Gauge theory of optimal doping criticality in the cuprates

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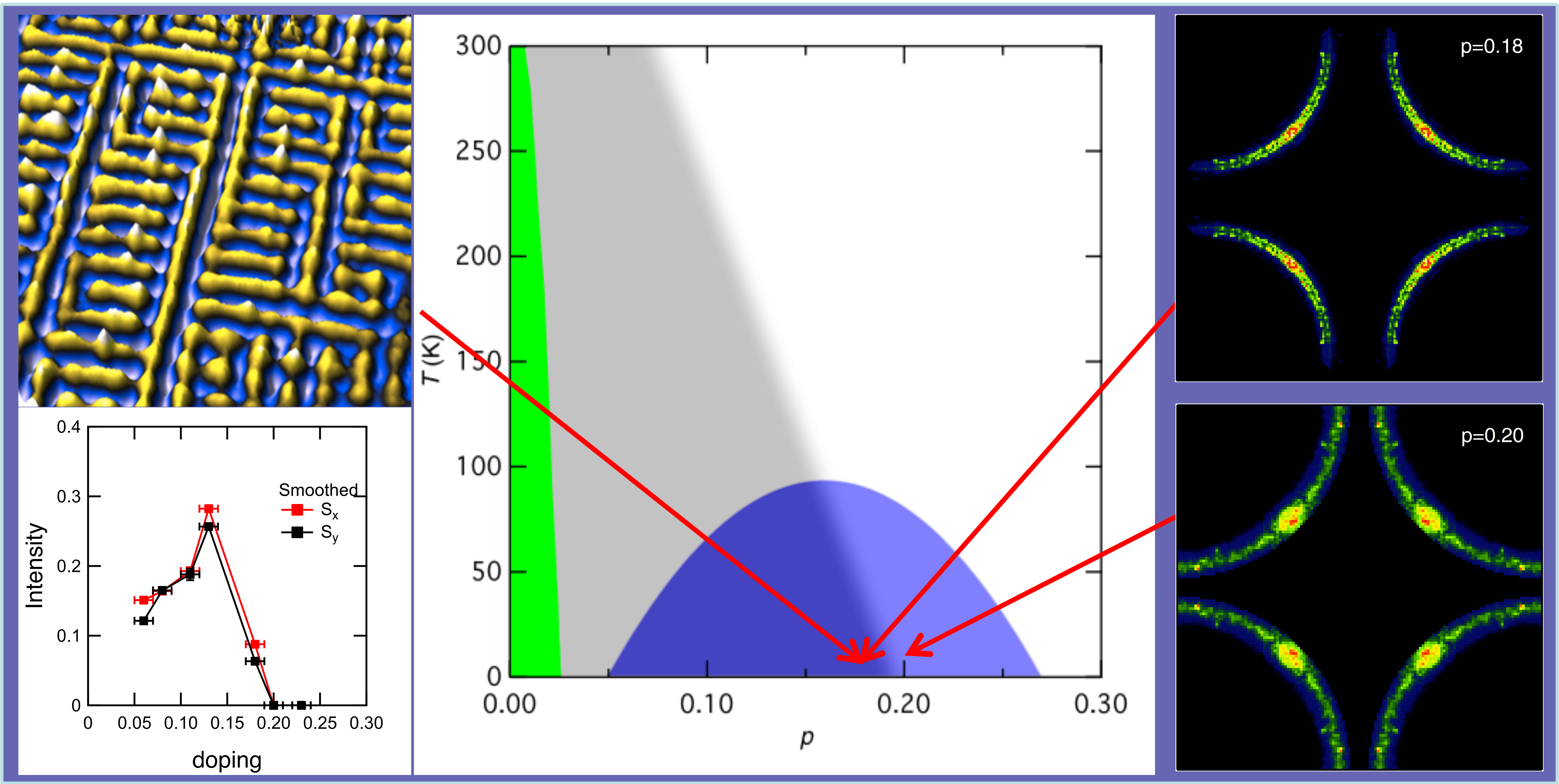
Talk online: sachdev.physics.harvard.edu

Fermi Surface and Pseudogap Evolution in a Cuprate Superconductor

Yang He, Yi Yin, M. Zech, A. Soumyanarayanan, I. Zeljkovic, M. M. Yee, M. C. Boyer, K. Chatterjee, W. D. Wise, Takeshi Kondo, T. Takeuchi, H. Ikuta, P. Mistark, R. S. Markiewicz, A. Bansil, S. Sachdev, E. W. Hudson, and J. E. Hoffman, Science **344**, 608 (2014)

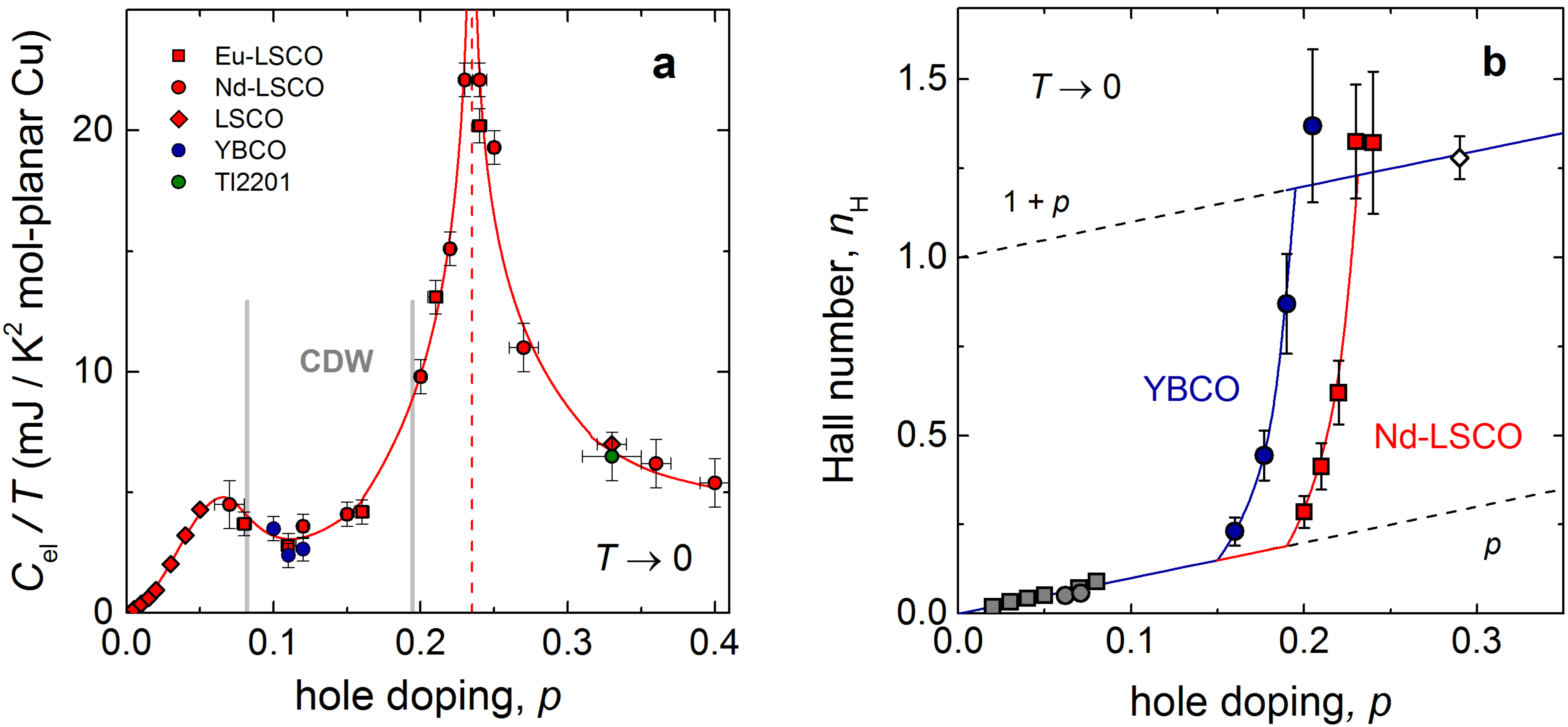
Simultaneous Transitions in Cuprate Momentum-Space Topology and Electronic Symmetry Breaking

K. Fujita, Chung Koo Kim, Inhee Lee, Jinho Lee, M. H. Hamidian, I. A. Firmo, S. Mukhopadhyay, H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, J. C. Davis, Science **344**, 612 (2014)



The remarkable underlying ground states of cuprate superconductors

Cyril Proust and Louis Taillefer, arXiv:1807.0507



Theoretical framework

We can (exactly) transform the Hubbard model to the "spin-fermion" model: **electrons** $c_{i\alpha}$ on the square lattice with dispersion

$$\mathcal{H}_c = -\sum_{i,\rho} t_\rho \left(c_{i,\alpha}^\dagger c_{i+\boldsymbol{v}_\rho,\alpha} + c_{i+\boldsymbol{v}_\rho,\alpha}^\dagger c_{i,\alpha} \right) - \mu \sum_i c_{i,\alpha}^\dagger c_{i,\alpha} + \mathcal{H}_{\text{int}}$$

are coupled to a magnetic moment order parameter $\Phi^p(i)$, $p = x, y, z$

$$\mathcal{H}_{\text{int}} = -\lambda \sum_i \Phi^p(i) c_{i,\alpha}^\dagger \sigma_{\alpha\beta}^p c_{i,\beta} + V_\Phi$$

Theoretical framework

For (fluctuating) SDW SRO, we transform to a rotating reference frame using the SU(2) rotation R_i

$$\begin{pmatrix} c_{i\uparrow} \\ c_{i\downarrow} \end{pmatrix} = R_i \begin{pmatrix} \psi_{i,+} \\ \psi_{i,-} \end{pmatrix},$$

in terms of fermionic "chargons" ψ_s and a **Higgs field** $H^a(i)$

$$\sigma^p \Phi^p(i) = R_i \, \sigma^a H^a(i) \, R_i^\dagger$$

The Higgs field is the SDW order in the rotating reference frame.

Theoretical framework

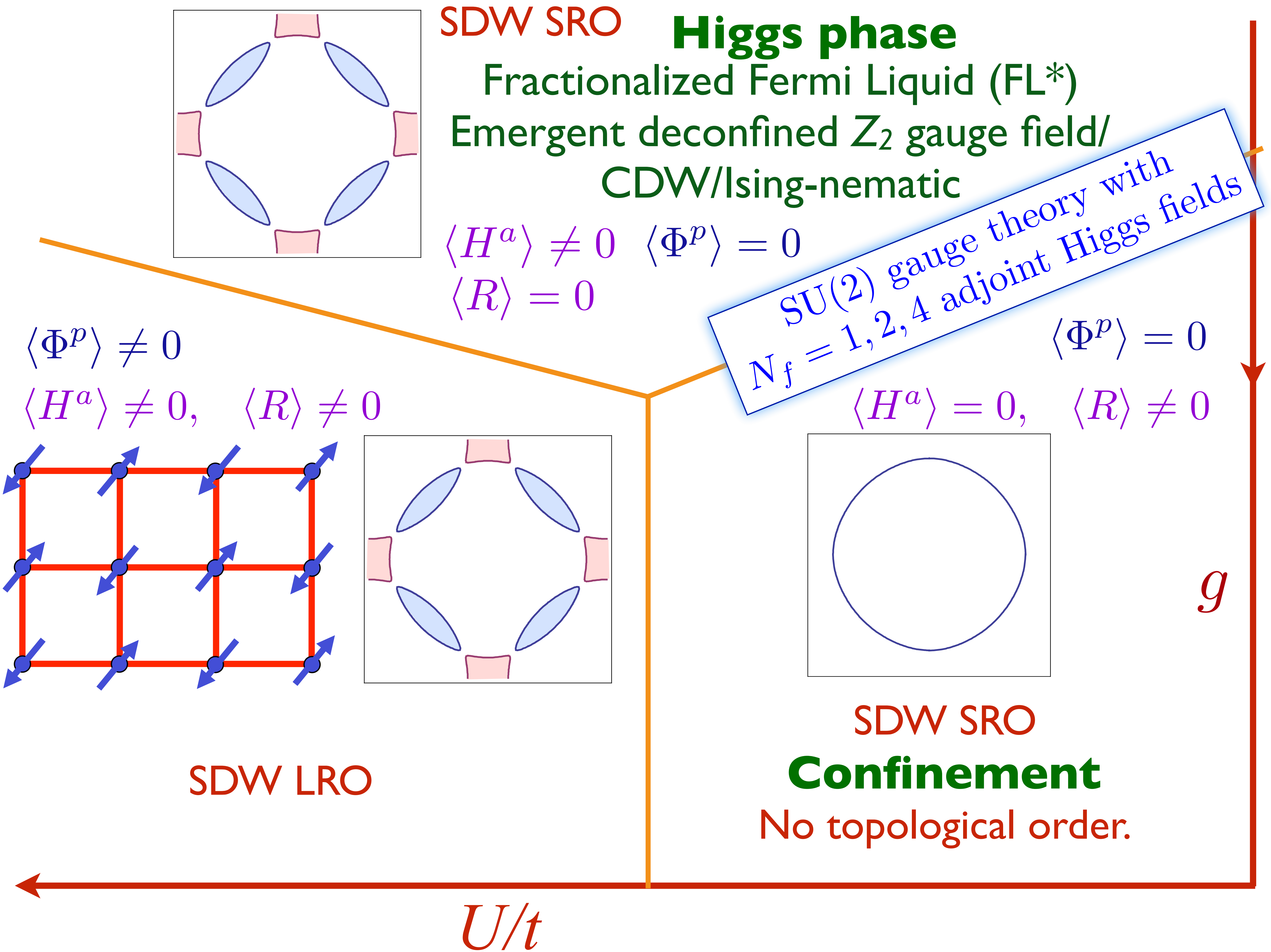
We obtain different numbers of adjoint Higgs scalars, N_h, depending upon the spatial dependence of the local spin correlations:

Neel correlations: $N_h = 1$,
$\boldsymbol{K} = (\pi, \pi)$,
$H^a(i) = H_1^a(\boldsymbol{r}) e^{i\boldsymbol{K}\cdot\boldsymbol{r}_i}$

Canted antiferromagnetic correlations: $N_h = 2$,
$\boldsymbol{K} = (\pi, \pi)$,
$H^a(i) = H_1^a(\boldsymbol{r}) e^{i\boldsymbol{K}\cdot\boldsymbol{r}_i} + H_2^a(\boldsymbol{r})$

Unidirectional incommensurate correlations: $N_h = 2$,
$\boldsymbol{K} = (\pi, \pi - \delta)$,
$H^a(i) = \mathrm{Re}\left\{\left[H_1^a(\boldsymbol{r}) + iH_2^a(\boldsymbol{r})\right] e^{i\boldsymbol{K}\cdot\boldsymbol{r}_i}\right\}$

Bidirectional incommensurate correlations: $N_h = 4$,
$\boldsymbol{K}_y = (\pi, \pi - \delta)$, $\boldsymbol{K}_x = (\pi - \delta, \pi)$,
$H^a(i) = \mathrm{Re}\left\{\left[H_1^a(\boldsymbol{r}) + iH_2^a(\boldsymbol{r})\right] e^{i\boldsymbol{K}_x\cdot\boldsymbol{r}_i} + \left[H_3^a(\boldsymbol{r}) + iH_4^a(\boldsymbol{r})\right] e^{i\boldsymbol{K}_y\cdot\boldsymbol{r}_i}\right\}$


SDW SRO
Higgs phase
Fractionalized Fermi Liquid (FL*)
Emergent deconfined Z_2 gauge field/
CDW/Ising-nematic
$\langle H^a \rangle \neq 0$ $\langle \Phi^p \rangle = 0$
$\langle R \rangle = 0$
SU(2) gauge theory with
$N_f = 1, 2, 4$ adjoint Higgs fields
$\langle \Phi^p \rangle \neq 0$
$\langle H^a \rangle \neq 0, \quad \langle R \rangle \neq 0$
$\langle \Phi^p \rangle = 0$
$\langle H^a \rangle = 0, \quad \langle R \rangle \neq 0$
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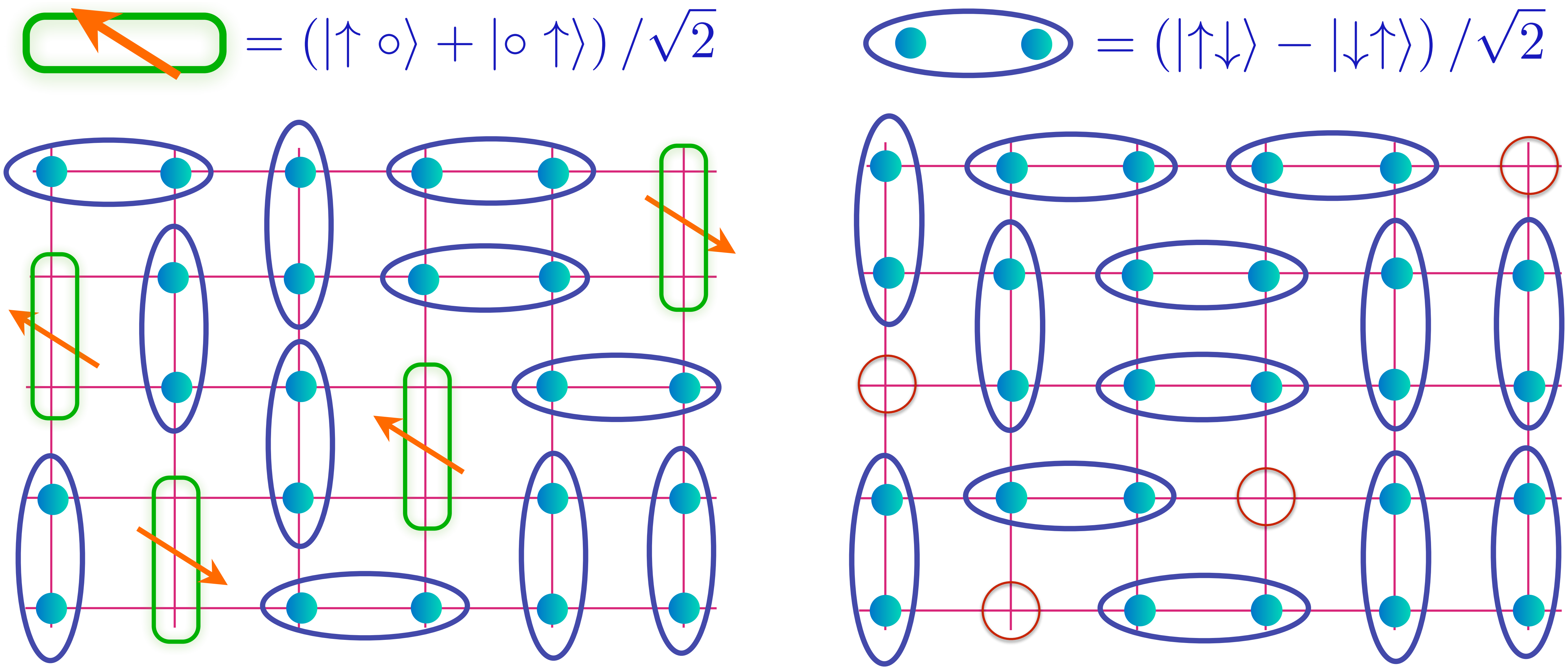
SDW SRO
Confinement
No topological order.
SDW LRO
U/t

Theory of the pseudogap phase



(a) FL* (b) ACL

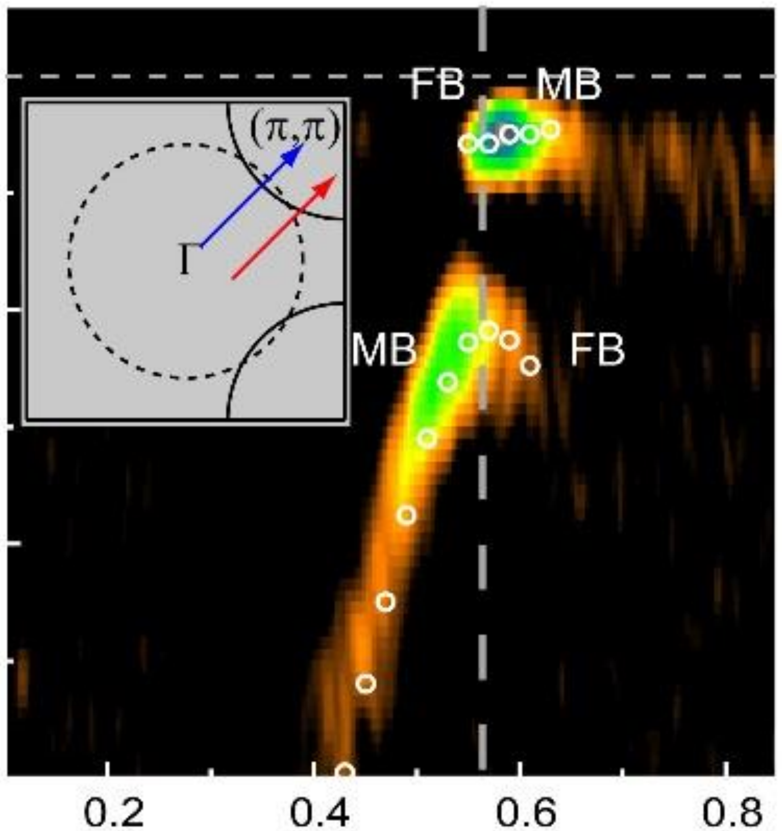
Metals with emergent gauge fields (the blue dimers):
(a) FL*: electron-like (b) ACL: spinless chargons
with quasiparticles on a Fermi surface of size *p*

Theory of the pseudogap phase

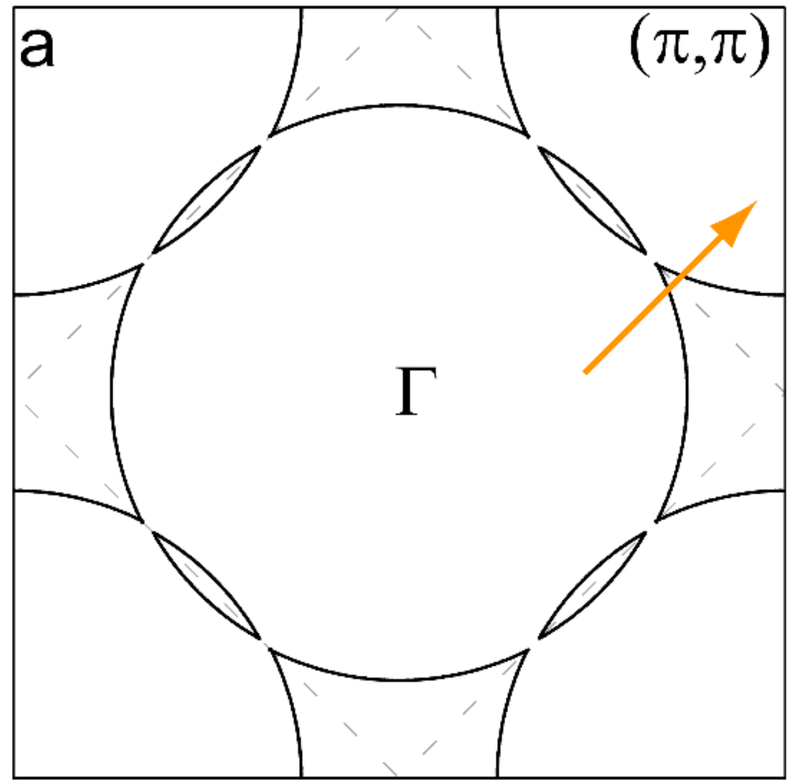
Field	Symbol	Statistics	$SU(2)_{gauge}$	$SU(2)_{spin}$	$U(1)_{e.m.charge}$
Electron	c	fermion	$\mathbf{1}$	$\mathbf{2}$	-1
AF order	Φ	boson	$\mathbf{1}$	$\mathbf{3}$	0
Chargon	ψ	fermion	$\mathbf{2}$	$\mathbf{1}$	-1
Spinon	R or z	boson	$\bar{\mathbf{2}}$	$\mathbf{2}$	0
Higgs	H	boson	$\mathbf{3}$	$\mathbf{1}$	0

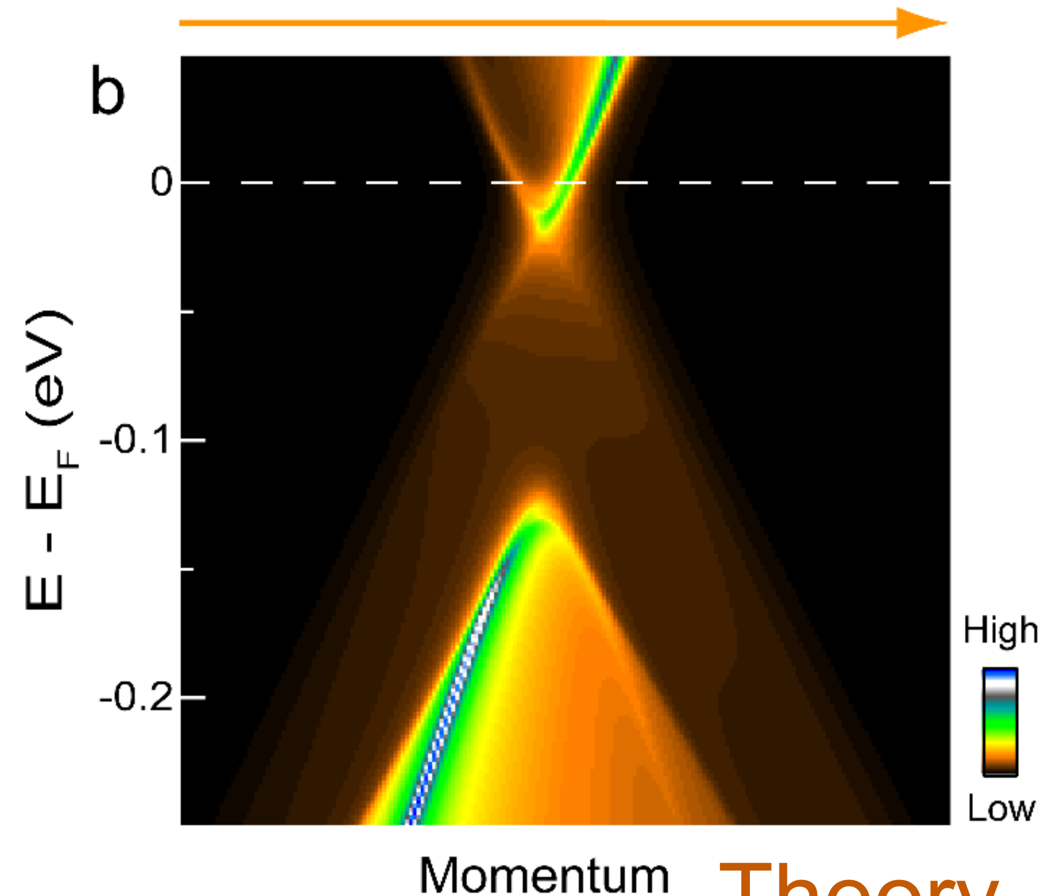
SU(2) gauge theory: fractionalize the SDW order parameter into the Higgs field (H) and the spinons (R); fractionalize the electron (c) into chargons (ψ) and spinons (R). When the Higgs field is condensed, the ψ fermions and R bosons are deconfined particles in an algebraic charge liquid (ACL) state, but with a strong residual attractive interaction from the t_{ij}. These can bind to form Fermi surfaces of quasiparticles with the same quantum numbers as an electron in a fractionalized Fermi liquid (FL*) state: the Fermi surfaces in the ACL/FL* states are reconstructed by the Higgs condensate, in a manner similar to a state with long-range SDW order. In the present SU(2) gauge theory, we ignored the interactions between the ψ and R in an ACL state, and obtained results in good agreement at intermediate temperatures with cluster DMFT, and with photoemission observations on NCCO.

Theory of the pseudogap phase



Experiment





Theory

Junfeng He, C. R. Rotundu, M. S. Scheurer, Y. He, M. Hashimoto, K. Xu, Y. Wang, E. W. Huang, T. Jia, S.-D. Chen, B. Moritz, D.-H. Lu, Y. S. Lee, T. P. Devereaux and Z.-X. Shen,
Fermi surface reconstruction in electron-doped cuprates without antiferromagnetic long-range order,
preprint

M. S. Scheurer, S. Chatterjee, Wei Wu, M. Ferrero, A. Georges, and S. Sachdev,
Topological order in the pseudogap metal
PNAS **115**, E3665 (2018)

Wei Wu, M. S. Scheurer, S. Chatterjee, S. Sachdev, A. Georges, and M. Ferrero,
Pseudogap and Fermi surface topology in the two-dimensional Hubbard model
Physical Review X **8**, 021048 (2018)

Theory of optimal doping criticality

Field	Symbol	Statistics	$SU(2)_{\text{gauge}}$	$SU(2)_{\text{spin}}$	$U(1)_{\text{e.m.charge}}$
Electron	c	fermion	**1**	**2**	-1
AF order	Φ	boson	**1**	**3**	0
Chargon	ψ	fermion	**2**	**1**	-1
Spinon	R or z	boson	$\bar{\mathbf{2}}$	**2**	0
Higgs	H	boson	**3**	**1**	0

SU(2) gauge theory for **quantum criticality**: Assume the R spinons and ψ chargons are gapped, and all the low energy fermionic excitations are electron-like across the quantum critical point. Integrate out the spinons R, the chargons ψ, and the high energy c_α to obtain effective theory for H_ℓ^a and the low energy c_α near the Fermi surface.

Theory of optimal doping criticality

SU(2) gauge theory

SU(2) gauge theory with N_h adjoint Higgs fields H_ℓ^a $(a = 1, 2, 3,\ \ell = 1 \ldots N_h)$
with potential $V(H_\ell^a)$ and SU(2) gauge field A_μ^a,
with a *quartic* coupling to gauge-invariant fermions
with a large Fermi surface.
The quartic coupling is (assumed) innocuous, unlike a Yukawa coupling.

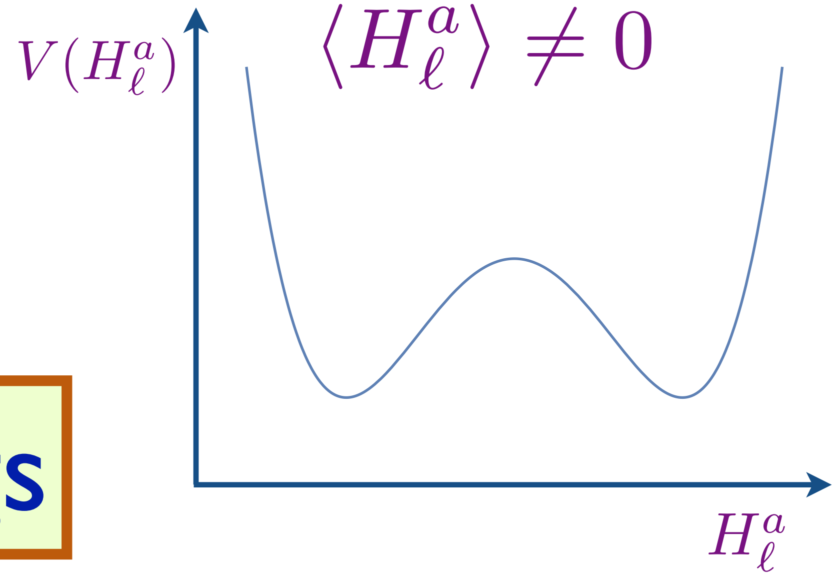
$$
\begin{aligned}
&(1/2)\left(\partial_\mu H_\ell^a - \epsilon_{abc} A_\mu^b H_\ell^c\right)^2 + V(H_\ell^a) \\
&- \sum_{i,\rho} t_\rho \left(c_{i,\alpha}^\dagger c_{i+\boldsymbol{v}_\rho,\alpha} + c_{i+\boldsymbol{v}_\rho,\alpha}^\dagger c_{i,\alpha} \right) - \mu \sum_i c_{i,\alpha}^\dagger c_{i,\alpha} \\
&+ \sum_i c_{i,\alpha}^\dagger c_{i,\alpha} H^a(i) H^a(i)
\end{aligned}
$$

$$V(H_\ell^a) = s\, H_\ell^a H_\ell^a + u_1 (H_\ell^a H_\ell^a)^2 + u_2\, H_\ell^a H_m^a H_\ell^b H_m^b + \ldots$$

$N_f = 1$

Phase diagrams of SU(2) gauge theory

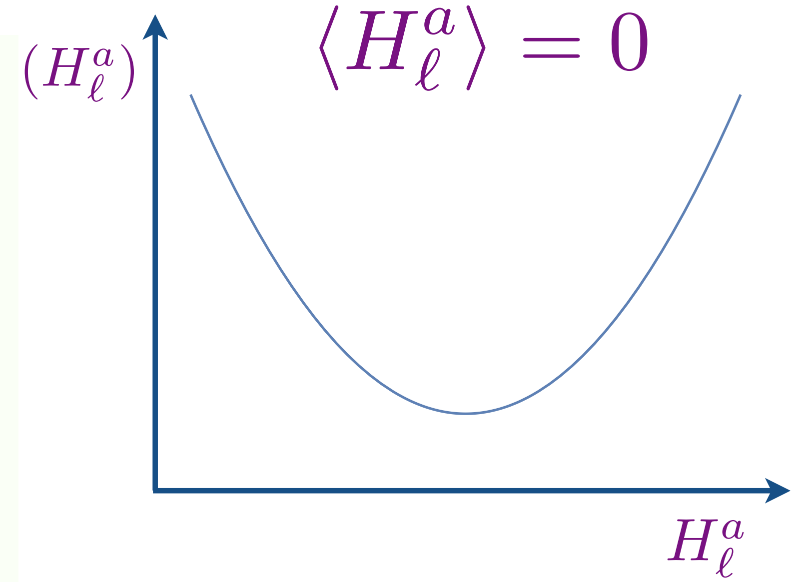
Higgs



Exponentially large confinement length

Reconstructed Fermi surfaces at distances smaller than the confinement length

Crossover



Confinement

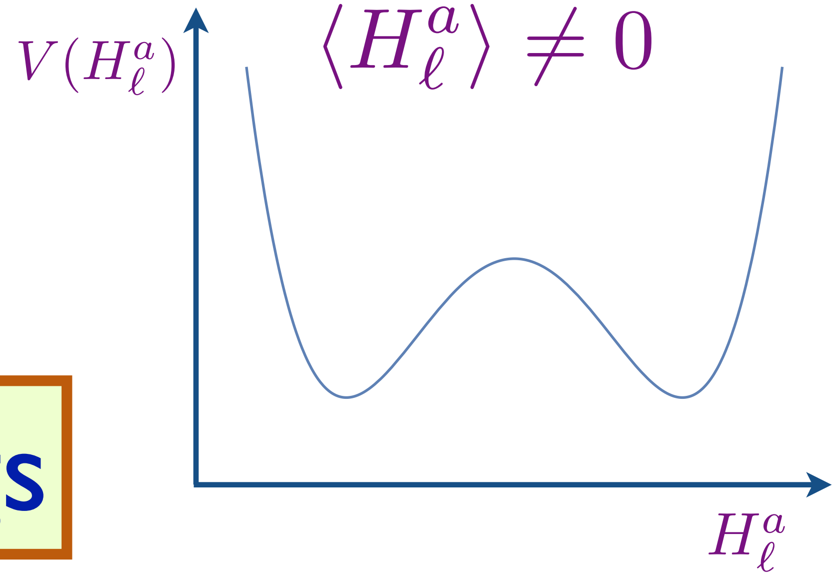
Fermi liquid with large Fermi surface

s

A. C. Davis, A. Hart, T.W. B. Kibble, and A. Rajantie, Phys. Rev. D 65, 125008 (2002)

$N_f = 4$

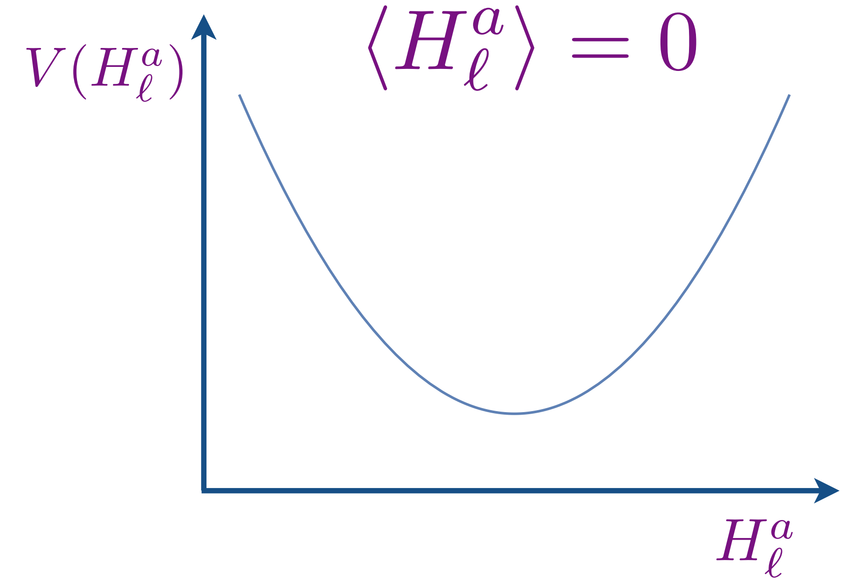
Phase diagrams of SU(2) gauge theory



Higgs

$u_2 > 0$:
Emergent deconfined $\mathbb{Z}_2$ gauge field
with Ising-nematic order and large CDW susceptibility
or
$u_2 < 0$:
Confining U(1) gauge field
with charge density wave order

Reconstructed (FL*) Fermi surfaces,
with large length scale confinement in the $u_2 < 0$ case



Confinement

Fermi liquid with
large Fermi surface

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Large N expansion yields $u_2 > 0$ near the quantum critical point. Influence of fermions can change sign of u_2 in the Higgs phase.

Deconfined critical SU(2) gauge theory

S. Hikami, Prog. Theor. Phys. **64**, 1425 (1980)