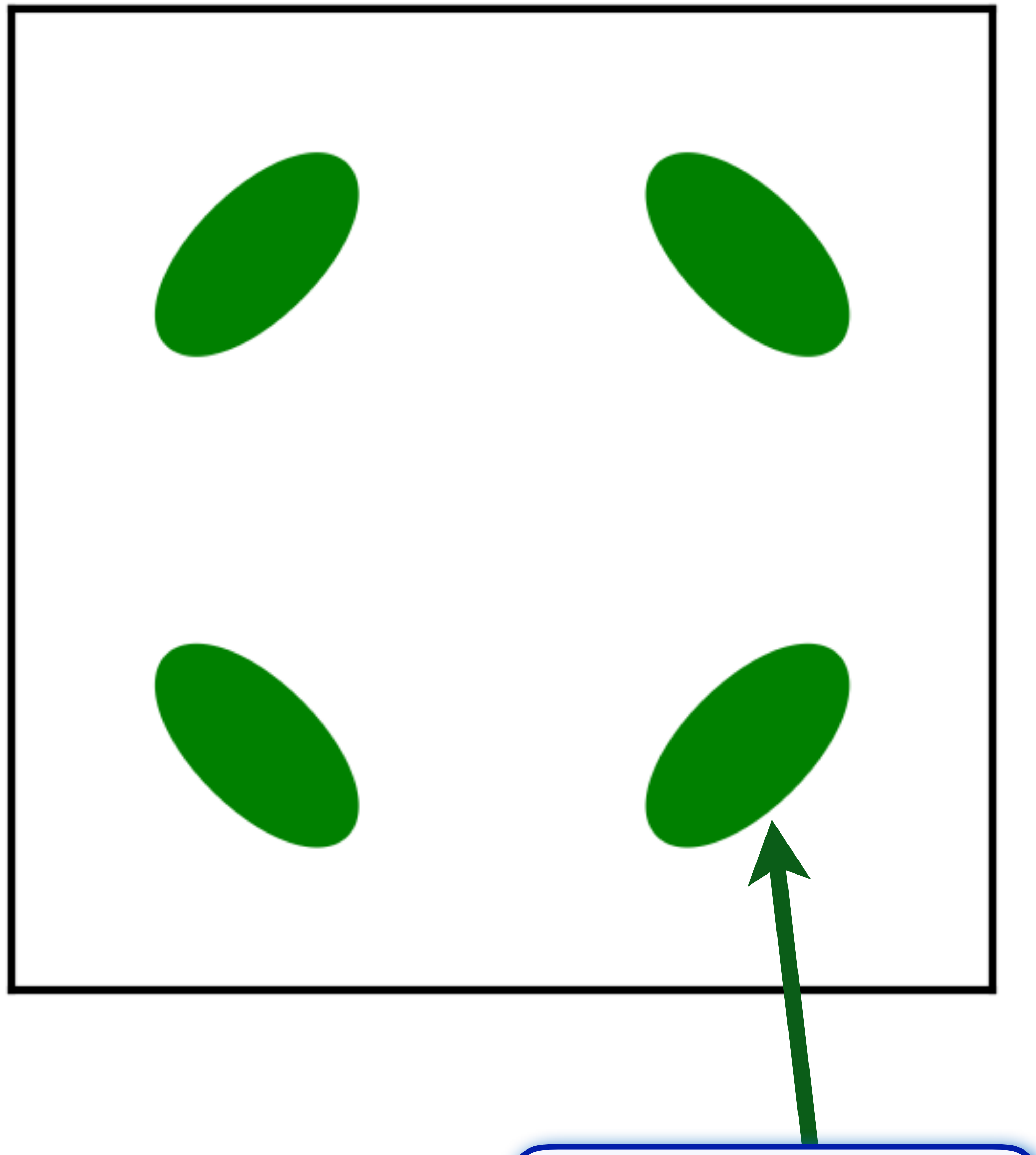

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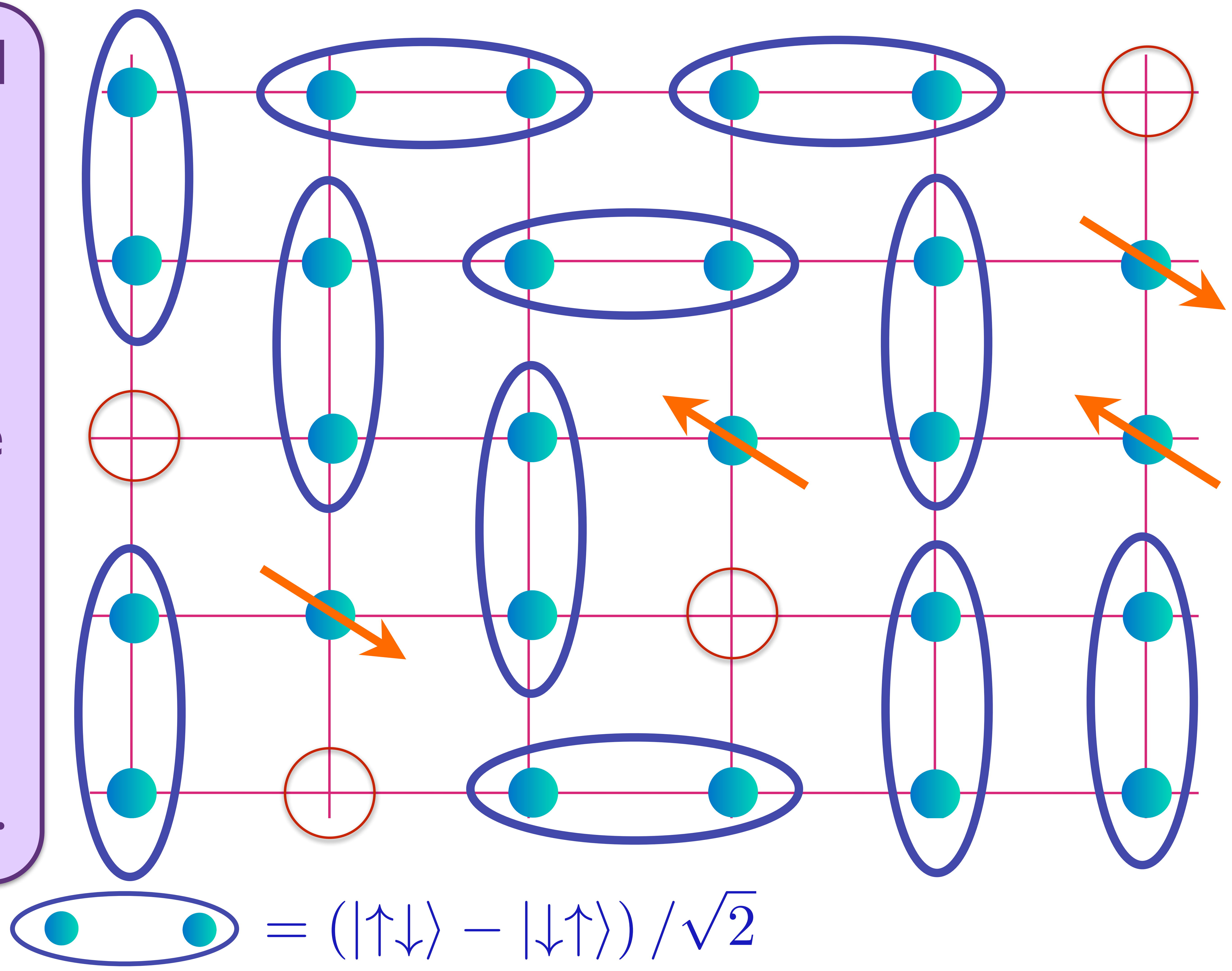

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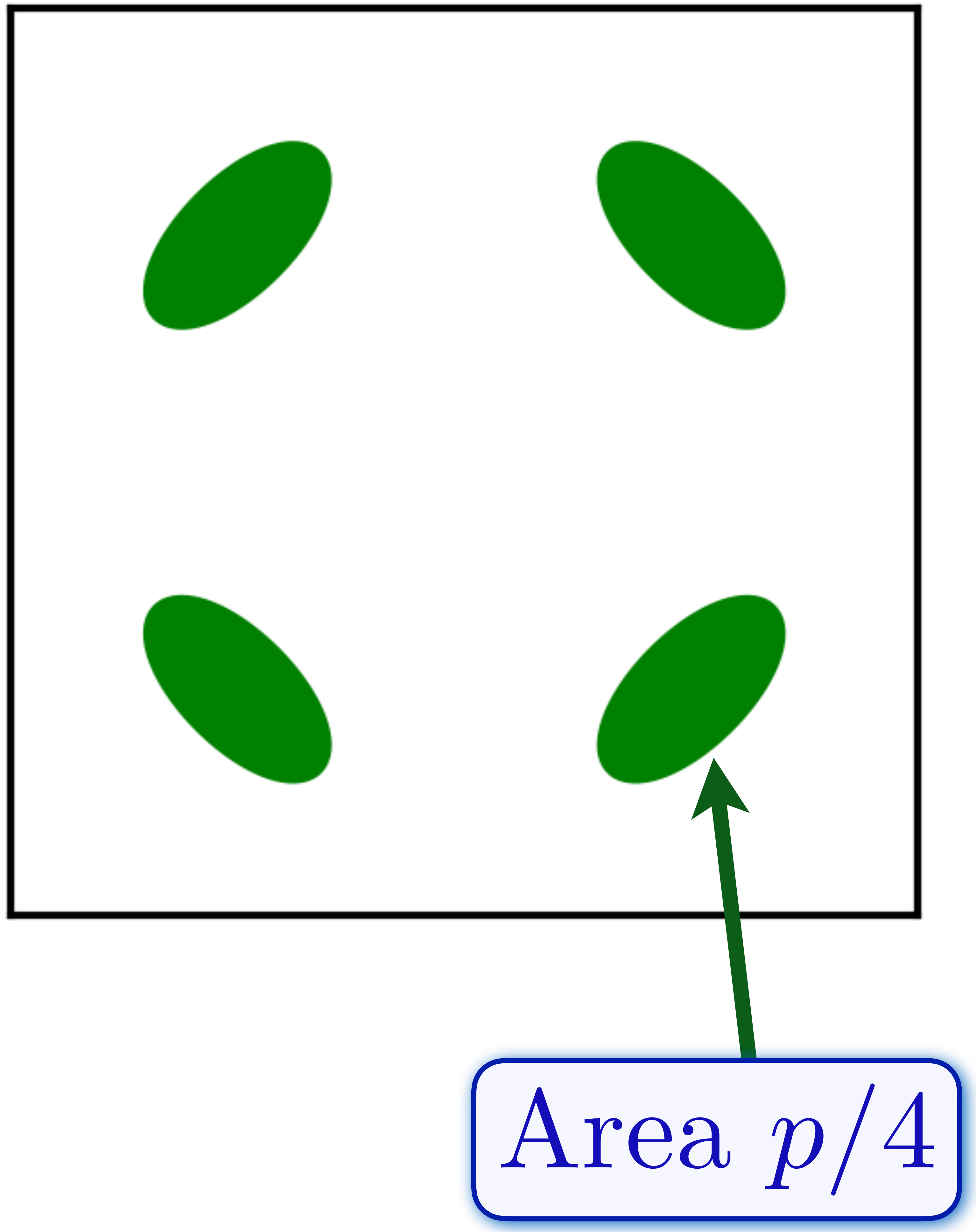

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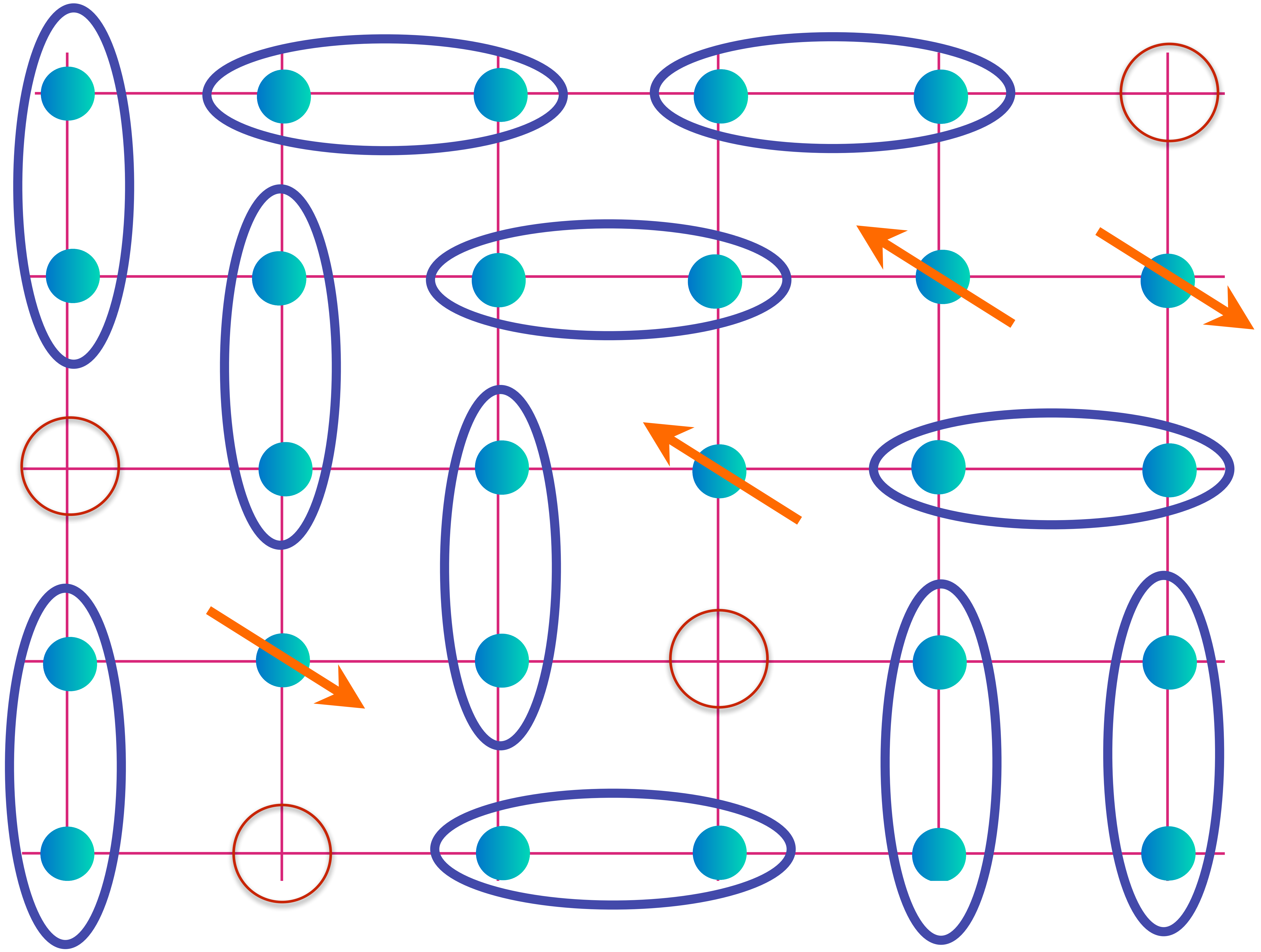

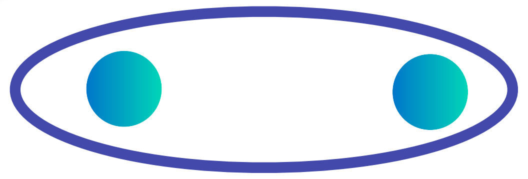 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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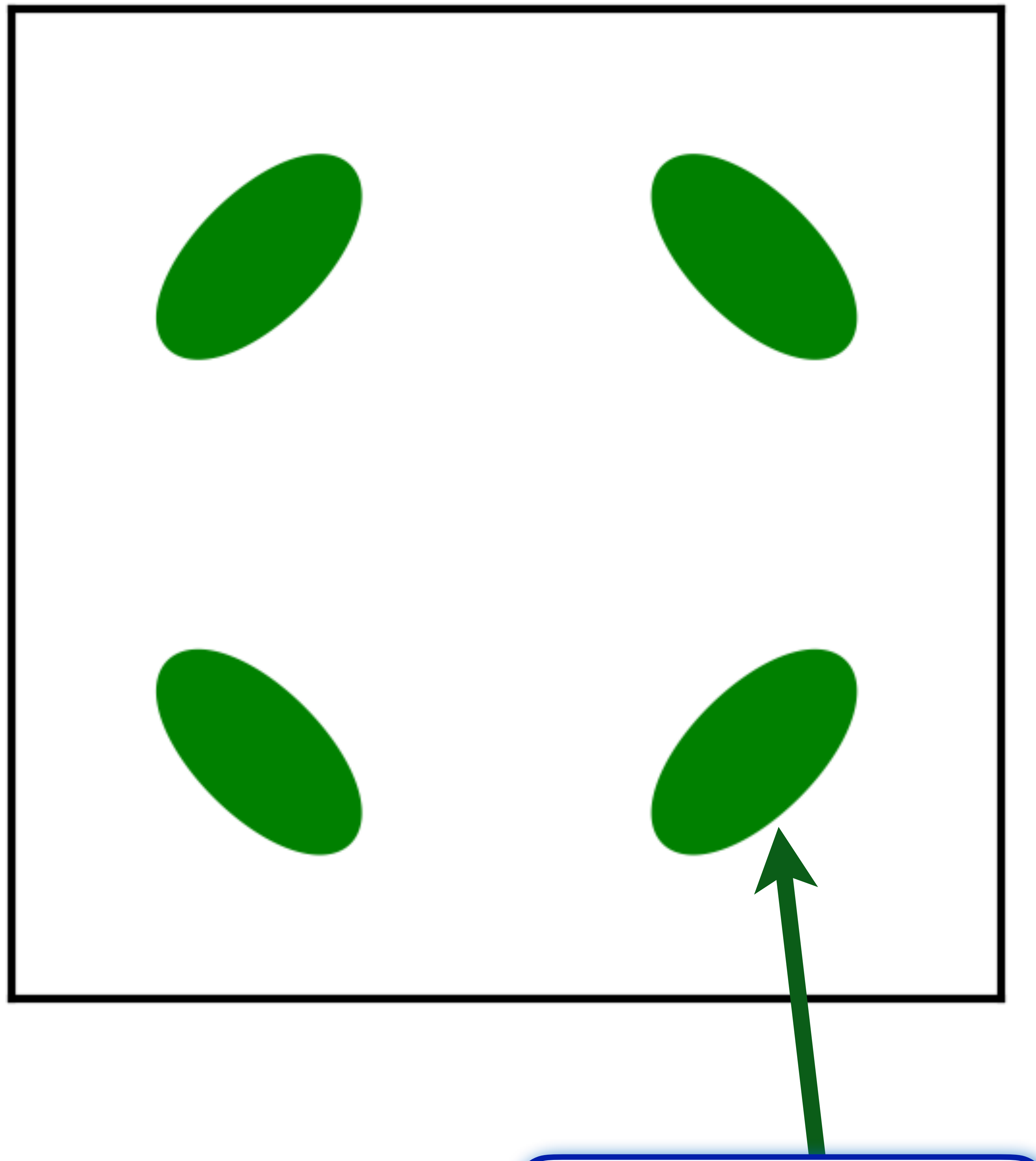

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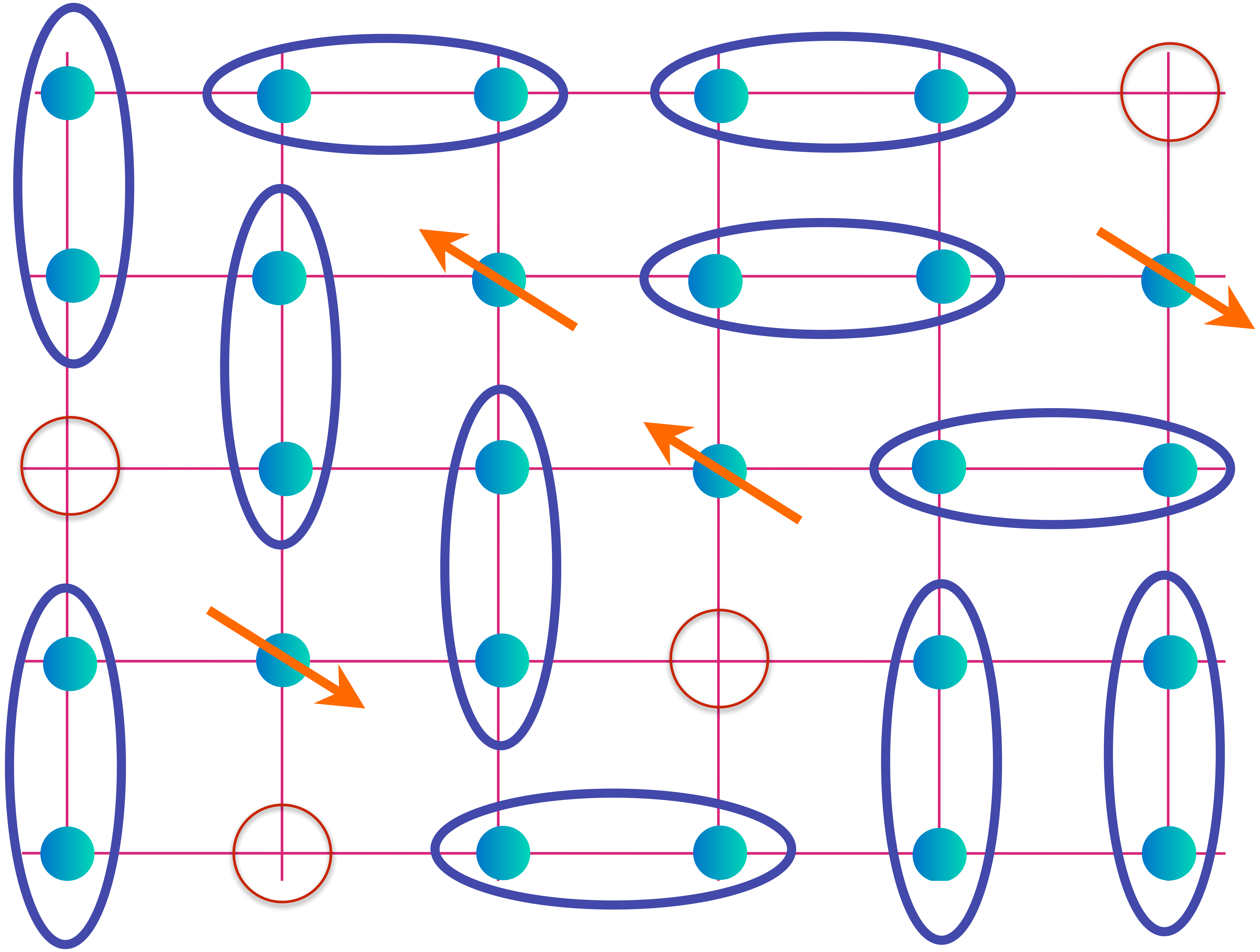
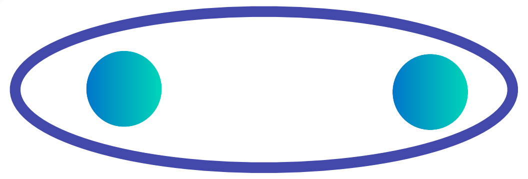
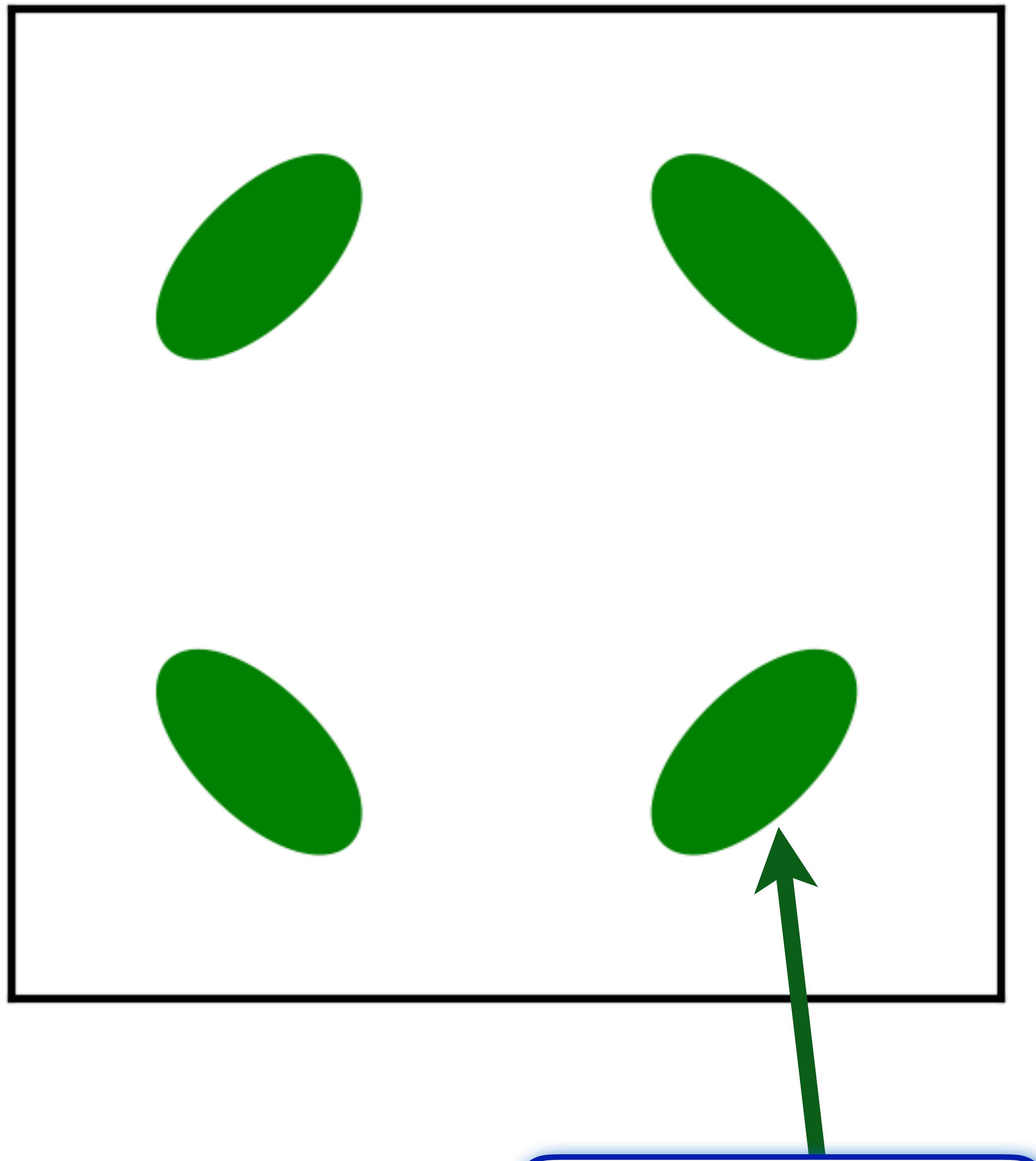


 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

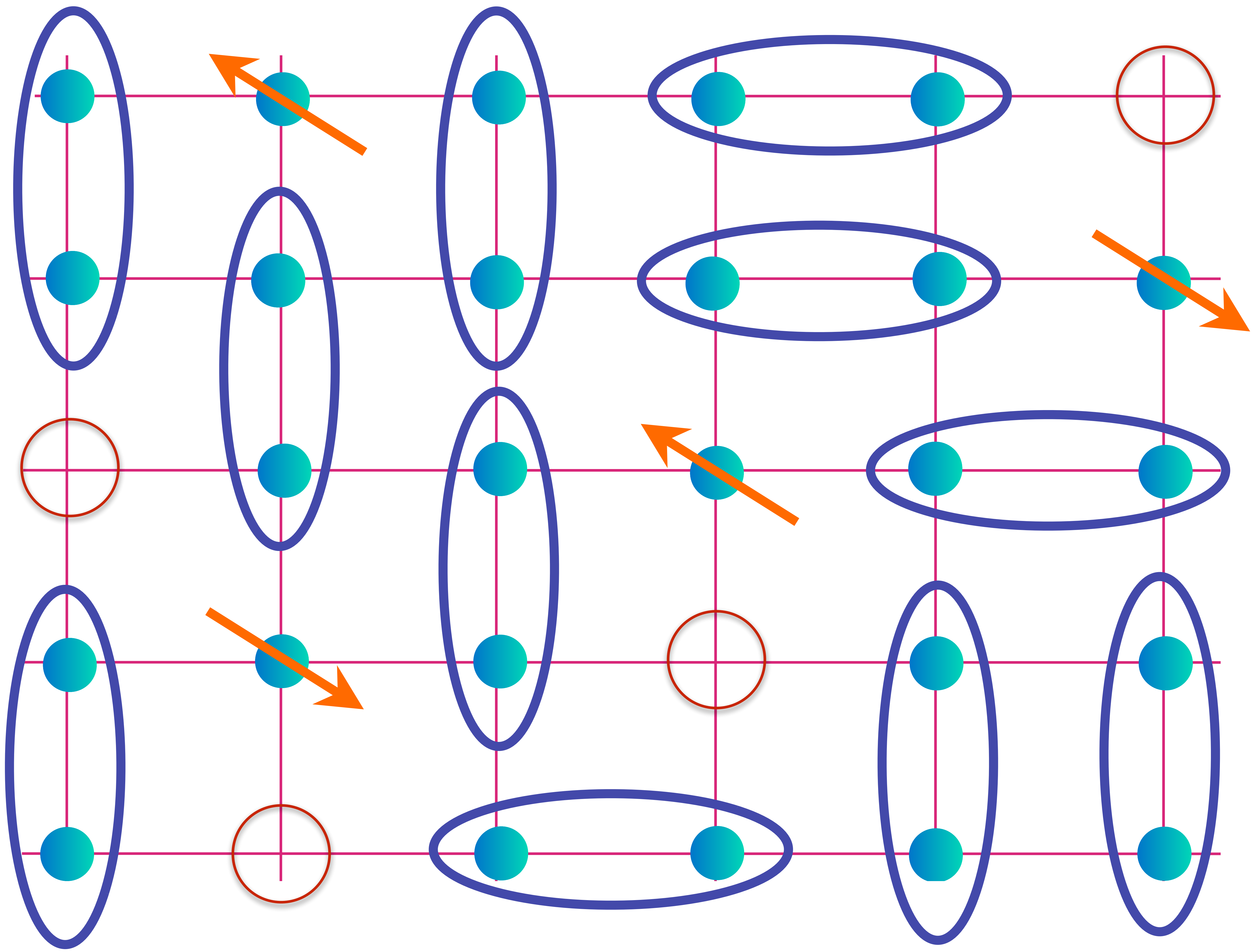


Area $p/4$

Doping an insulating antiferromagnet with holes of density p

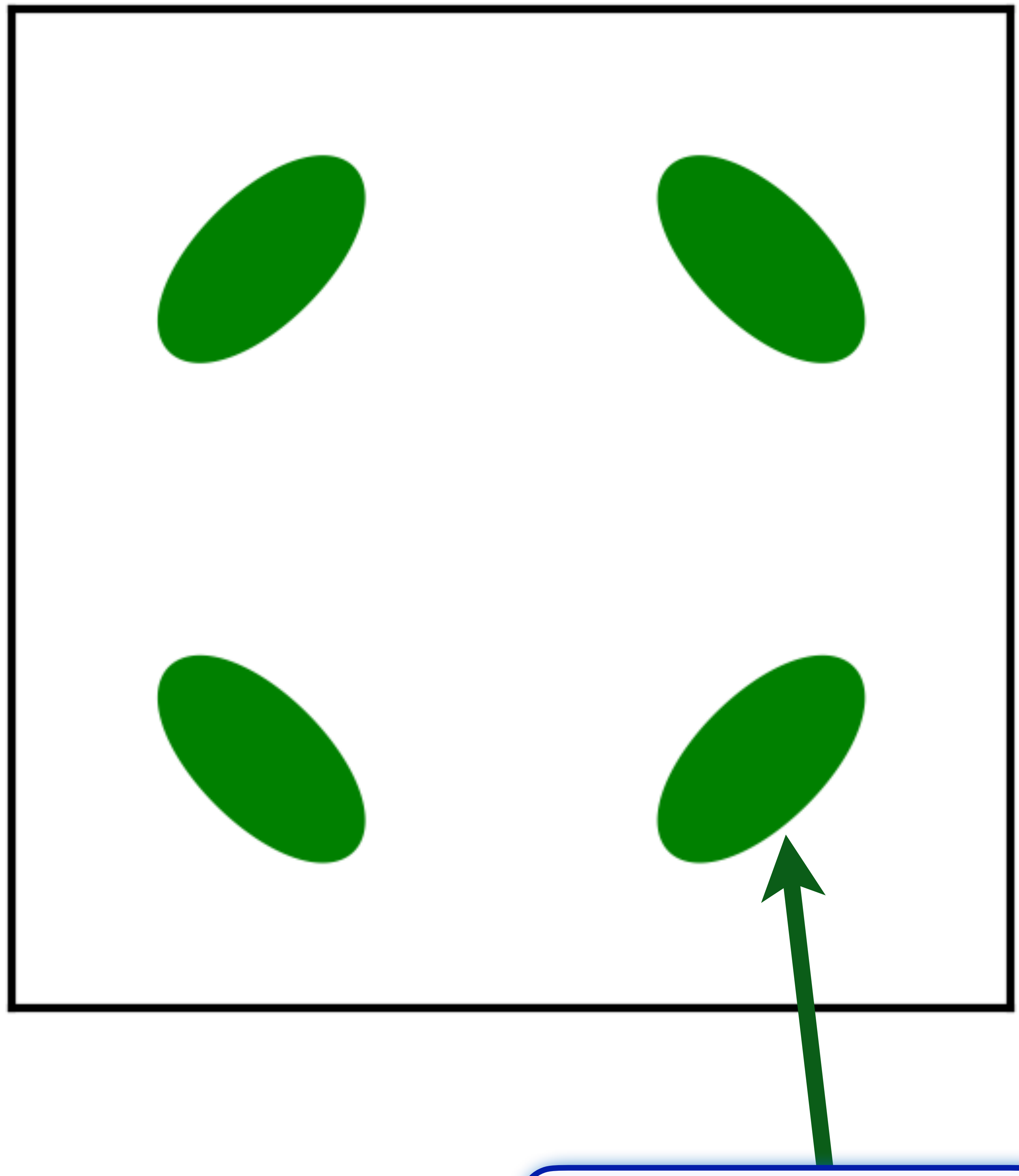
Holon metal

Spin liquid with density p of spinless, charge +e "holons" and charge 0 spin-1/2 "spinons".



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

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



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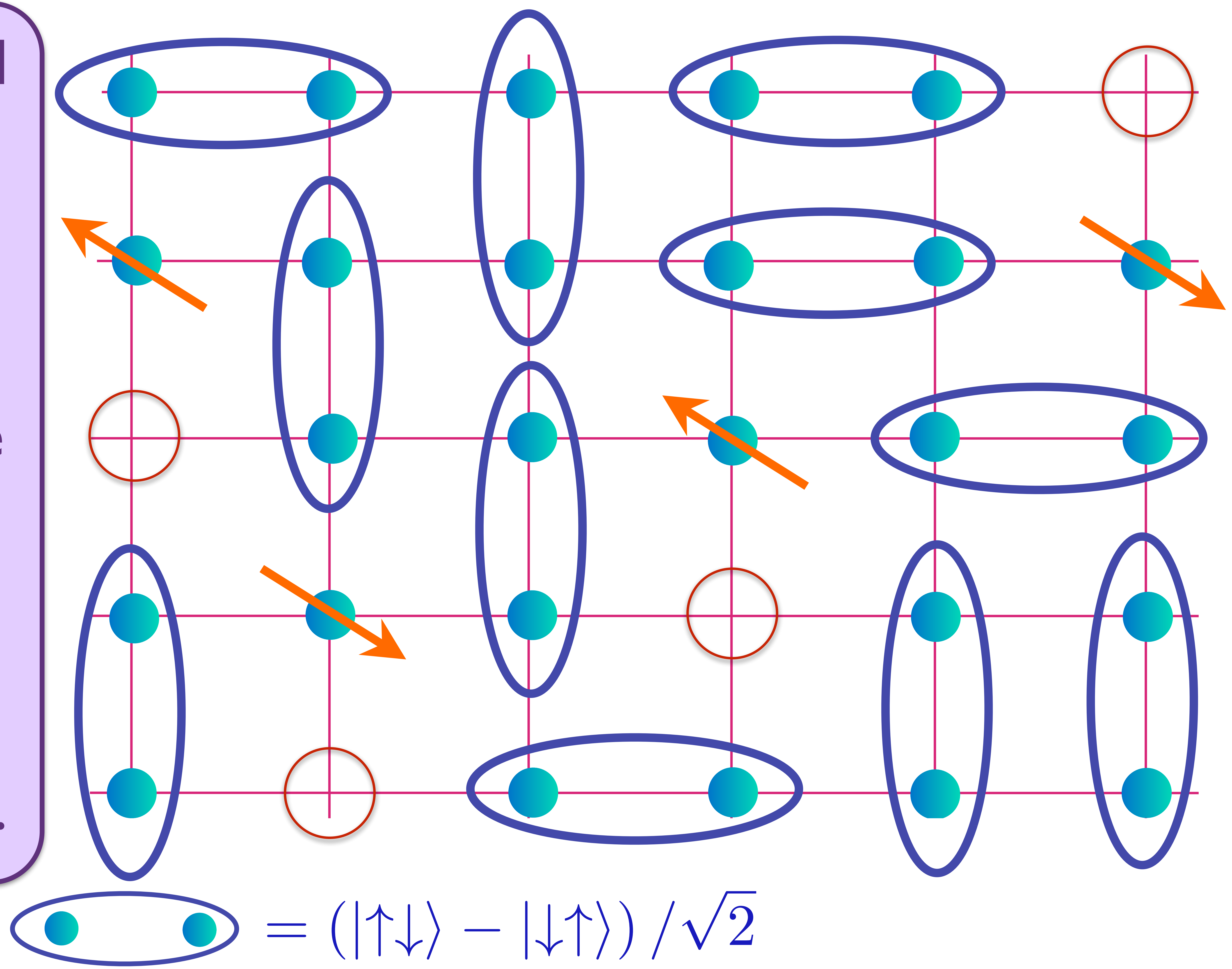

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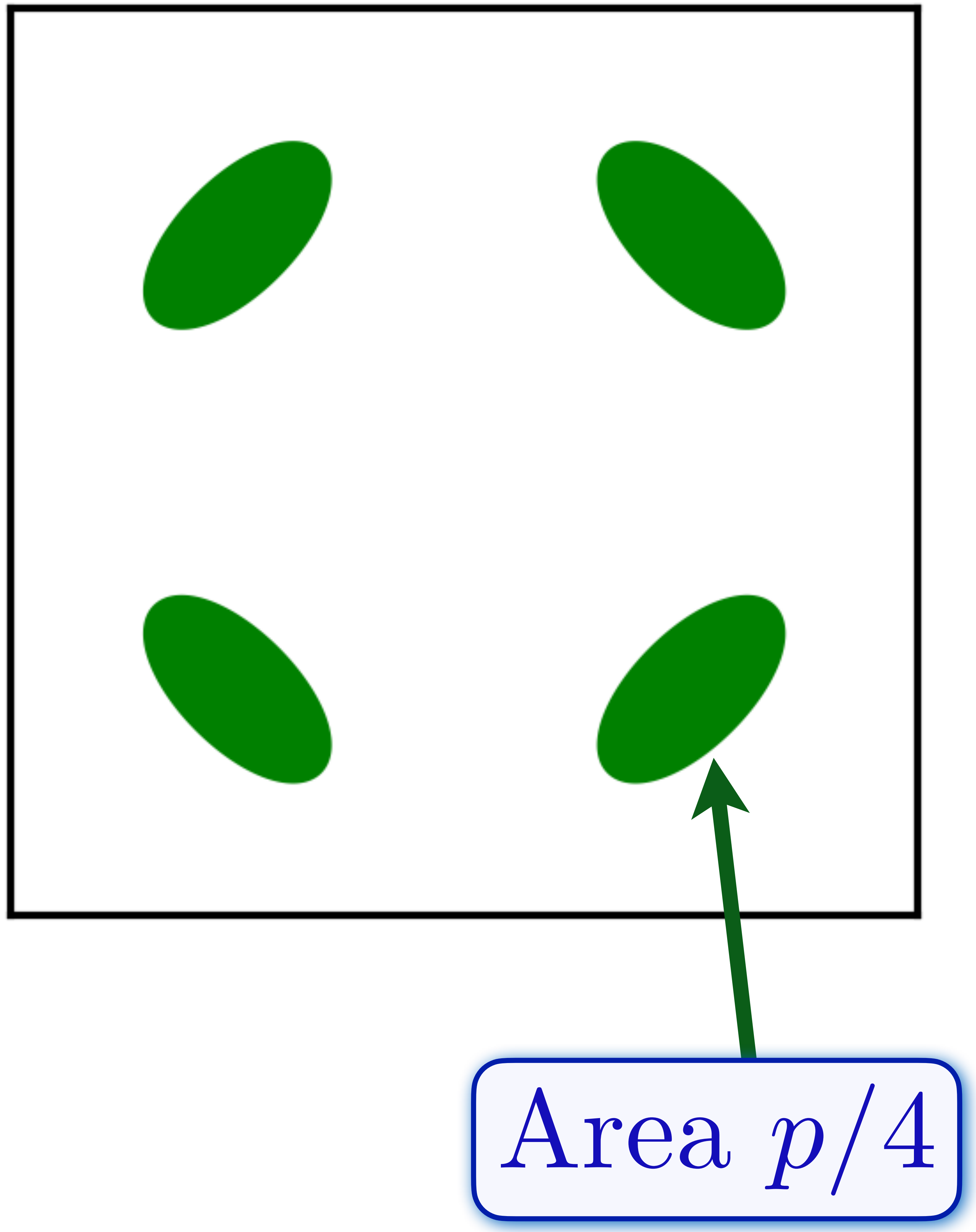

Doping an insulating antiferromagnet with holes of density p

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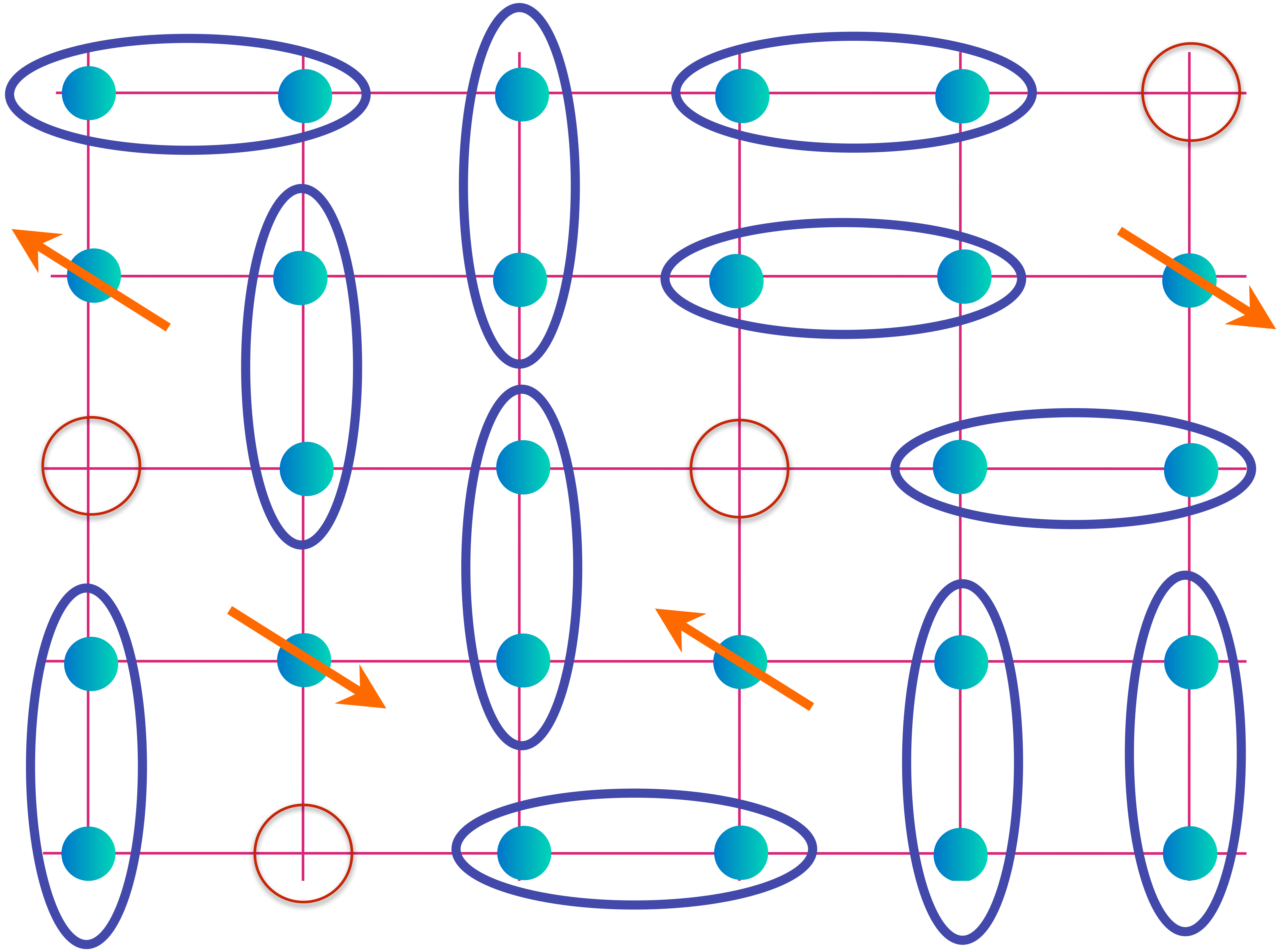
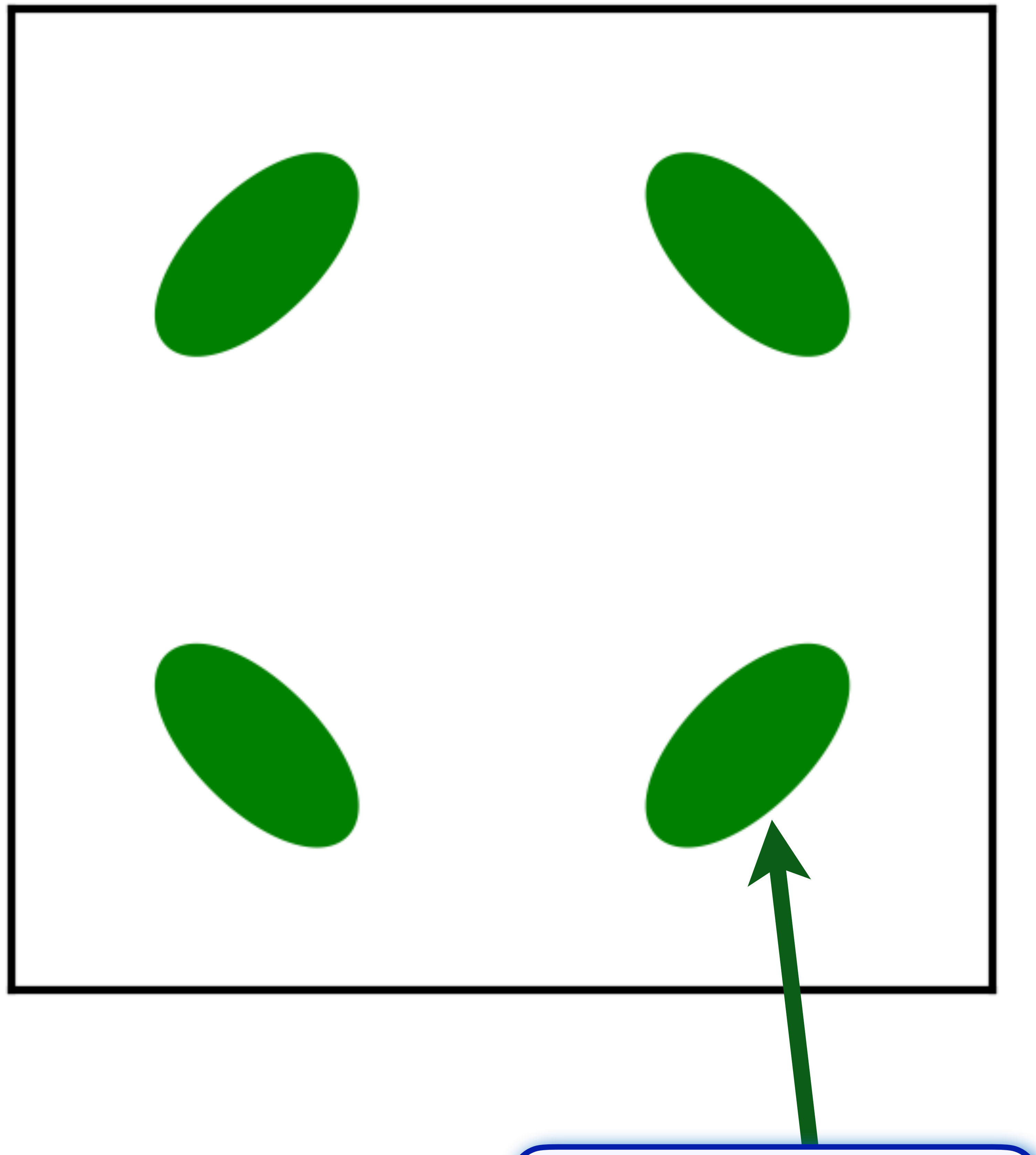


$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



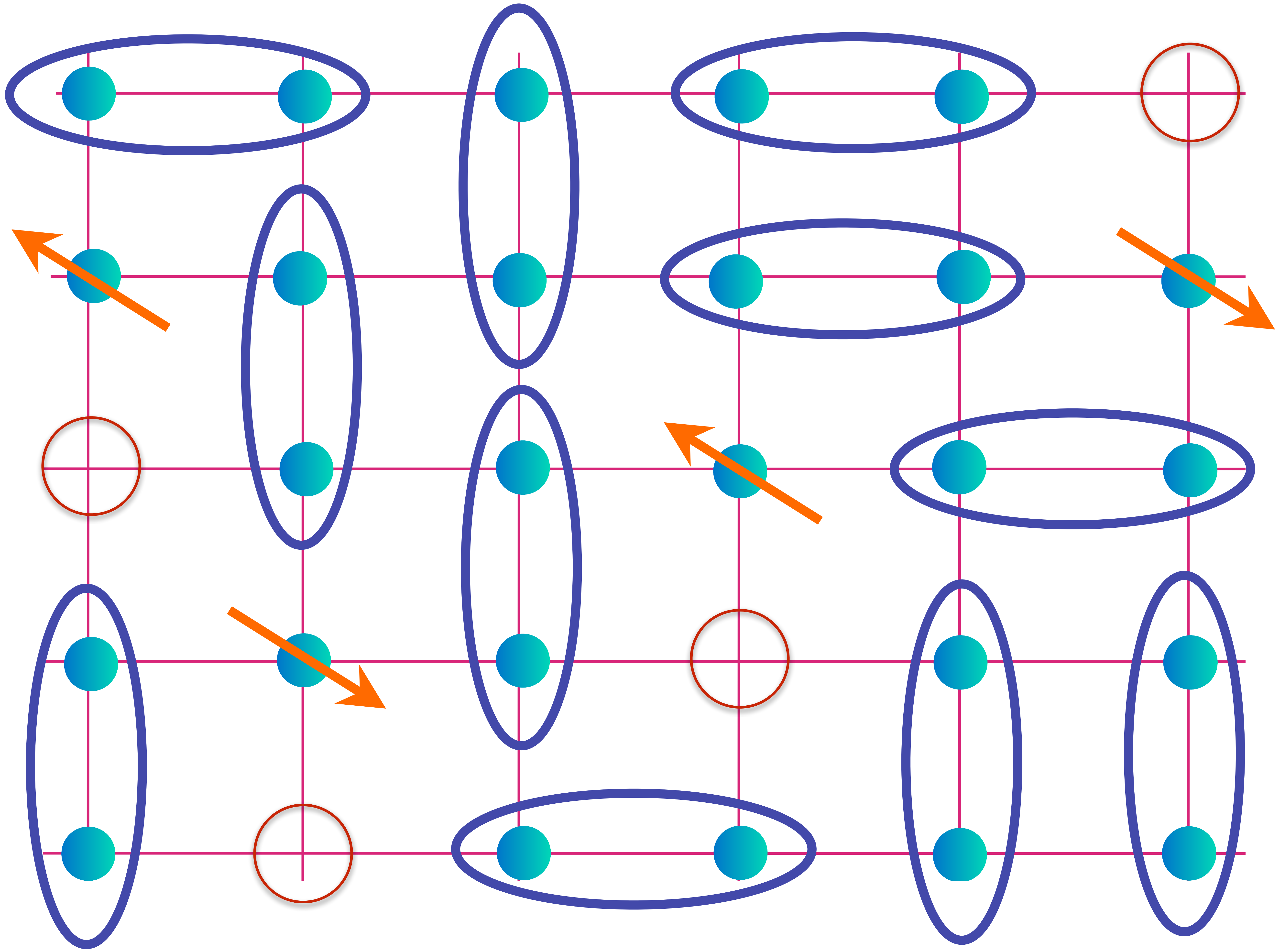
Area $p/4$

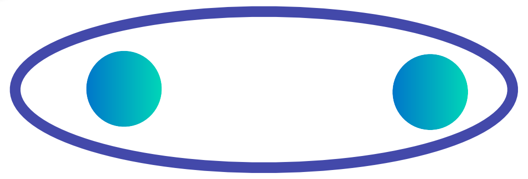
Doping an insulating antiferromagnet with holes of density p

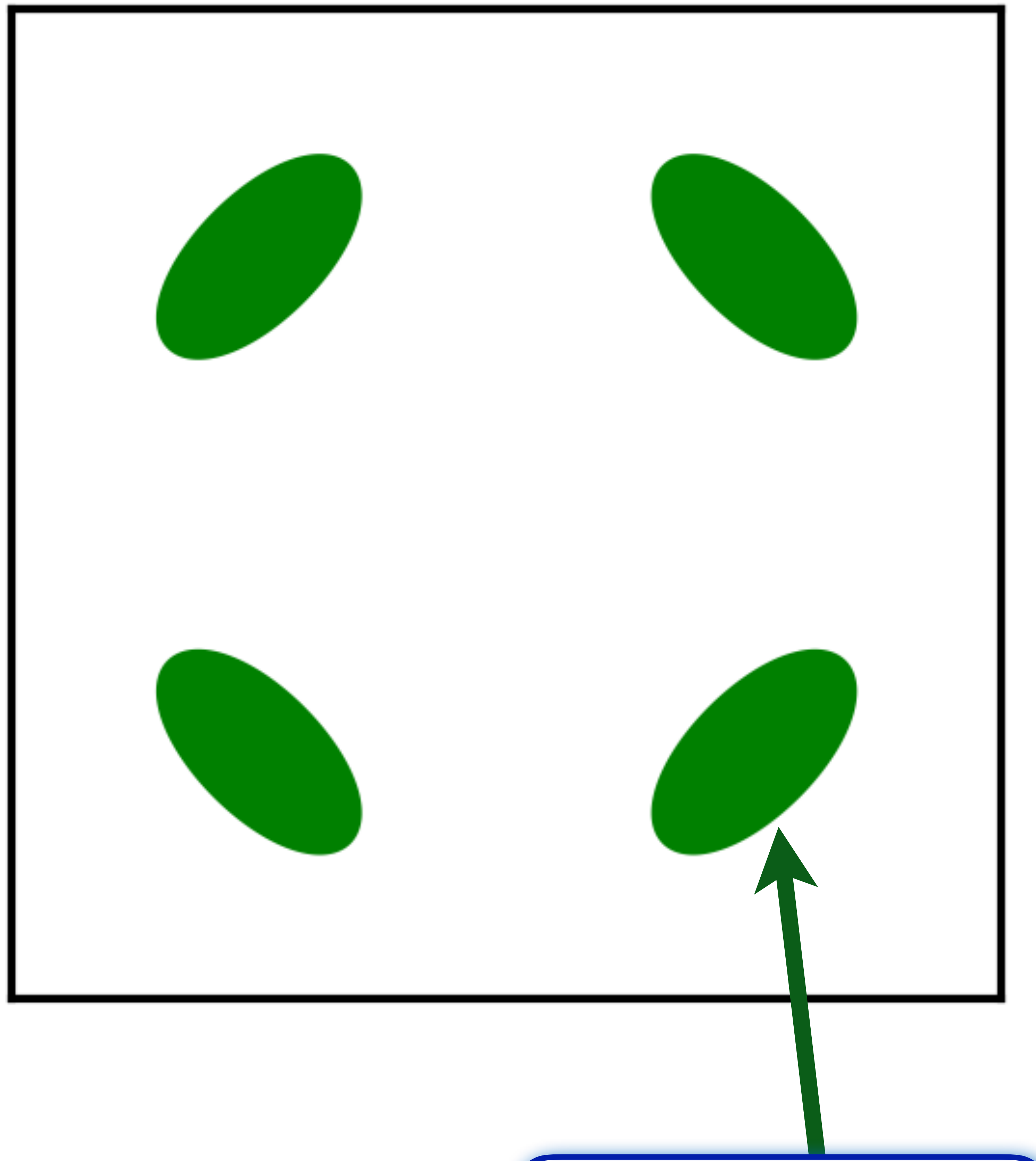
Holon metal

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

Spin liquid with density p of spinless, charge +e “holons” and charge 0 spin-1/2 “spinons”.




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



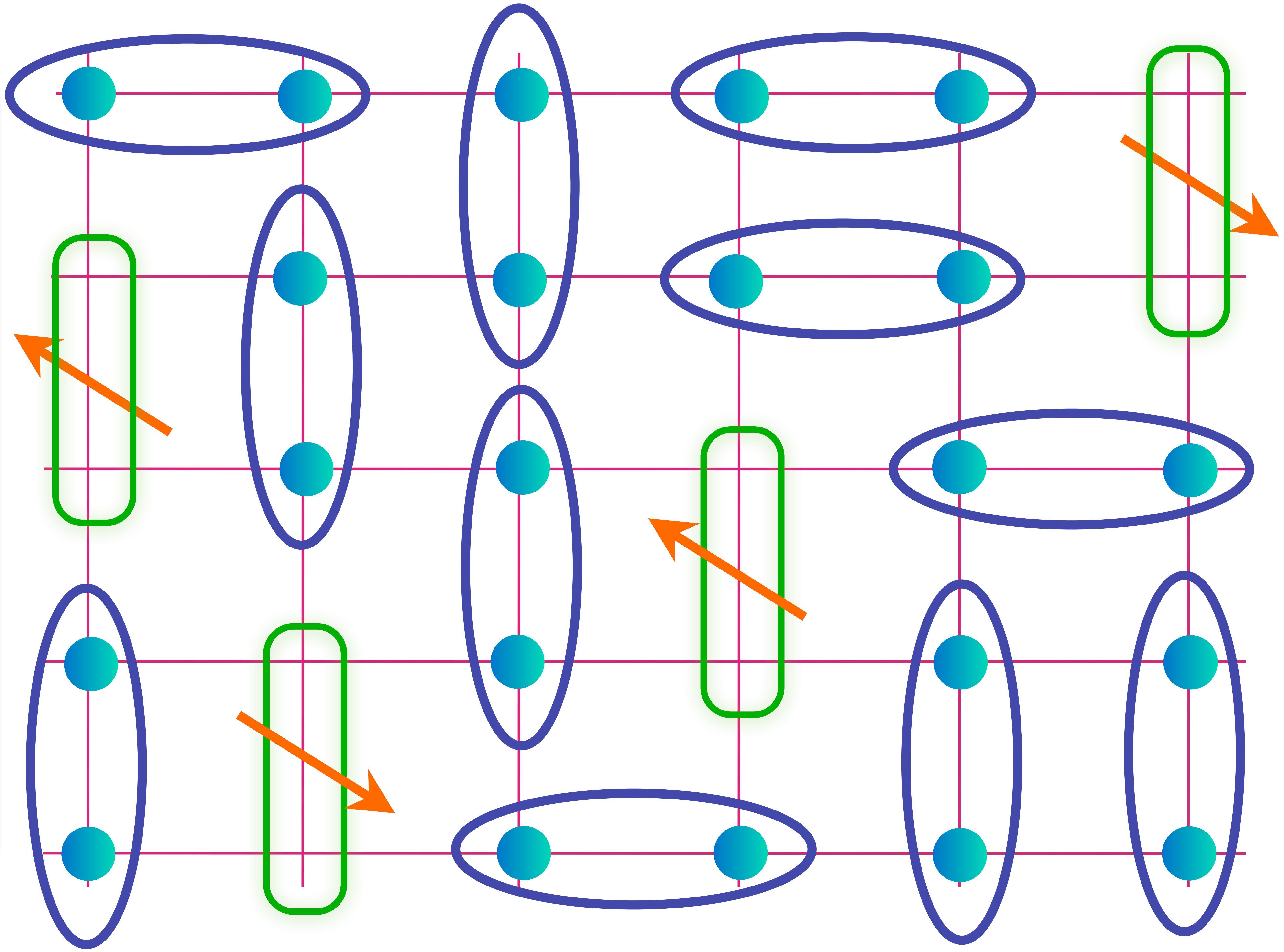
Area $p/4$

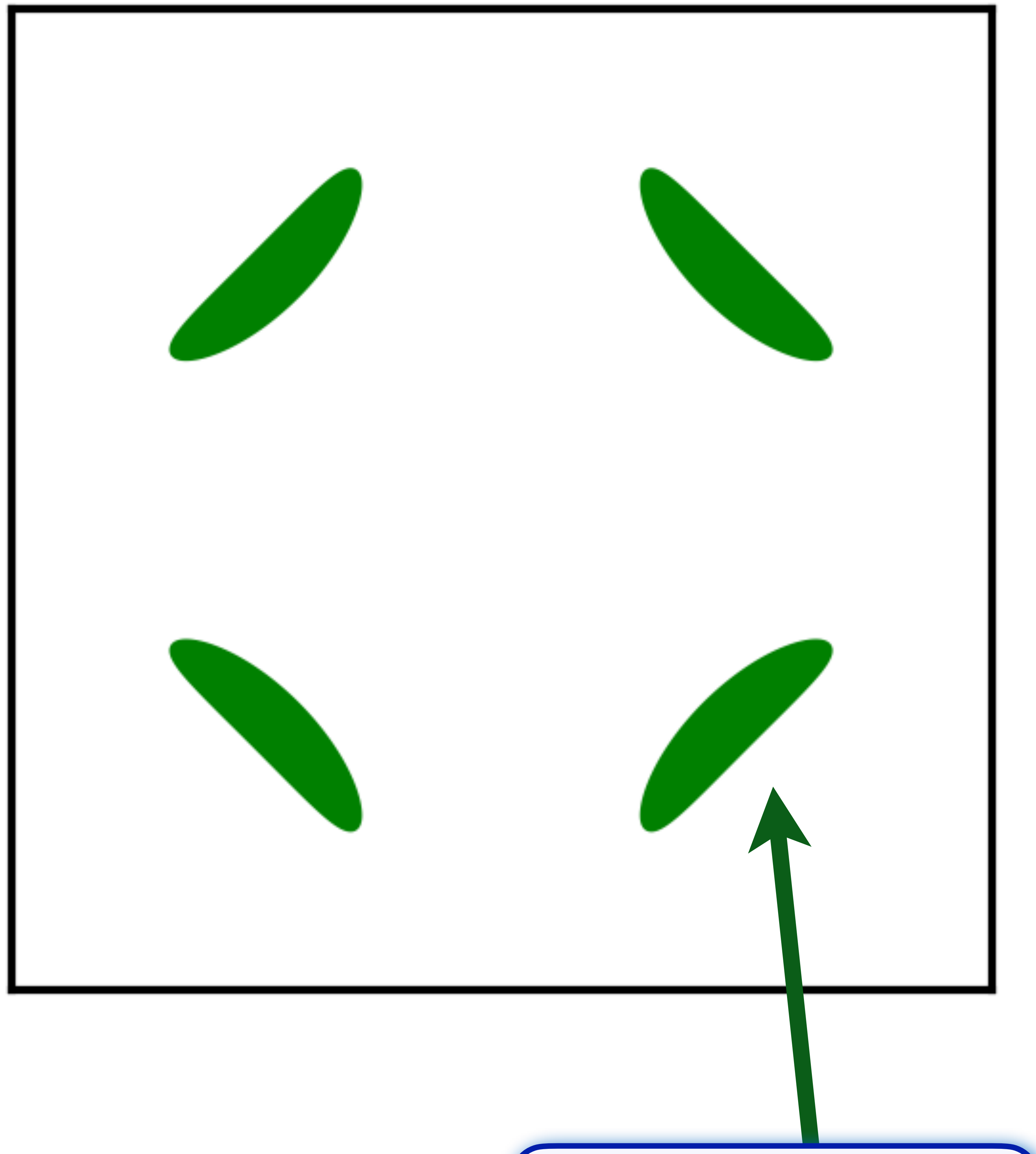
Doping an insulating antiferromagnet with holes of density p

FL*

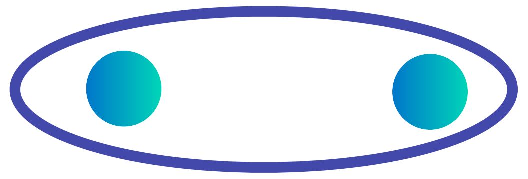
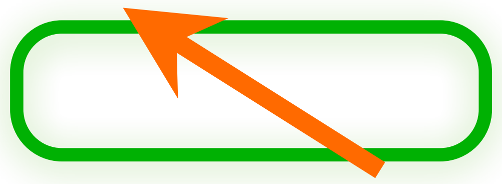
Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

Each green "dimer" is a bound state (a "magnetic polaron") of a vacancy and a free spin





Area $p/8$

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

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003); R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)
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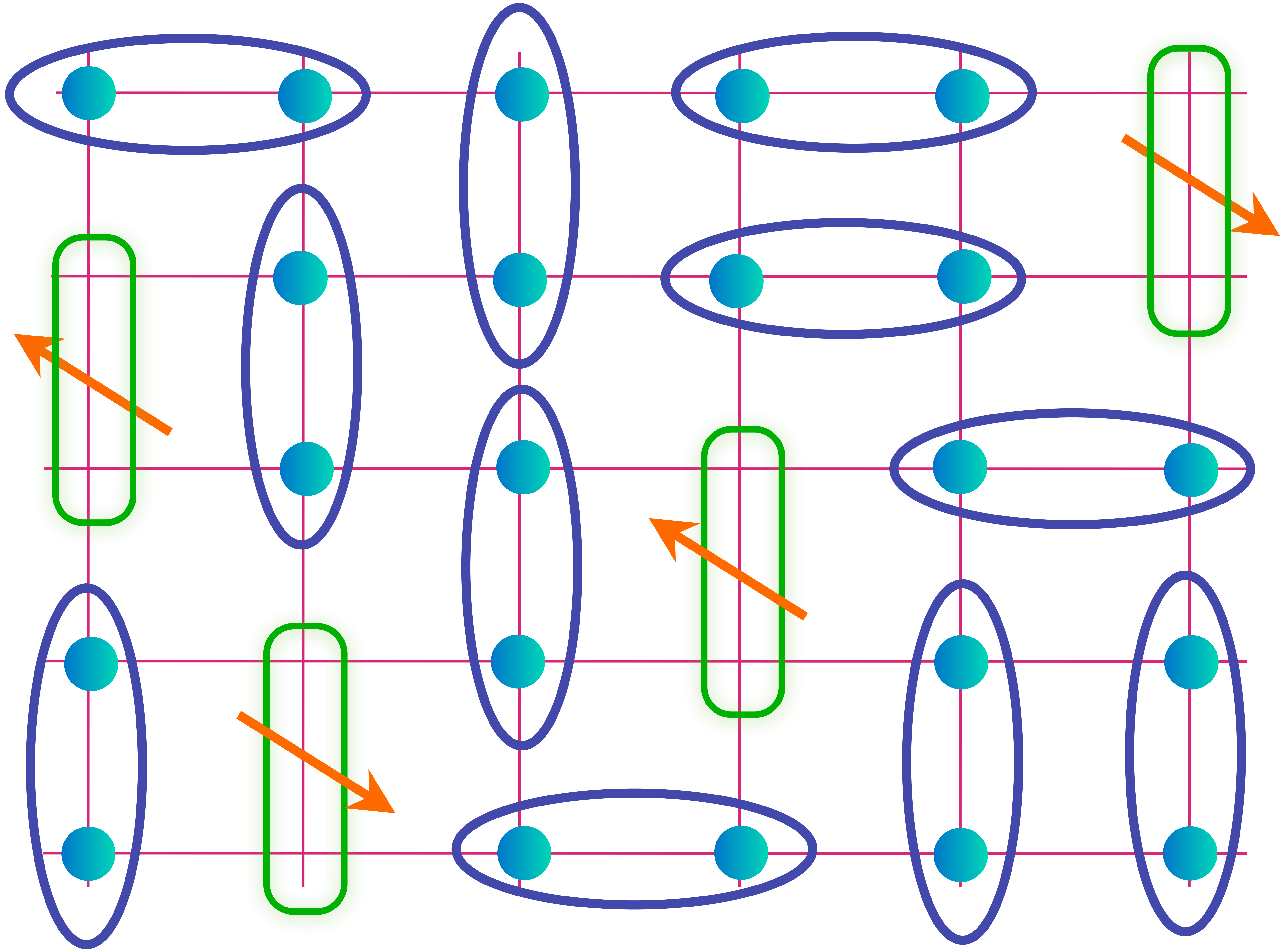
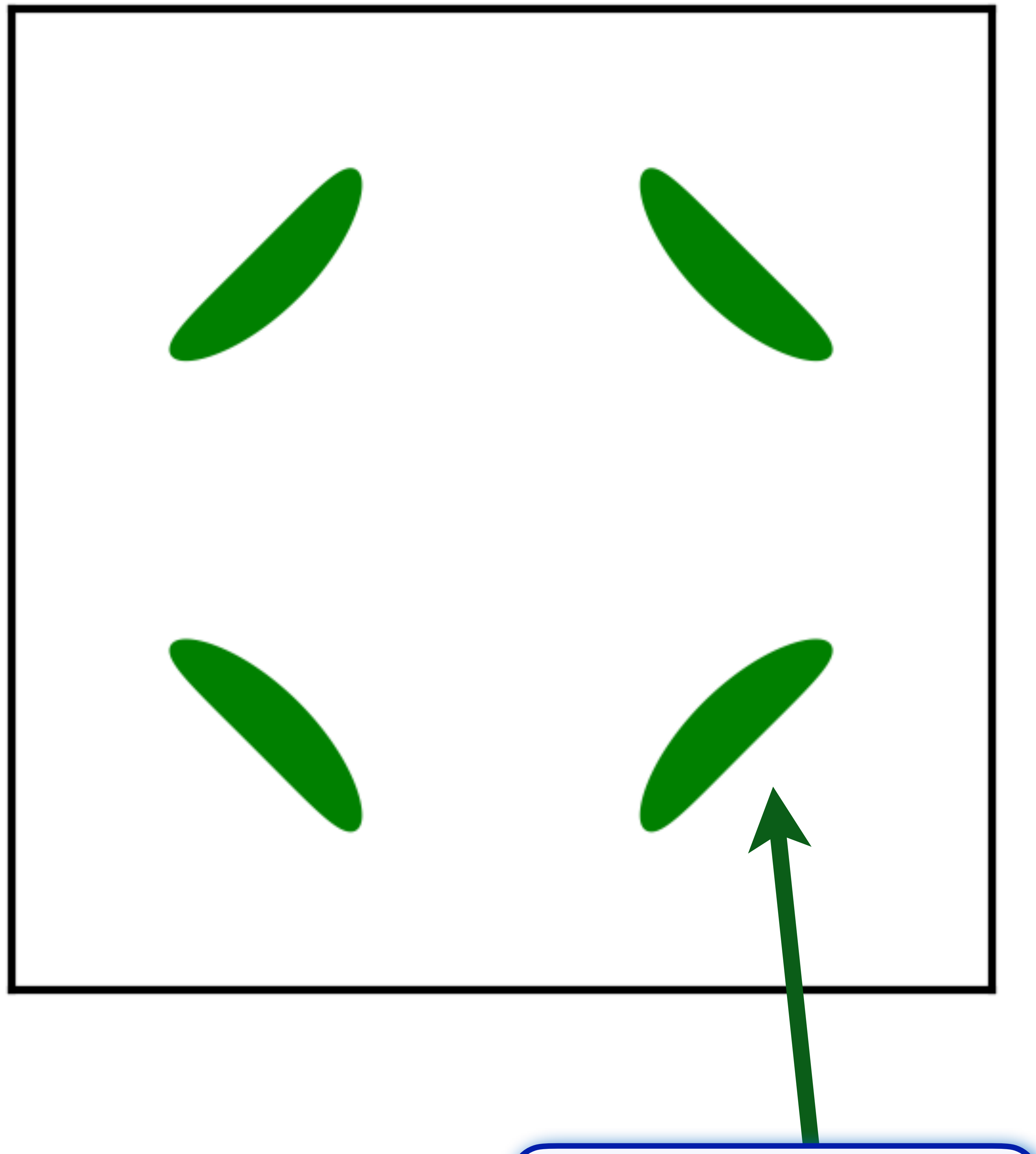
Doping an insulating antiferromagnet with holes of density p

FL*

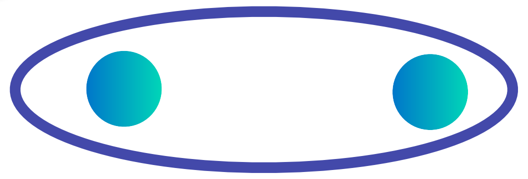
Metal with density p of spin-1/2, charge +e "holes" (or "magnetic polarons") and charge 0 spin-1/2 "spinons".

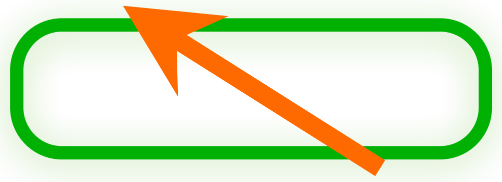


Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



Area $p/8$

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

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

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003); R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)
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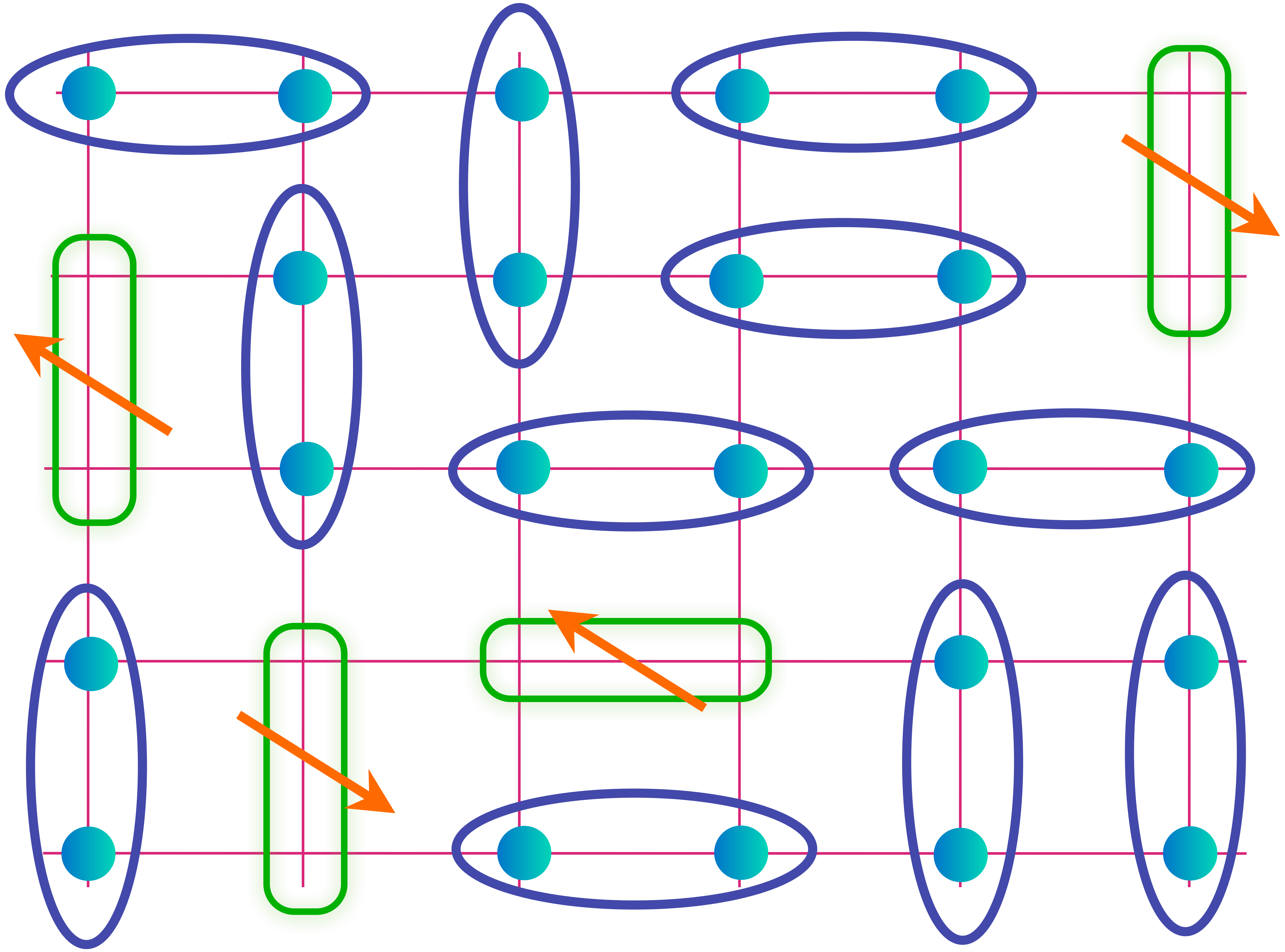
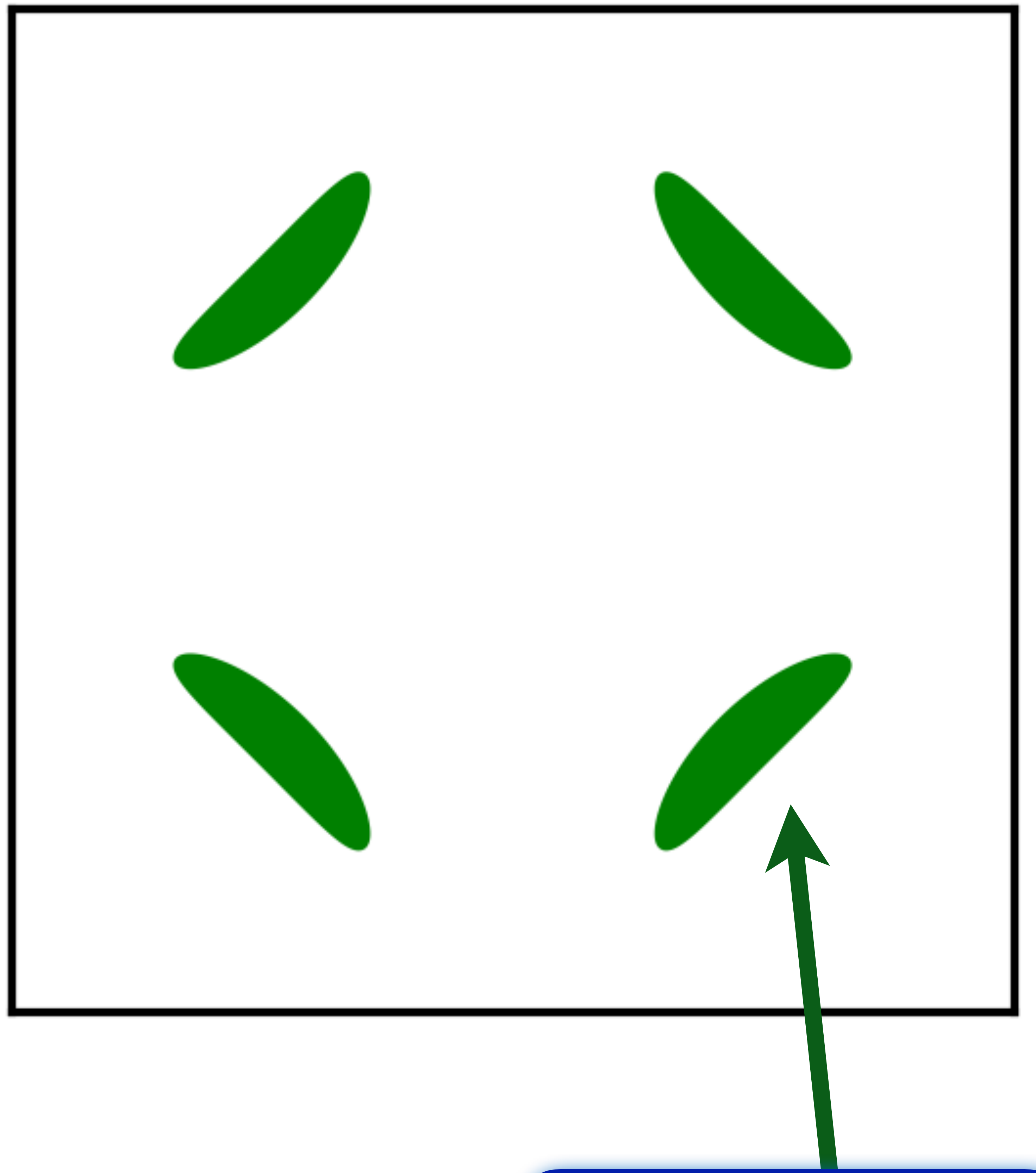


Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



Area $p/8$

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

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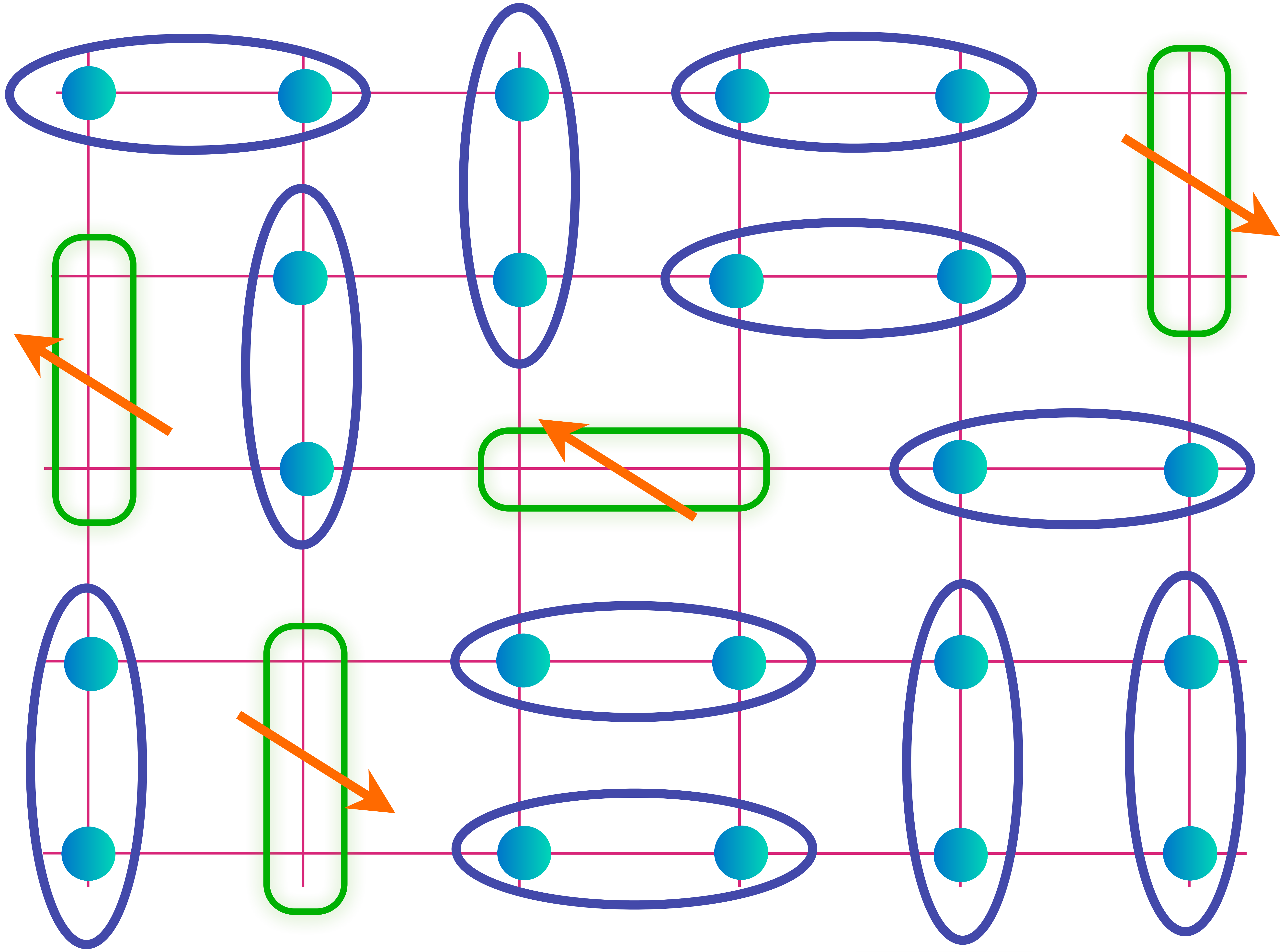

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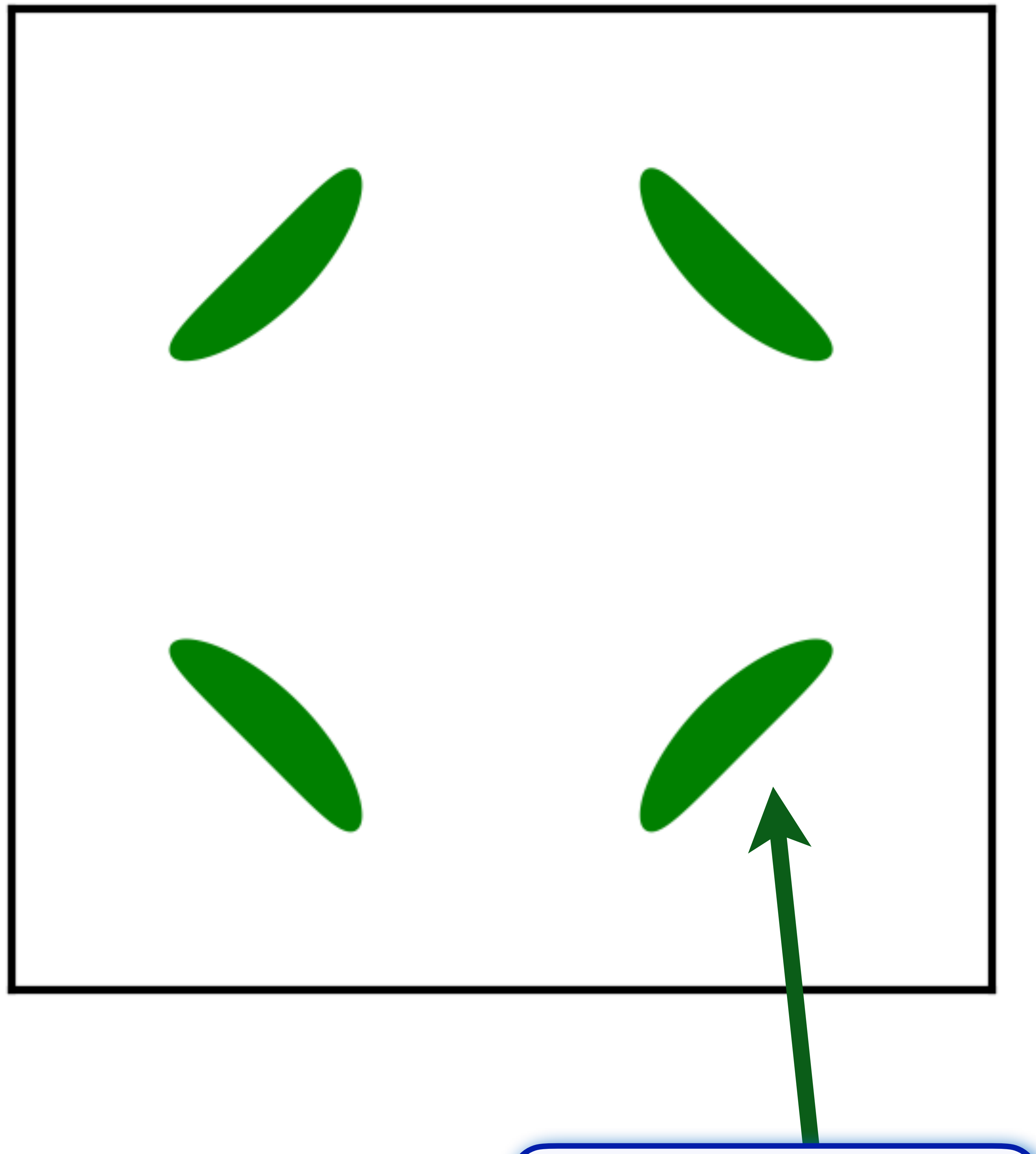
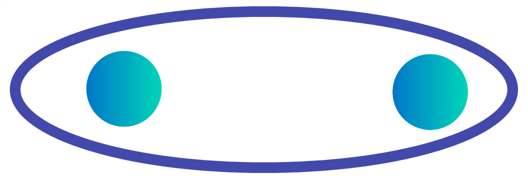
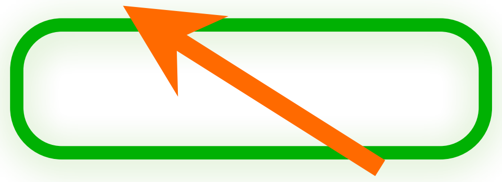


Area $p/8$

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

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

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FL*

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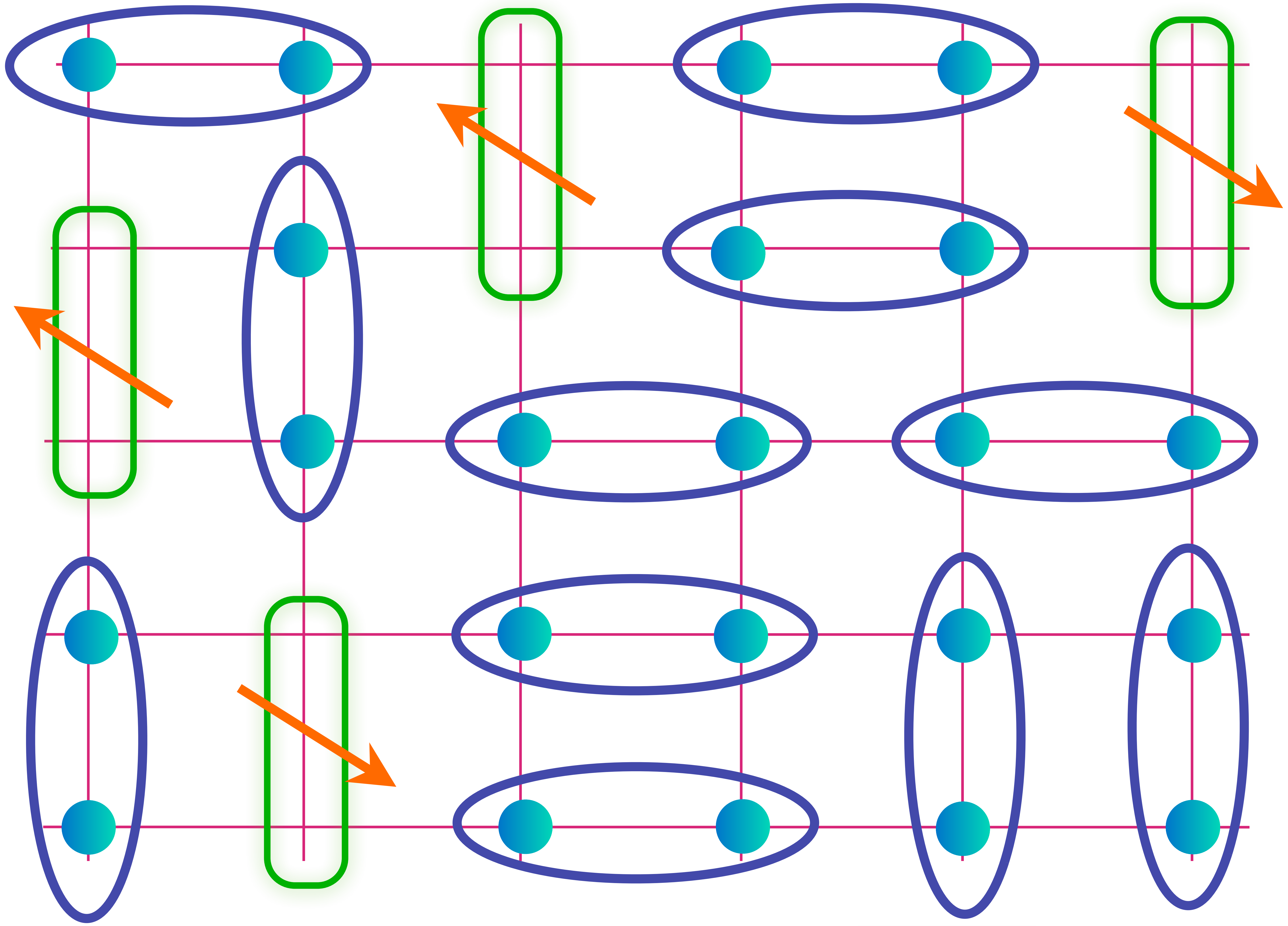
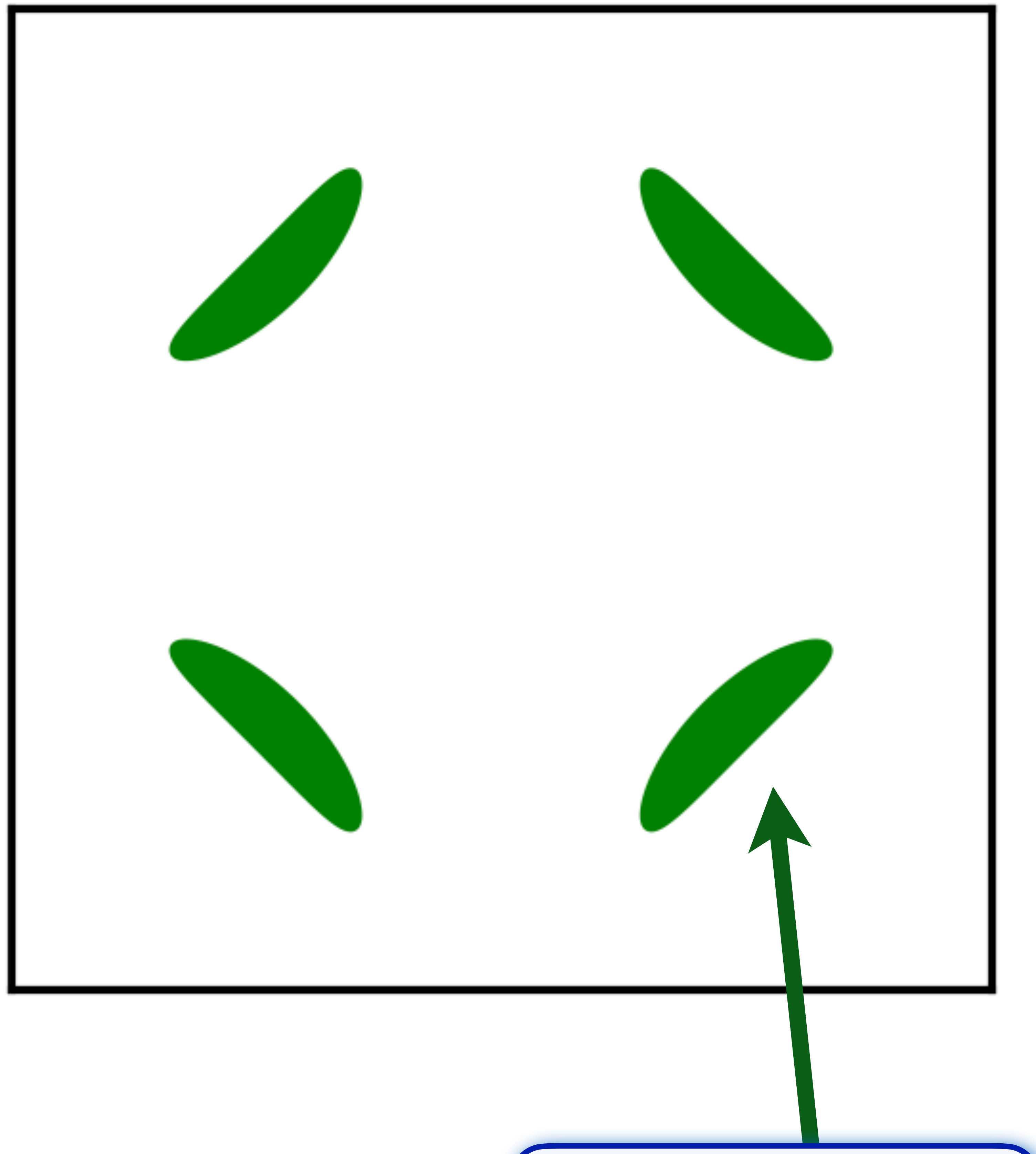
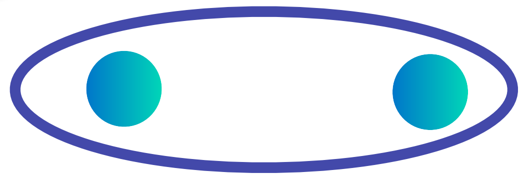
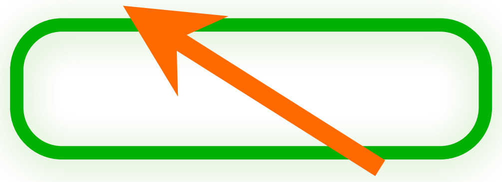




Area $p/8$

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

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

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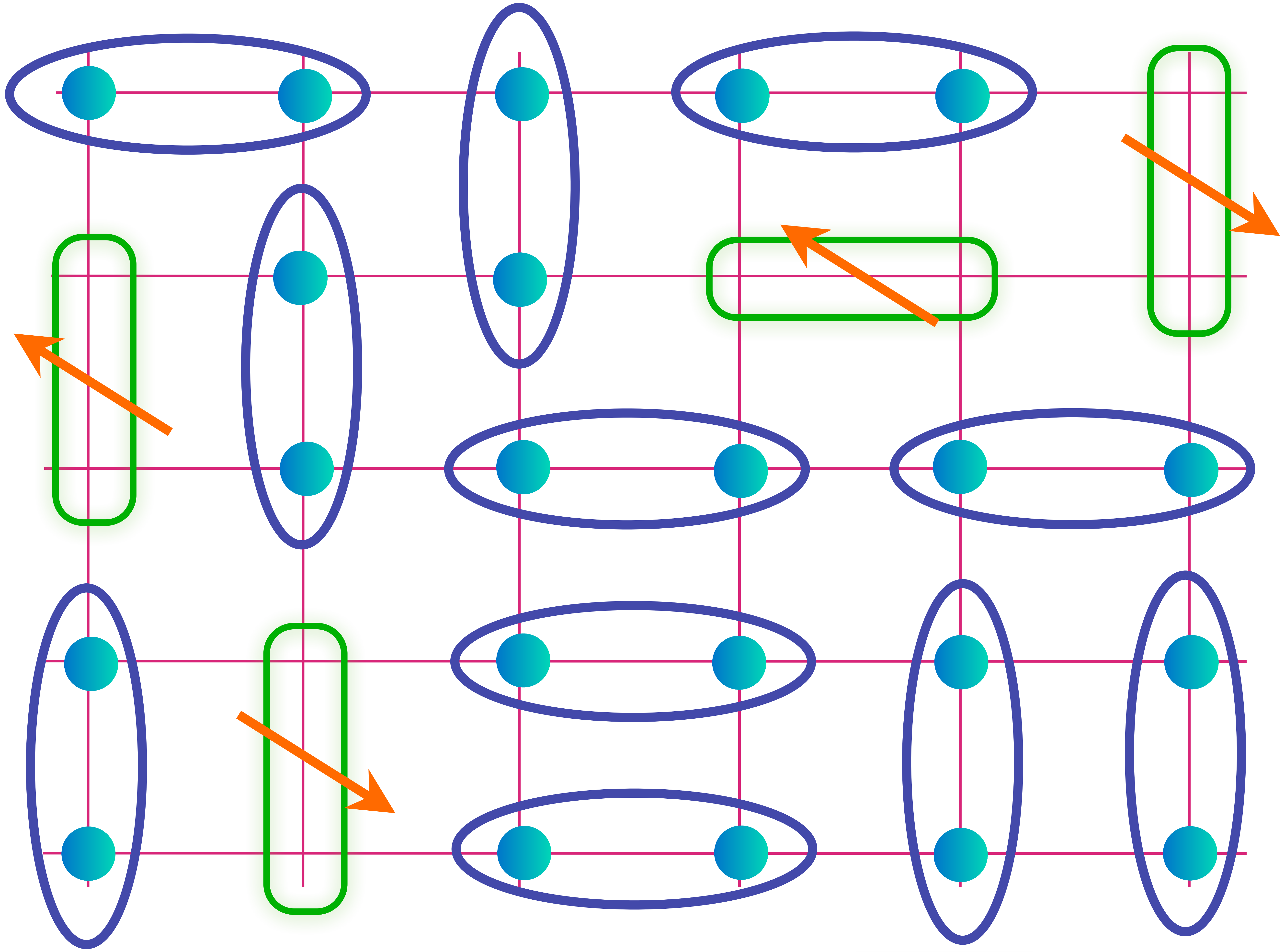

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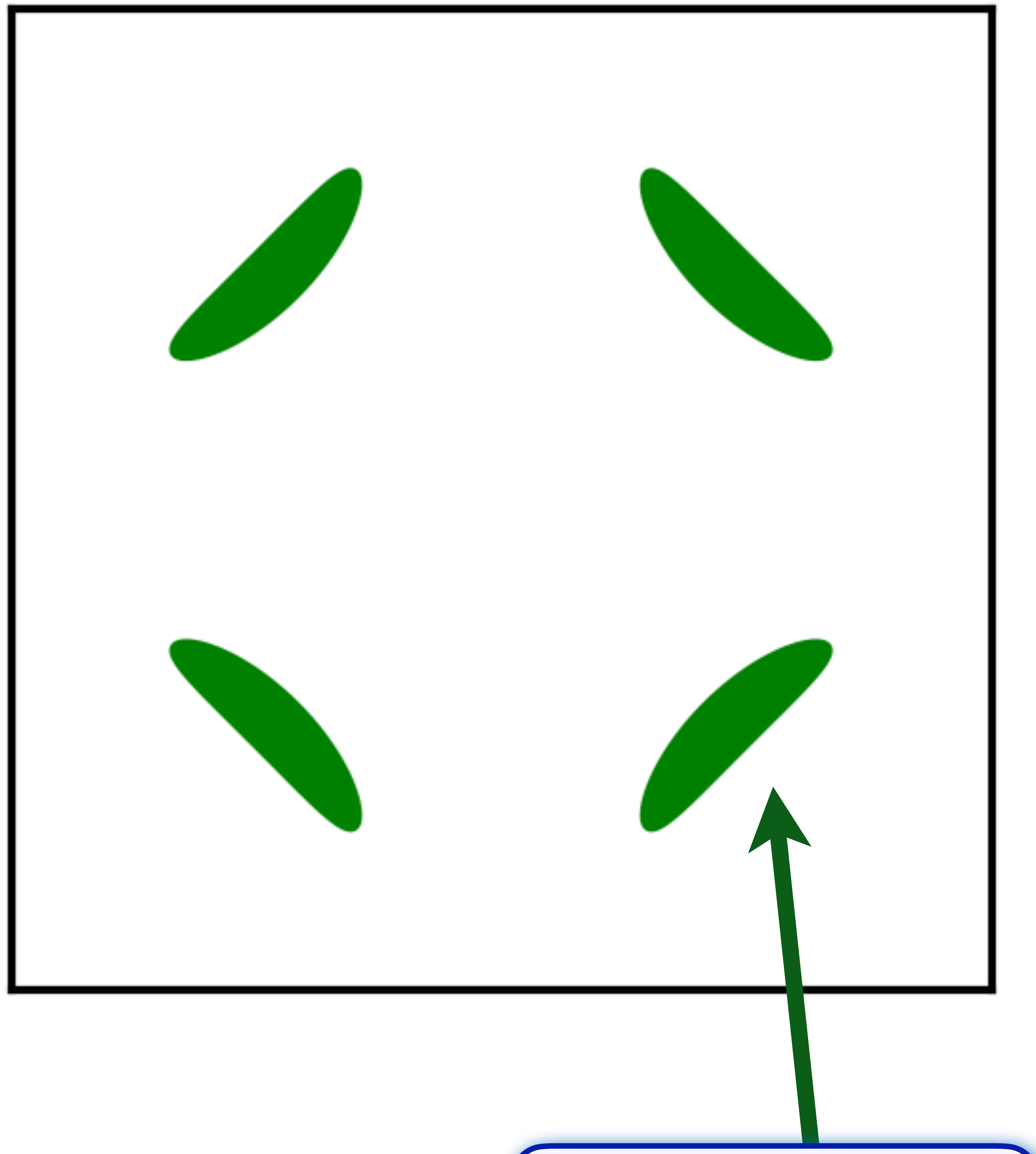
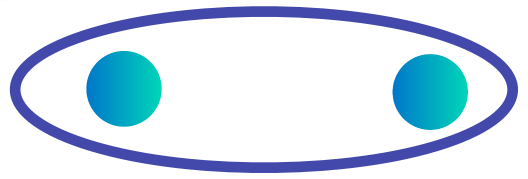
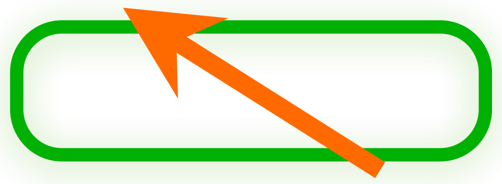


Area $p/8$

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

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

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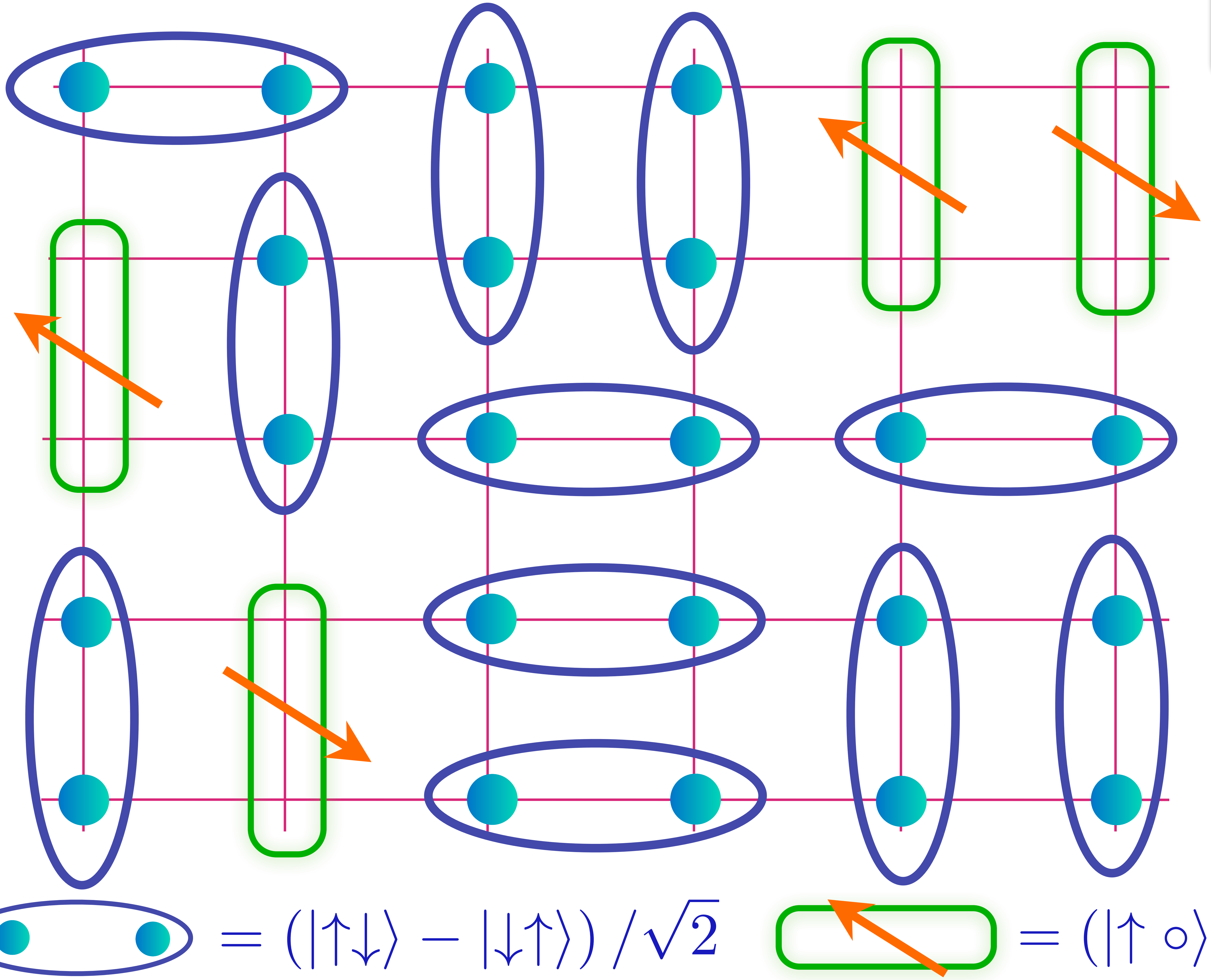
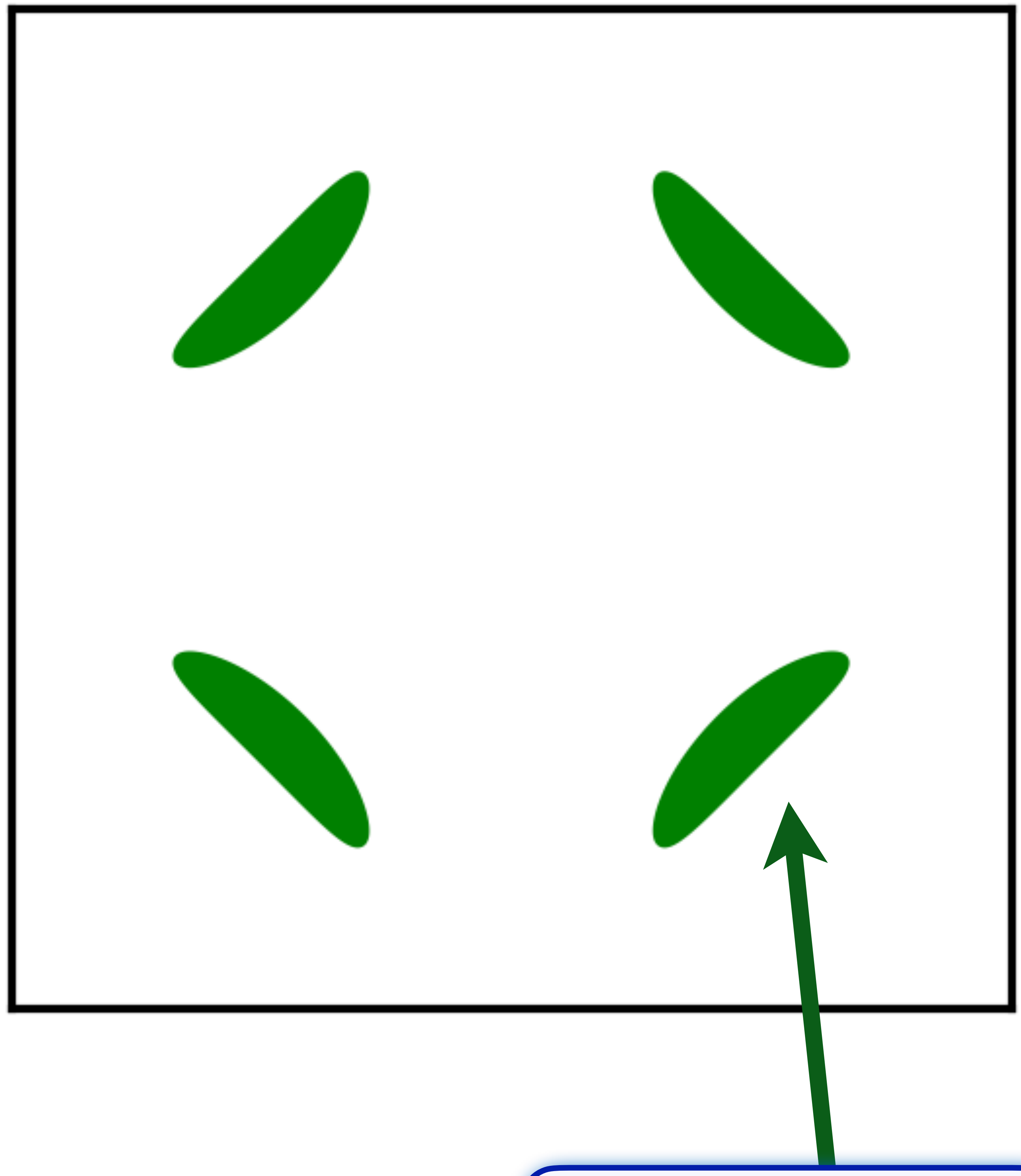


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2} \qquad = \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$$

Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)



Area $p/8$

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003); R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)
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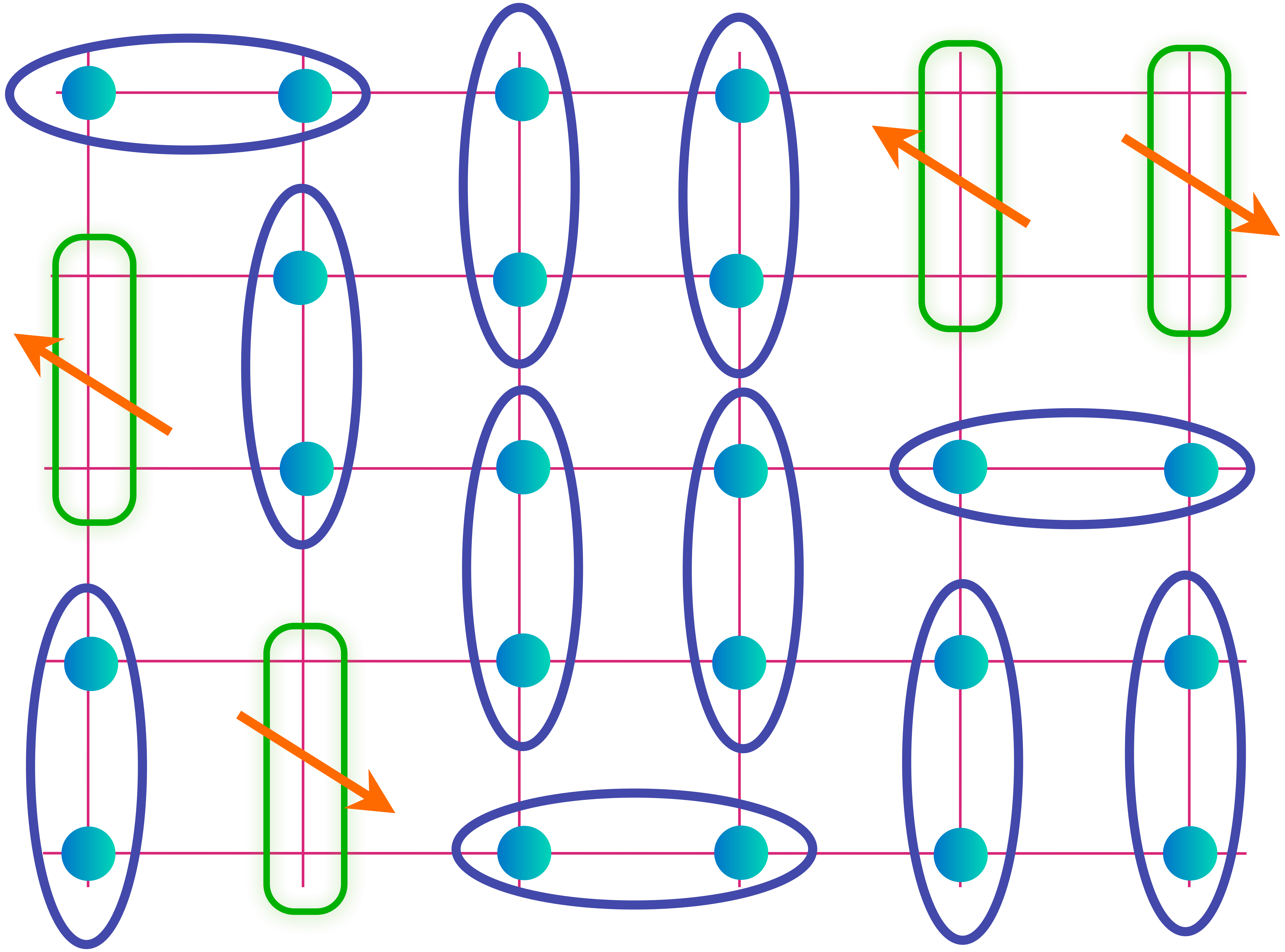

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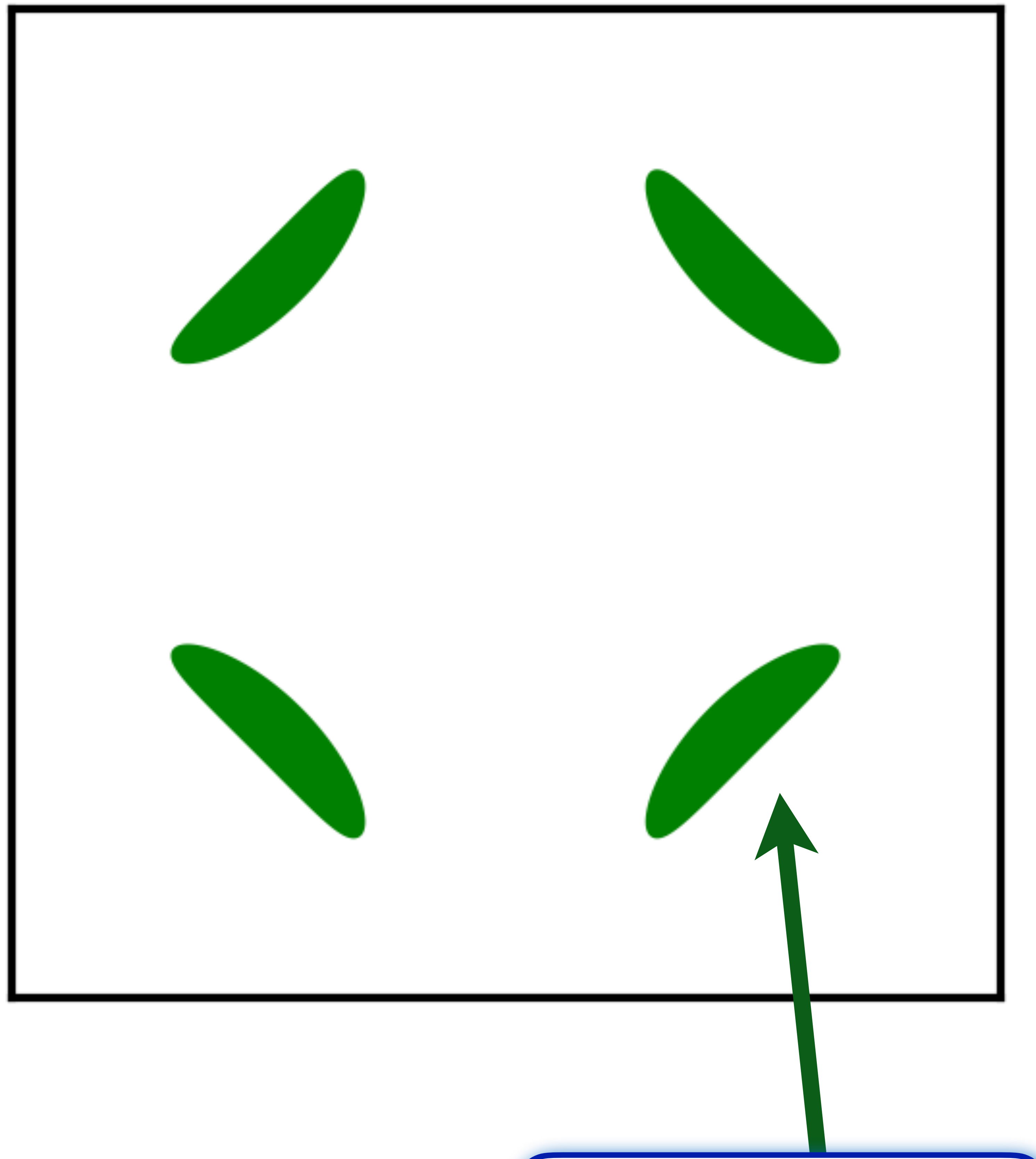
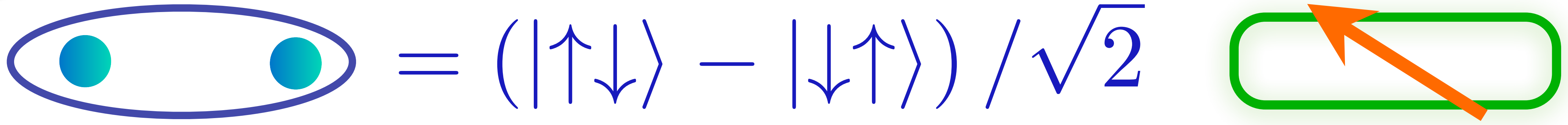


Area $p/8$



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

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003); R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)
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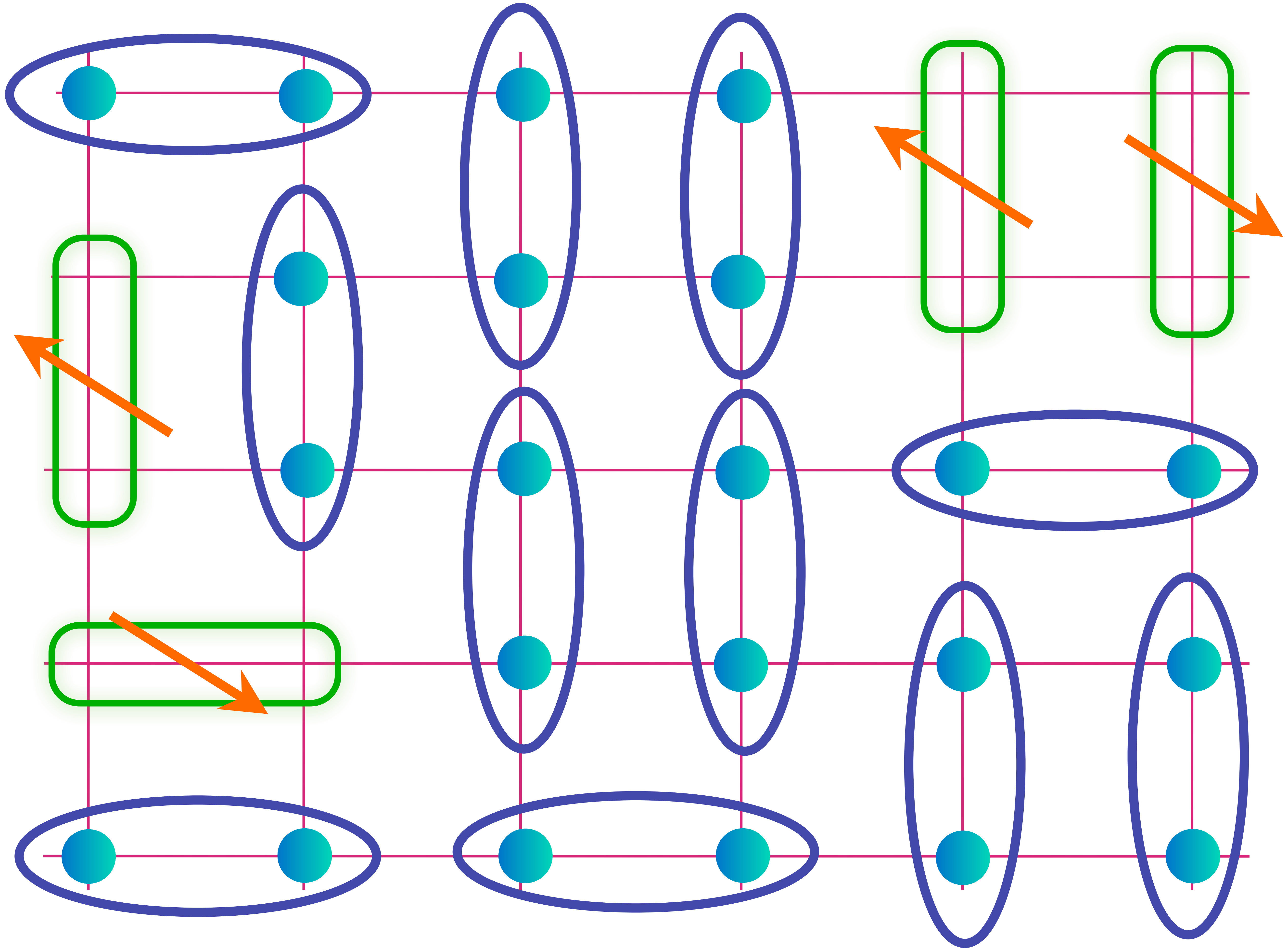

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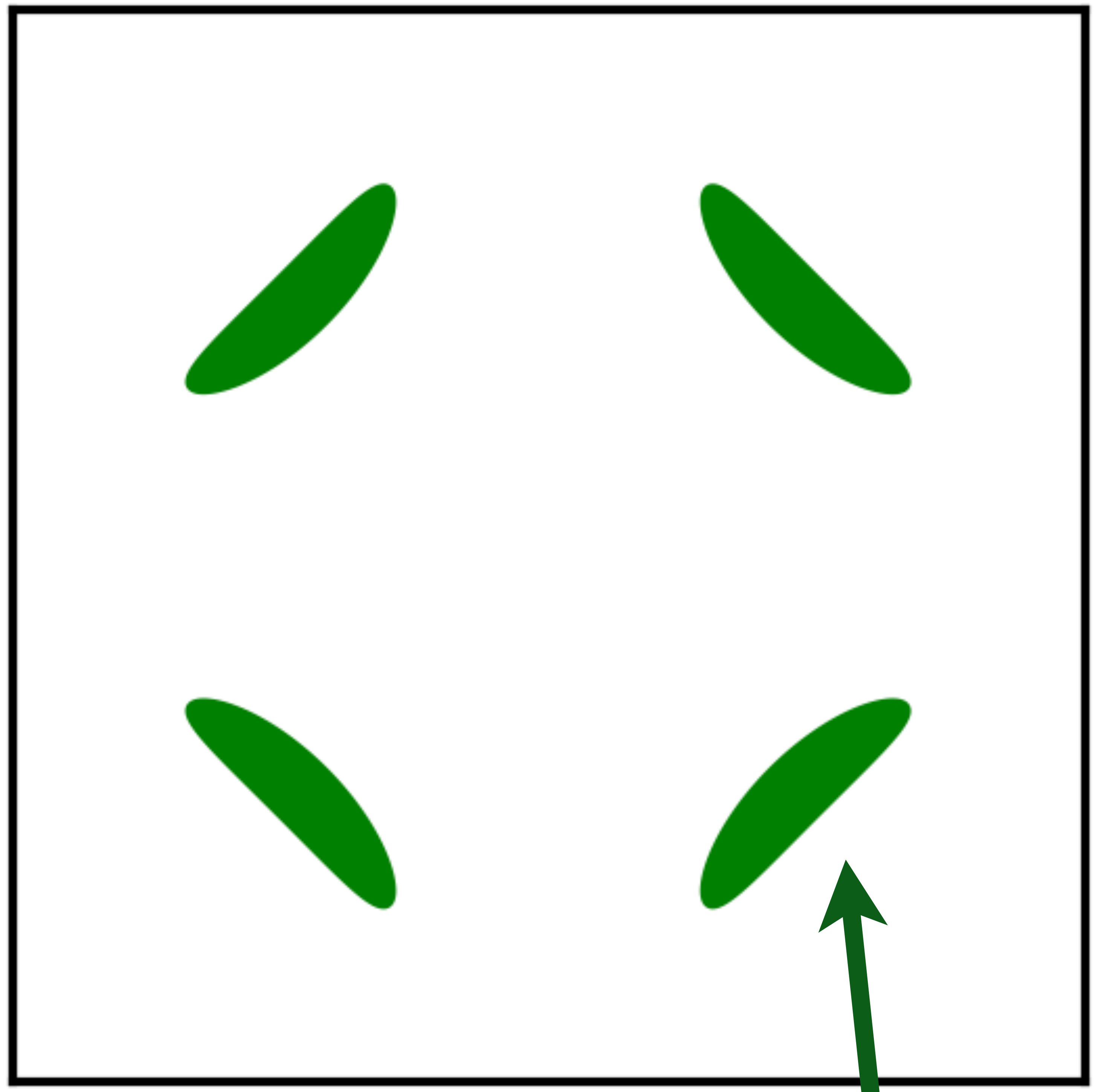

Area $p/8$

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

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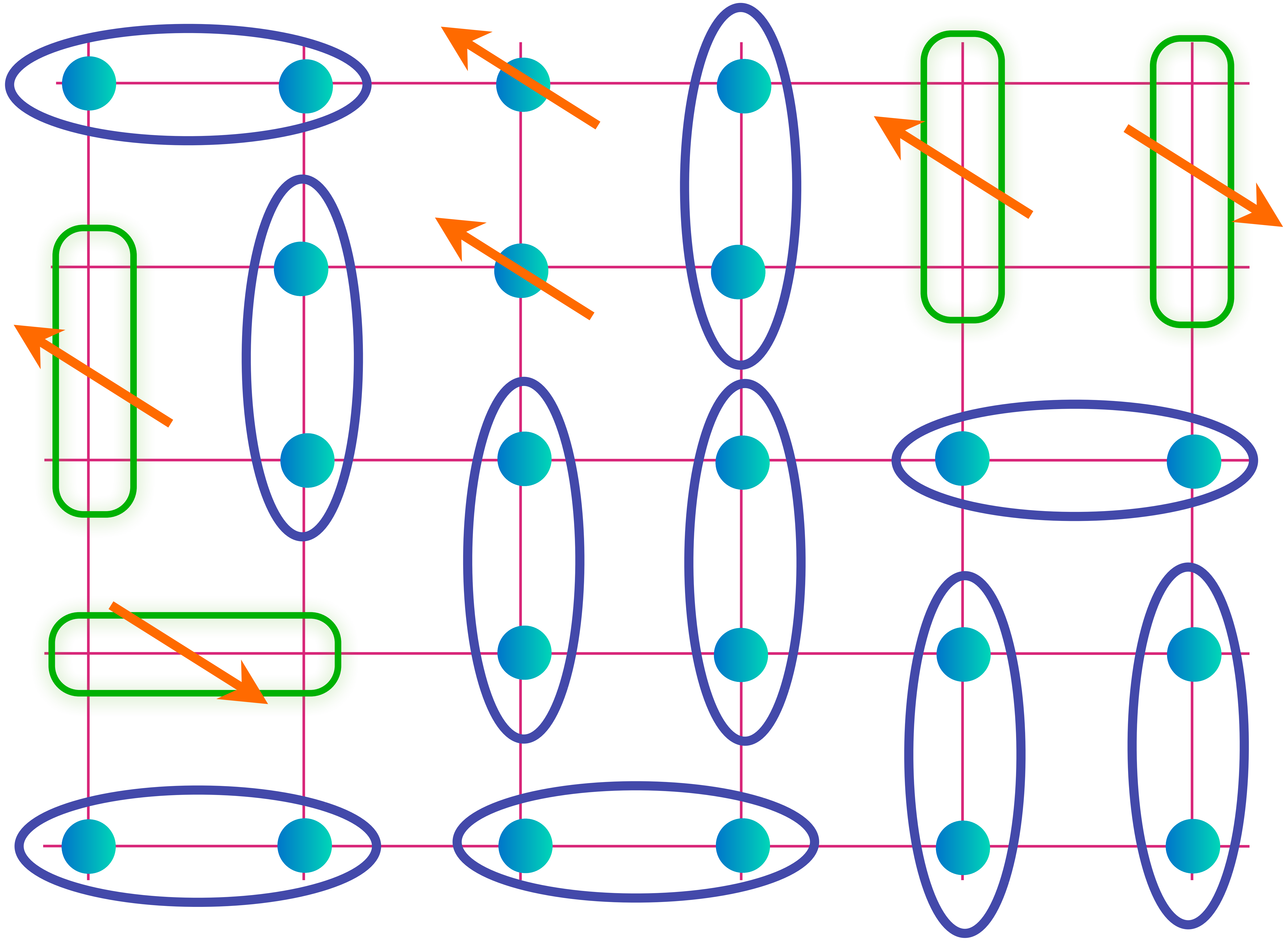
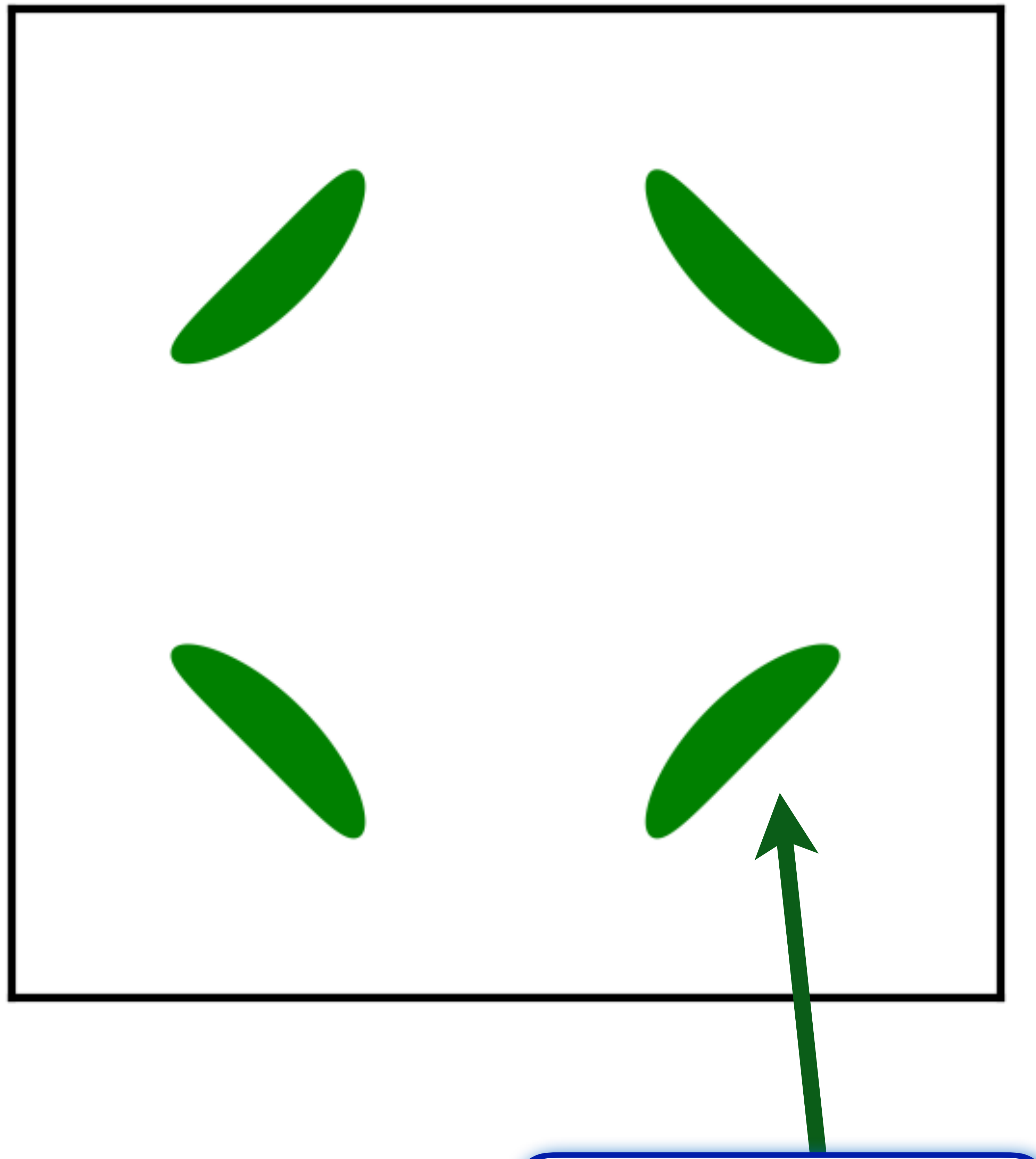
Doping an insulating antiferromagnet with holes of density p

FL*

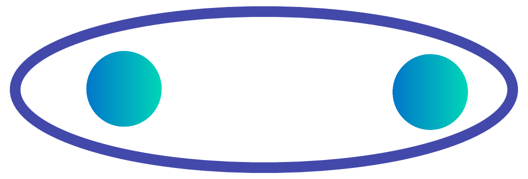
Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

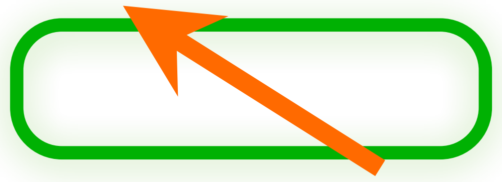
The FL* state retains the spinon excitations





Area $p/8$

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

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

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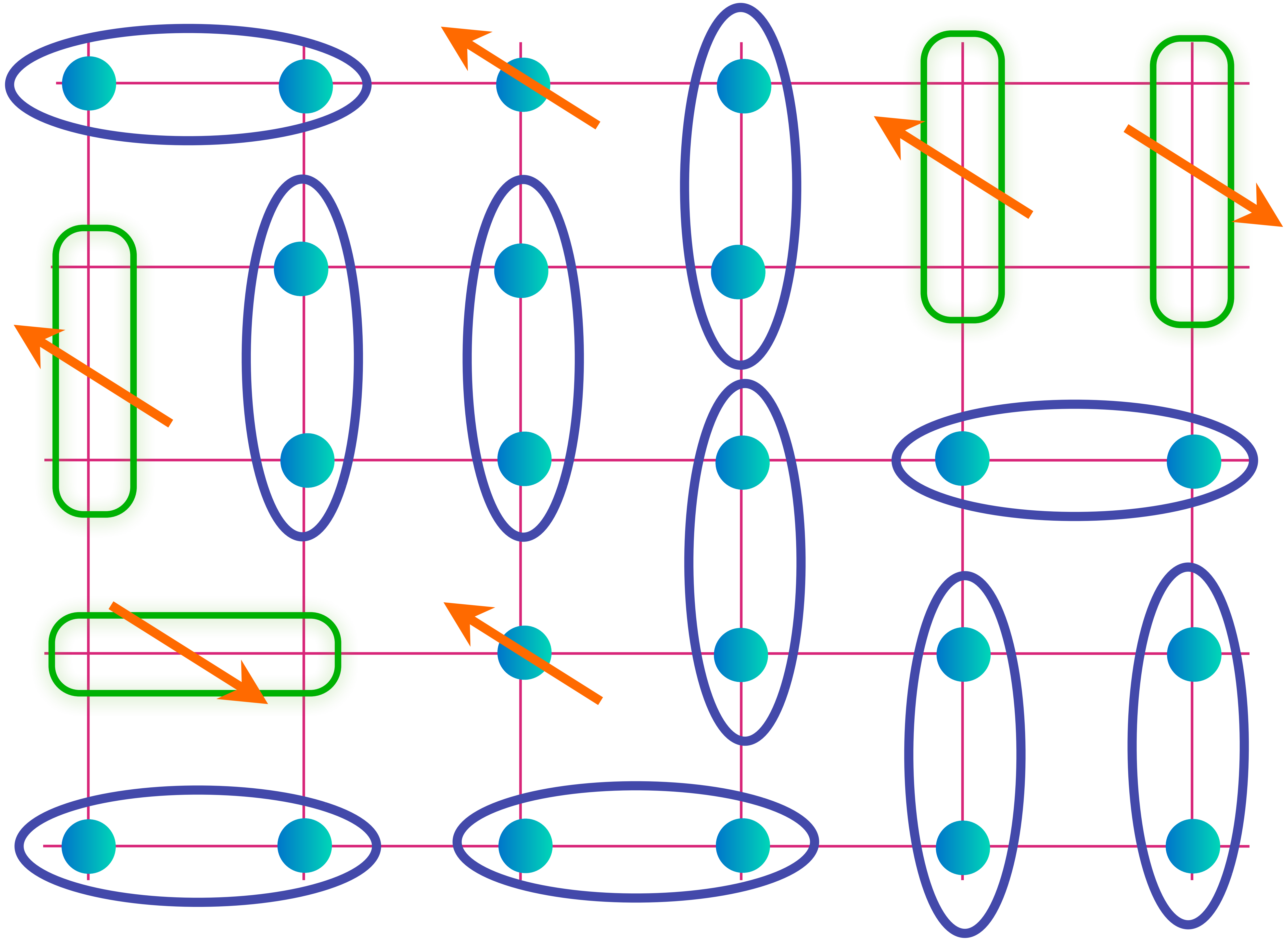
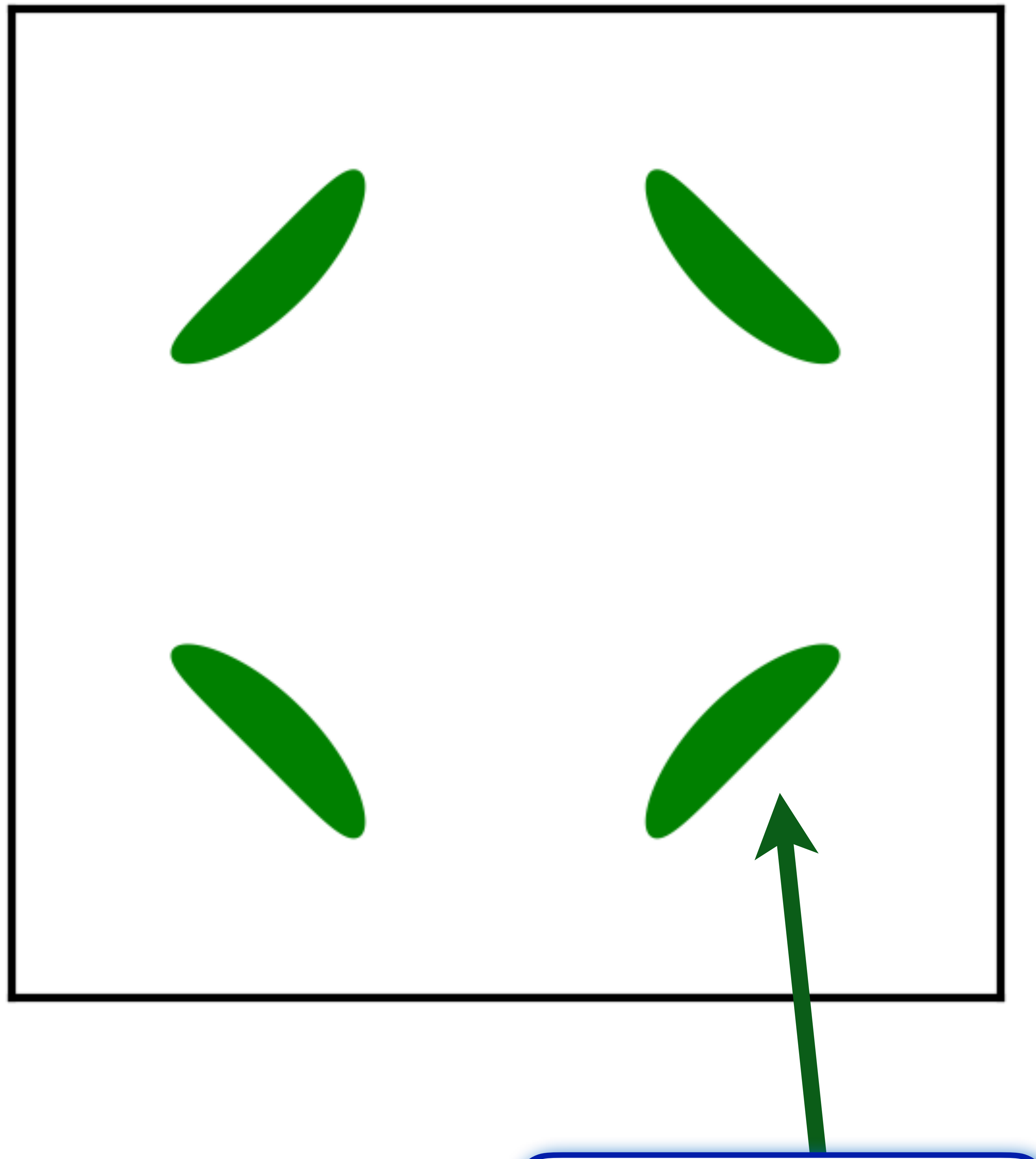
Doping an insulating antiferromagnet with holes of density p

FL*

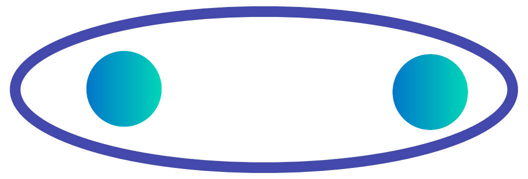
Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

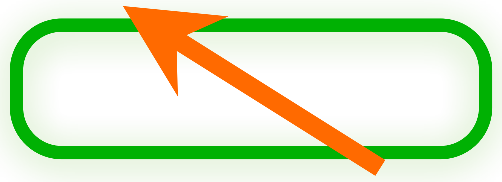
The FL* state retains the spinon excitations





Area $p/8$

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

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

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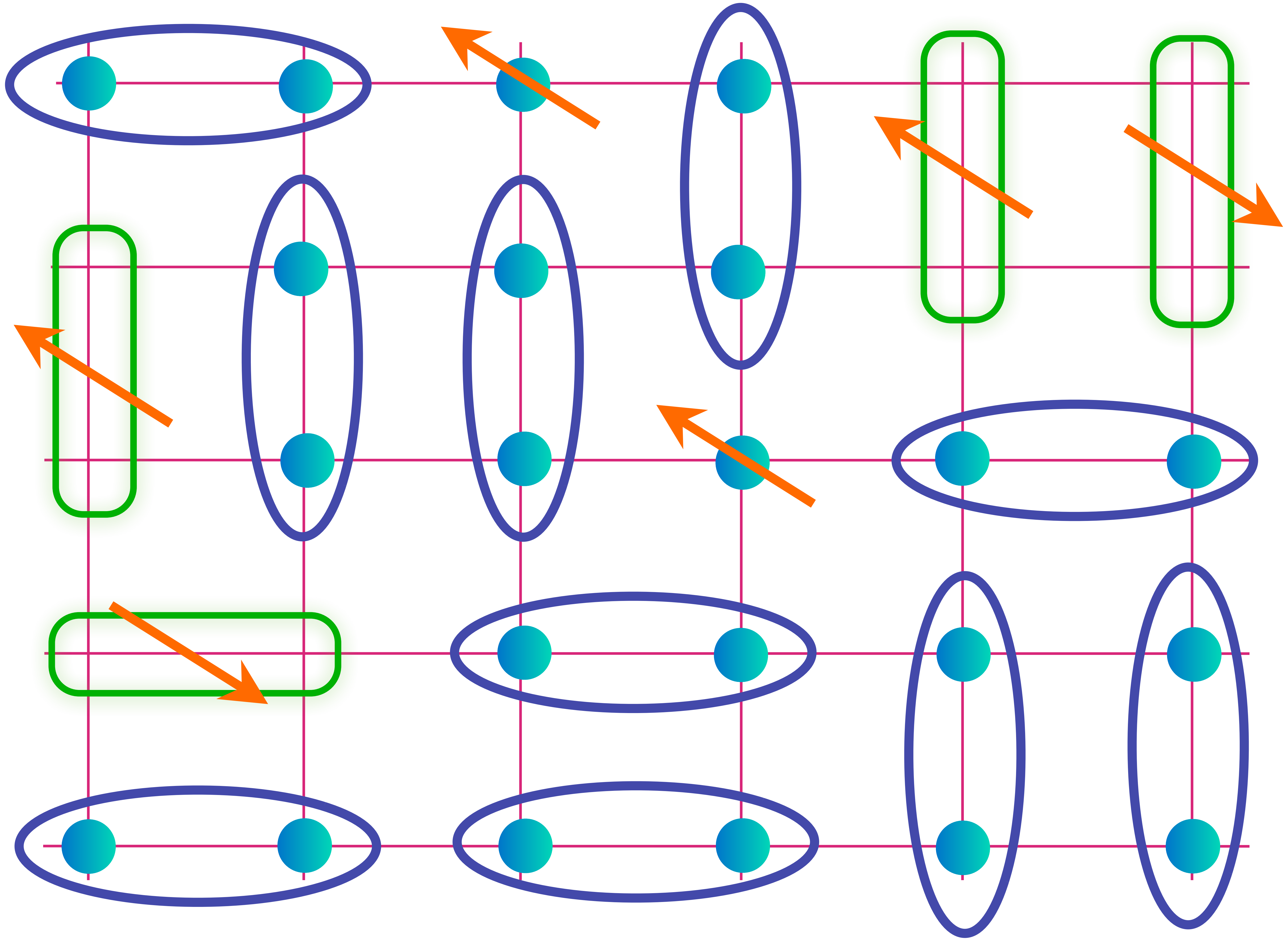
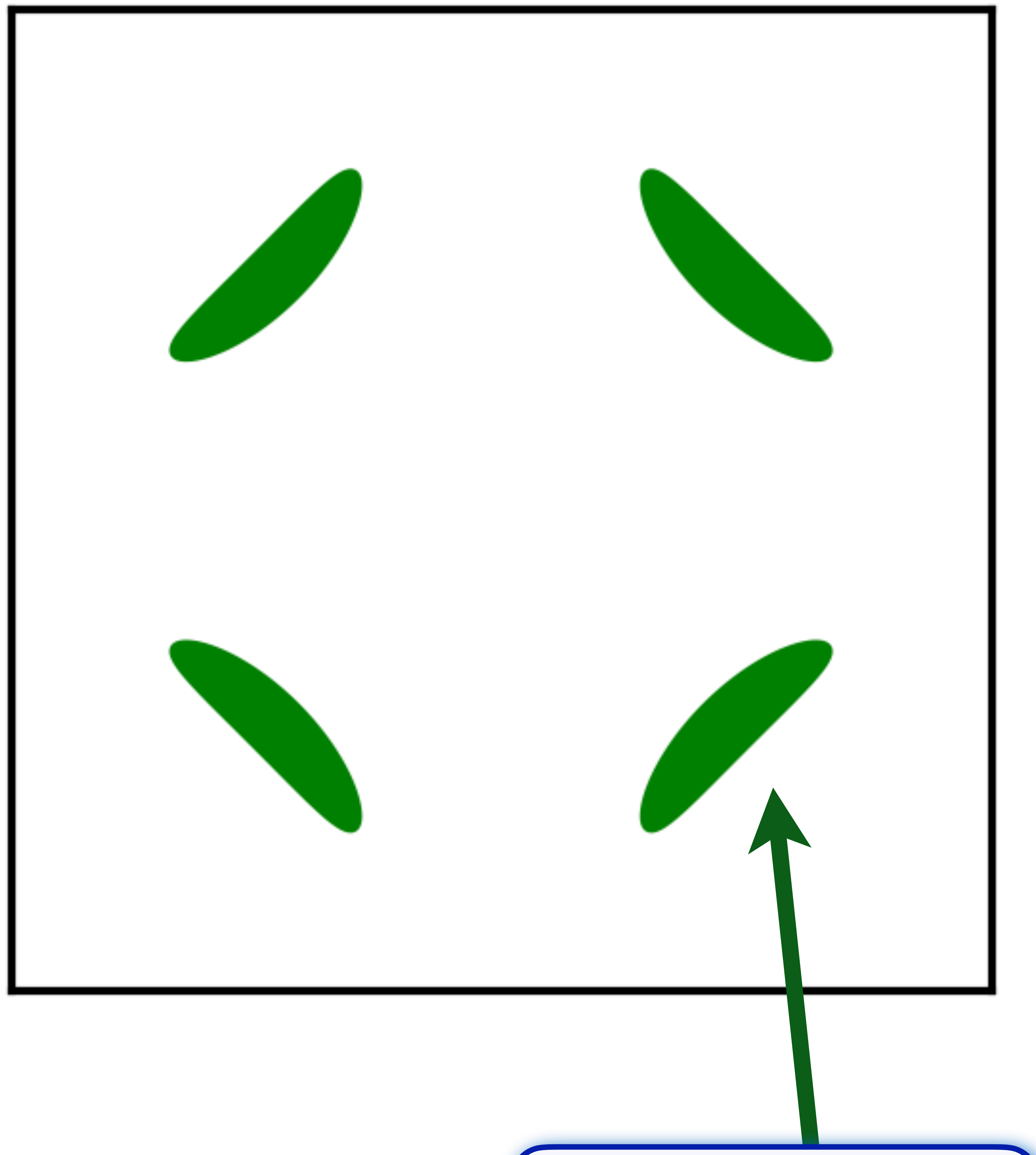
Doping an insulating antiferromagnet with holes of density p

FL*

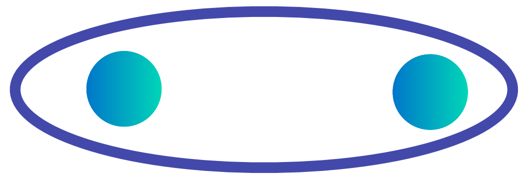
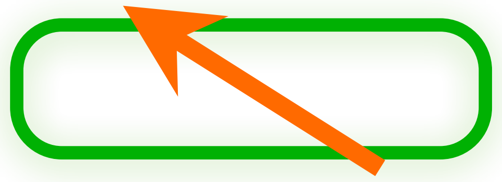
Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

The FL* state retains the spinon excitations





Area $p/8$

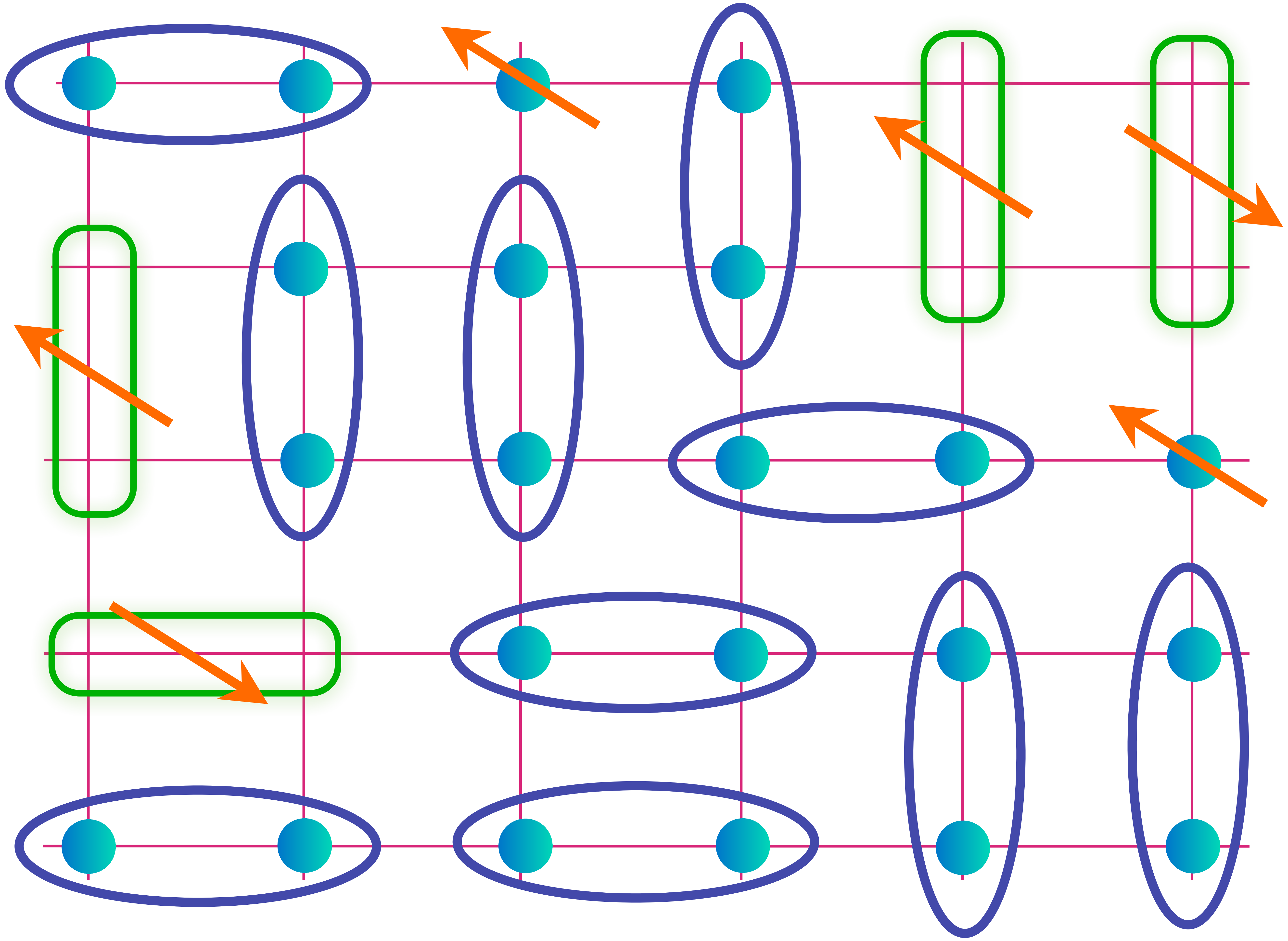
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$  $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003); R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

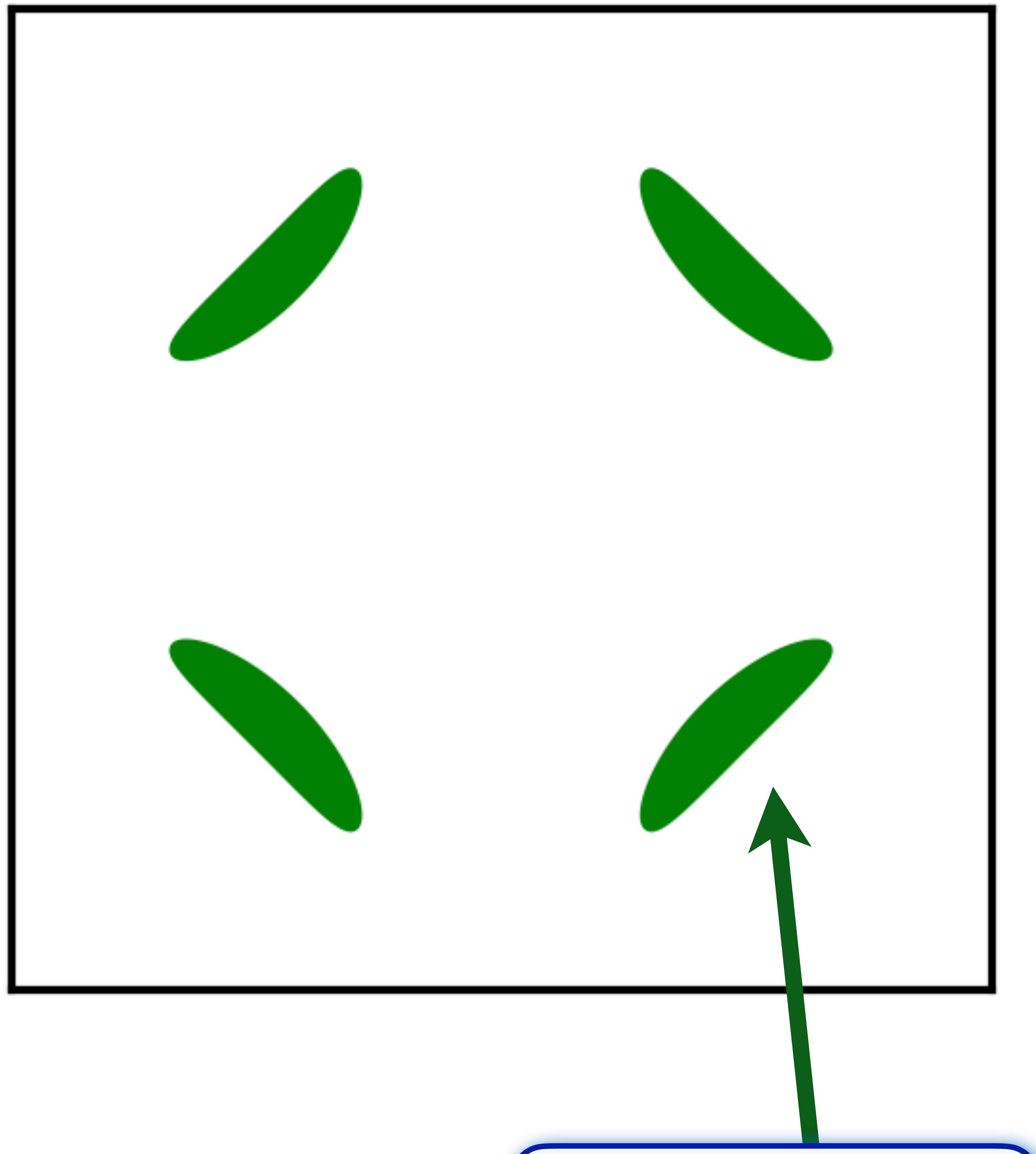
Doping an insulating antiferromagnet with holes of density p

FL*

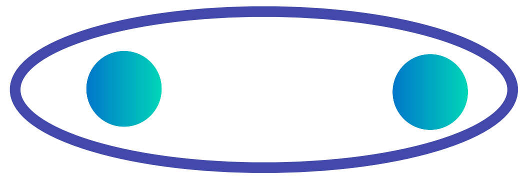
Oshikawa anomaly is satisfied by sum of spin liquid (1) and Fermi surface anomalies (p)

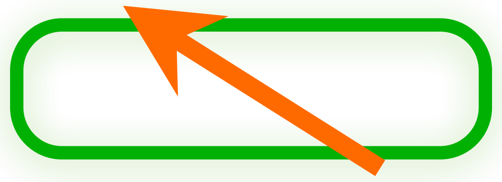


The FL* state retains the spinon excitations



Area $p/8$

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

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

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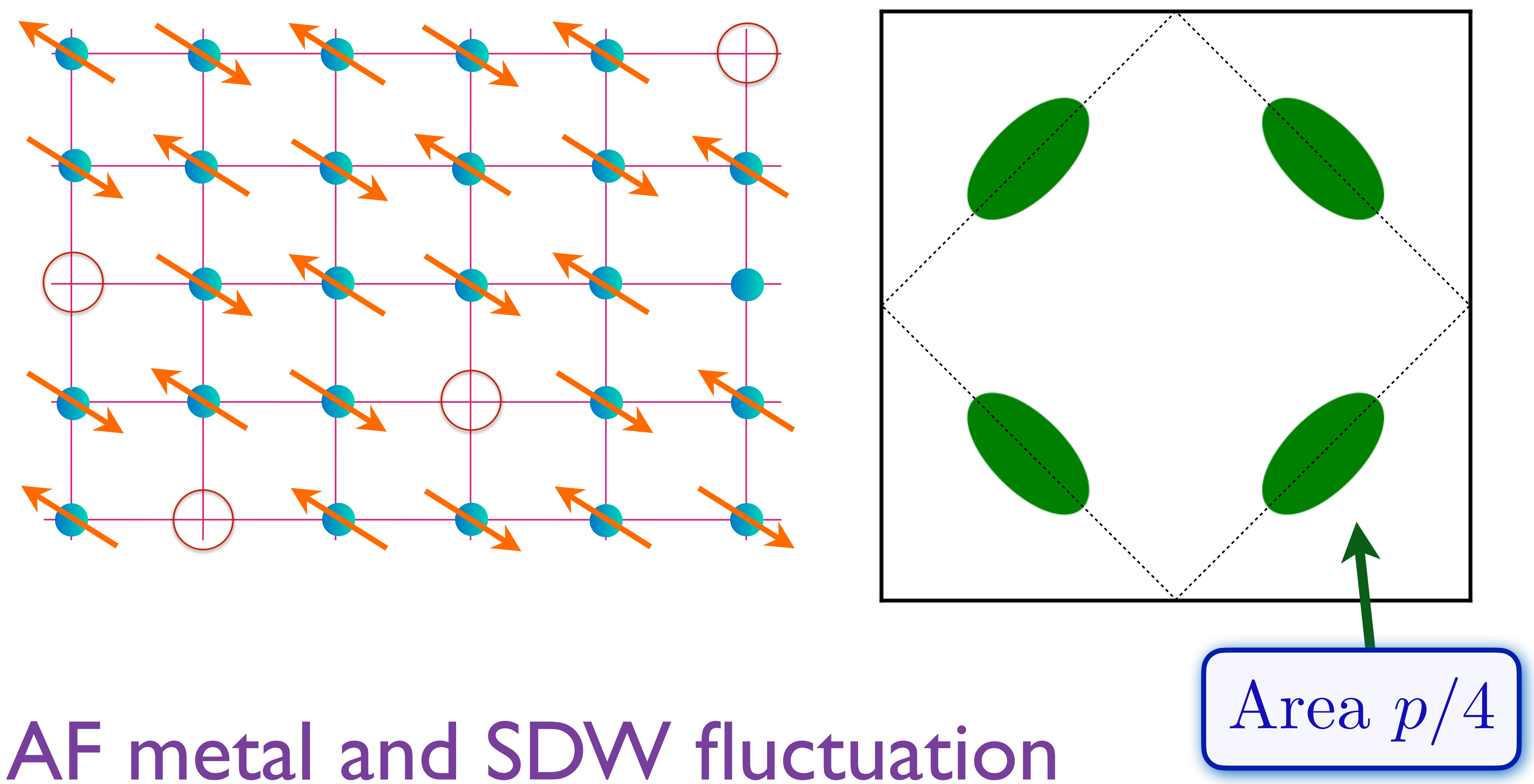
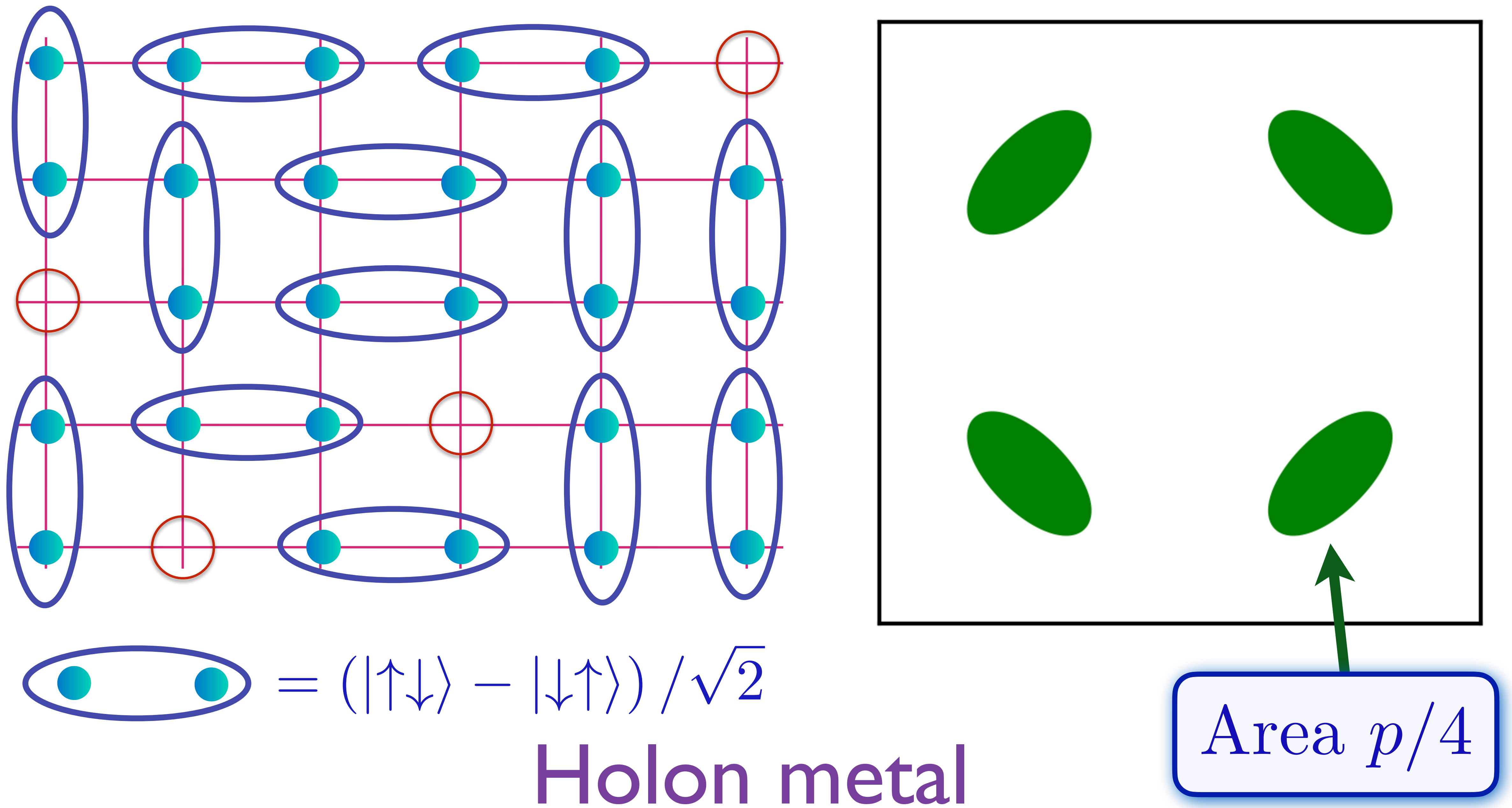
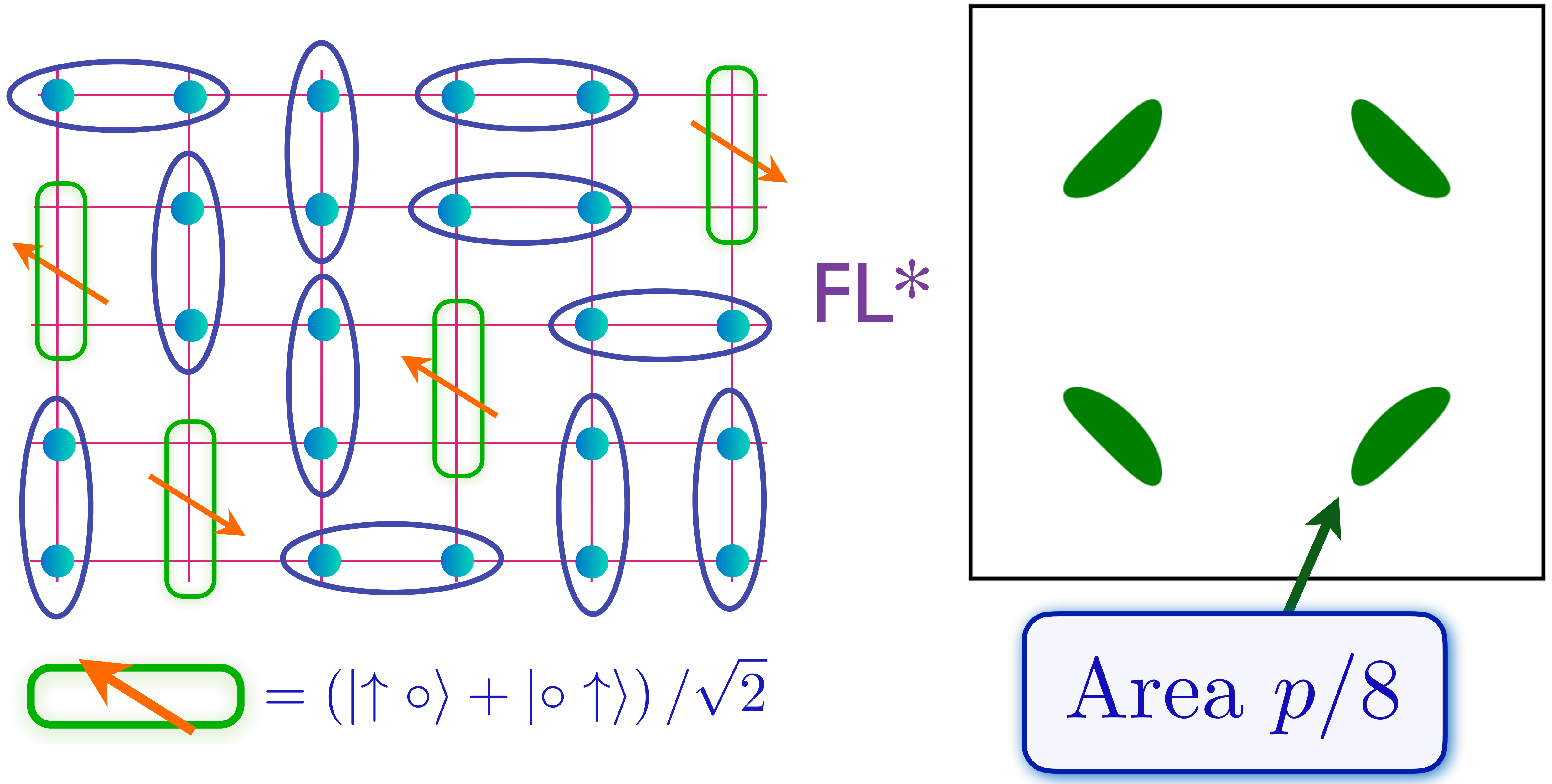


AF metal and SDW fluctuation



Holon metal

T. Senthil, S. S., M. Vojta, PRL **90**, 216403 (2003);
R. K. Kaul, A. Kolezhuk, M. Levin, S.S., T. Senthil, PRB **75**, 235122 (2007)
M. Punk, A. Allais, and S. S., PNAS **112**, 9552 (2015)
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, S. S., PRB **105**, 075146 (2022)

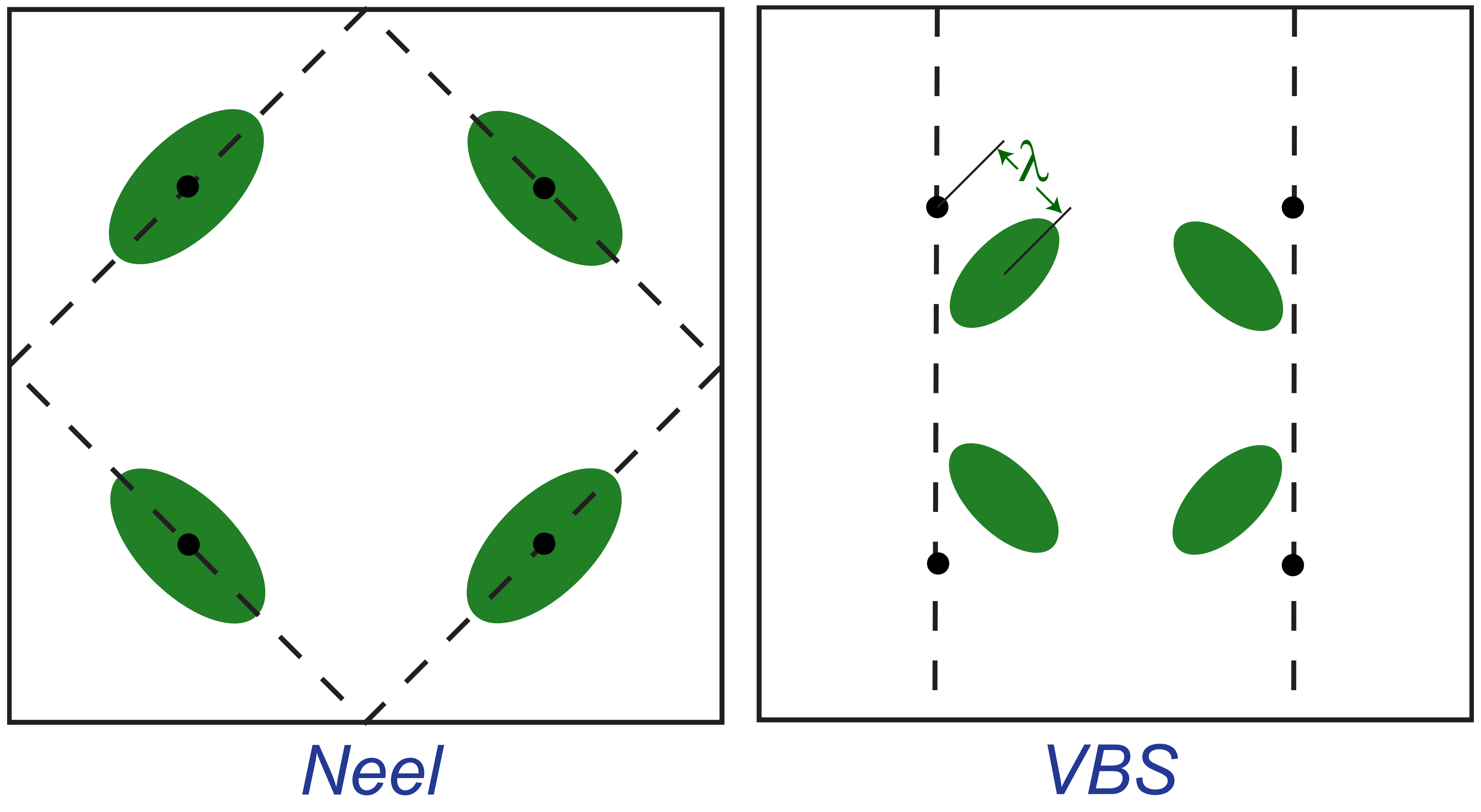


Fermi surface areas are *quantized* and robust to all corrections!
Factor of 2 between SDW fluctuation and FL*

PHYSICAL REVIEW B **75**, 235122 (2007)

Hole dynamics in an antiferromagnet across a deconfined quantum critical point

Ribhu K. Kaul,[1] Alexei Kolezhuk,[1,2] Michael Levin,[1] Subir Sachdev,[1] and T. Senthil[3,4]



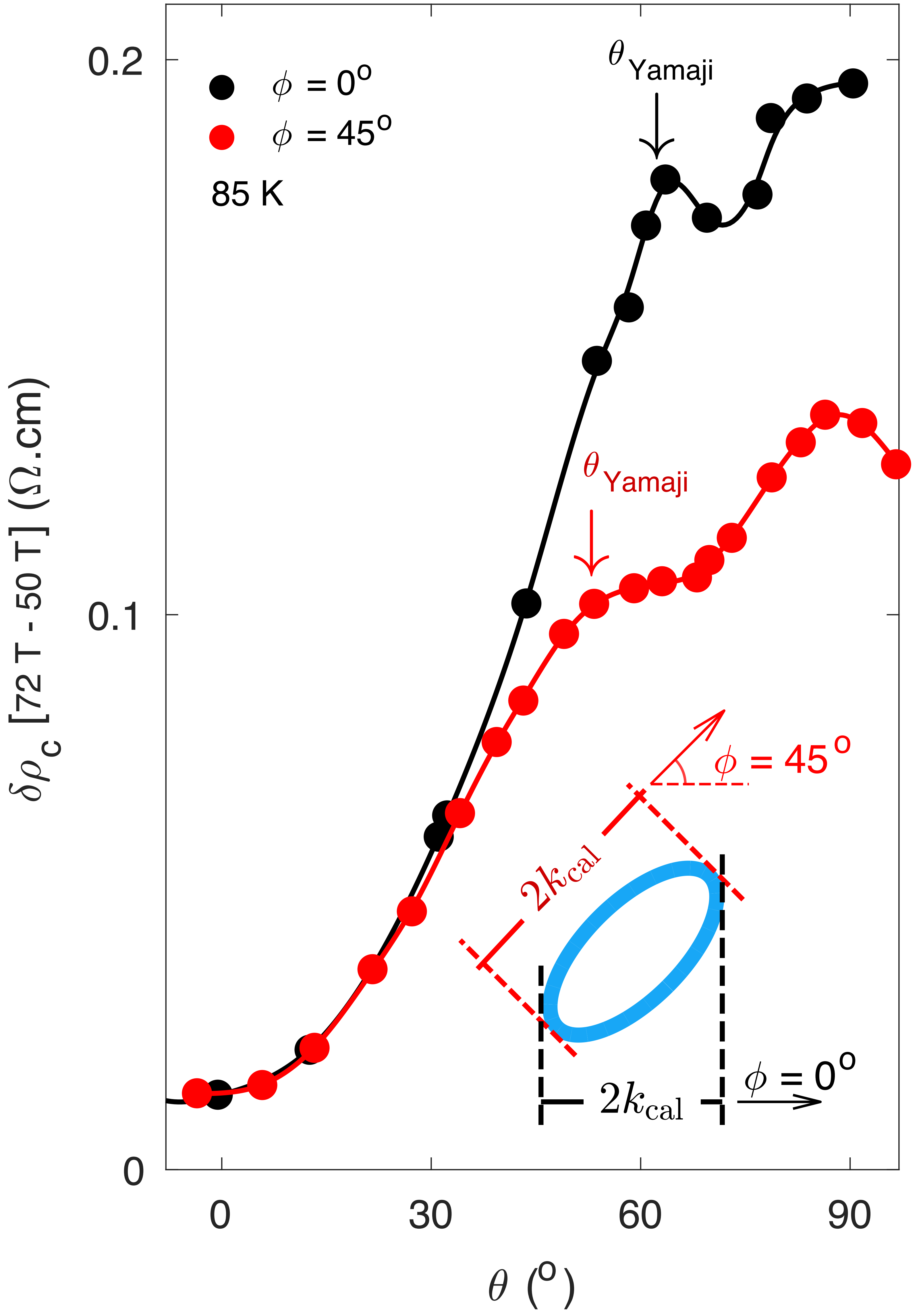
The dashed line in the Néel phase indicates the boundary of the magnetic Brillouin zone. Only the Fermi surfaces within this zone contribute to the Luttinger counting, and so the area of each ellipse is $\mathcal{A}_F=(2\pi)^2\delta/4$. In the VBS phase, all four pockets are inequivalent, and so the area of each ellipse is $\mathcal{A}_F=(2\pi)^2\delta/8$.

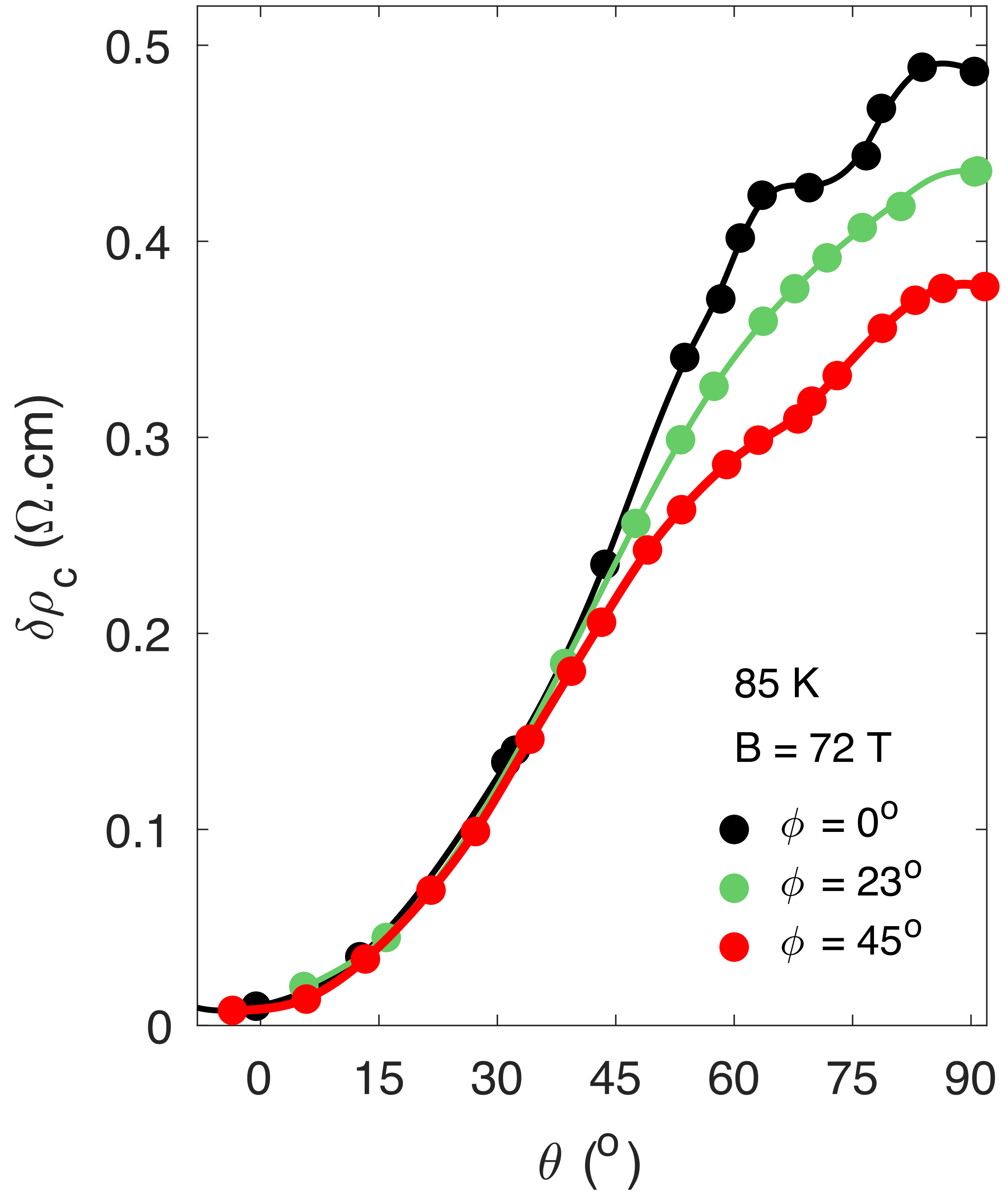
Fermi surface areas are *quantized* and robust to all corrections!
Factor of 2 between SDW fluctuation and FL*

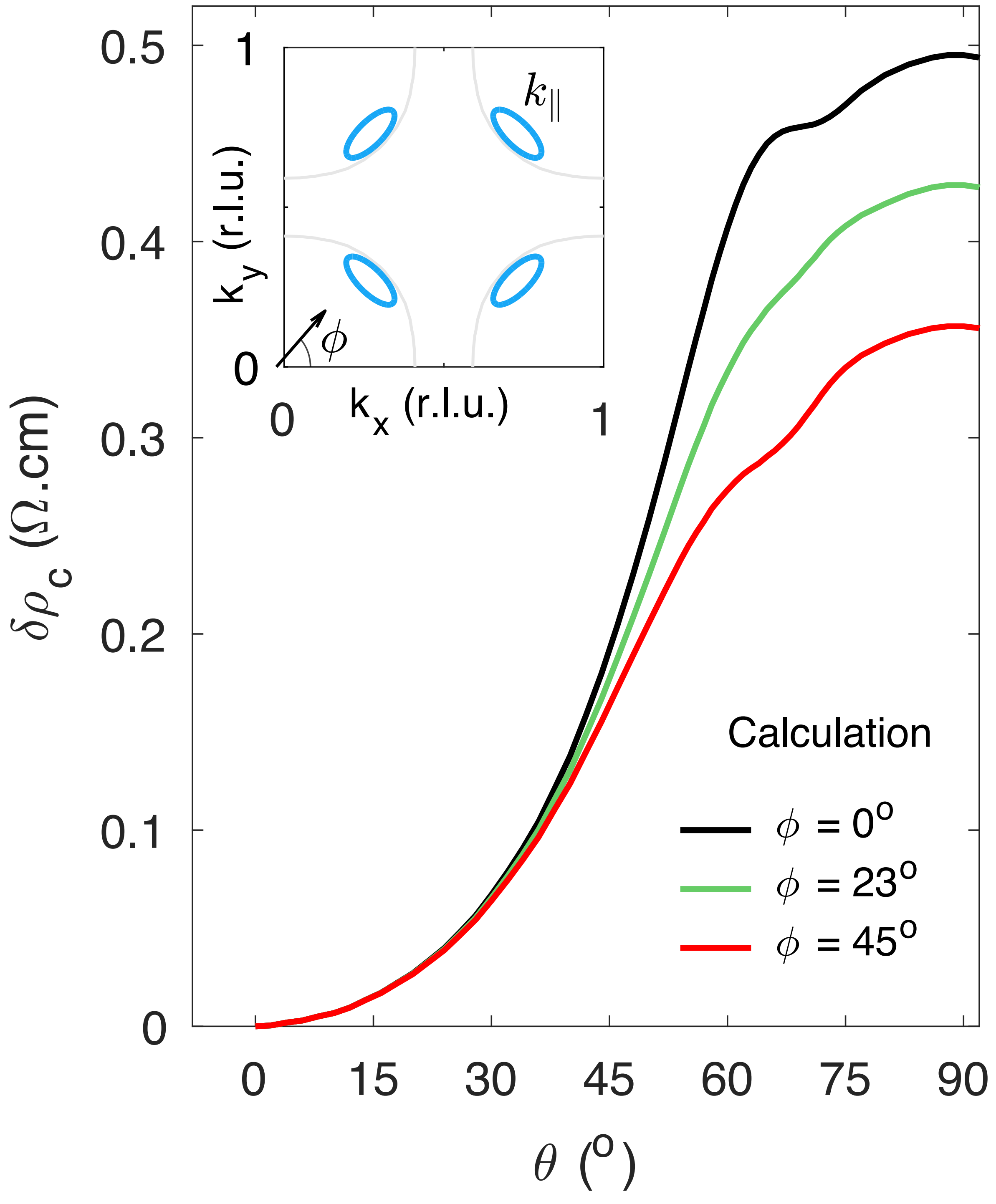
Observation of the Yamaji effect in a cuprate superconductor

Mun K. Chan [1], Katherine A. Schreiber[1], Oscar E. Ayala-Valenzuela [1], Eric D. Bauer [2], Arkady Shekhter [1] & Neil Harrison [1]

nature physics
arXiv:2411.10631
Published online: 16 September 2025







Doping
$p = 0.1$

"The small size of the pockets determined from the Yamaji effect is … approximately 1.3% of the Brillouin zone area"

Observation of the Yamaji effect in a cuprate superconductor

Mun K. Chan[1]✉, Katherine A. Schreiber[1], Oscar E. Ayala-Valenzuela[1], Eric D. Bauer[2], Arkady Shekhter[1] & Neil Harrison[1]

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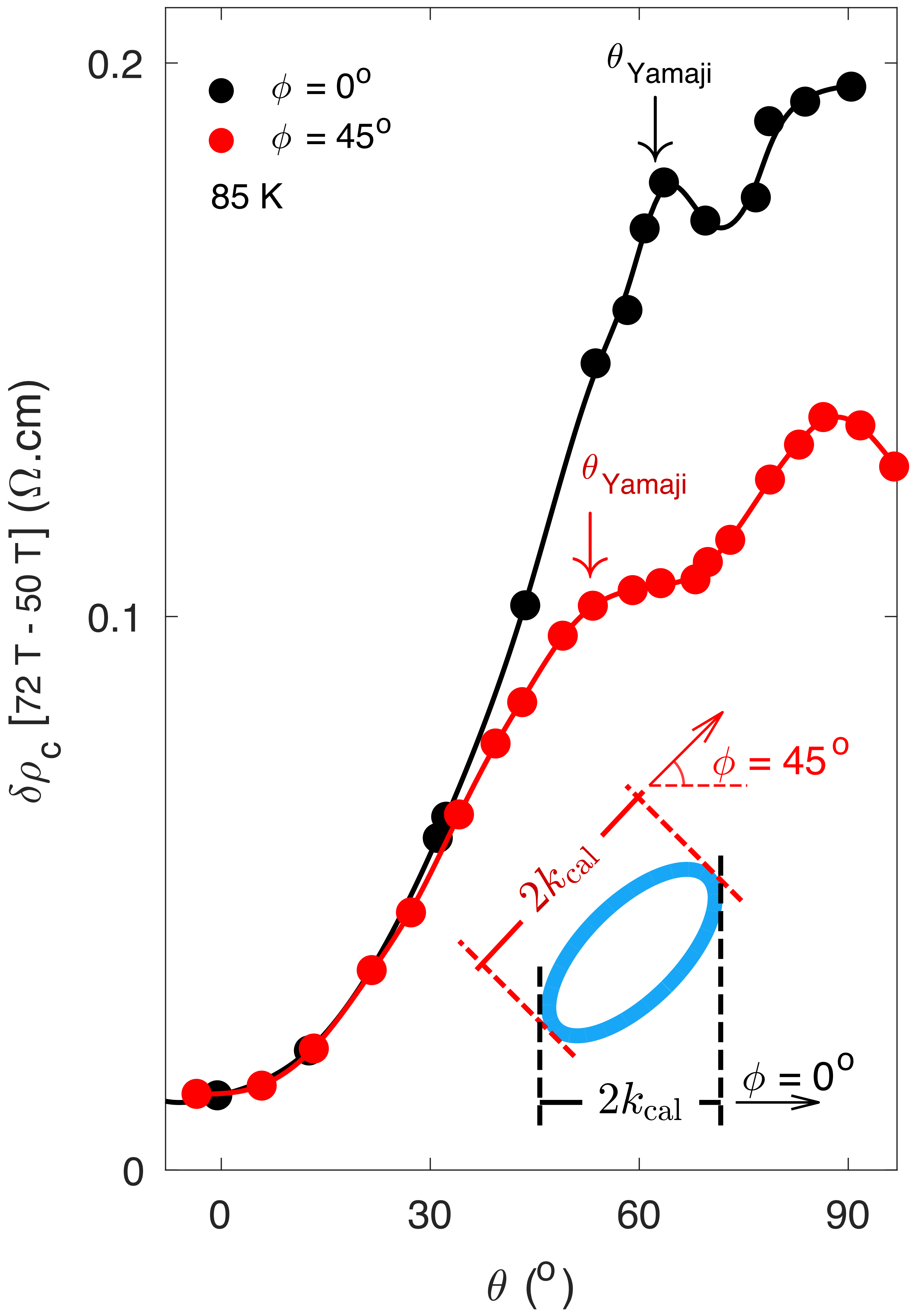

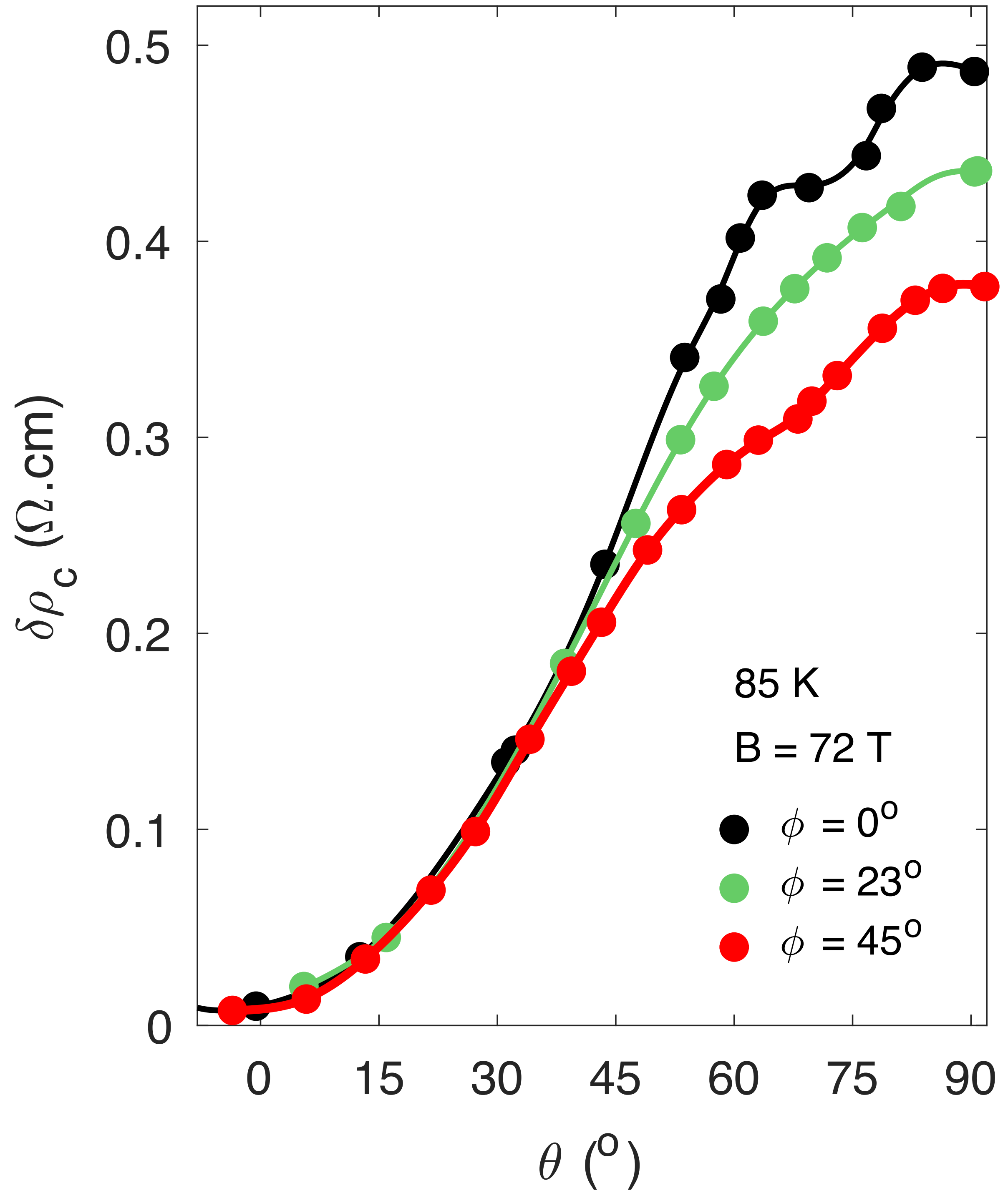

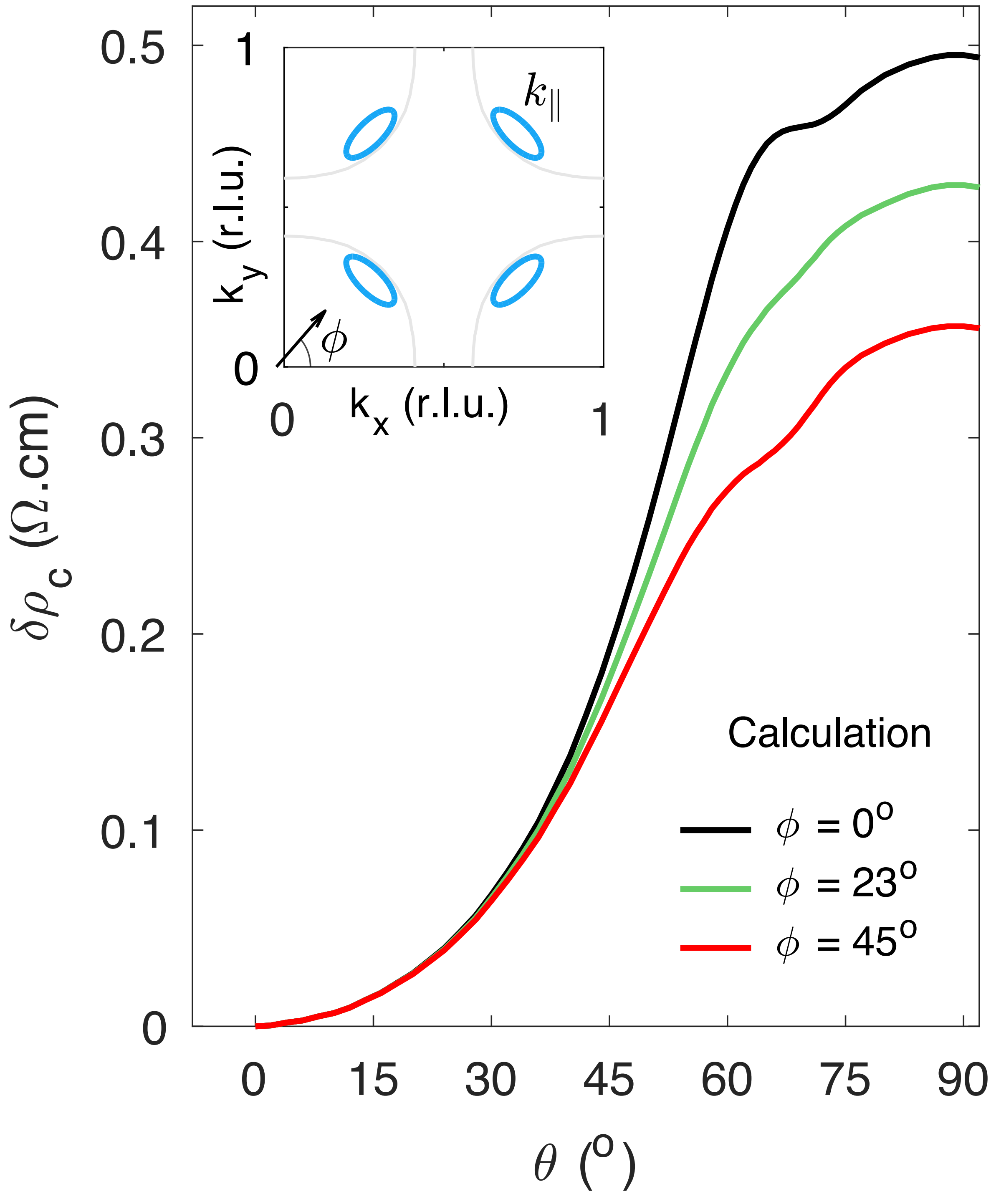

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"The small size of the pockets determined from the Yamaji effect is … approximately 1.3% of the Brillouin zone area"

FL* pocket fraction $= p/8 = 1.25\%$!
Fluctuating AF metal fraction $= p/4 = 2.5\%$.

(p/8 also in YRZ ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar?)

Observation of the Yamaji effect in a cuprate superconductor

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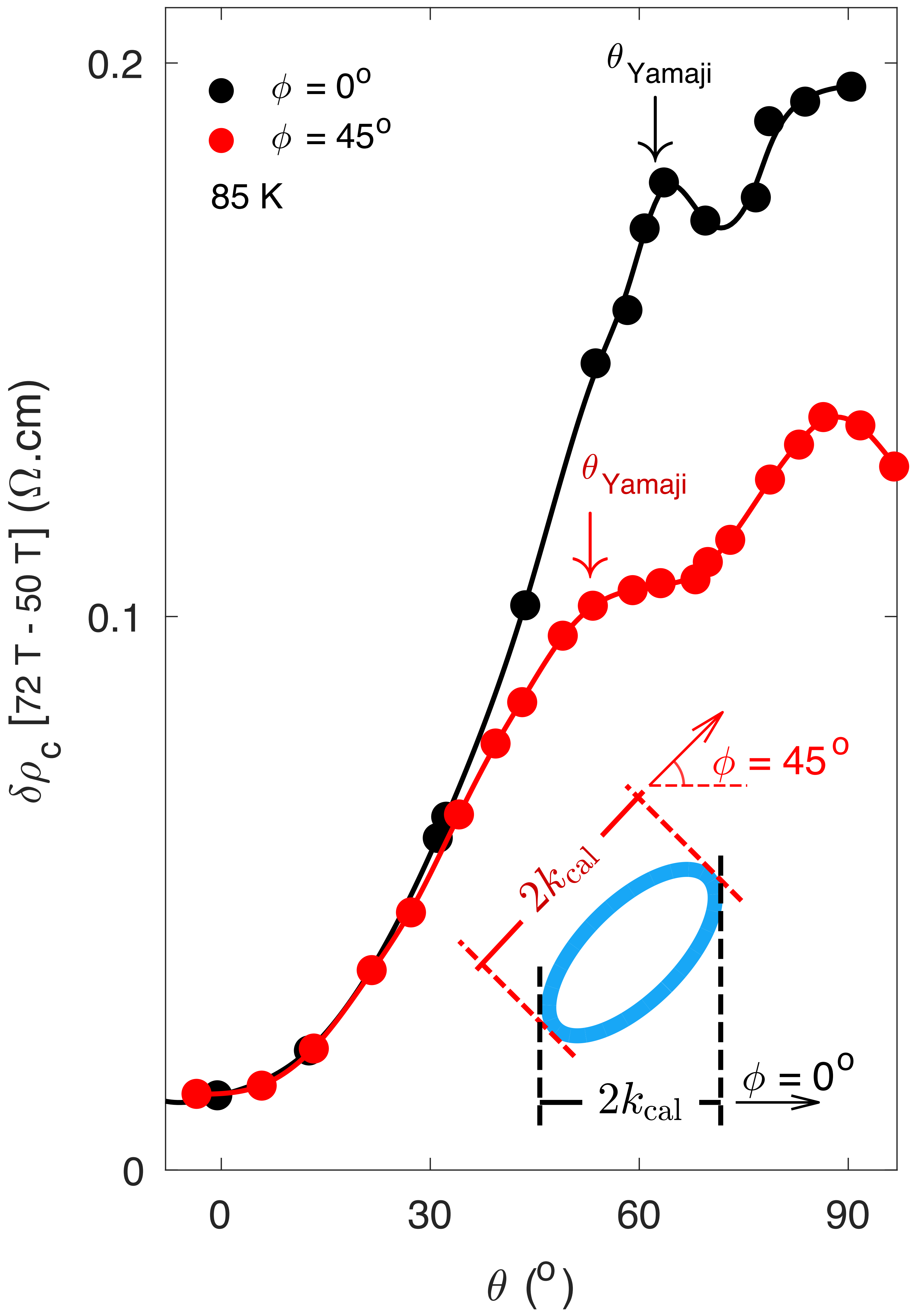

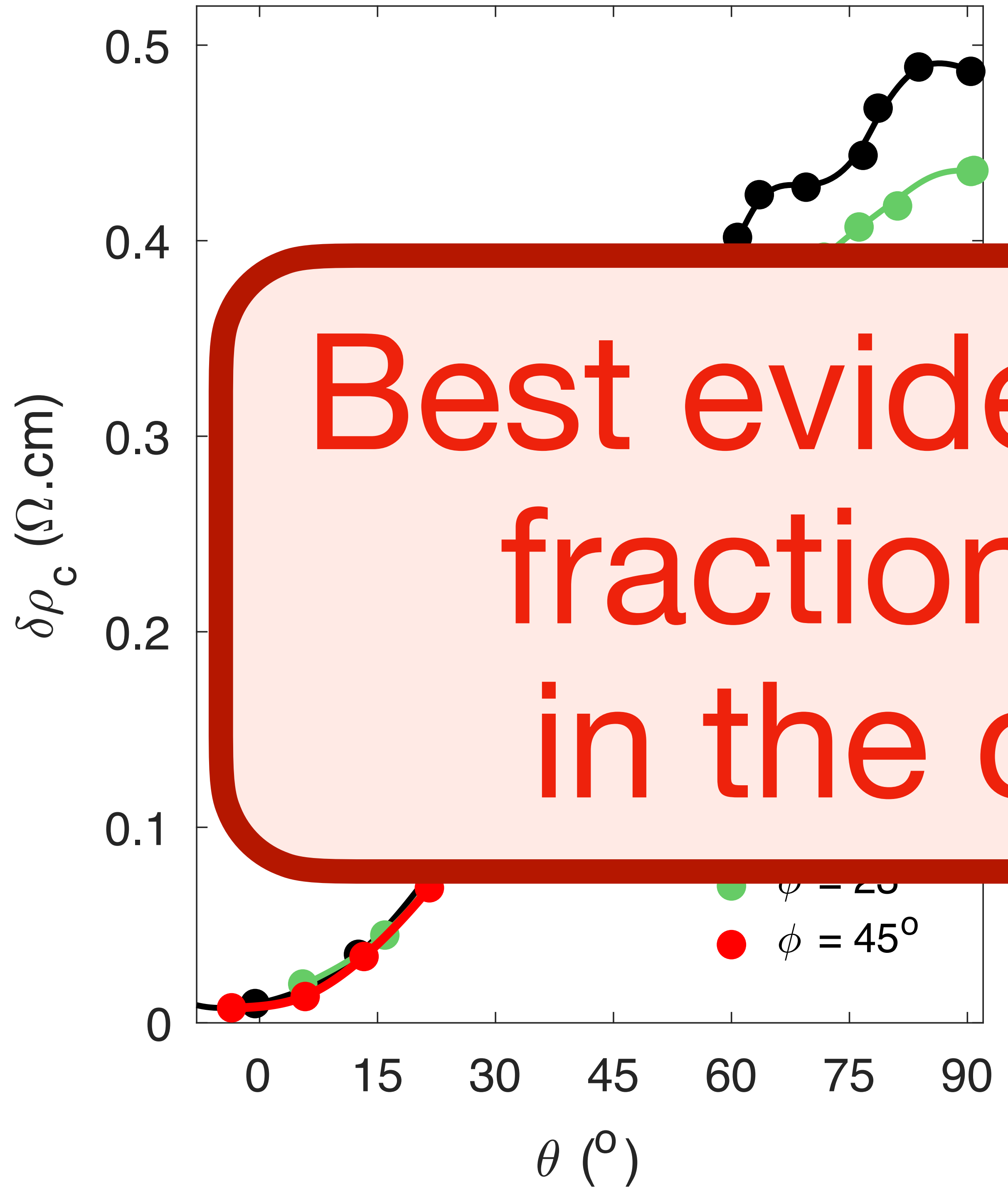

Best evidence yet for fractionalization in the cuprates

Doping
$p = 0.1$

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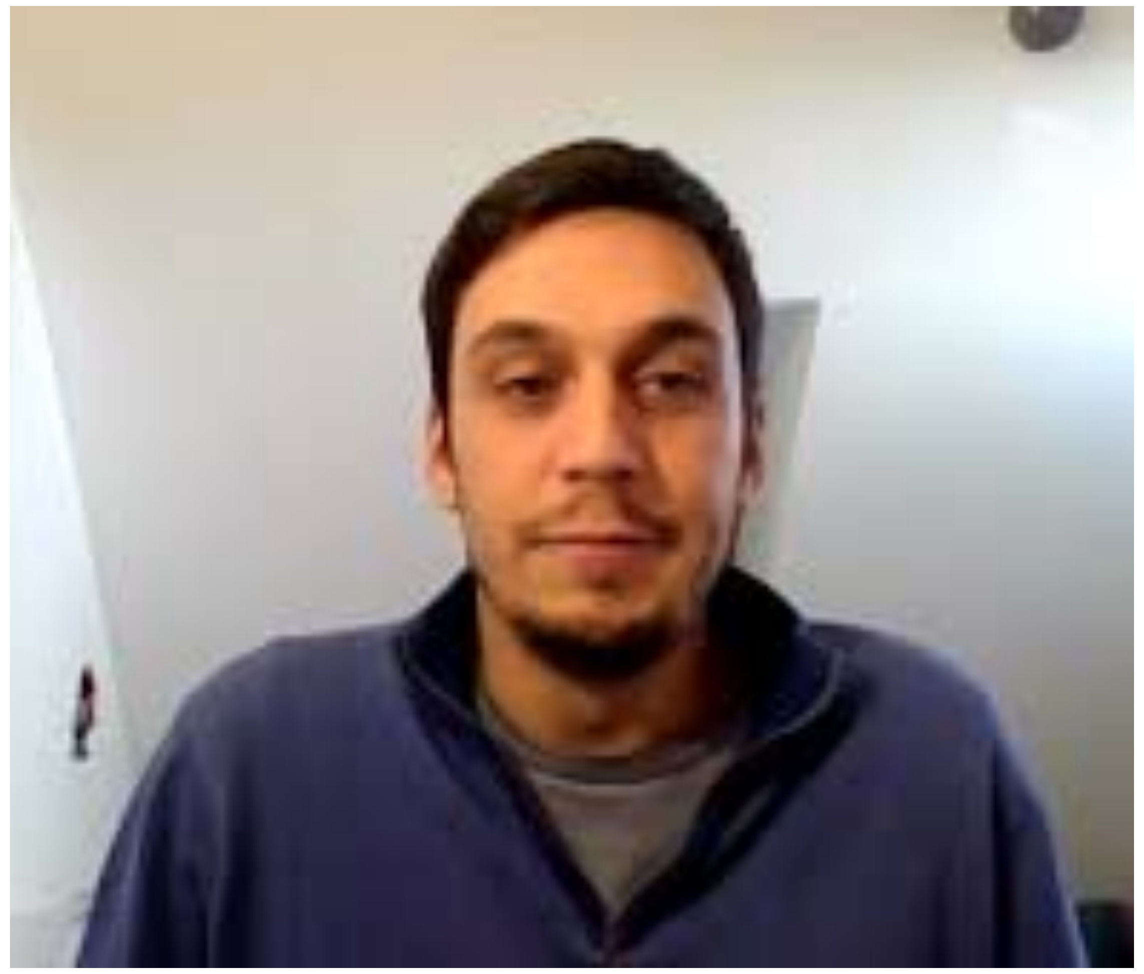
(p/8 also in YRZ ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar?)

Coupling hole pockets to spin liquid

(required by non-Luttinger area of hole pockets)

Maine Christos
Caltech



Pietro Bonetti

Alexander
Nikolaenko

Thermal SU(2) lattice gauge theory of the cuprate pseudogap: reconciling Fermi arcs and hole pockets

H. Pandey, M. Christos, P.M. Bonetti, R. Shanker, A. Nikolaenko, S. Sharma, S.S., arXiv:2507.05336

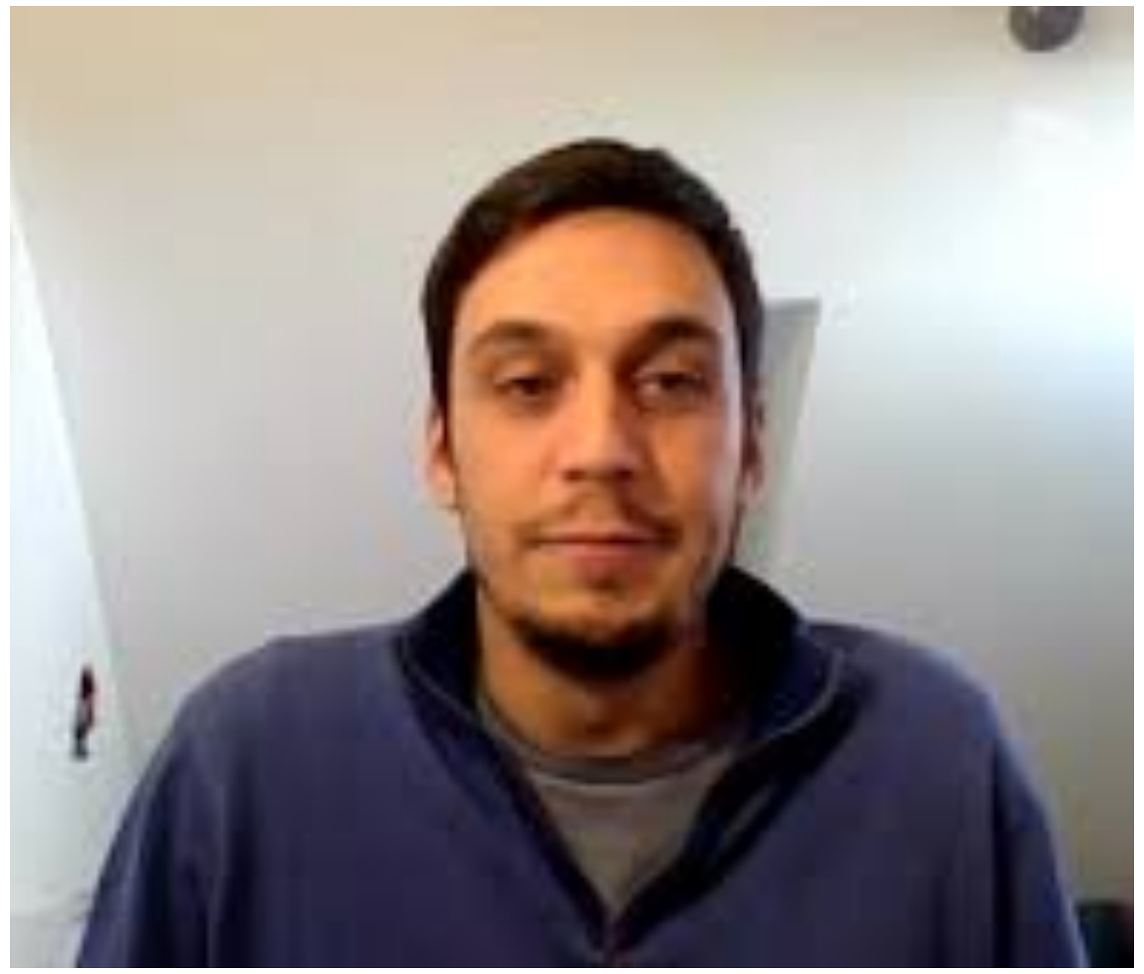
The Institute of Mathematical Sciences, Chennai

Harshit Pandey

Ravi Shanker

Sayantan Sharma

Maine Christos
Caltech



Pietro Bonetti

Alexander
Nikolaenko

Aavishkar Patel
ICTS, Bengaluru

arXiv > cond-mat > arXiv:2508.20164

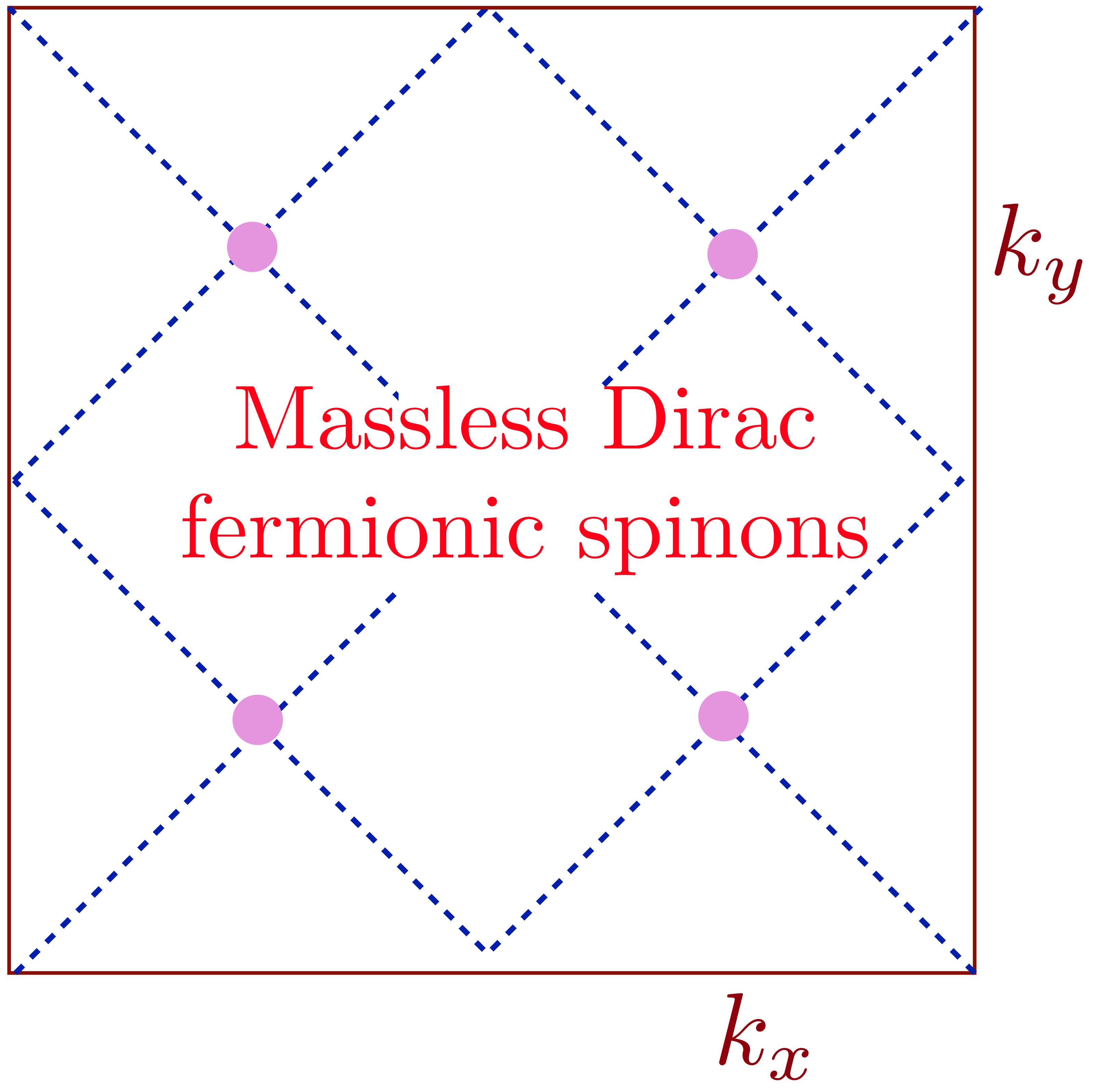
Condensed Matter > Strongly Correlated Electrons

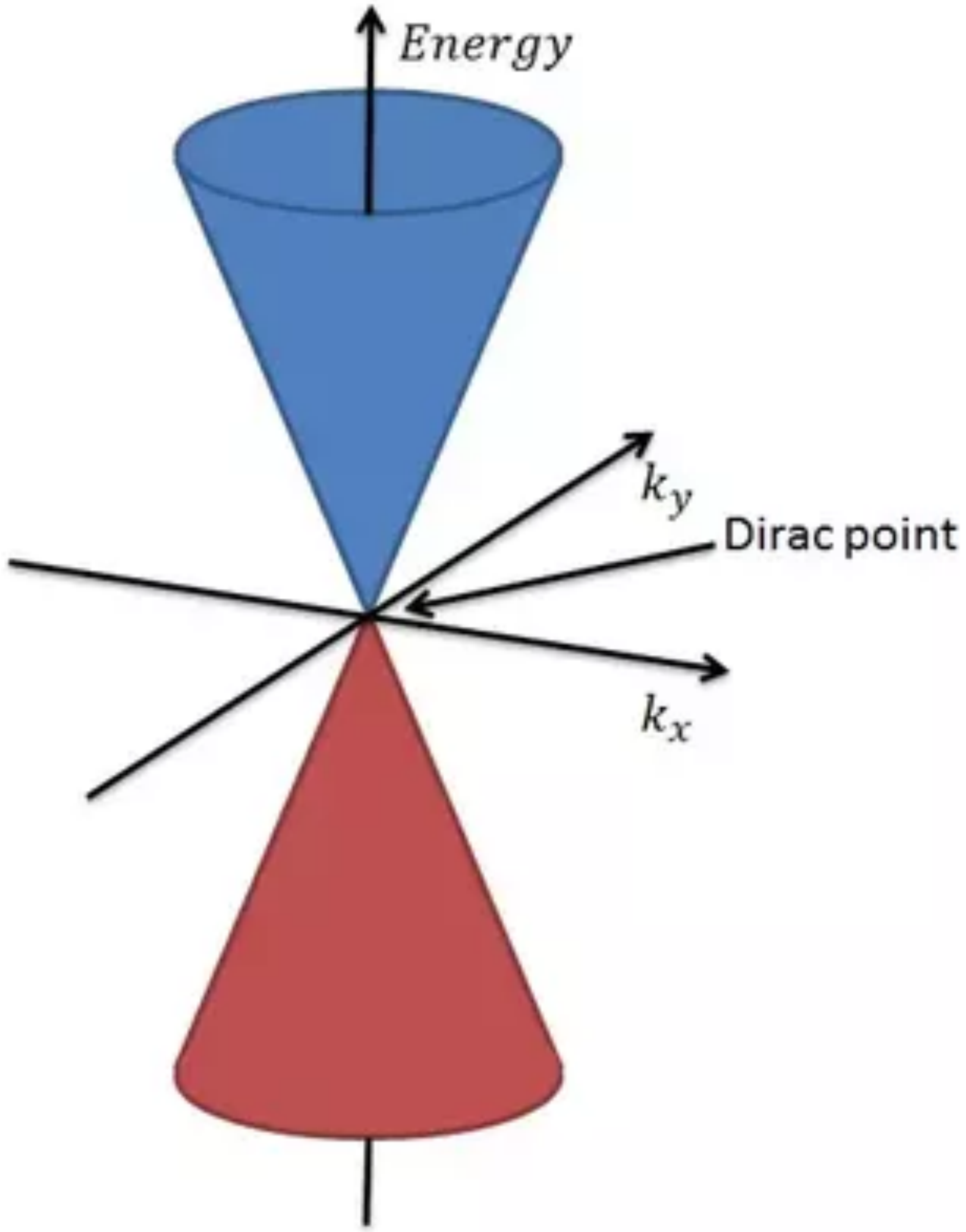
[Submitted on 27 Aug 2025]

Critical quantum liquids and the cuprate high temperature superconductors

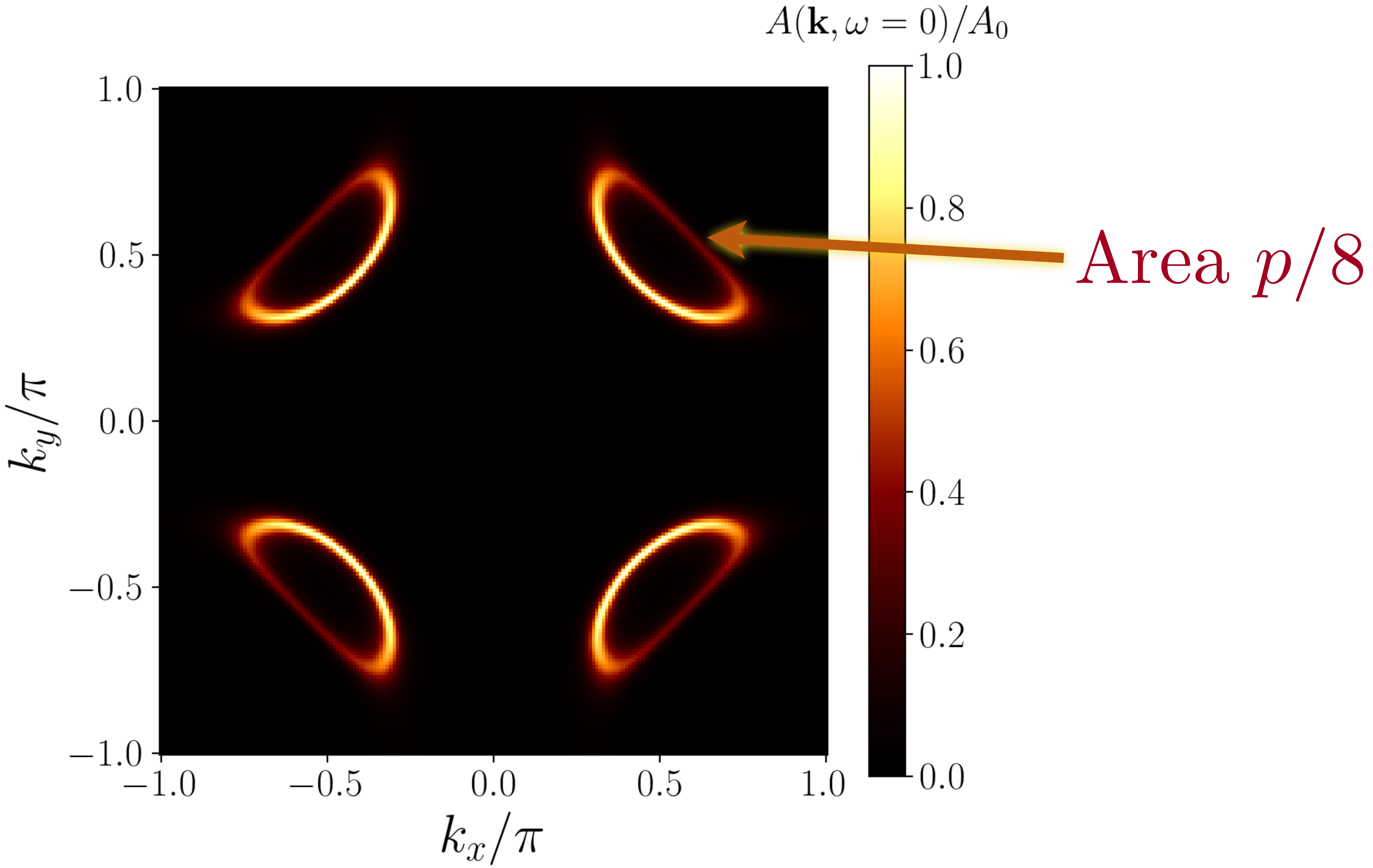
- Identification of spin liquid: critical spin liquid without quasiparticles. One description is a SU(2) gauge theory with $N_f = 2$ massless Dirac spinons in 2+1 dimensions. (Curious fact: QCD is a SU(3) gauge theory with $N_f = 3$ massless Dirac quarks in 3+1 dimensions.)

I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)
N. Read and S. Sachdev, PRL **62**, 1694 (1989)
C. Wang, A. Nahum, M. A. Metlitski, C. Xu, T. Senthil, *Phys. Rev. X* **7**, 031051 (2017)
Zheng Zhou, Liangdong Hu, Wei Zhu, Yin-Chen He, PRX **14**, 021044 (2024)



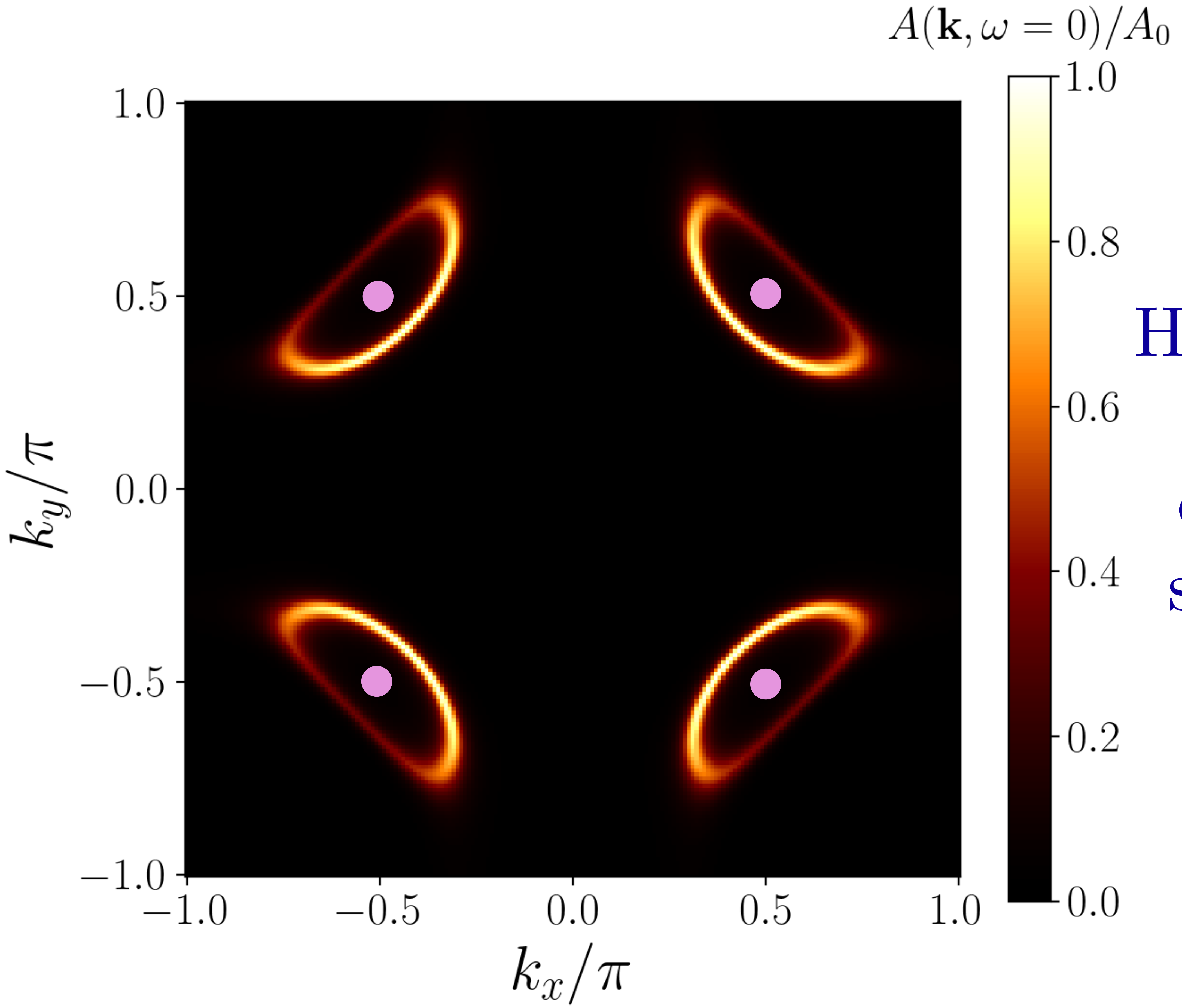


- Dope spin liquid with *holes*, <u>not</u> holons.
  The Ancilla Layer Model (ALM) enables a theory of FL* hole pockets for a general spin liquid.



Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, S. S., PRB **105**, 075146 (2022)

- Theory of pseudogap (and its low T instabilities): Hole pockets coupled to critical spin liquid by a charge e Higgs field of the thermal SU(2) gauge theory.



Hole pockets
and
decoupled
spin liquid

Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, S. S., PRB **105**, 075146 (2022)

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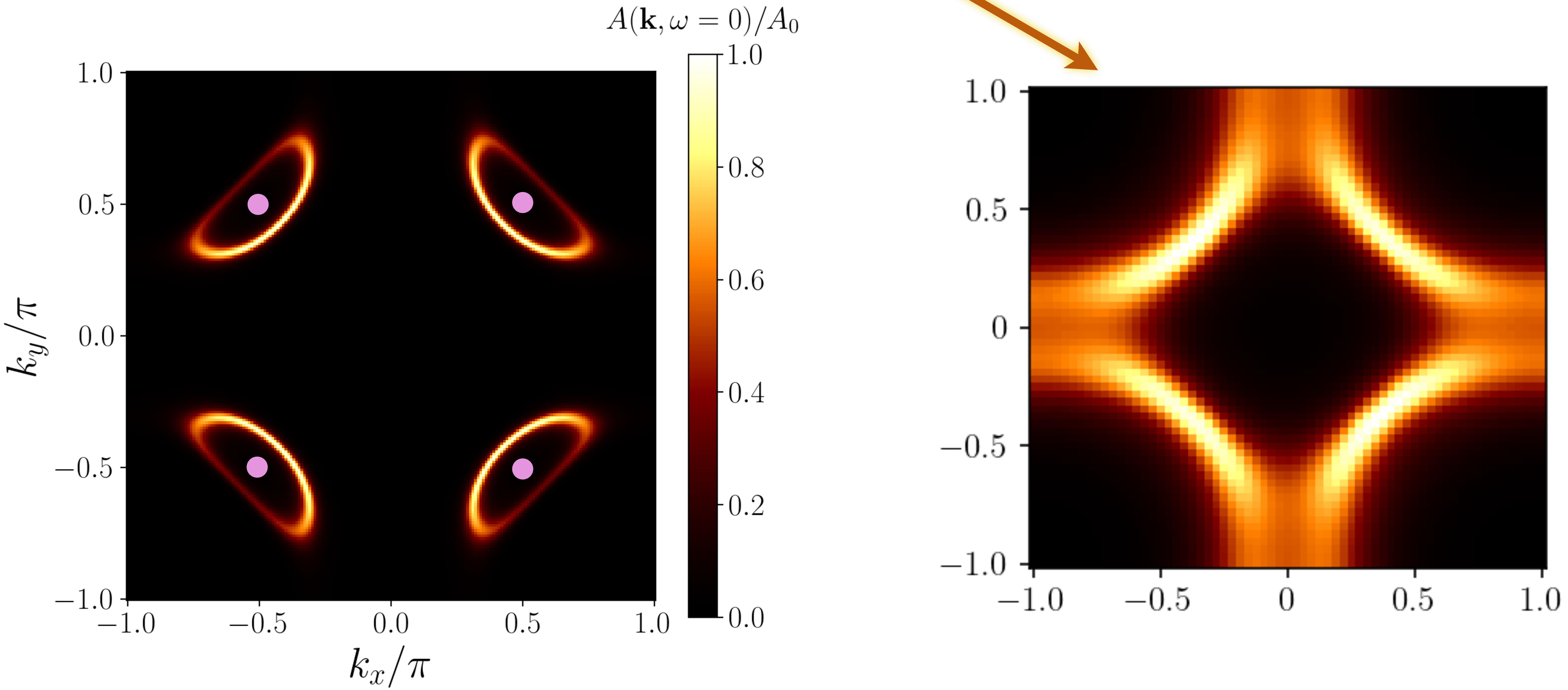

H. Pandey, M. Christos, P.M. Bonetti, R. Shanker, S. Sharma, S.S., arXiv:2507.05336

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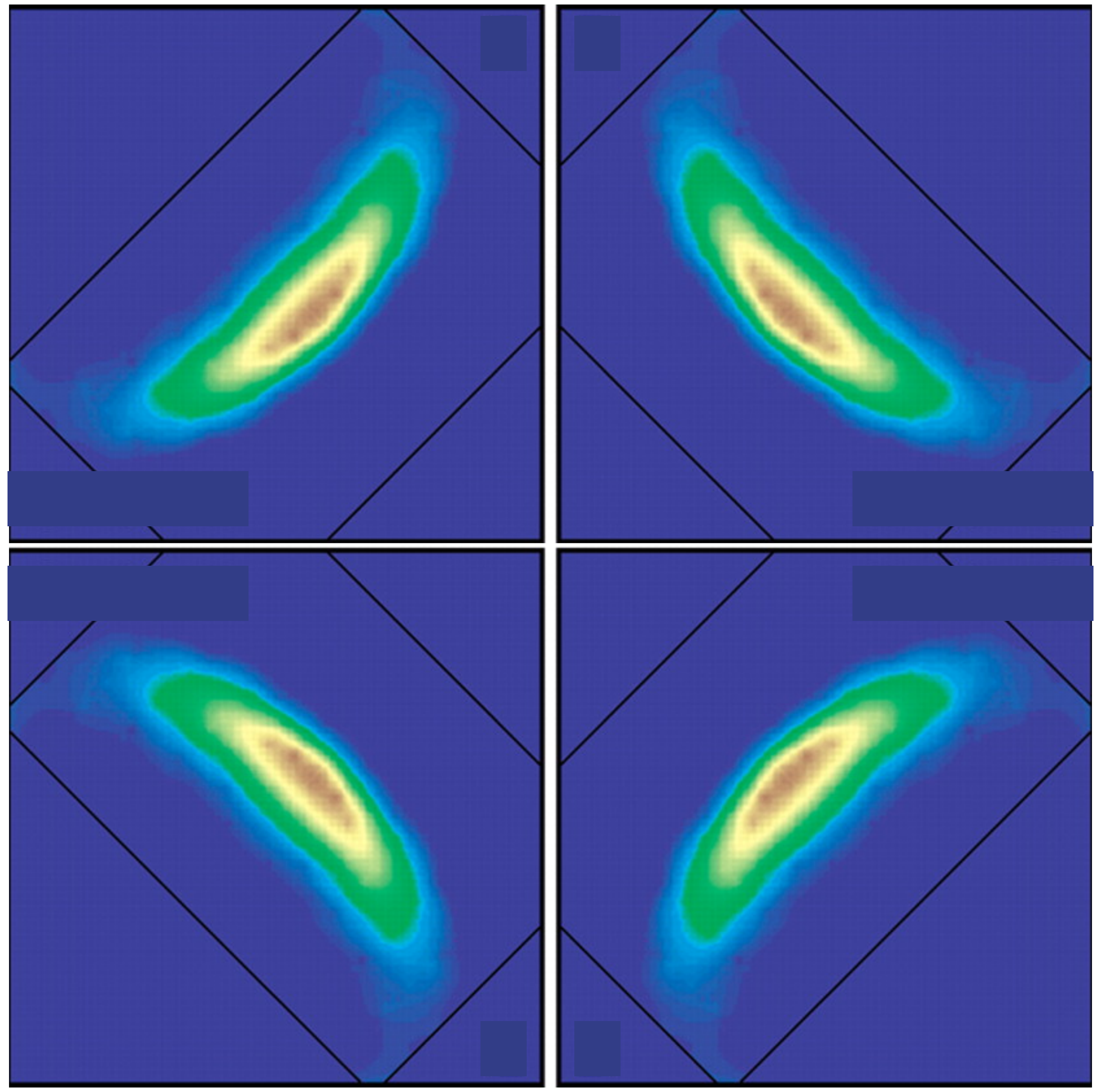
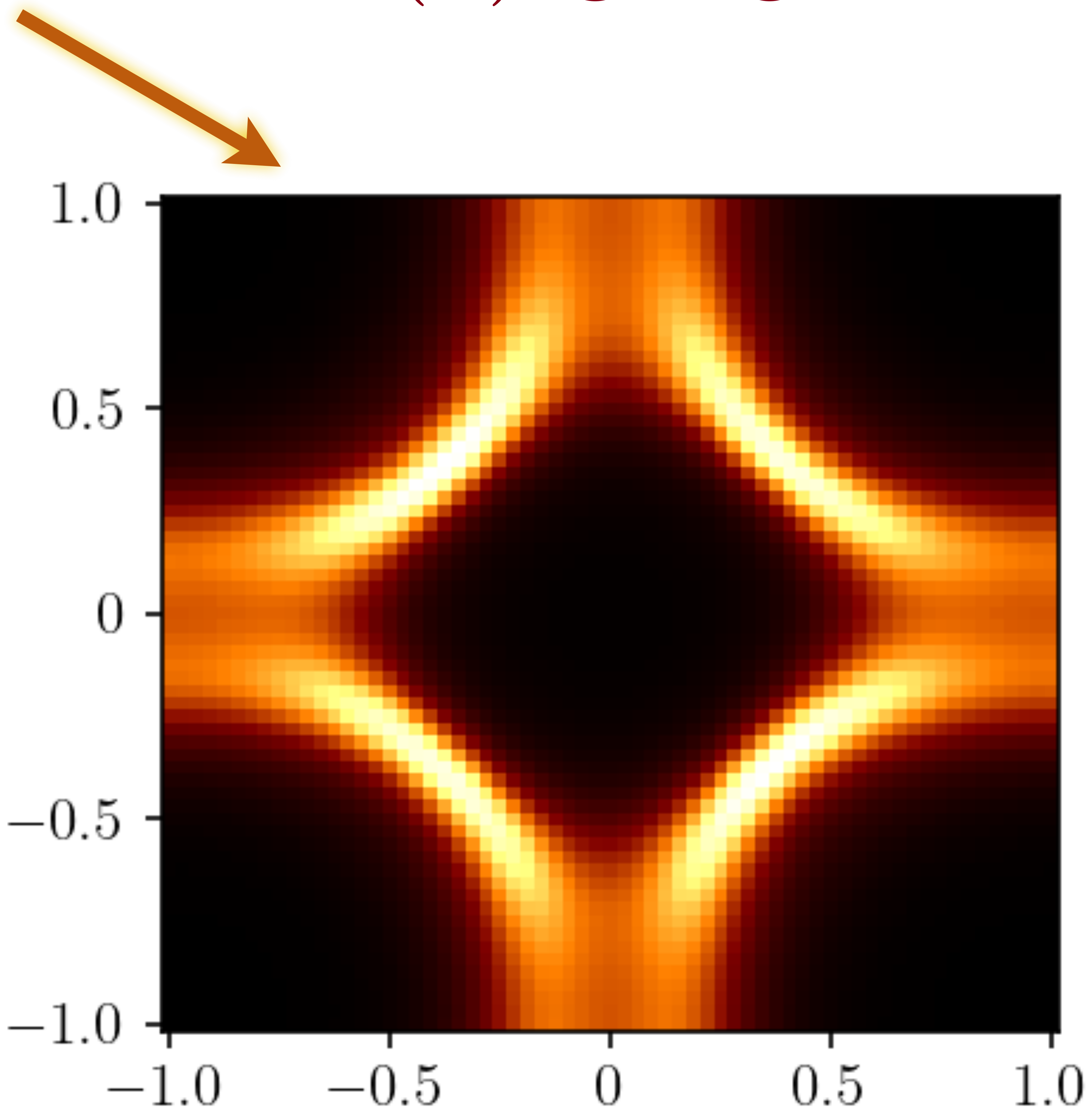


Kyle M. Shen, ...Z.-X. Shen, Science **307**, 901 (2005)



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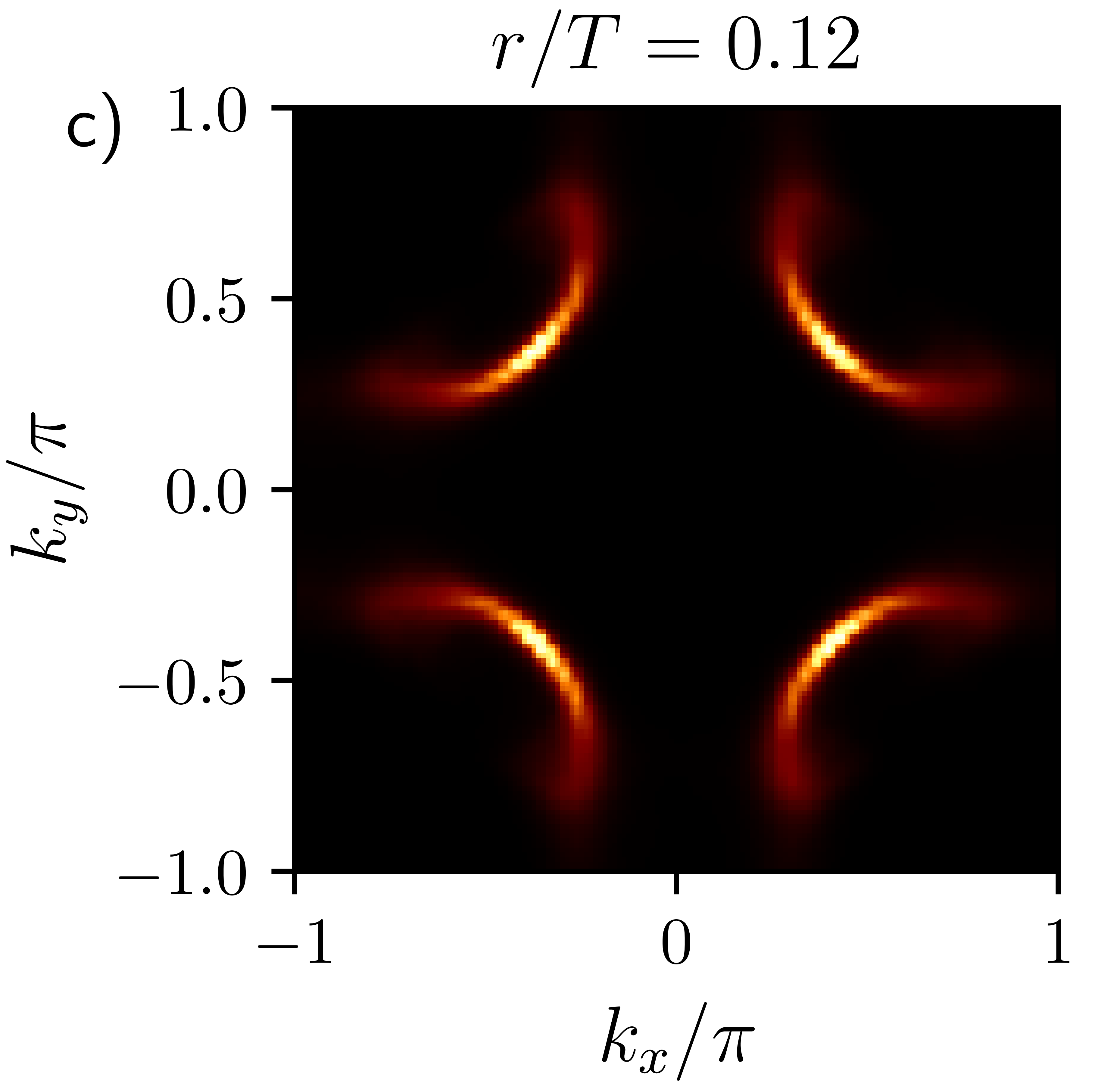
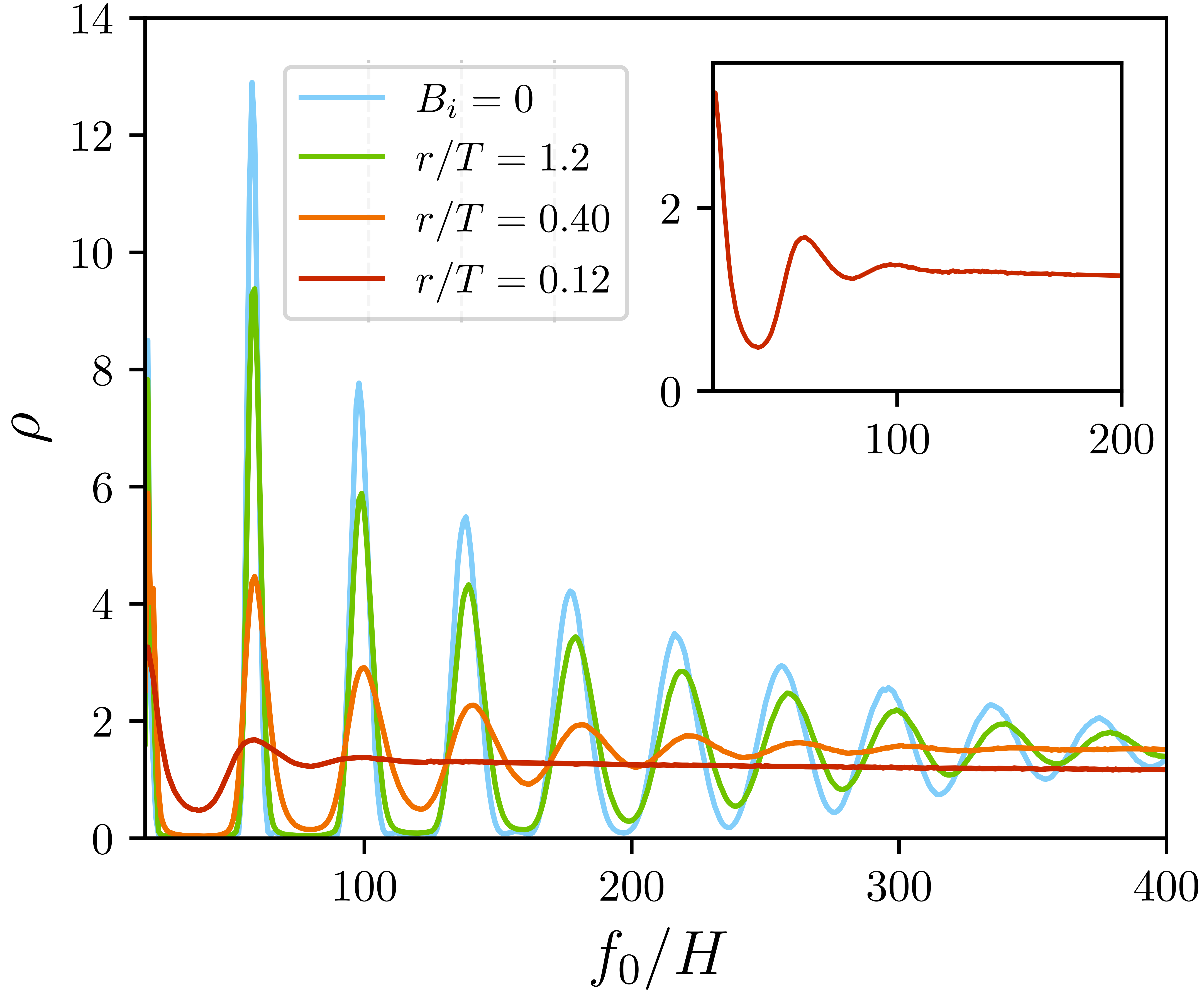


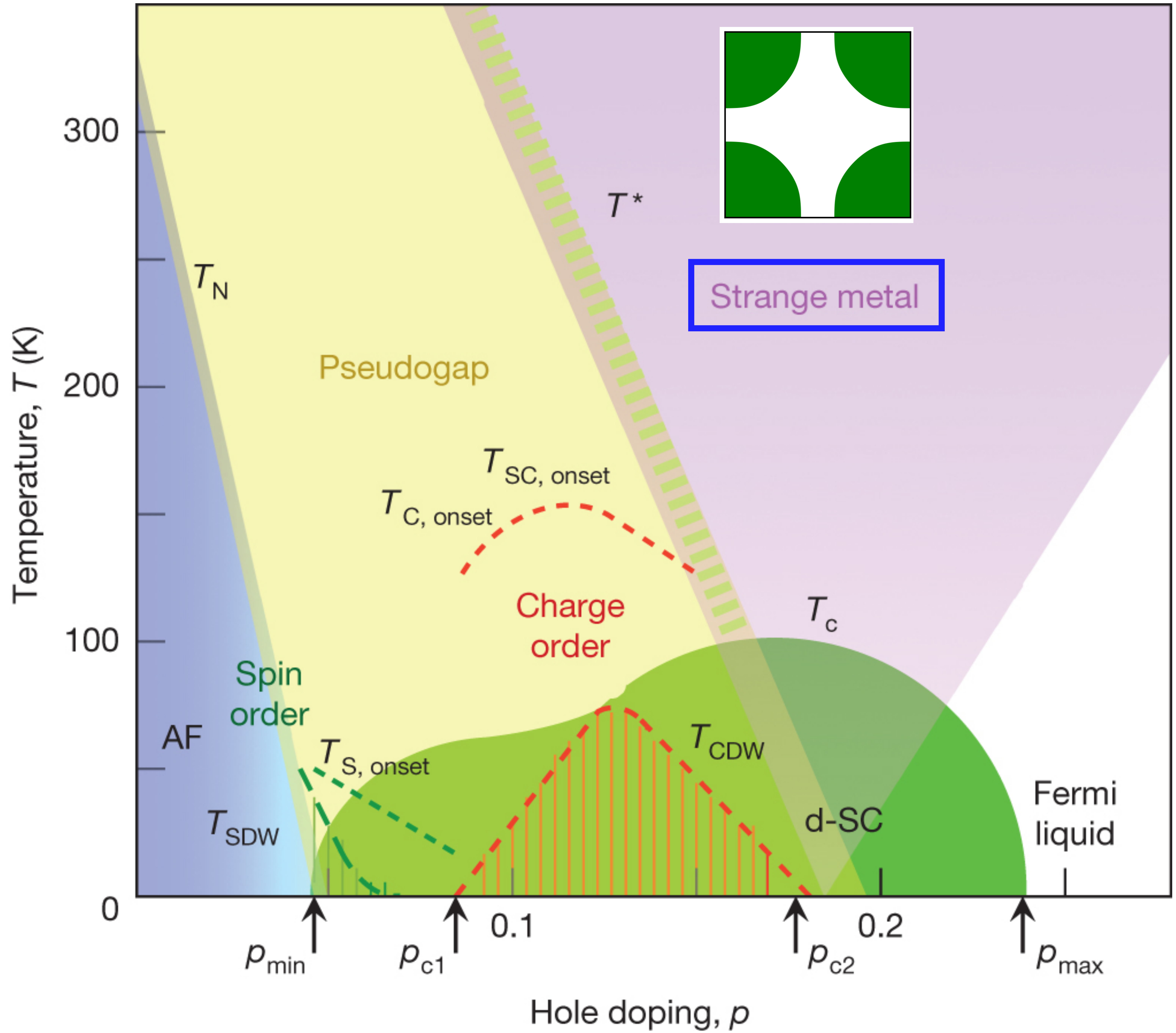


Fermi arcs co-exist with quantum oscillations of hole pockets of area $p/8$.

H. Pandey, M. Christos, P.M. Bonetti, R. Shanker, S. Sharma, S.S., arXiv:2507.05336

Strange metal
and phase diagram

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)

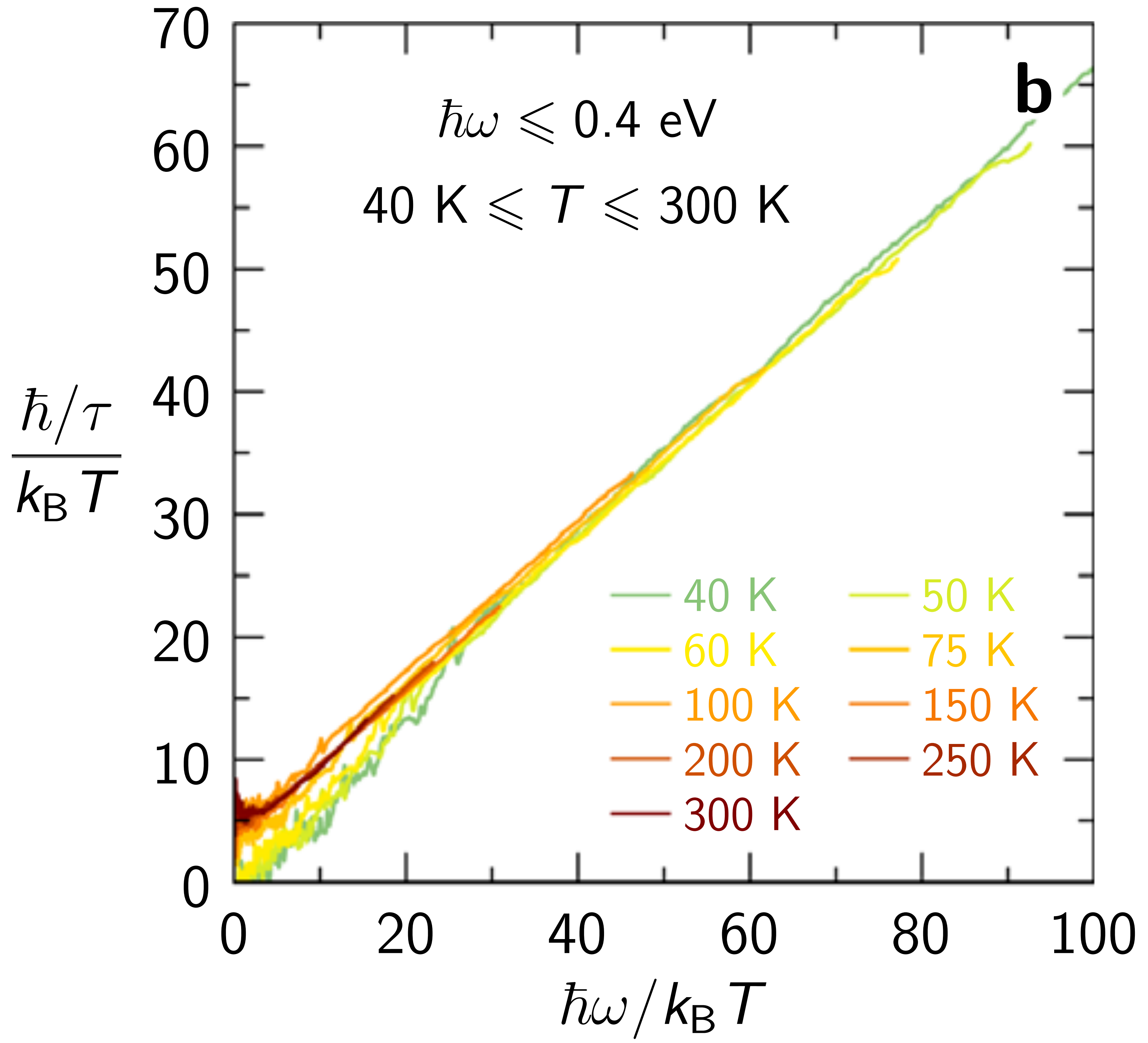


Planckian dynamics !

of large Fermi surface

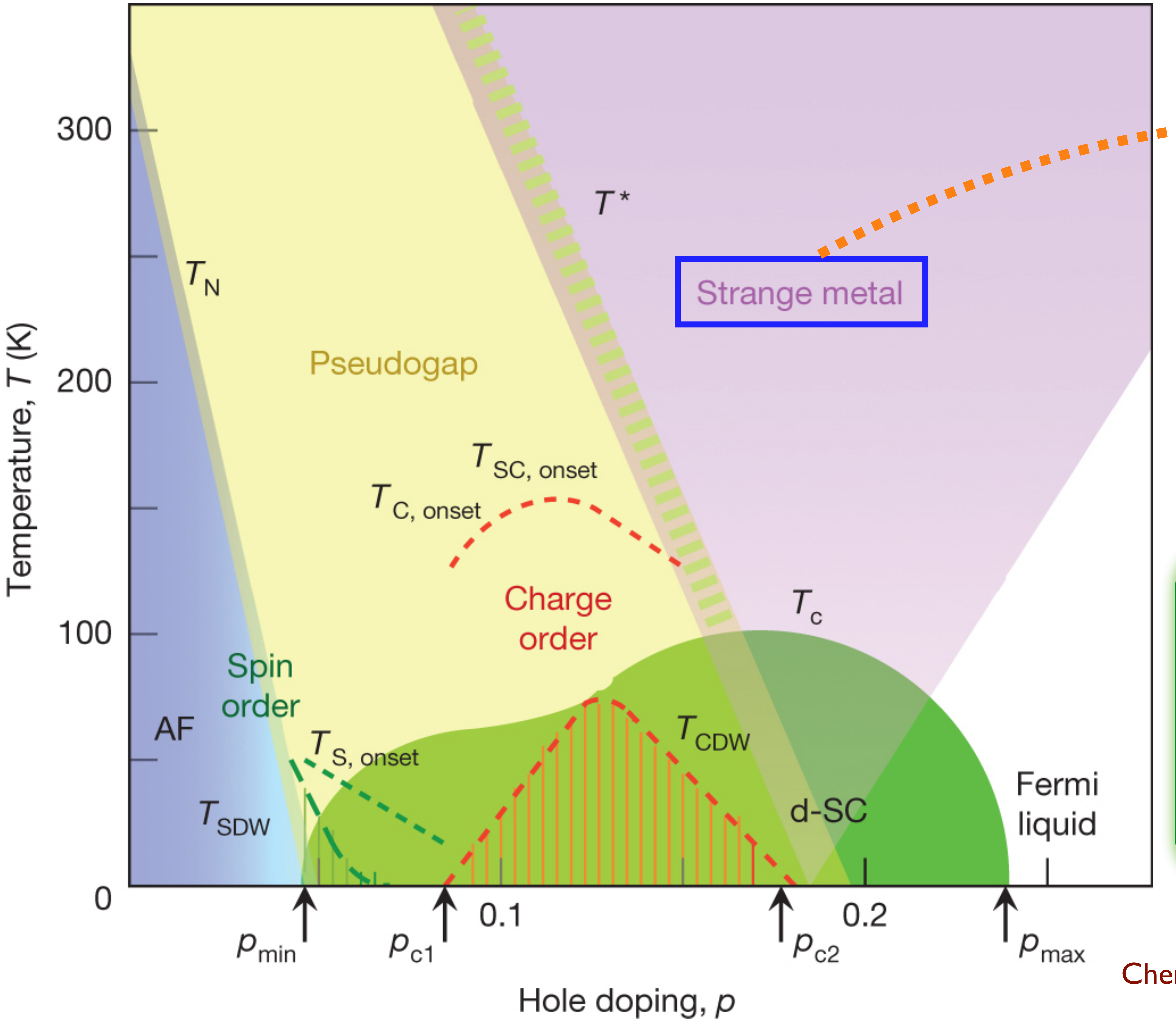
Electron scattering time τ from optical conductivity

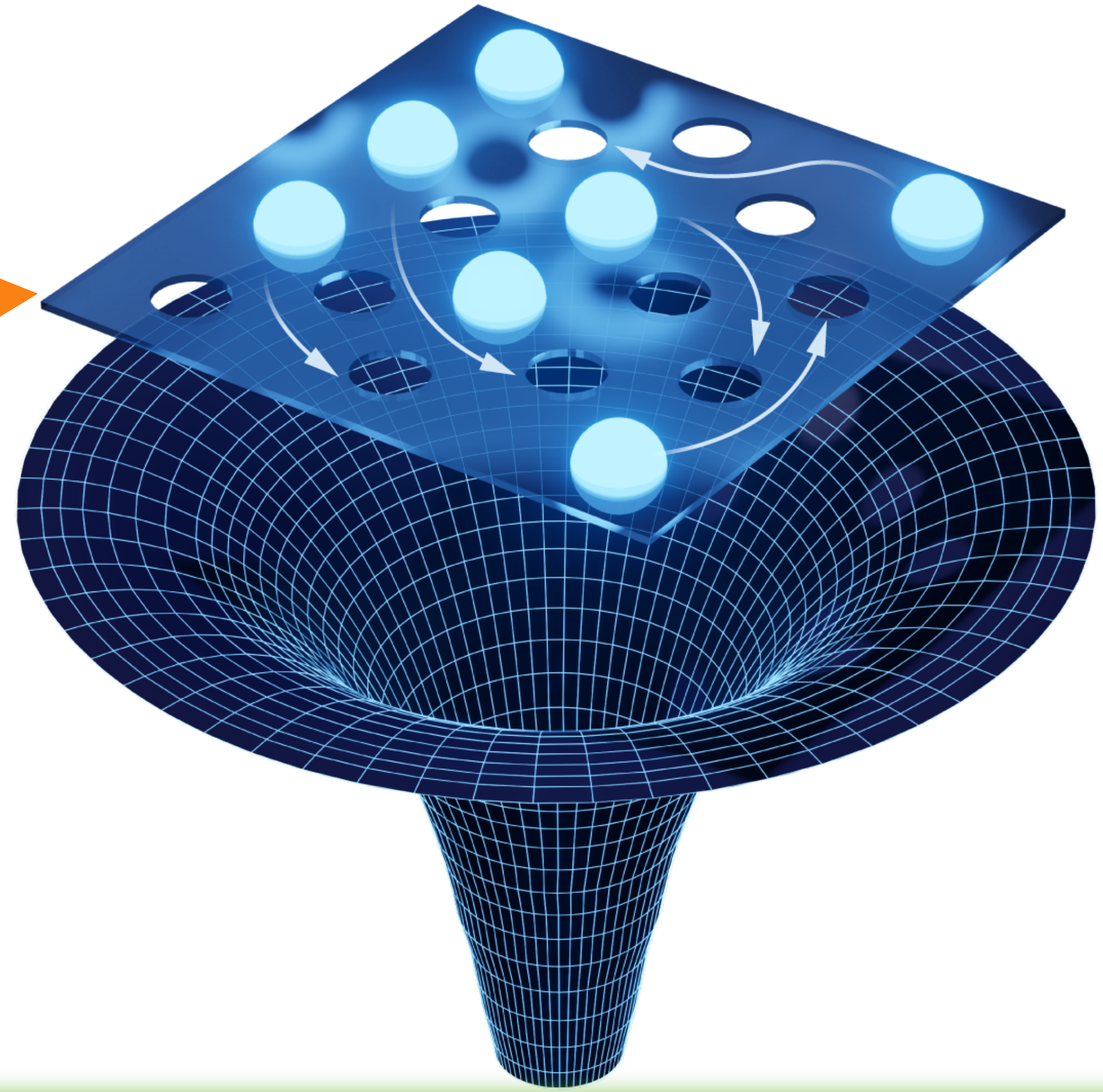
$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$



B. Michon, C. Berthod, C. W. Rischau, A. Ataei, L. Chen, S. Komiya, S. Ono, L. Taillefer, D. van der Marel, A. Georges, Nature Comm. **14**, 3033 (2023)

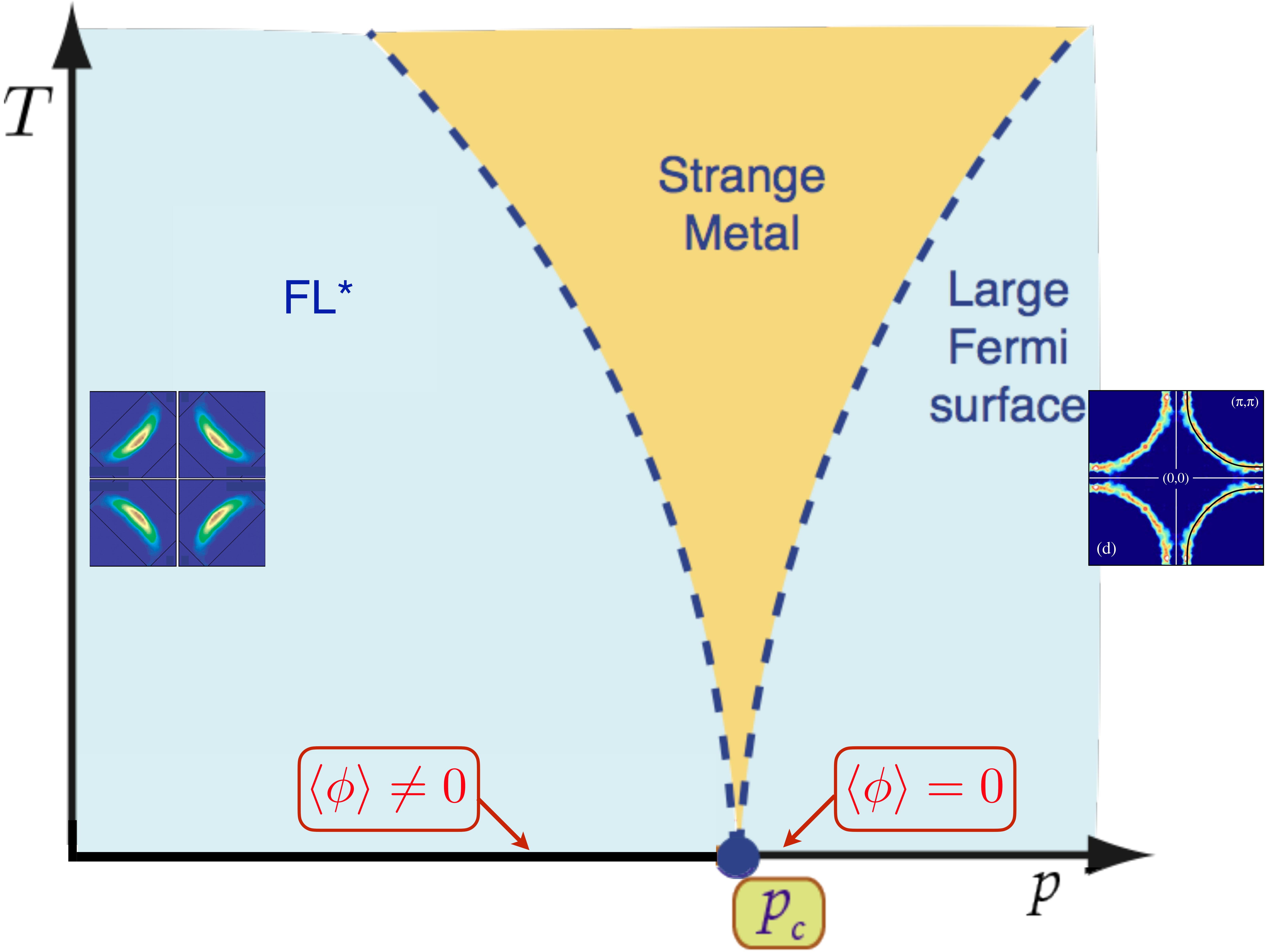
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)





Explain with a local, two-dimensional extension of the Sachdev-Ye-Kitaev (SYK) model of mobile electrons, a <u>*critical charge liquid*</u>

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023);
Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentinis, Jorg Schmalian, S.S., Ilya Esterlis, PRL **133**, 186502 (2024)



Quantum-criticality
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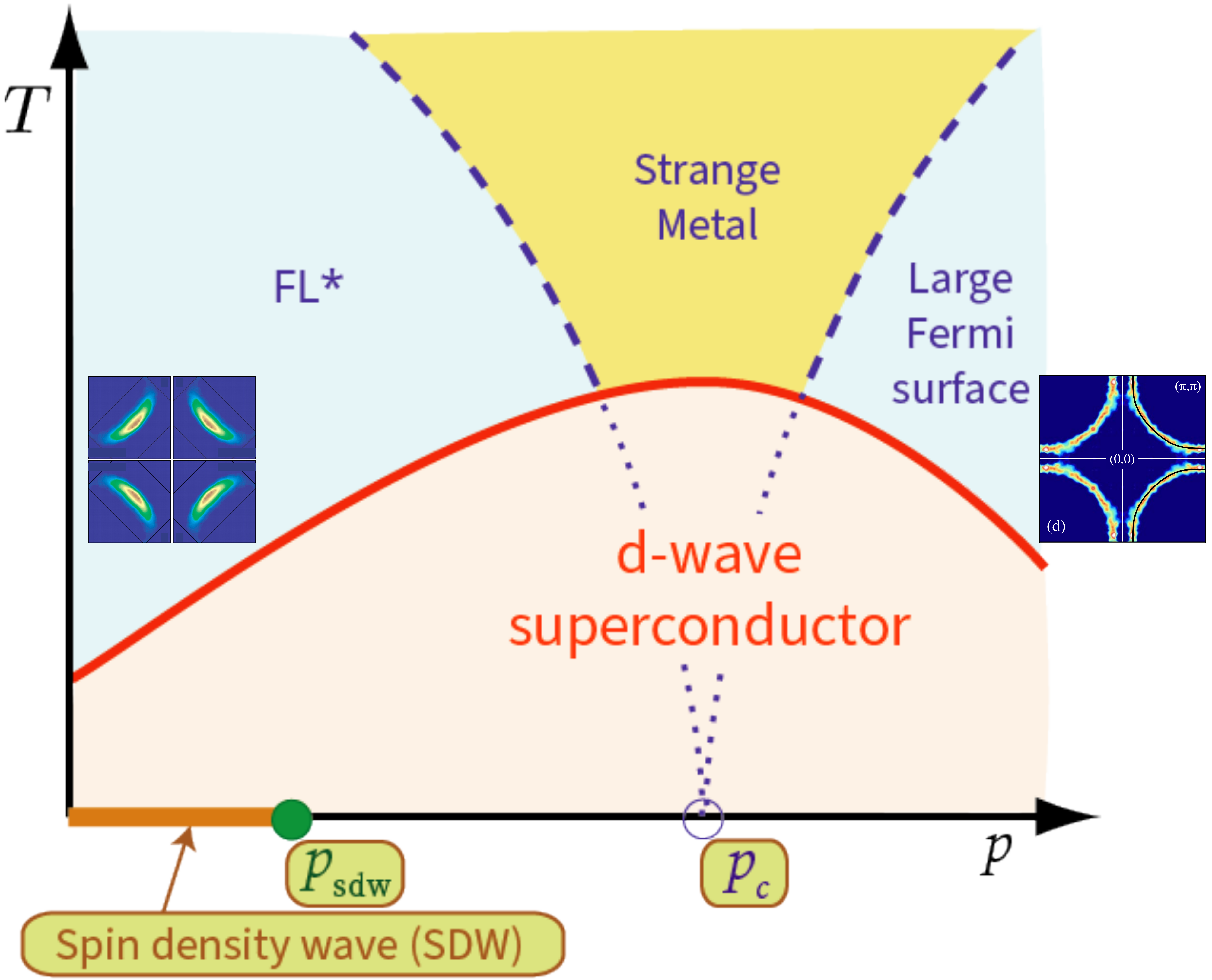
at $p = p_c$,
with no symmetry breaking.
ϕ is a Higgs field with
emergent gauge charge.



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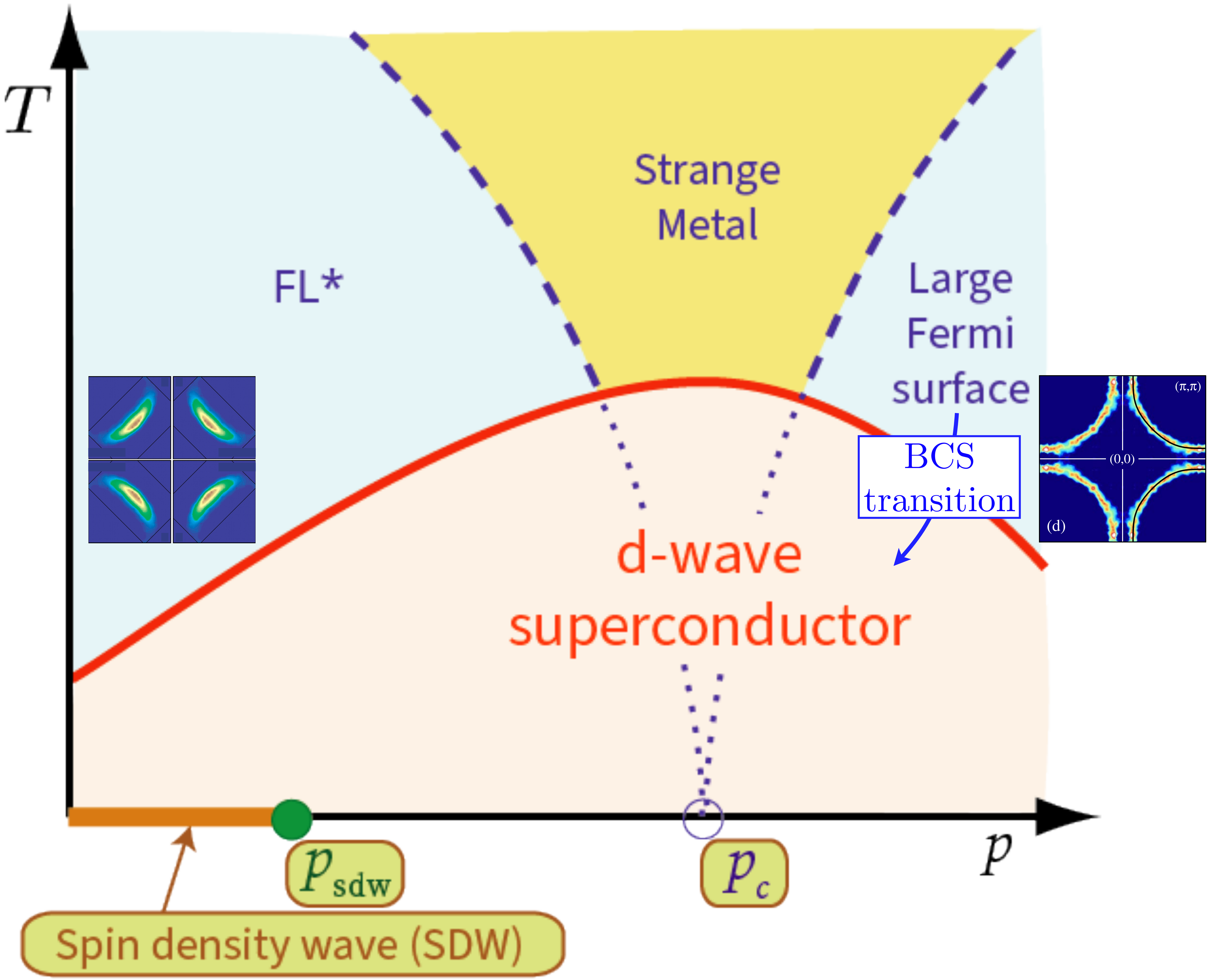
ϕ is a Higgs field with
emergent gauge charge.

Both metals lead to the
same d-wave superconductor
at lower temperatures, and
so there is transition at
$p = p_c$ within the
superconducting state.



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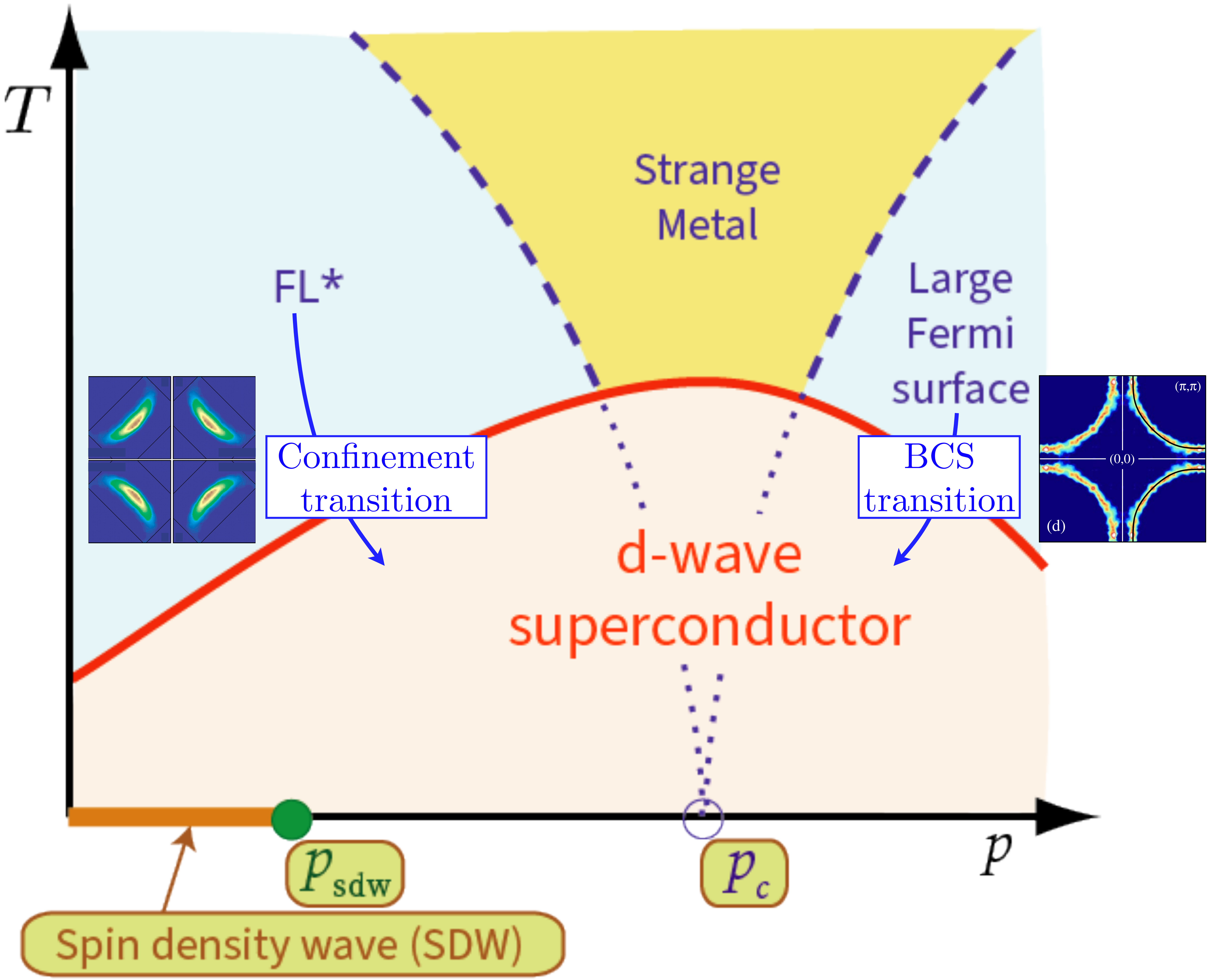
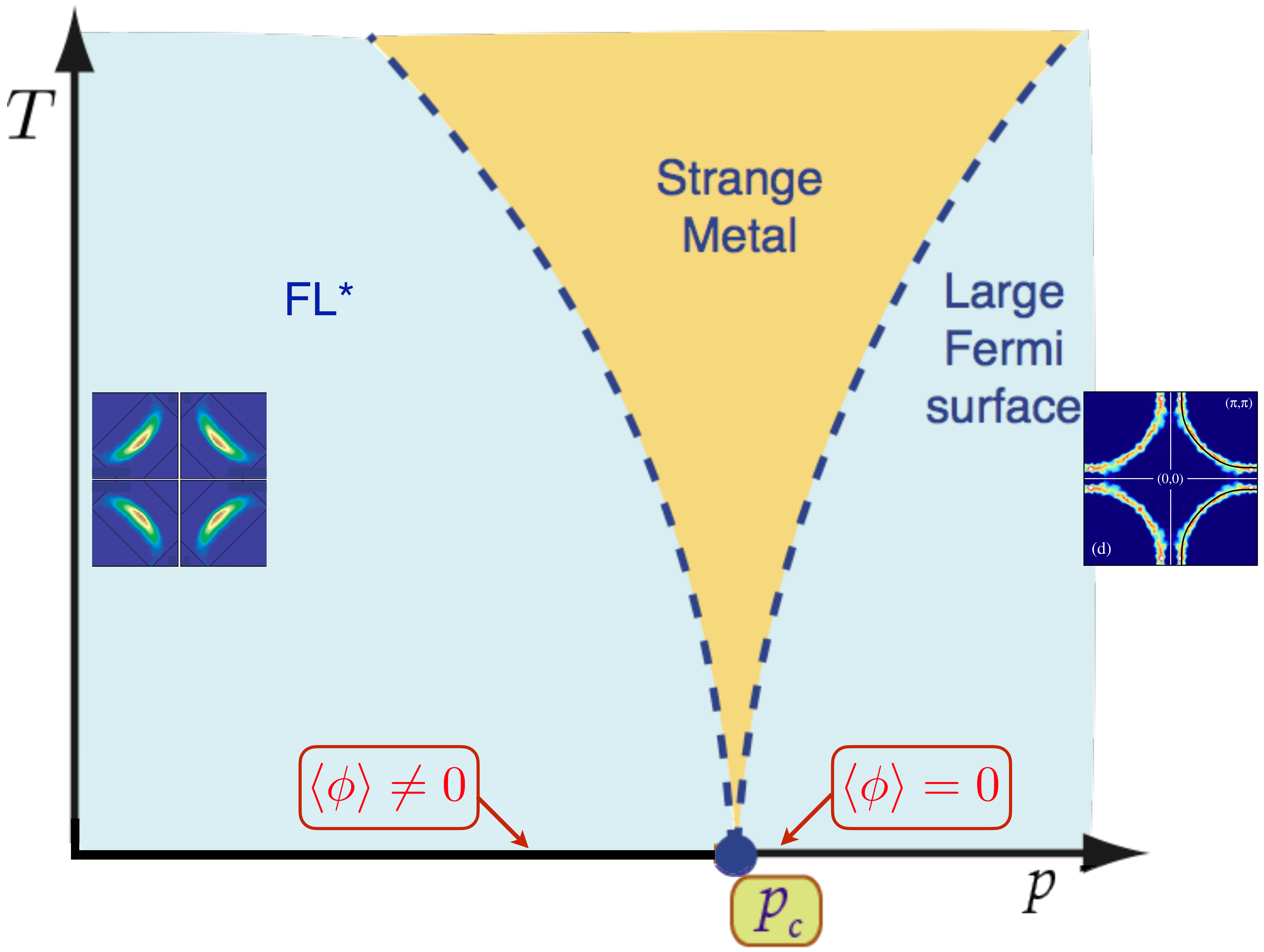


Quantum-criticality of a quantum phase transition between two metals (FL* and FL) at $p = p_c$, with no symmetry breaking. ϕ is a Higgs field with emergent gauge charge.

Both metals lead to the same *d*-wave superconductor at lower temperatures, and so there is transition at $p = p_c$ within the superconducting state.



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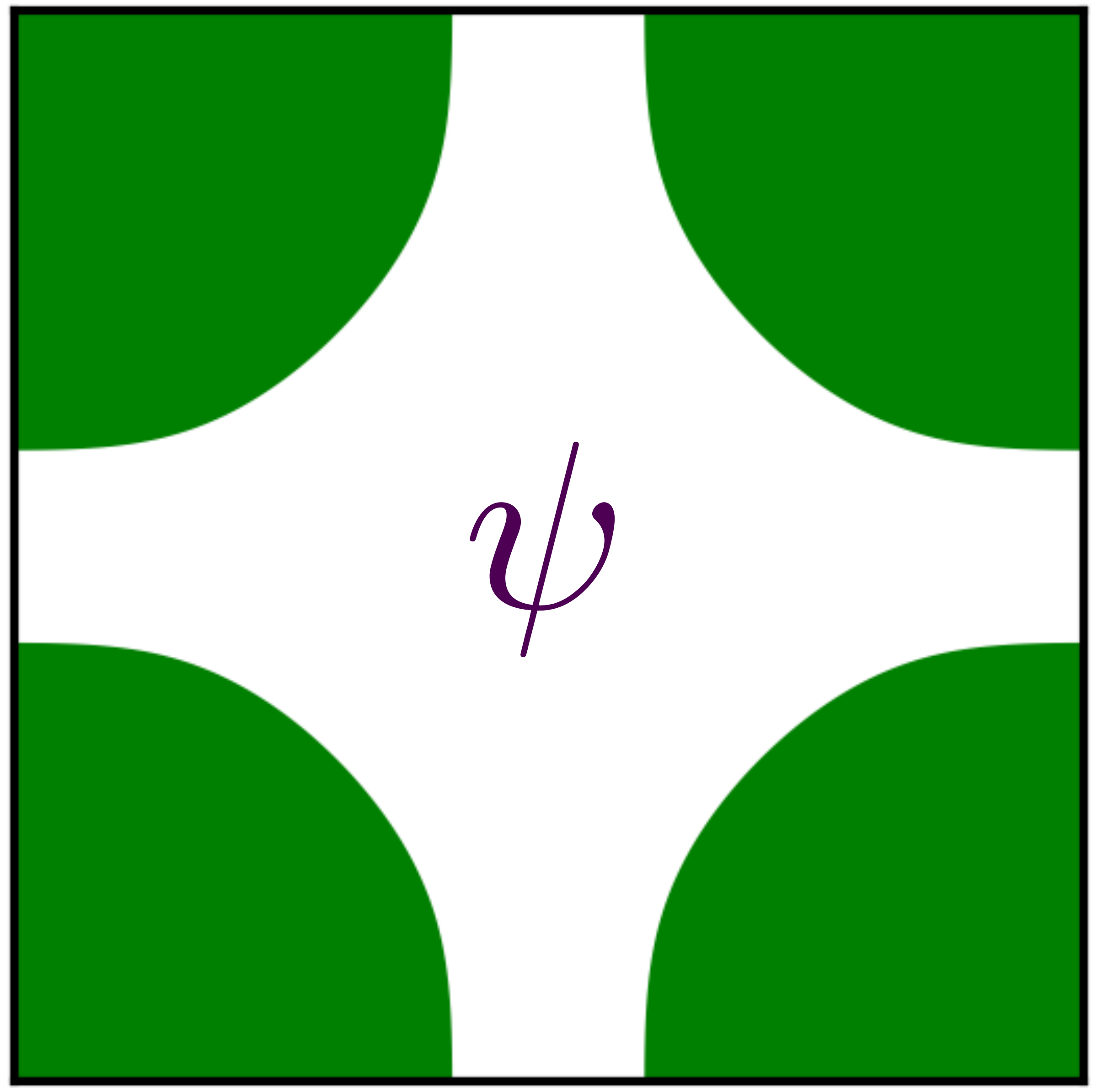
2d-YSYK model: Fermi surface + critical boson with interaction disorder

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

$$\mathcal{L}_\psi = \psi_{\boldsymbol{k}}^\dagger \left(\frac{\partial}{\partial \tau} + \varepsilon(\boldsymbol{k}) \right) \psi_{\boldsymbol{k}}$$



Critical Higgs boson ϕ driving FL*-FL transition.

$$[\phi(\boldsymbol{r})]^2 + [g + g'(\boldsymbol{r})]\, \psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})\, \phi(\boldsymbol{r})$$

$$+ v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

Spatially random Yukawa coupling $g'(\boldsymbol{r})$ with $\overline{g'(\boldsymbol{r})} = 0$, $\overline{g'(\boldsymbol{r})g'(\boldsymbol{r}')} = g'^2\delta(\boldsymbol{r} - \boldsymbol{r}')$

Spatially random potential $v(\boldsymbol{r})$ with $\overline{v(\boldsymbol{r})} = 0$, $\overline{v(\boldsymbol{r})v(\boldsymbol{r}')} = v^2\delta(\boldsymbol{r} - \boldsymbol{r}')$

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Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023)

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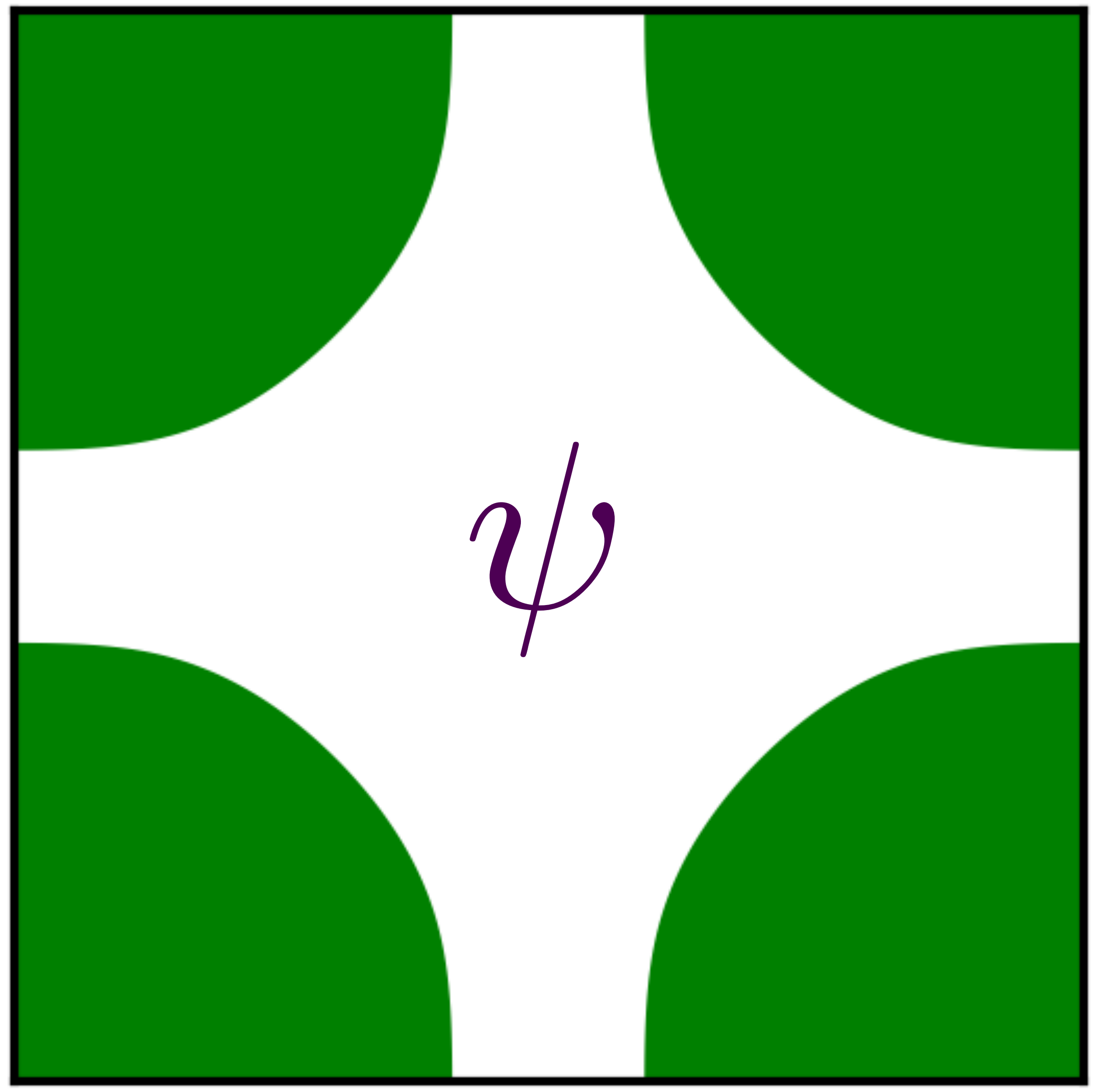

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$$+ v(\boldsymbol{r})\psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r})$$

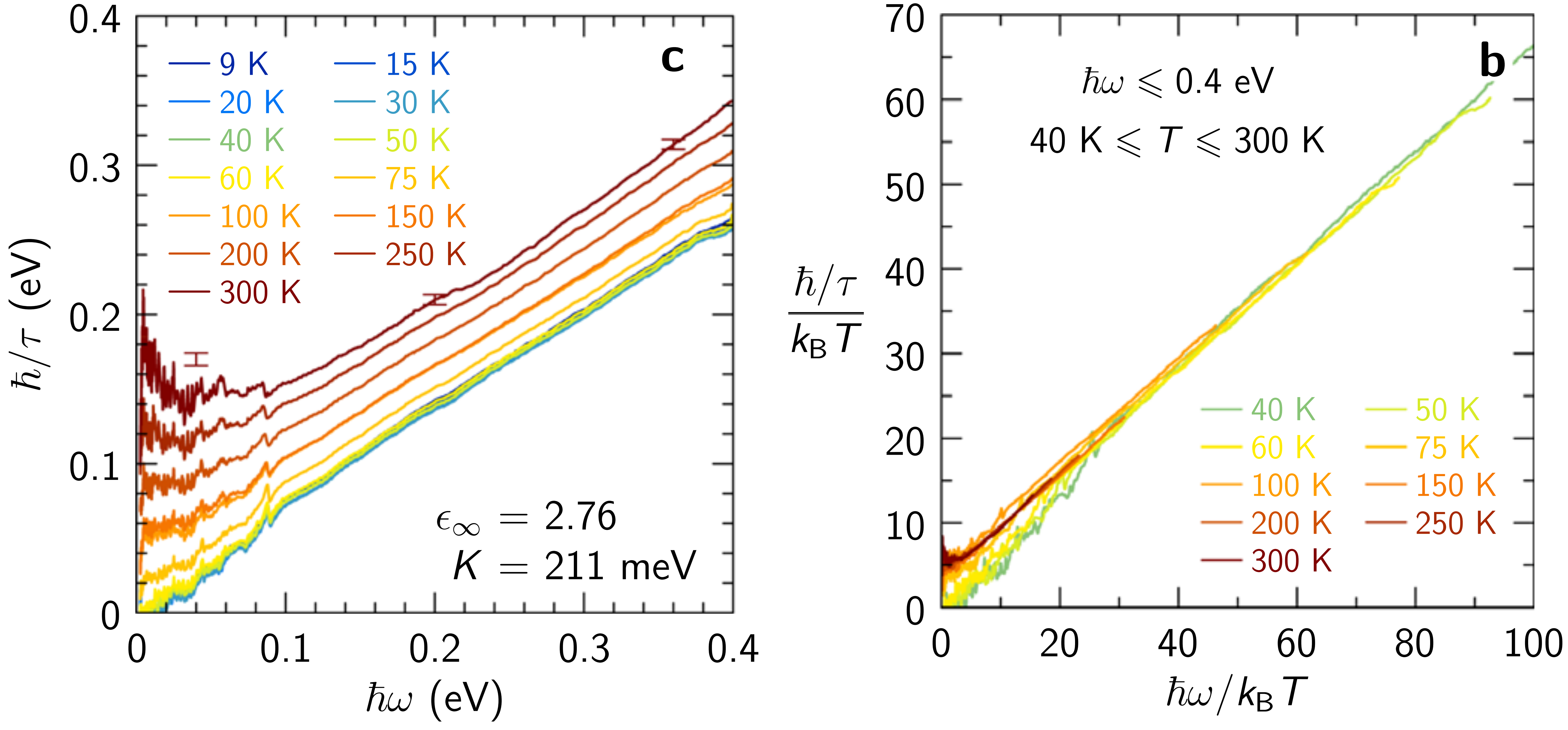
Saddle-point equations

$$\Sigma(\tau, \mathbf{r}) = g^2 D(\tau, \mathbf{r}) G(\tau, \mathbf{r}) + v^2 G(\tau, \mathbf{r}) \delta^2(\mathbf{r}) + {g'}^2 G(\tau, \mathbf{r}) D(\tau, \mathbf{r}) \delta^2(\mathbf{r}),$$

$$\Pi(\tau, \mathbf{r}) = -g^2 G(-\tau, -\mathbf{r}) G(\tau, \mathbf{r}) - {g'}^2 G(-\tau, \mathbf{r}) G(\tau, \mathbf{r}) \delta^2(\mathbf{r}),$$

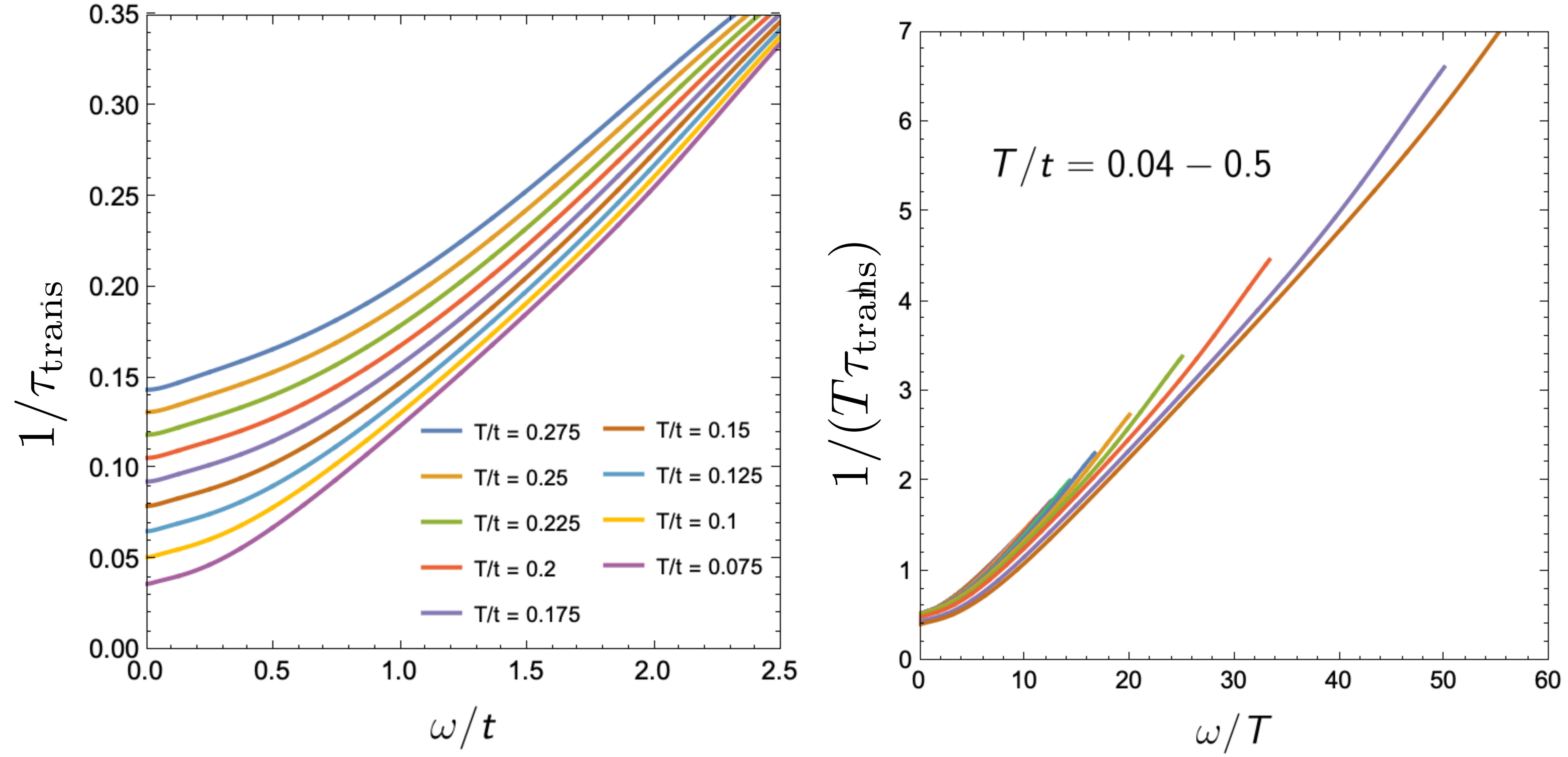
$$G(i\omega, \mathbf{k}) = \frac{1}{i\omega - \varepsilon(\mathbf{k}) + \mu - \Sigma(i\omega, \mathbf{k})},$$

$$D(i\Omega, \mathbf{q}) = \frac{1}{\Omega^2 + \mathbf{q}^2 + m_b^2 - \Pi(i\Omega, \mathbf{q})}.$$



$$\sigma(\omega) = i \frac{e^2 K/(\hbar d_c)}{\hbar\omega \frac{m^*(\omega)}{m} + i \frac{\hbar}{\tau(\omega)}}$$

B. Michon, C. Berthod, C.W. Rischau, A. Ataei, L. Chen, S. Komiya, S. Ono, L. Taillefer, D. van der Marel, A. Georges, Nature Comm. **14**, 3033 (2023)



Planckian dynamics!

$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$

and entropy $S(T \to 0) \sim T \ln(1/T)$ in 2d-YSYK model (unlike zero temperature entropy in SYK model).

Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentinis, Jorg Schmalian, S.S., Ilya Esterlis, PRL **133**, 186502 (2024)

A **critical spin liquid**
(SU(2) gauge theory with massless
Dirac and Higgs matter)
for the FL* pseudogap

and a **critical charge liquid**
(the 2d-Yukawa-SYK model)
for the strange metal.

Gapless and strongly interacting,
many-body systems with
no particle-like excitations