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Critical quantum liquids, and the cuprate high temperature superconductors

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Critical quantum liquids, and the cuprate high temperature superconductors

Stony Brook University
September 23, 2025

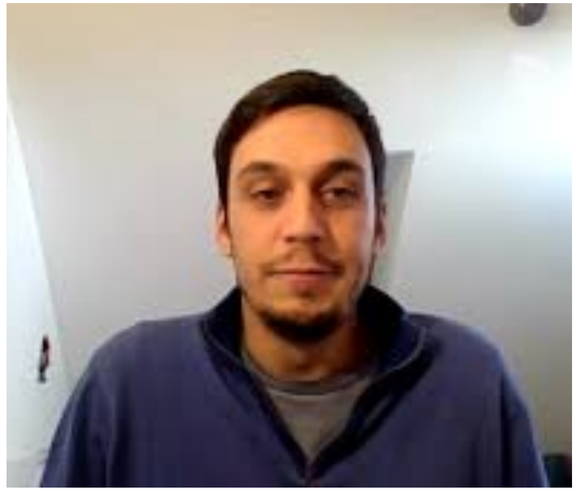
Subir Sachdev







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



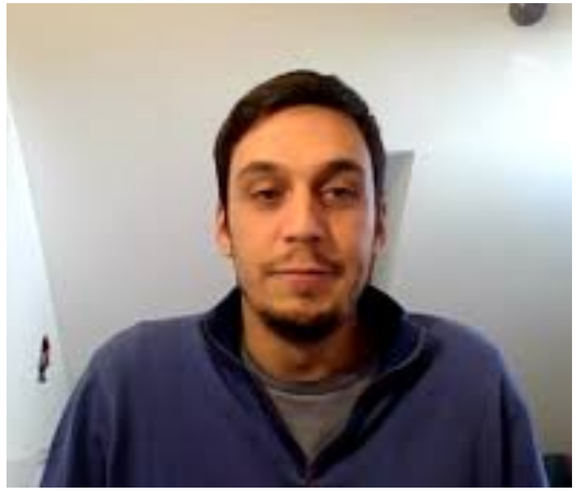
Ravi Shanker



Sayantan Sharma



Maine Christos
Caltech



Pietro Bonetti



Alexander
Nikolaenko



Aavishkar Patel
ICTS, Bengaluru

arXiv > cond-mat > arXiv:2508.20164

Condensed Matter > Strongly Correlated Electrons

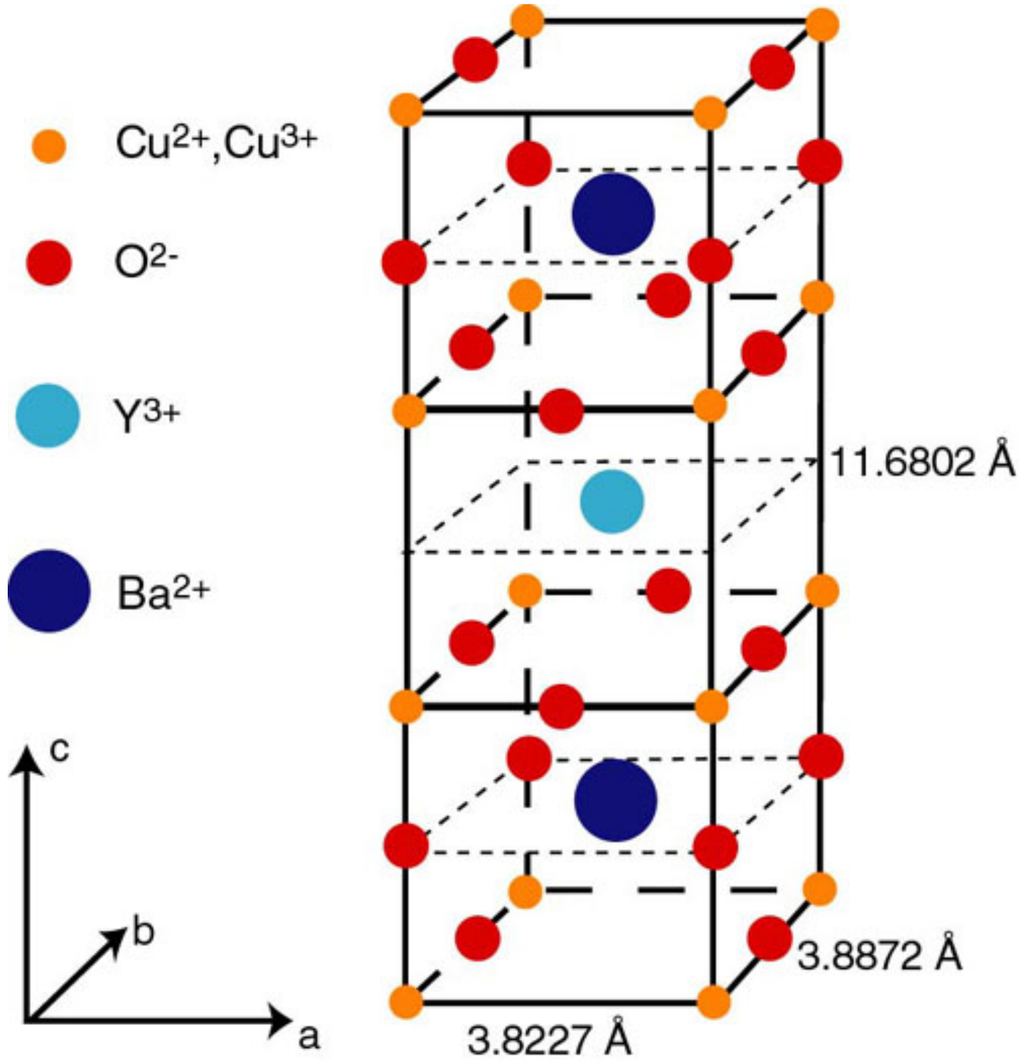
[Submitted on 27 Aug 2025]

Critical quantum liquids and the cuprate high temperature superconductors

Cuprate high temperature superconductors







$$YBa_2Cu_3O_{6+x}$$

Solid State Physics:

Pre 1986:
Mostly independent electrons (with pairing in BCS theory of superconductivity)

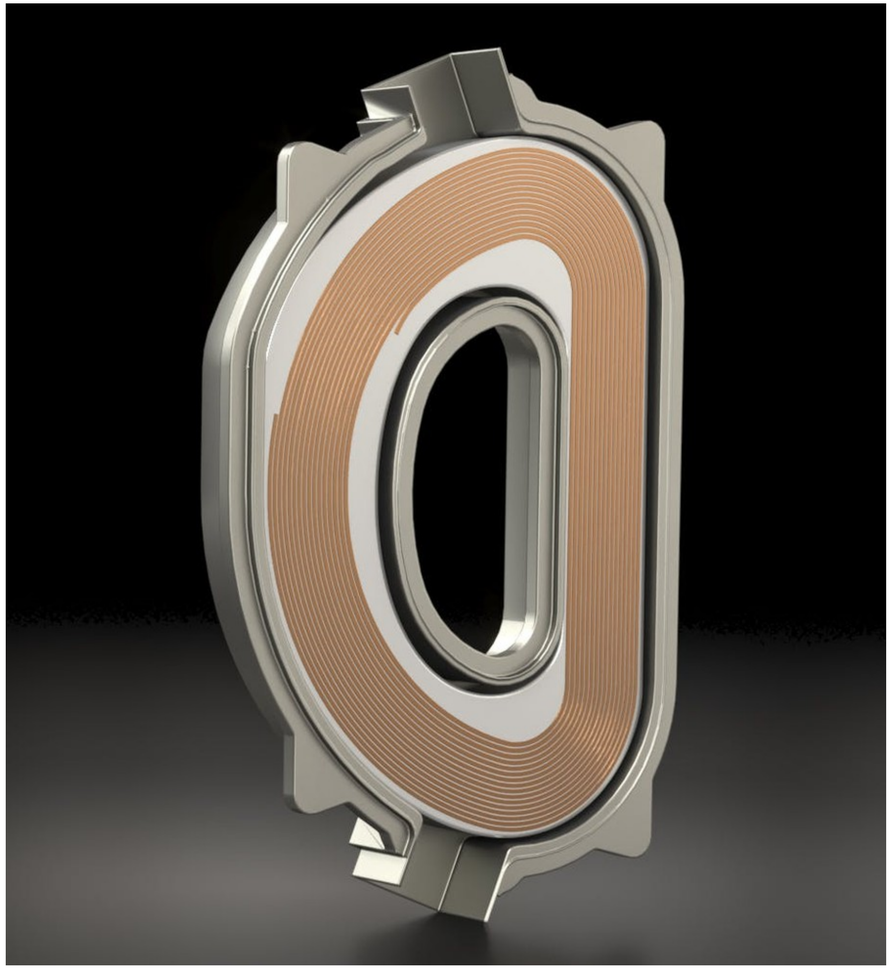
Post 1986:
Many-electron entanglement

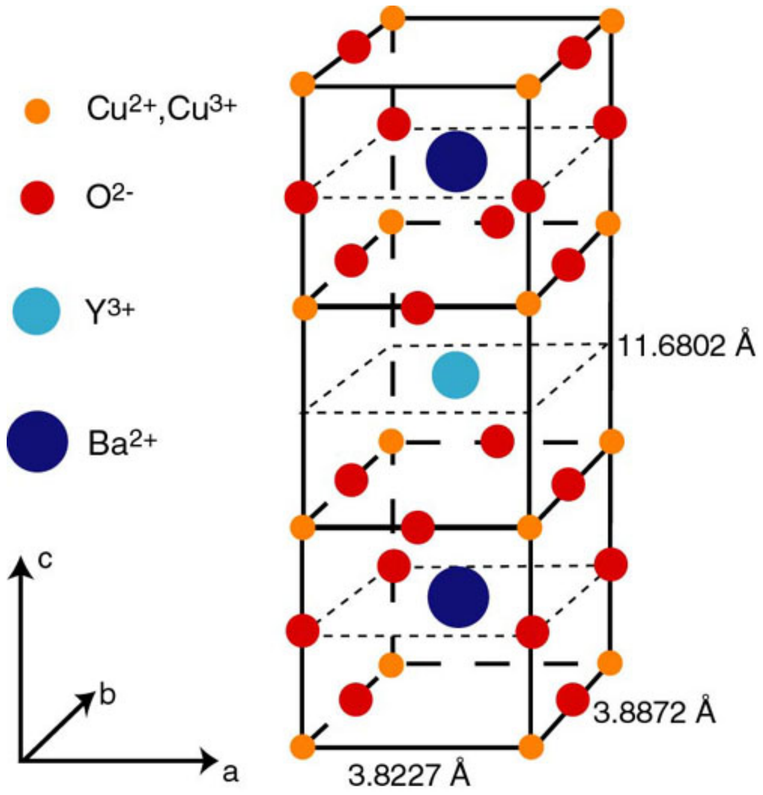
HTS Magnets: Enabling Technology

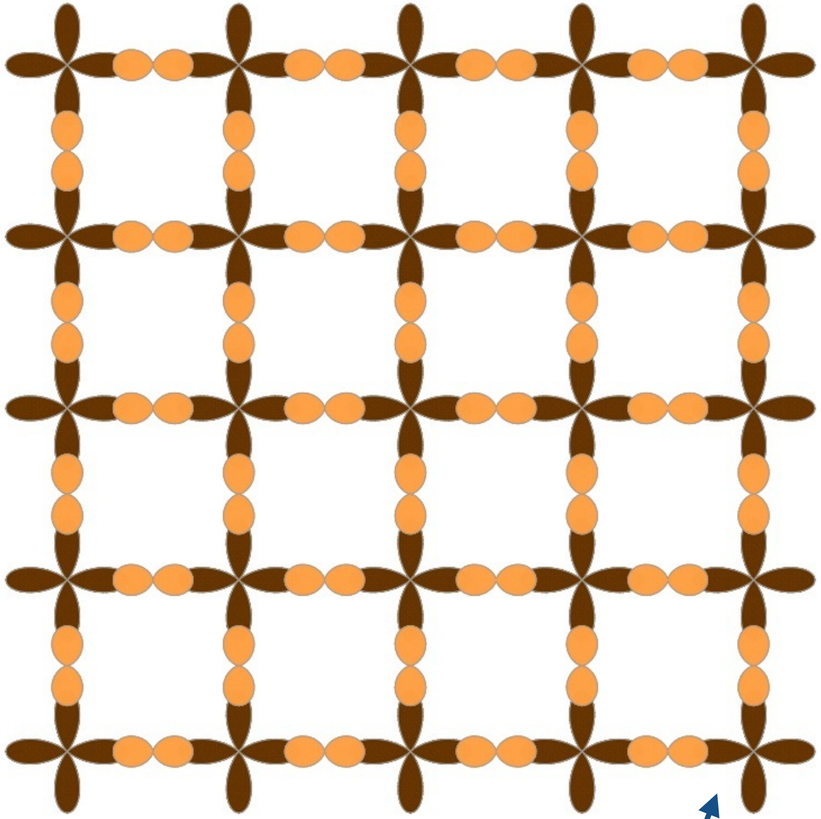
The surest path to limitless, clean, fusion energy

YBCO magnets allow for smaller, faster, and less expensive tokamaks for plasma fusion

Commonwealth Fusion Systems

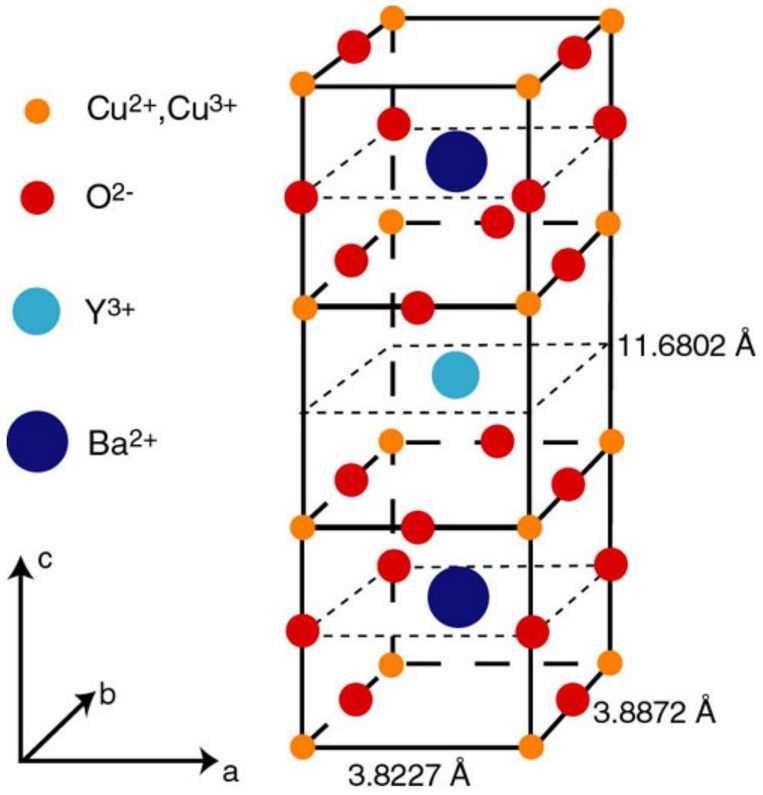


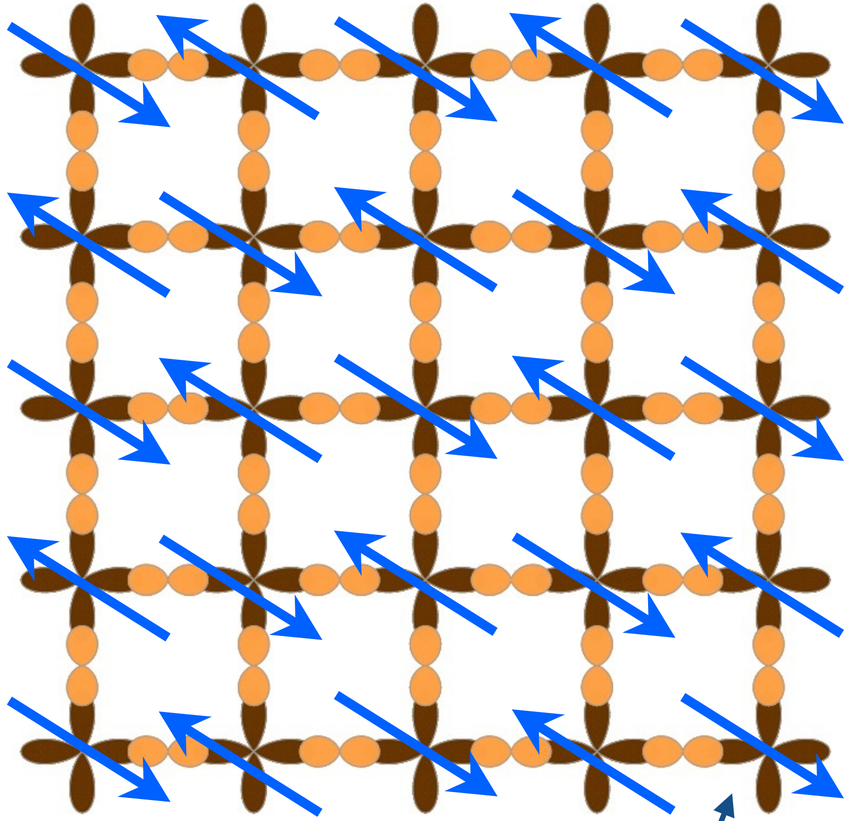




$YBa_2Cu_3O_{6+x}$

Cu

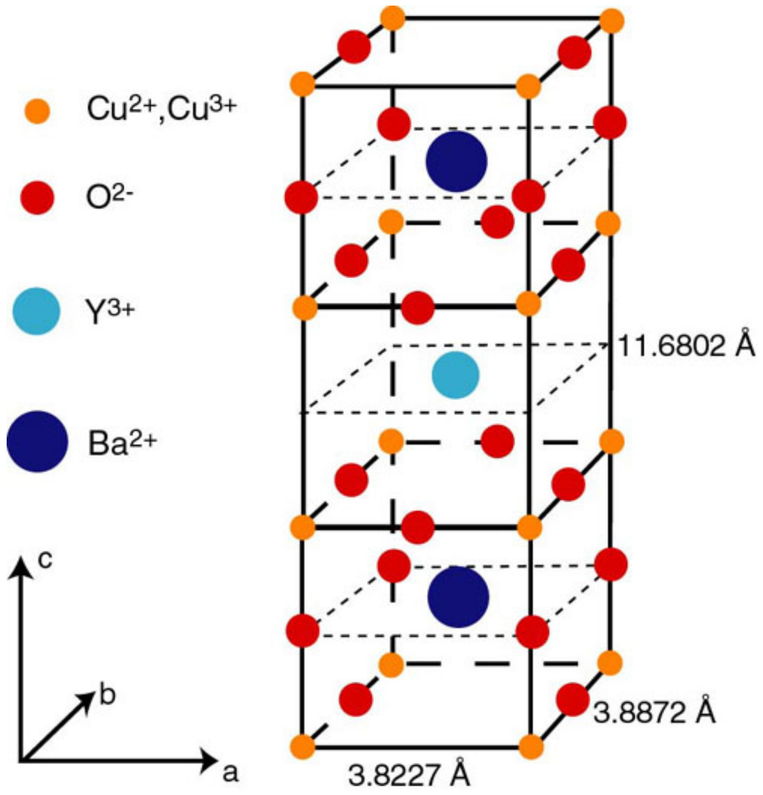


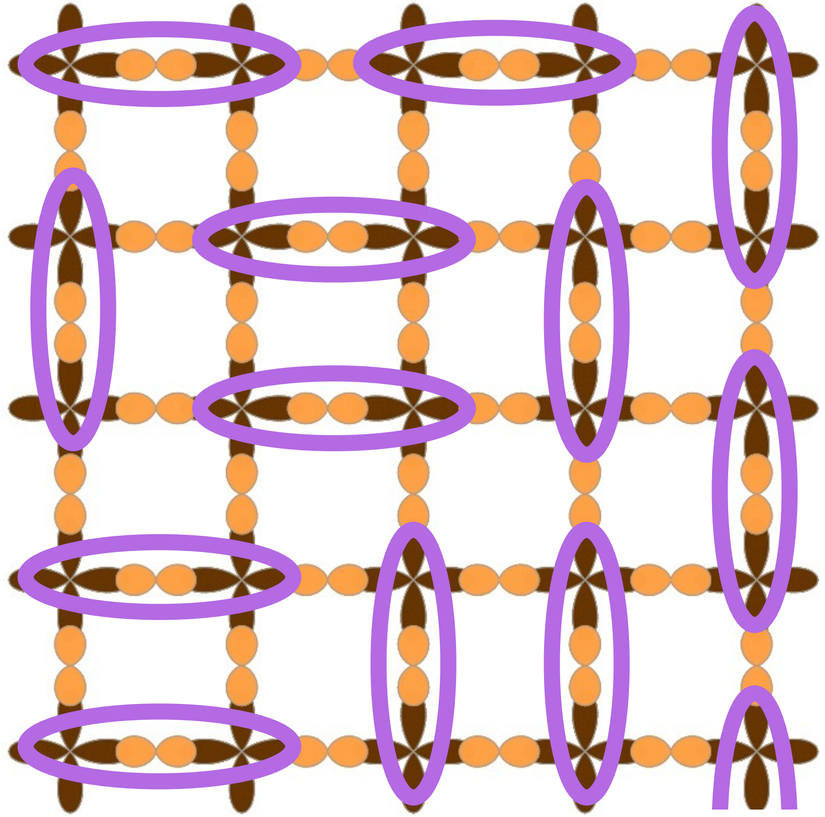


$YBa_2Cu_3O_{6+x}$

Cu

Antiferromagnetic insulator at a density of one electron per Cu





$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

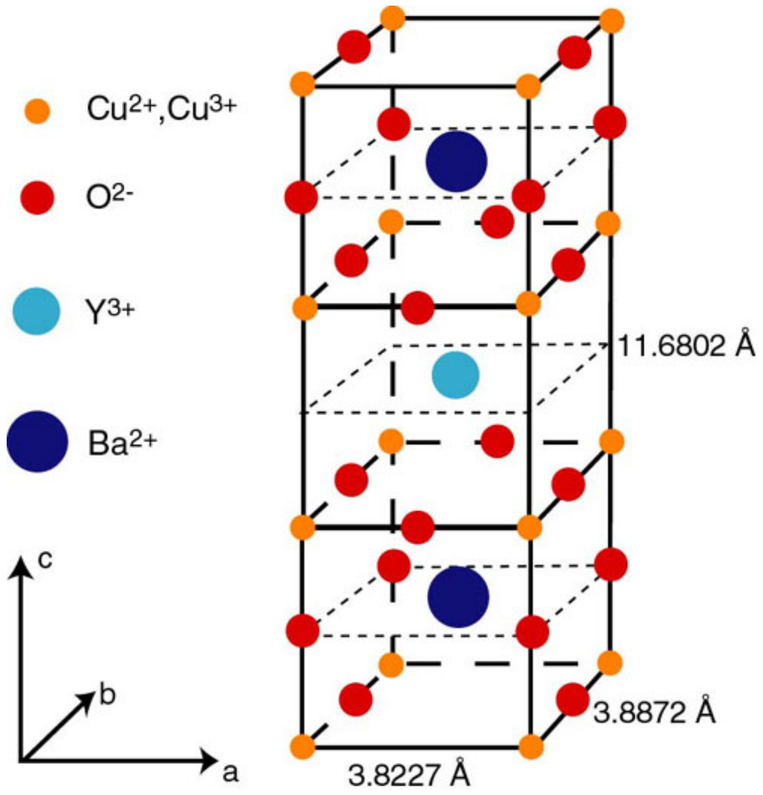
$\mathcal{D} \rightarrow$ dimer covering of lattice

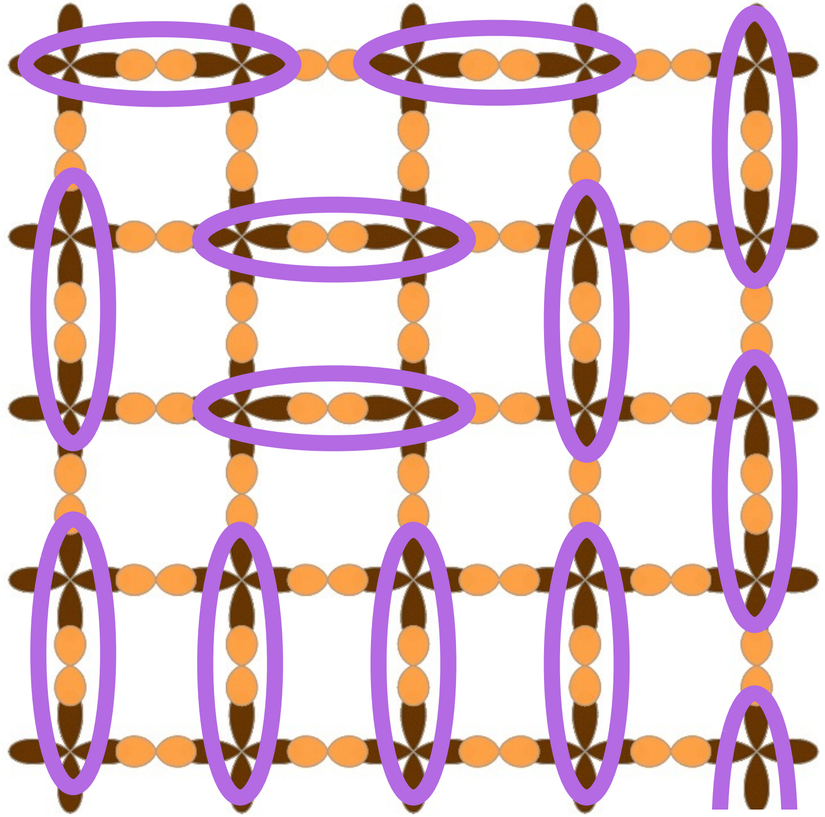
$$YBa_2Cu_3O_{6+x}$$



$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

P.W. Anderson and G. Baskaran (1988): The key to high temperature superconductivity is the formation of a "resonating valence bond state" (a type of **quantum spin liquid**) which entangles the electrons on Cu





$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

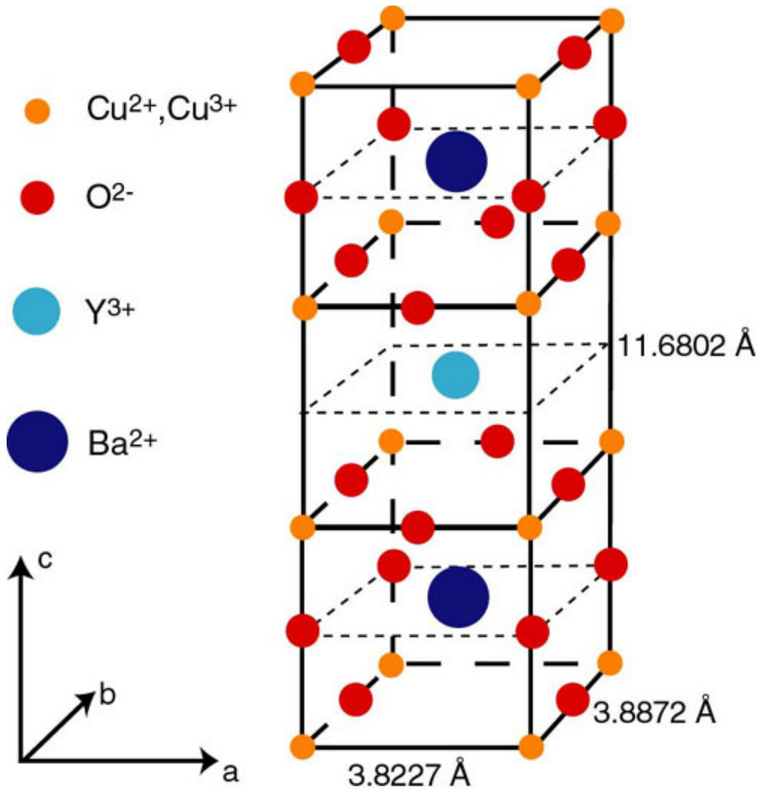
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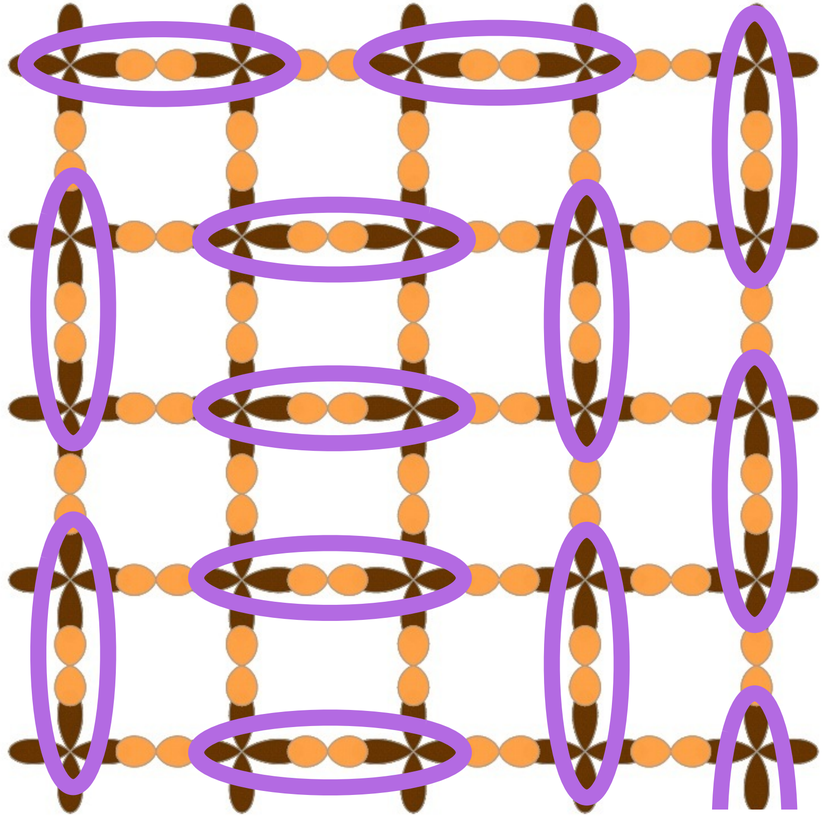
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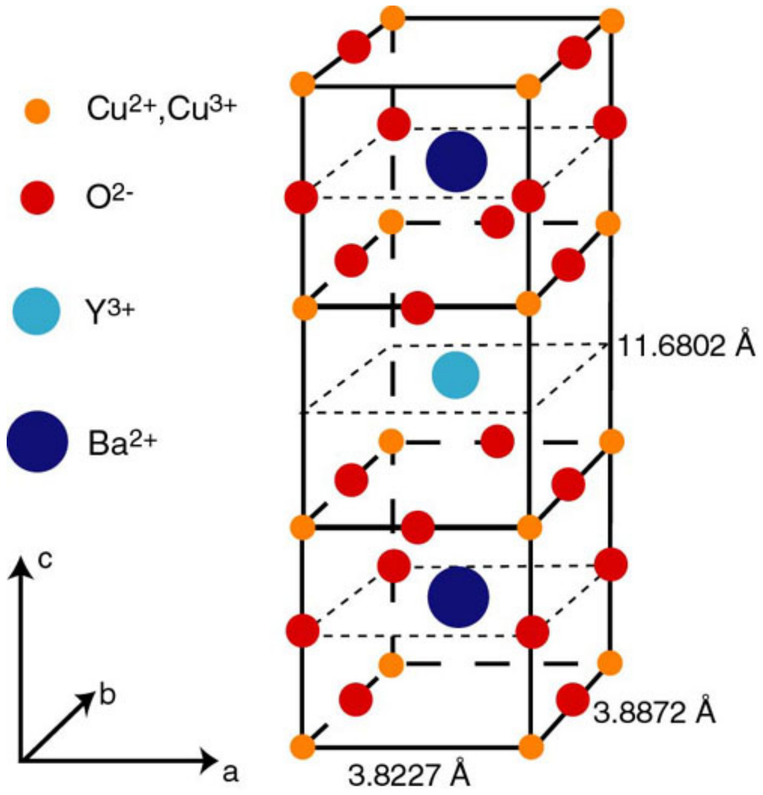
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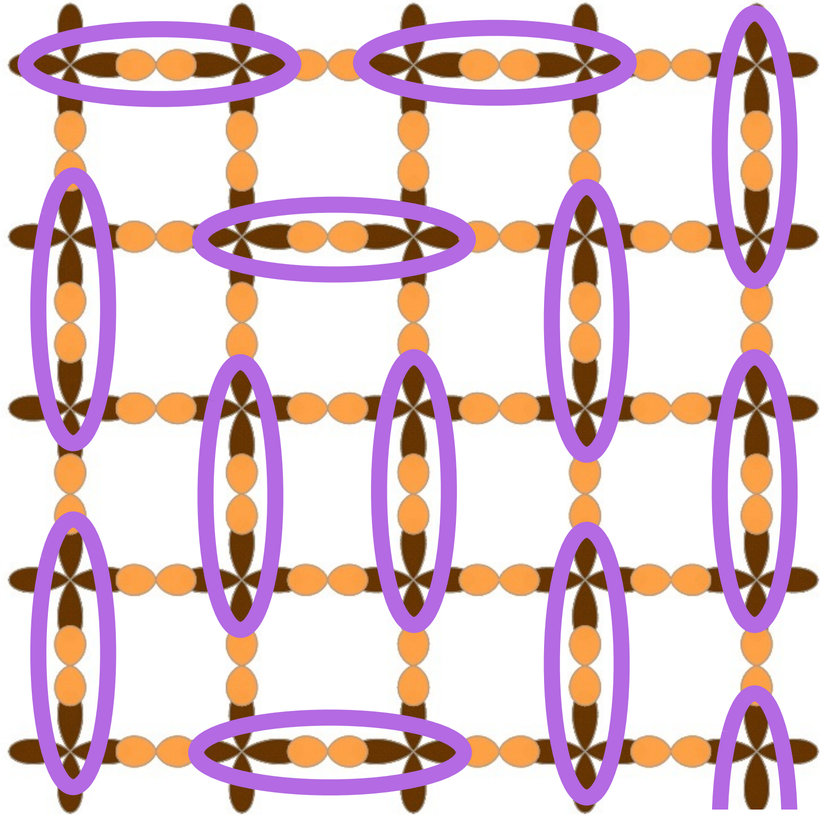
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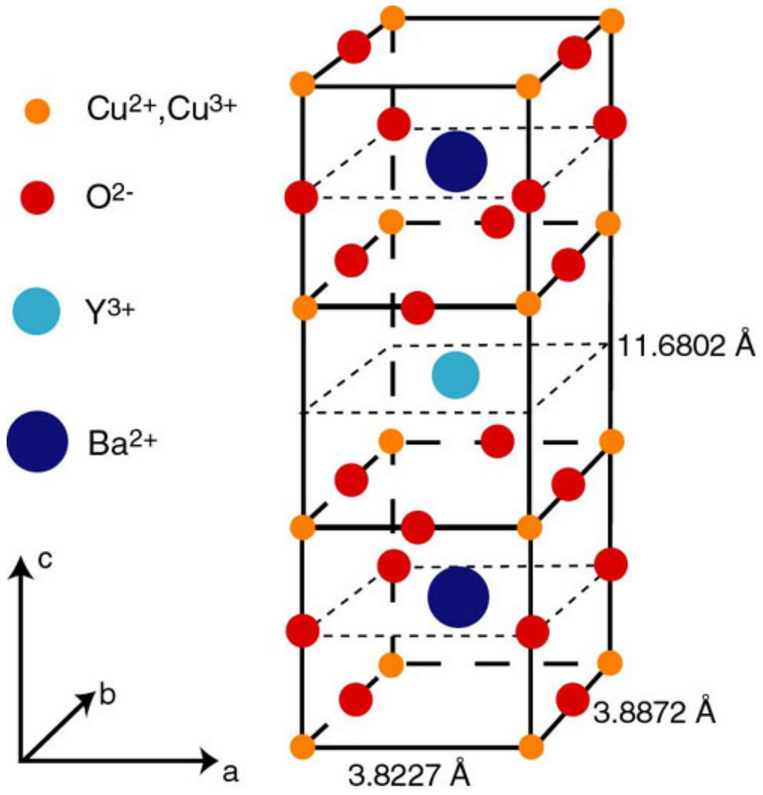
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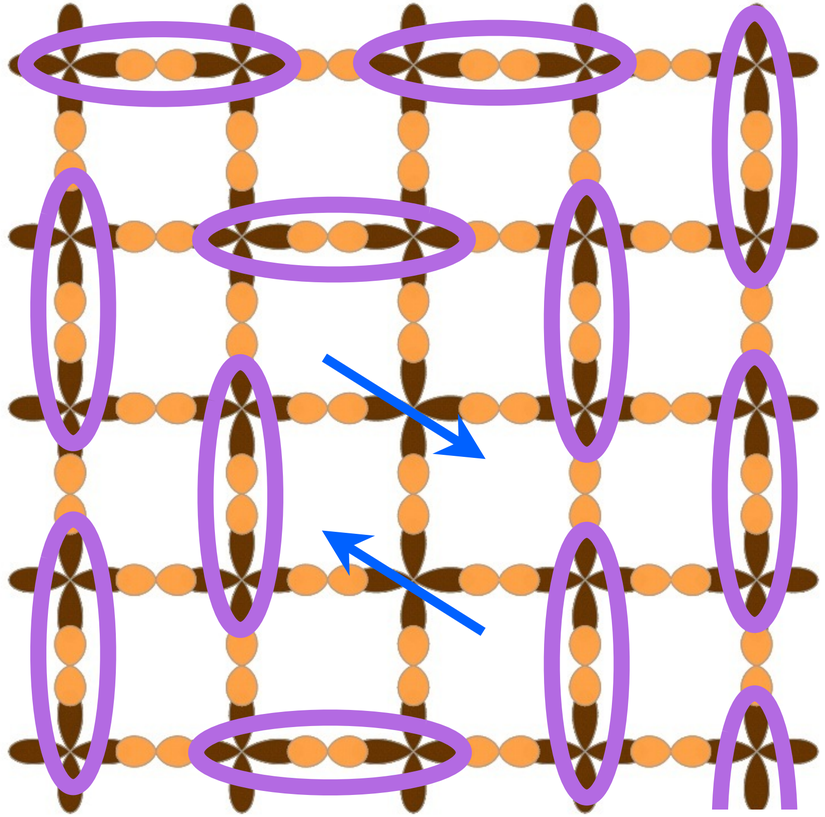
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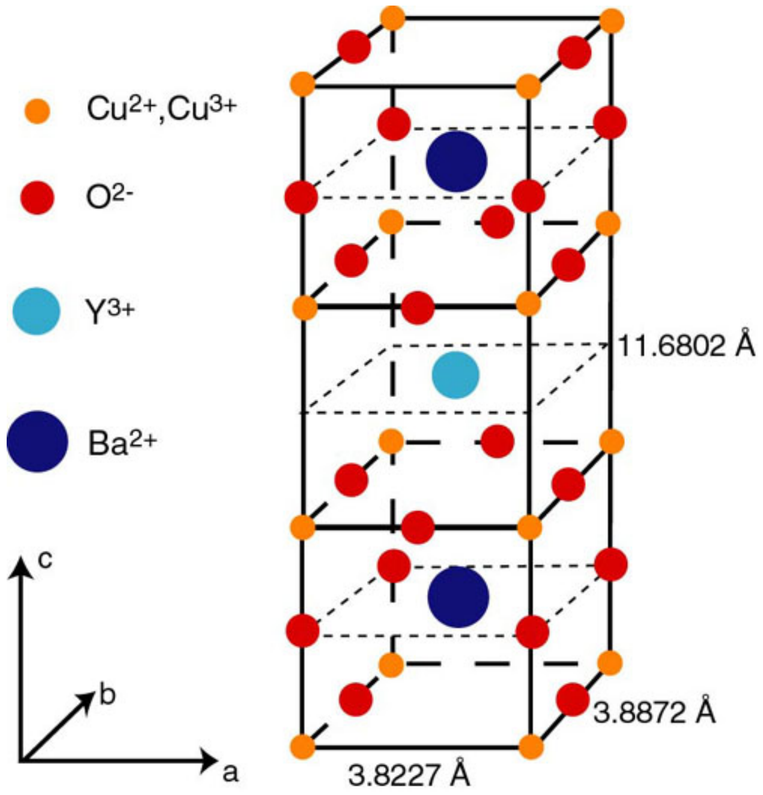


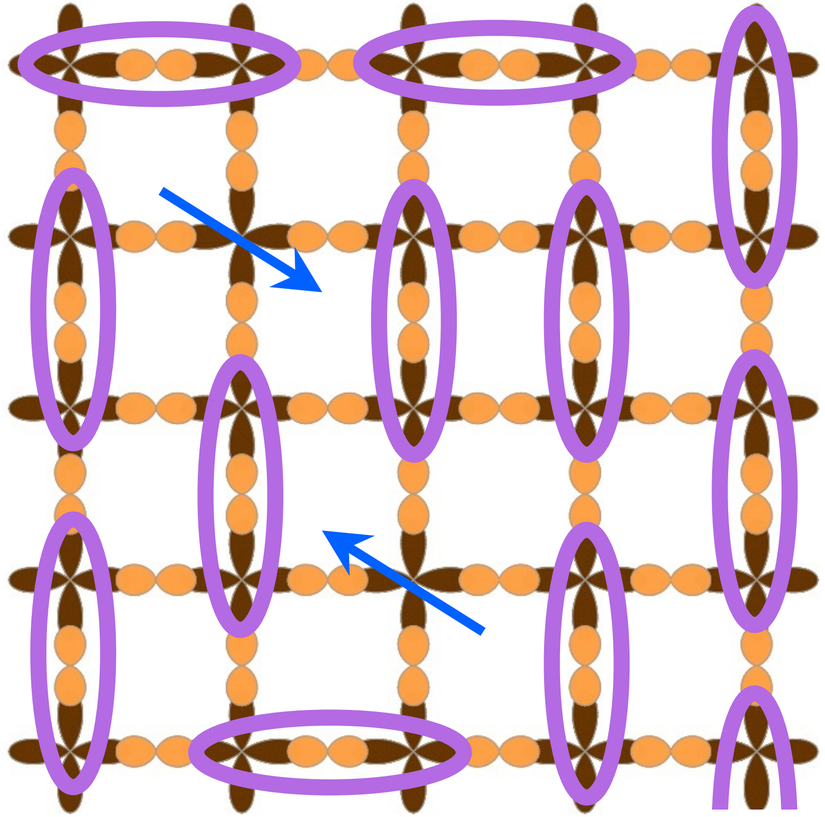


$YBa_2Cu_3O_{6+x}$

 $= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$

Key feature: fractionalization. Excitations are particle-like, but cannot be created by local operators: they are classified under distinct superselection/anyon sectors.



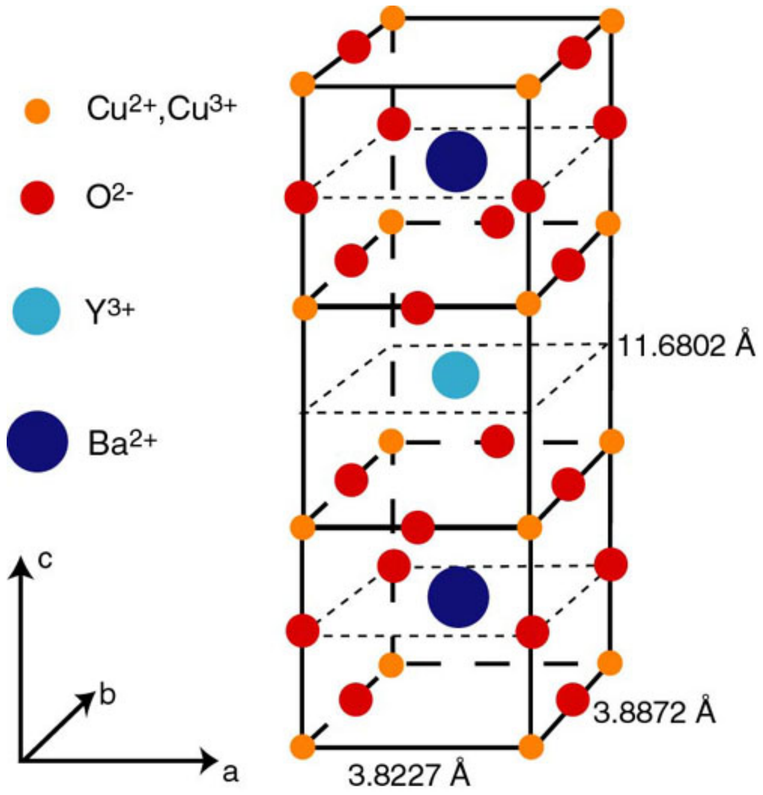


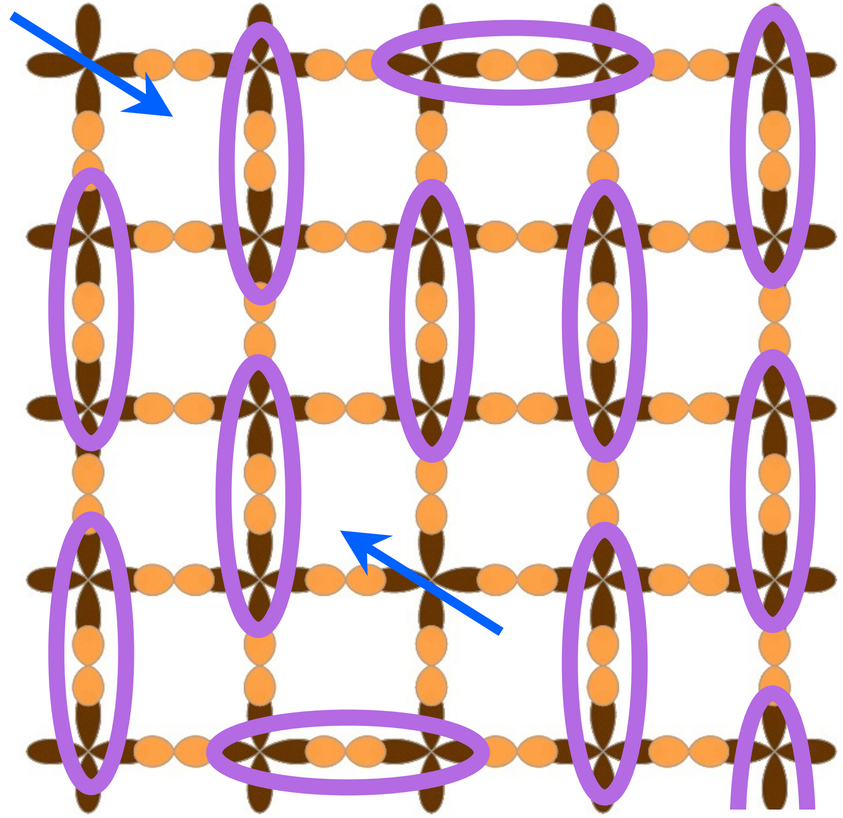
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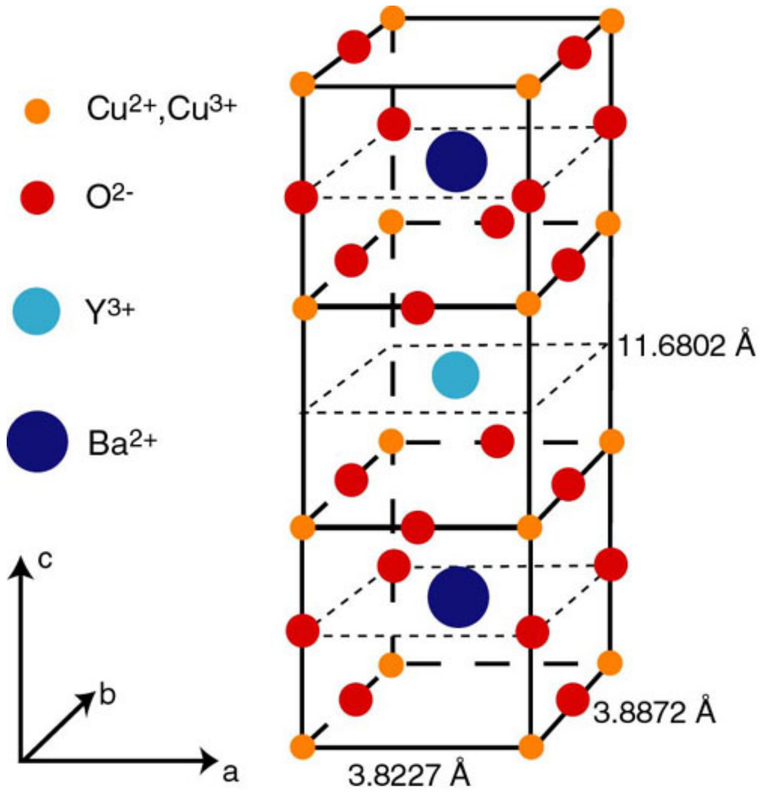


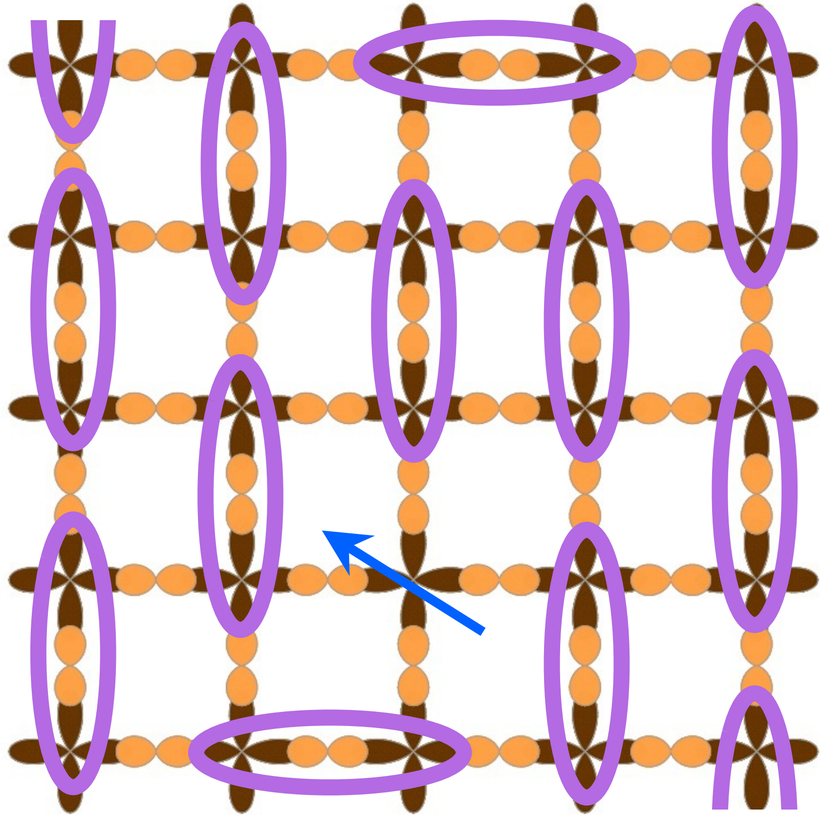


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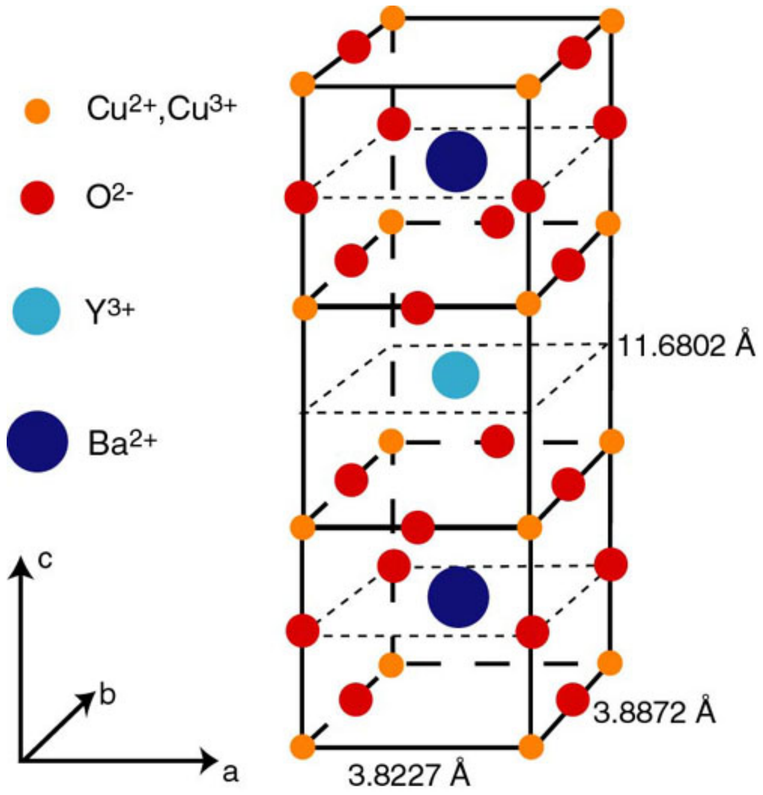


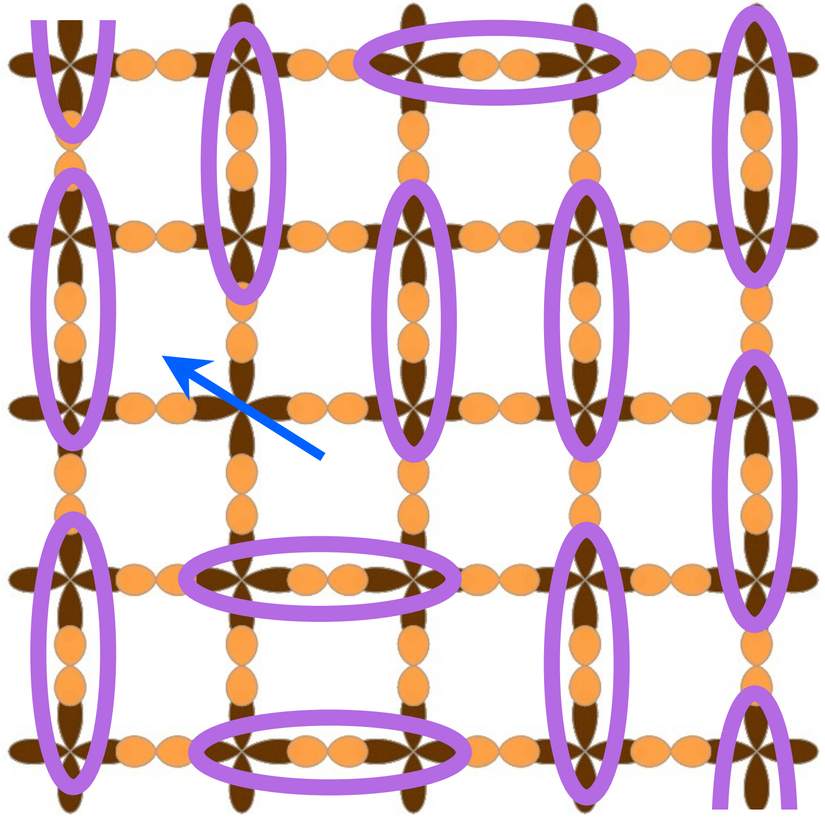
Spin S=1/2, charge neutral spinon

$YBa_2Cu_3O_{6+x}$

$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

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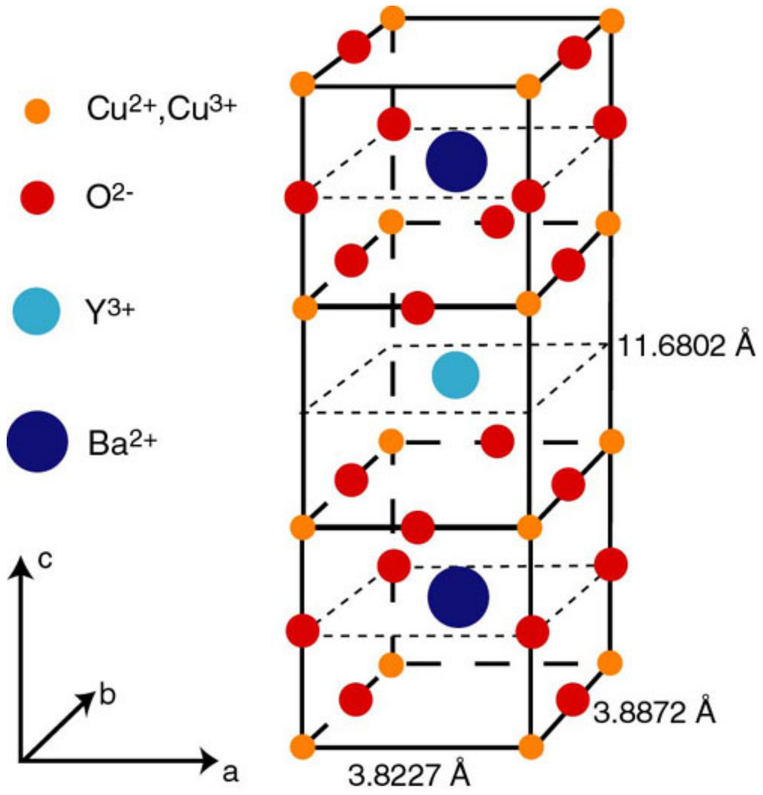


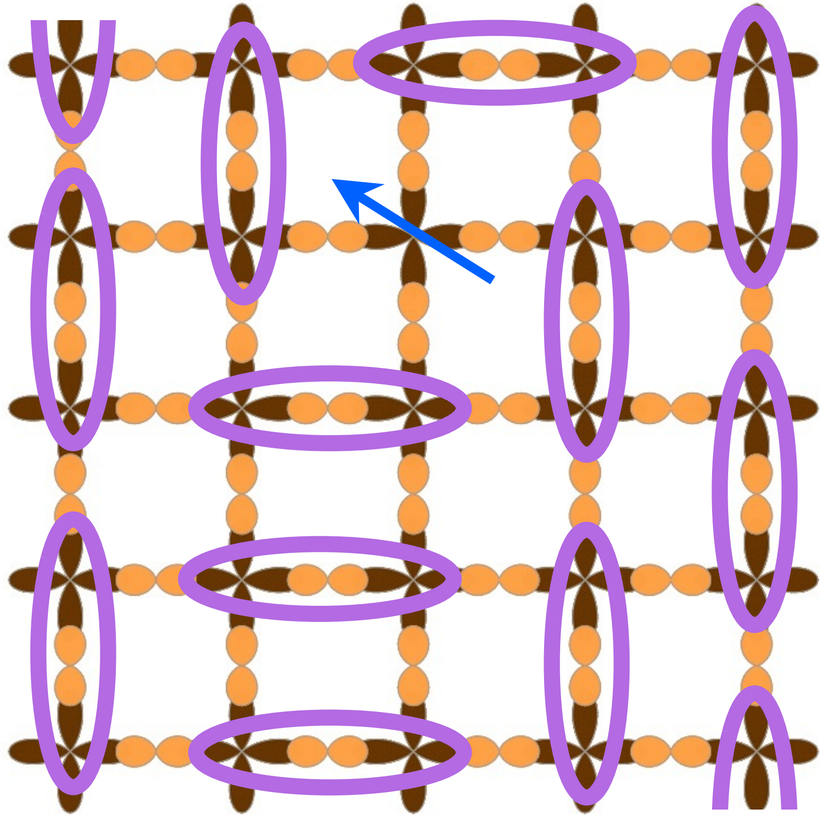
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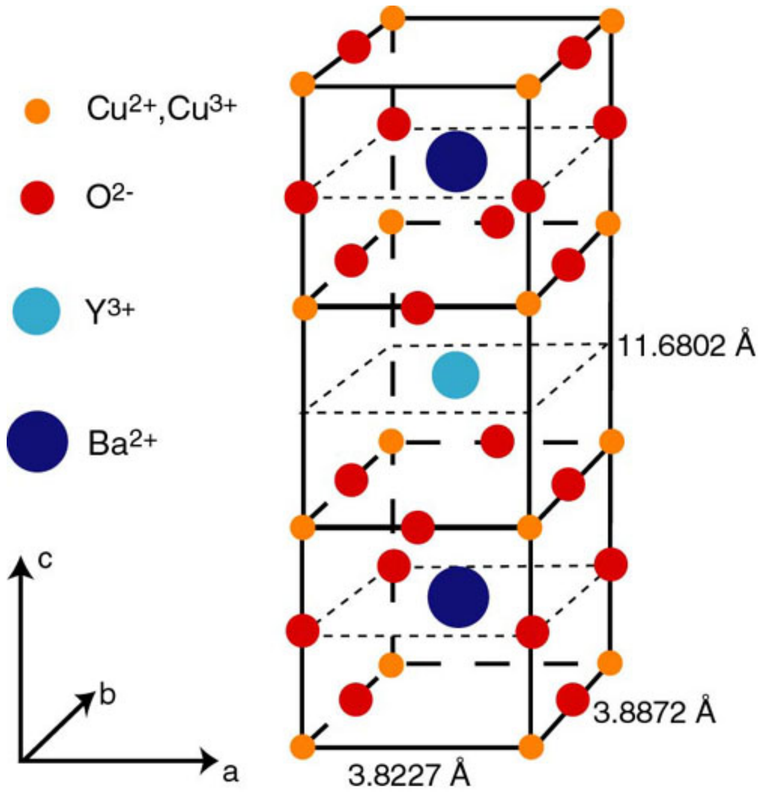


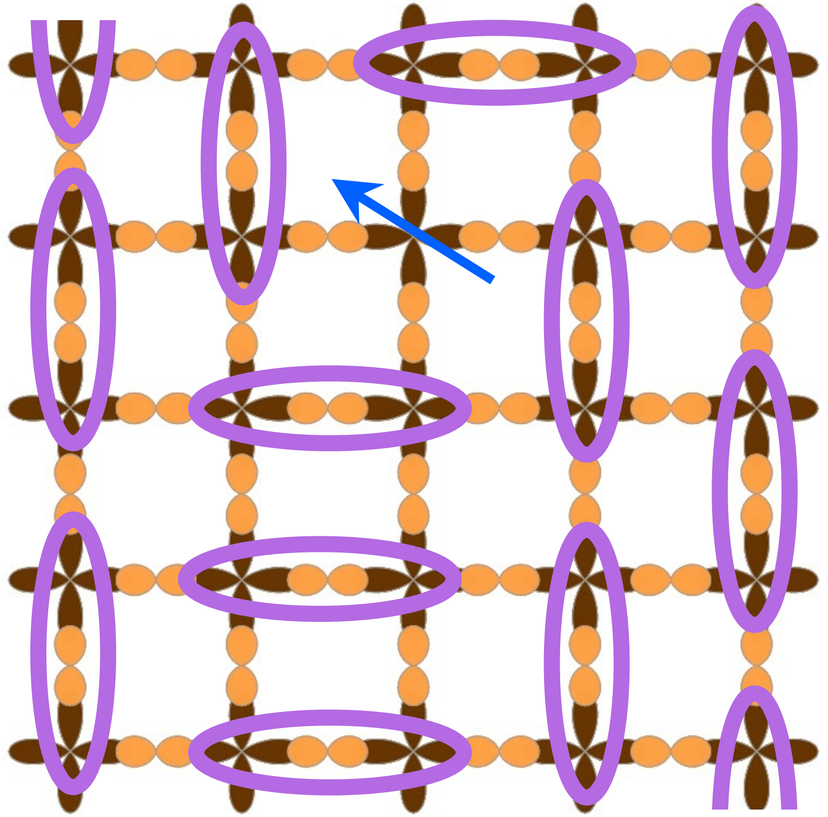
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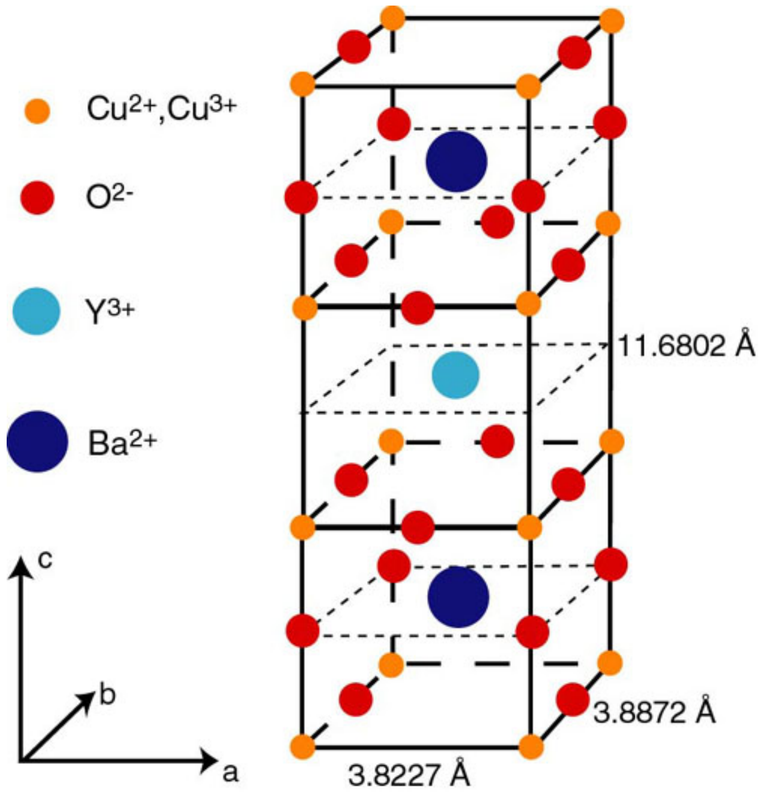


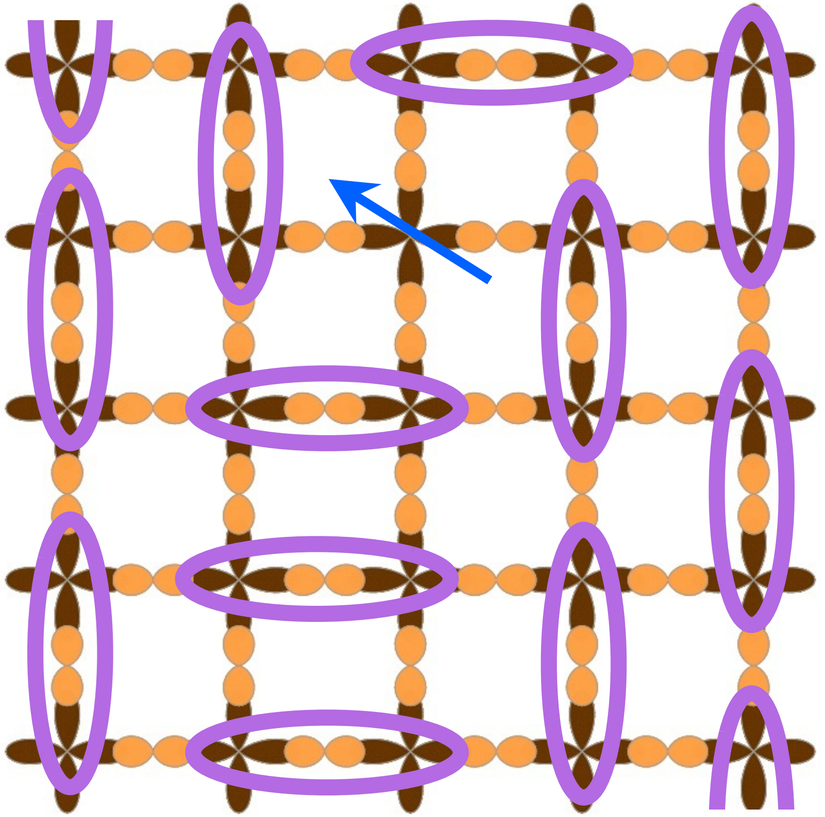
Spin S=1/2, charge neutral spinon

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Key feature: fractionalization. Excitations are particle-like, but cannot be created by local operators: they are classified under distinct superselection/anyon sectors. Kitaev: this is useful for quantum error correction.





Spin S=1/2, charge neutral spinon

$YBa_2Cu_3O_{6+x}$

$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

- Theory of gapped spin liquids of insulators in two dimensions. ✓
  The simplest, and closest to Anderson's RVB state, is the $\mathbb{Z}_2$ spin liquid (Read and S.S. 1991), with the same anyons as the toric code (Kitaev 1996). Implemented in Google's fault tolerant qubit.

We will use a

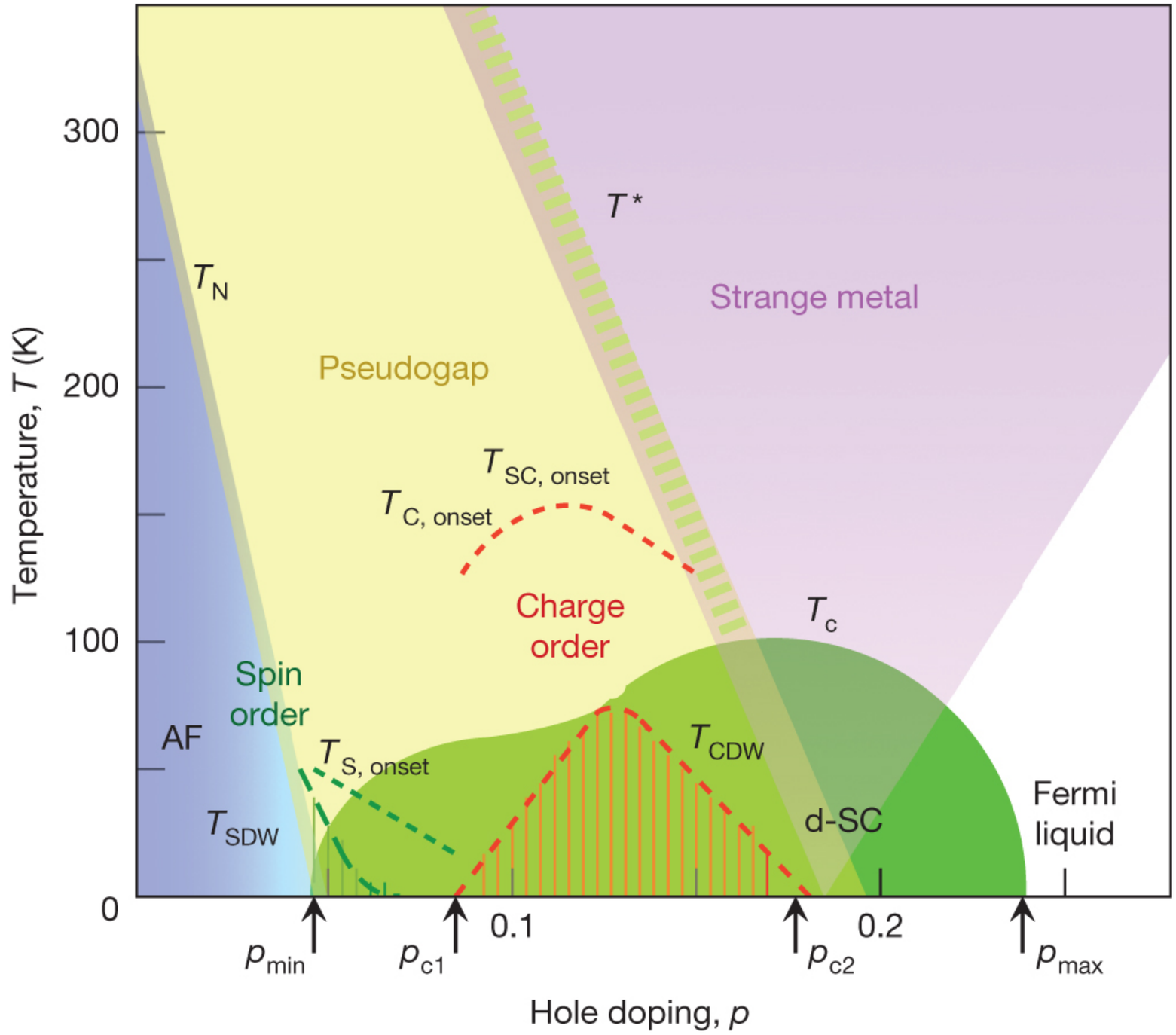


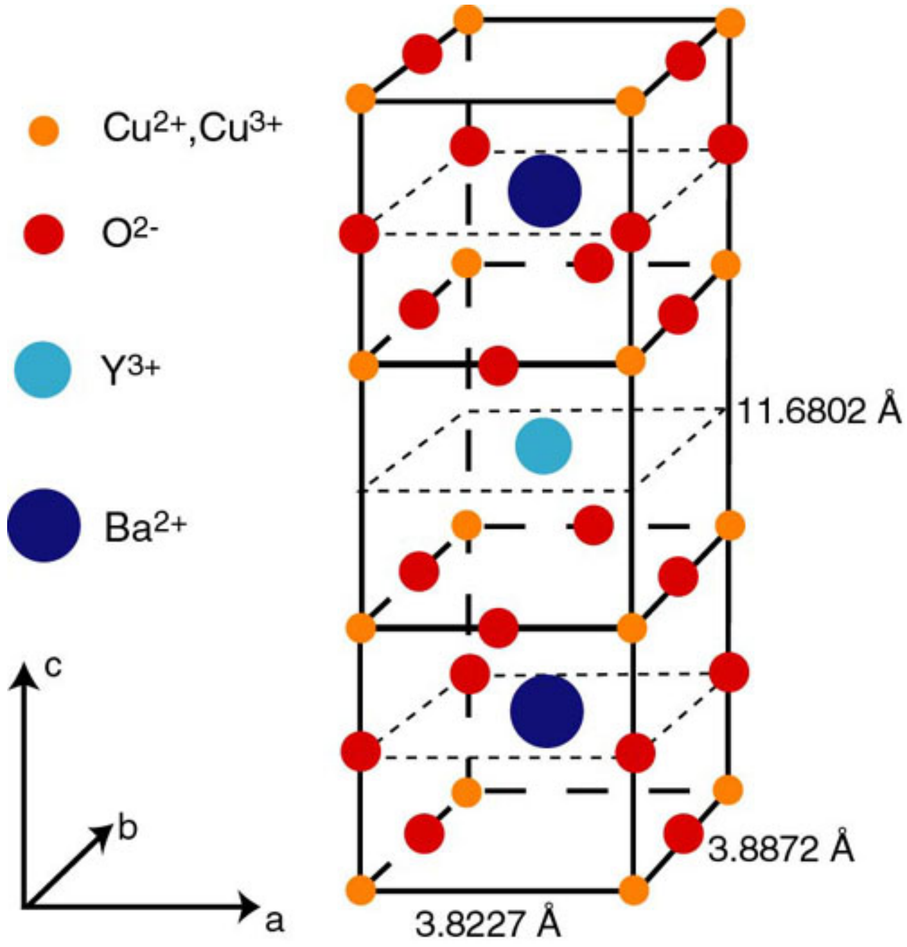
critical spin liquid
(a SU(2) gauge theory with
massless Dirac and Higgs matter)

and a **critical charge liquid**
(the SYK model)

which are gapless and
strongly interacting, with
no particle-like excitations

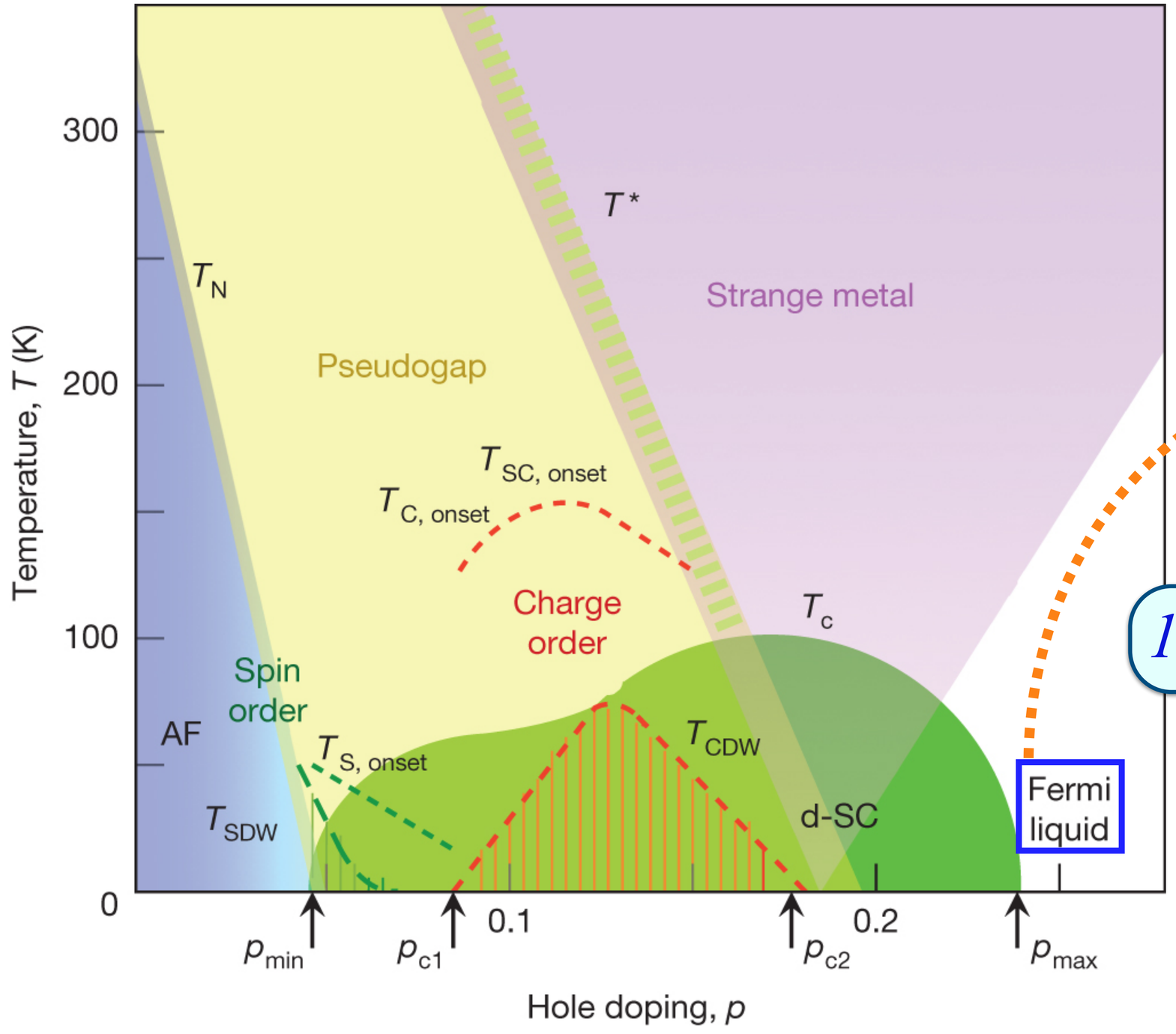
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



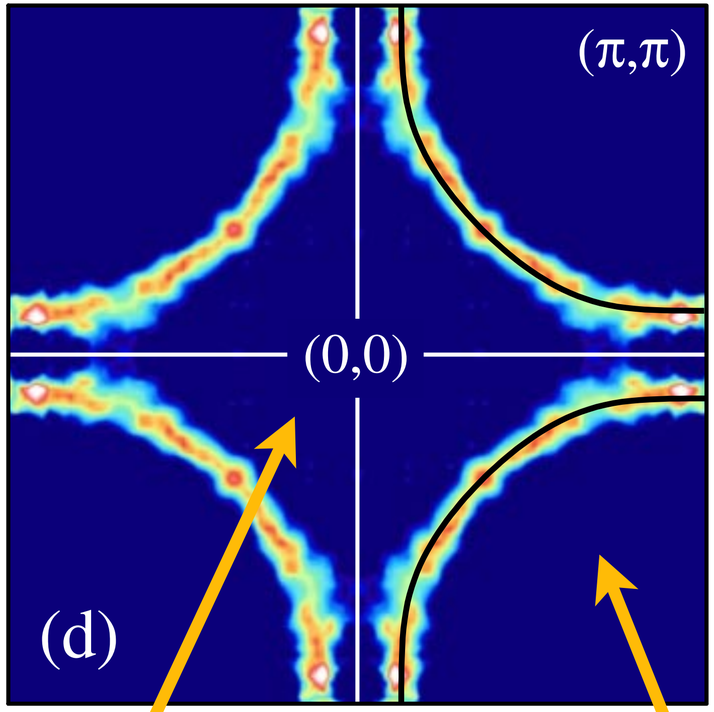


$YBa_2Cu_3O_{6+x}$

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



M. Platé *et al.*, PRL **95**, 077001 (2005)

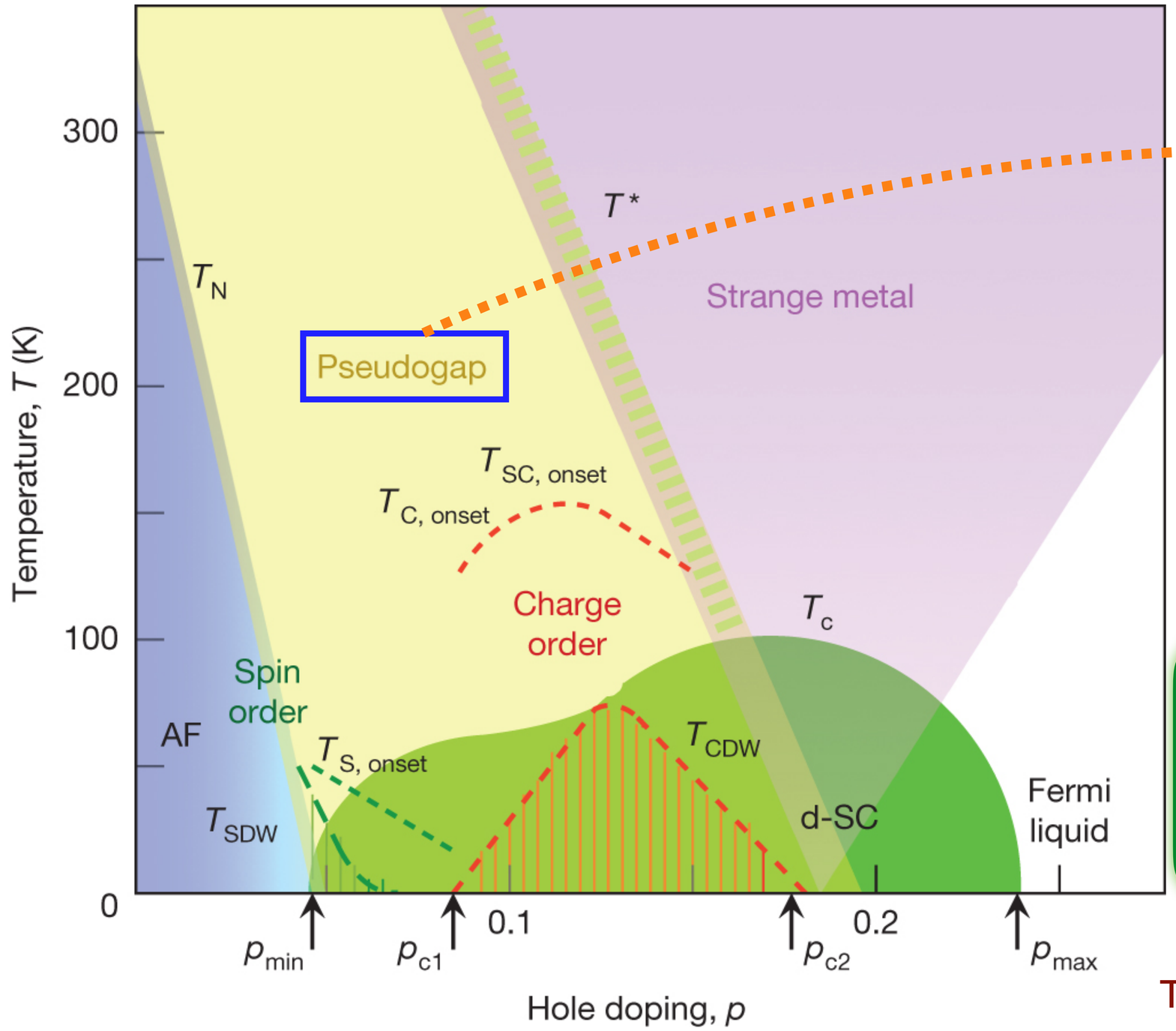


1-p electrons

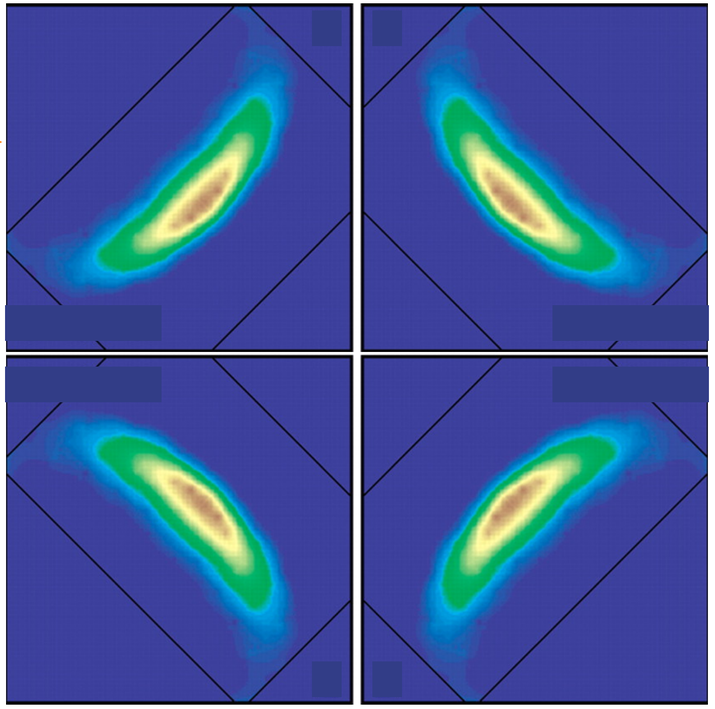
1+p holes

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

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



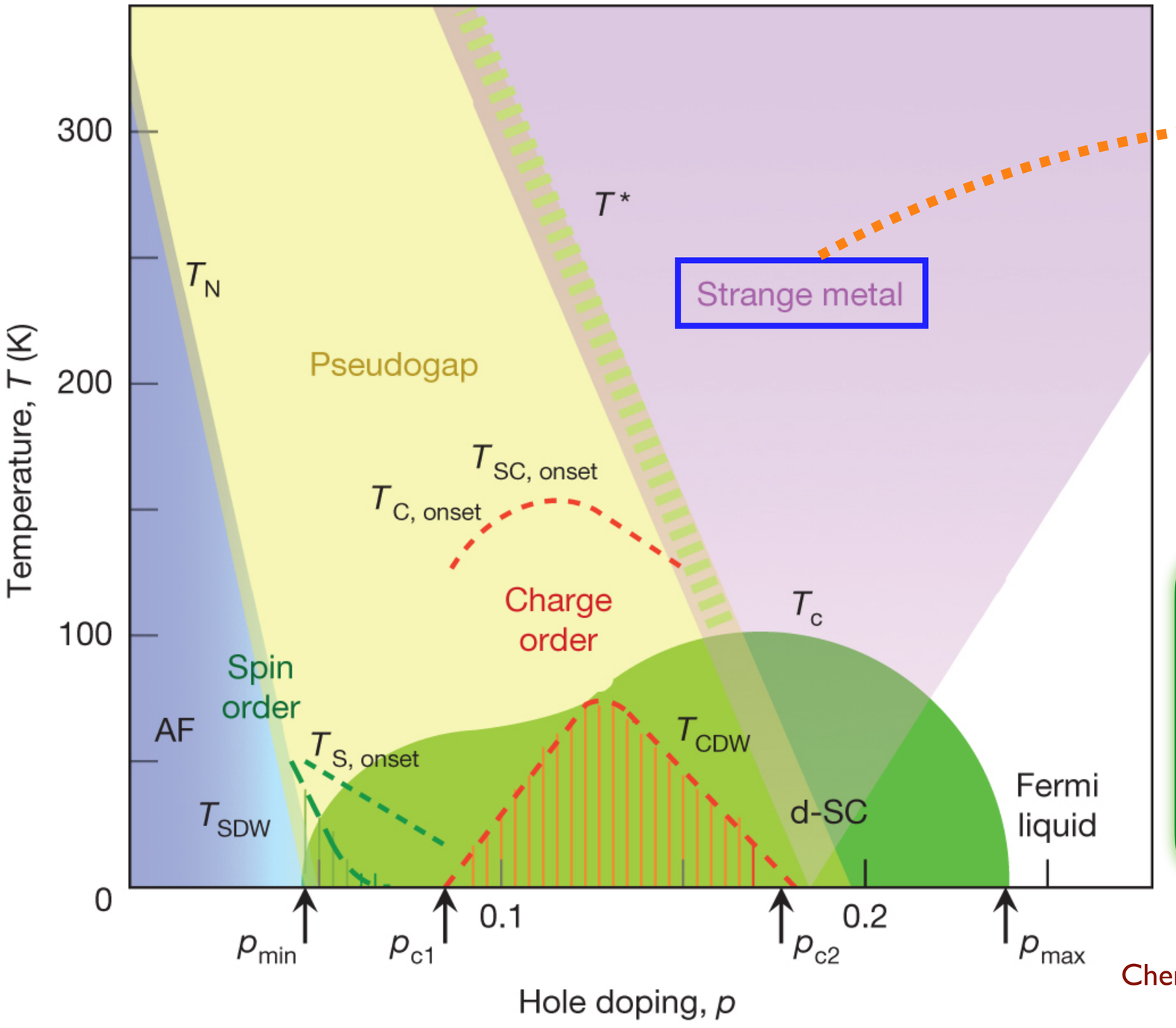
Kyle M. Shen *et al.*, Science **307**, 901 (2005)

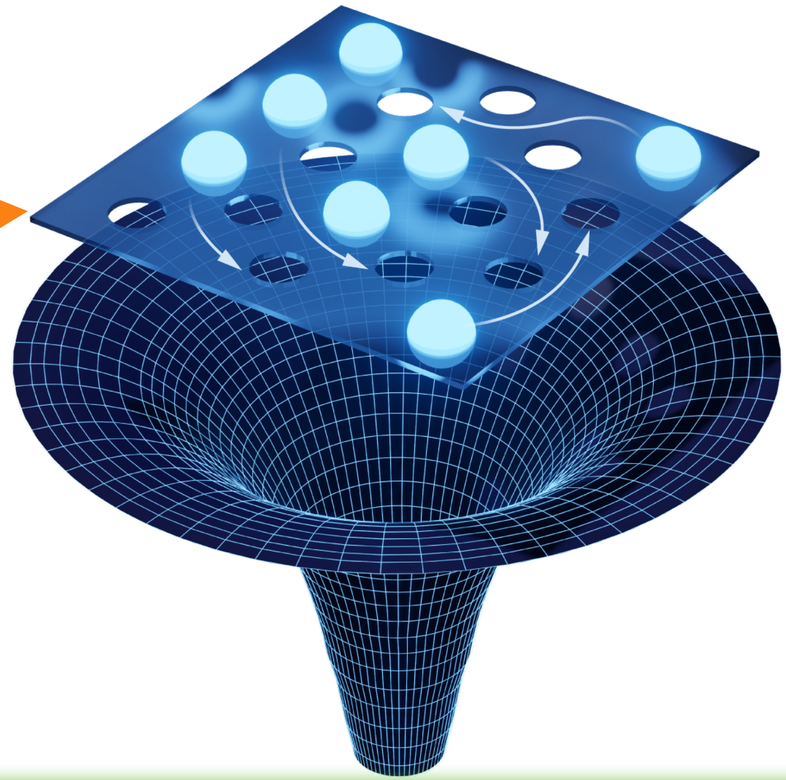


Will explain with a Fractionalized Fermi Liquid (FL*) which evades the Luttinger constraint by a *critical spin liquid*

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

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



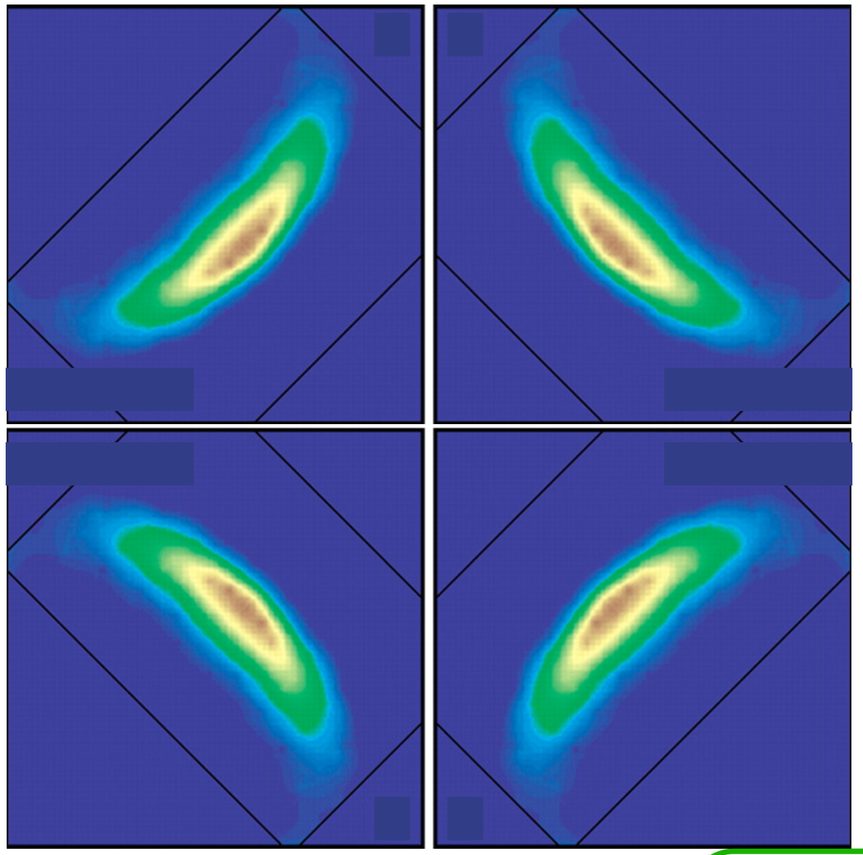


Will explain with a local, two-dimensional extension of the Sachdev-Ye-Kitaev (SYK) model of mobile electrons, a *critical charge liquid*

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)

Experiments on the cuprate pseudogap phase

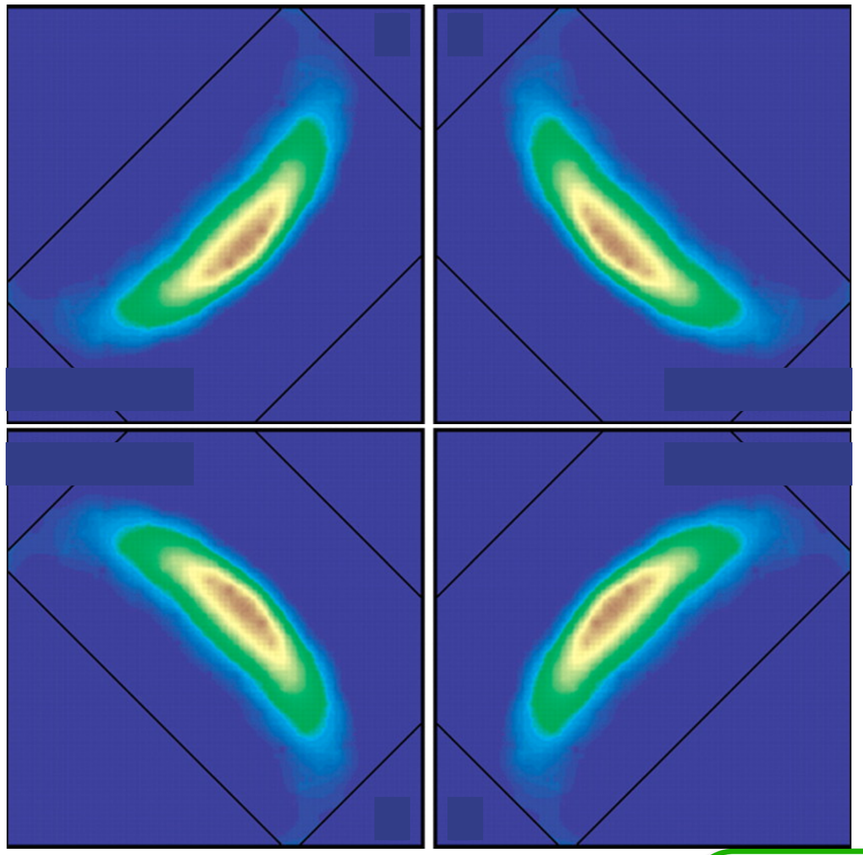
Photoemission at small p



"Fermi arcs"

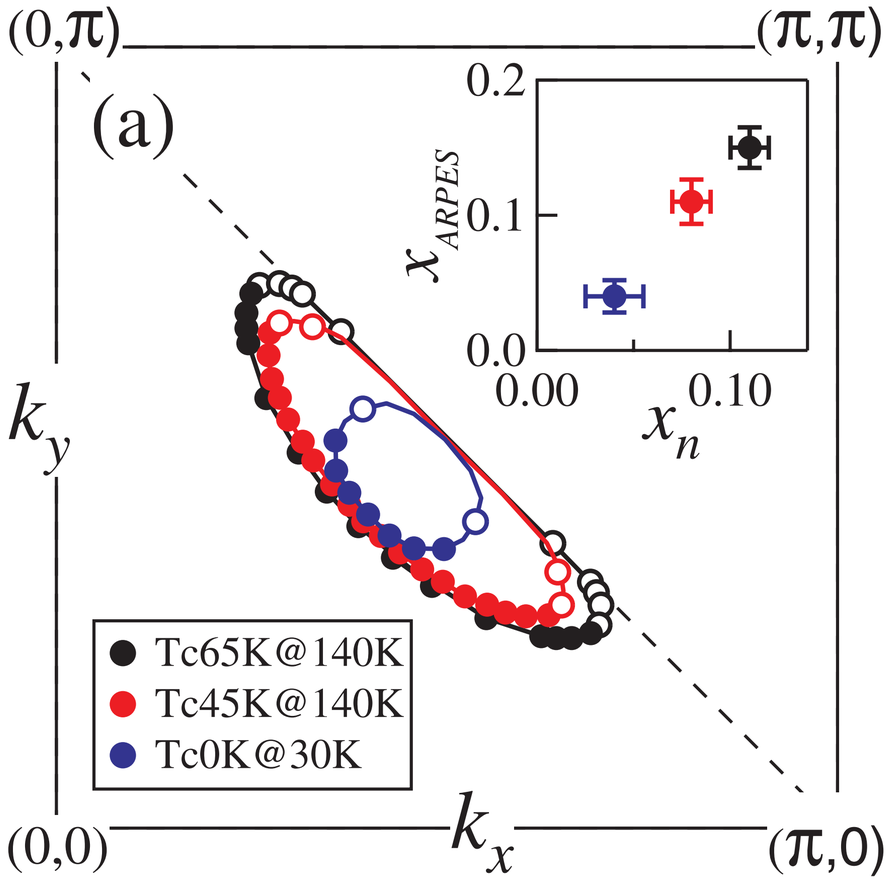
Kyle M. Shen, F. Ronning, D. H. Lu,
F. Baumberger, N. J. C. Ingle,
W. S. Lee, W. Meevasana, Y. Kohsaka,
M. Azuma, M. Takano, H. Takagi,
Z.-X. Shen, Science **307**, 901 (2005)

Photoemission at small 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)

"Fermi arcs"
or
hole pockets?

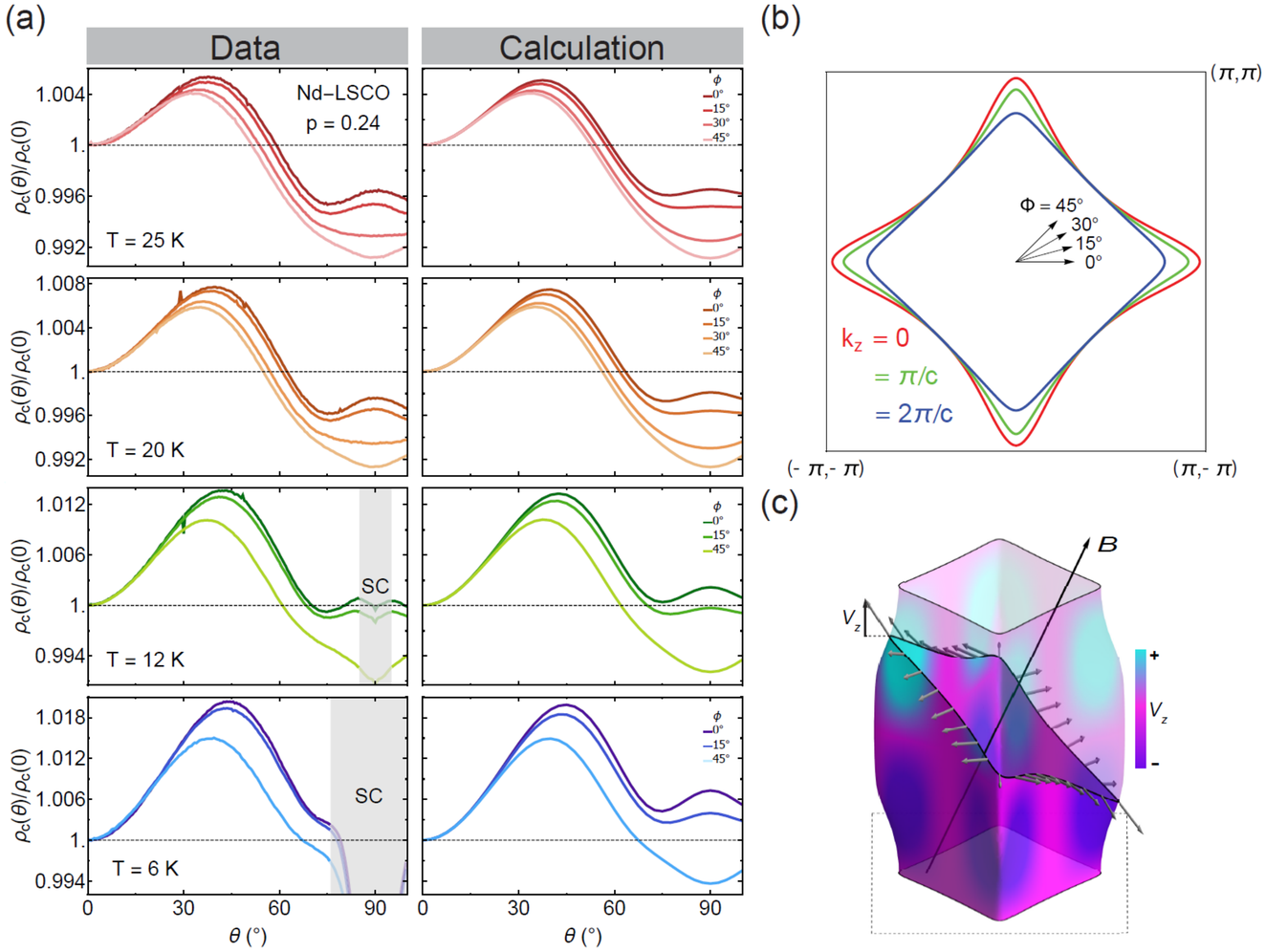


Reconstructed Fermi Surface of Underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ Cuprate Superconductors,
H.-B. Yang, J. D. Rameau, Z.-H. Pan, G. D. Gu,
P. D. Johnson, H. Claus, D. G. Hinks,
and T. E. Kidd, PRL **107**, 047003 (2011).

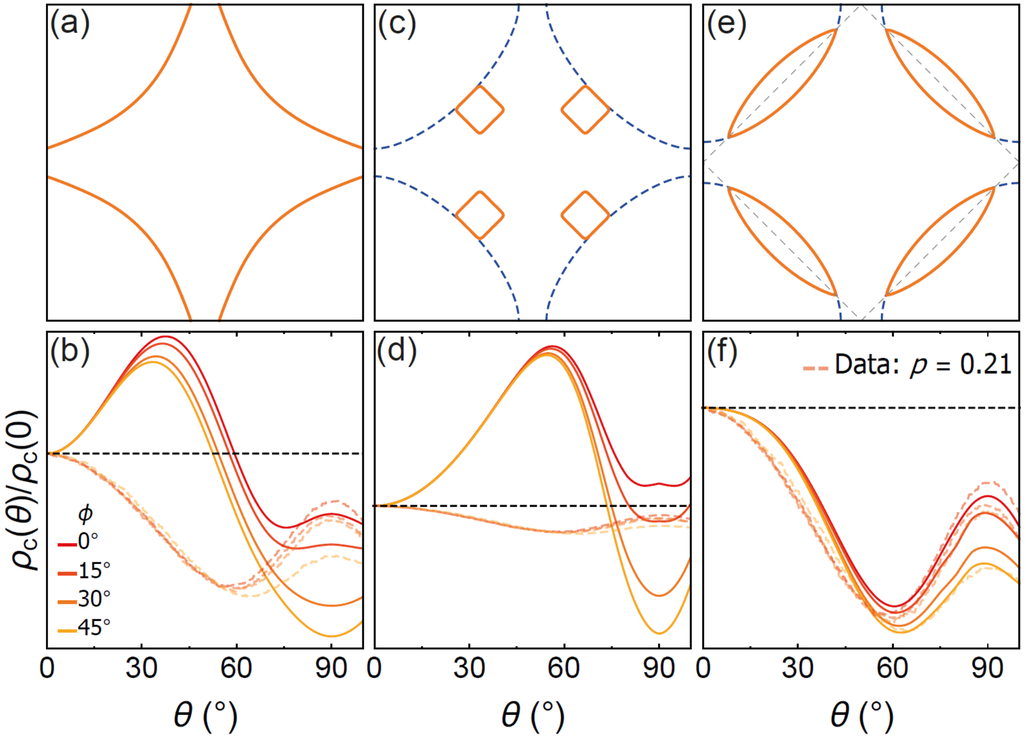
Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

Yawen Fang, Gaël Grissonnanche, Anaëlle Legros, Simon Verret, Francis Laliberté, Clément Collignon, Amirreza Ataei, Maxime Dion, Jianshi Zhou, David Graf, M. J. Lawler, Paul Goddard, Louis Taillefer, and B. J. Ramshaw, *Nature Physics* **18**, 558 (2022)

Angle-dependent magnetoresistance (ADMR) of $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$



$p > p_c$ Large Fermi surface

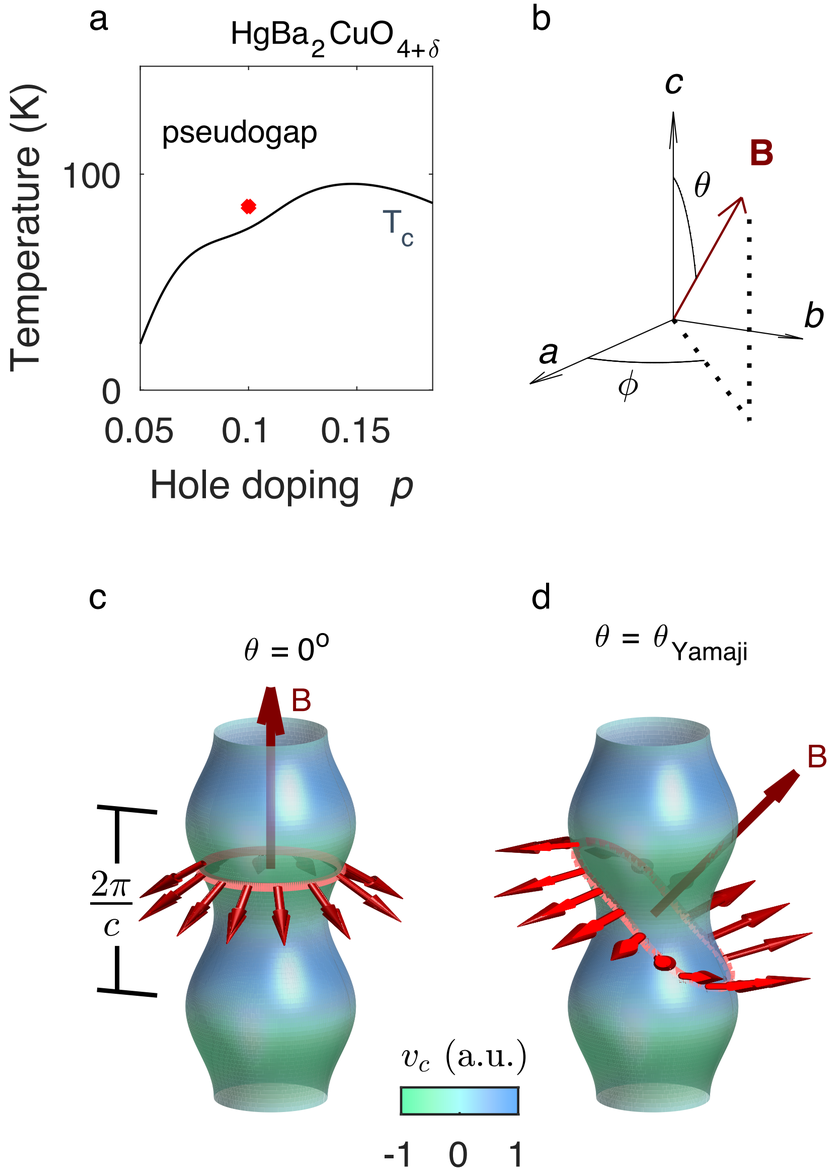


$p < p_c$ Reconstructed Fermi surface

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



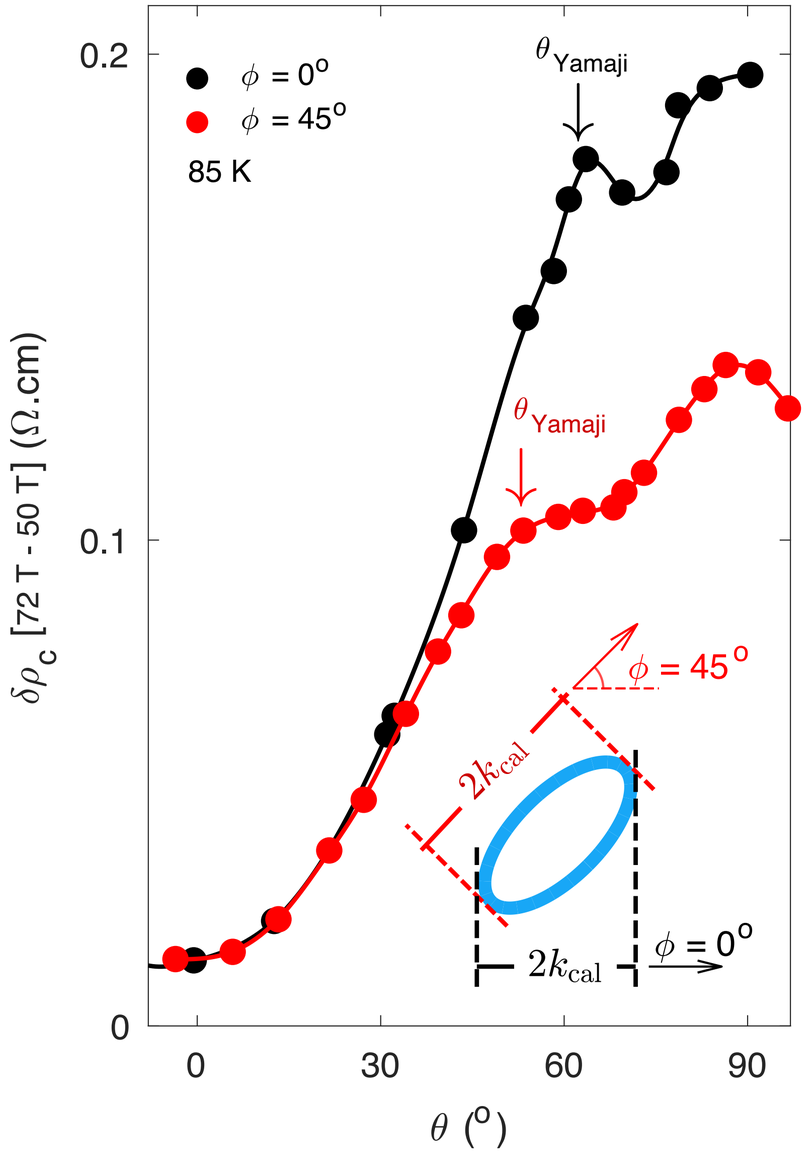
At the Yamaji angle, the orbits in the plane orthogonal to $\boldsymbol{B}$ have an area which is independent of momentum in the c direction, to first order in the hopping along the c direction.

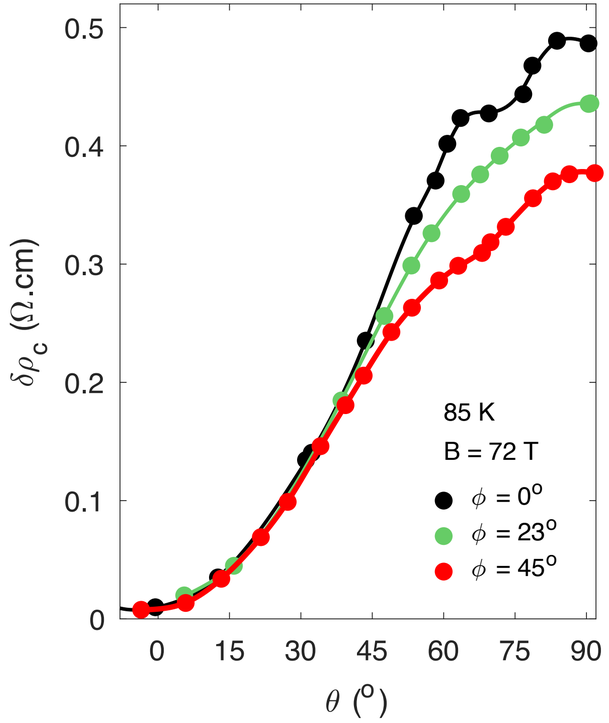
K. Yamaji JPSJ **58**, 1520 (1989)

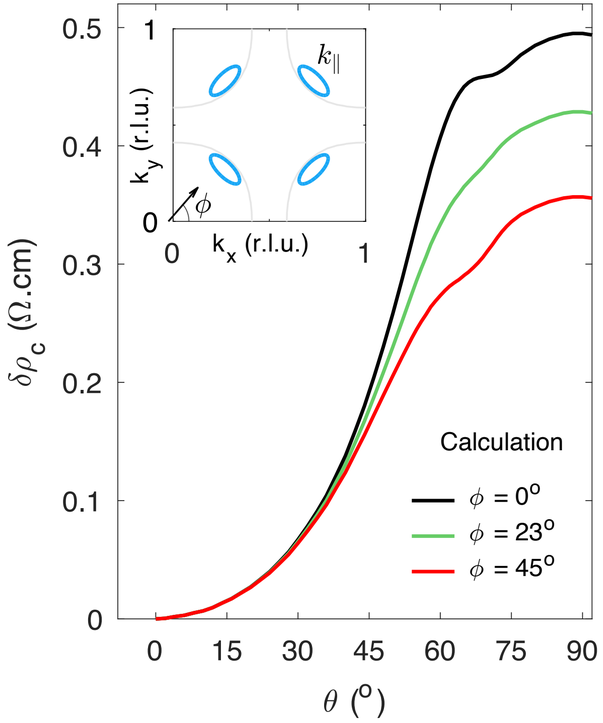
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Doping
$p = 0.1$

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

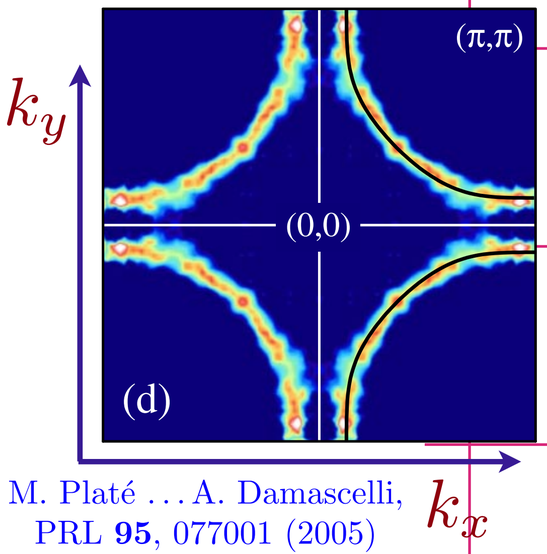
Experiments on the cuprate pseudogap phase

"Fermi arcs" or hole pockets??

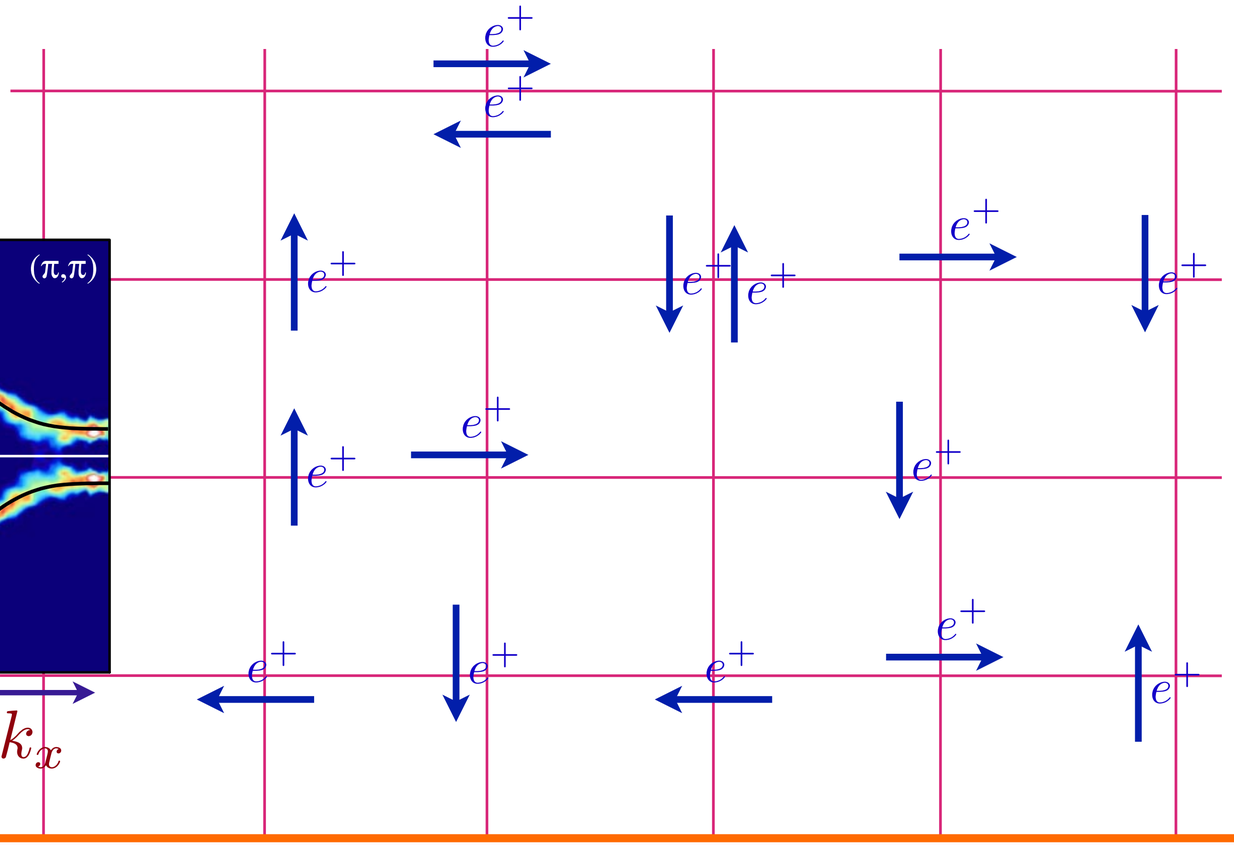
FL* theory of the hole pockets

Doping an insulating antiferromagnet with holes of density p

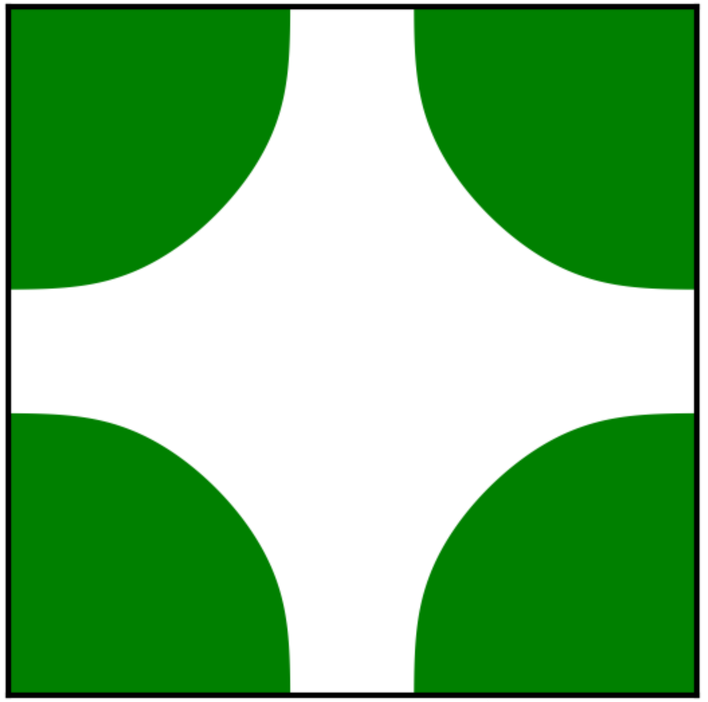
Ordinary metal



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



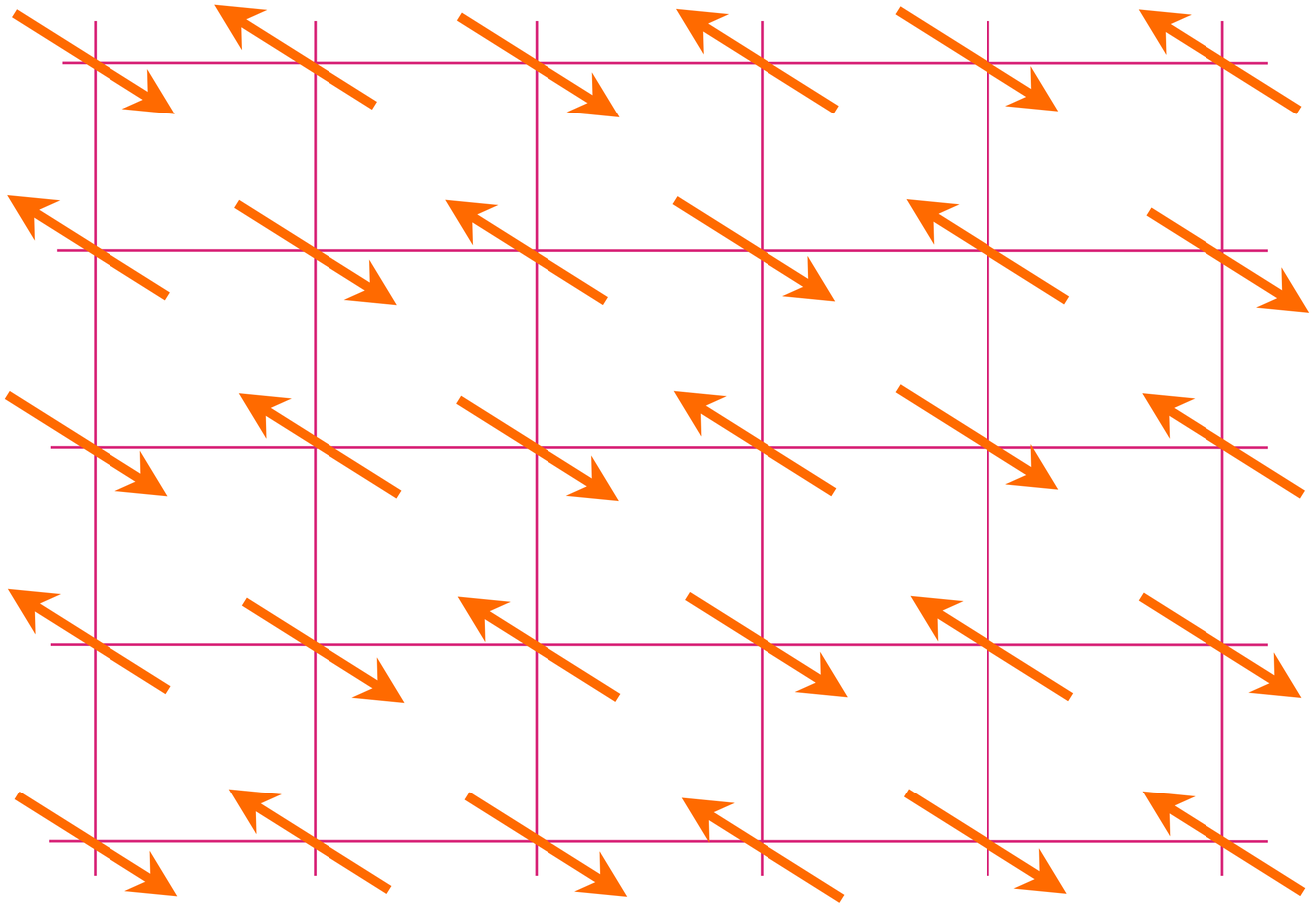
Luttinger area.
No broken symmetry



Area $(1+p)/2$

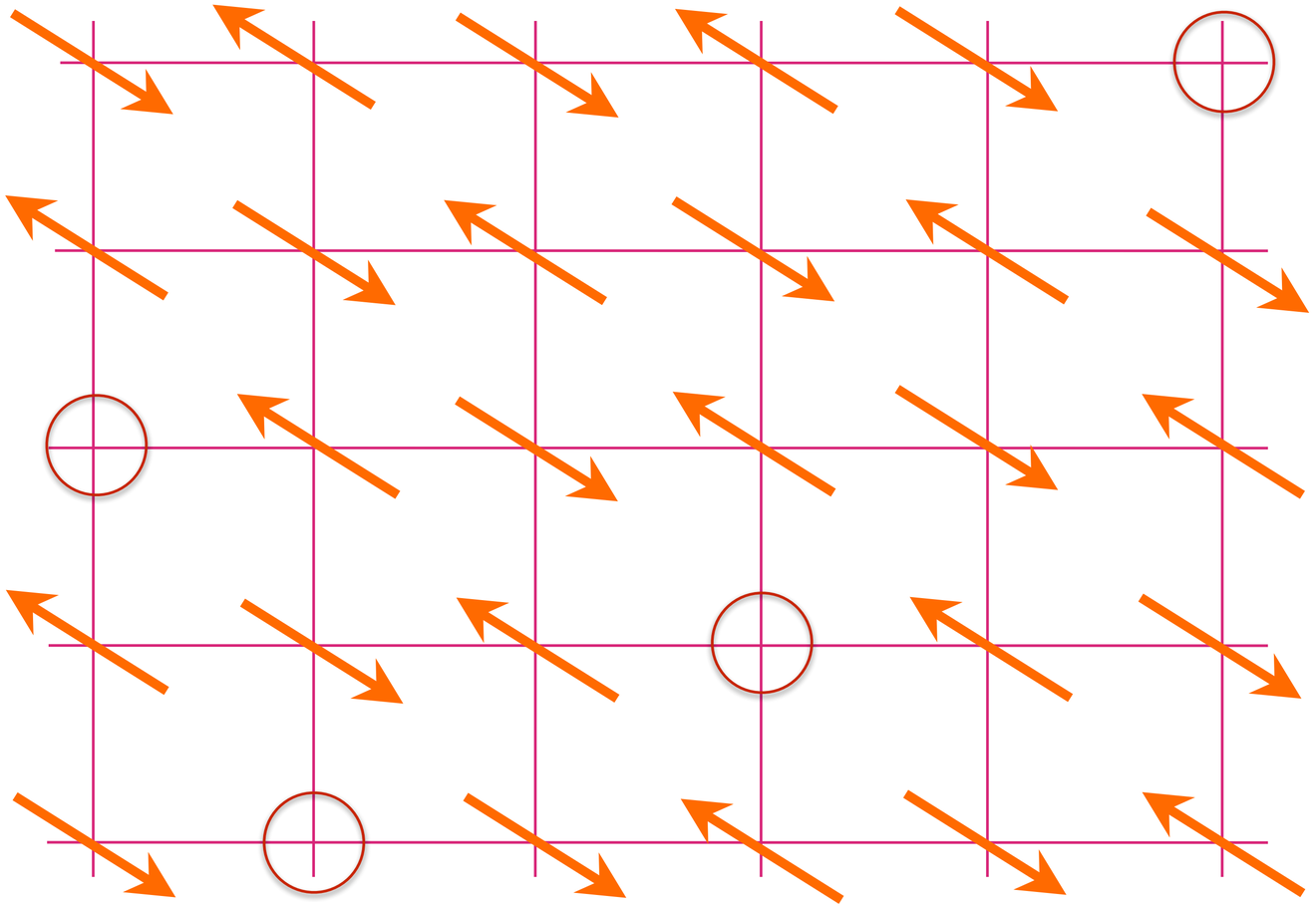
At large p, we obtain a gas of nearly free fermionic holes of density $1+p$ (relative to the filled band with 2 electrons per site)

Insulating antiferromagnet

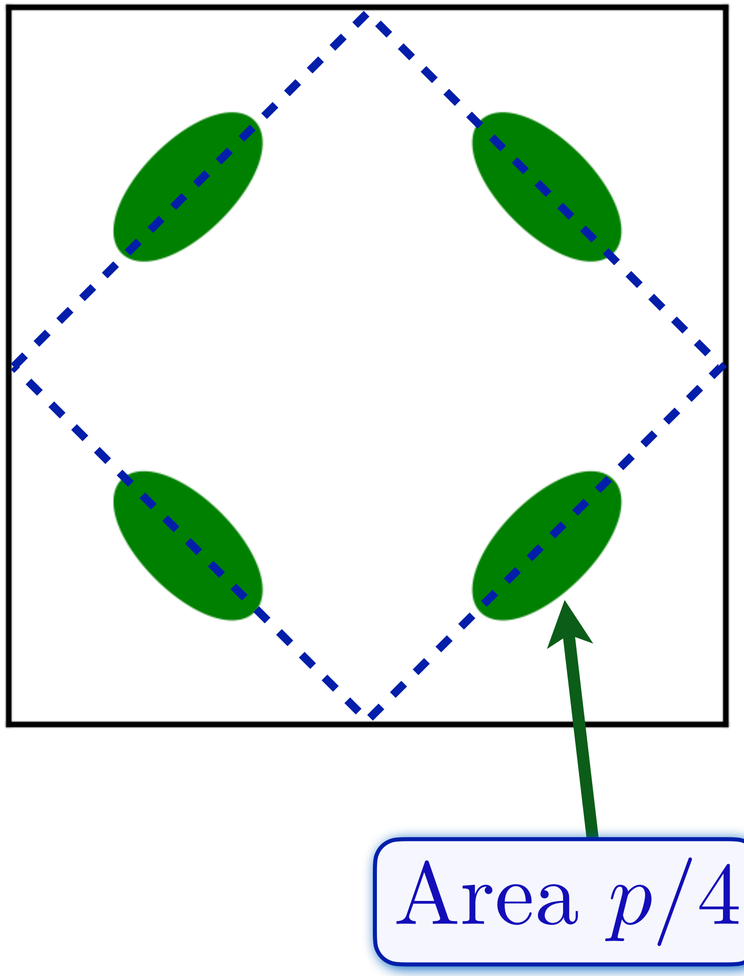


Doping an insulating antiferromagnet with holes of density p

AF metal



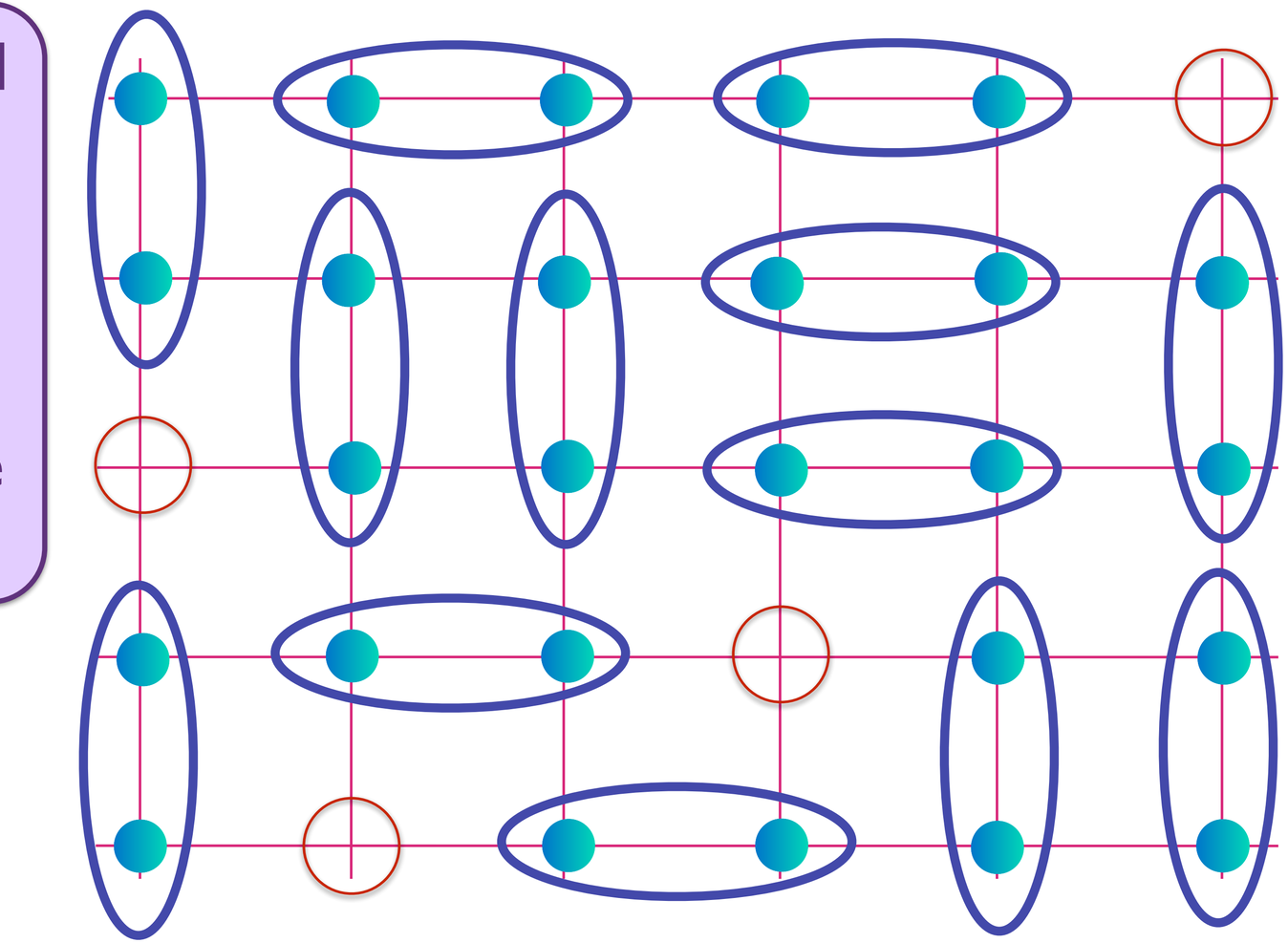
Luttinger area.
Broken symmetry



Doping an insulating antiferromagnet with holes of density p

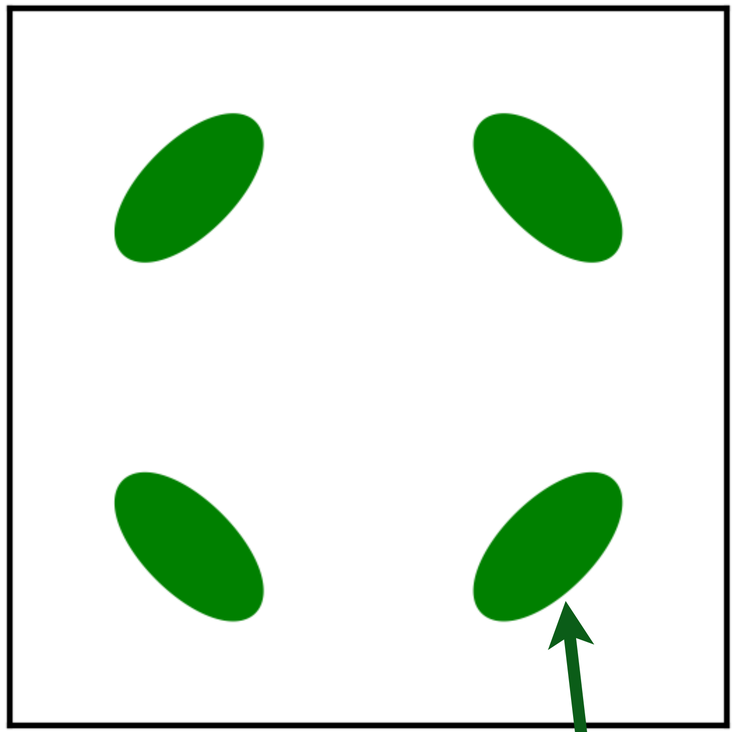
Holon metal

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



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

non-Luttinger area.
Spin liquid



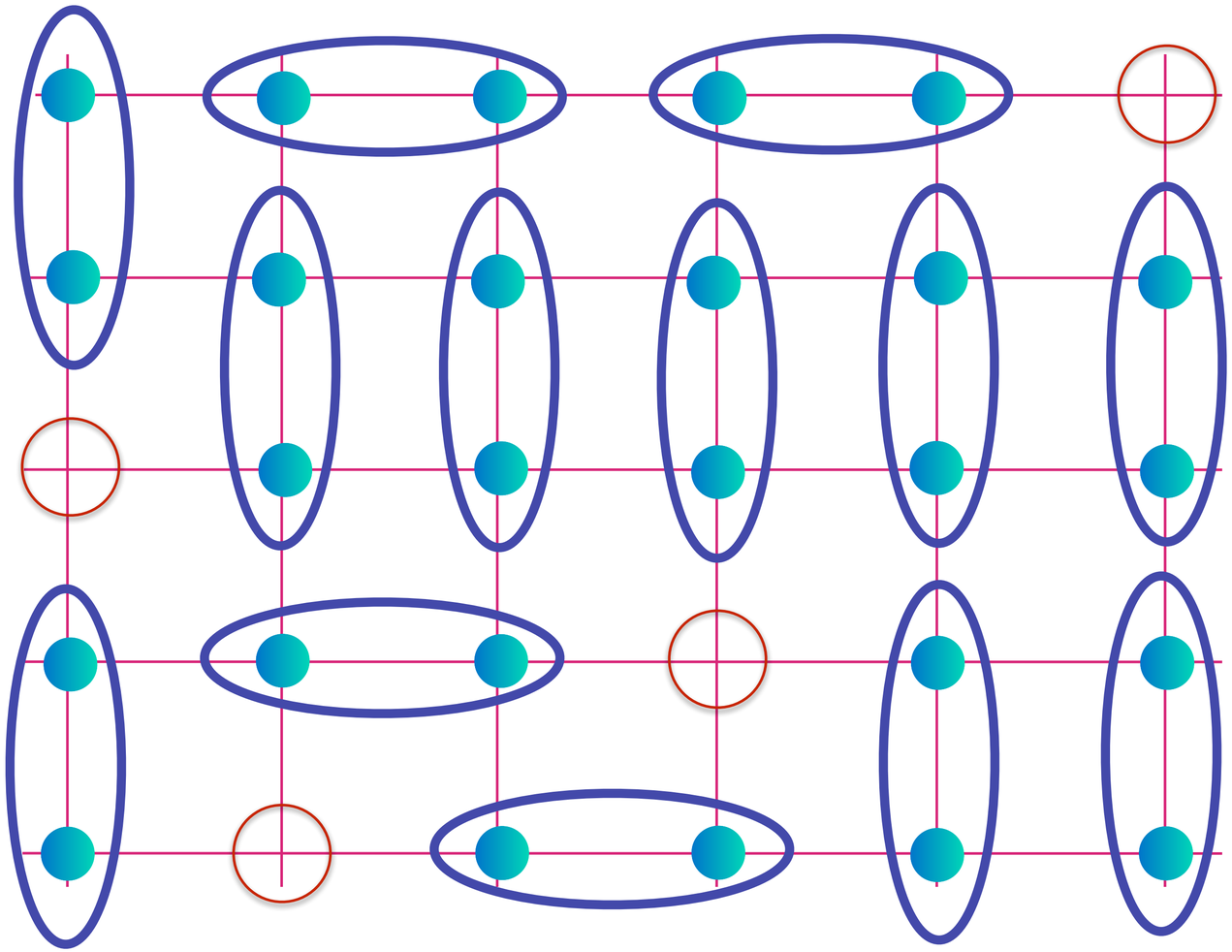
Area $p/4$

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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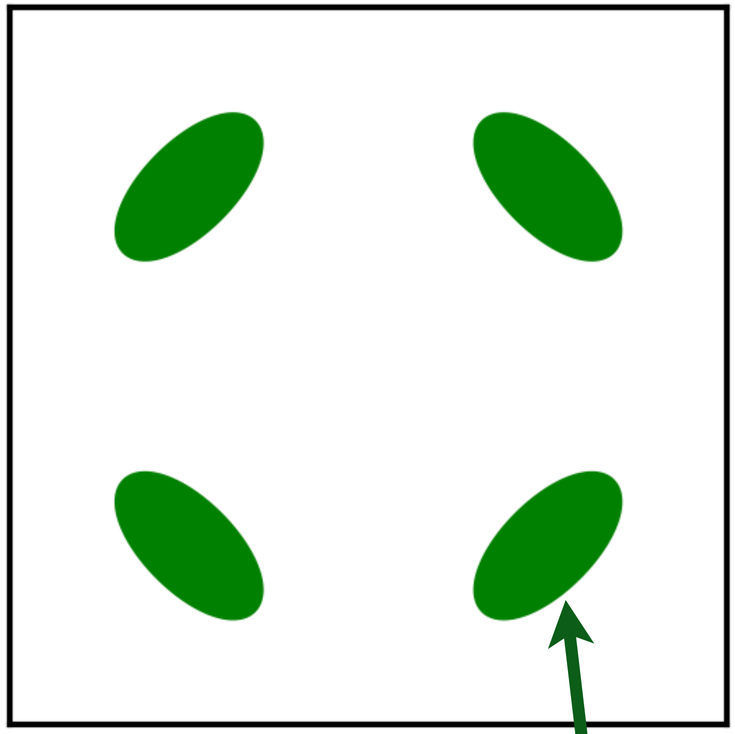
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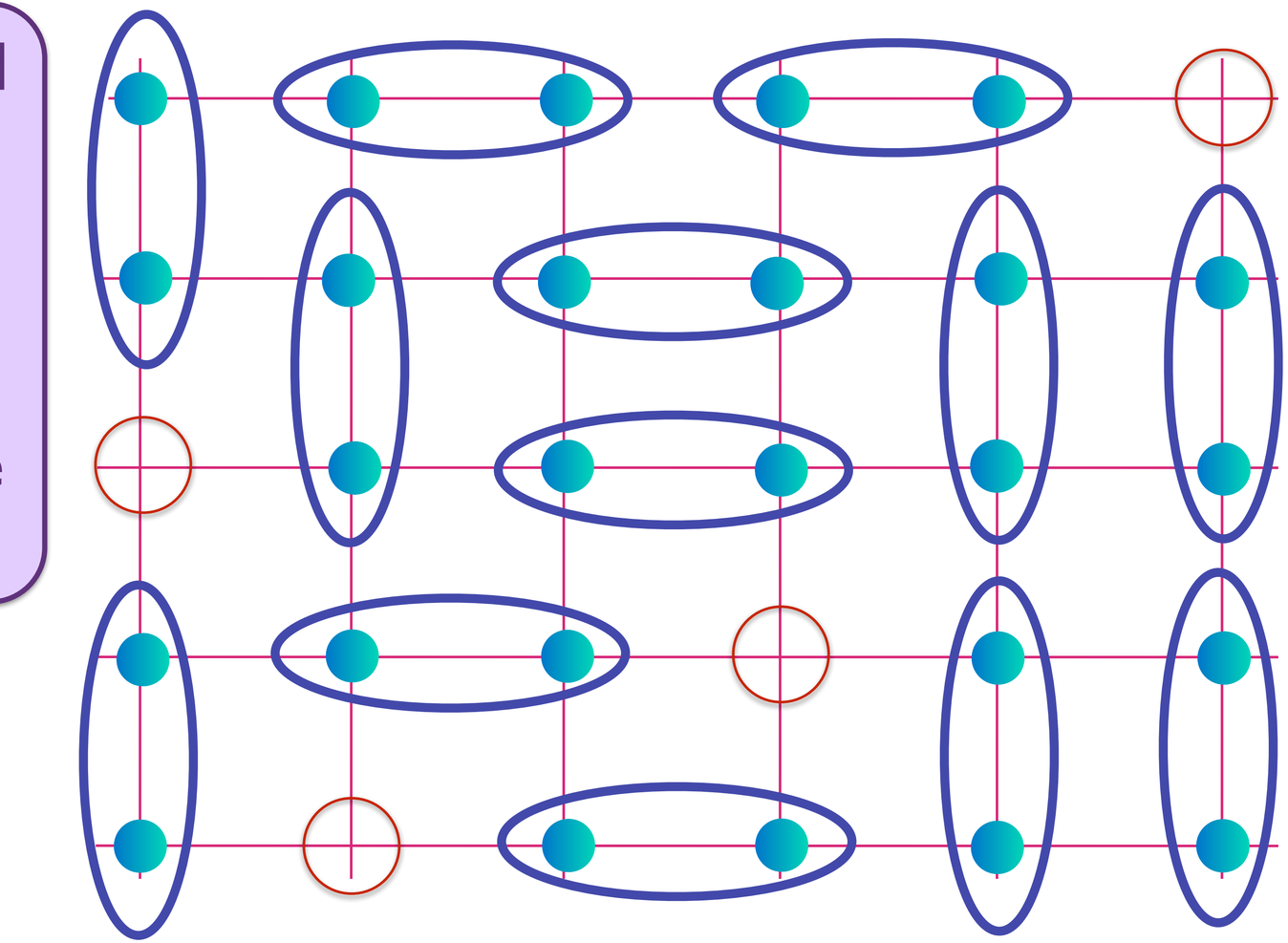
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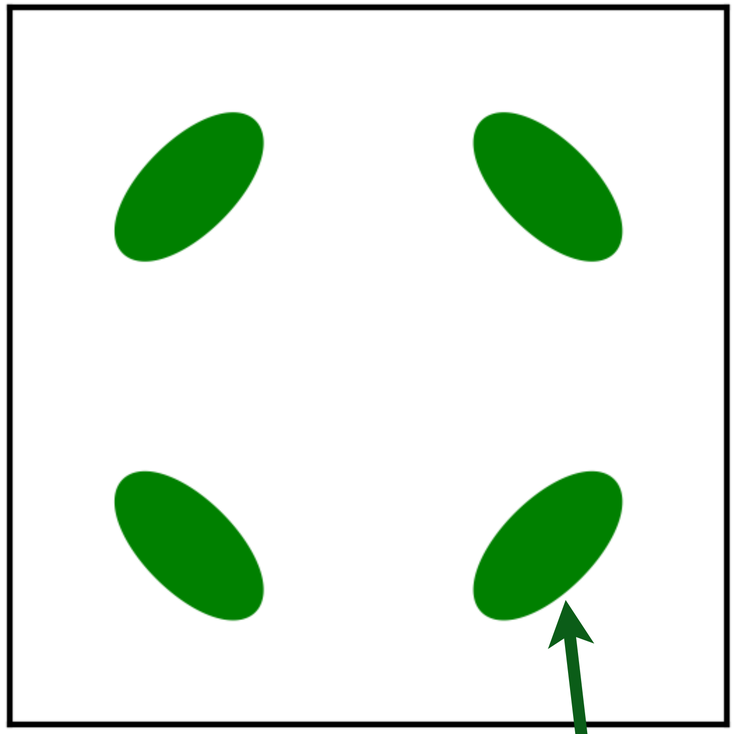
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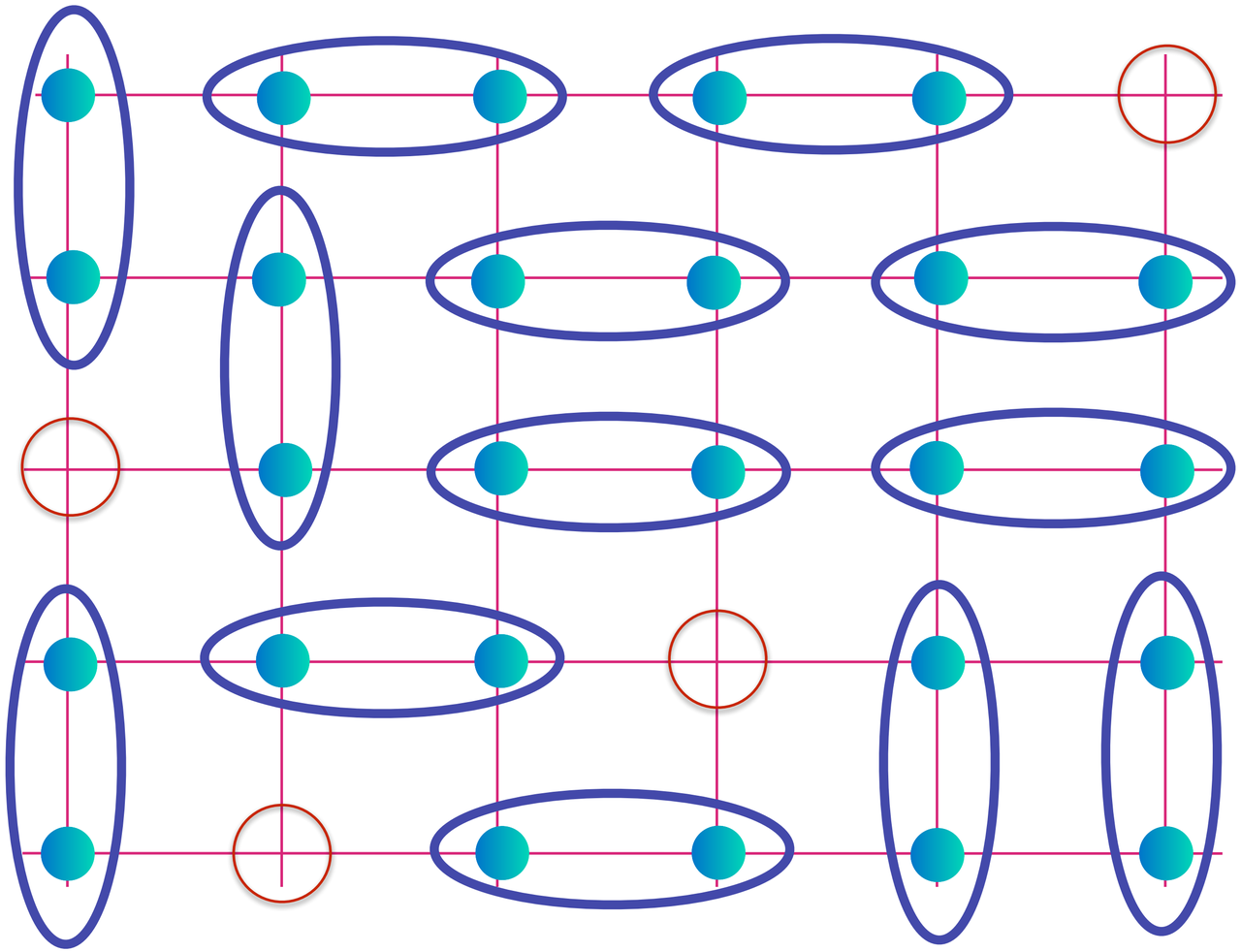
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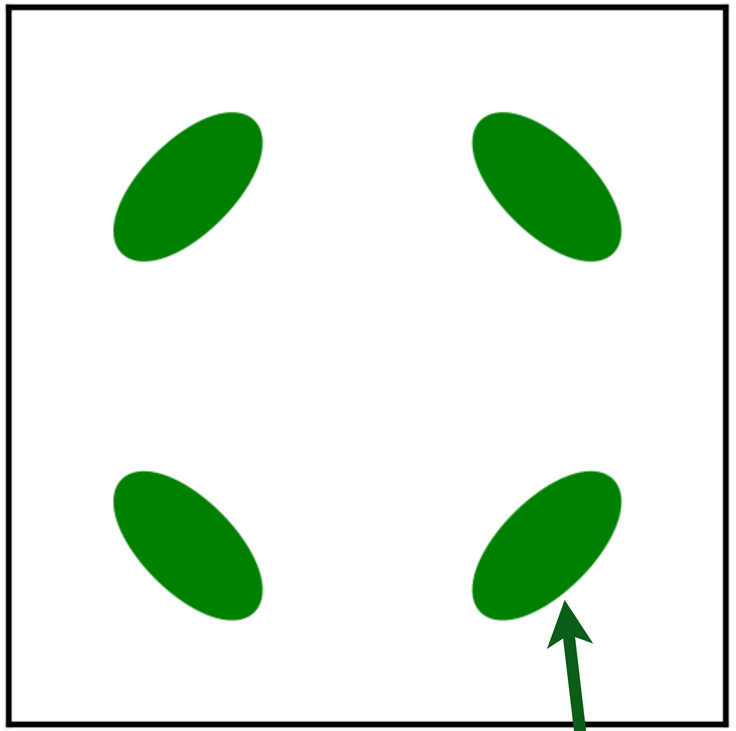
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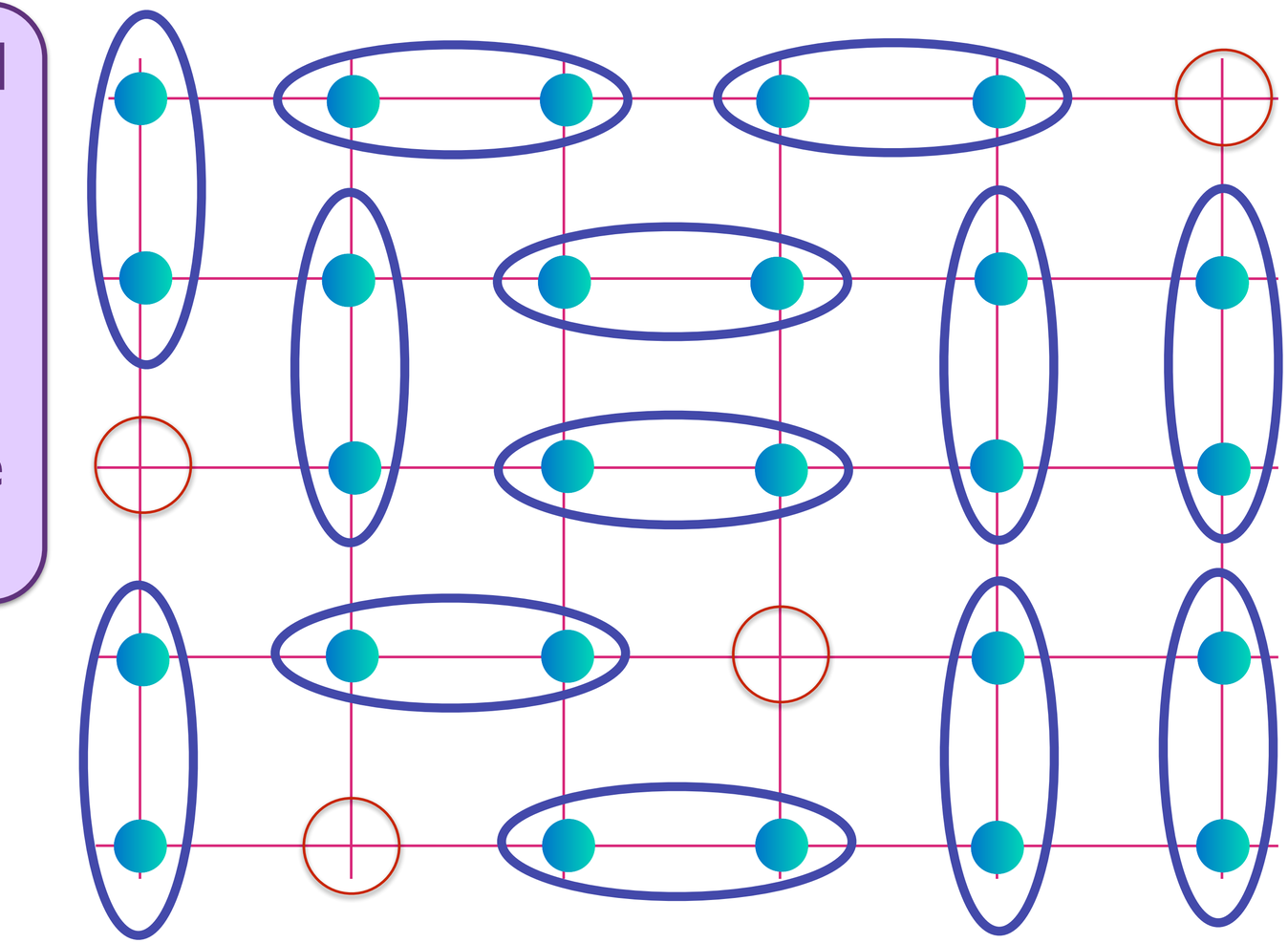
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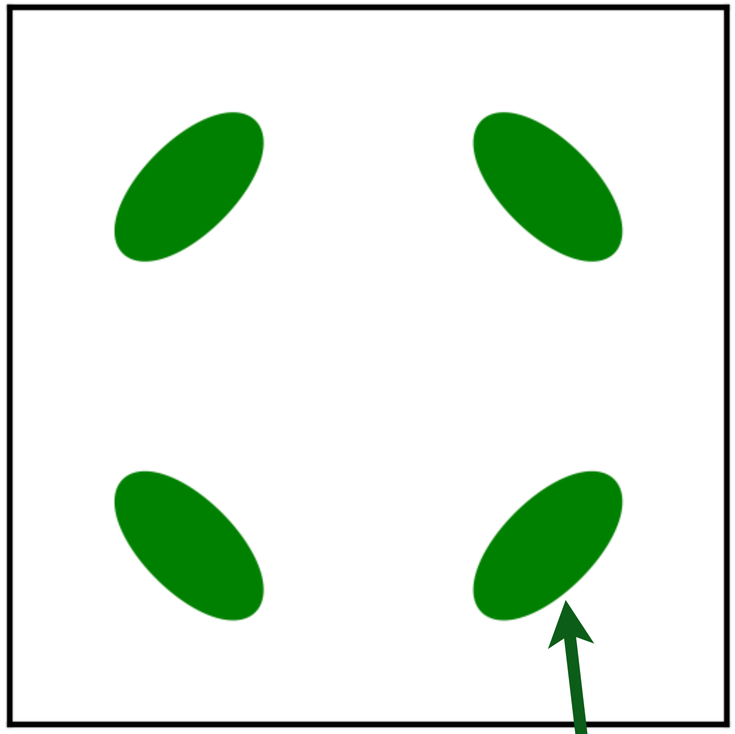
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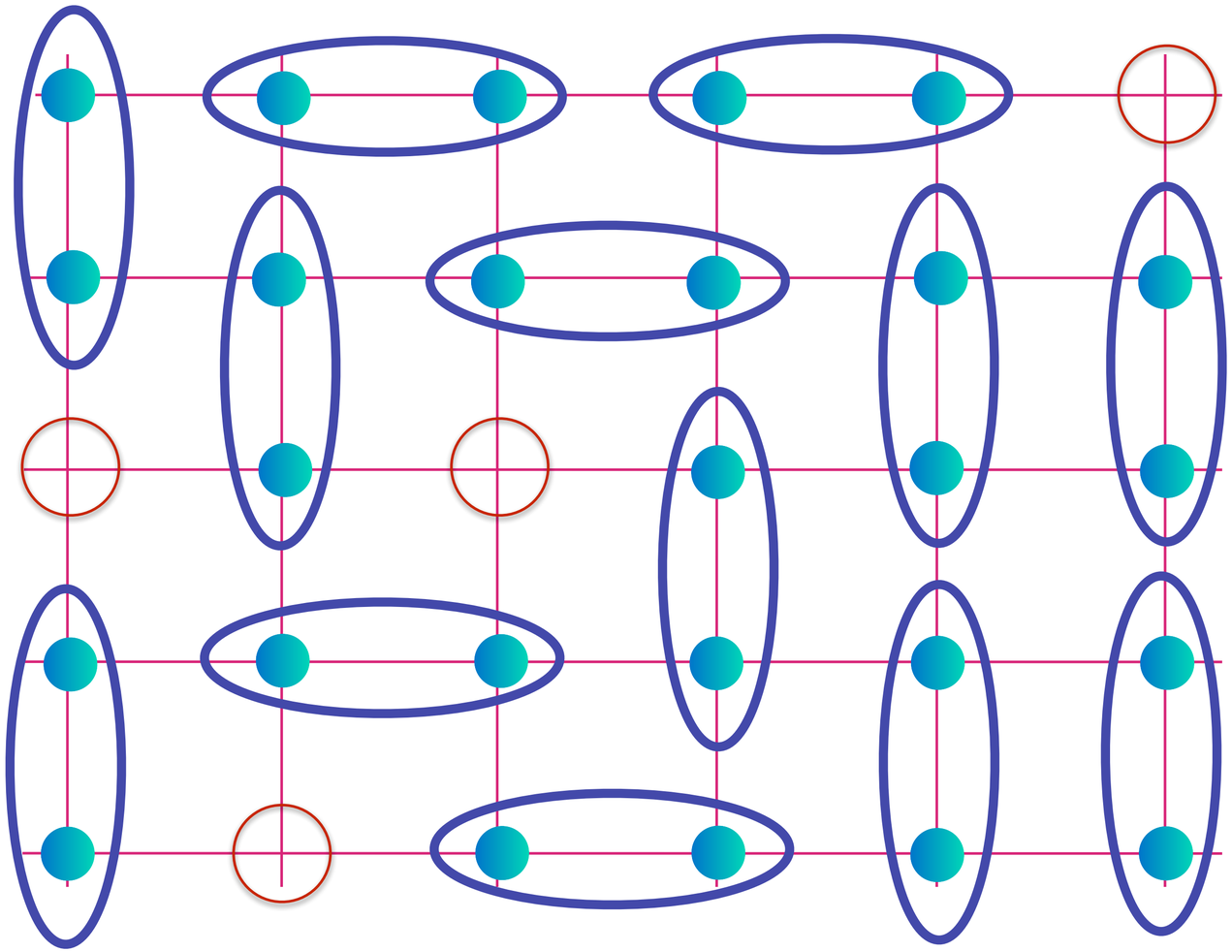
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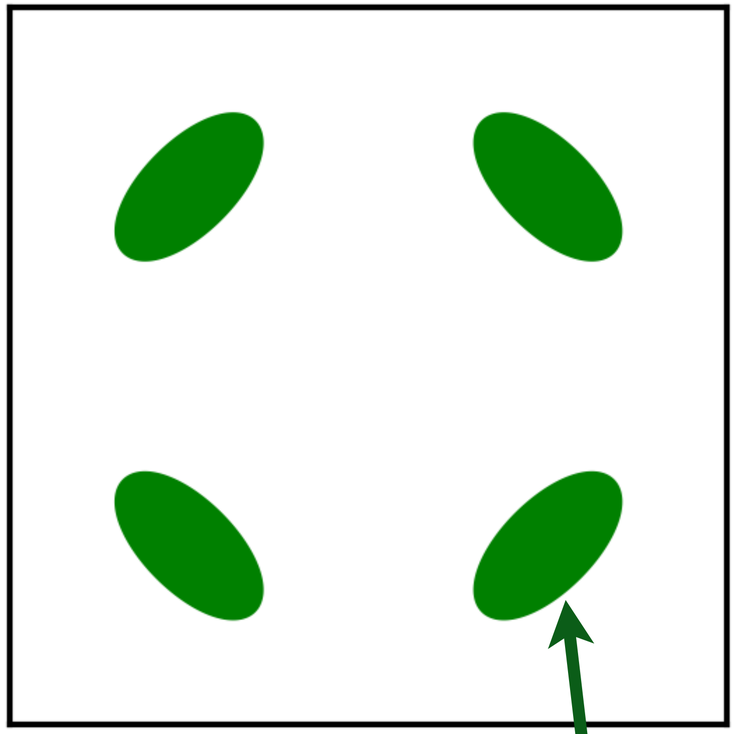
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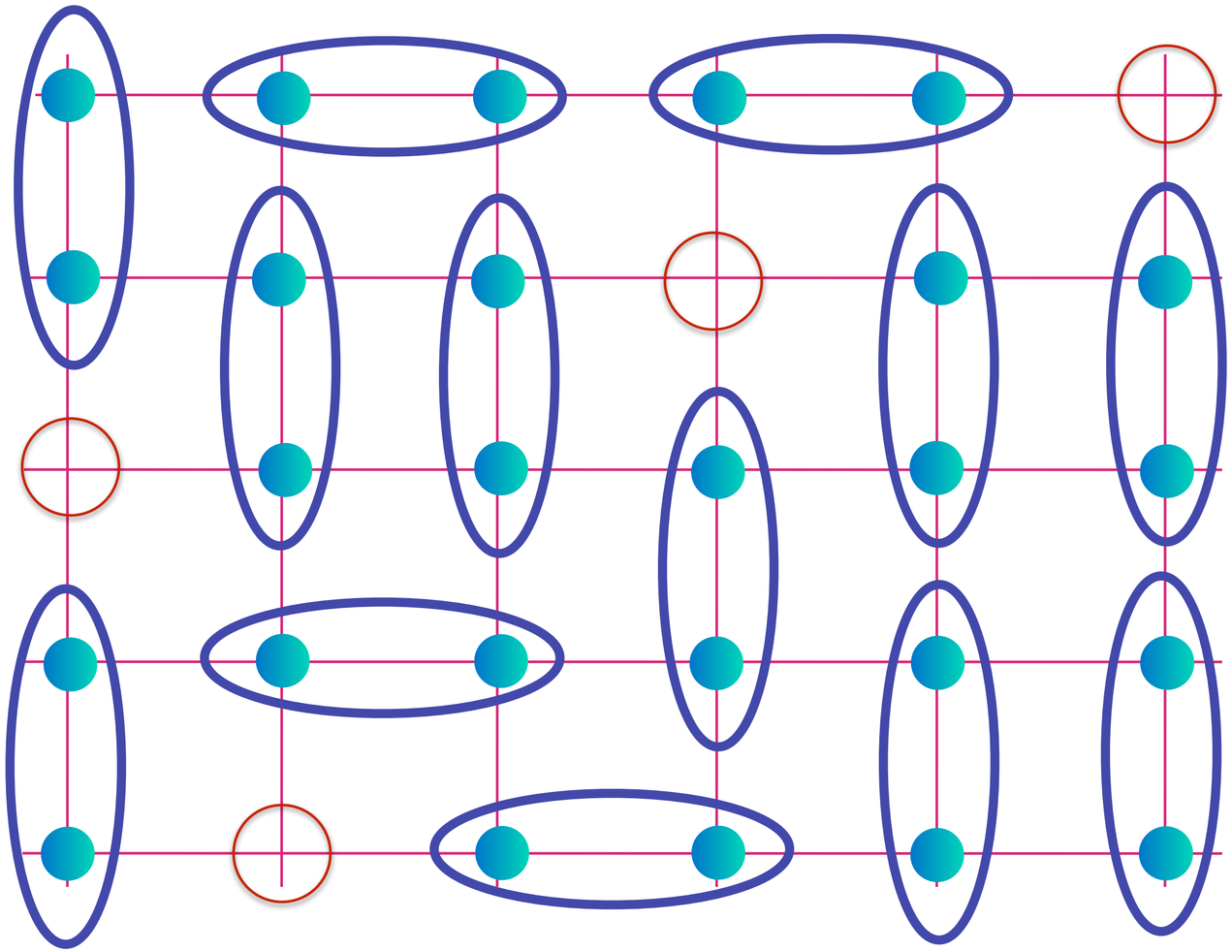
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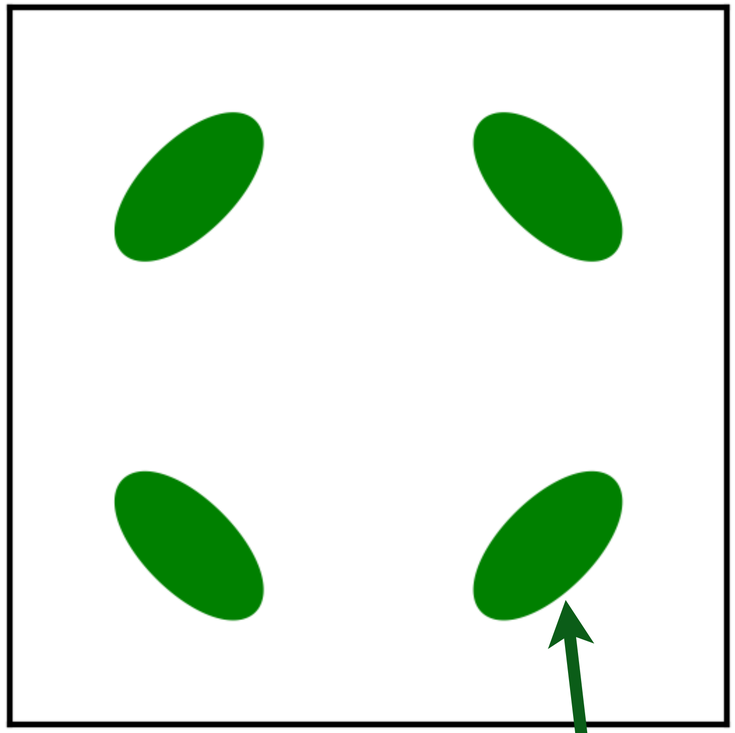
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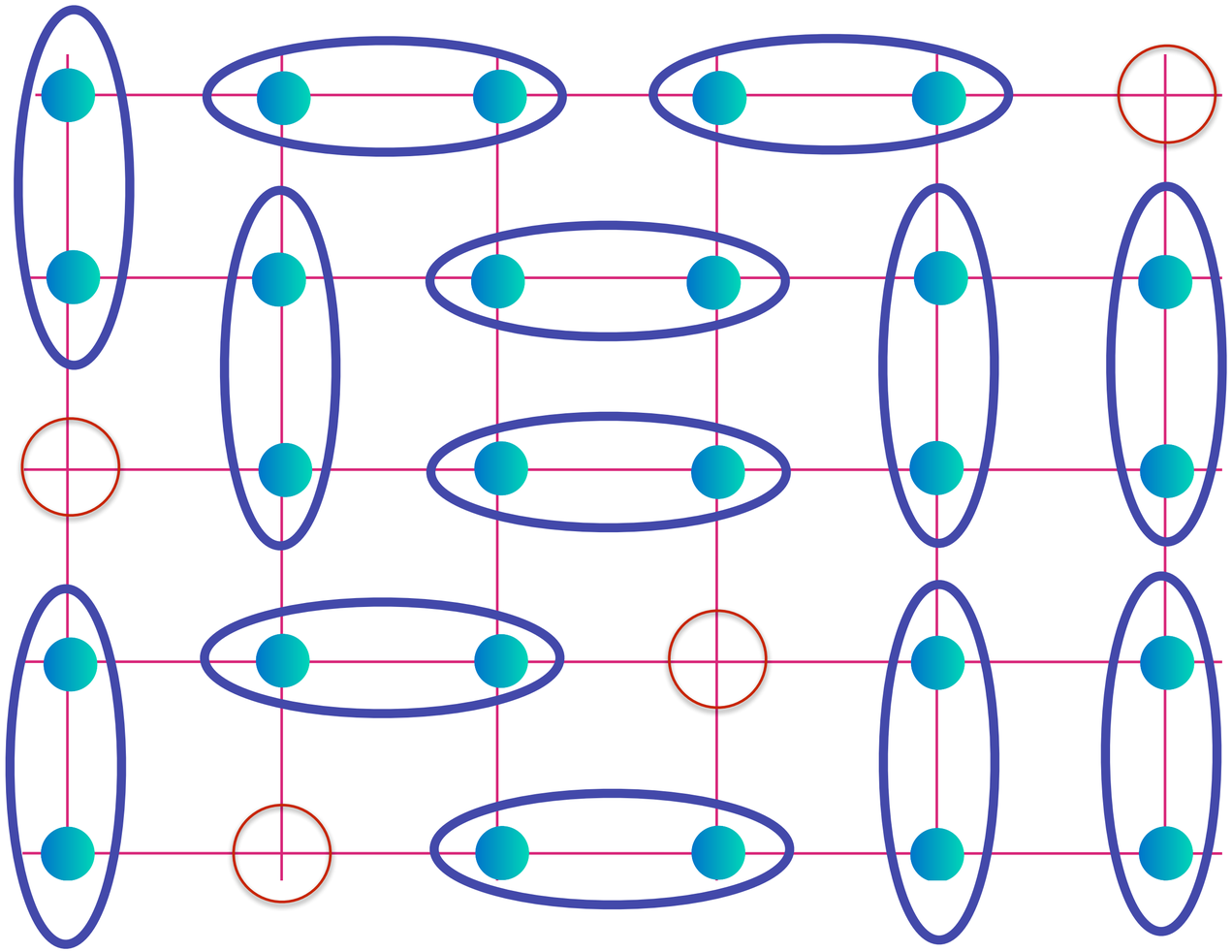
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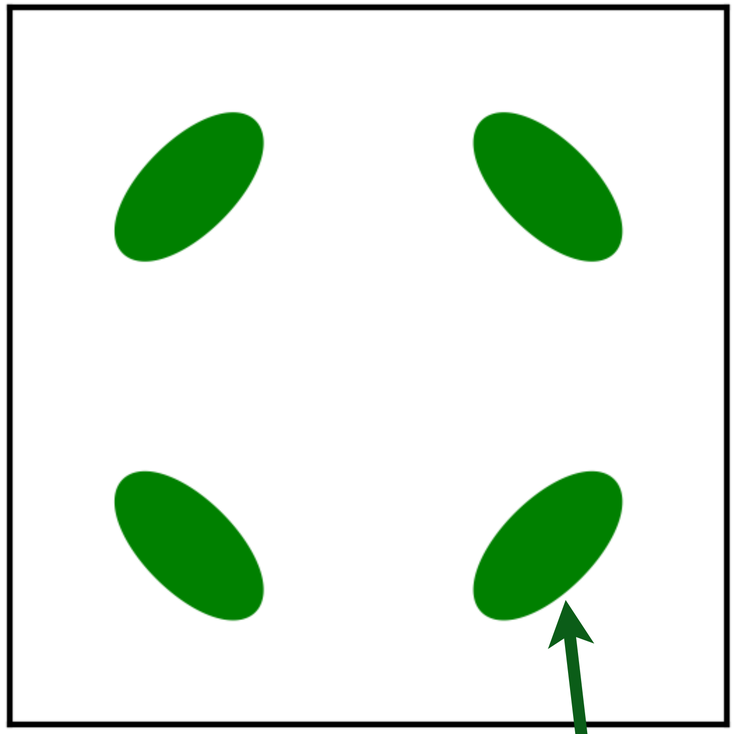
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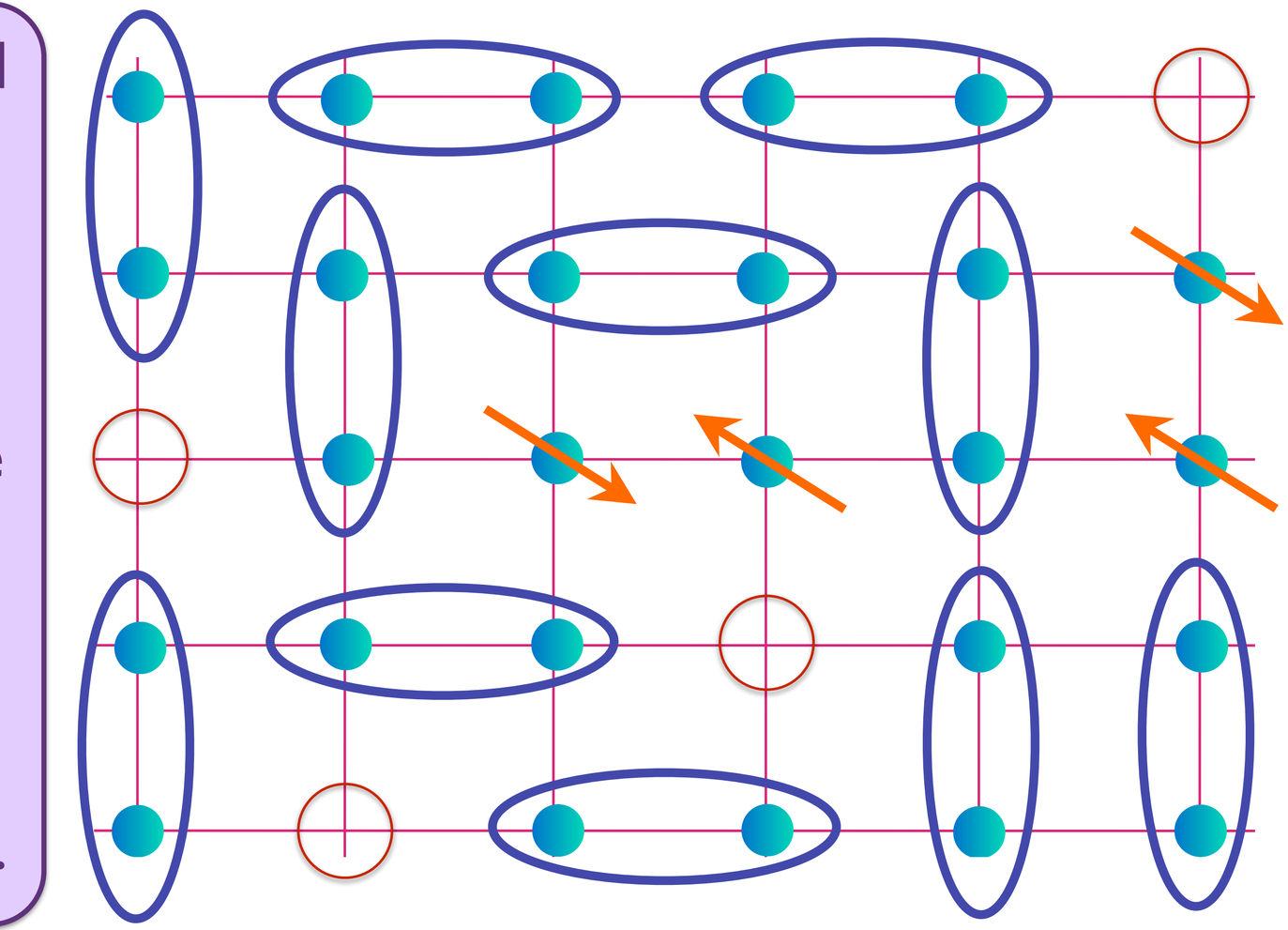
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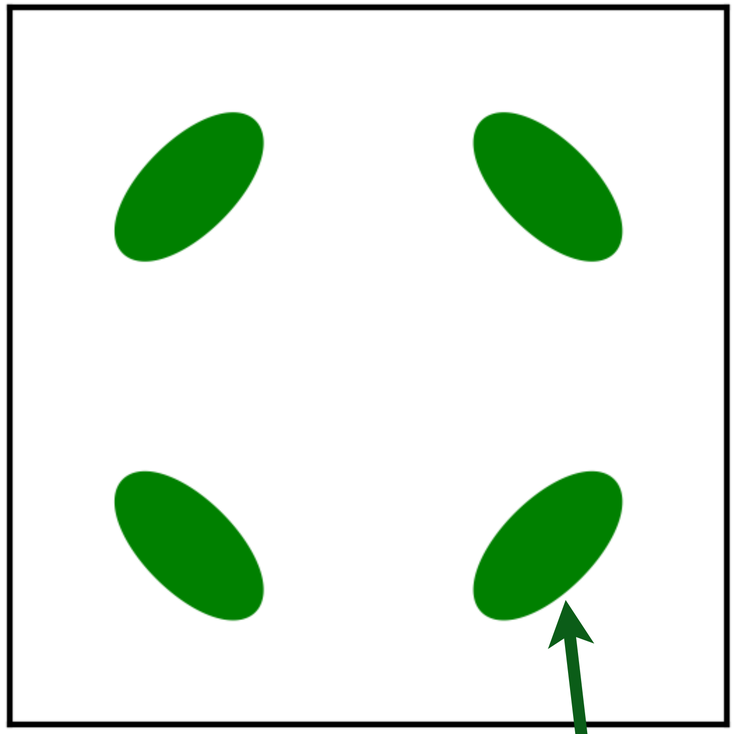
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non-Luttinger area.
Spin liquid

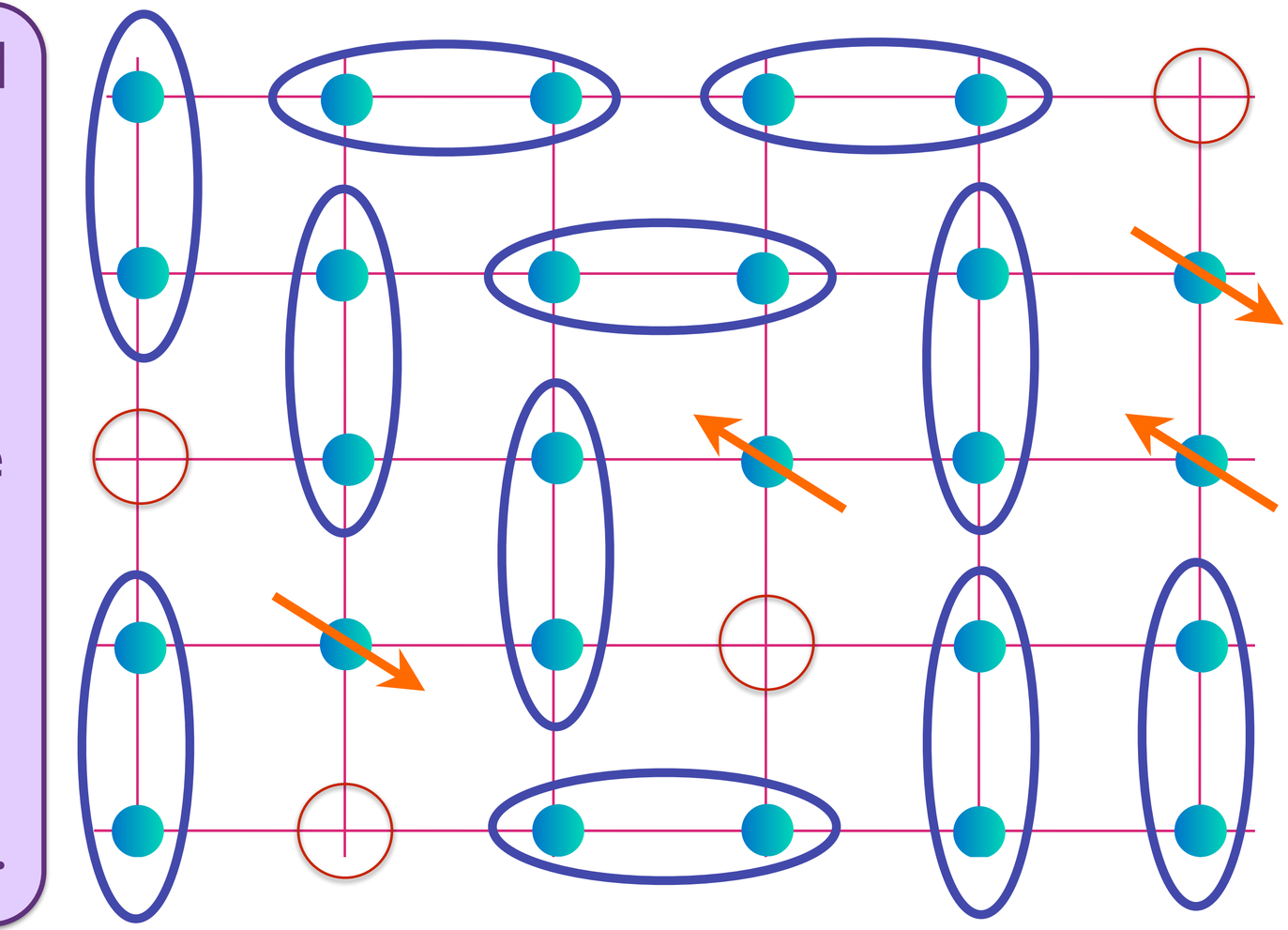


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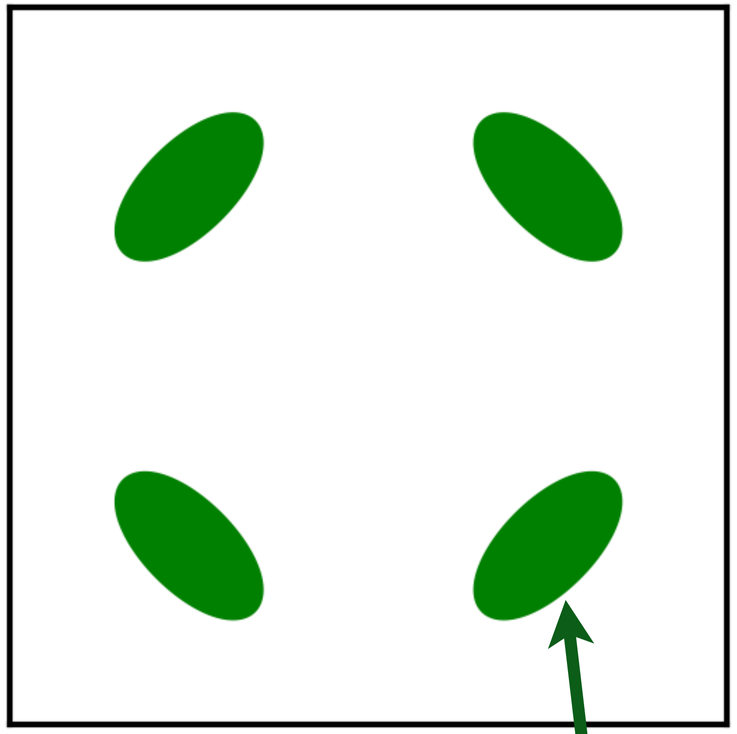
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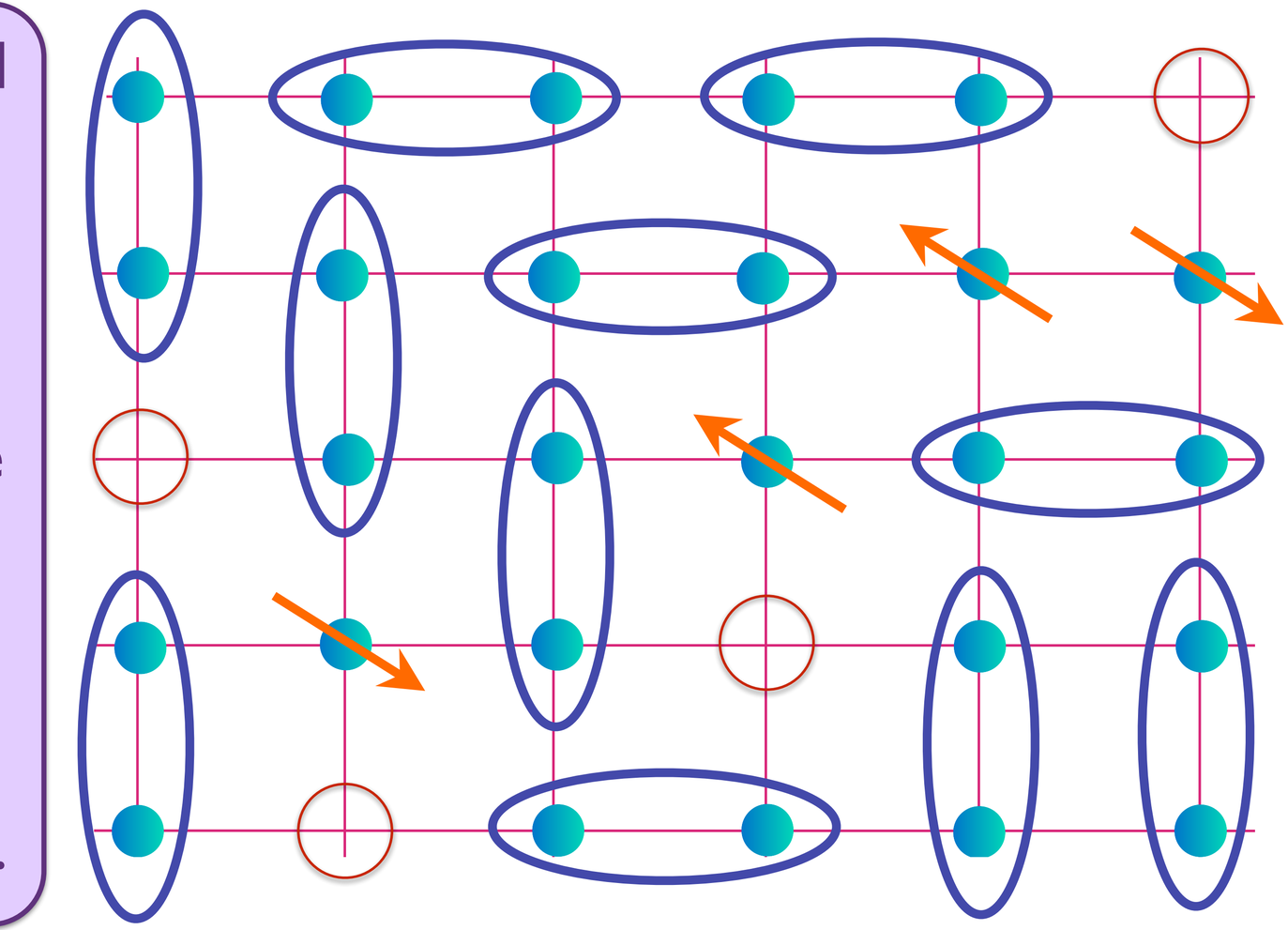


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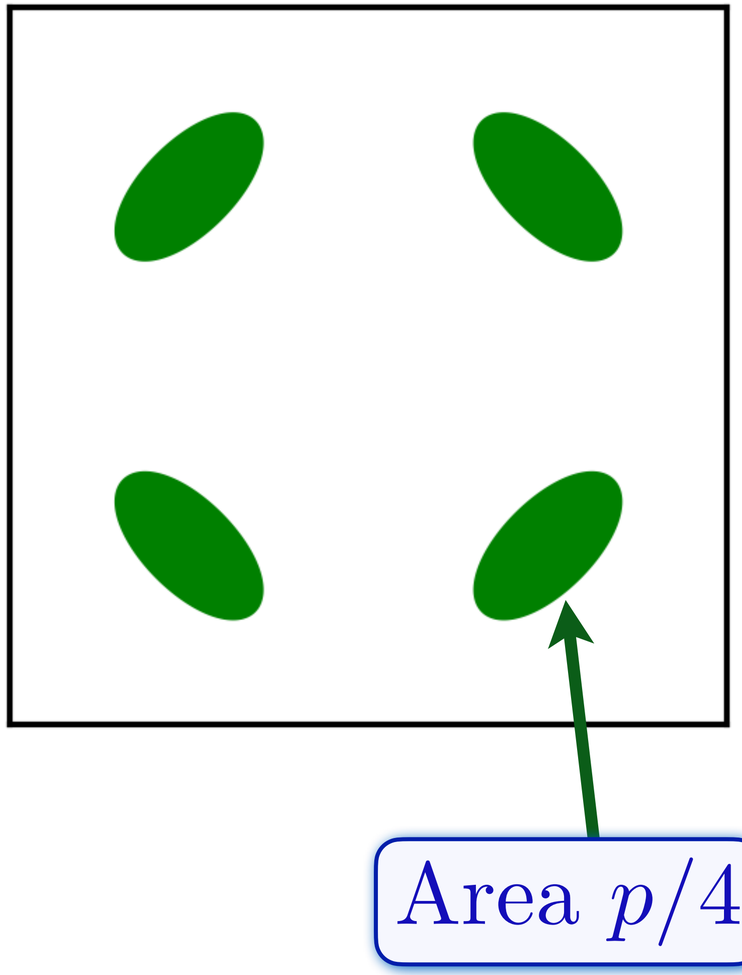
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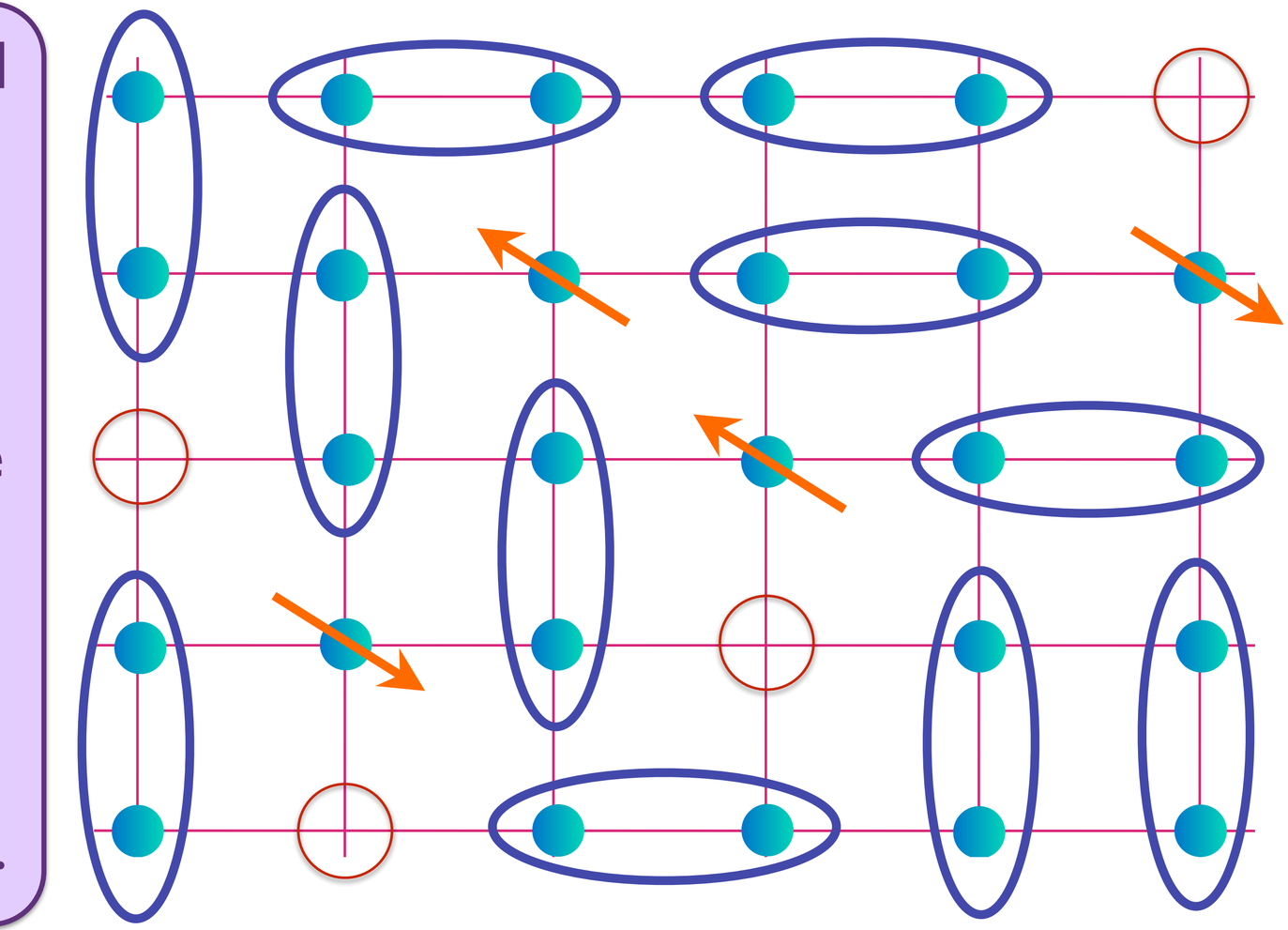
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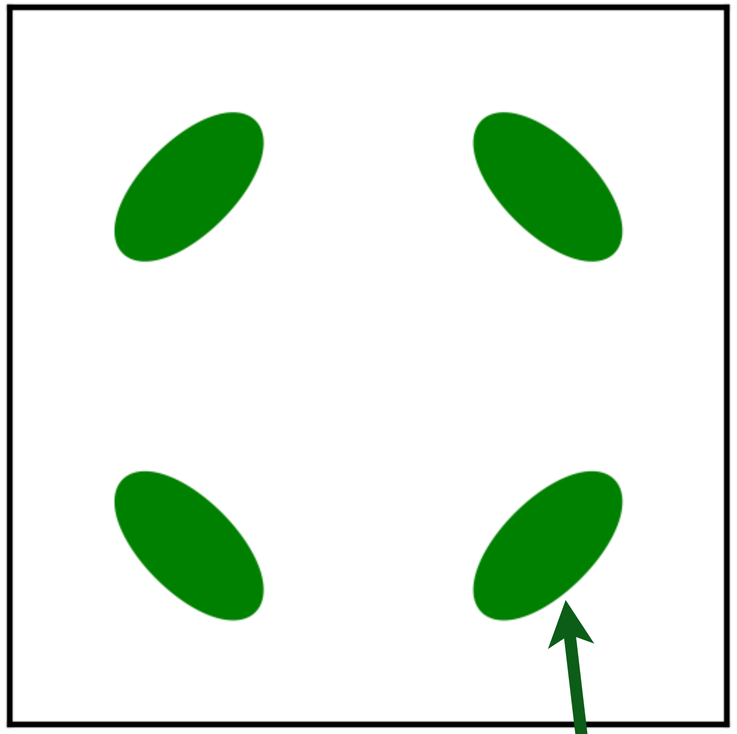
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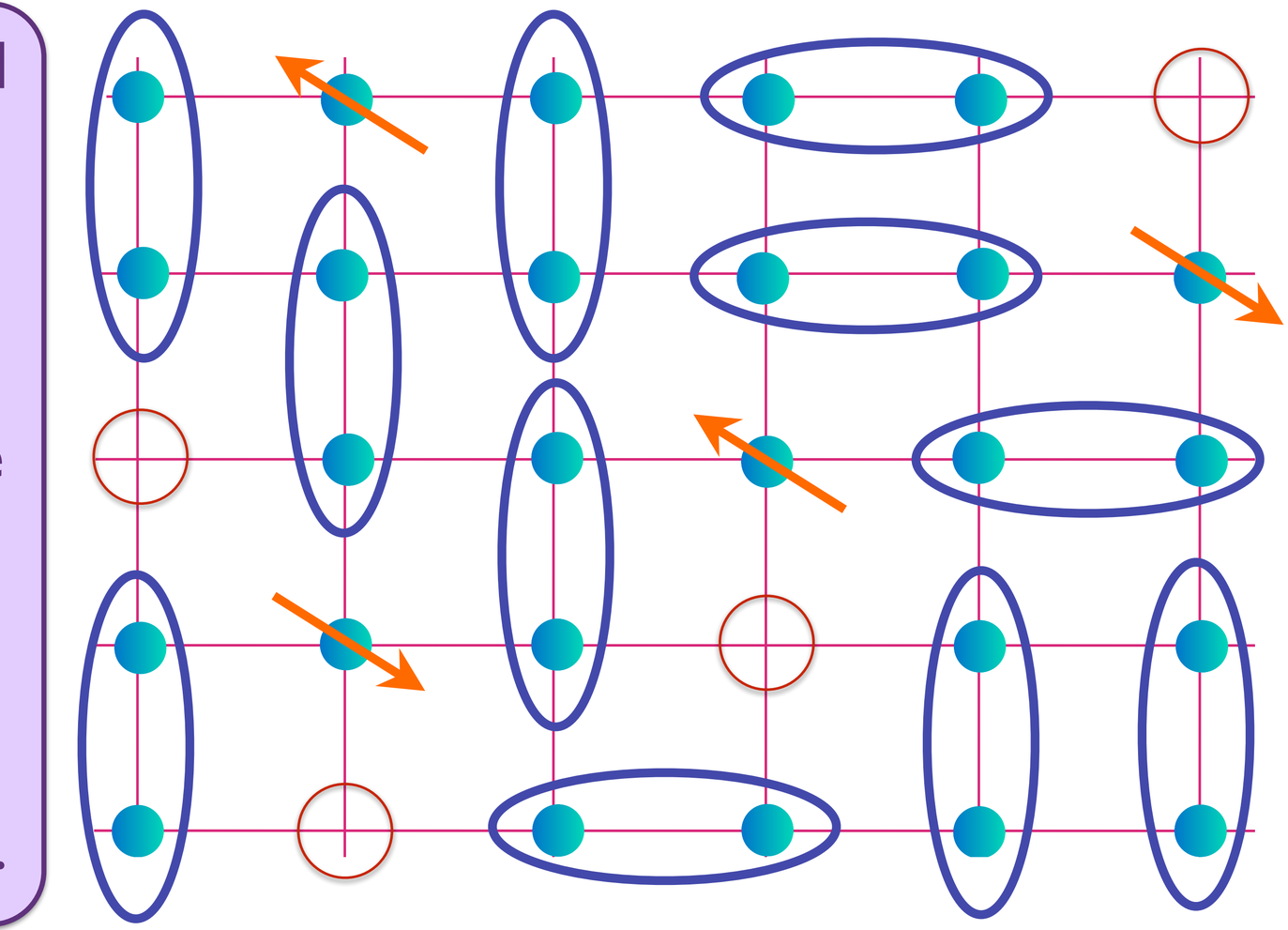


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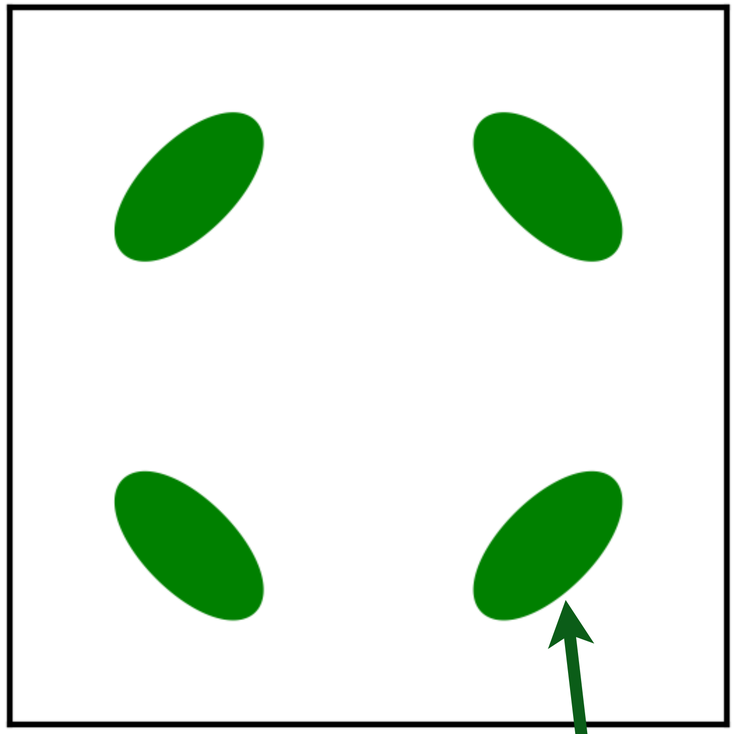
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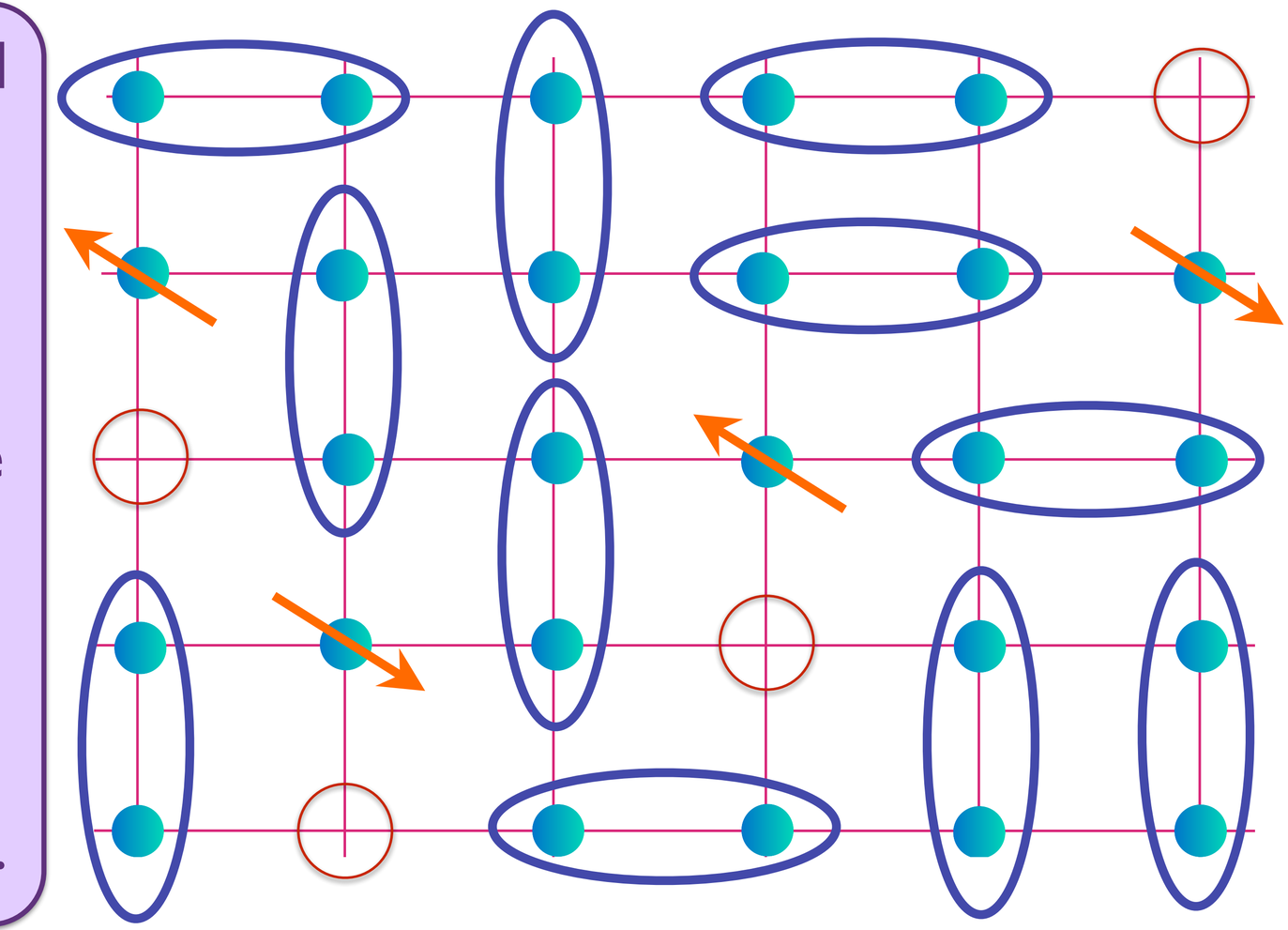


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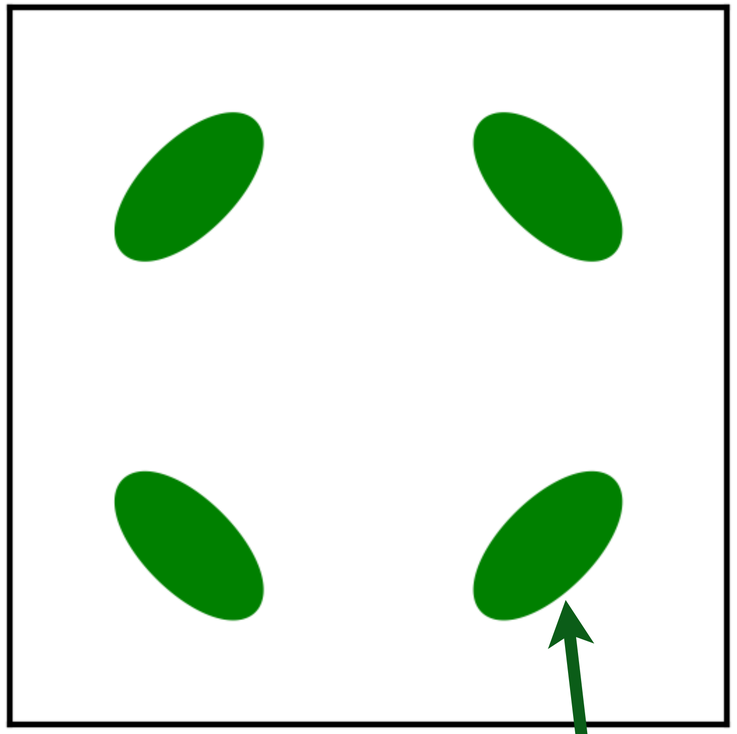
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non-Luttinger area.
Spin liquid

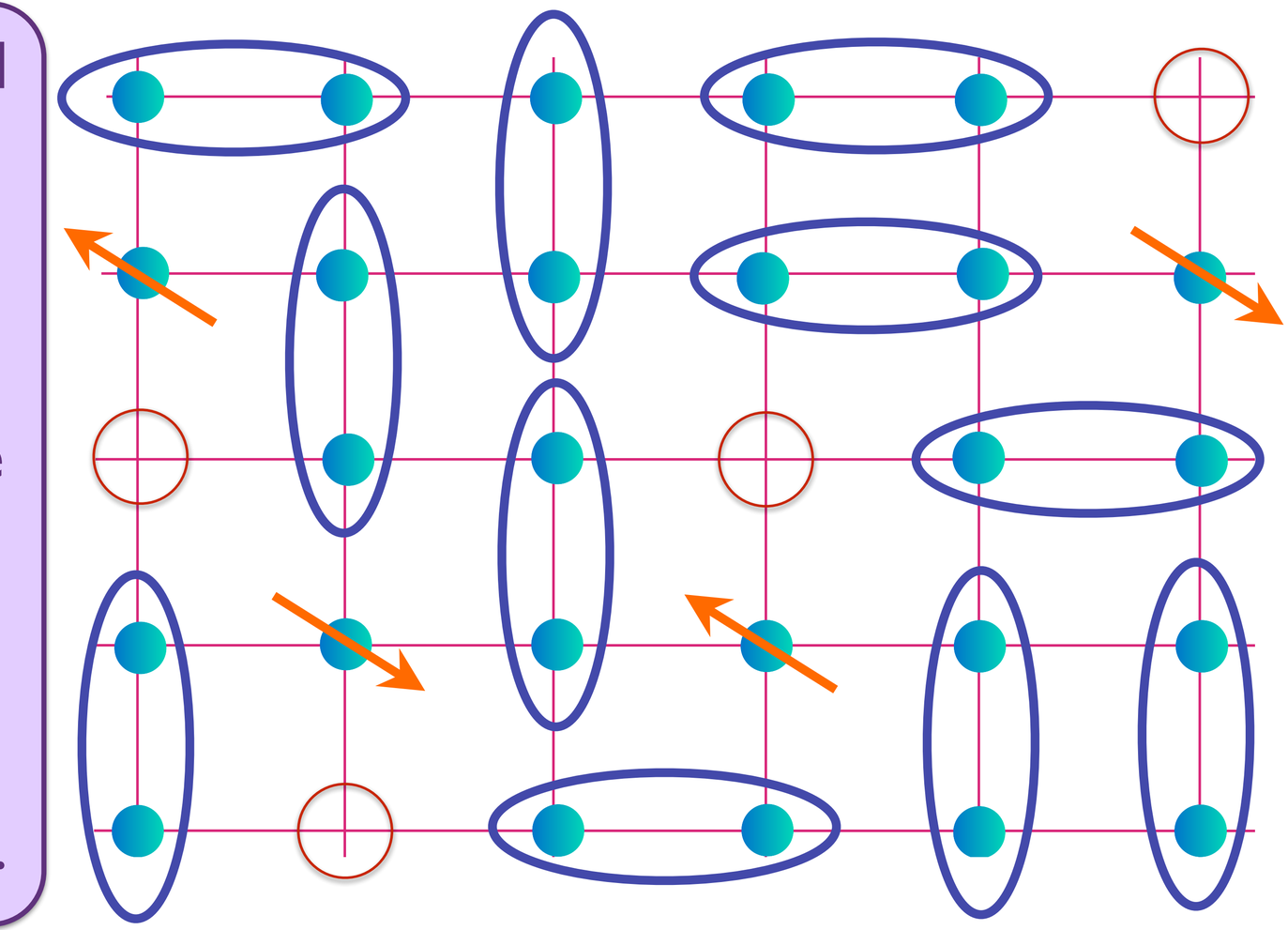


Area $p/4$

Doping an insulating antiferromagnet with holes of density p

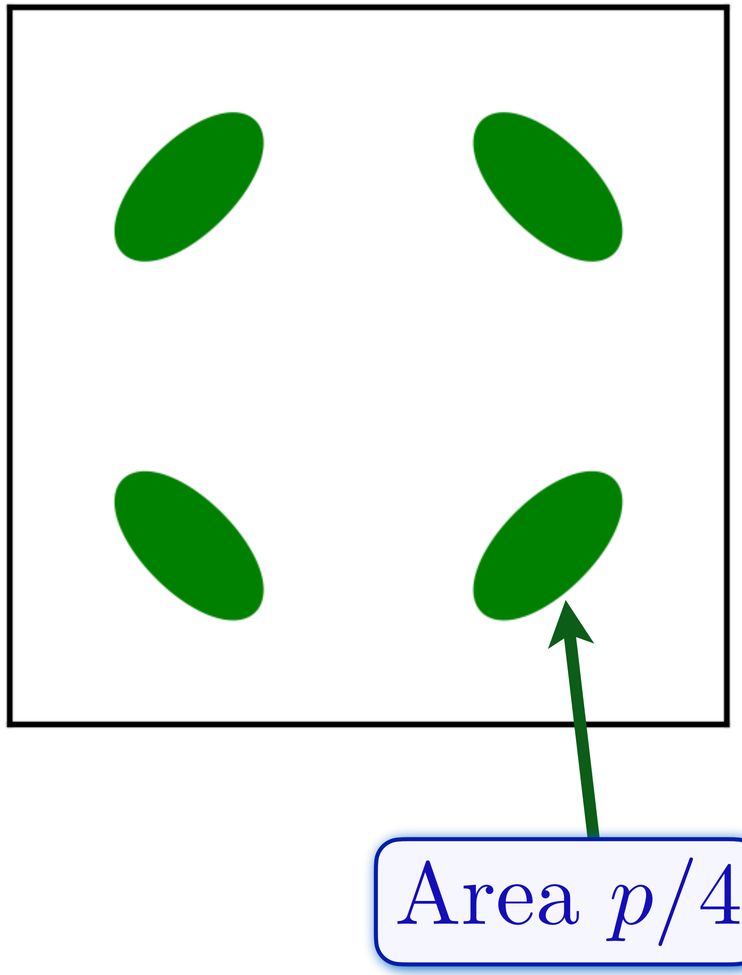
Holon metal

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



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

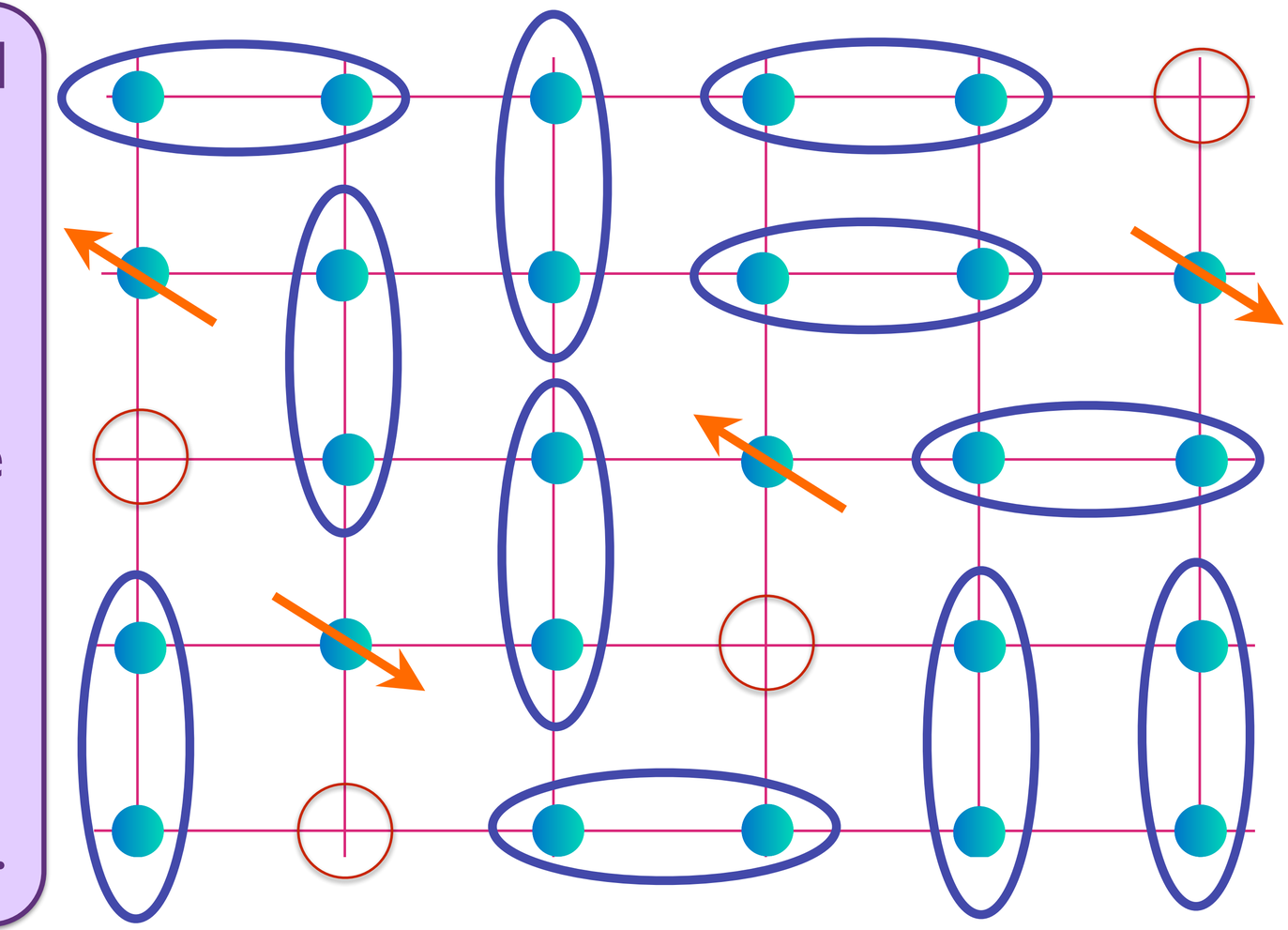
non-Luttinger area.
Spin liquid



Doping an insulating antiferromagnet with holes of density p

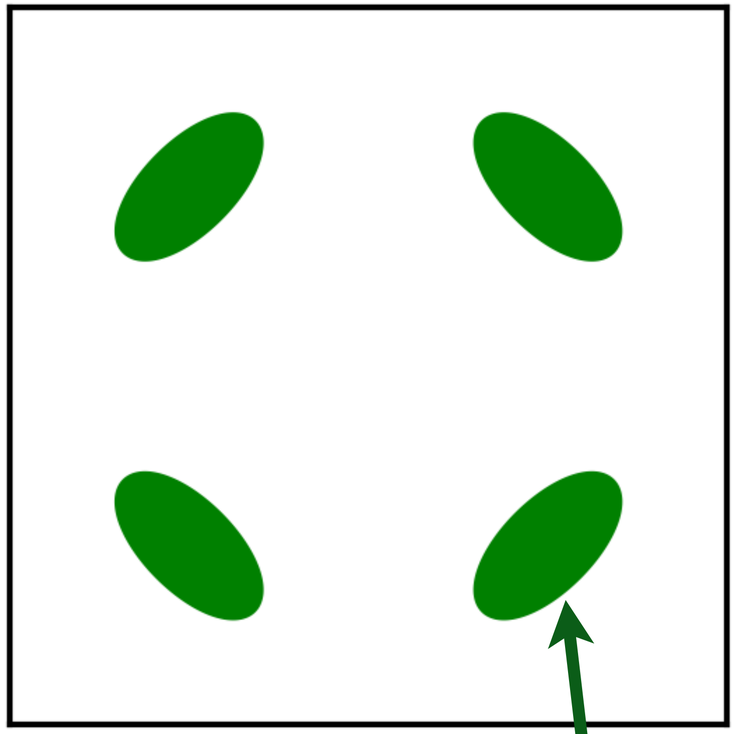
Holon metal

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



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

non-Luttinger area.
Spin liquid

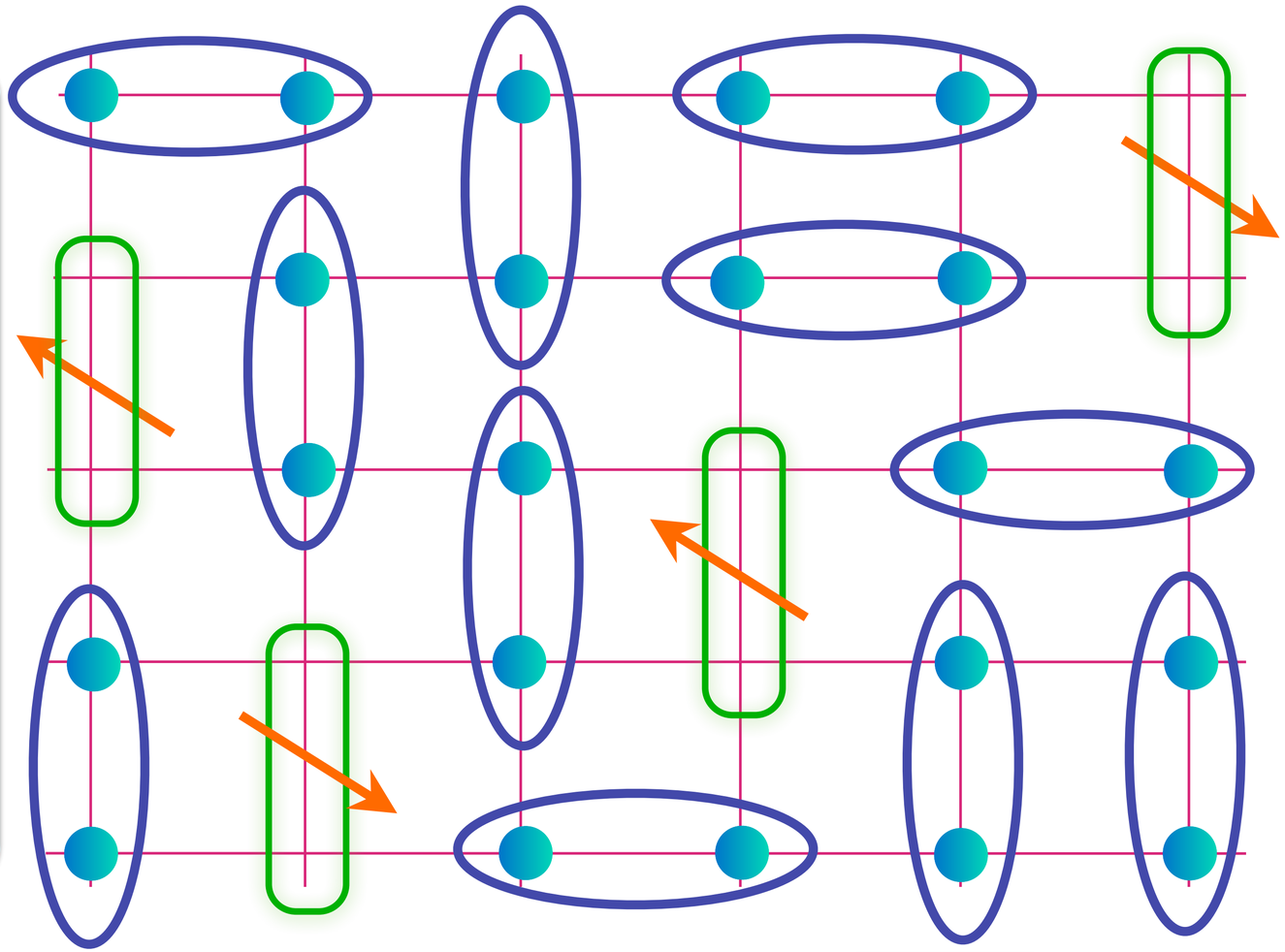


Area $p/4$

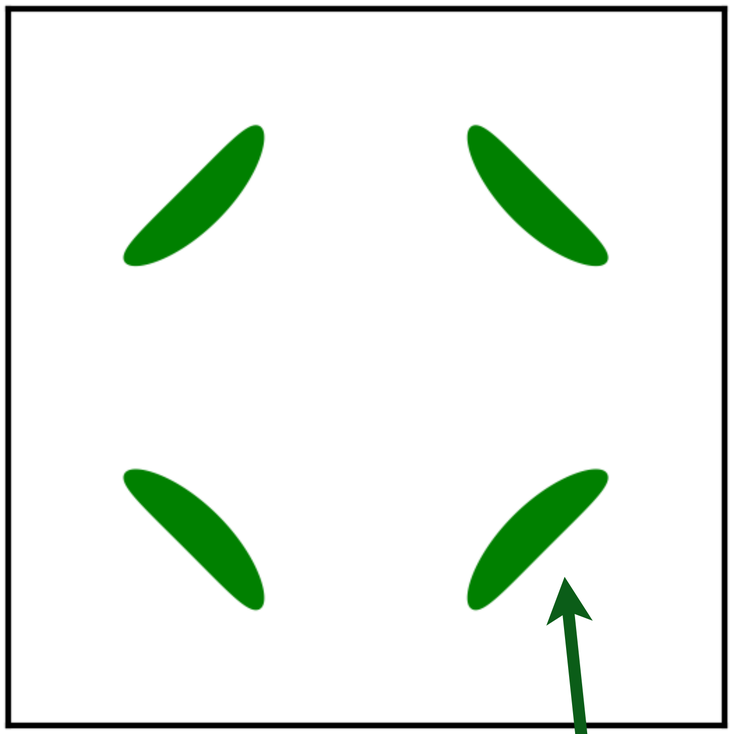
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



Area $p/8$

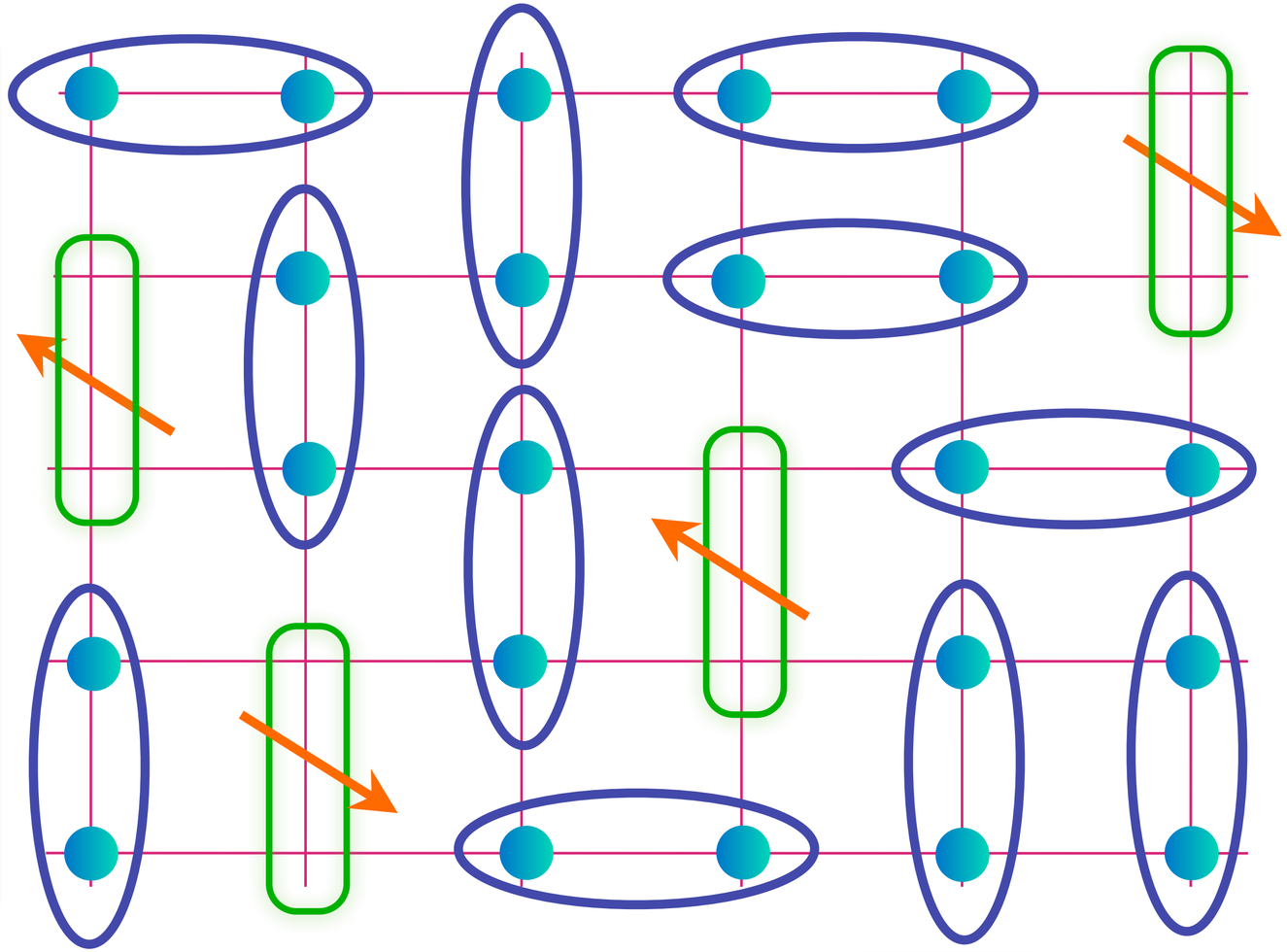
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

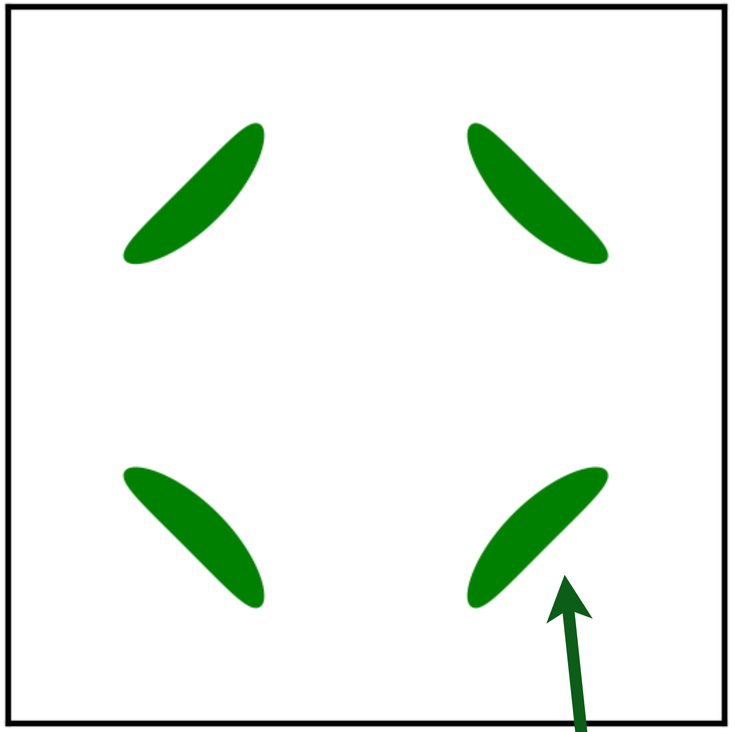
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



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

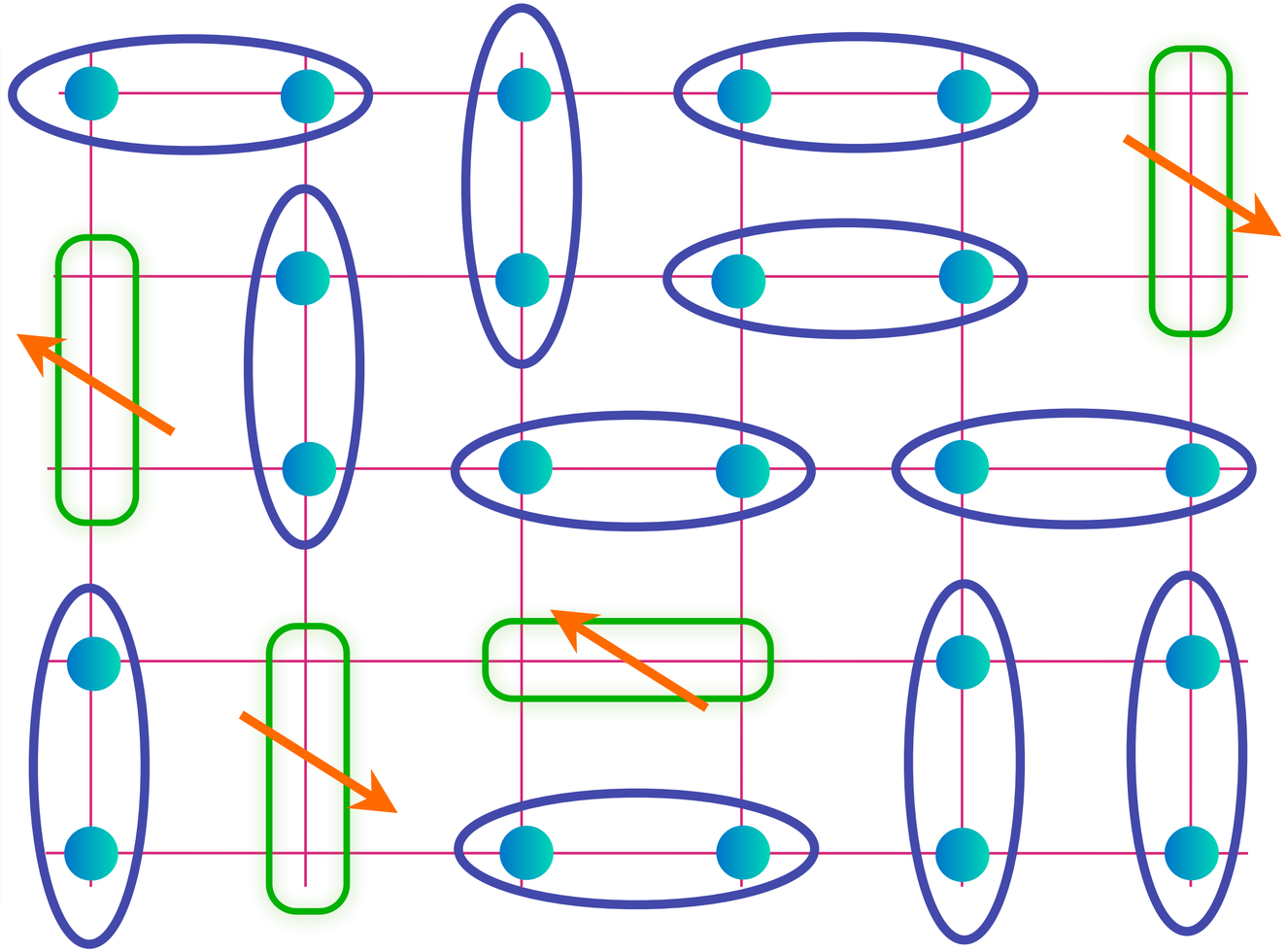
$= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

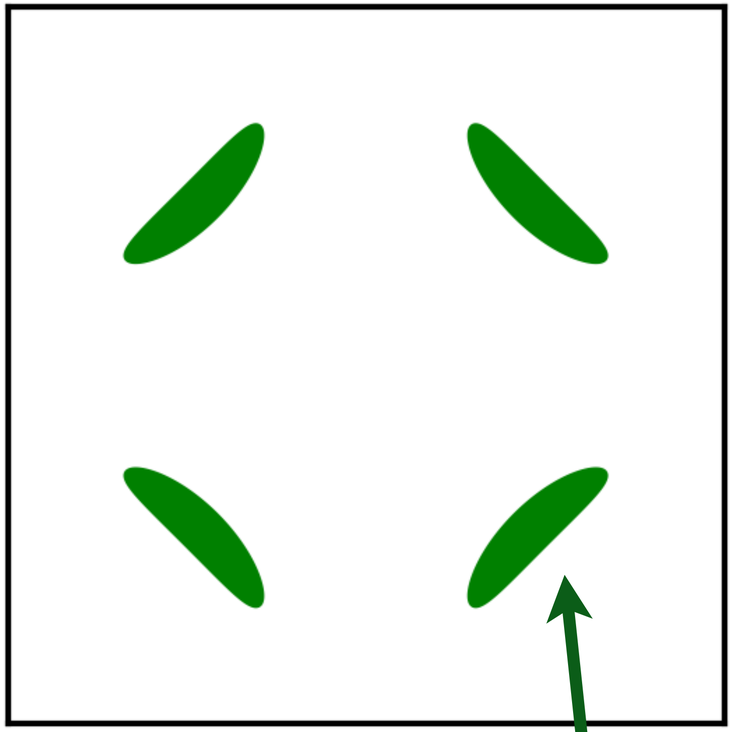
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



Area $p/8$

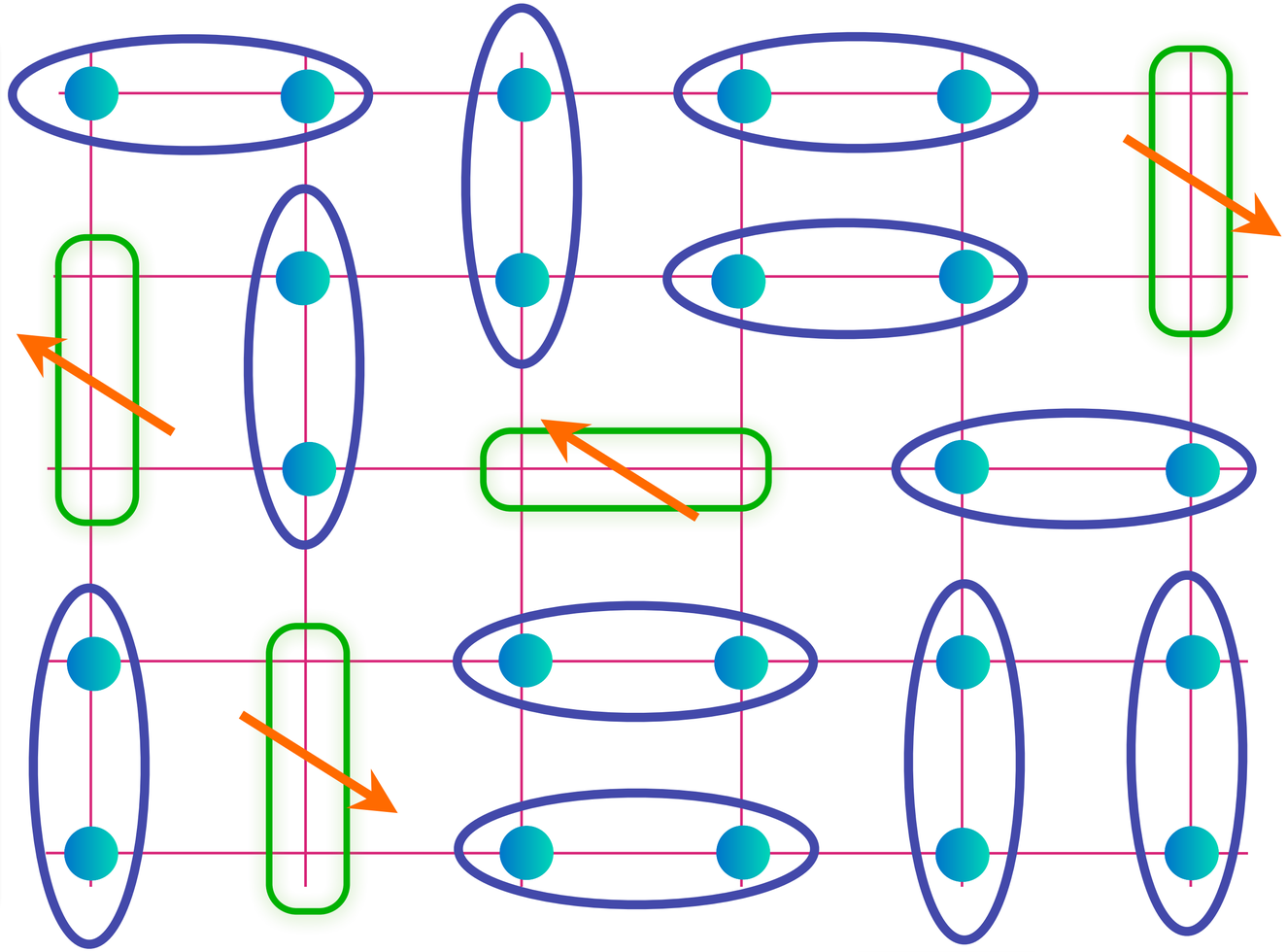
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

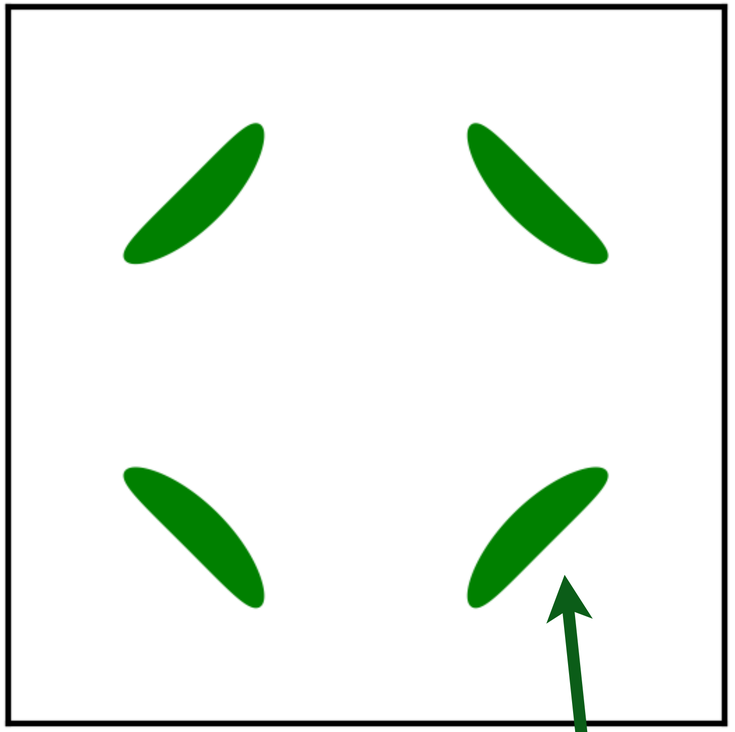
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



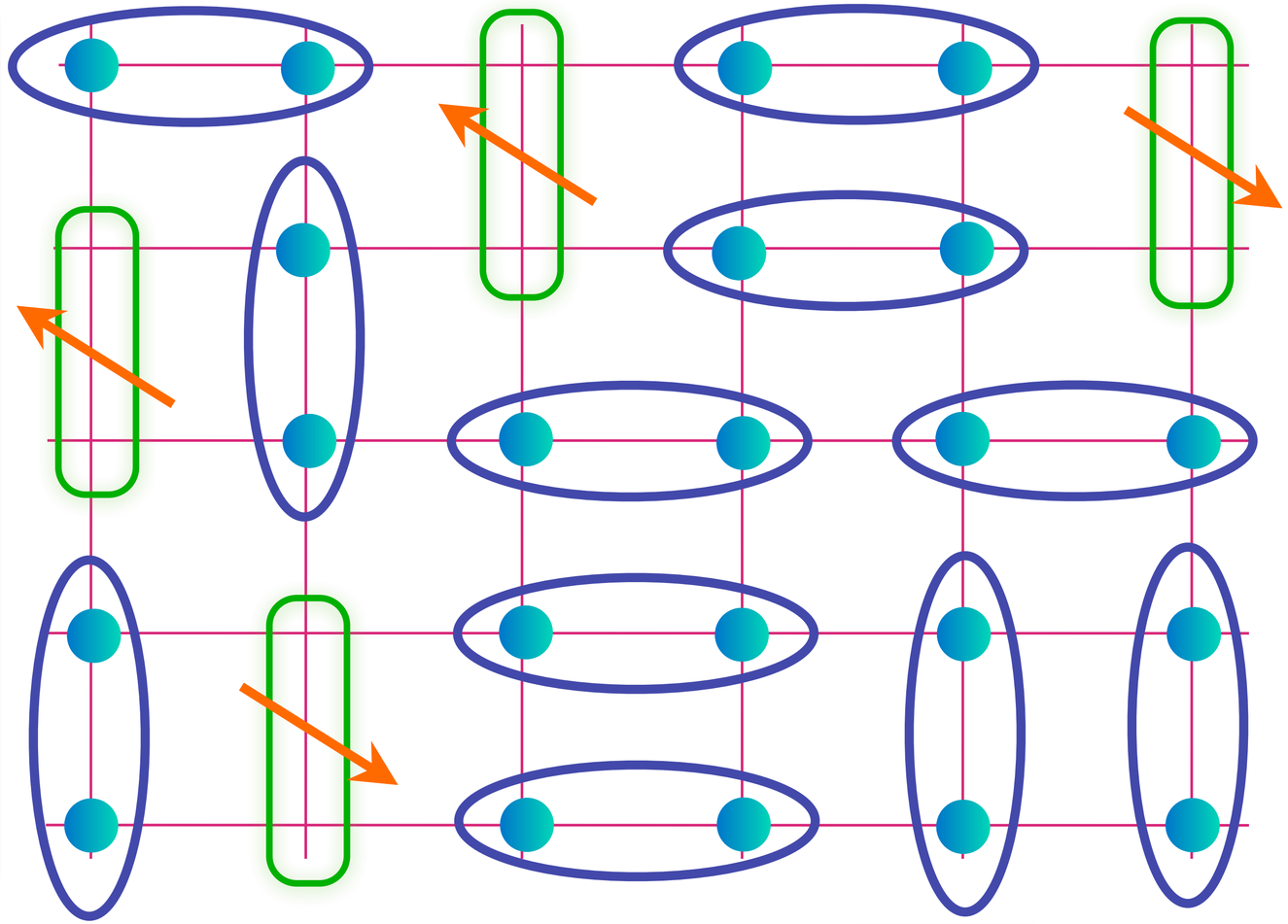
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

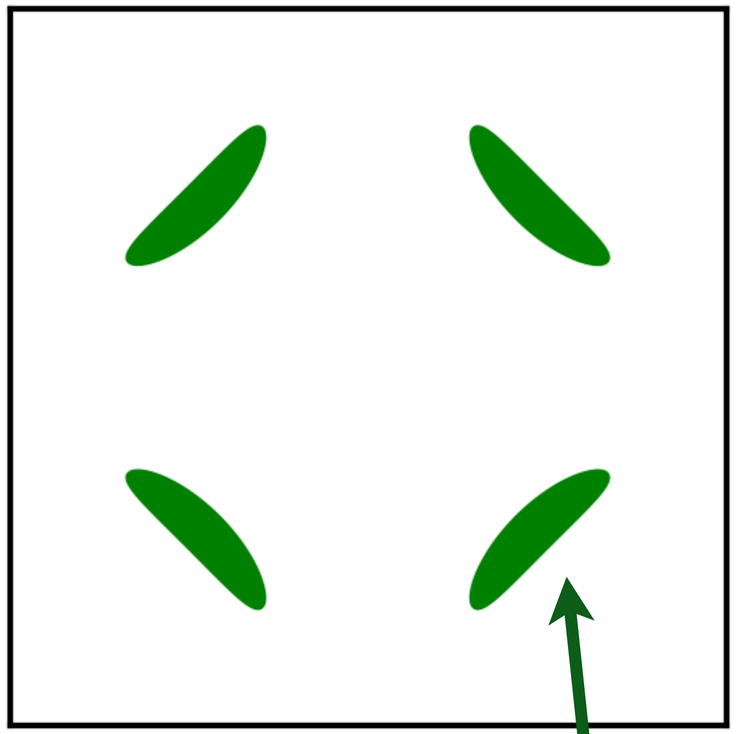
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area. Spin liquid



Area $p/8$

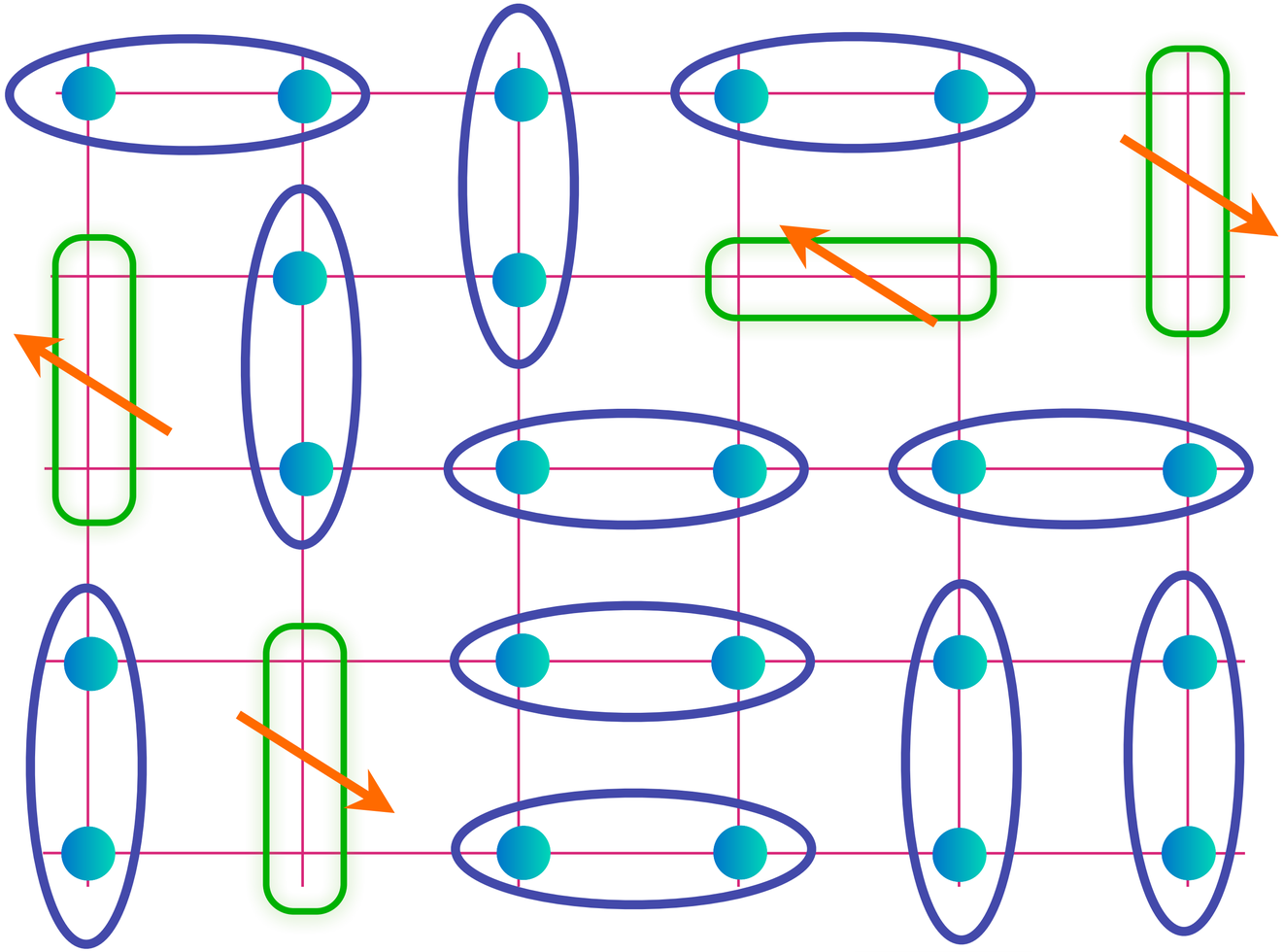
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

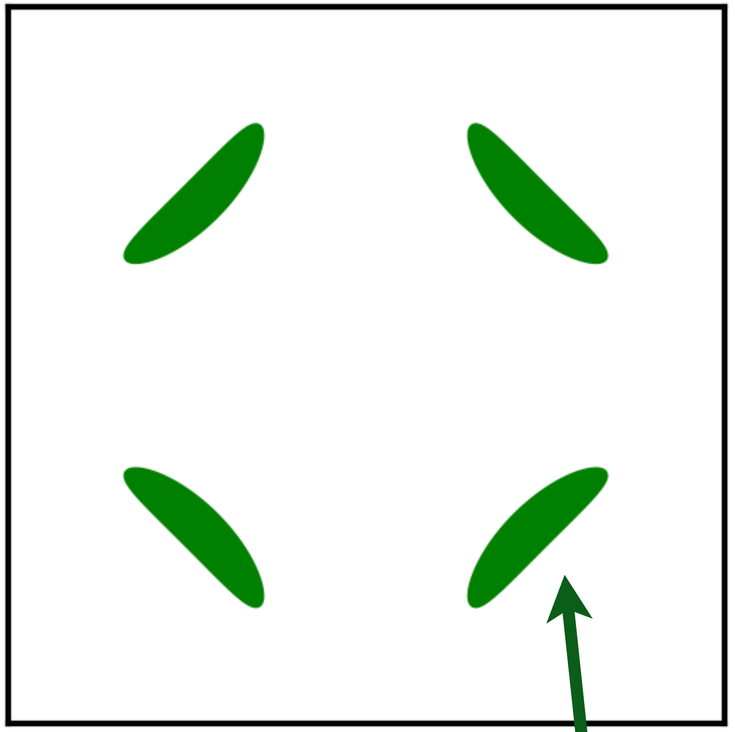
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



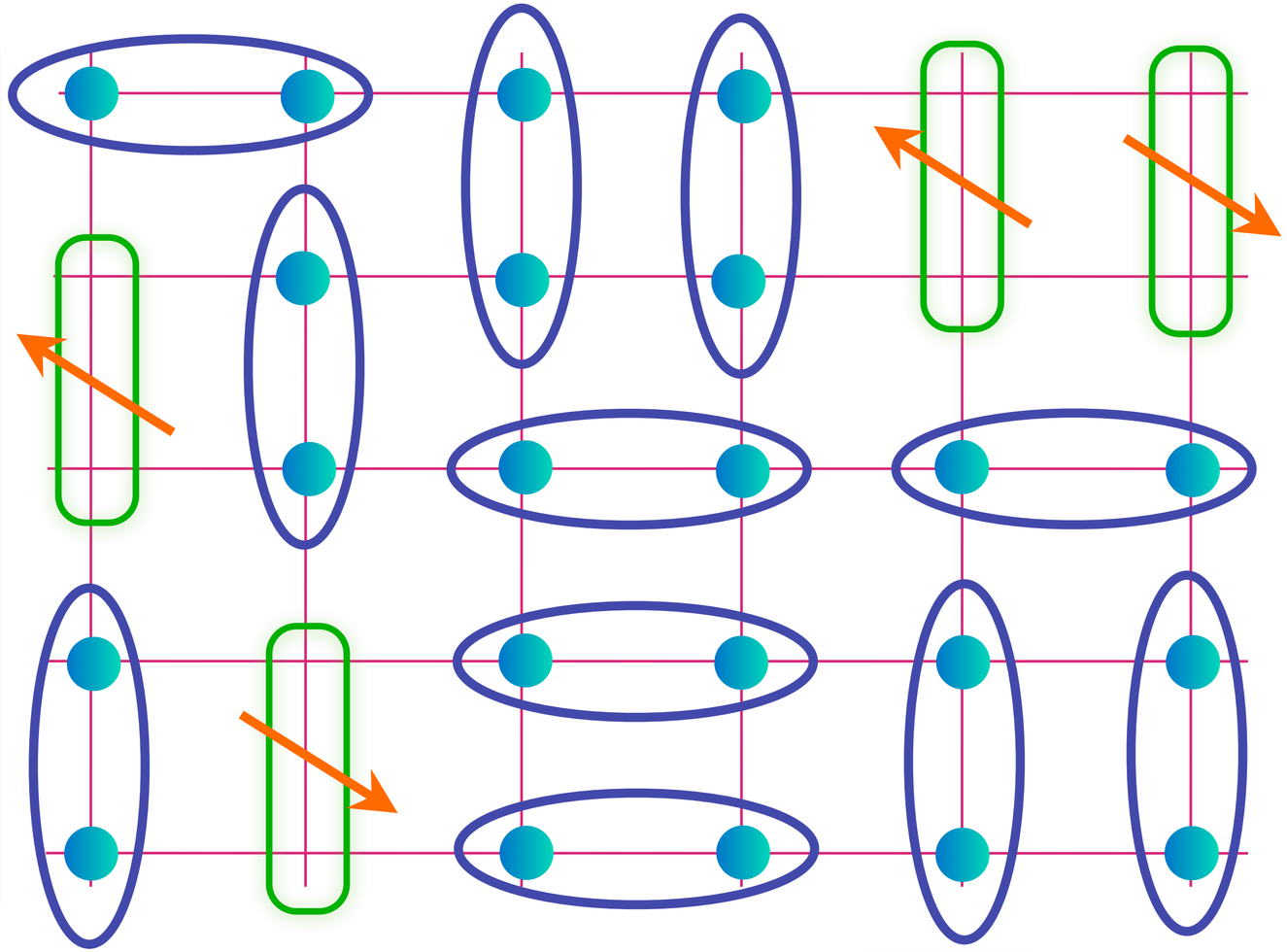
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$

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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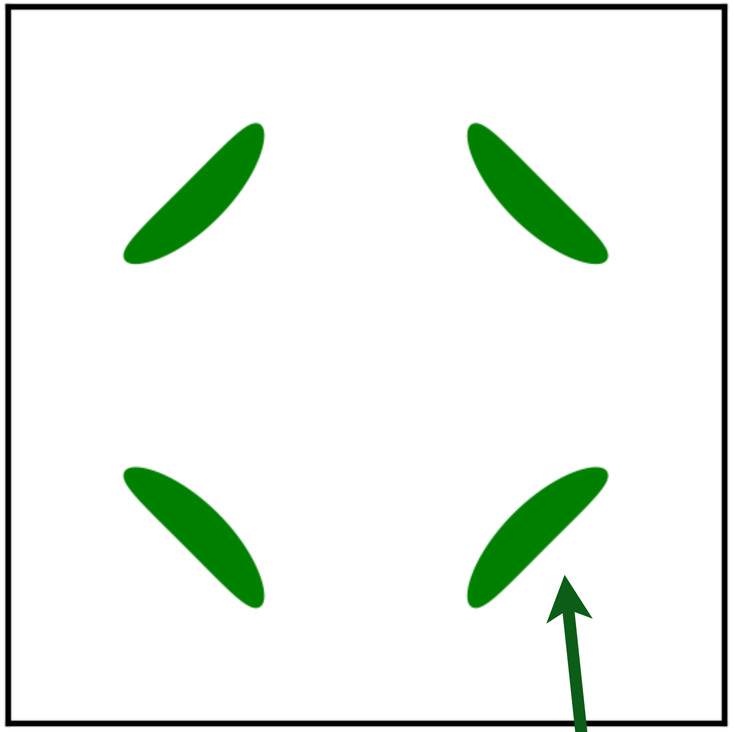
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



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

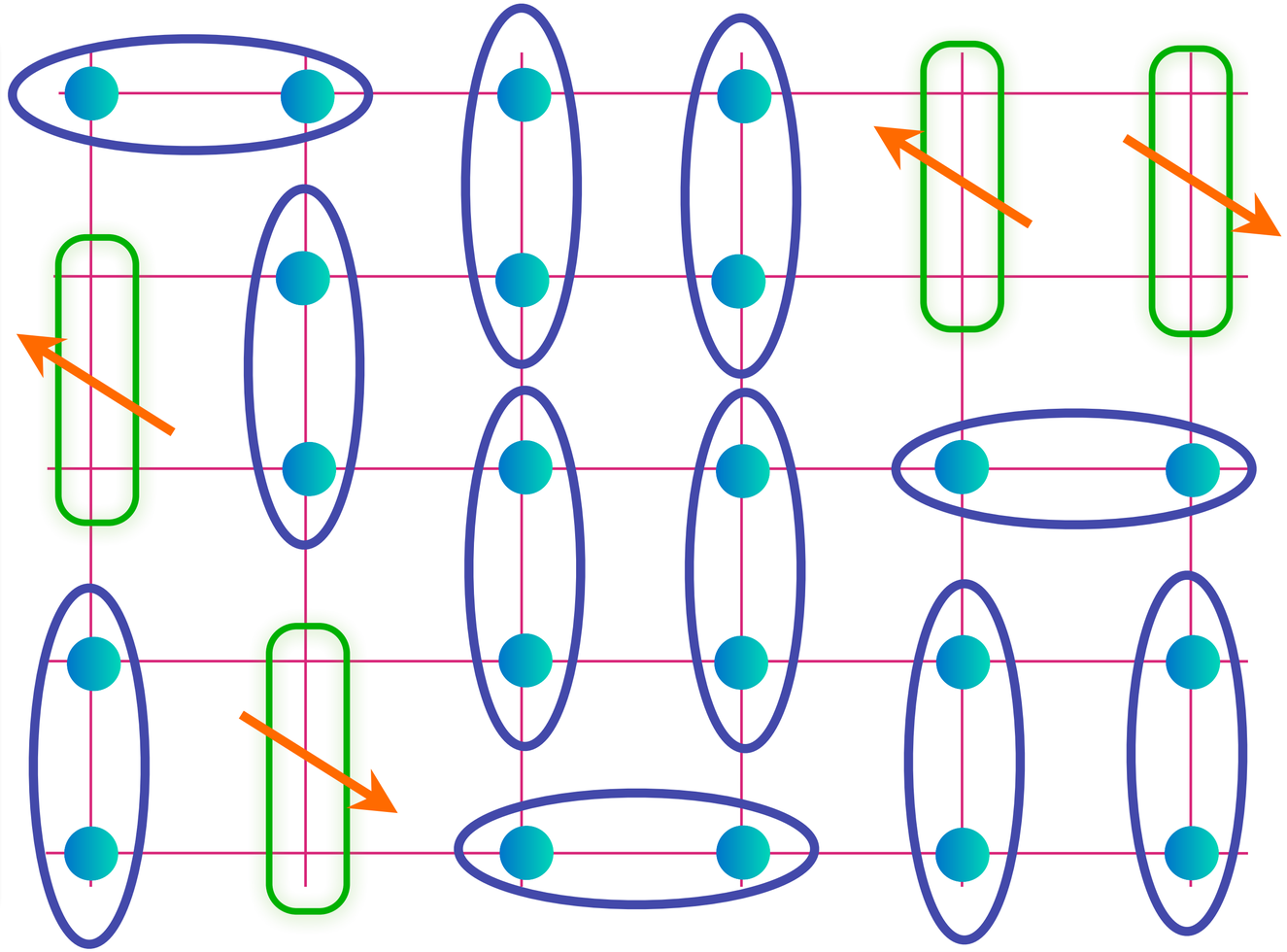
$= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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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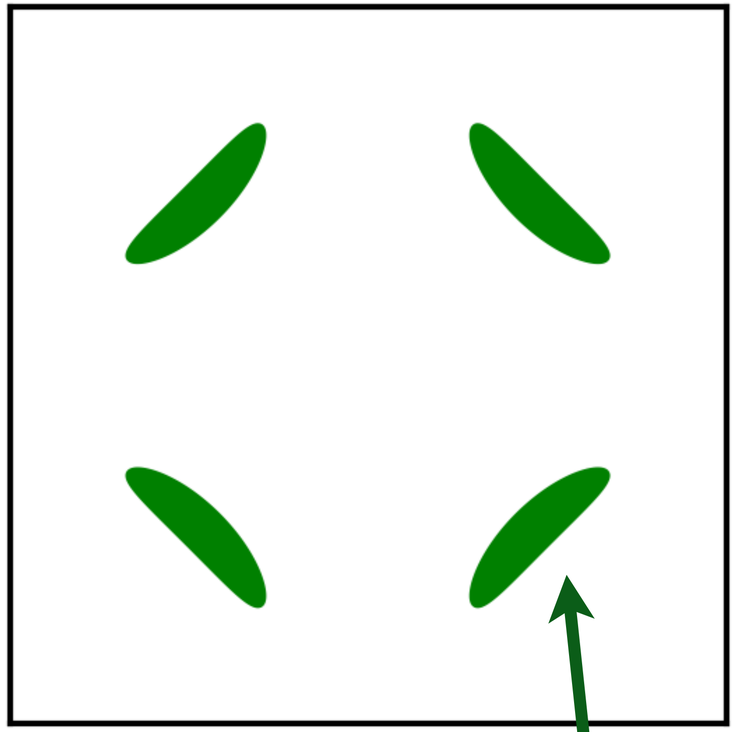
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



Area $p/8$

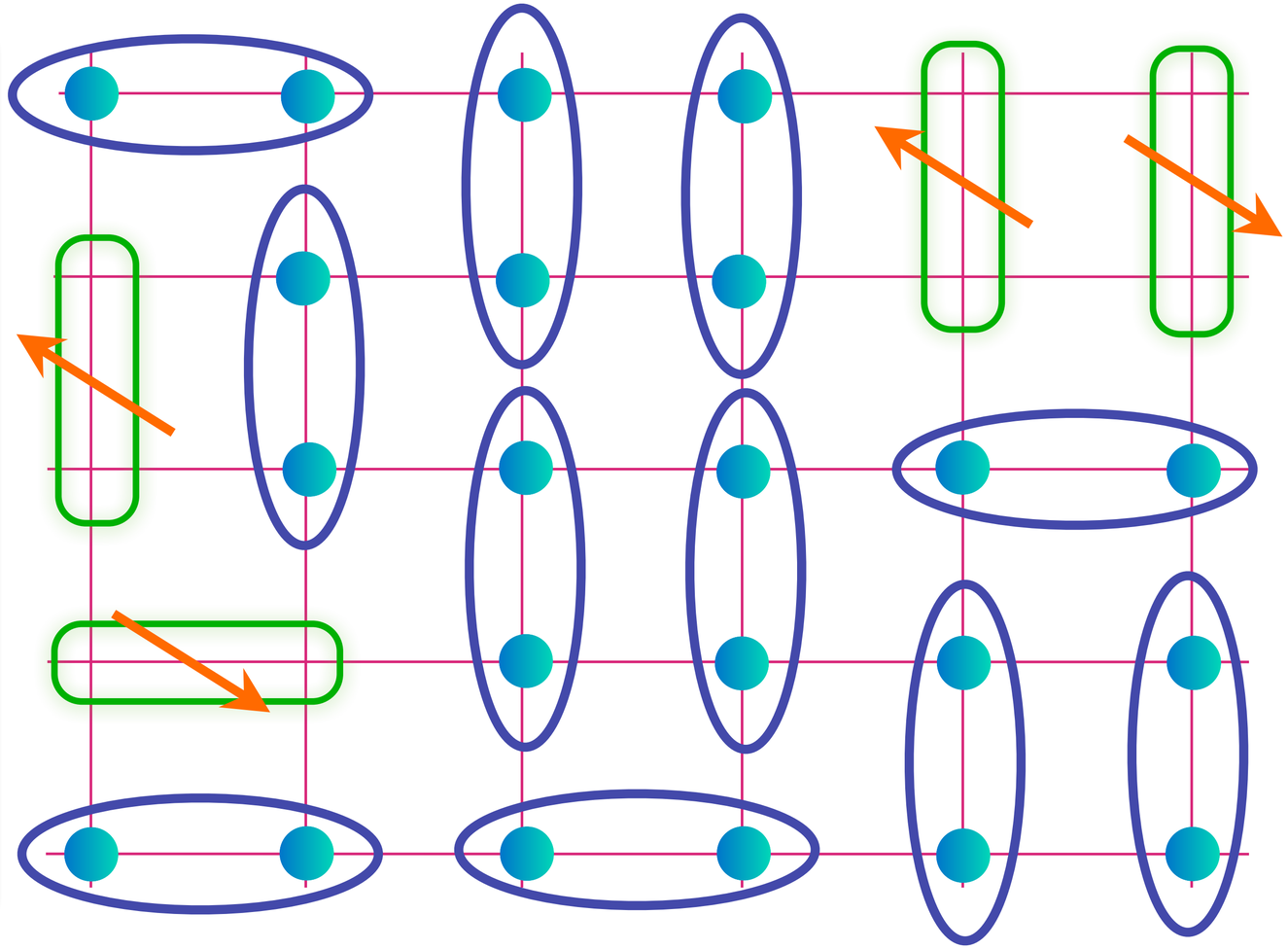
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

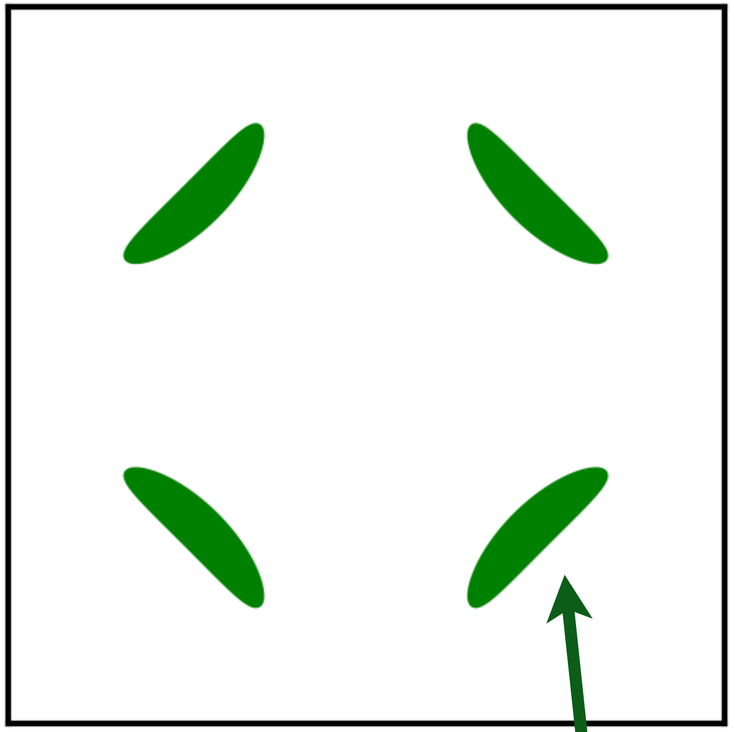
Doping an insulating antiferromagnet with holes of density p

FL*

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



non-Luttinger area.
Spin liquid



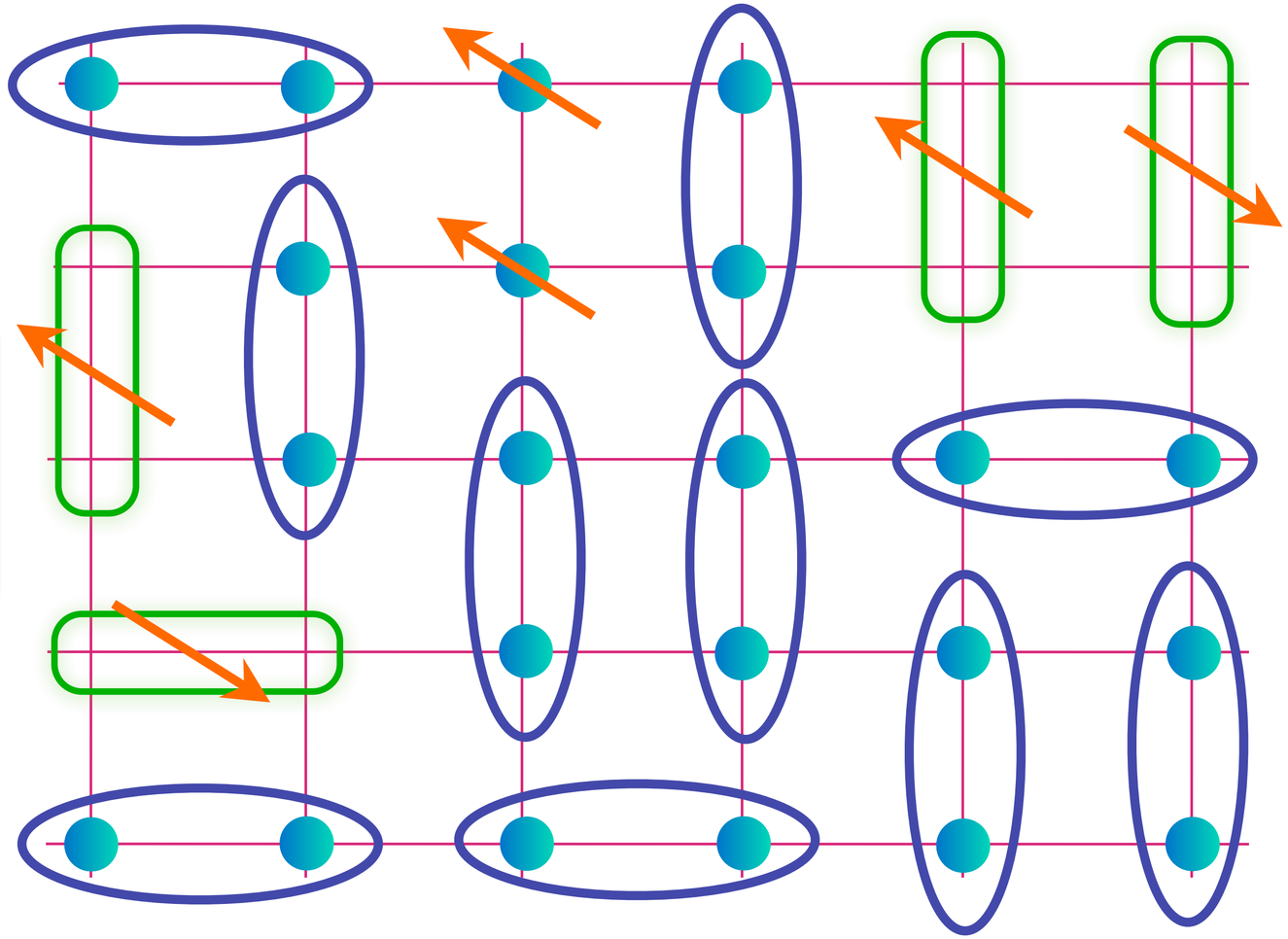
Area $p/8$

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

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

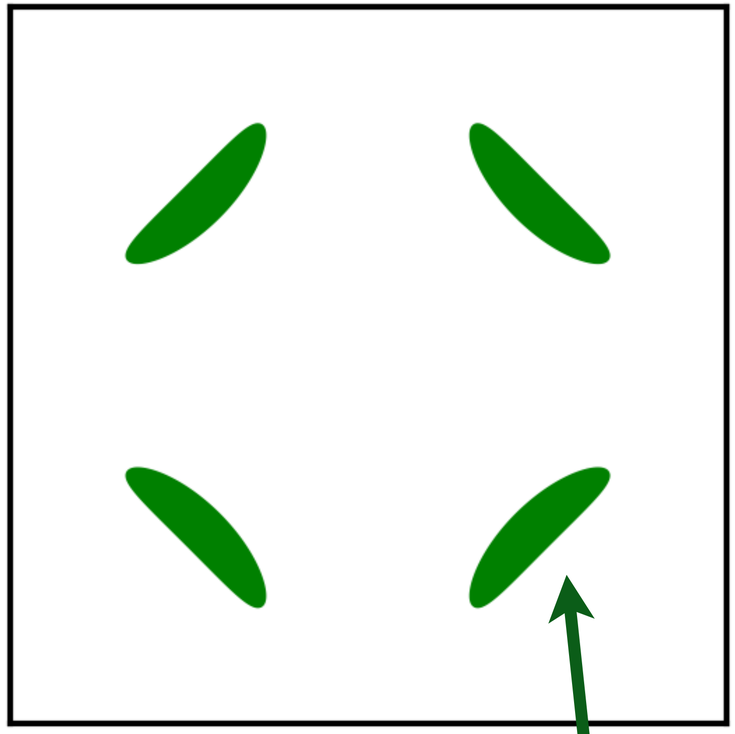
Doping an insulating antiferromagnet with holes of density p

FL*



The FL* state retains the spinon excitations

non-Luttinger area.
Spin liquid



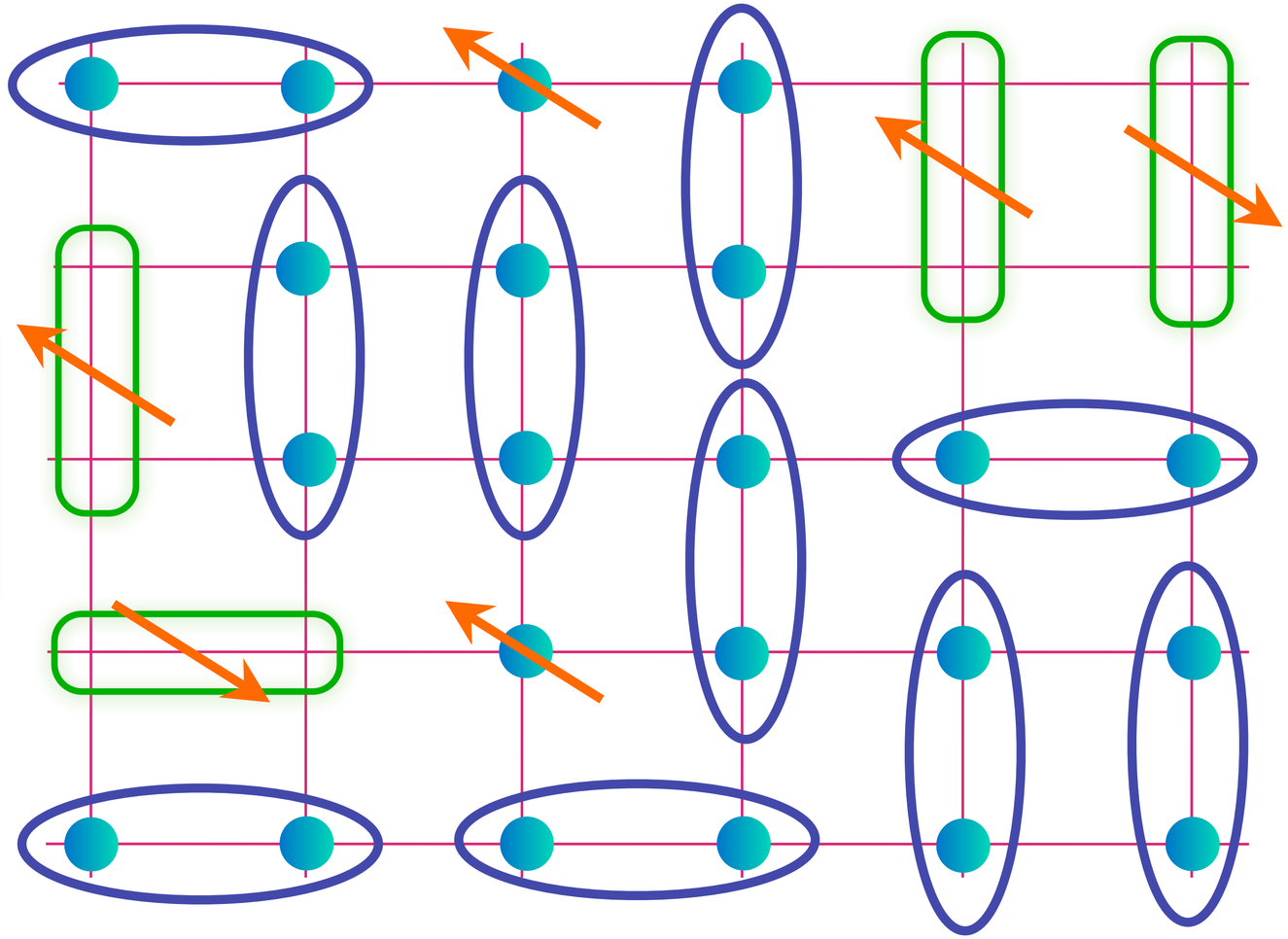
Area $p/8$

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

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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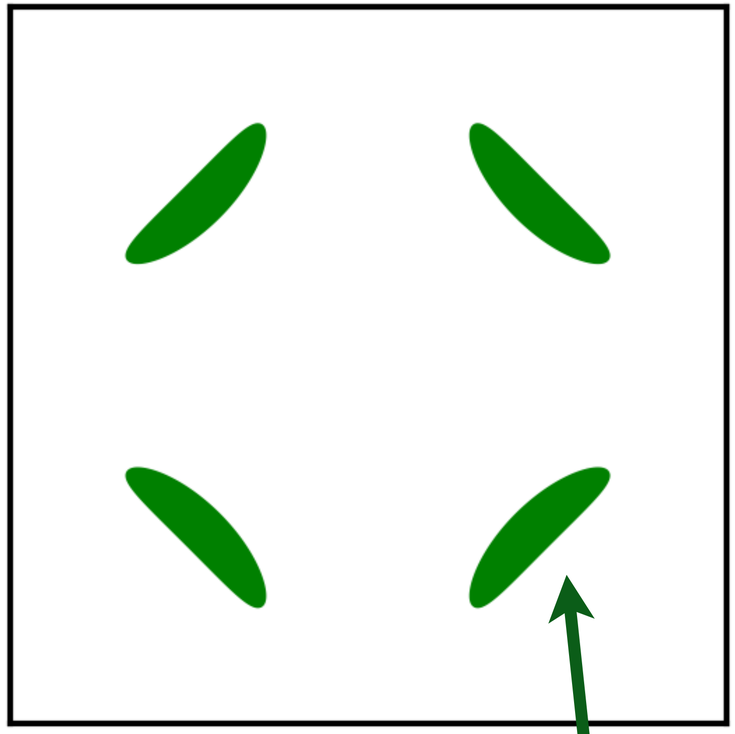
Doping an insulating antiferromagnet with holes of density p

FL*



The FL* state retains the spinon excitations

non-Luttinger area.
Spin liquid



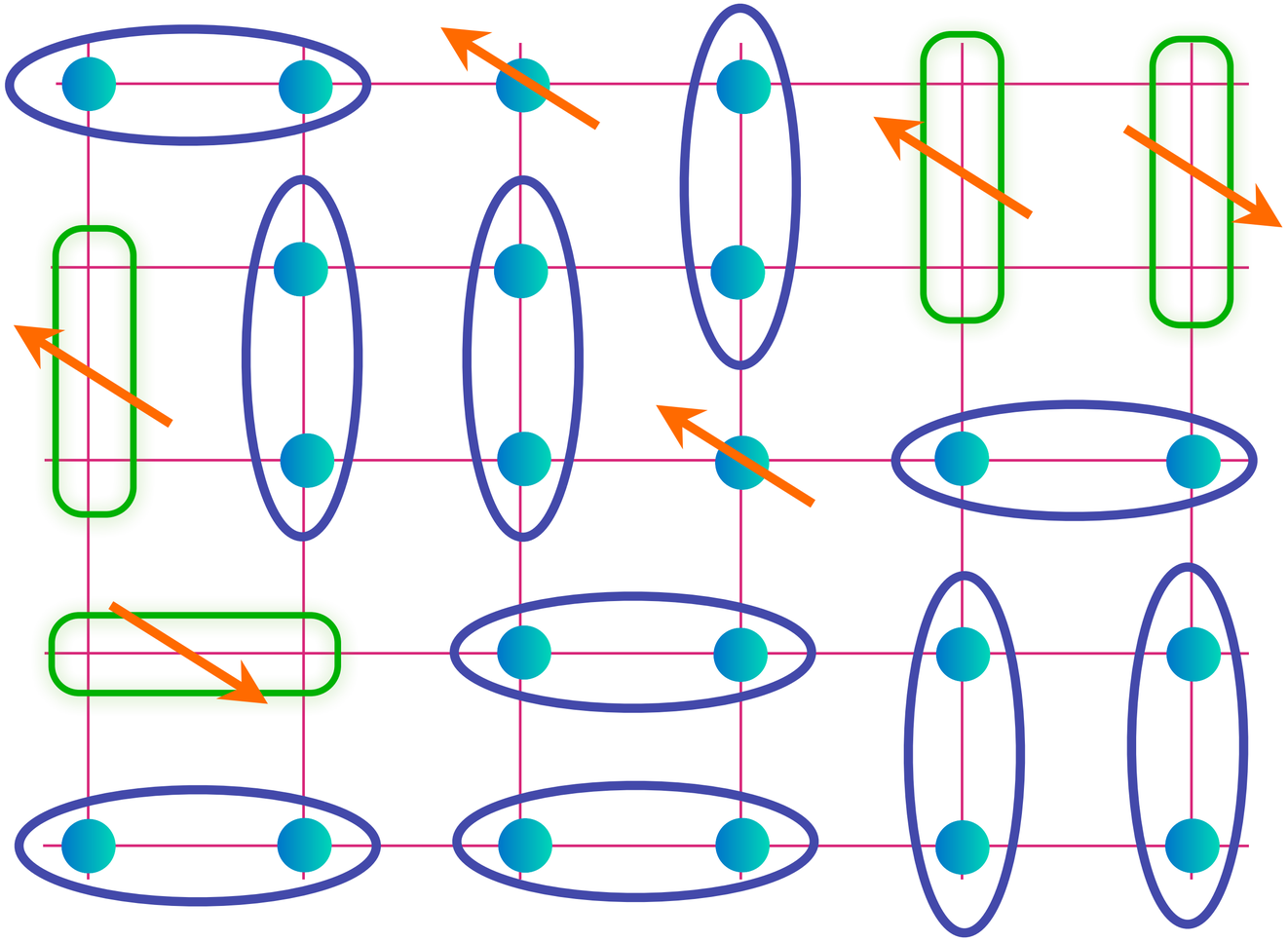
Area $p/8$

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

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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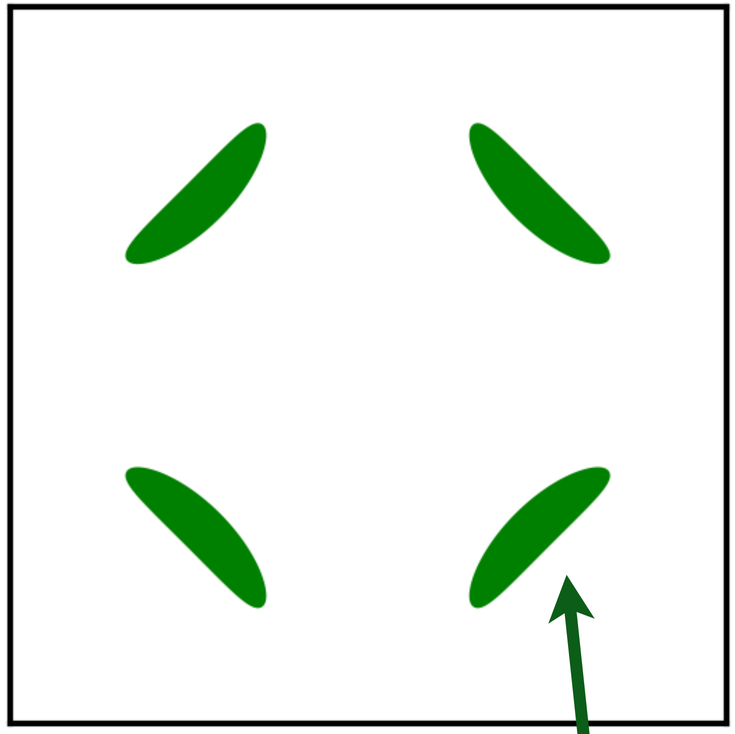
Doping an insulating antiferromagnet with holes of density p

FL*



The FL* state retains the spinon excitations

non-Luttinger area.
Spin liquid



Area $p/8$

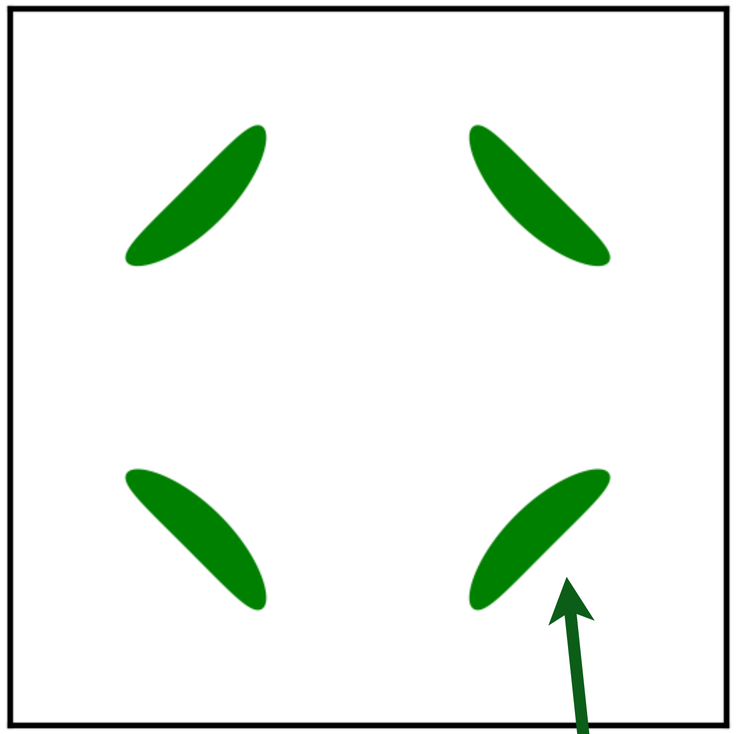
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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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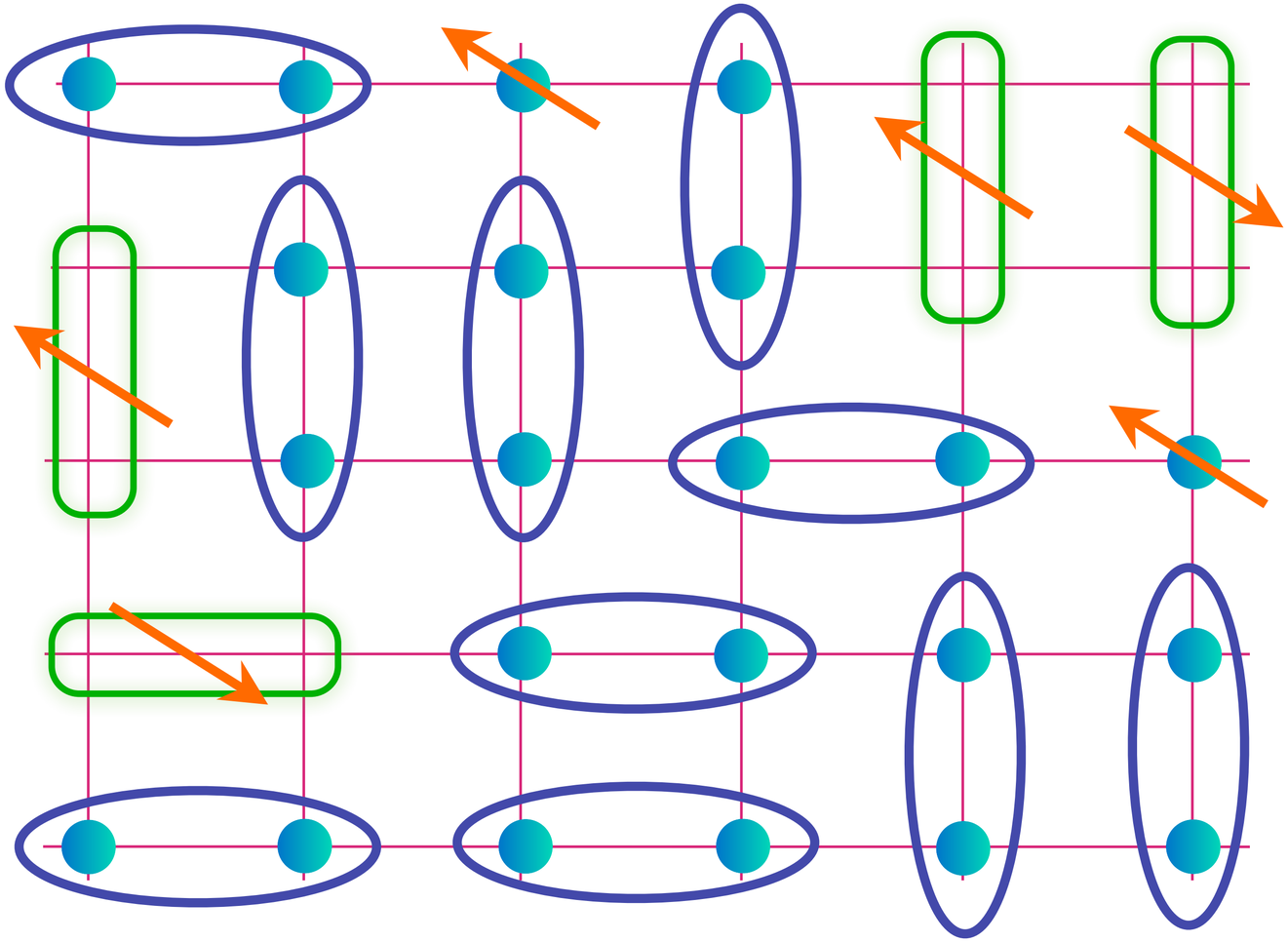
Doping an insulating antiferromagnet with holes of density p

FL*

non-Luttinger area.
Spin liquid



The FL* state retains the spinon excitations



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

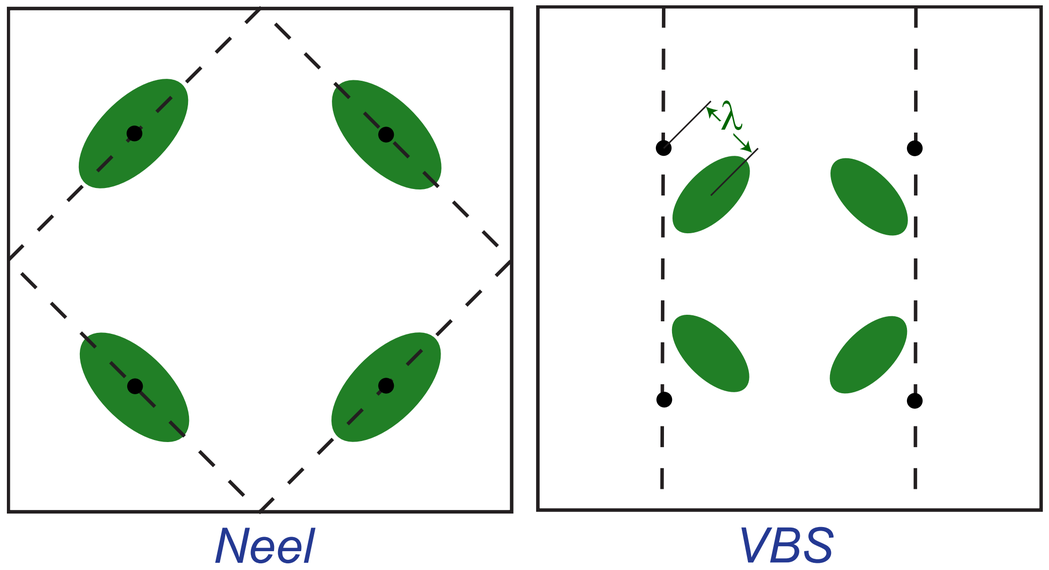
$= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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

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]



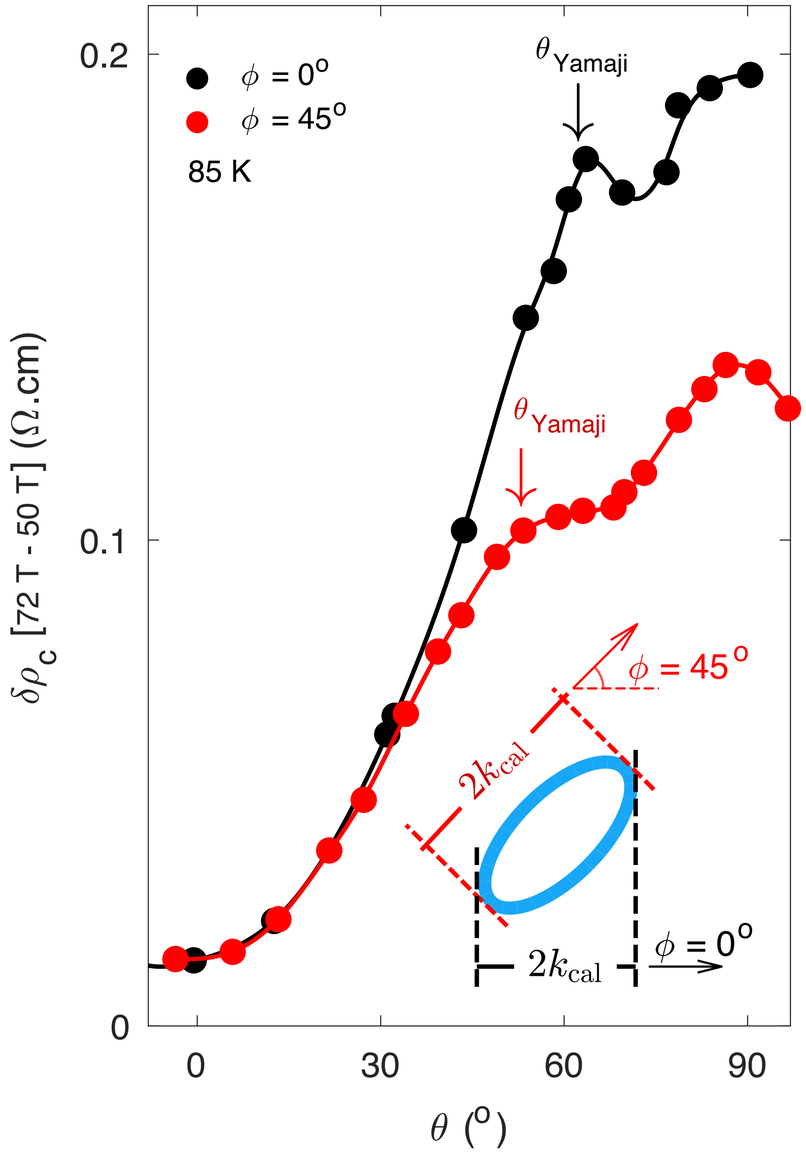
The dashed line in the Néel phase indicates the boundary of the magnetic Brillouin zone. Only the Fermi surfaces within this zone contribute to the Luttinger counting, and so the area of each ellipse is $\mathcal{A}_F=(2\pi)^2\delta/4$. In the VBS phase, all four pockets are inequivalent, and so the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

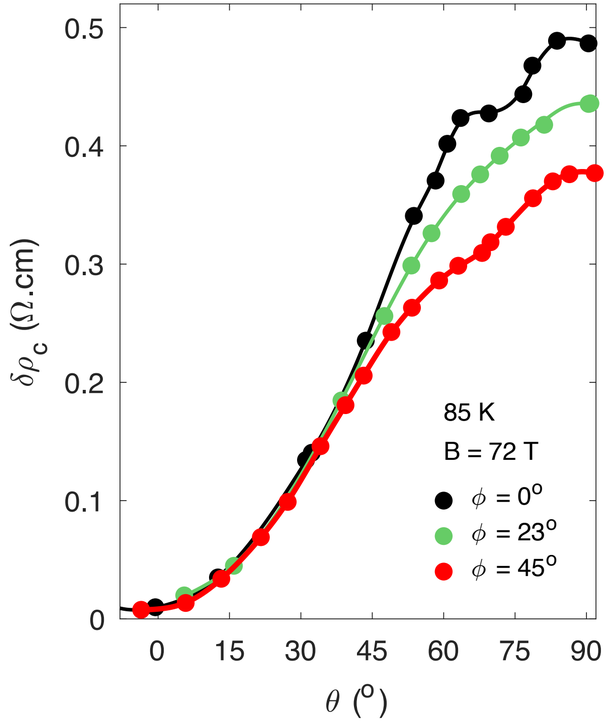
Fermi surface areas are robust to all corrections! Factor of 2 between SDW fluctuation and FL*

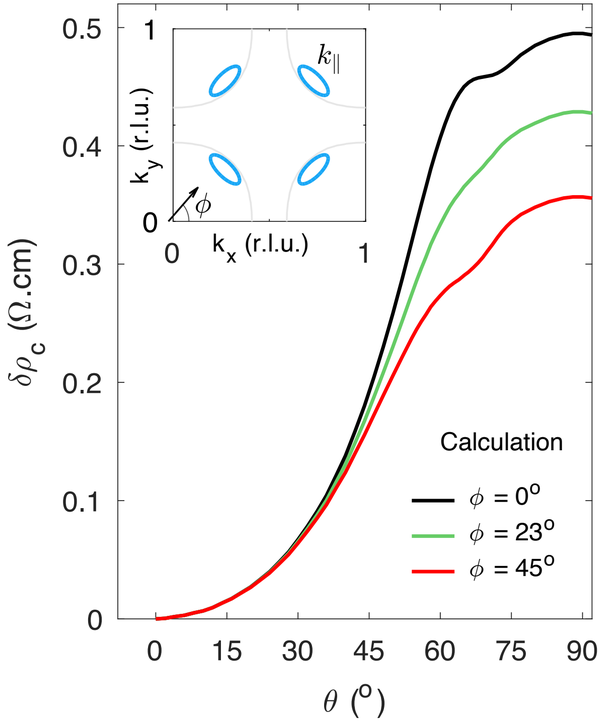
Observation of the Yamaji effect in a cuprate superconductor

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







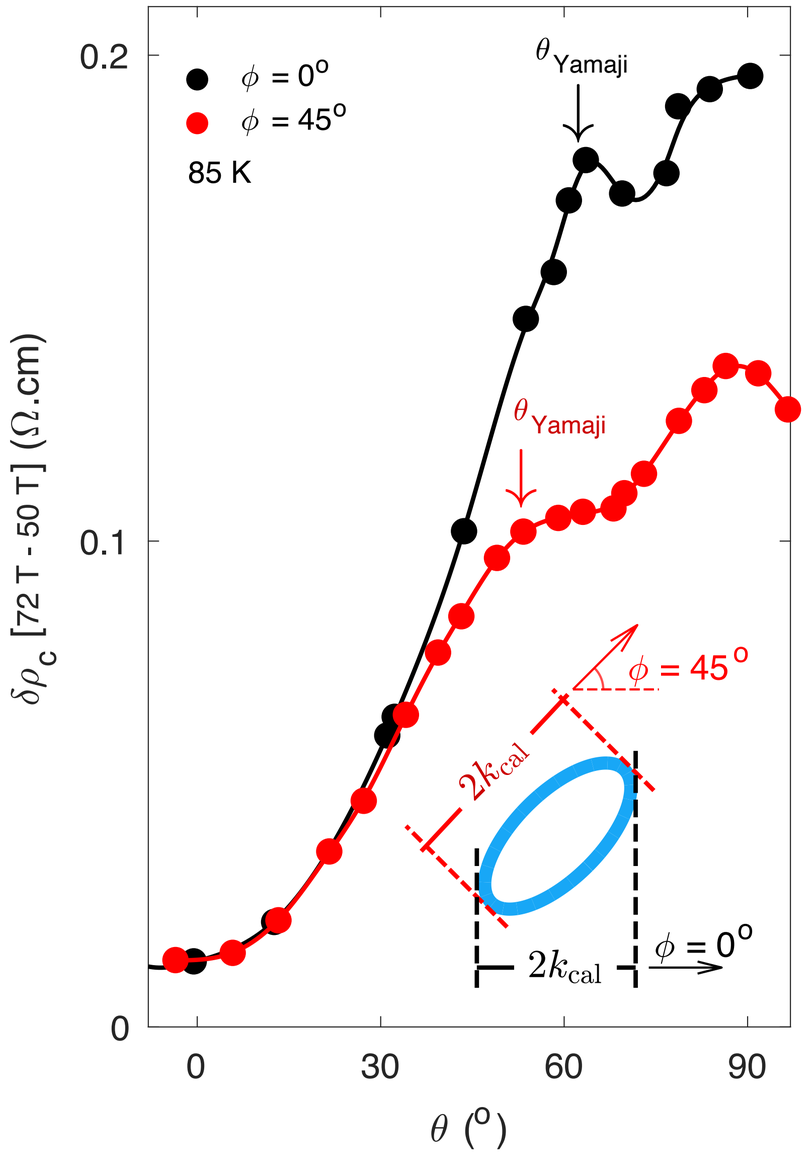
Doping
$p = 0.1$

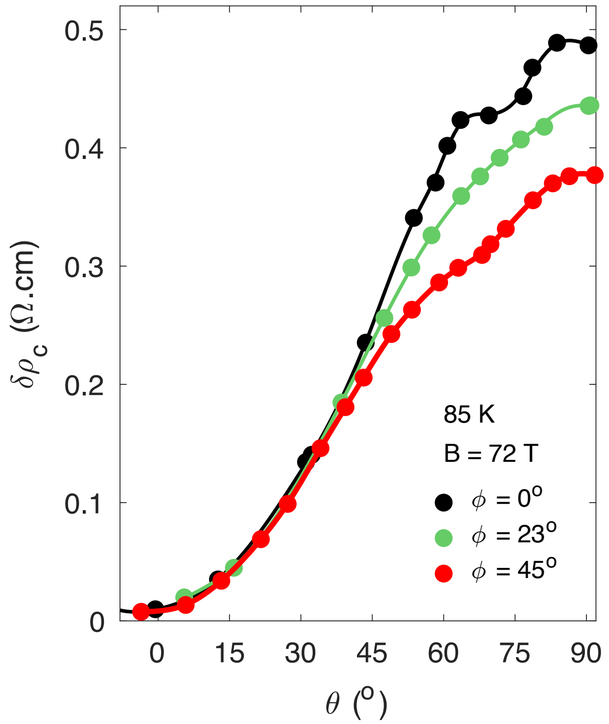
"The small size of the pockets determined from the Yamaji effect is . . . approximately 1.3% of the Brillouin zone area"

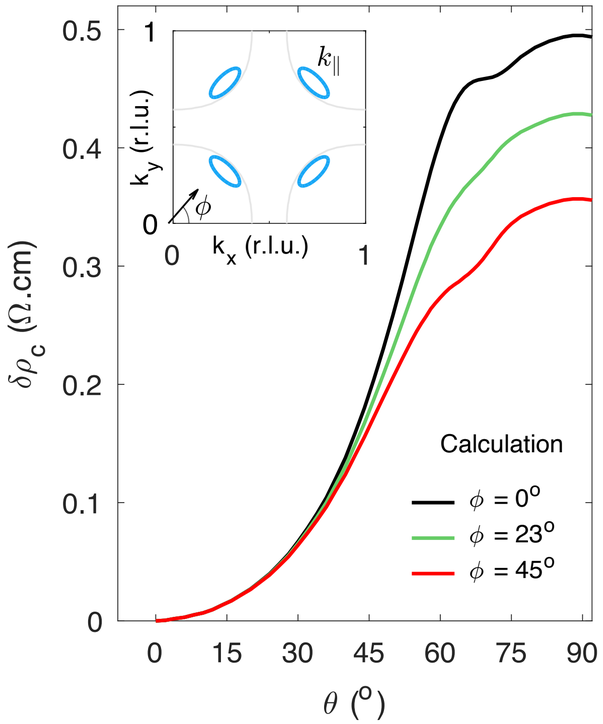
Observation of the Yamaji effect in a cuprate superconductor

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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"

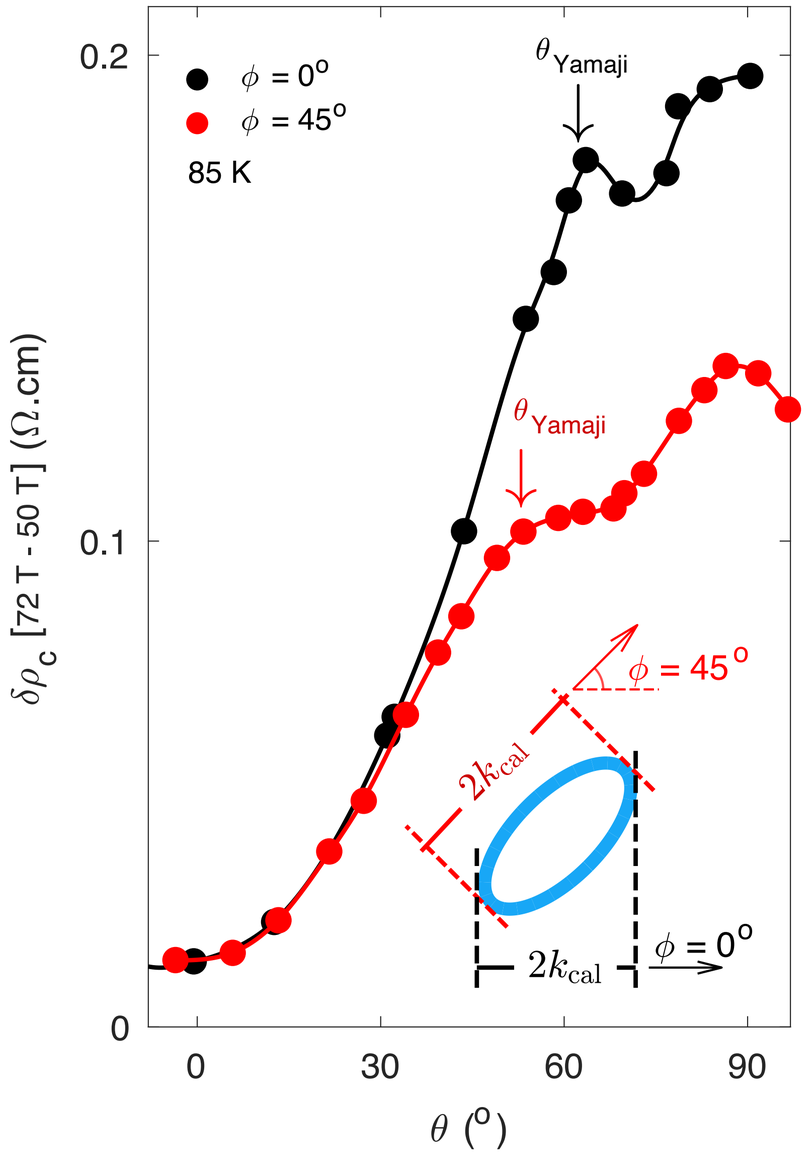
FL* pocket fraction $= p/8 = 1.25\%$!
Fluctuating AF metal fraction $= p/4 = 2.5\%$.

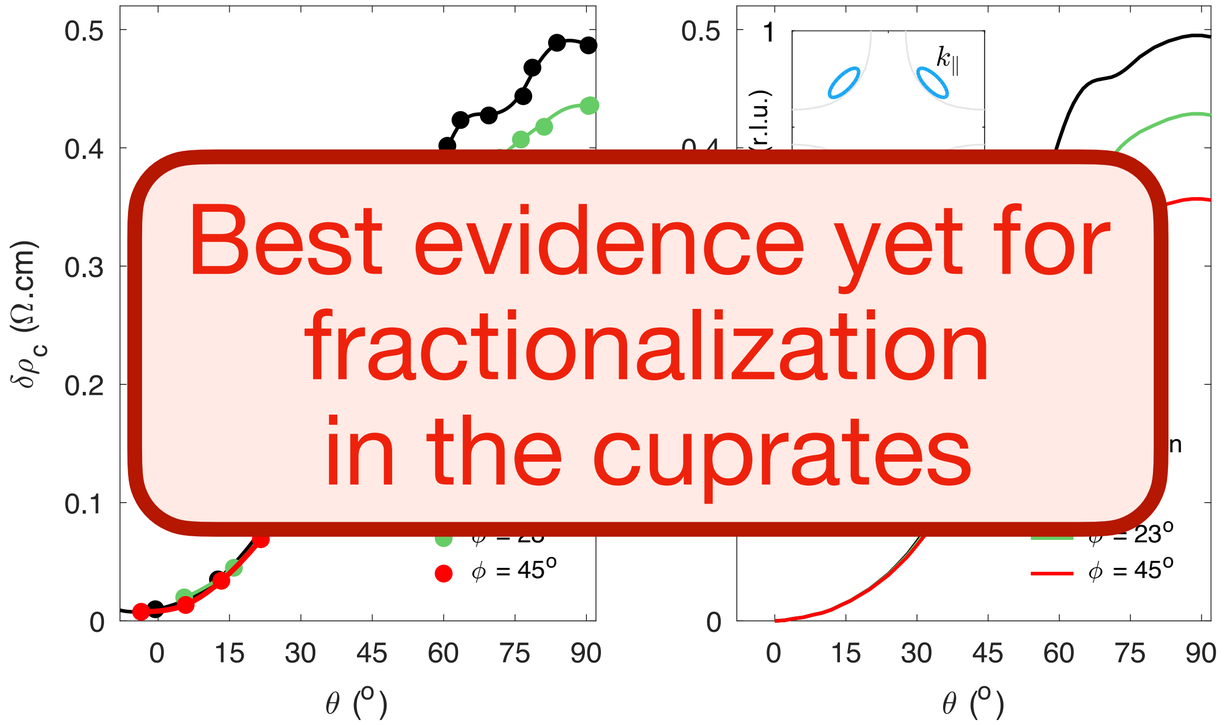
($p/8$ also in YRZ ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar?)

Observation of the Yamaji effect in a cuprate superconductor

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





Best evidence yet for fractionalization in the cuprates

Doping $p = 0.1$

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

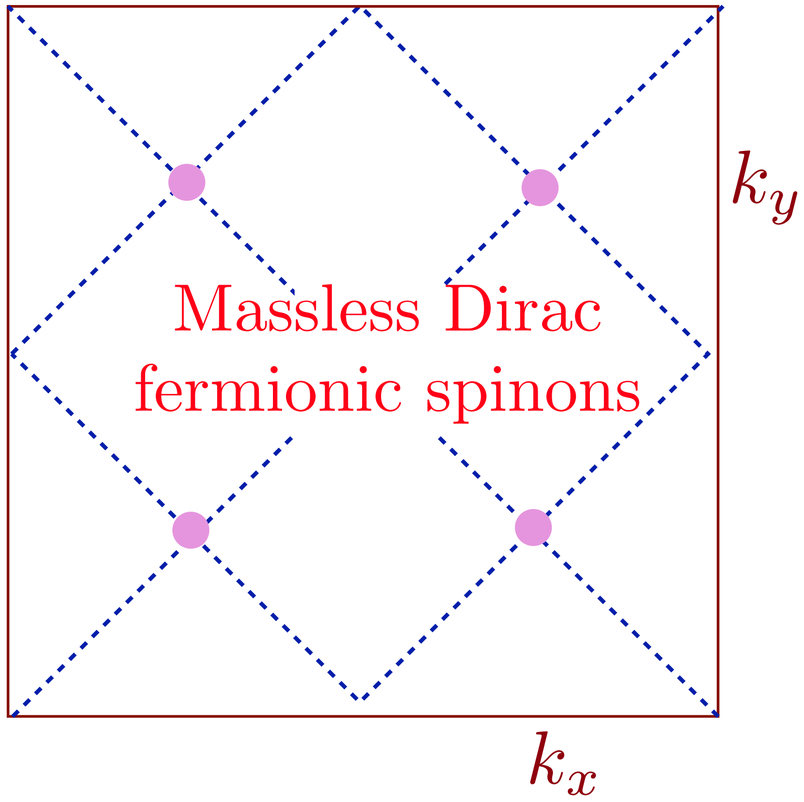
FL* pocket fraction $= p/8 = 1.25\%$!
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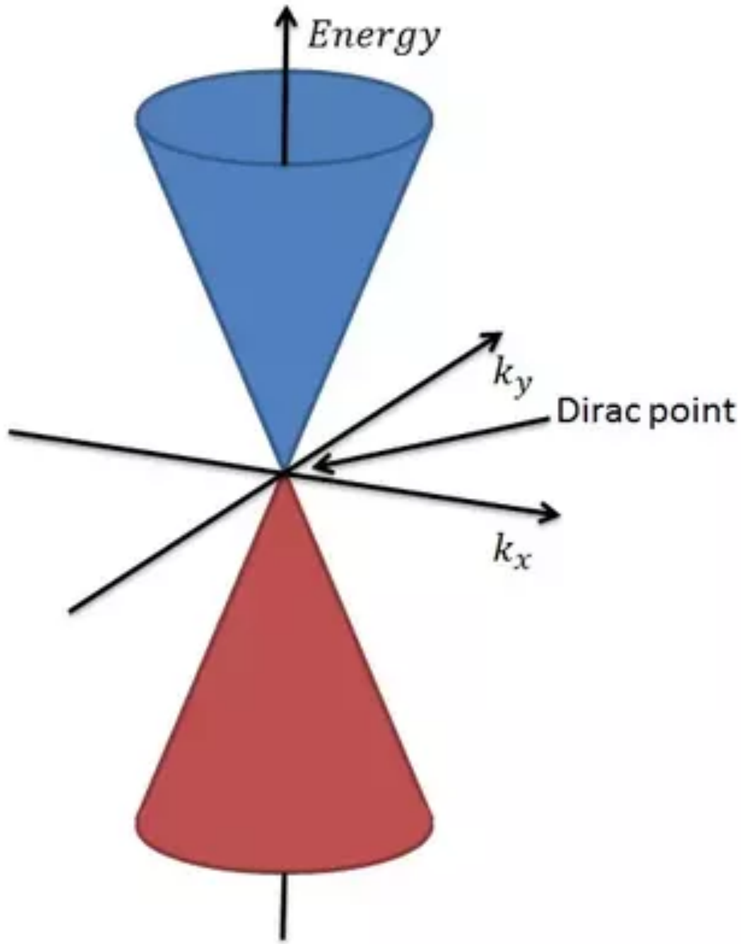
($p/8$ also in YRZ ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar?)

FL* theory:
hole pockets in magnetotransport
and
Fermi arcs in photoemission

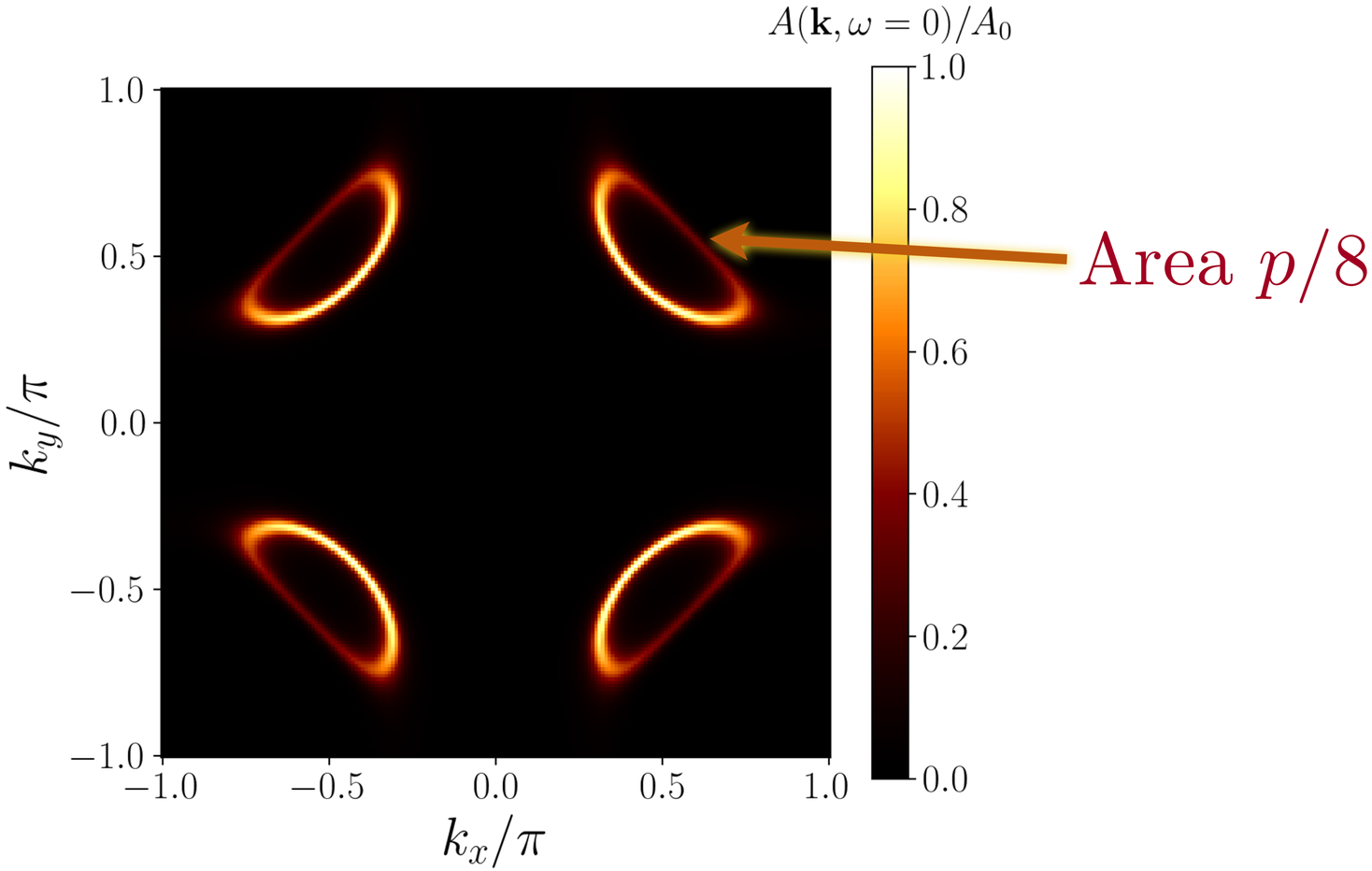
- Identification of spin liquid: critical spin liquid without quasiparticles. One description is a SU(2) gauge theory with $N_f = 2$ massless Dirac spinons.

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)



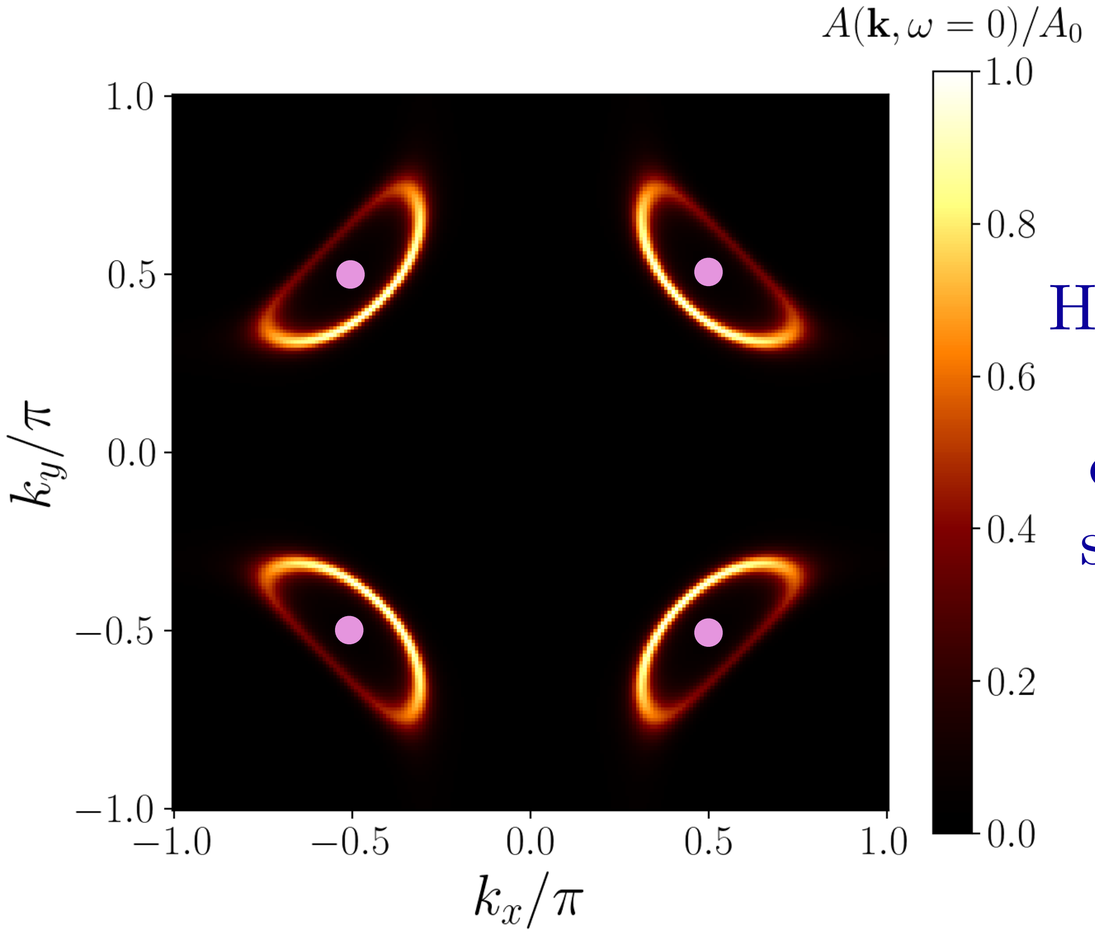


- Dope spin liquid with *holes*, <u>not</u> holons.
  The Ancilla Layer Model (ALM) enables a theory of FL* hole pockets for a general spin liquid.



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.

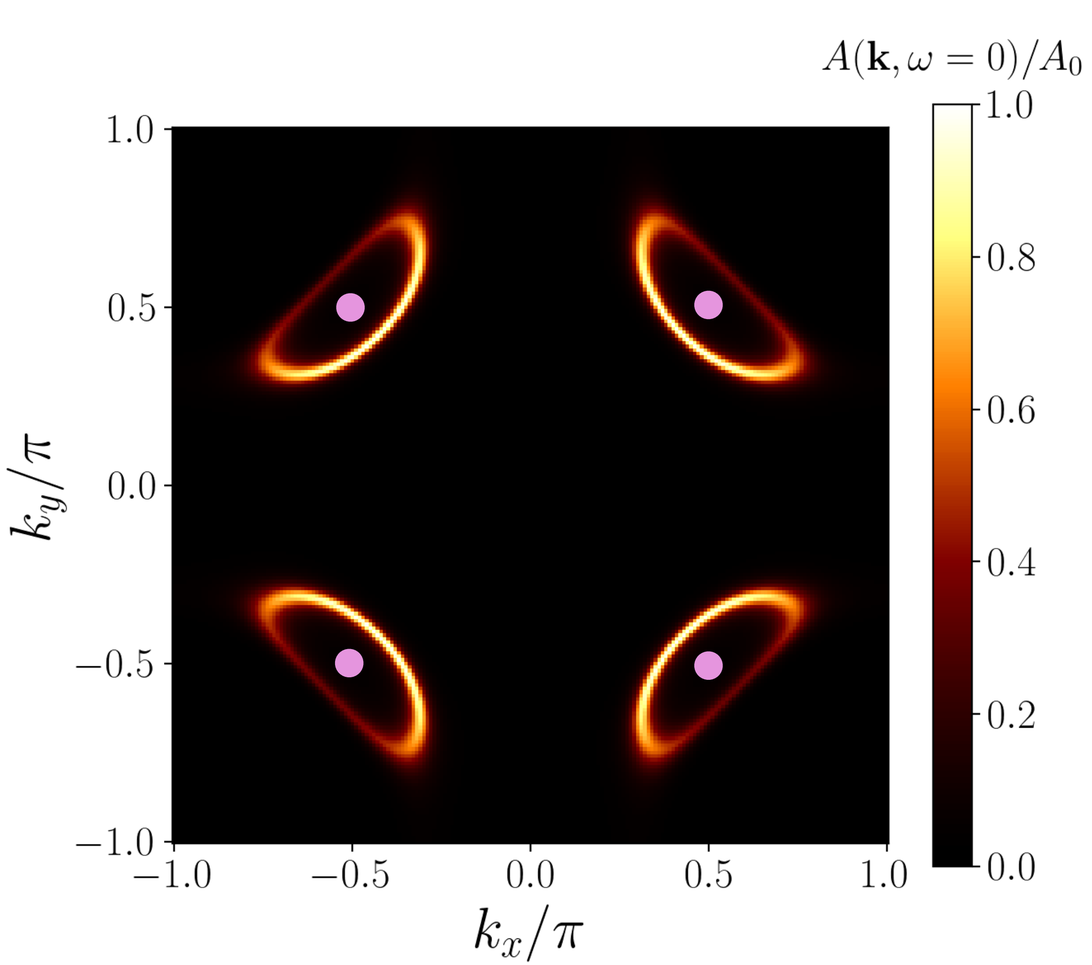


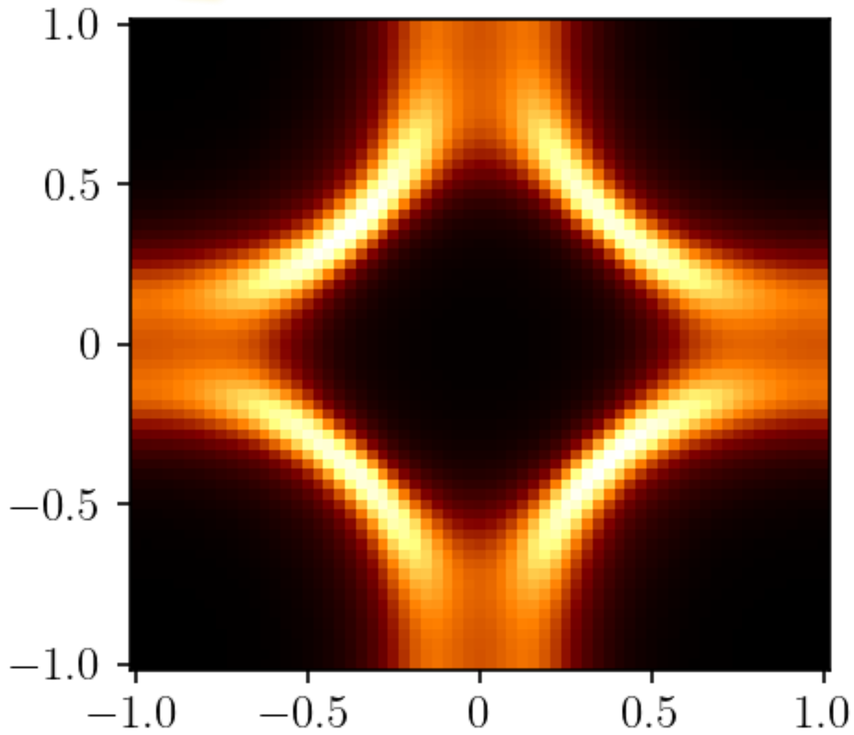
Hole pockets and decoupled spin liquid

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)

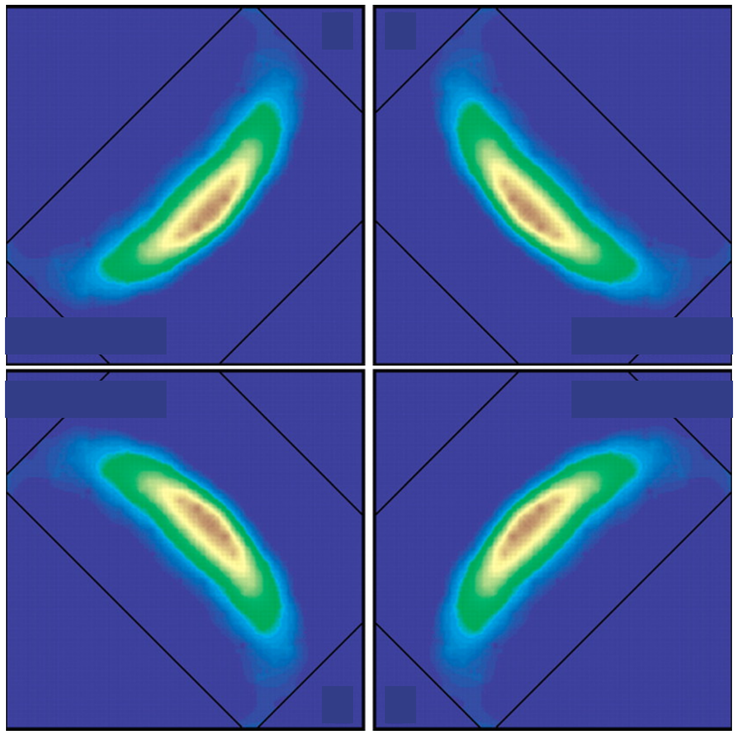
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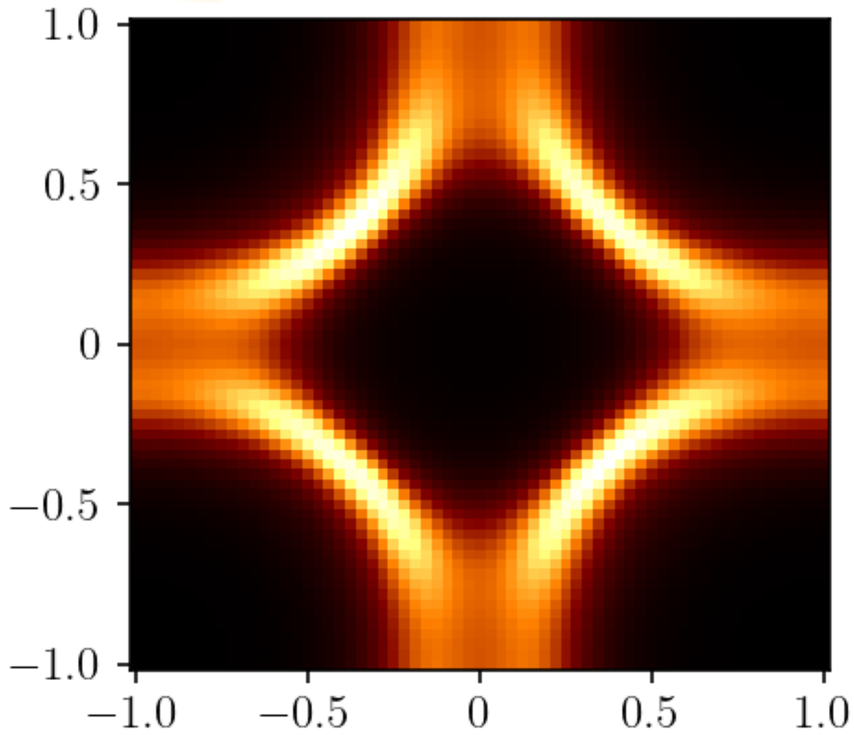




H. Pandey, M. Christos, P.M. Bonetti, R. Shanker, S. Sharma, S.S., arXiv:2507.05336

- 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.

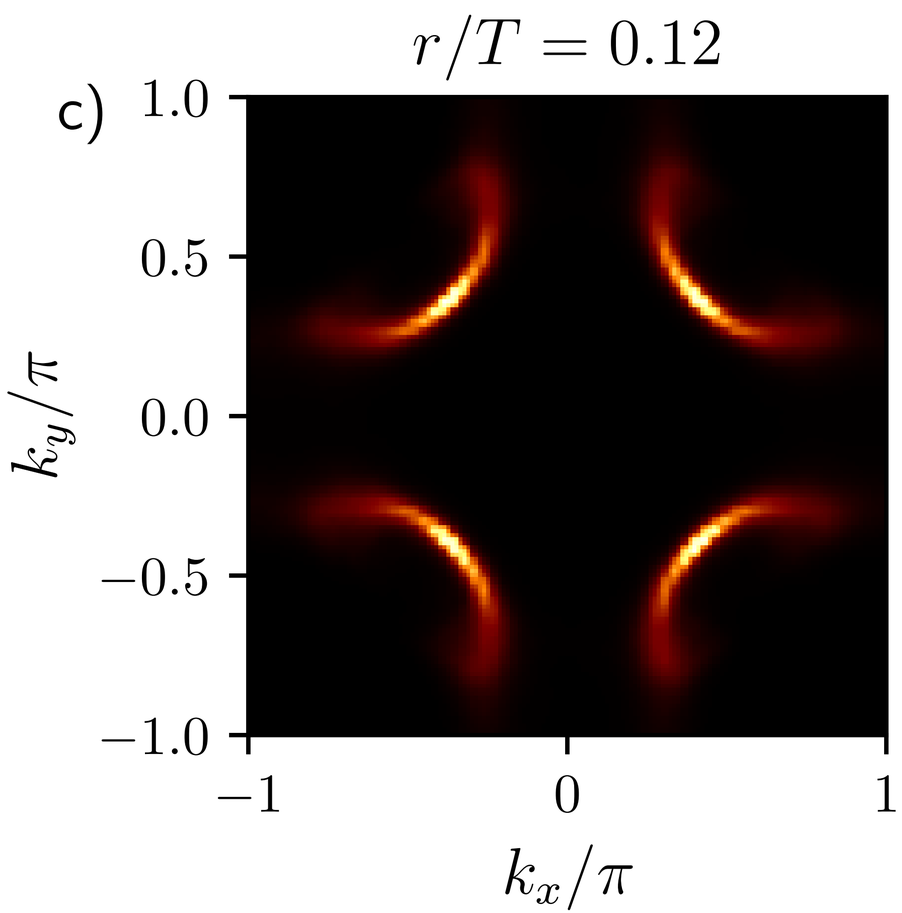


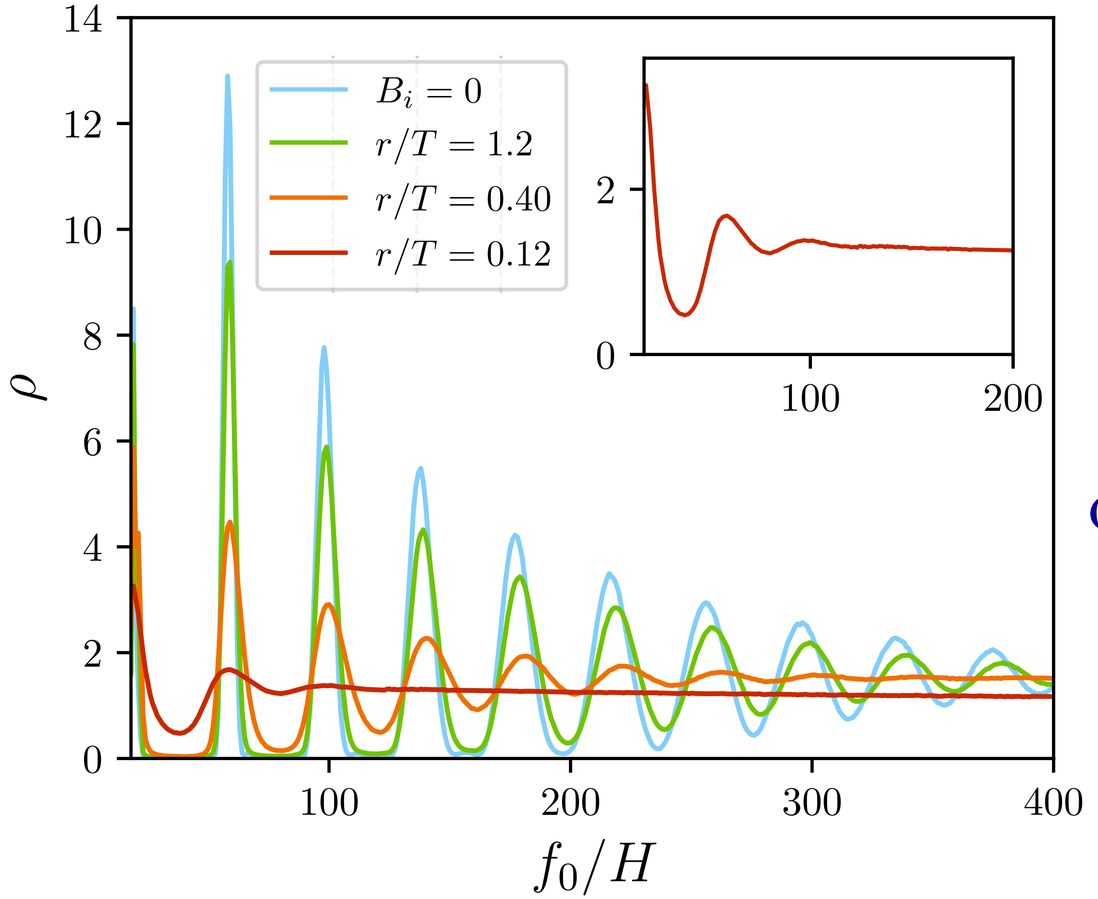


Kyle M. Shen, . . . Z.-X. Shen, Science **307**, 901 (2005)

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

- 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.



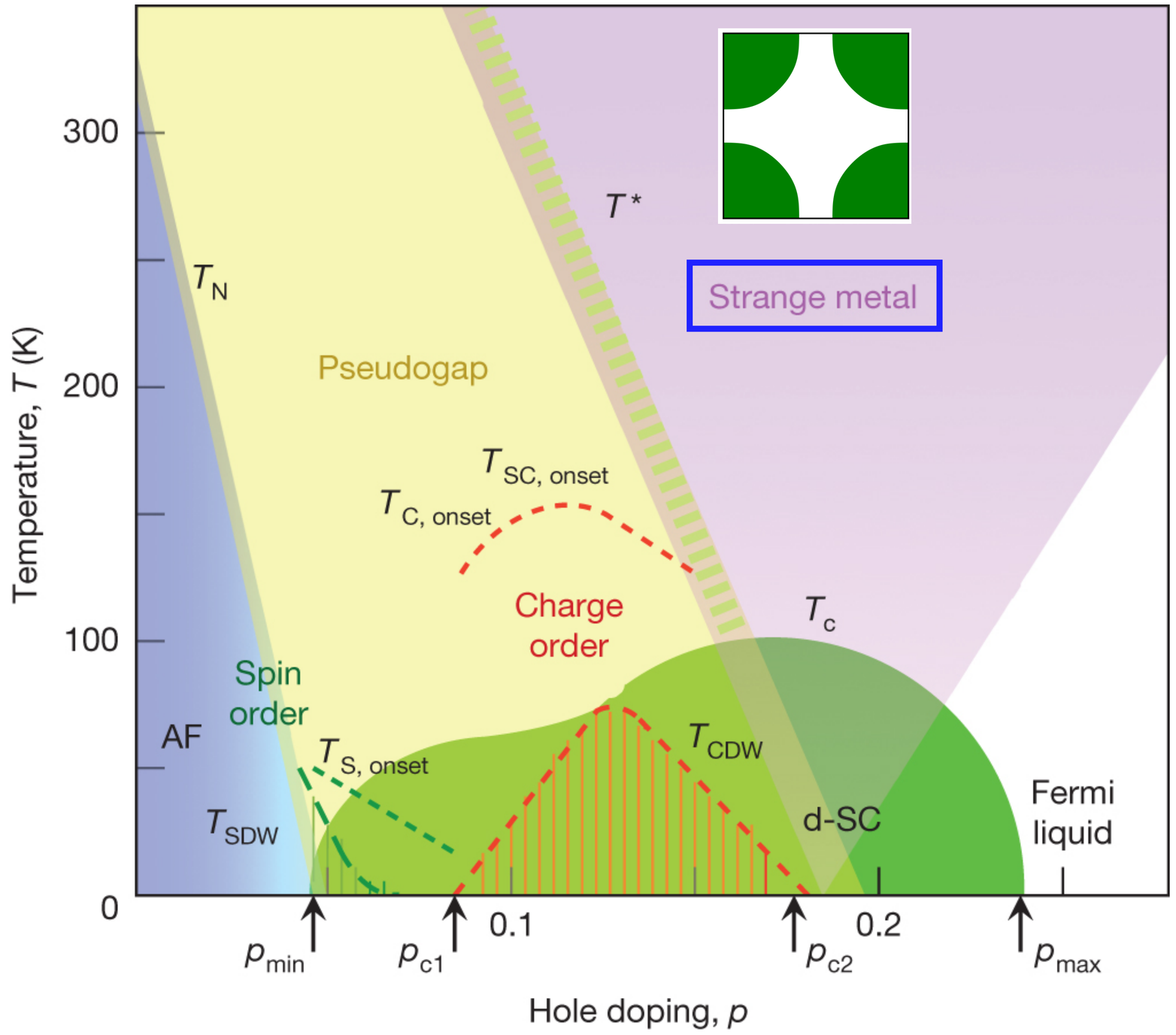


Fermi arcs co-exist with quantum oscillations of hole pockets of area $p/8$.

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

Critical quantum charge liquids: From SYK to strange metals

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

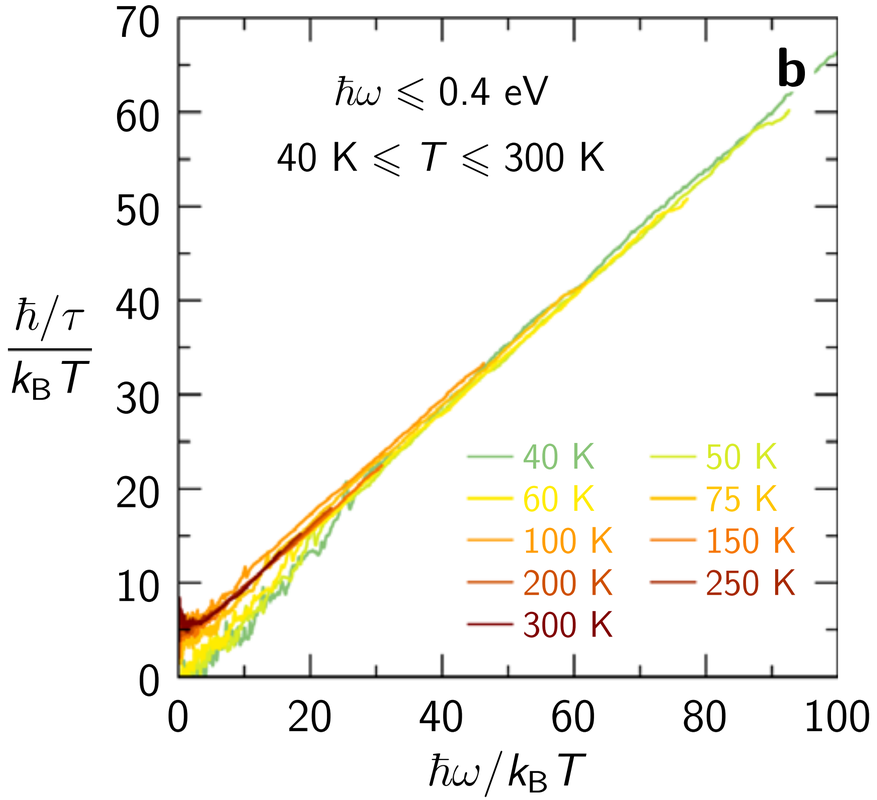


Planckian dynamics !

of large Fermi surface

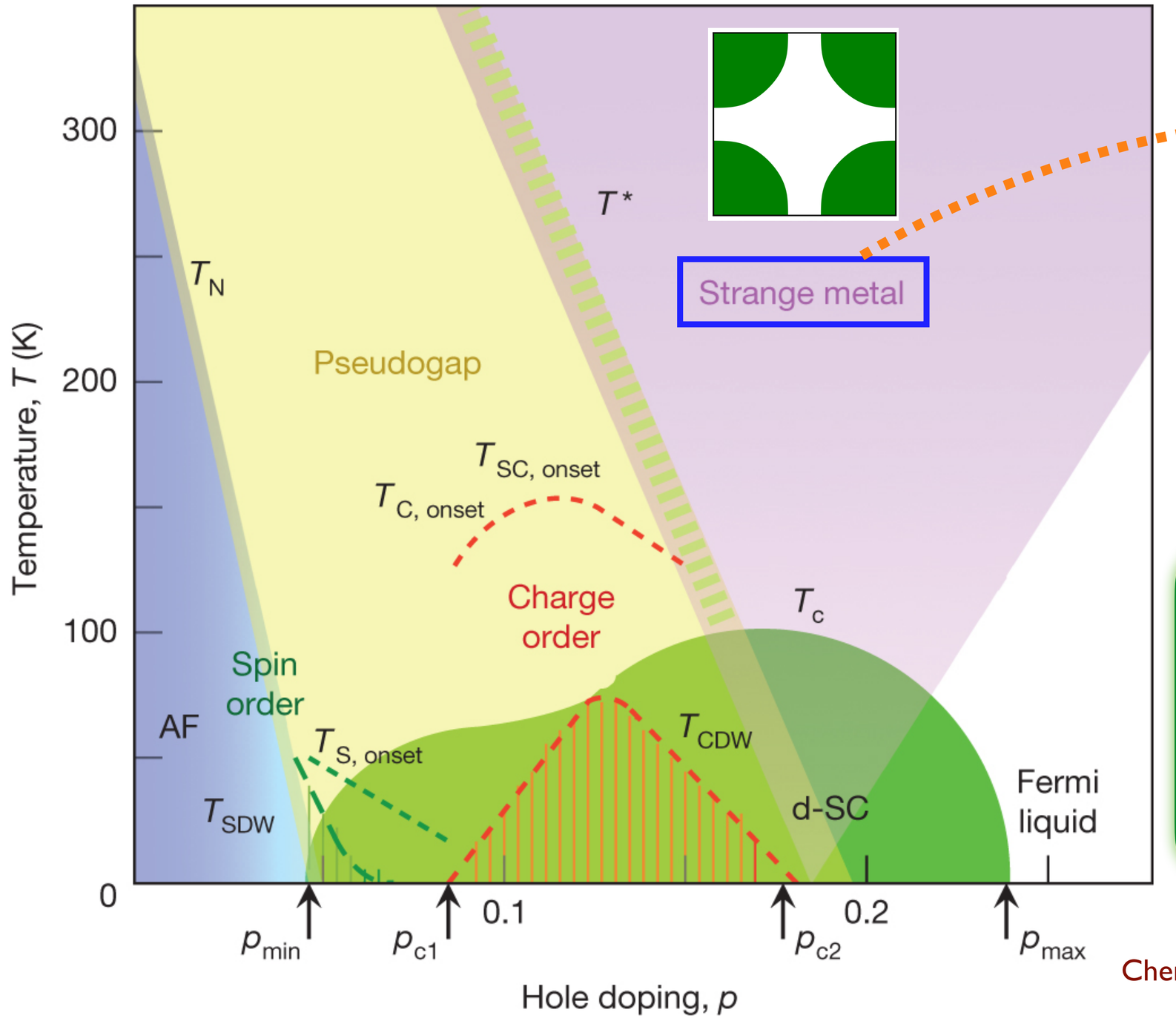
Electron scattering time τ from optical conductivity

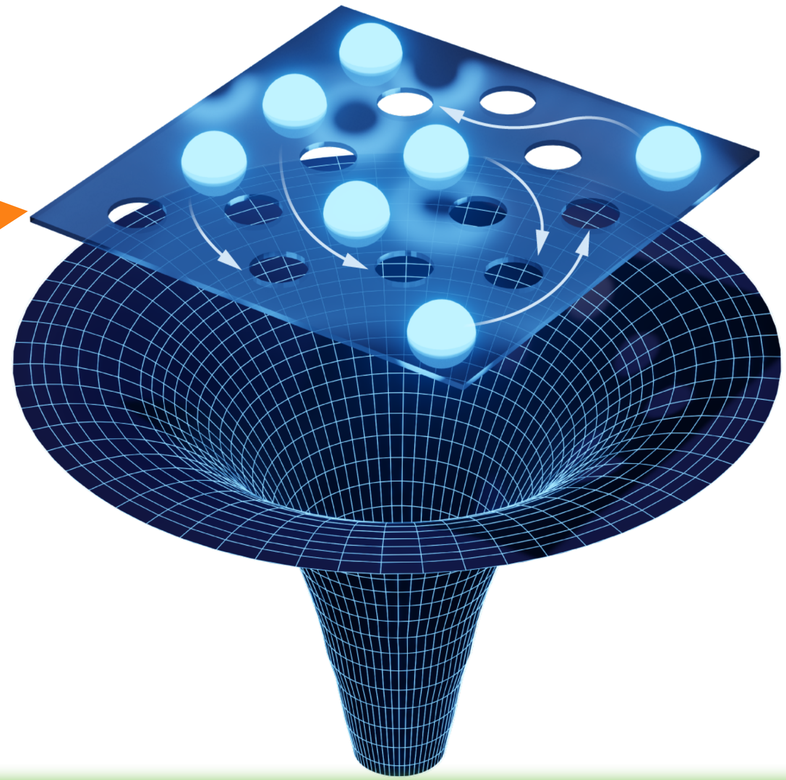
$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$



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)



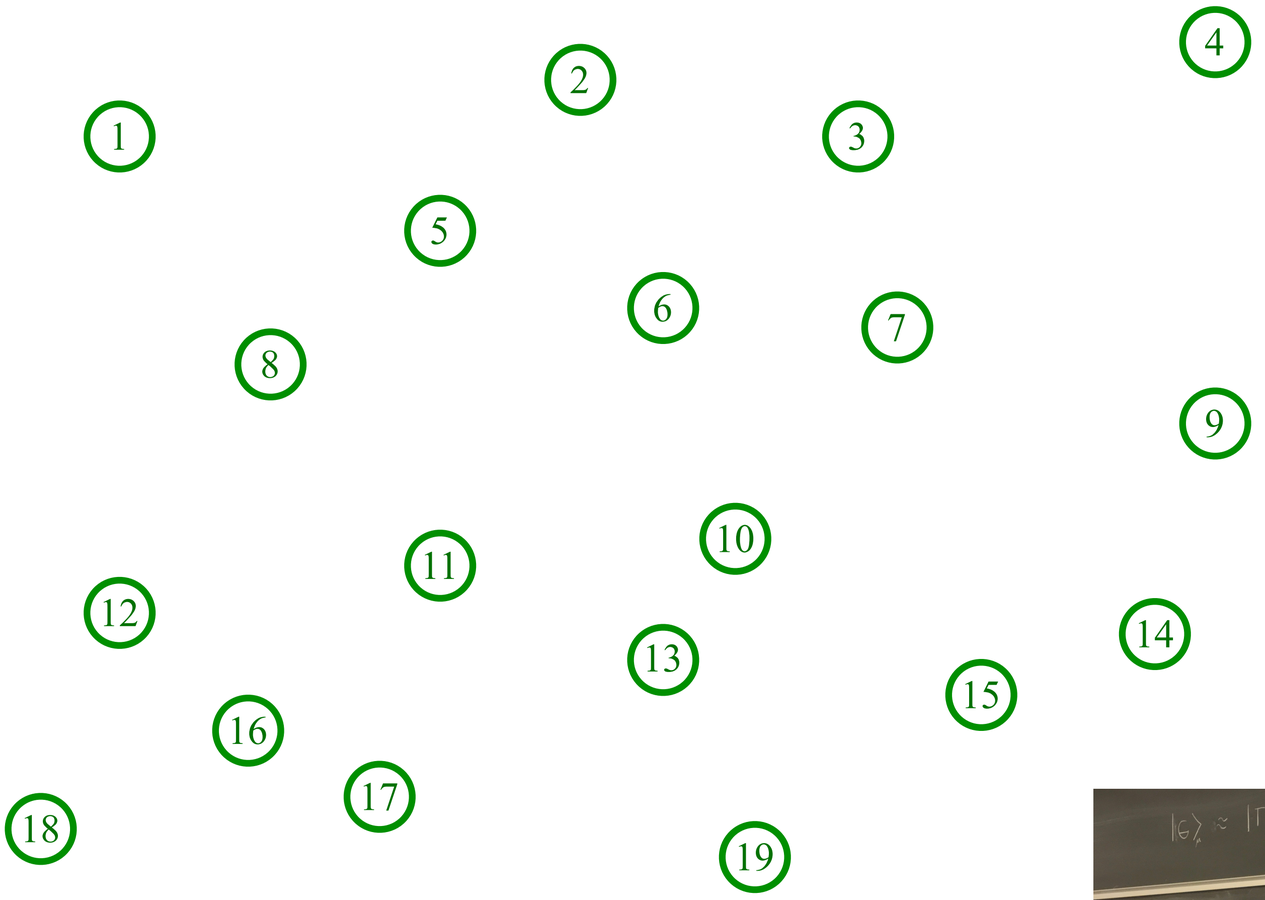


Will explain with a local, two-dimensional extension of the Sachdev-Ye-Kitaev (SYK) model of mobile electrons, a *critical charge liquid*

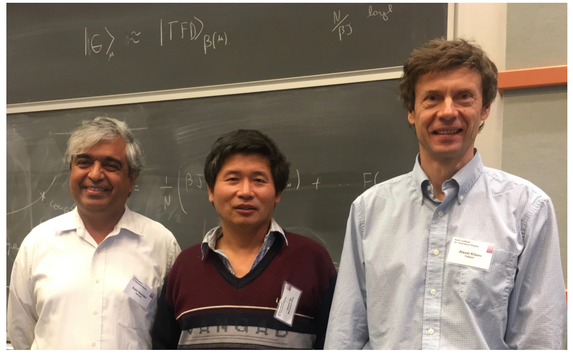
Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. Sachdev, *Science* **381**, 790 (2023);
Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentinis, Jorg Schmalian, S.S., Ilya Esterlis, PRL **133**, 186502 (2024)

The SYK model

Sachdev, Ye (1993); Kitaev (2015)

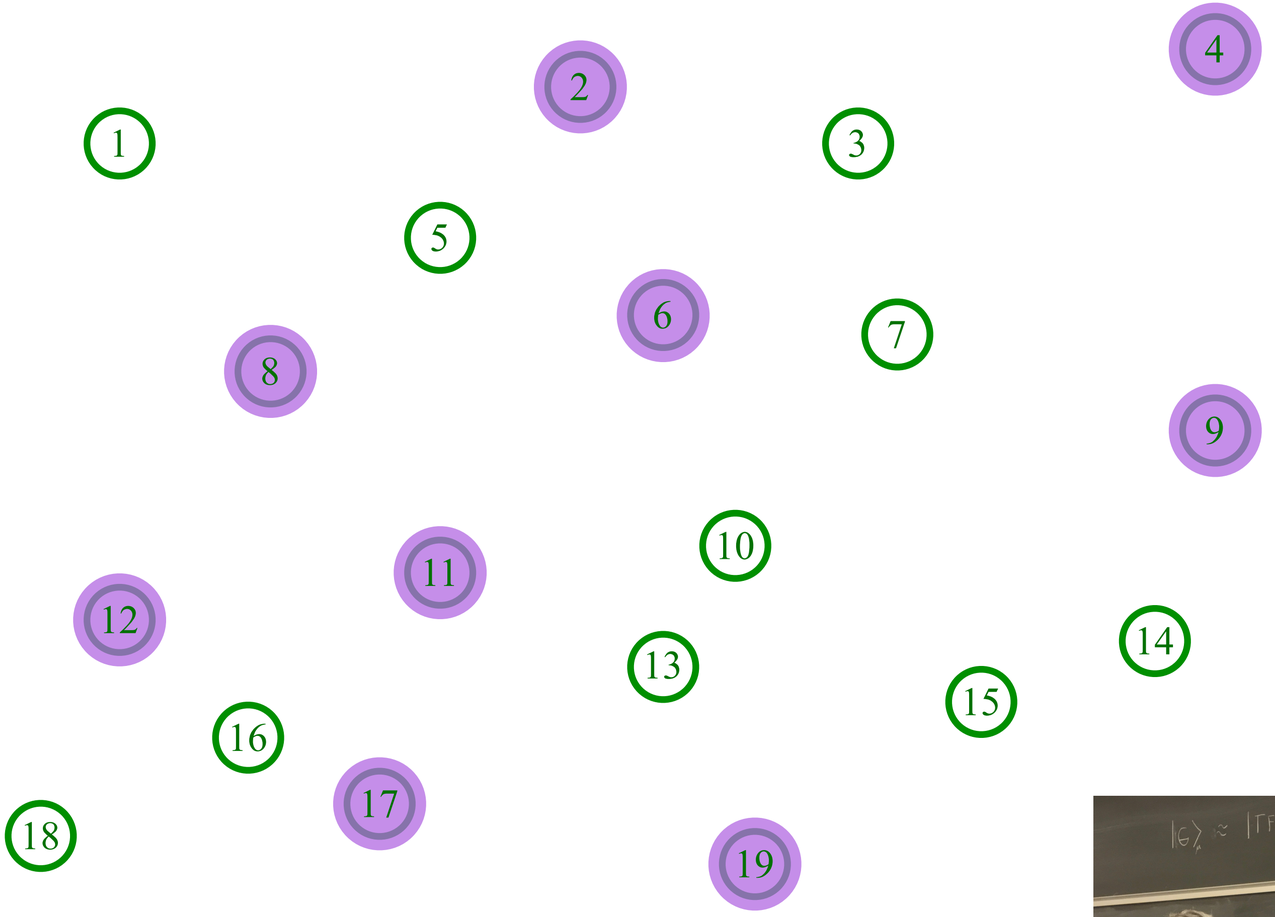


Pick a set of random positions

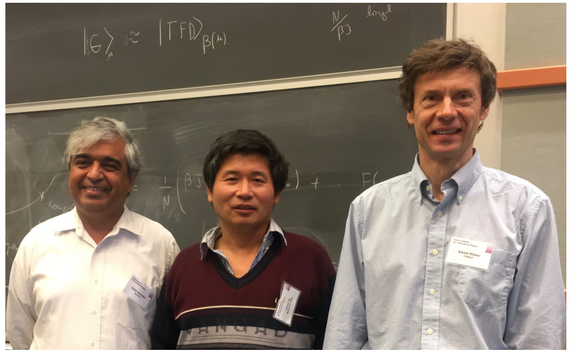


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



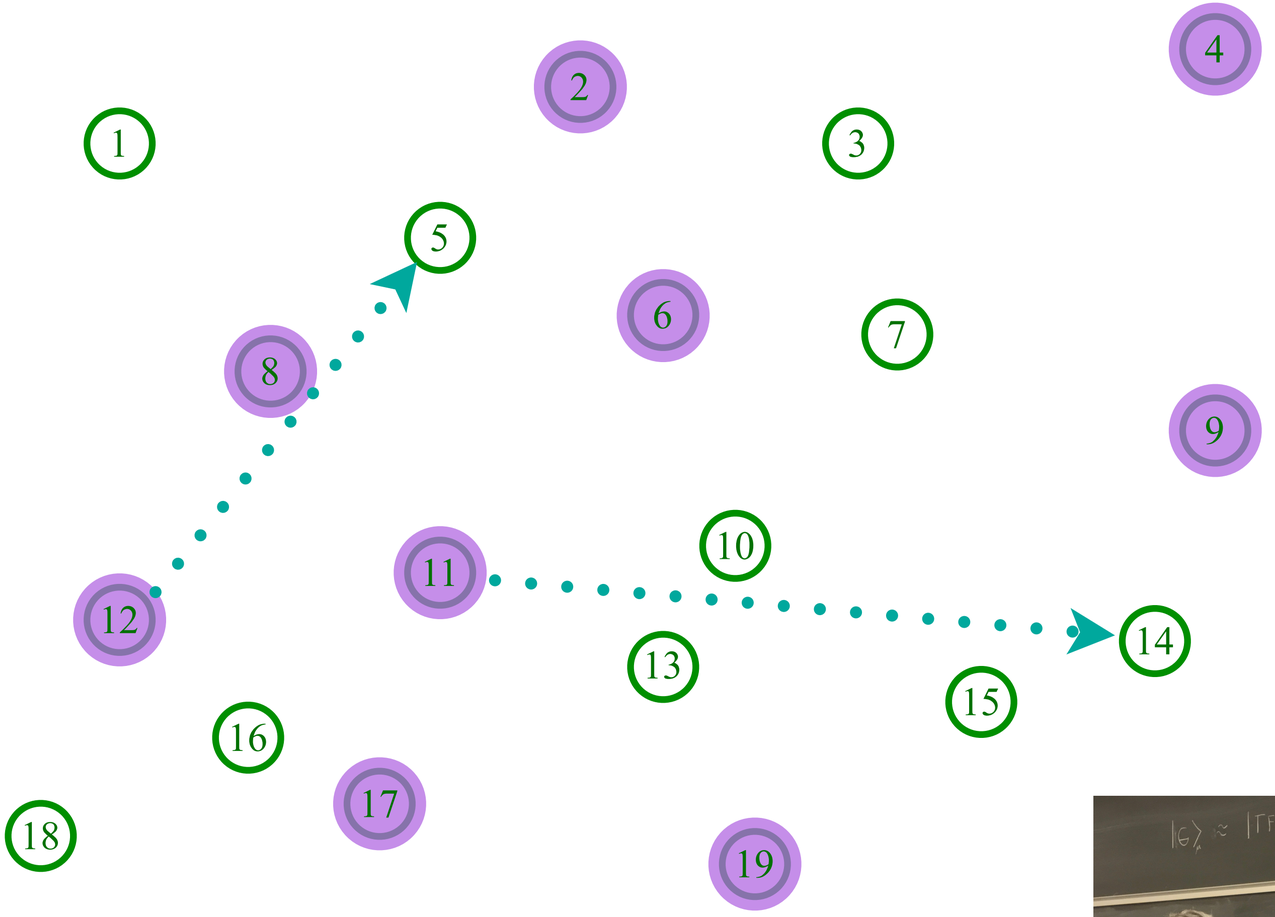
Place electrons randomly on some sites



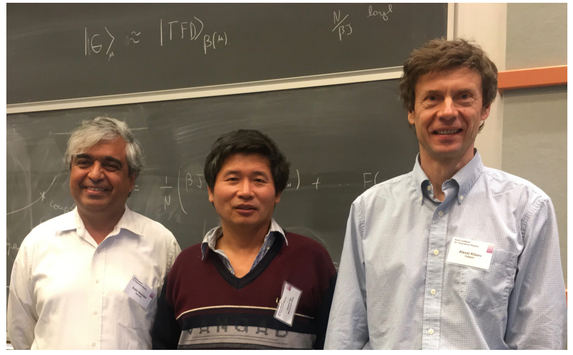
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{11,12;5,14}$$



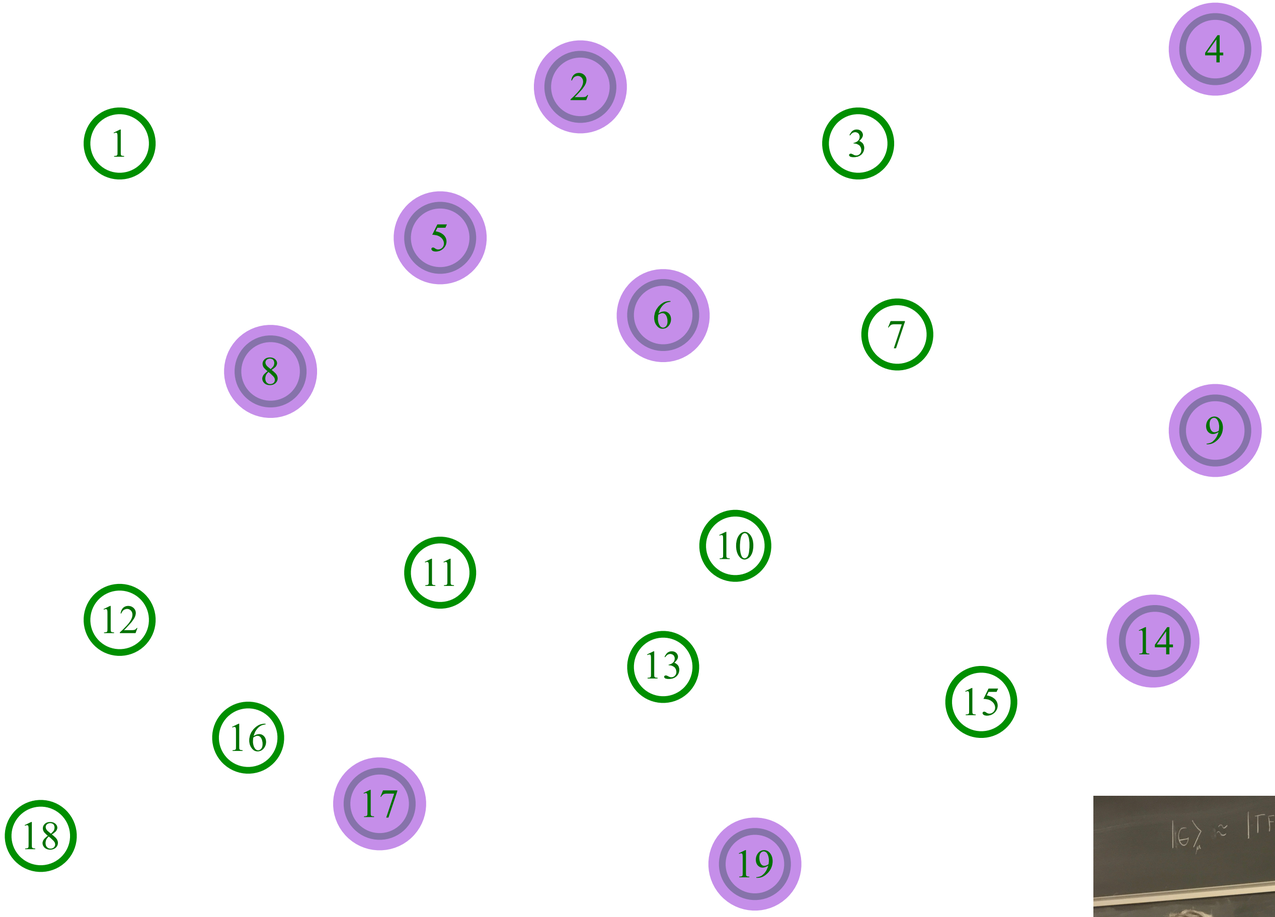
Place electrons randomly on some sites



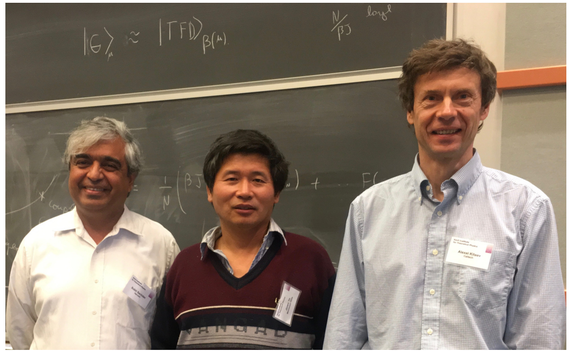
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Sachdev, Ye (1993); Kitaev (2015)

$U_{11,12;5,14}$



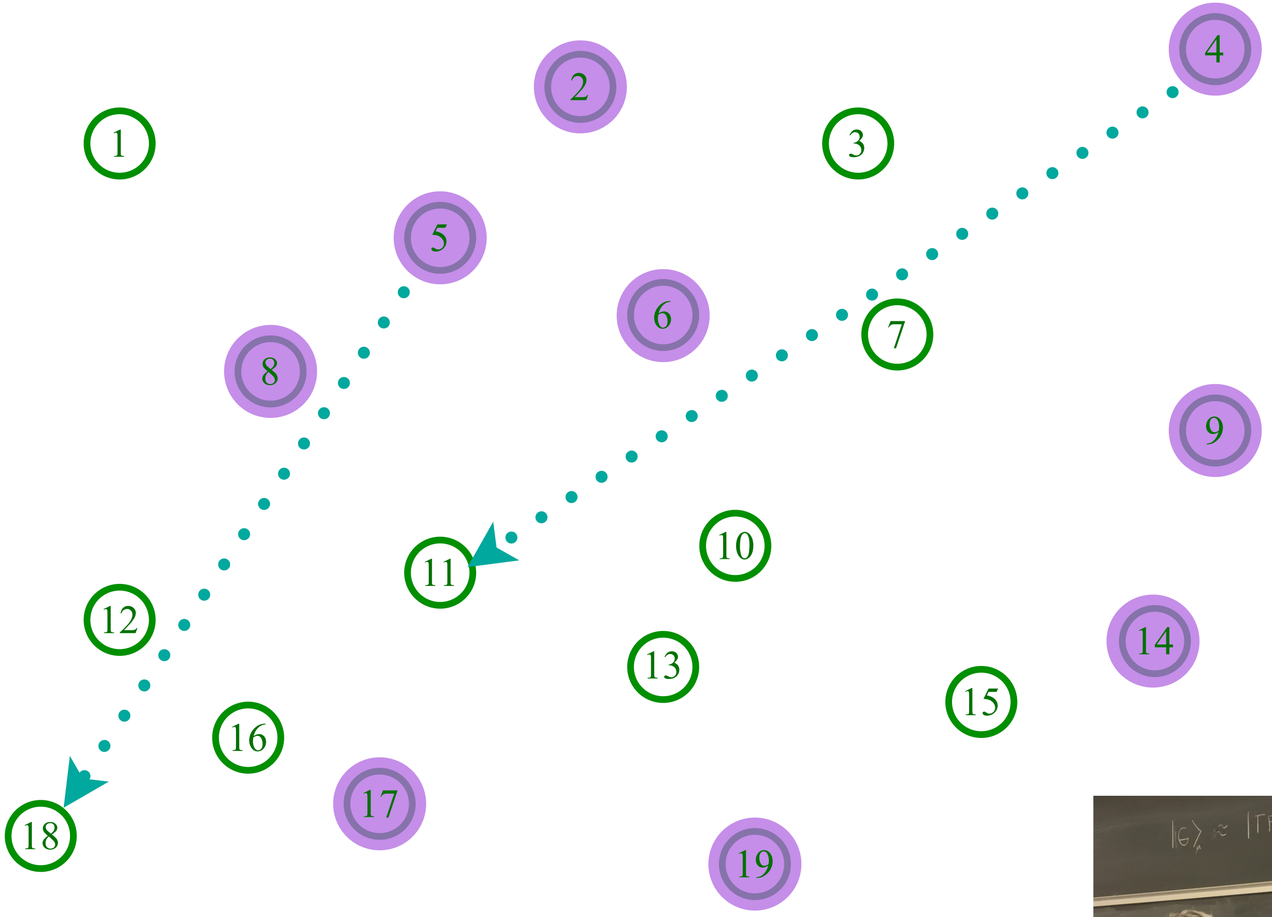
Entangle electrons pairwise randomly



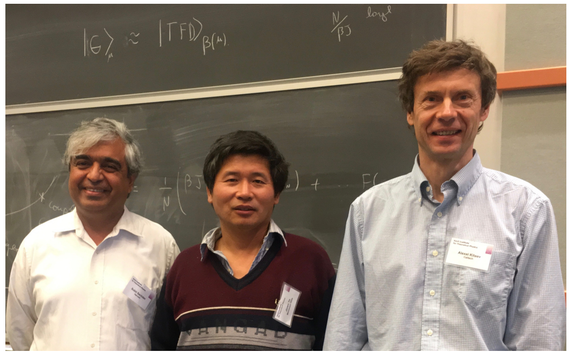
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$U_{4,5;11,18}$



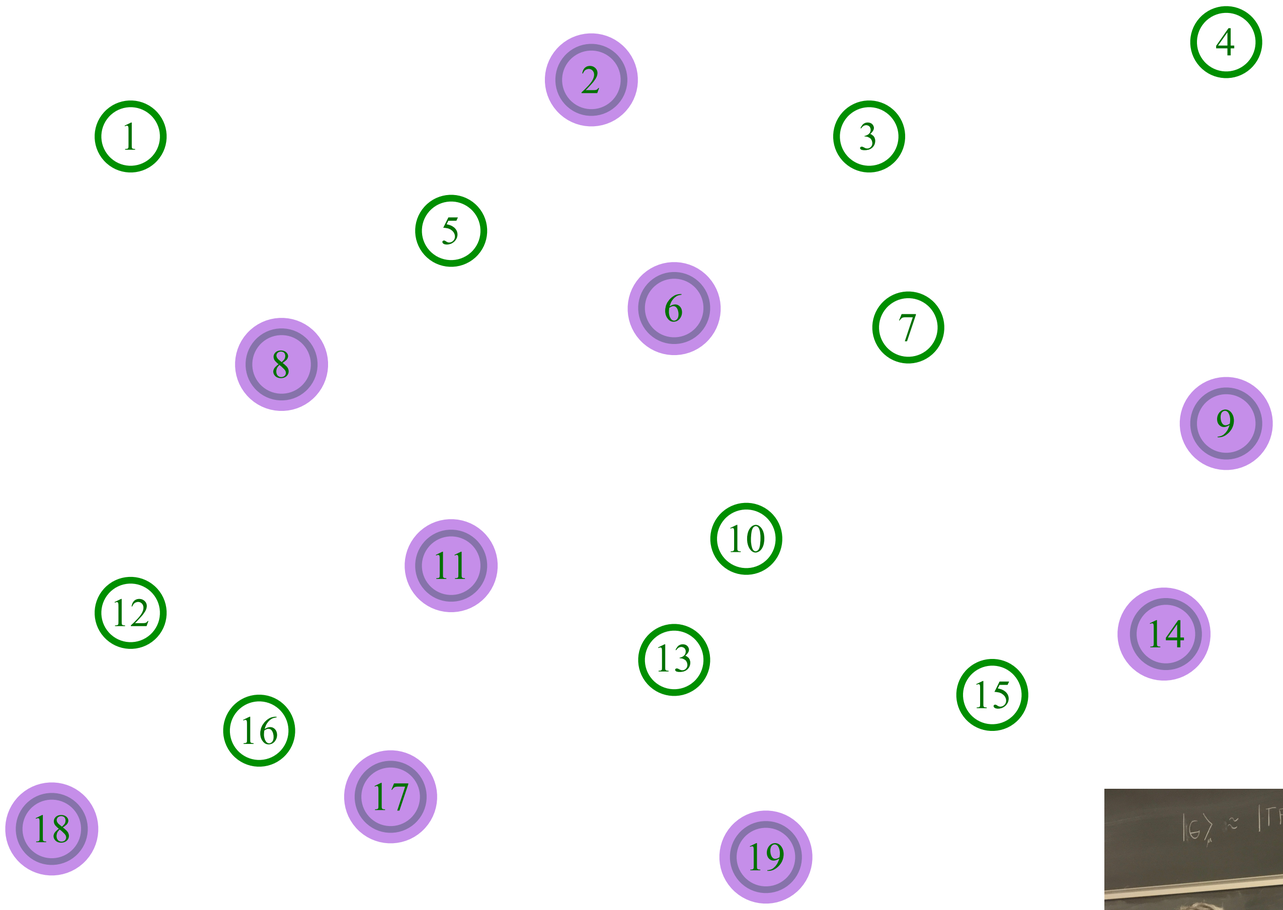
Entangle electrons pairwise randomly



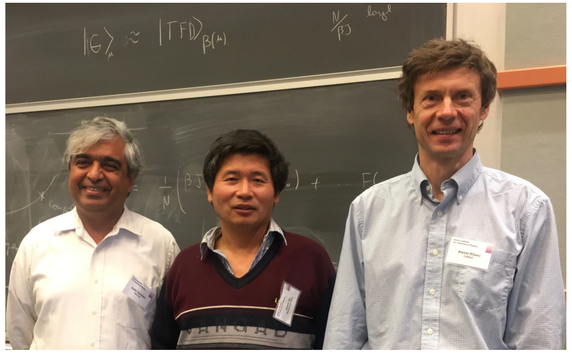
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$U_{4,5;11,18}$



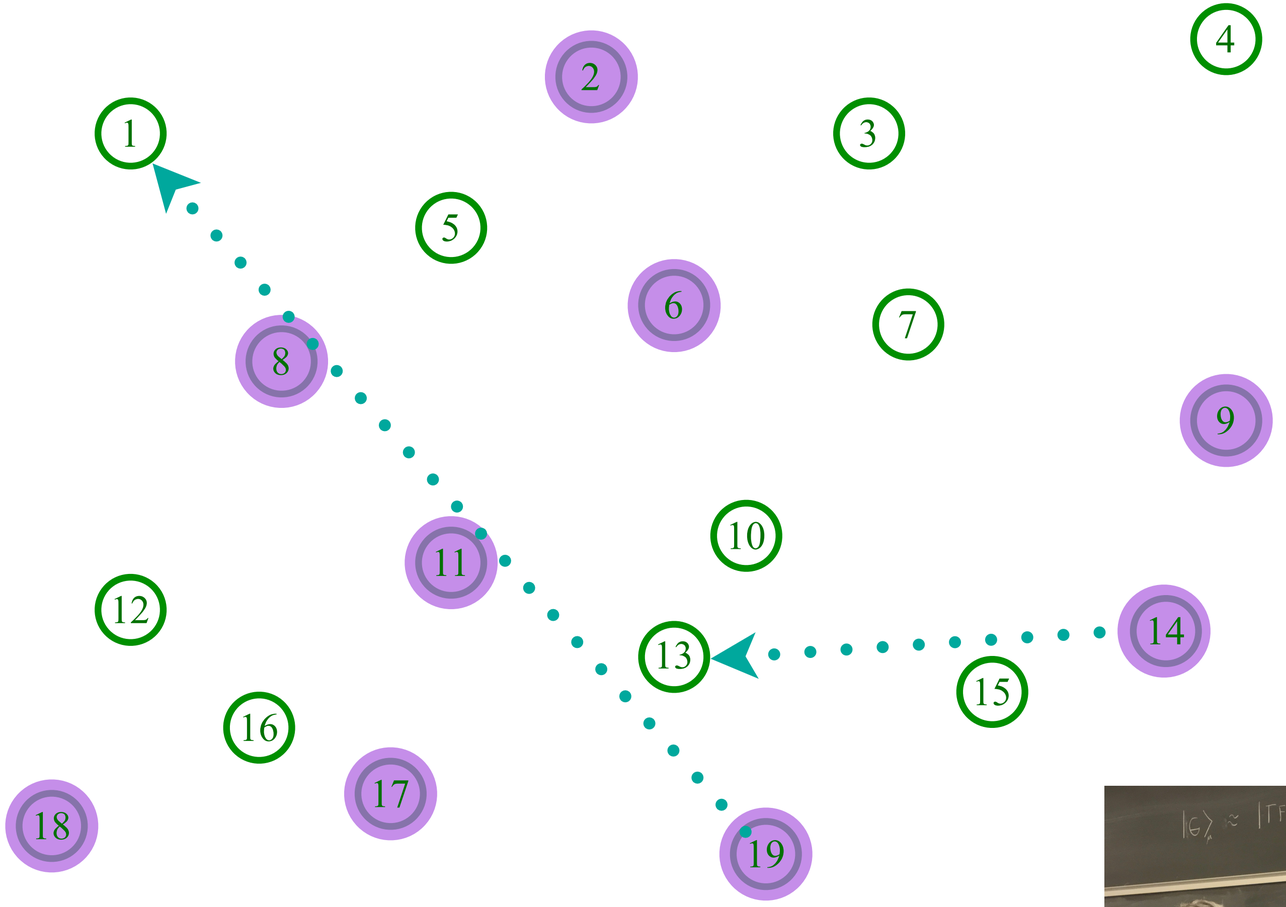
Entangle electrons pairwise randomly



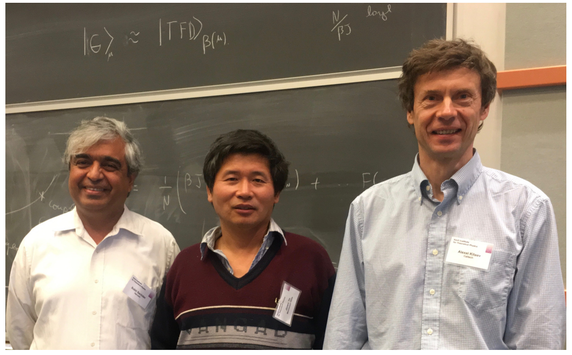
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{14,19;1,13}$$



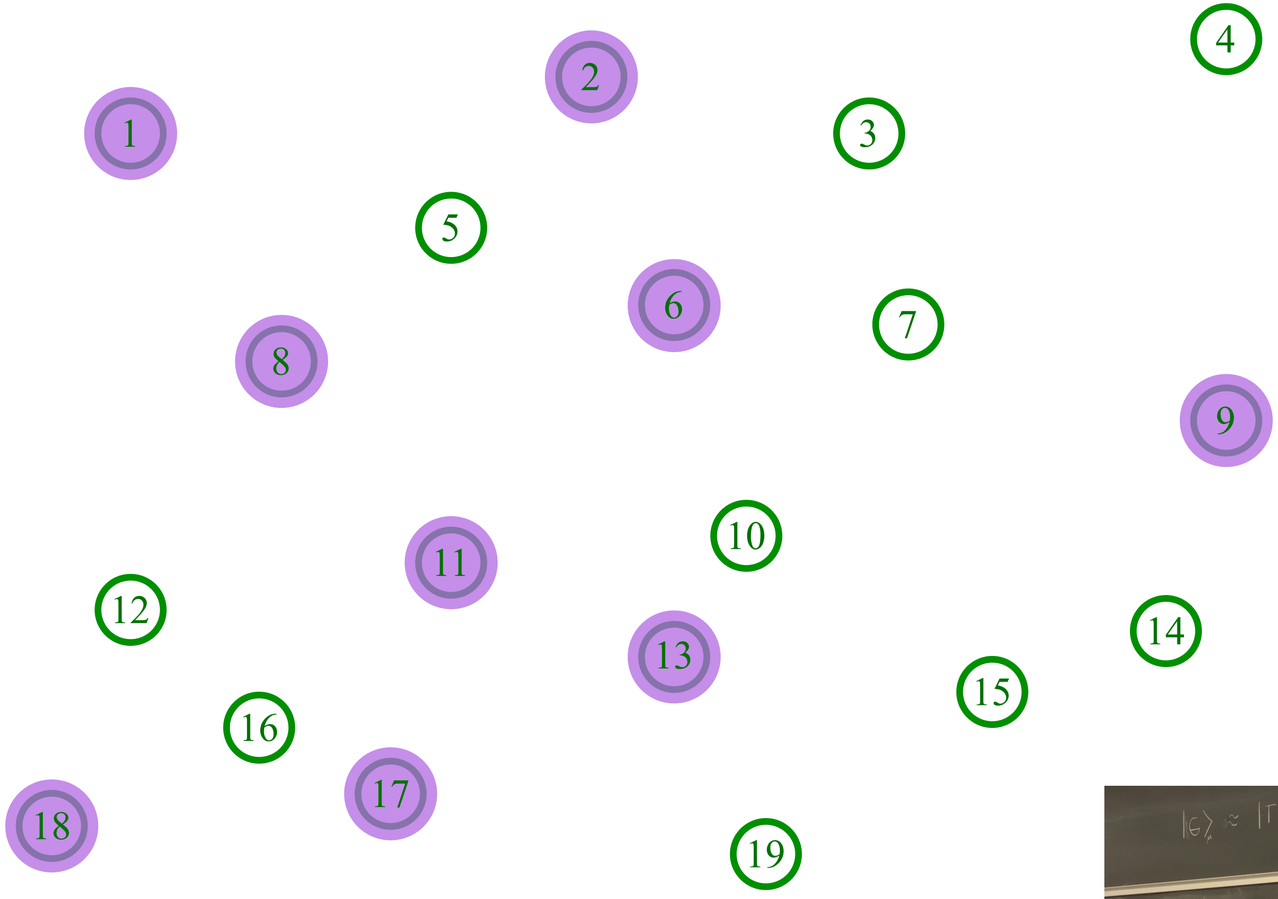
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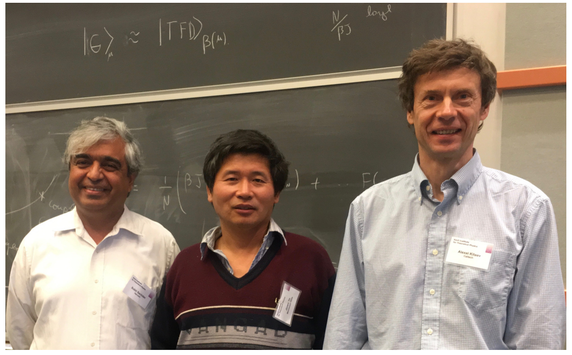
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{14,19;1,13}$$



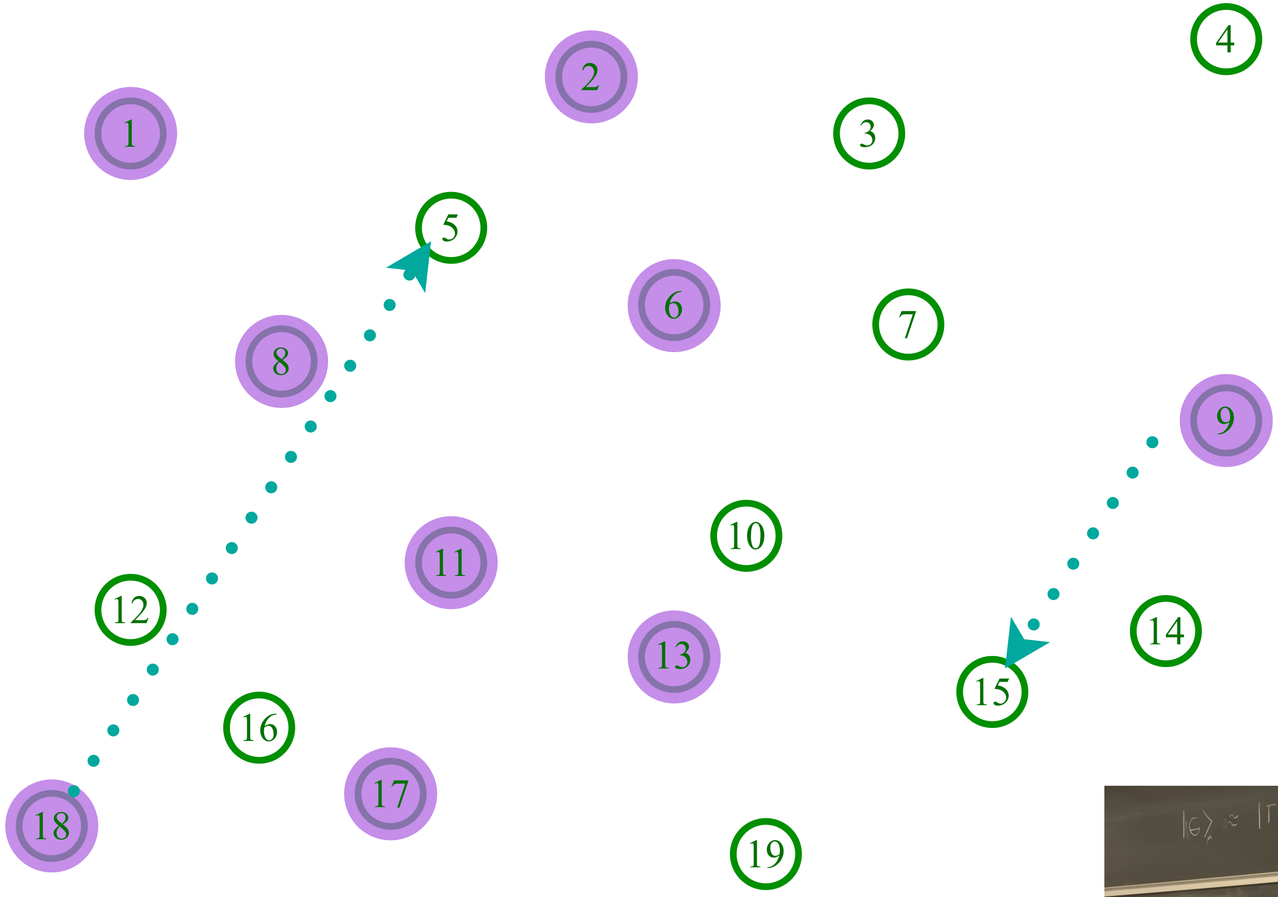
Entangle electrons pairwise randomly



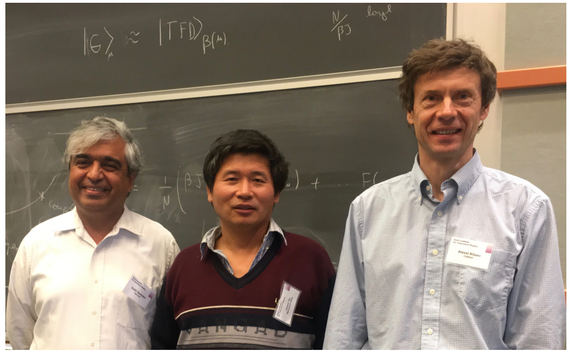
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$U_{9,18;5,15}$



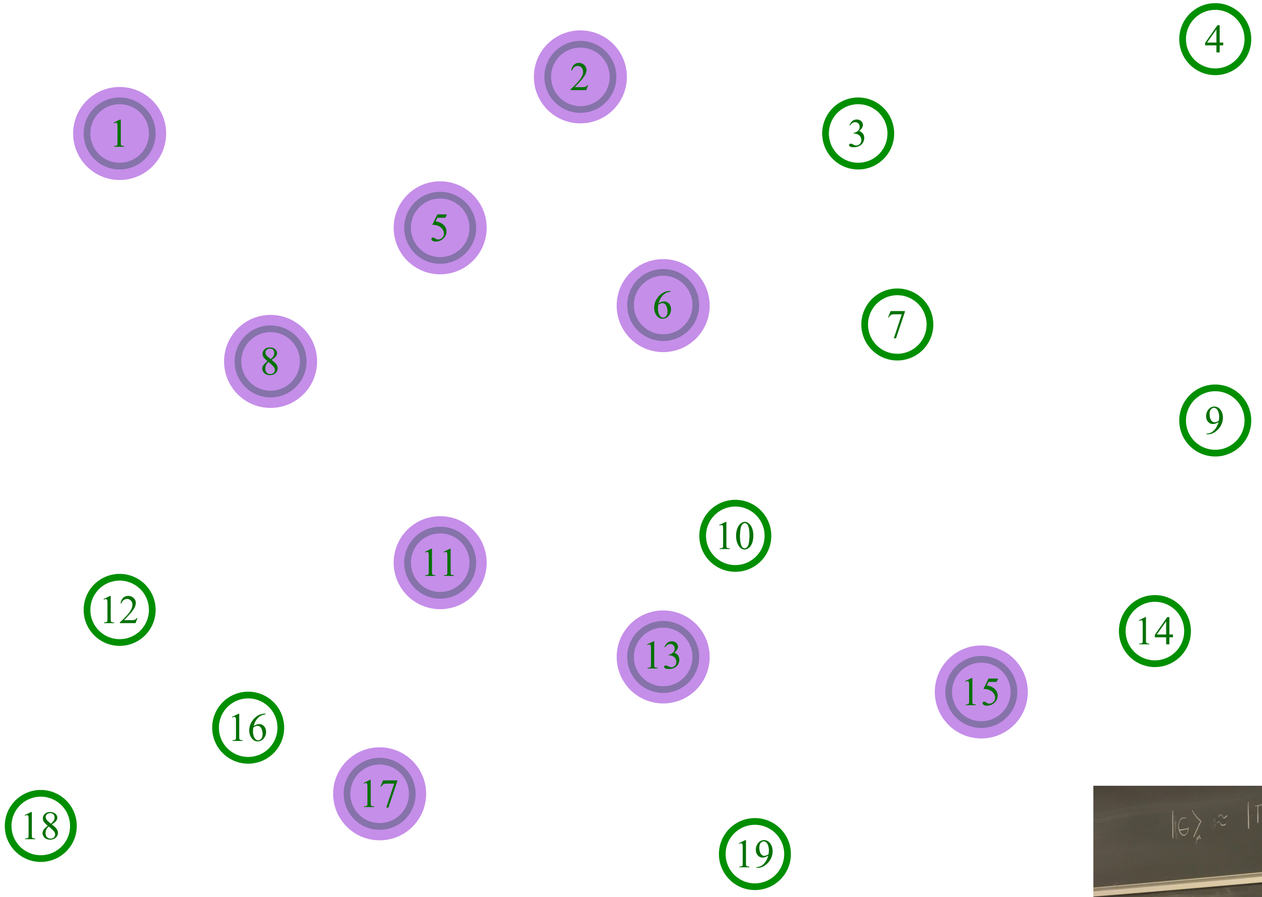
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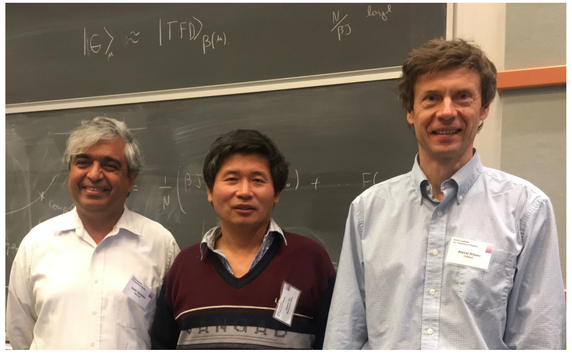
The SYK model

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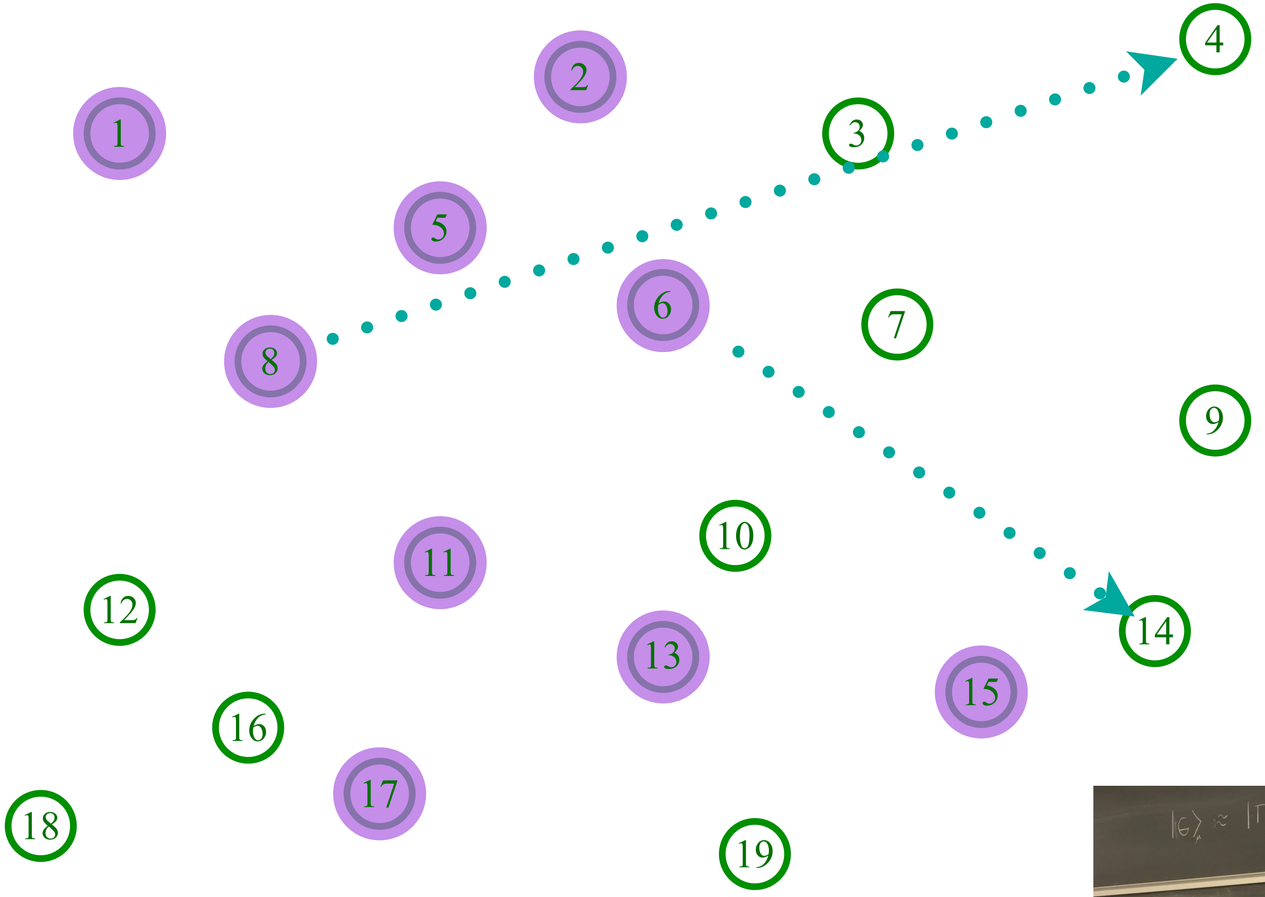
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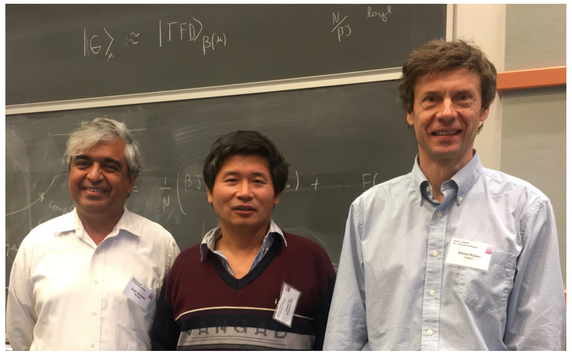
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$U_{6,8;4,14}$



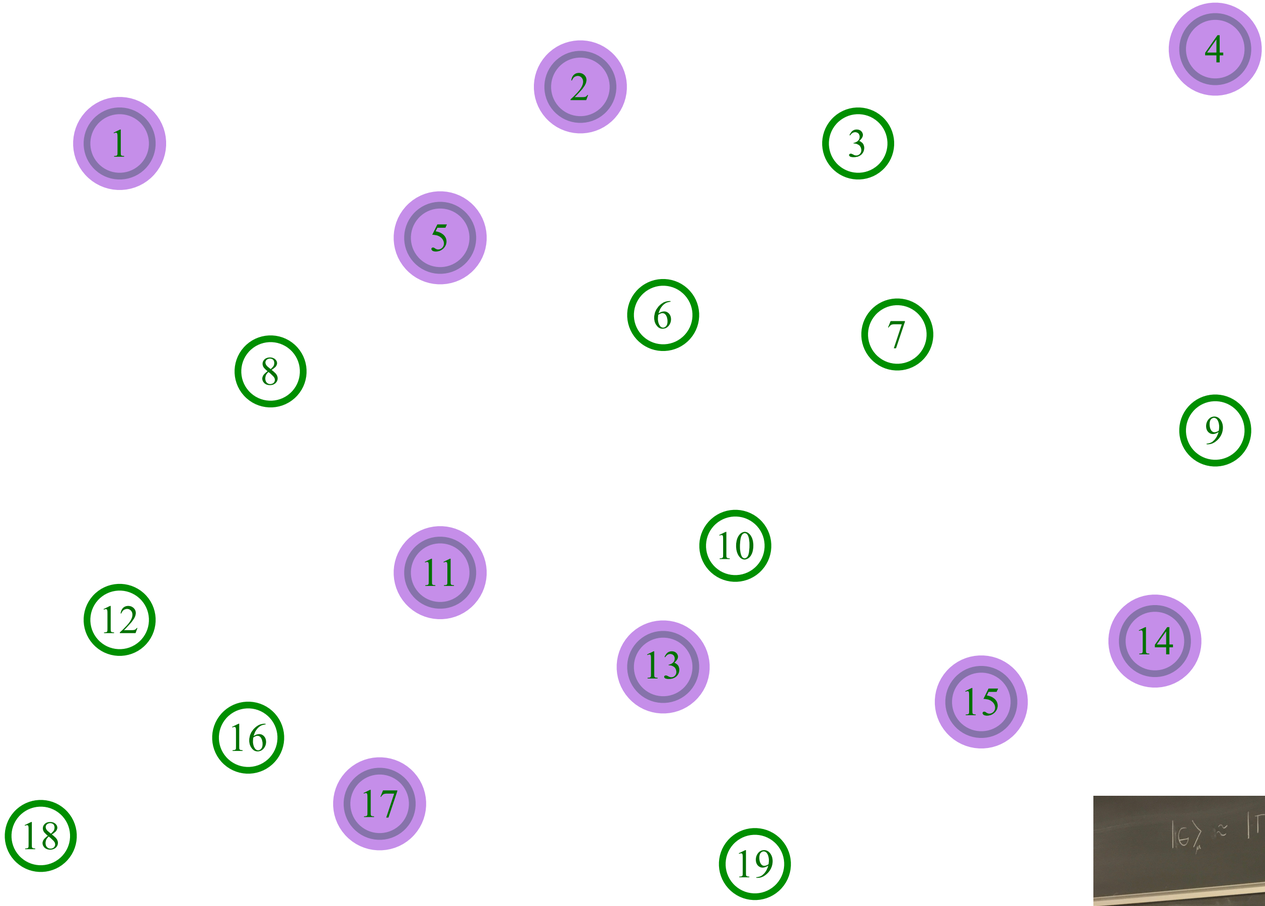
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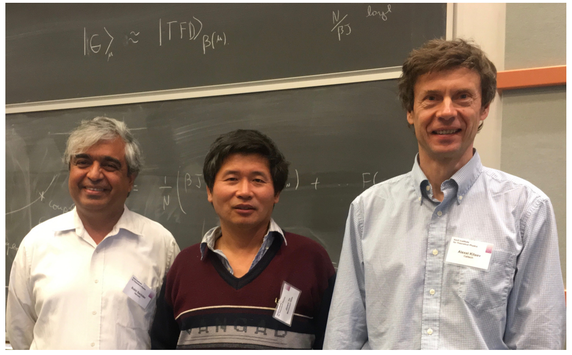
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

$U_{6,8;4,14}$



Entangle electrons pairwise randomly



The Sachdev-Ye-Kitaev (SYK) model

(See also: the "2-Body Random Ensemble" in nuclear physics; did not obtain the large N limit;
T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

$$\mathcal{H} = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta=1}^{N} U_{\alpha\beta;\gamma\delta}\, c_\alpha^\dagger c_\beta^\dagger c_\gamma c_\delta - \mu \sum_\alpha c_\alpha^\dagger c_\alpha$$

$$c_\alpha c_\beta + c_\beta c_\alpha = 0 \quad , \quad c_\alpha c_\beta^\dagger + c_\beta^\dagger c_\alpha = \delta_{\alpha\beta}$$

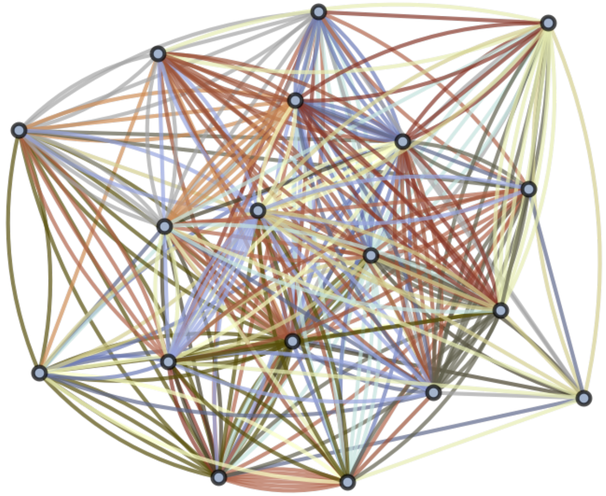
$$\mathcal{Q} = \frac{1}{N} \sum_\alpha c_\alpha^\dagger c_\alpha \, ; \quad [\mathcal{H}, \mathcal{Q}] = 0 \, ; \quad 0 \leq \mathcal{Q} \leq 1$$

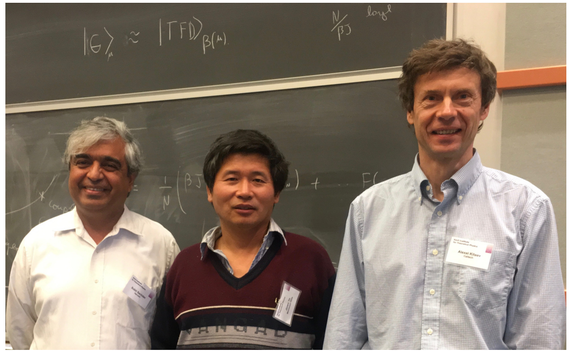
$U_{\alpha\beta;\gamma\delta}$ are independent random variables with $\overline{U_{\alpha\beta;\gamma\delta}} = 0$ and $\overline{|U_{\alpha\beta;\gamma\delta}|^2} = U^2$

$N \to \infty$ yields critical strange metal.

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)





The Sachdev-Ye-Kitaev (SYK) model

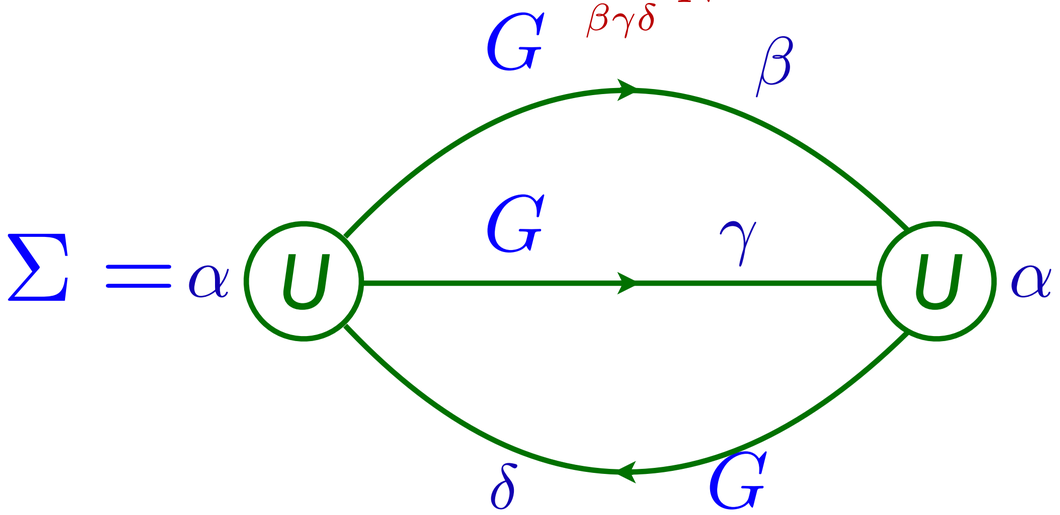
Feynman graph expansion in $U_{\alpha\beta;\gamma\delta}$, and graph-by-graph average, yields exact equations in the large N limit:

$$G(i\omega) = \frac{1}{i\omega + \mu - \Sigma(i\omega)} \quad , \quad \Sigma(\tau) = -U^2 G^2(\tau) G(-\tau)$$

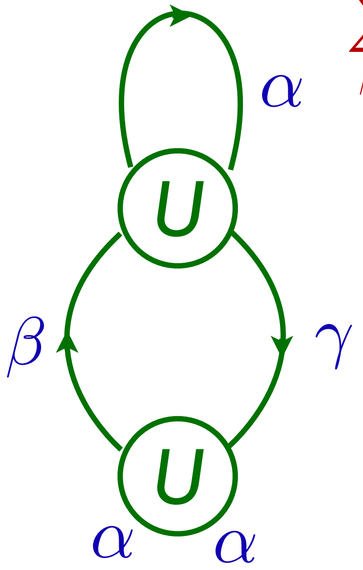
$$G(\tau = 0^-) = \mathcal{Q}.$$

Solution $G(\omega) \sim T^{-1/2} F(\hbar\omega / k_B T)$

$$\sum_{\beta\gamma\delta} \frac{U^2}{N^3} = U^2$$



$$\sum_{\beta\gamma} \frac{U^2}{N^3} = \frac{U^2}{N}$$



S. Sachdev and J. Ye,
PRL **70**, 3339 (1993)

A. Georges and O. Parcollet
PRB **59**, 5341 (1999)



The SYK model

Consequences of emergent time-reparameterization and conformal symmetries in low-energy theory in 0+1 spacetime dimensions:

1. Planckian dynamics!

$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right) \text{ independent of } U.$$

No bosons, fermions, anyons ...

S. Sachdev and J. Ye, PRL **70**, 3339 (1993); A. Georges and O. Parcollet PRB **59**, 5341 (1999)

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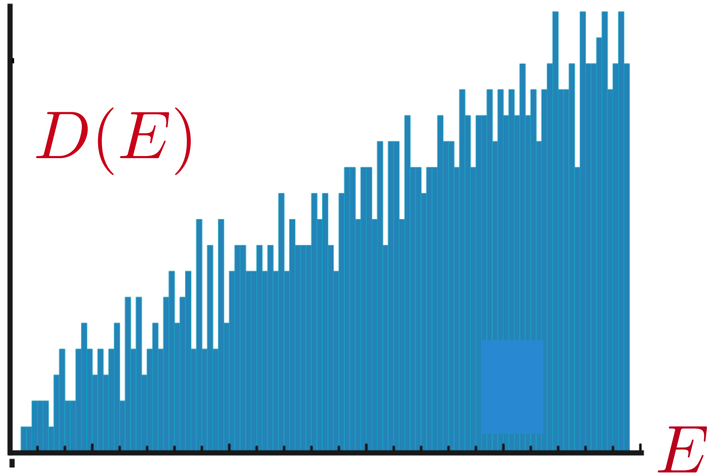
No bosons, fermions, anyons ...



2. Zero temperature entropy
without exponential ground state degeneracy!

$$\lim_{T\to 0}\lim_{N\to\infty}\frac{1}{N}S(T) = s_0 \quad , \quad D(E\to 0) = e^{N s_0}\sinh(\sqrt{2N\gamma E})$$

$$s_0 = 0.464847699170805107 49.... \text{ for } Q = 1/2.$$



A. Georges, O. Parcollet, and S. Sachdev (**GPS**), Physical Review B **63**, 134406 (2001)

The Sachdev-Ye-Kitaev (SYK) model

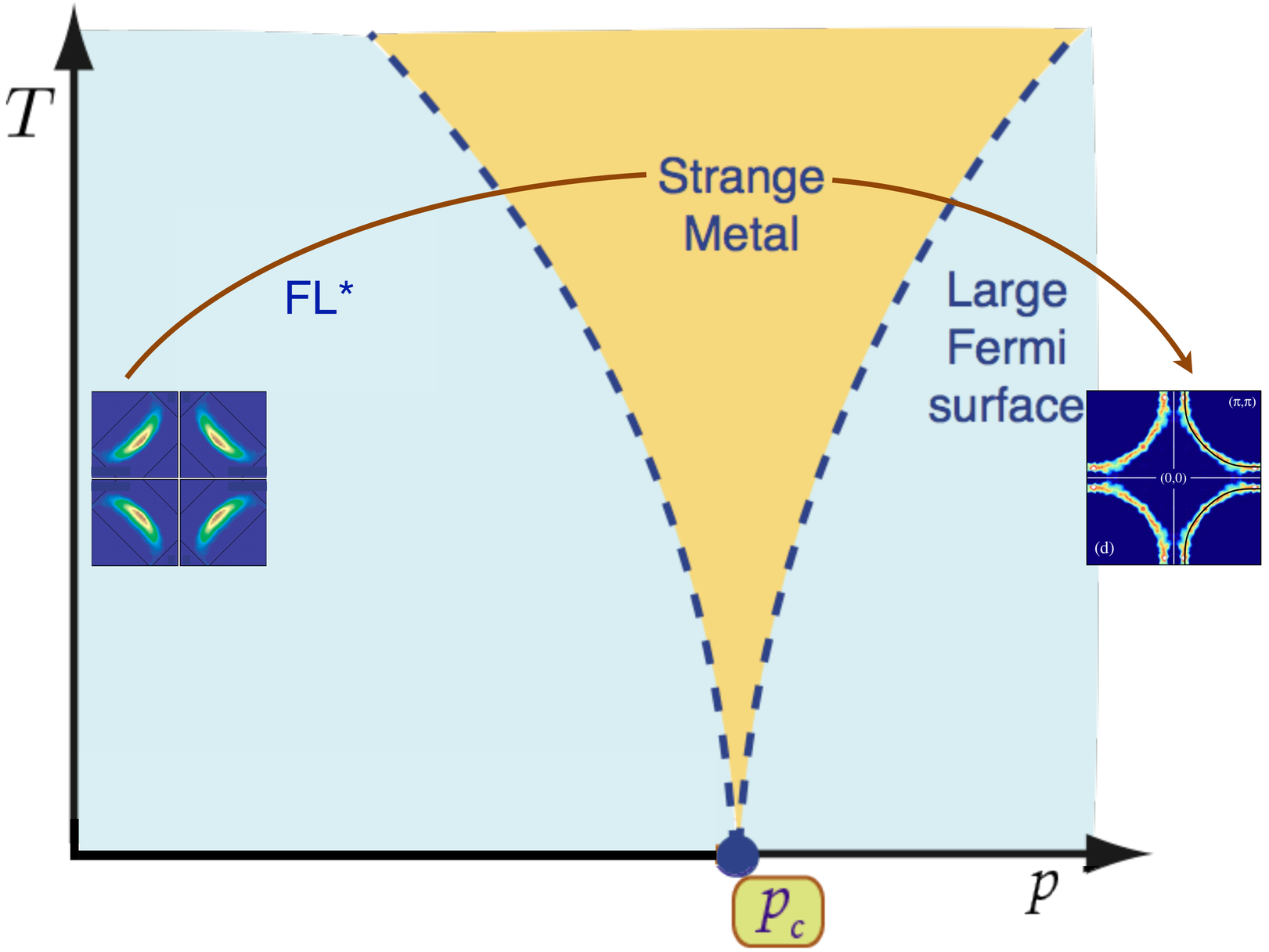
Sachdev, Ye (1993); Kitaev (2015)

A solvable model of multi-particle quantum entanglement.

Yields a quantum state whose excitations are not particle-like i.e. no bosons, fermions, anyons….

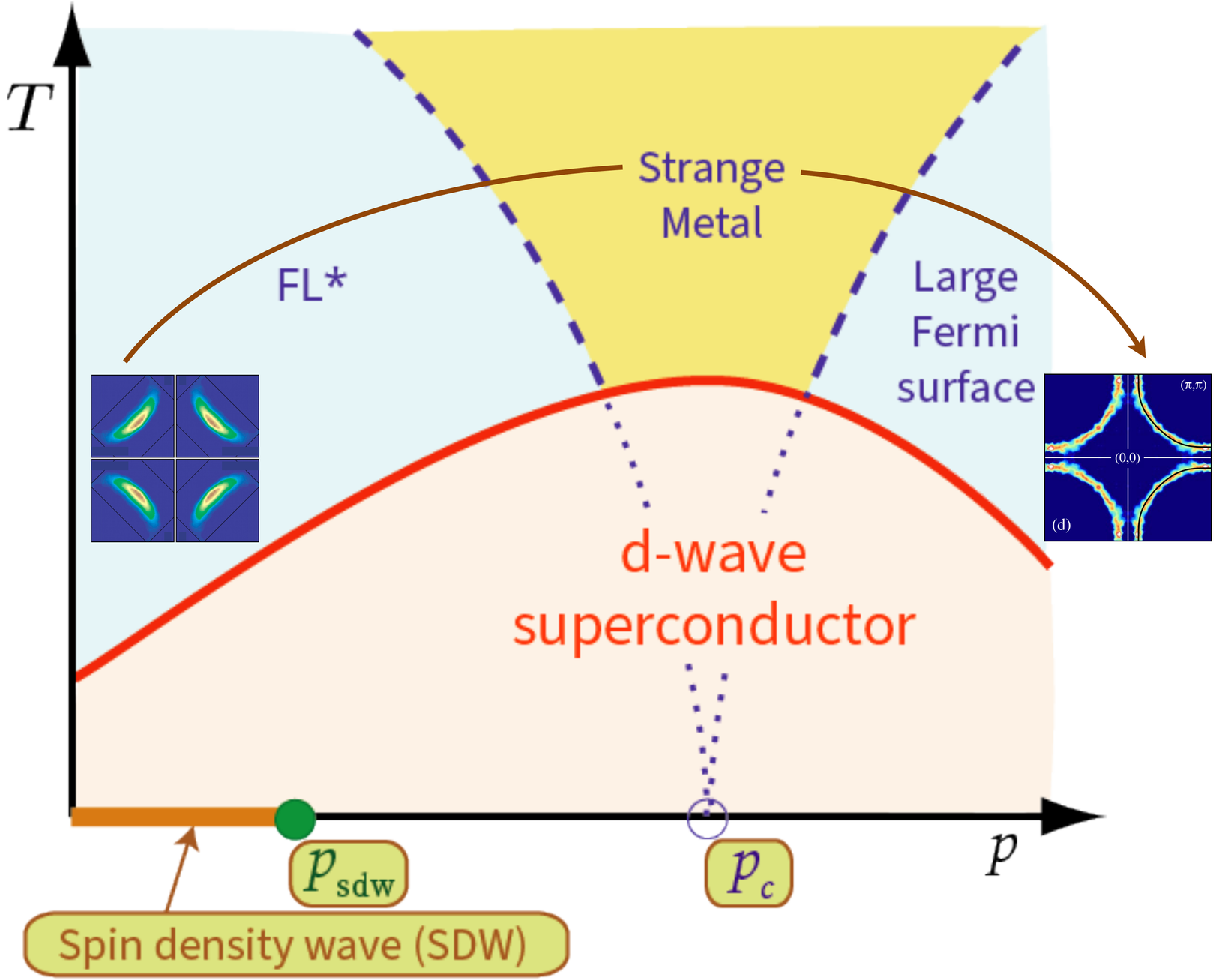
Current is carried by an "entangled quantum soup"

S. Sachdev, arXiv:0907.0008 (2009)



Quantum-criticality
of a
quantum phase transition
between two metals
(FL* and FL)
at $p = p_c$,
with no symmetry breaking.

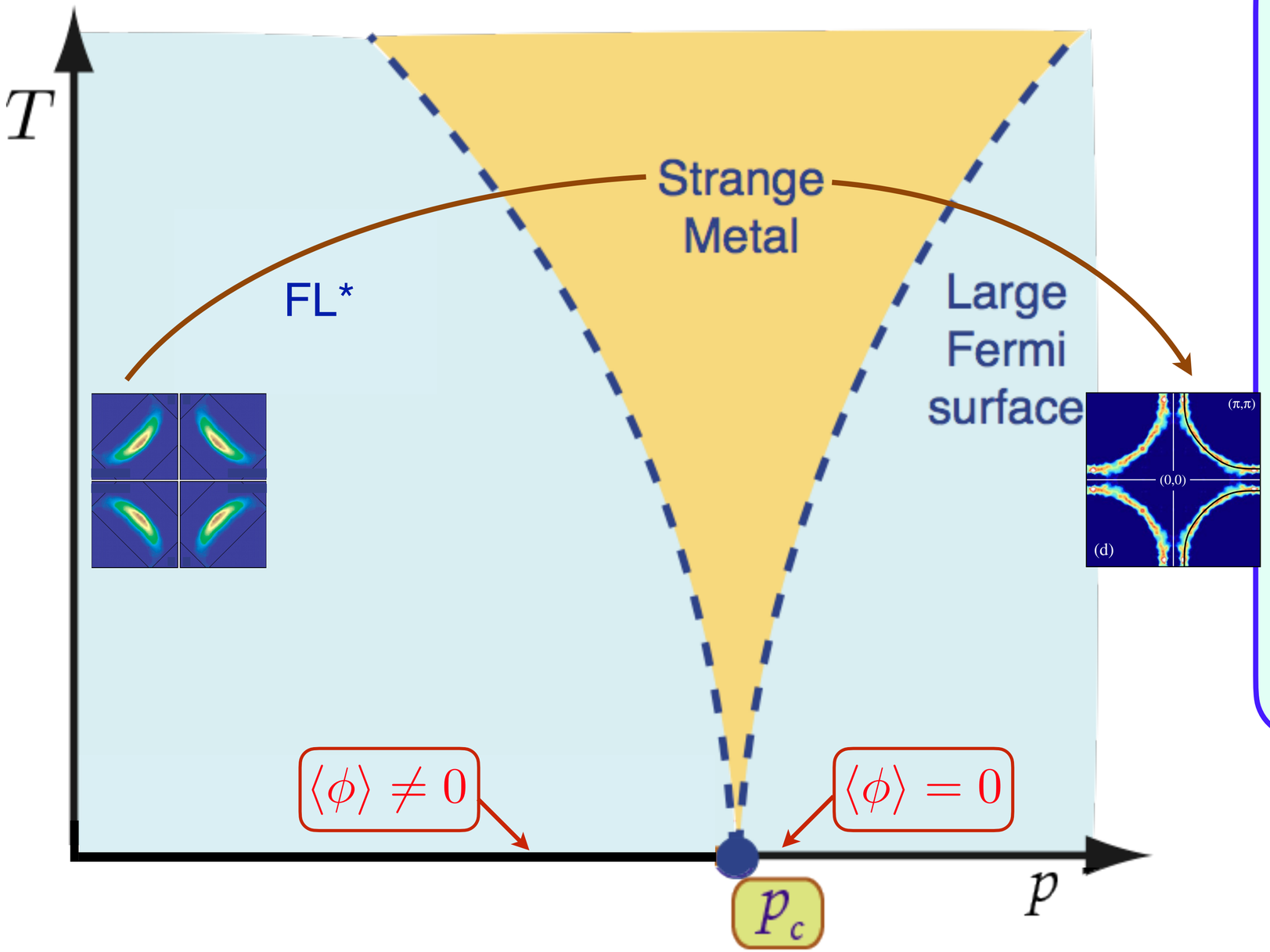
S. Sachdev, arXiv:0907.0008 (2009)



Quantum-criticality
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quantum phase transition
between two metals
(FL* and FL)
at $p = p_c$,
with no symmetry breaking.

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.

S. Sachdev, arXiv:0907.0008 (2009)



Quantum-criticality of incipient FL*-FL transition at $p = p_c$ described by $2d$-Yukawa-SYK model of the large Fermi surface and a Higgs boson ϕ with local, spatially random interactions.

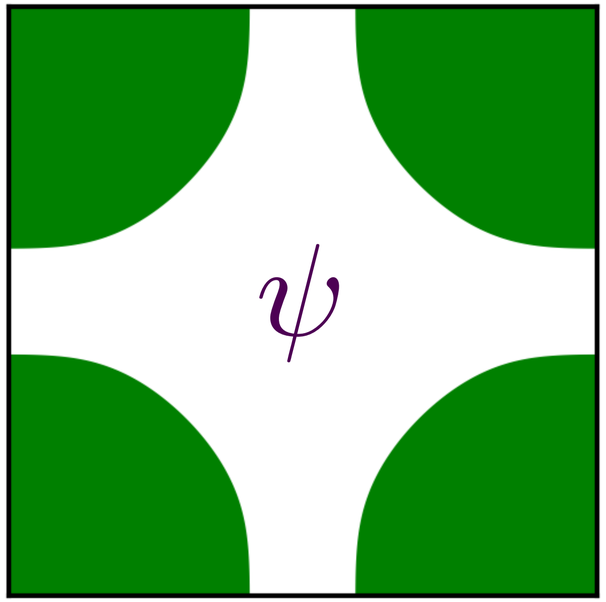
Obeys equations similar to SYK in momentum and frequency space.

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)

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

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

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



Critical Higgs boson ϕ
driving FL*-FL transition.

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

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

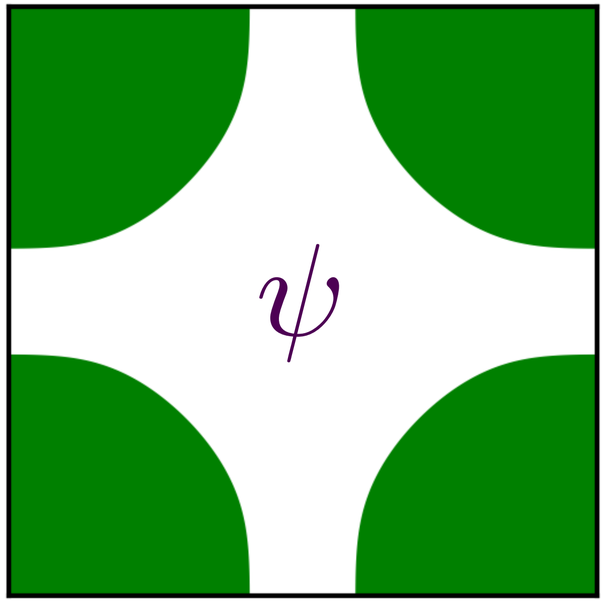
Spatially random Yukawa coupling $g'(\boldsymbol{r})$ with $\overline{g'(\boldsymbol{r})} = 0$, $\overline{g'(\boldsymbol{r})g'(\boldsymbol{r}')} = g'^2\delta(\boldsymbol{r} - \boldsymbol{r}')$

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

Saddle-point equations

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

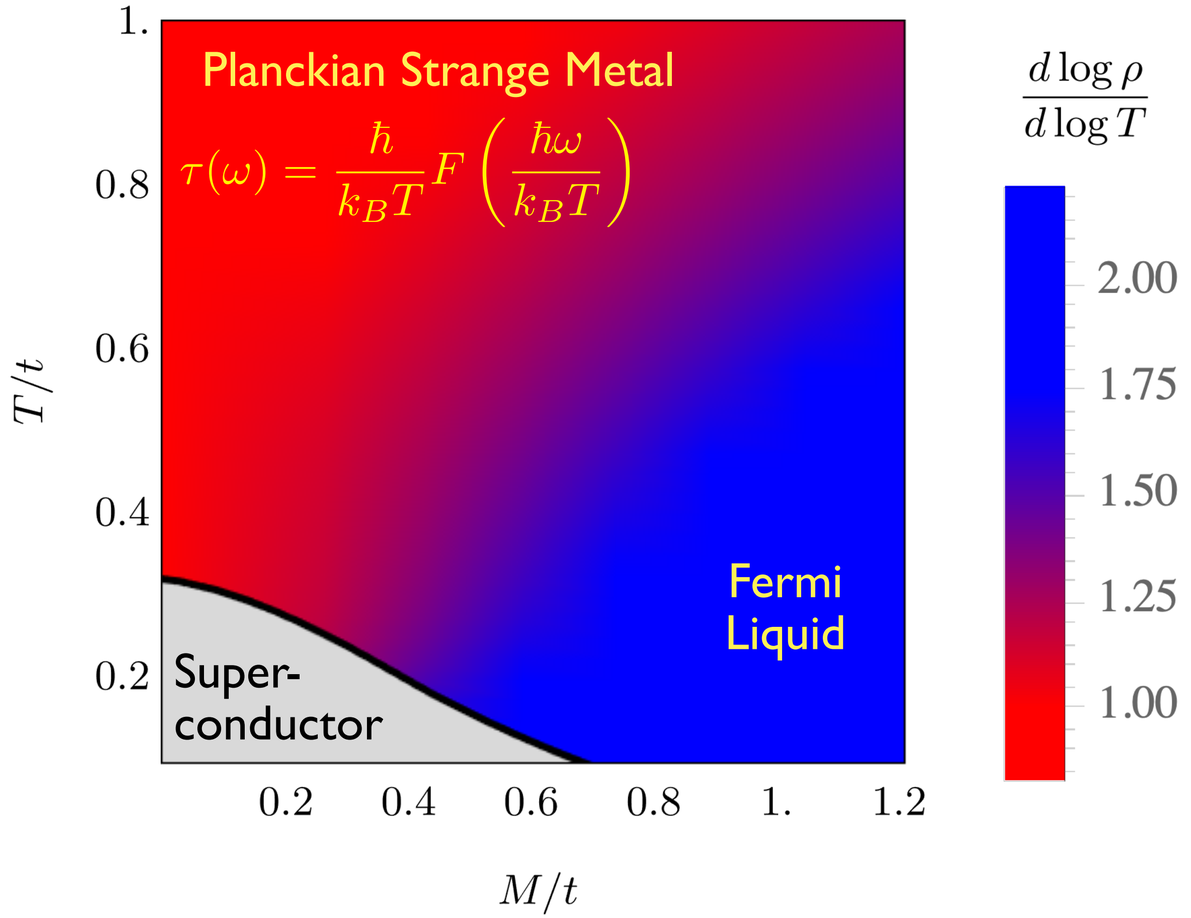
$$\Pi(\tau, \mathbf{r}) = -g^2 G(-\tau, -\mathbf{r}) G(\tau, \mathbf{r}) - g'^2 G(-\tau, \mathbf{r}) G(\tau, \mathbf{r}) \delta^2(\mathbf{r}),$$

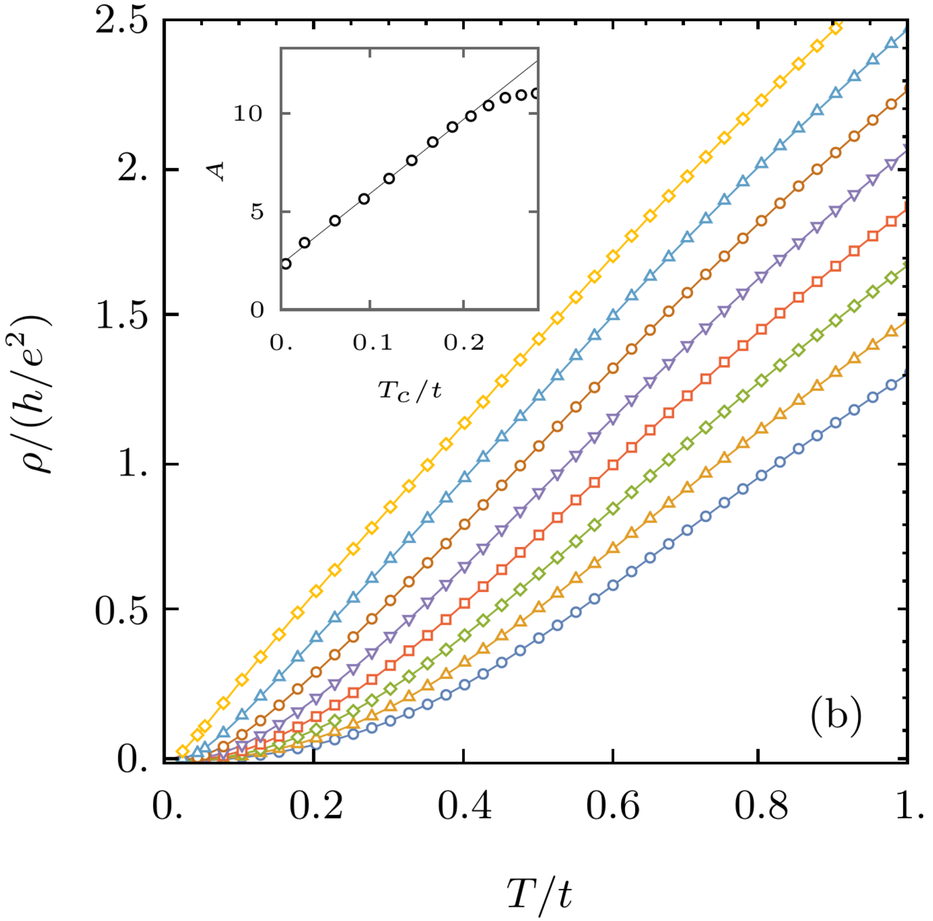
$$G(i\omega, \mathbf{k}) = \frac{1}{i\omega - \varepsilon(\mathbf{k}) + \mu - \Sigma(i\omega, \mathbf{k})},$$

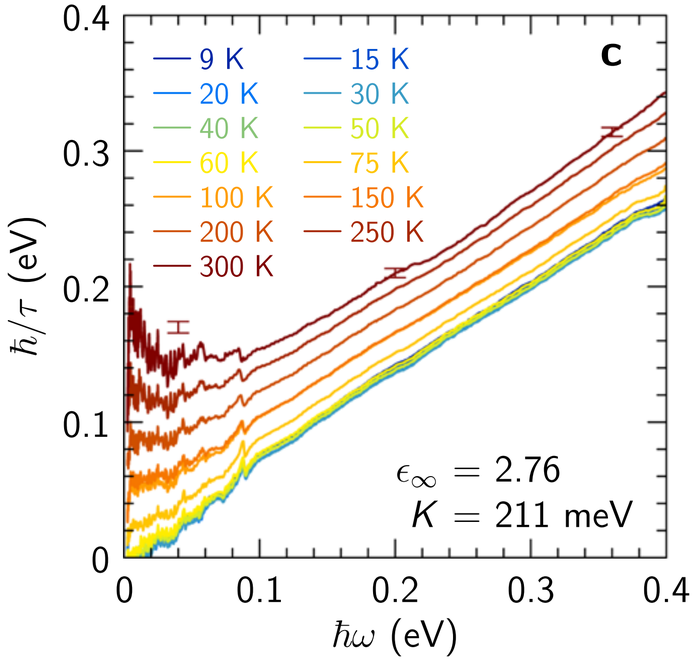
$$D(i\Omega, \mathbf{q}) = \frac{1}{\Omega^2 + \mathbf{q}^2 + m_b^2 - \Pi(i\Omega, \mathbf{q})}.$$

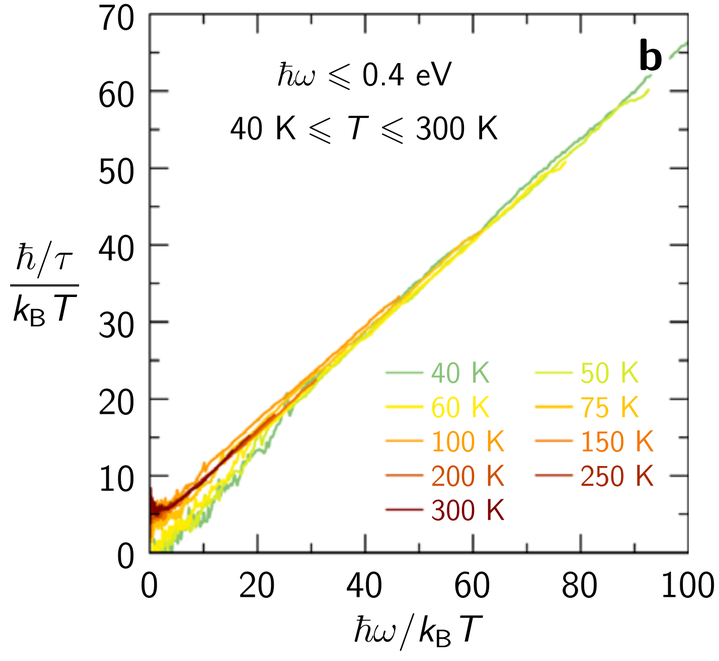
Strange metal and superconductor in the two-dimensional Yukawa-Sachdev-Ye-Kitaev model

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



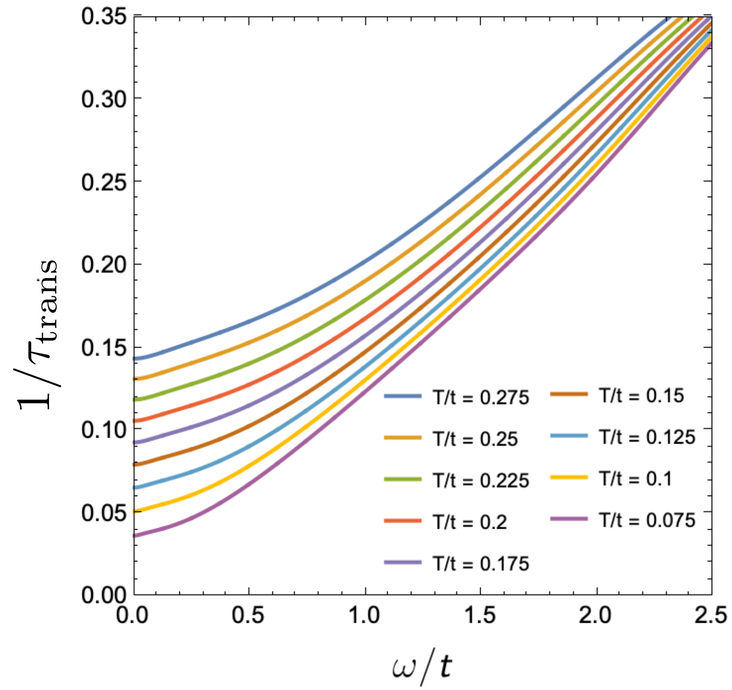


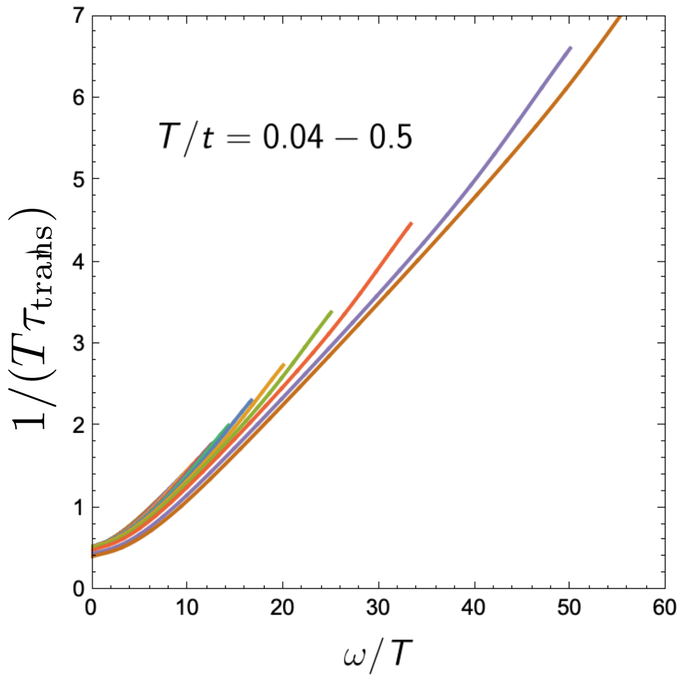




$$\sigma(\omega) = i\frac{e^2 K/(\hbar d_c)}{\hbar\omega\dfrac{m^*(\omega)}{m} + i\dfrac{\hbar}{\tau(\omega)}}$$

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)



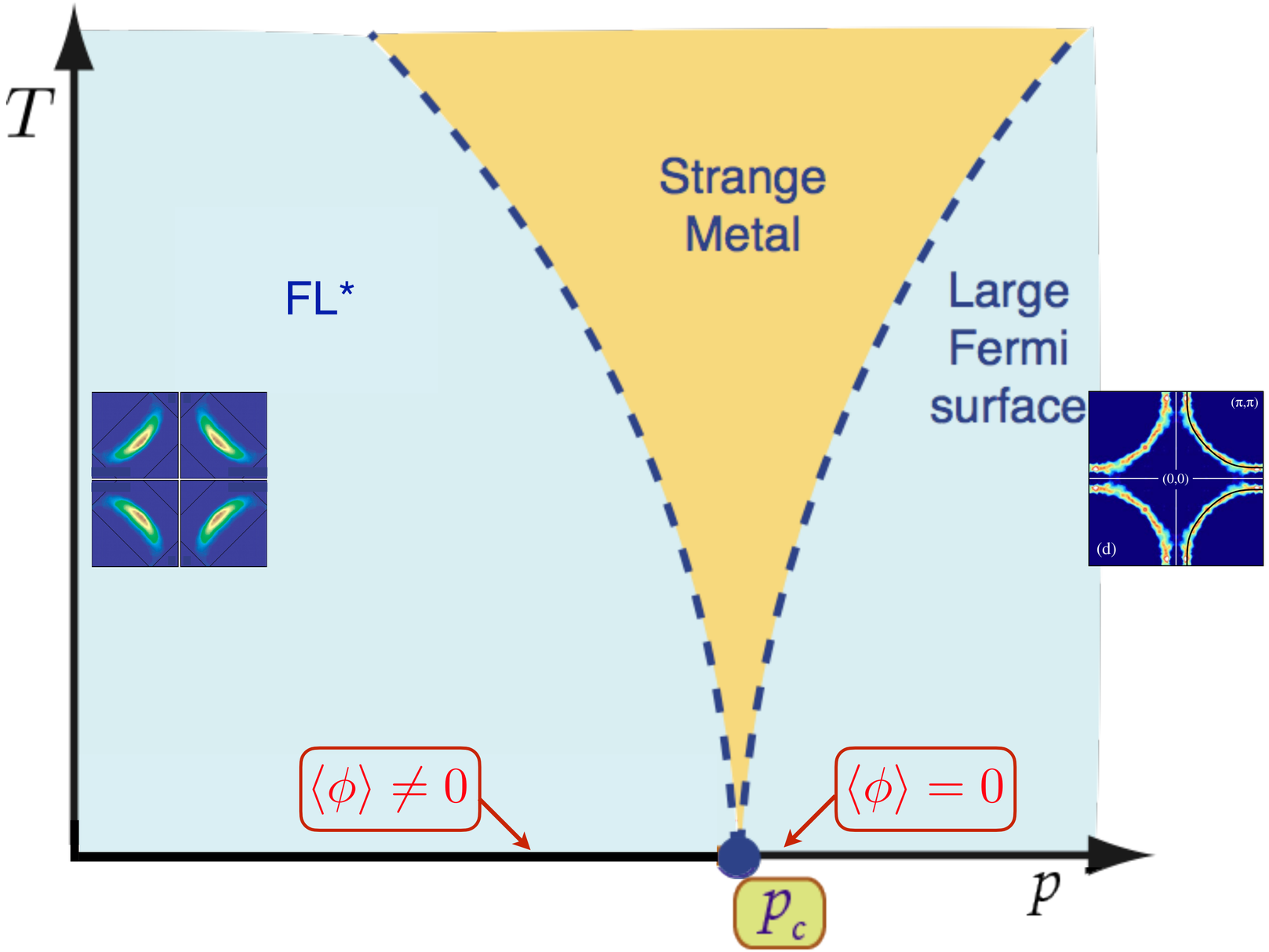


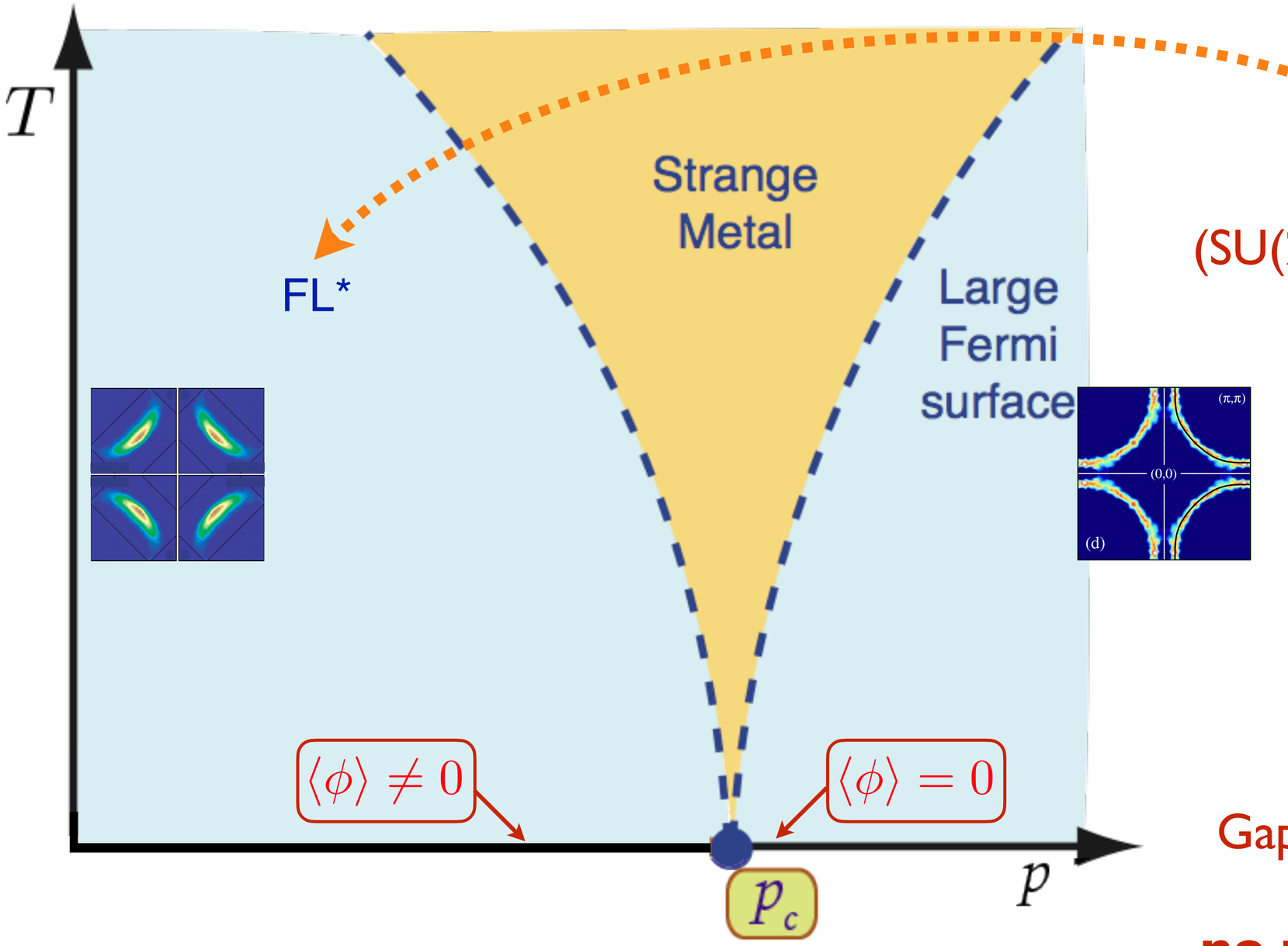
Planckian dynamics!

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

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

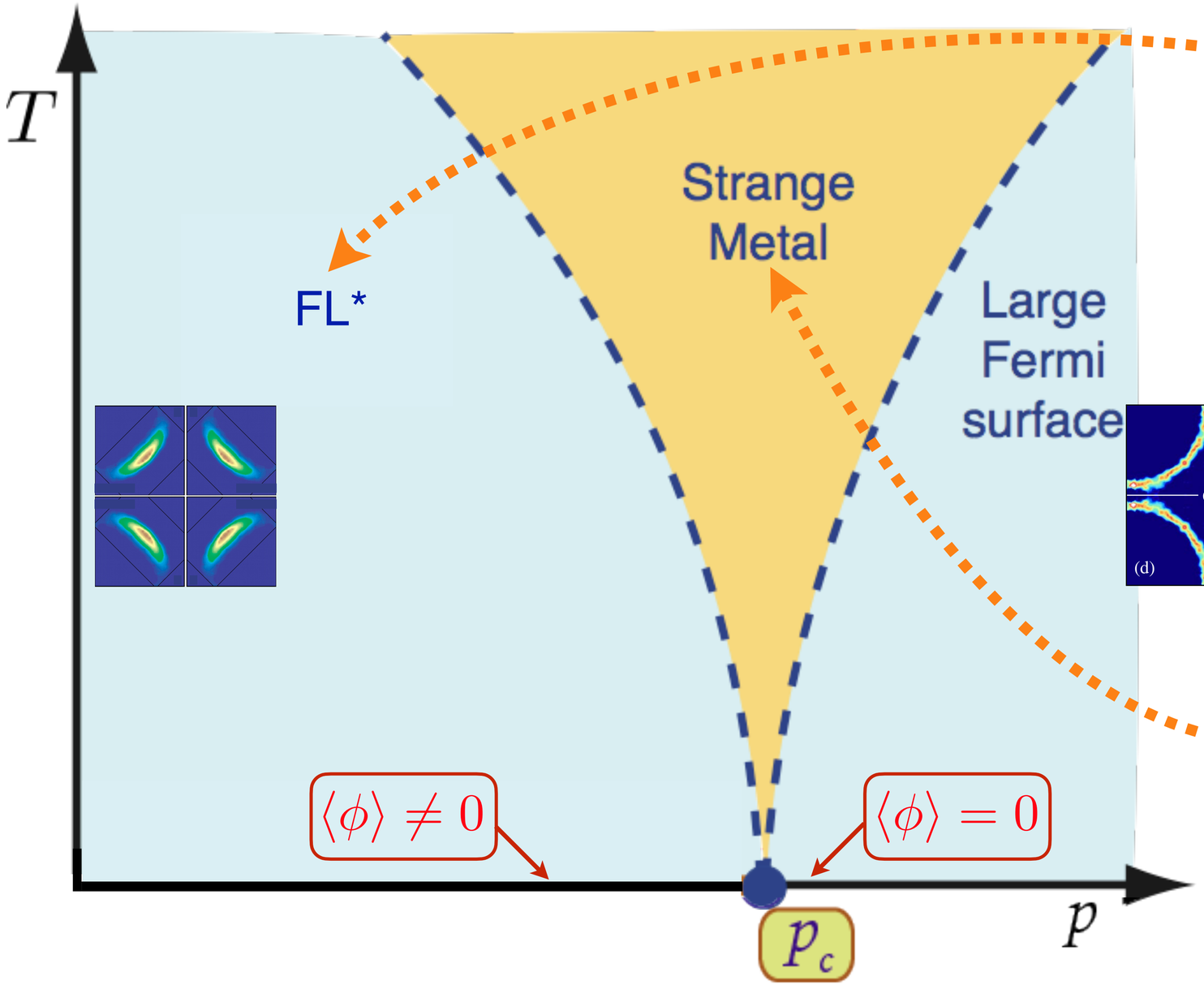
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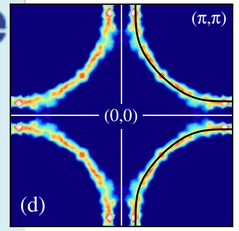

T
Strange
Metal
FL*
Large
Fermi
surface
(π,π)
(0,0)
(d)
$\langle\phi\rangle \neq 0$
$\langle\phi\rangle = 0$
p_c
p



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

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

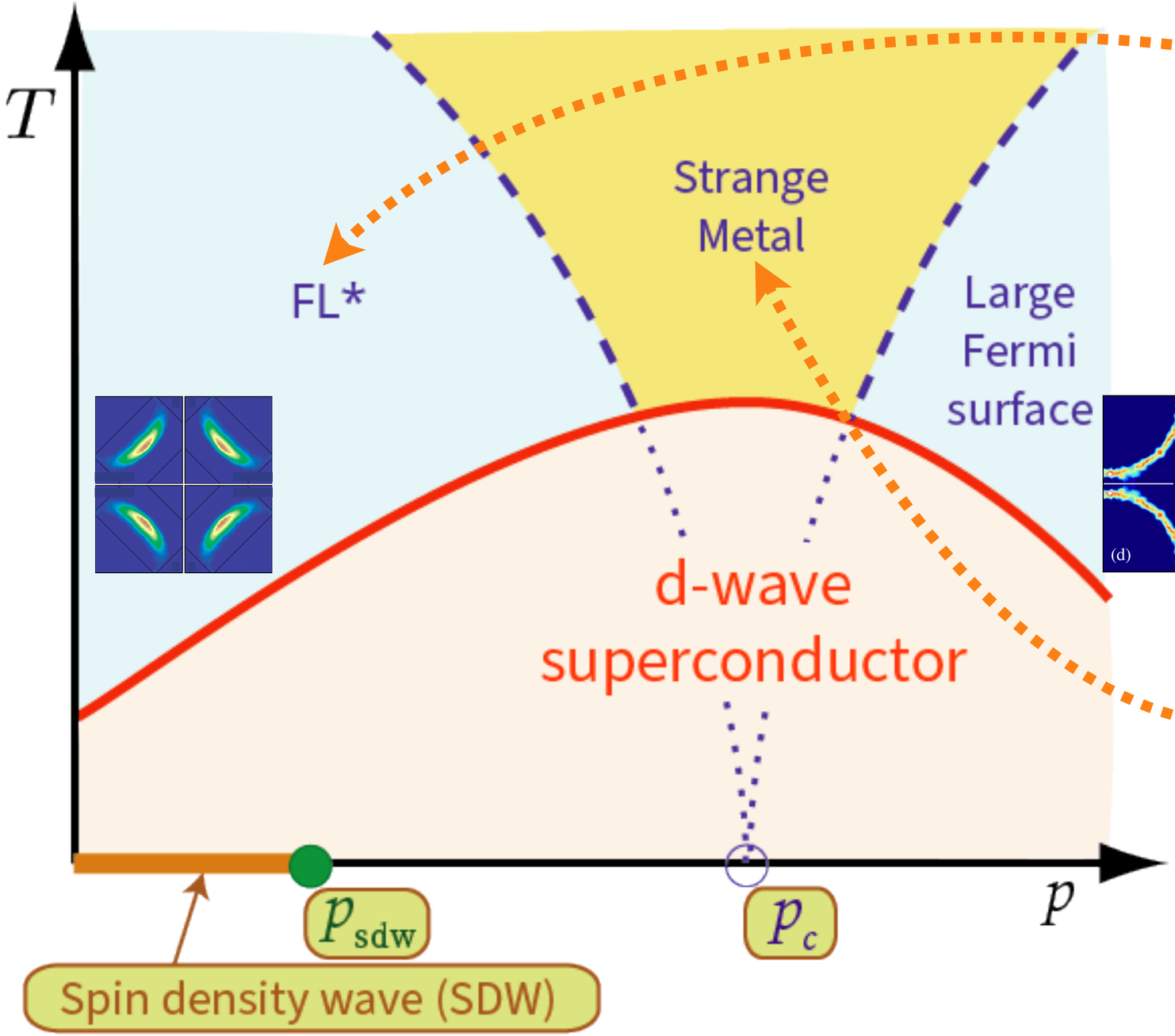




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