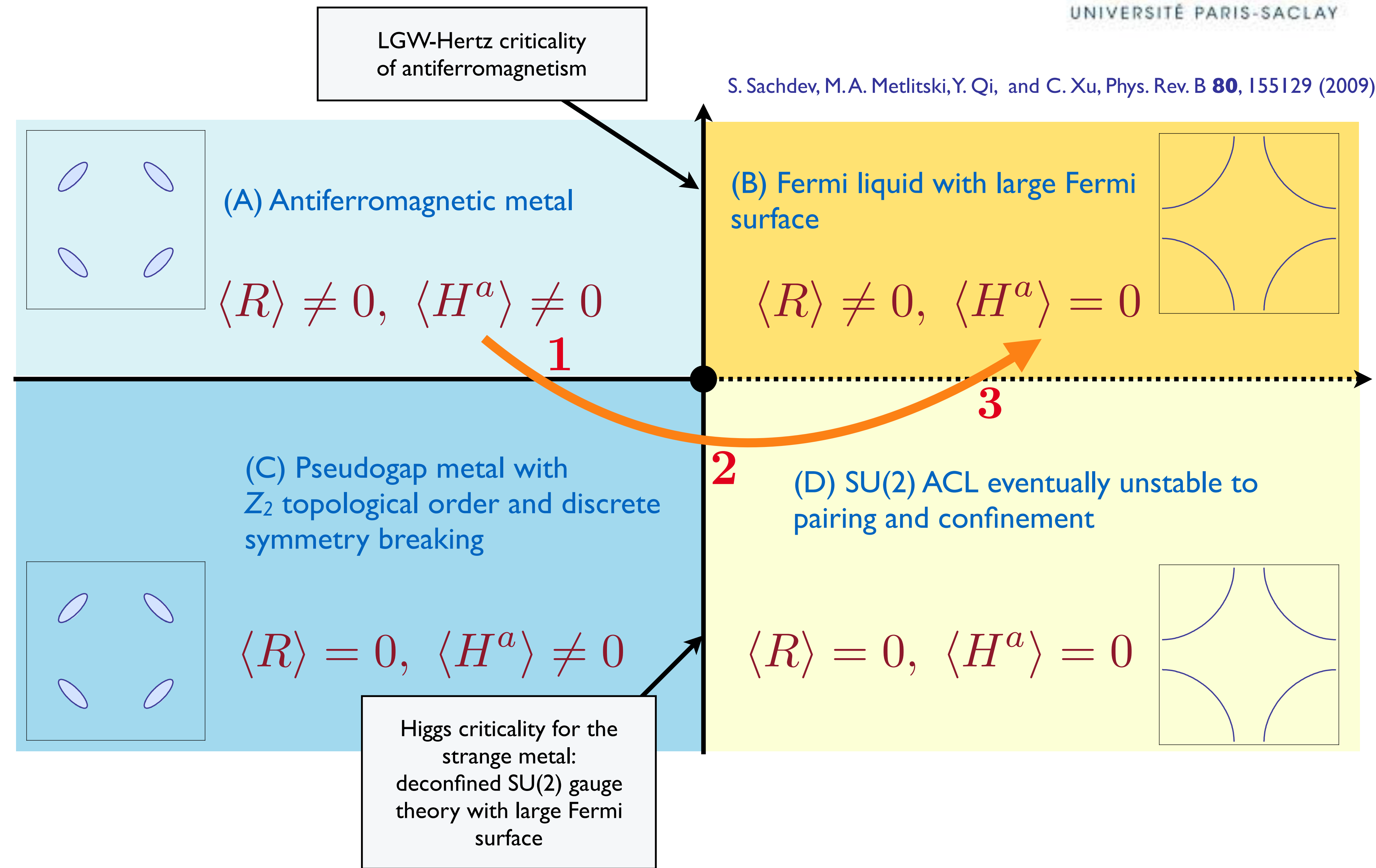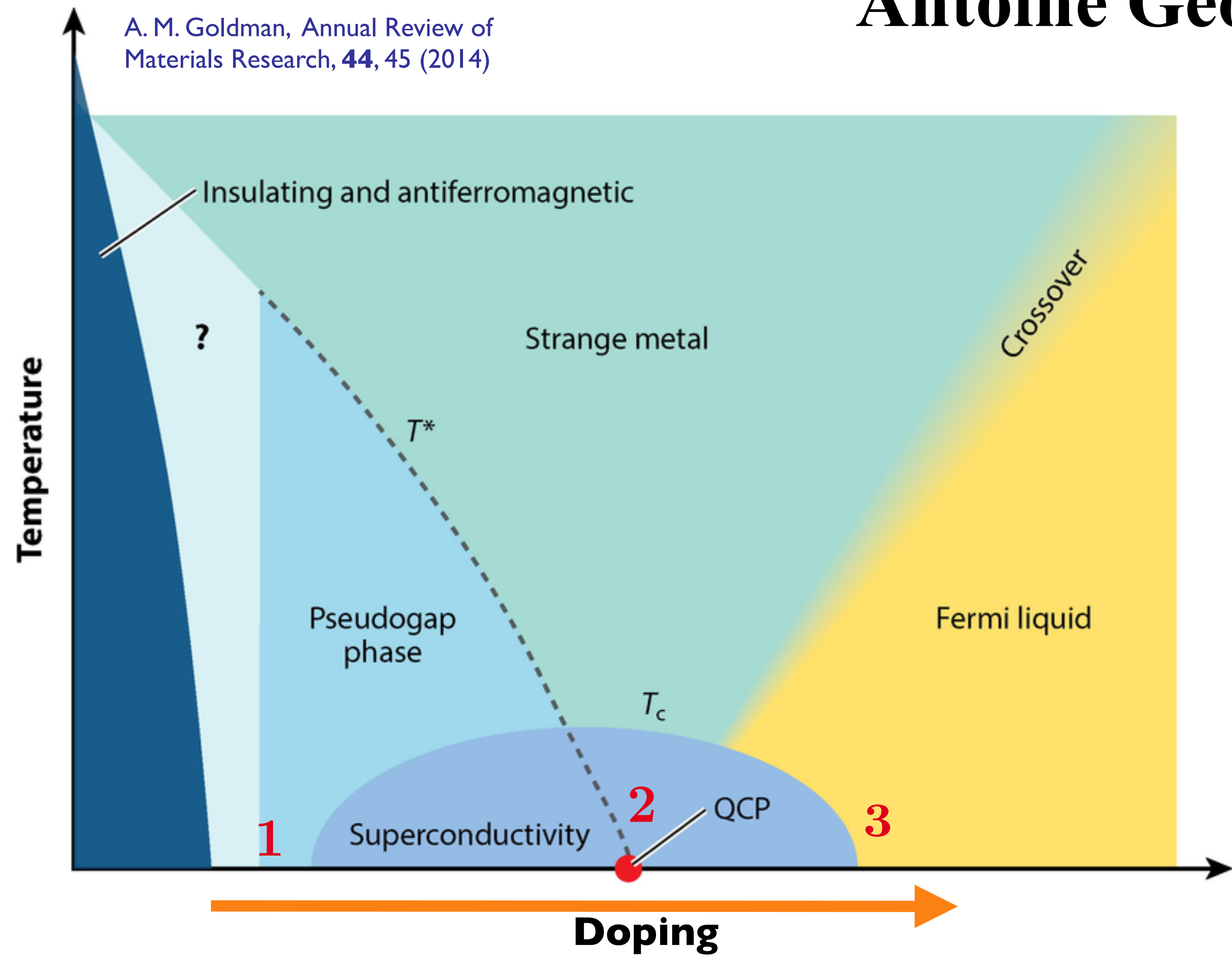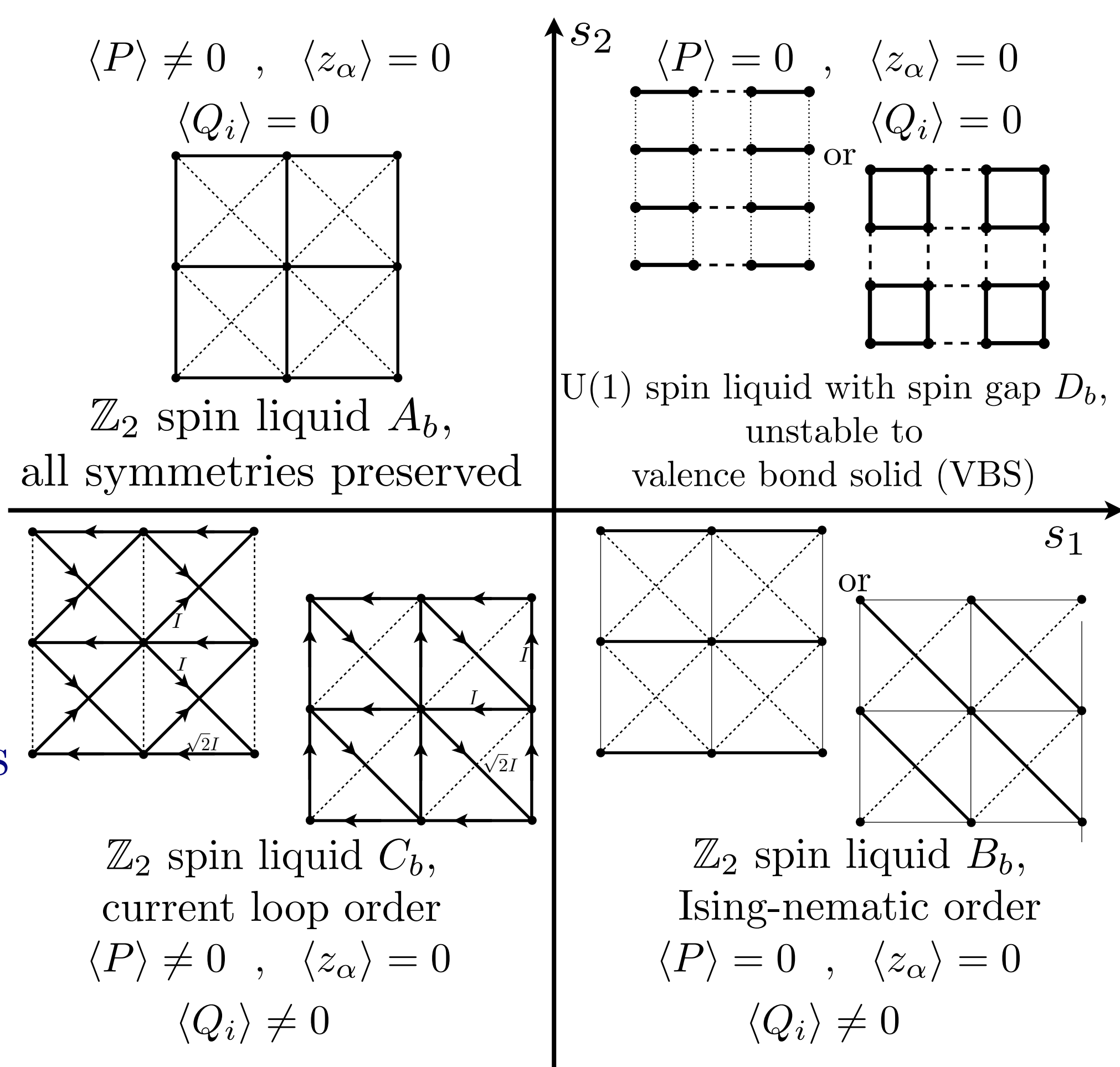# Topological order and DMFT/QMC spectra for the pseudogap metal of the cuprates

Mathias Scheurer, Shubhayu Chatterjee, Michel Ferrero, Antoine Georges, Subir Sachdev, Wei Wu

A. M. Goldman, Annual Review of Materials Research, **44**, 45 (2014)

LGW-Hertz criticality of antiferromagnetism

S. Sachdev, M.A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)

(A) Antiferromagnetic metal
$$\langle R \rangle \neq 0, \ \langle H^a \rangle \neq 0$$

(B) Fermi liquid with large Fermi surface
$$\langle R \rangle \neq 0, \ \langle H^a \rangle = 0$$

(C) Pseudogap metal with Z_2 topological order and discrete symmetry breaking
$$\langle R \rangle = 0, \ \langle H^a \rangle \neq 0$$

(D) SU(2) ACL eventually unstable to pairing and confinement
$$\langle R \rangle = 0, \ \langle H^a \rangle = 0$$

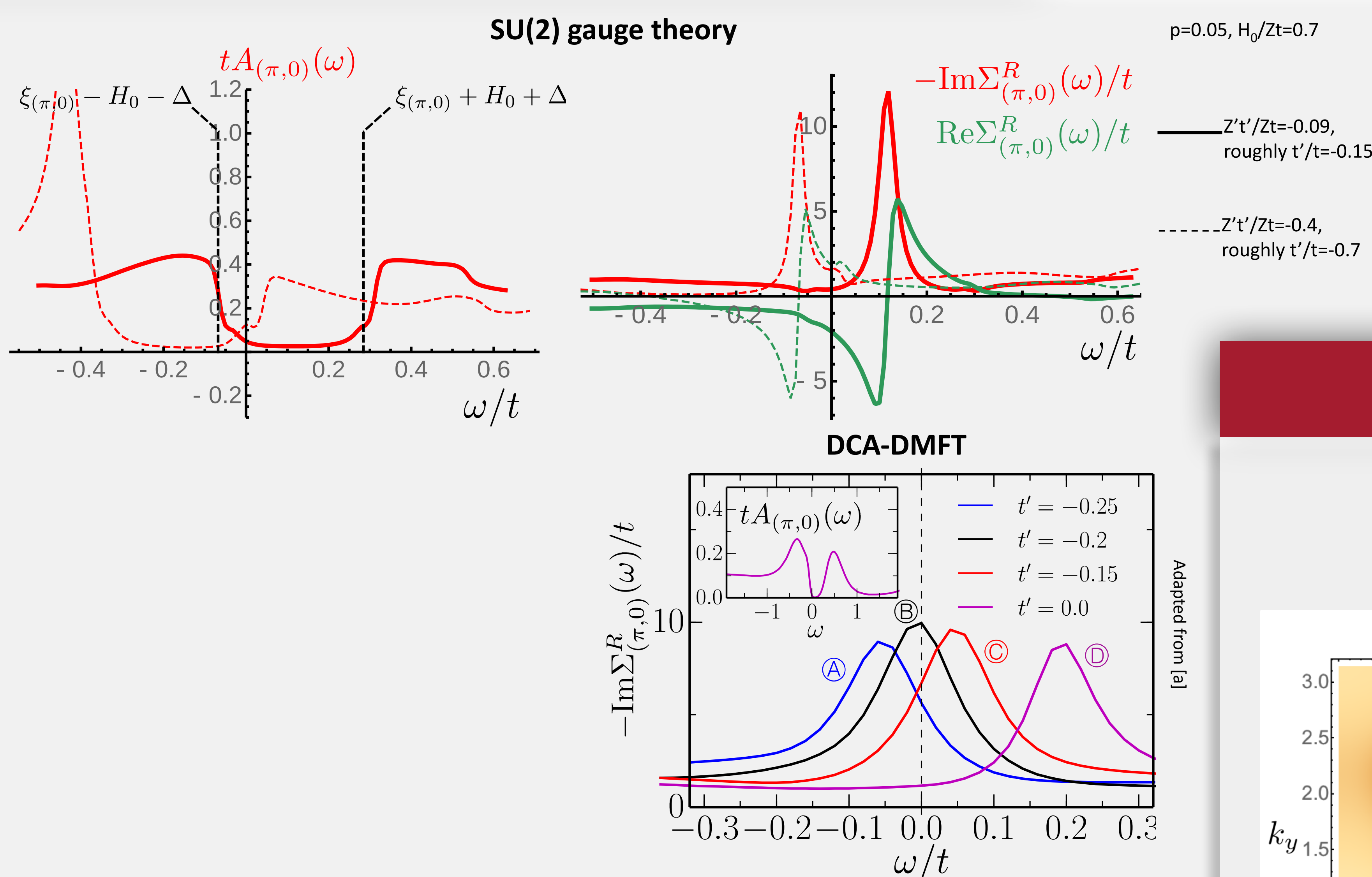Higgs criticality for the strange metal: deconfined SU(2) gauge theory with large Fermi surface

SU(2) gauge theory with bosonic spinons R, adjoint Higgs field H^a, and fermionic chargons ψ. R is a 2×2 unitary matrix which transforms the spin components of the electron into a rotating reference frame. The Higgs field, H^a, measures the local magnetic order in the rotating reference frame.

S. Chatterjee, S. Sachdev, and M. S. Scheurer, arXiv:1705.06289

The Higgs phase (C) realizes varieties of Z_2 topological order which intertwine with different broken symmetries (P and Q are related to components of the Higgs condensate H^a, and z_α to the spinon field R).

$\langle P \rangle \neq 0$, $\langle z_\alpha \rangle = 0$
$\langle Q_i \rangle = 0$

Z_2 spin liquid A_b, all symmetries preserved

$\langle P \rangle = 0$, $\langle z_\alpha \rangle = 0$
$\langle Q_i \rangle = 0$

U(1) spin liquid with spin gap D_b, unstable to valence bond solid (VBS)

Z_2 spin liquid C_b, current loop order
$\langle P \rangle \neq 0$, $\langle z_\alpha \rangle = 0$
$\langle Q_i \rangle \neq 0$

Z_2 spin liquid B_b, Ising-nematic order
$\langle P \rangle = 0$, $\langle z_\alpha \rangle = 0$
$\langle Q_i \rangle \neq 0$

$$c = R\,\psi \quad , \quad \sigma^a \Phi^a = R\,\sigma^b H^b\,R^\dagger$$

Field	Symbol	Statistics	$SU(2)_{gauge}$	$SU(2)_{spin}$	$U(1)_{e.m.charge}$
Electron	c	fermion	**1**	**2**	-1
Magnetic moment	Φ^a	boson	**1**	**3**	0
Chargon	ψ	fermion	**2**	**1**	-1
Spinon	R	boson	**2̄**	**2**	0
Higgs	H^a	boson	**3**	**1**	0

Spectra at the antinodal point (pi,0)

SU(2) gauge theory

DCA-DMFT

Adapted from [a]

Significant evidence for the presence of topological order in the pseudogap metal state of cluster DMFT/QMC studies of the Hubbard model.

Results for full Brillouin zone

SU(2) gauge theory

q-Integrand ⟶ Full Green's function

At larger T, **DQMC**: (T/t=0.25, U/t=7, t'/t=-0.1, p=0.042)

DCA-DMFT

k-interpolated **DMFT**

Adapted from [a]

Common features of phase C of SU(2) gauge theory and DMFT/QMC spectra:

- Nodal/anti-nodal dichotomy: spectra are metallic in the nodal directions, and "Mott insulating" along the anti-nodal directions

- Large enhancement of low frequency self-energy near $(\pi, 0)$.

- Near zeros of the electron Green's function along a "Luttinger surface". These signal topological order in Higgs phase, and a modified Luttinger theorem for the ψ Fermi surfaces.

[a] Stanescu and Kotliar, Phys. Rev. B **74**, 125110 (2006).