Quantum Monte Carlo Simulations on Gauge fields couple to Matter fields

ZI YANG MENG
孟子杨

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Rhine Samajdar (Harvard)
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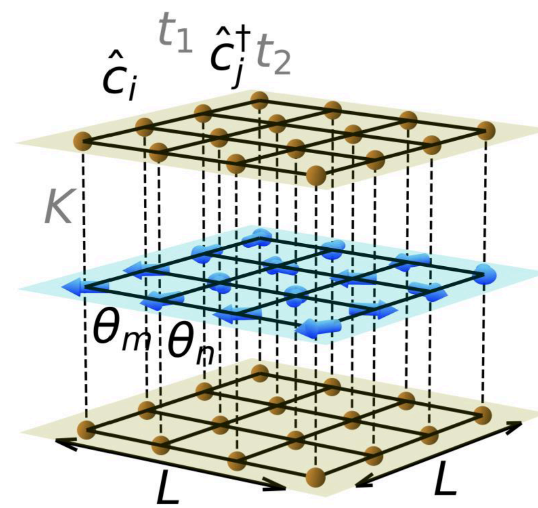
Content

1. Non-Fermi-Liquid
   Quantum critical metals
   Luttinger's theorem
   Matter fields coupled to gauge fields



- PRX 7, 031058 (2017)
- PNAS 116 (34), 16760 (2019)
- npj Quantum Materials 5, 65 (2020)
- PRB 105, L041111 (2022)
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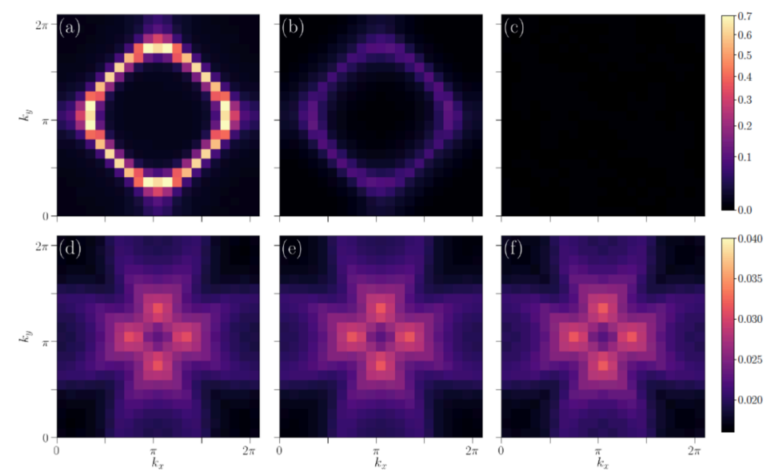

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- CPL 37, 047103 (2020)
- PRB 103, 165131 (2021)
- ......

2. Fractionalisation, topological order in frustrated magnets
   Quantum dimer models

- PRL 121, 077201 (2018)
- PRL 121, 057202 (2018)
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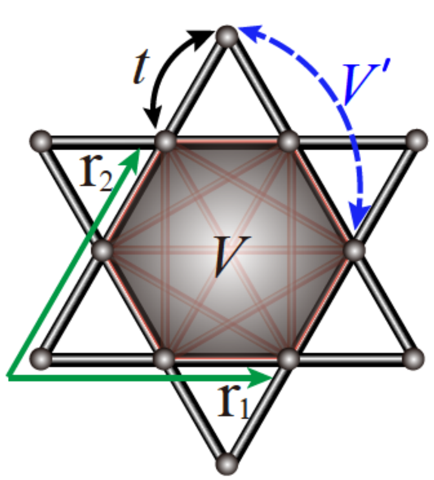

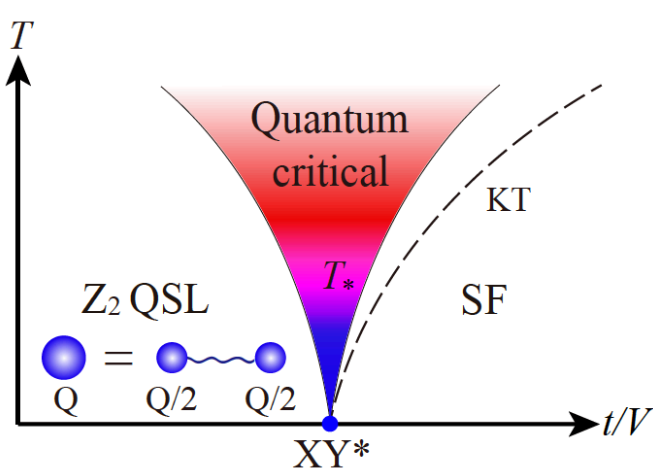

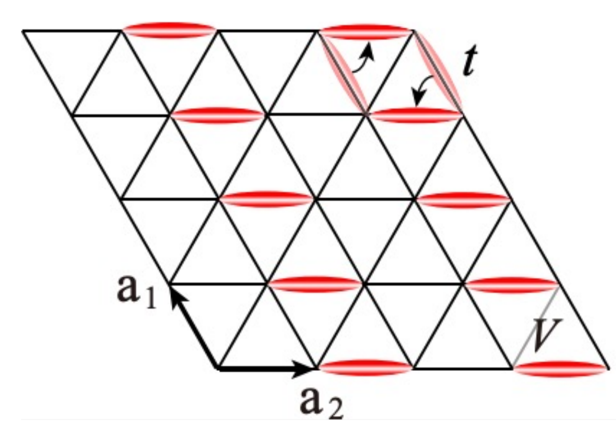

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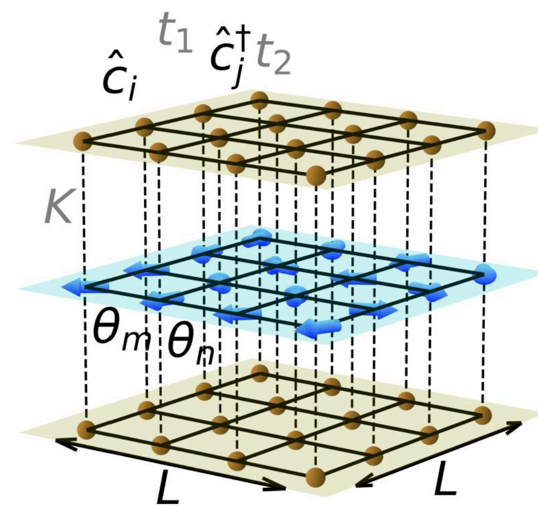

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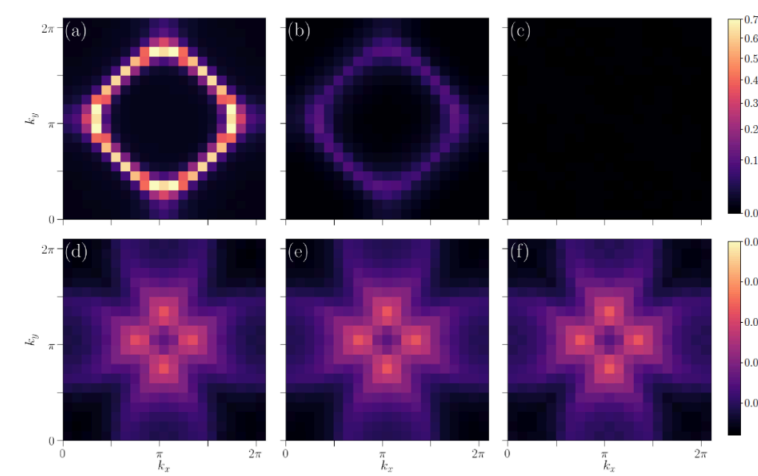

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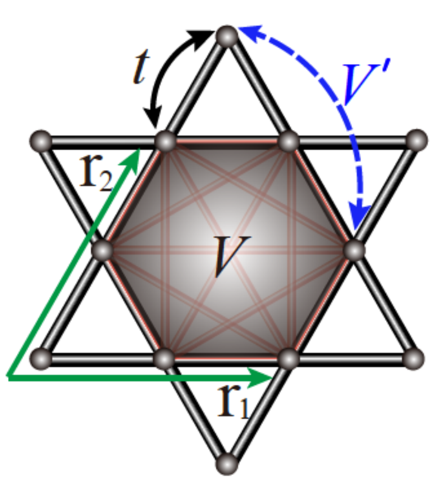
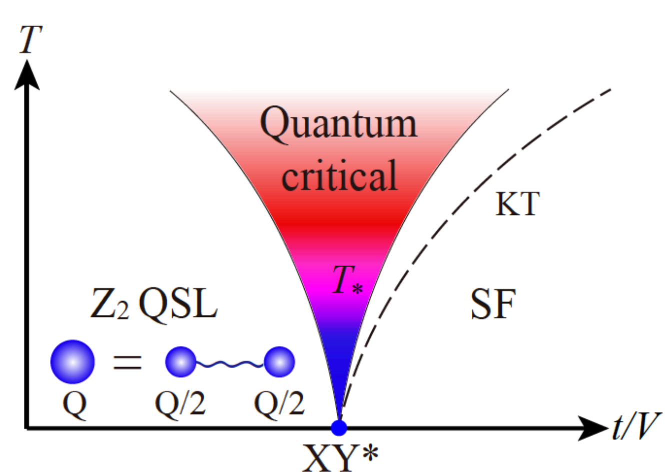
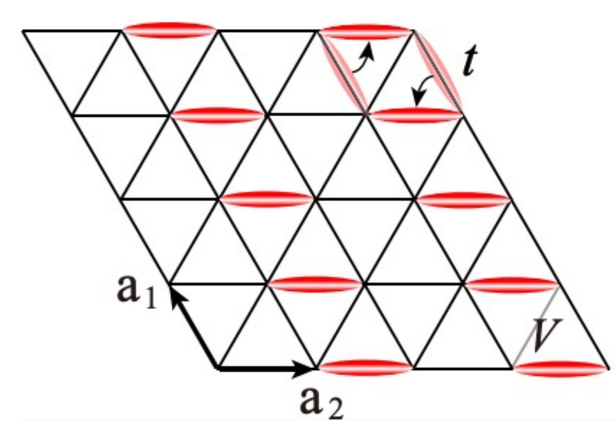






Determinant quantum Monte Carlo

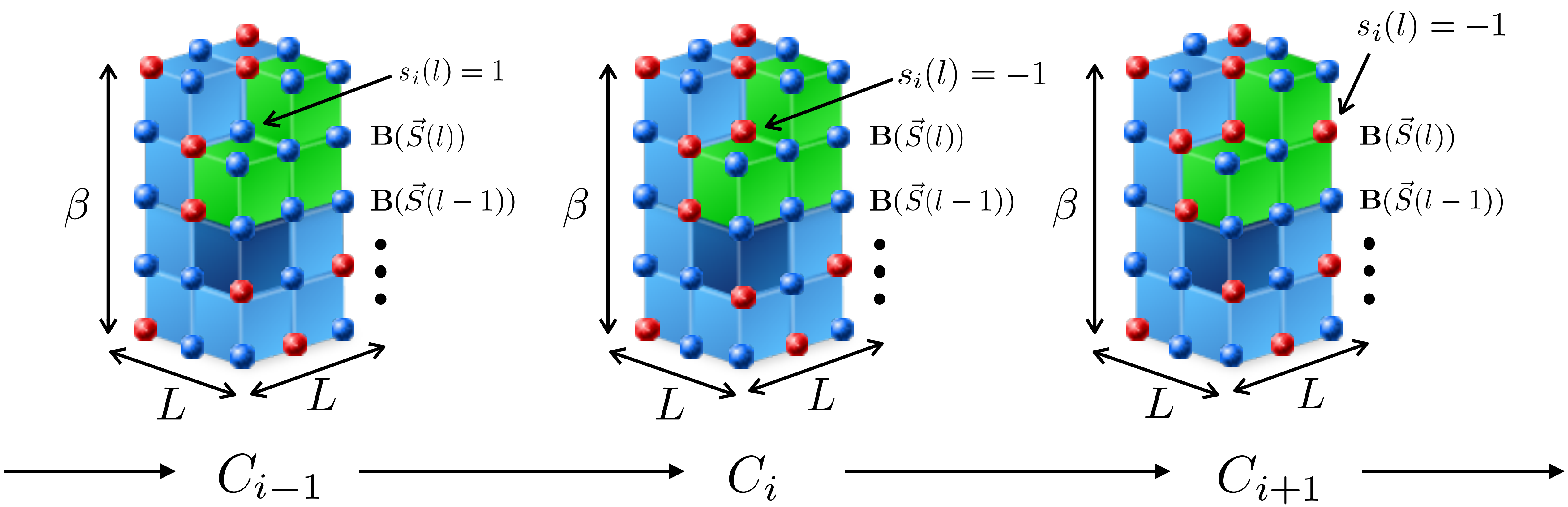
- Write Path-integral into determinant

$$Z = \mathrm{Tr}[\prod_{l=1}^{m} e^{-\Delta\tau \hat{H}_t} e^{-\Delta\tau \hat{H}_U}] = C^m \sum_{\vec{s}_1, \vec{s}_2, \cdots, \vec{s}_m} \det[\mathbf{1} + \mathbf{B}_m \mathbf{B}_{m-1} \cdots \mathbf{B}_1]$$

$$\mathbf{B}_l = e^{-\Delta\tau \mathbf{H_t}} e^{-\Delta\tau \mathbf{H_U}(\vec{s}(l))}$$

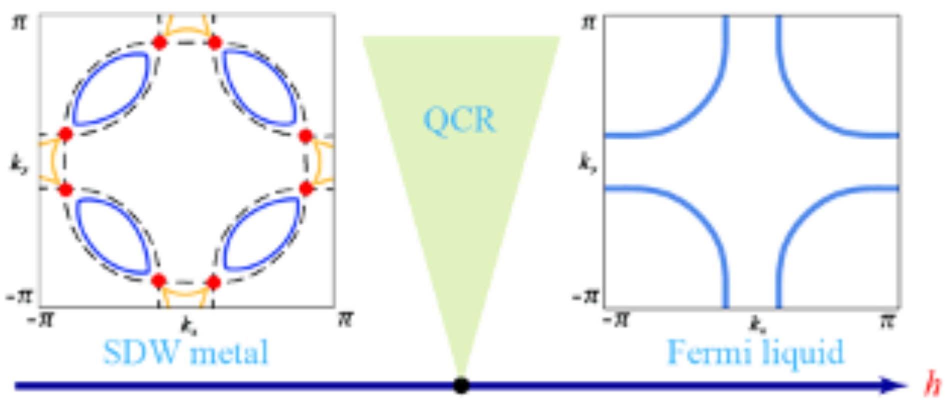
- Monte Carlo sampling in configuration space

$$\mathbf{H_U}(\vec{s}(l)) \propto \alpha \vec{s}(l)$$

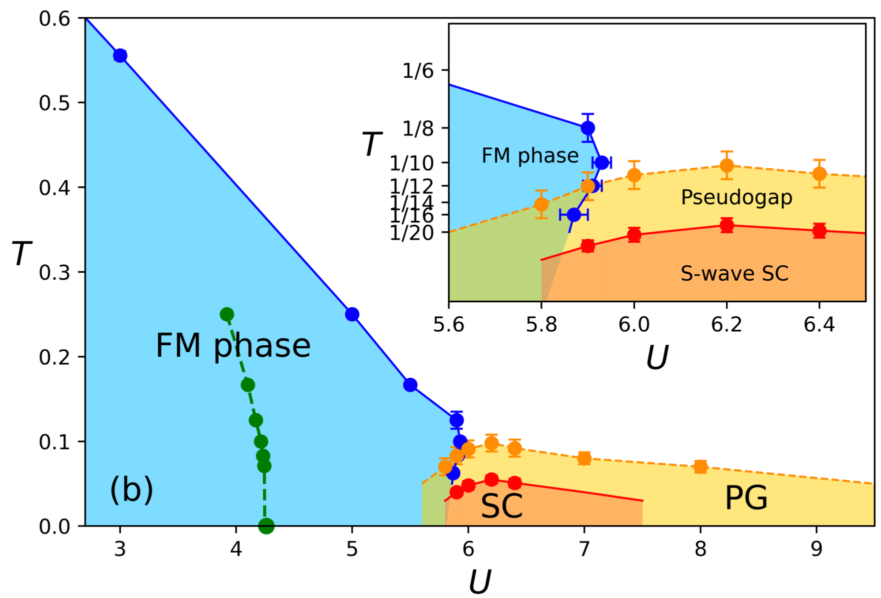


Sign Problem in quantum Monte Carlo simulation, Gaopei Pan & ZYM, arXiv:2204.08777

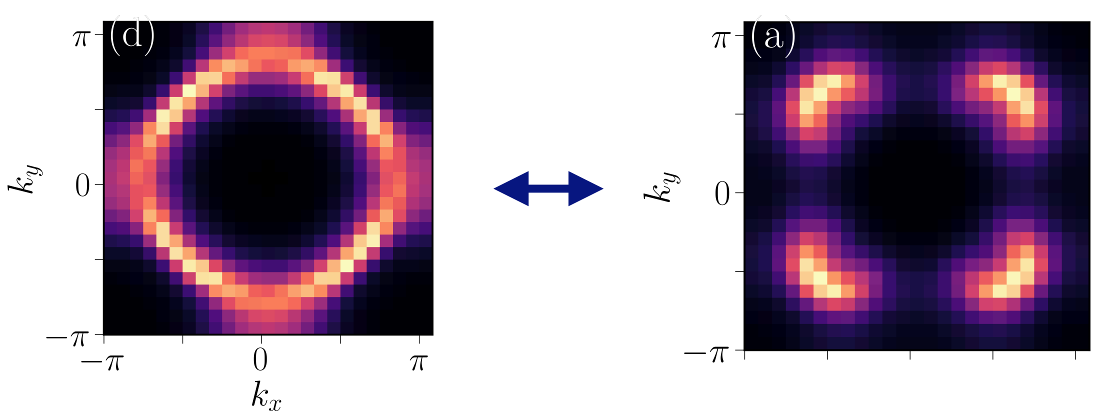
Fermions couple to critical boson / gauge modes



PNAS 116 (34), 16760 (2019)

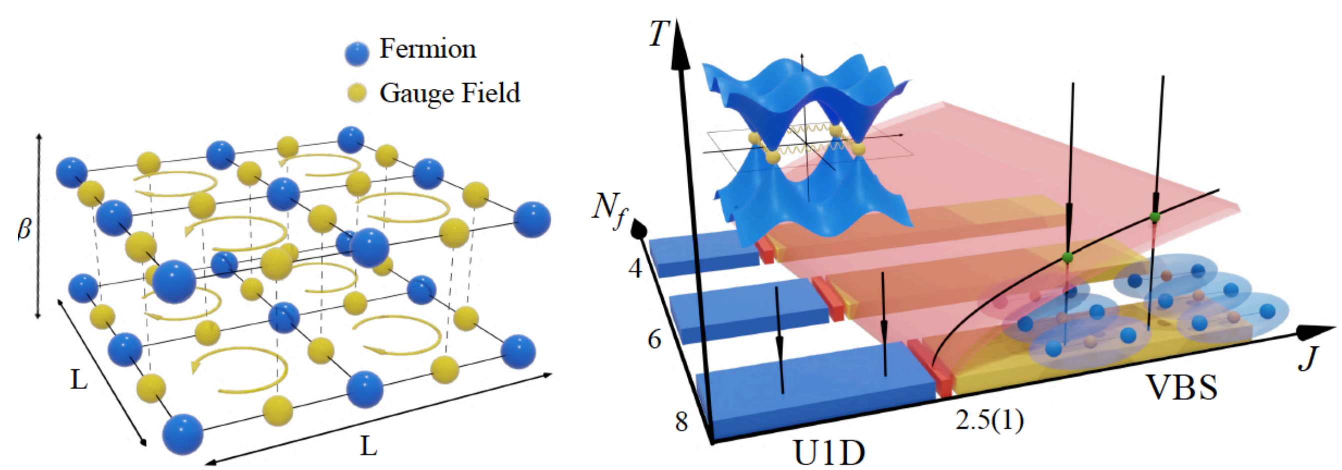


Nat. Comm. in press (2022)



PRB 103, 165131 (2021)

- Itinerant quantum critical point
- Non-Fermi-liquid
- Pseudogap and superconductivity
- Z2 gauge field, orthogonal metal, Fermi arc
- U1 gauge field, Dirac / algebraic spin liquid



PRX 9, 021022 (2019)

Model

$$H = \sum_{\mathbf{k},\alpha} \mathbf{v}_k \cdot (\mathbf{k} - \mathbf{k}_F) c^\dagger_{\mathbf{k},\alpha} c_{\mathbf{k},\alpha} + \sum_{\mathbf{q}} \chi_0^{-1}(\mathbf{q}) \mathbf{S}_{\mathbf{q}} \cdot \mathbf{S}_{-\mathbf{q}} + g \sum_{\mathbf{q},\mathbf{k},\alpha,\beta} c^\dagger_{\mathbf{k}+\mathbf{q},\alpha} \sigma_{\alpha,\beta} c_{\mathbf{k},\beta} \cdot \mathbf{S}_{-\mathbf{q}}$$

$$S = -\int_0^\beta d\tau \int_0^\beta d\tau' \sum_{k,\alpha} c^\dagger_{\mathbf{k},\sigma} G_0^{-1}(\mathbf{k}, \tau - \tau') c_{\mathbf{k},\sigma}(\tau')$$
$$+\frac{1}{2} \int_0^\beta d\tau \int_0^\beta d\tau' \sum_q \chi_0^{-1}(\mathbf{q}) \mathbf{S}_q(\tau) \cdot \mathbf{S}_{-q}(\tau')$$
$$+g \int_0^\beta d\tau \sum_q \mathbf{s}_q(\tau) \cdot \mathbf{S}_{-q}(\tau)$$

$$\chi_0(\mathbf{q}, \omega) = \frac{\chi_0}{\xi^{-2} + (\mathbf{q} - \mathbf{Q})^2 - (\omega / v_s)^2}$$

$$G_0^{-1}(\mathbf{k}, \tau) = \partial_\tau - \mathbf{v}_k \cdot (\mathbf{k} - \mathbf{k}_F)$$

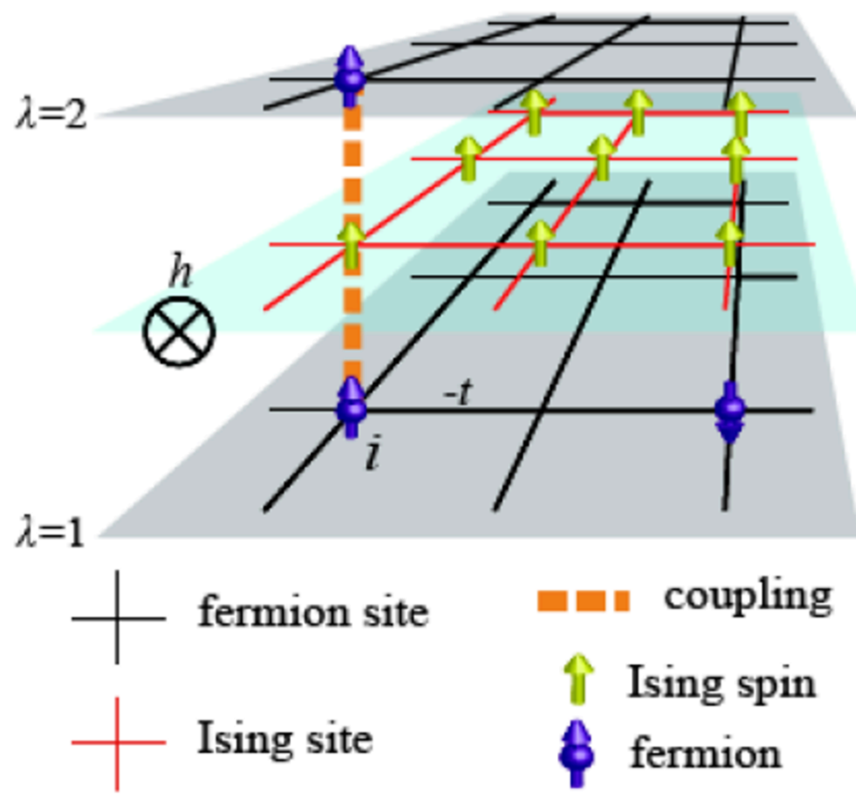
- Abanov, Chubukov, Schmalian, Adv. in Phys. 52, 119 (2003)
- Metlitski, Sachdev, PRB 82, 075127 (2010)
- Metlitski, Sachdev, PRB 82, 075128 (2010)
- Sung-Sik Lee, Annu. Rev. Condens. Matter Phys 9, 227 (2018)

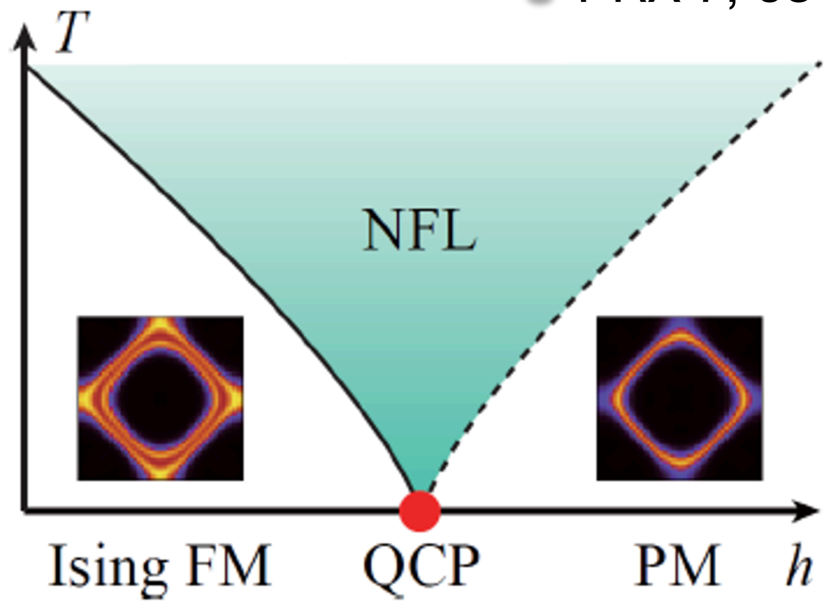
Revealing fermionic quantum criticality from new Monte Carlo techniques
Xiao Yan Xu, Zi Hong Liu, Gaopei Pan, Yang Qi, Kai Sun, ZYM
J. Phys.: Condens. Matter 31 463001 (2019)

Non-Fermi Liquid at (2+1)D Ferromagnetic Quantum Critical Point

Xiao Yan Xu,[1] Kai Sun,[2] Yoni Schattner,[3] Erez Berg,[3] and Zi Yang Meng[1]

PRX 7, 031058 (2017)





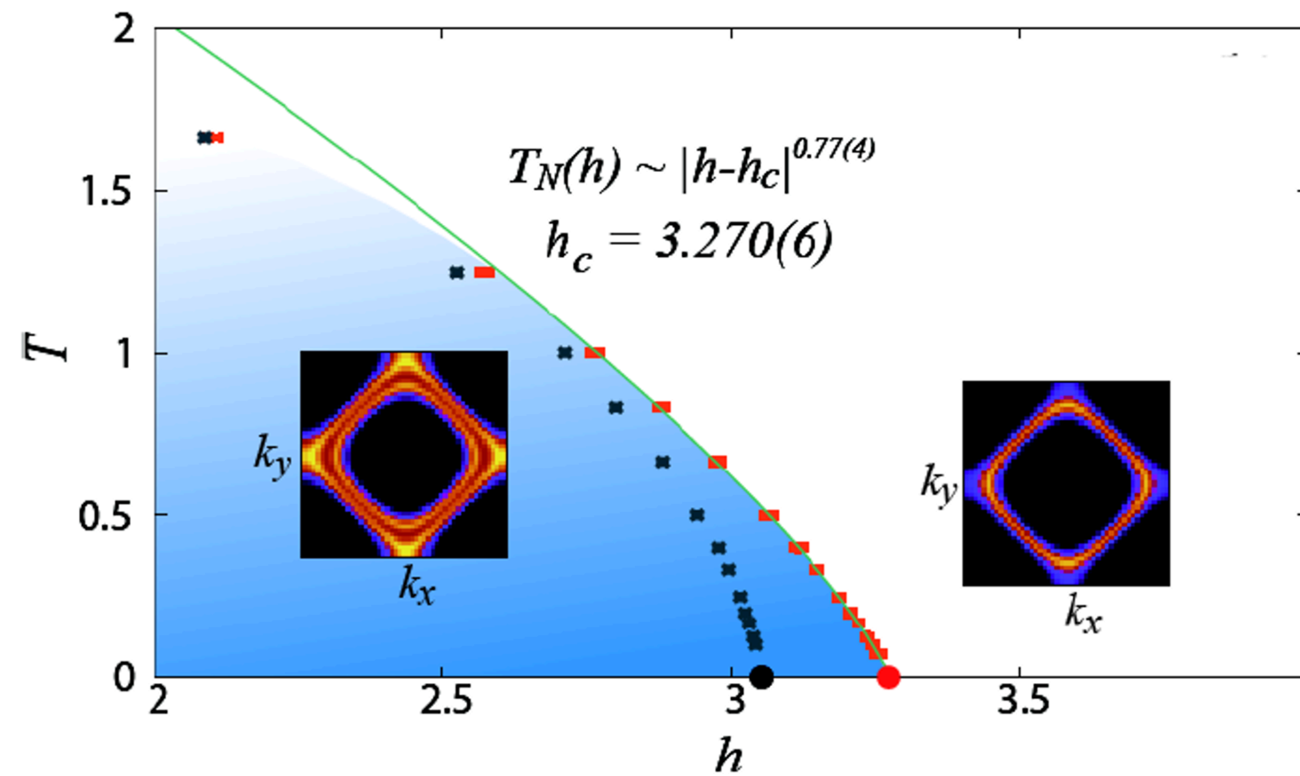
$\underbrace{SU(2) \times SU(2)}_{\text{orbital rotation for } \uparrow \text{ and } \downarrow}$ $\underbrace{U(1) \times U(1)}_{\text{charge conservation for } \uparrow \text{ and } \downarrow}$ $\underbrace{Z_2}_{\text{interchange } \uparrow \text{ and } \downarrow \text{ while flipping } s^z}$

$$\hat{H} = \hat{H}_f + \hat{H}_s + \hat{H}_{sf}$$

$$\hat{H}_f = -t \sum_{\langle ij \rangle \lambda \sigma} \hat{c}^{\dagger}_{i\lambda\sigma} \hat{c}_{j\lambda\sigma} + h.c. - \mu \sum_{i\lambda\sigma} \hat{n}_{i\lambda\sigma}$$

$$\hat{H}_s = -J \sum_{\langle ij \rangle} \hat{s}^z_i \hat{s}^z_j - h \sum_i \hat{s}^x_i$$

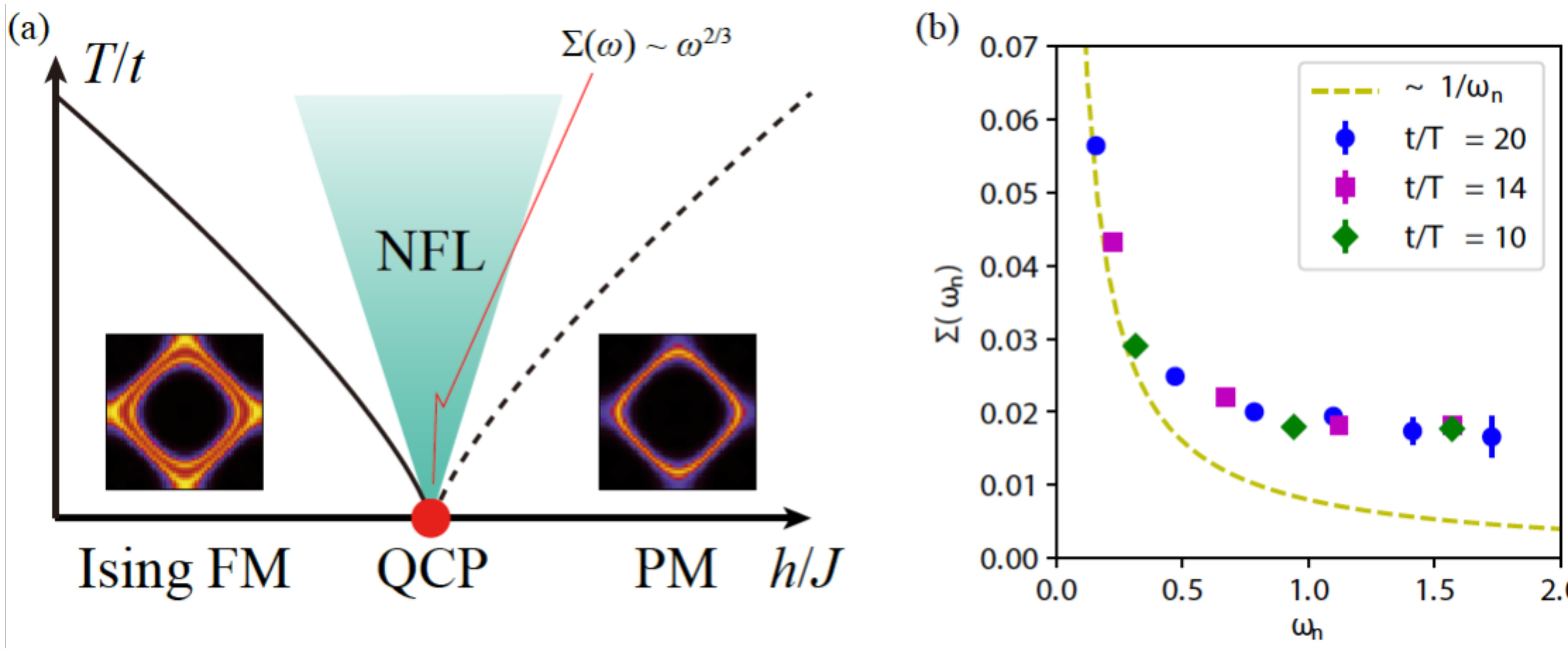
$$\hat{H}_{sf} = -\xi \sum_{i\lambda} s^z_i (n_{i\lambda\uparrow} - n_{i\lambda\downarrow})$$



Identification of non-Fermi liquid fermionic self-energy from quantum Monte Carlo data

Xiao Yan Xu[1]✉, Avraham Klein[2], Kai Sun[3], Andrey V. Chubukov[2] and Zi Yang Meng[4,5,6]✉

npj Quantum Materials 5, 65 (2020)



$\omega_F \quad << \quad \Sigma \quad << \quad \pi T\,,\ \bar{g}\,,\ \omega_b \quad << \quad E_F$

QMC data

$$\Sigma(\omega_n) = \Sigma_T(\omega_n) + \Sigma_Q(\omega_n)$$

$$\Sigma_T(\omega_n) \approx \alpha(T)/\omega_n$$

$$\Sigma_Q(\omega_n) \to \omega_n^{2/3}$$

$\bar{g} \ll$ **bandwidth**/E_F

$$\Sigma(\omega_n) \ll \omega_n$$

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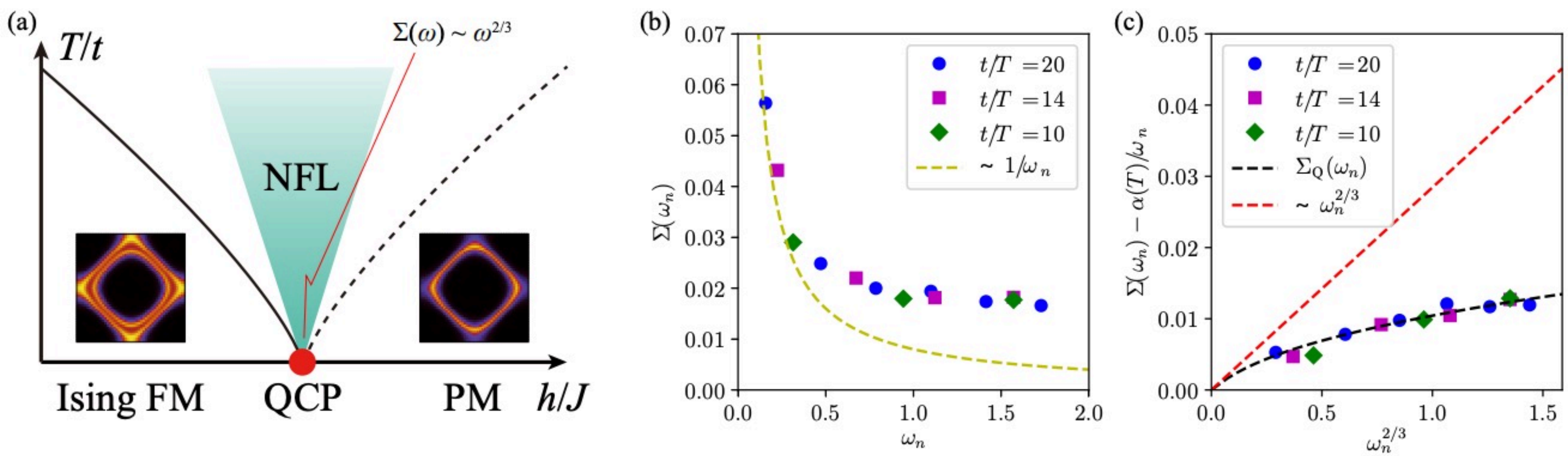


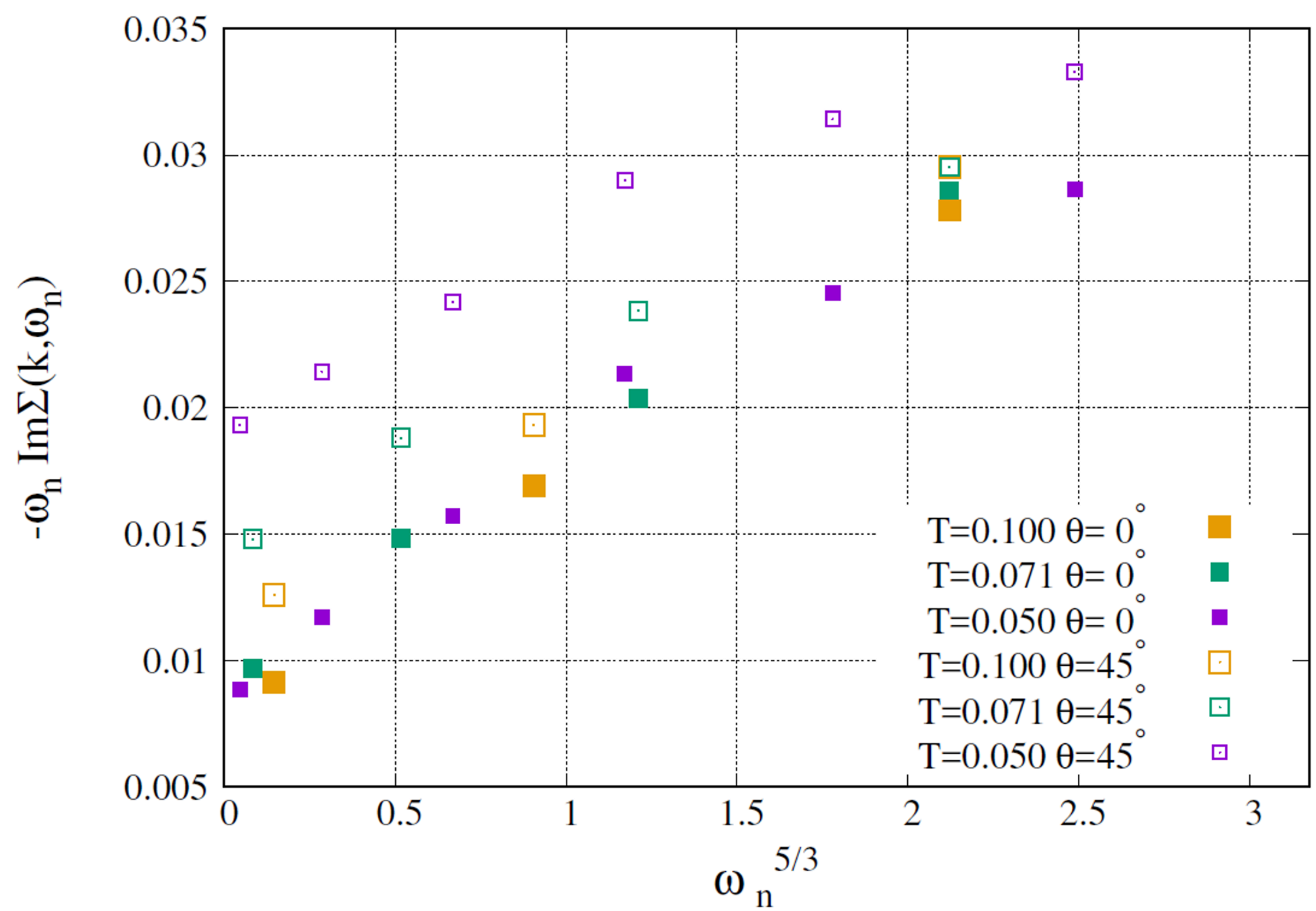
$$\Sigma(\omega_n) = \Sigma_T(\omega_n) + \Sigma_Q(\omega_n)$$

$$\Sigma_T(\omega_n) = \alpha(T)/\omega_n$$

$$\Sigma_Q(\omega_n) = \omega_F^{1/3}\omega_n^{2/3} + \cdots$$

$$\omega_F = \frac{\bar{g}^2}{8\pi^2 3^{3/2}\mathcal{V}_F v_F^2 N_f}$$

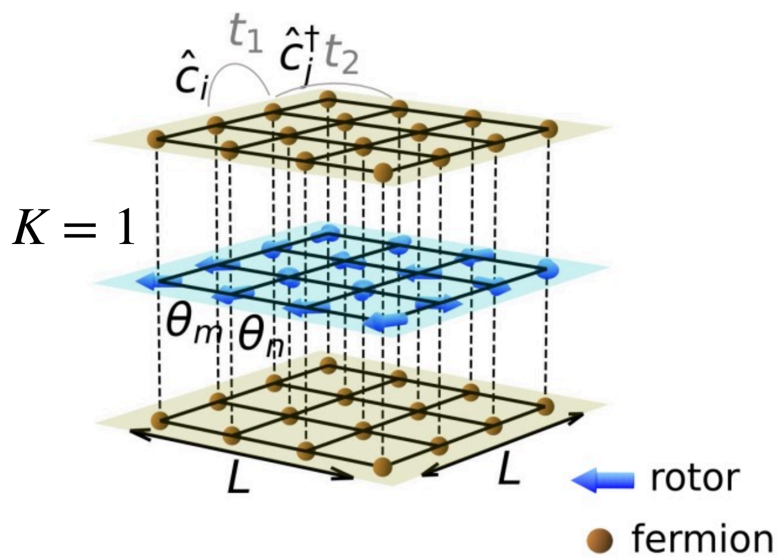
$$\omega_n\Sigma(\omega_n) = \alpha(T) + \omega_F^{1/3}\omega_n^{5/3} + \cdots$$

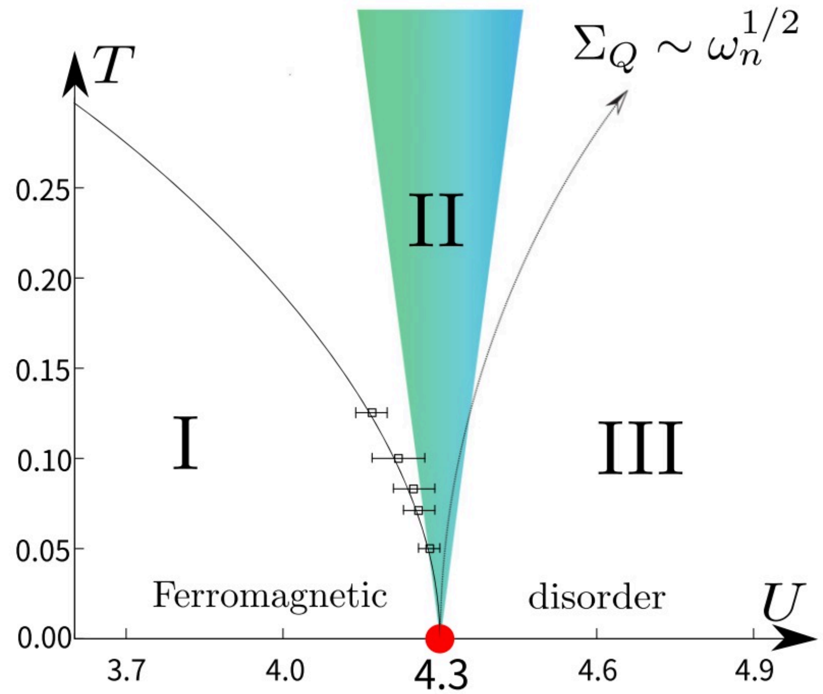


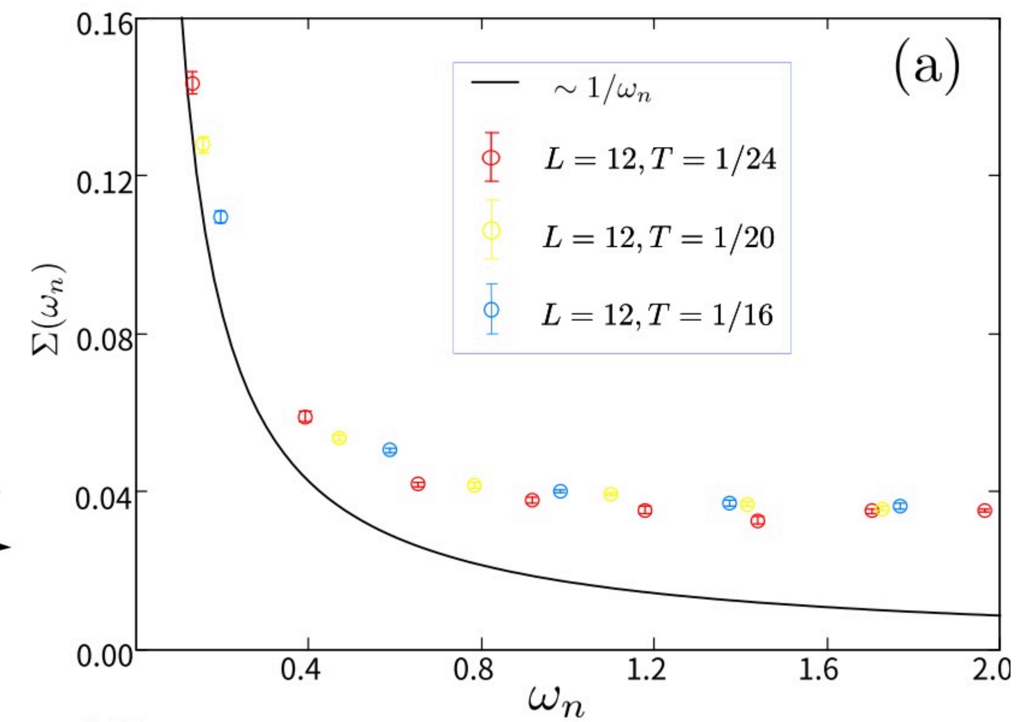
Dynamical exponent of a quantum critical itinerant ferromagnet: A Monte Carlo study

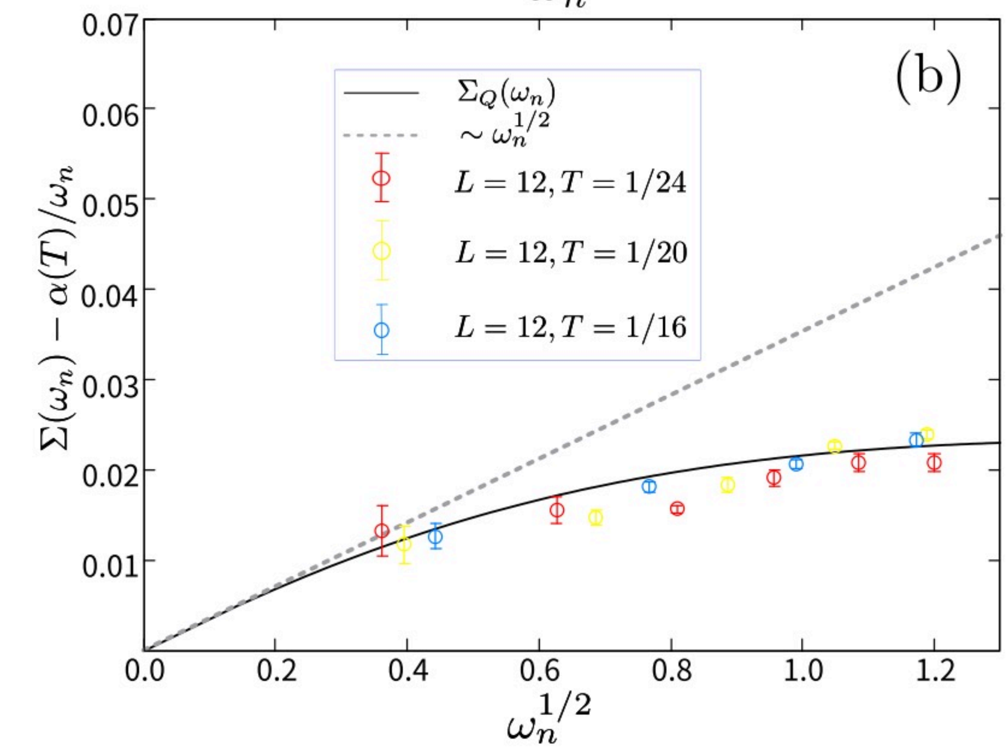
Yuzhi Liu[1,2] Weilun Jiang,[1,2] Avraham Klein[3] Yuxuan Wang,[4] Kai Sun,[5] Andrey V. Chubukov[6] and Zi Yang Meng[7,1,*]

PRB 105, L041111 (2022)









$$H = H_f + H_{qr} + H_{qr-f}$$

$$\hat{H}_{\mathrm{f}} = -t_1 \sum_{\langle i,j\rangle\sigma\lambda} \hat{c}^+_{i\sigma\lambda}\hat{c}_{j\sigma\lambda} - t_2 \sum_{\langle\langle i,j\rangle\rangle\sigma\lambda} \hat{c}^+_{i\sigma\lambda}\hat{c}_{j\sigma\lambda} - \mu \sum_{i\sigma\lambda} \hat{n}_{i\sigma\lambda}$$

$$\hat{H}_{\mathrm{qr}} = \frac{U}{2}\sum_i \hat{L}_i^2 - t_b \sum_{\langle i,j\rangle} \cos\left(\hat{\theta}_i - \hat{\theta}_j\right)$$

$$\hat{H}_{\text{qr-f}} = -\frac{K}{2}\sum_{i\lambda} \hat{c}^+_{i\lambda}\boldsymbol{\sigma}\hat{c}_{i\lambda}\cdot\hat{\boldsymbol{\theta}}_i = -\frac{K}{2}\sum_{i\lambda}\left(\hat{c}^+_{i\lambda}\sigma^x\hat{c}_{i\lambda}\cdot\cos\hat{\theta}_i + \hat{c}^+_{i\lambda}\sigma^y\hat{c}_{i\lambda}\cdot\sin\hat{\theta}_i\right)$$

$$\Sigma_T(\omega_n) \sim \alpha(T)/\omega_n$$

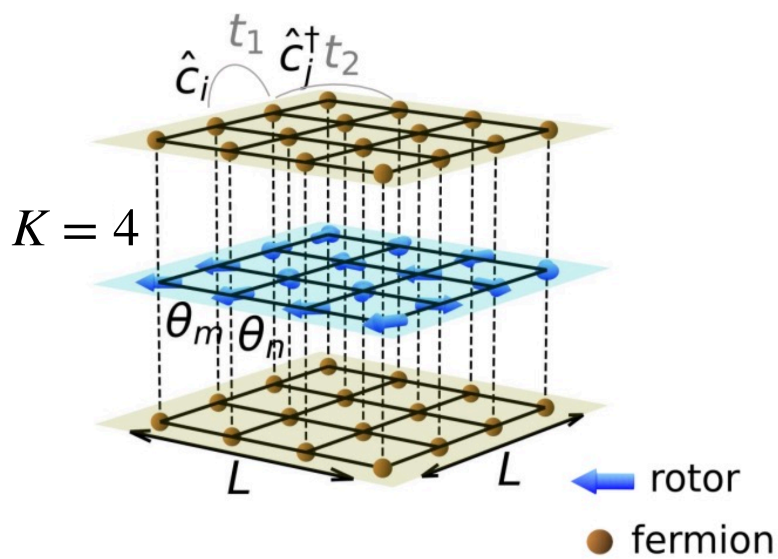
$$\Sigma(\omega_n) = \Sigma_T(\omega_n) + \Sigma_Q(\omega_n)$$

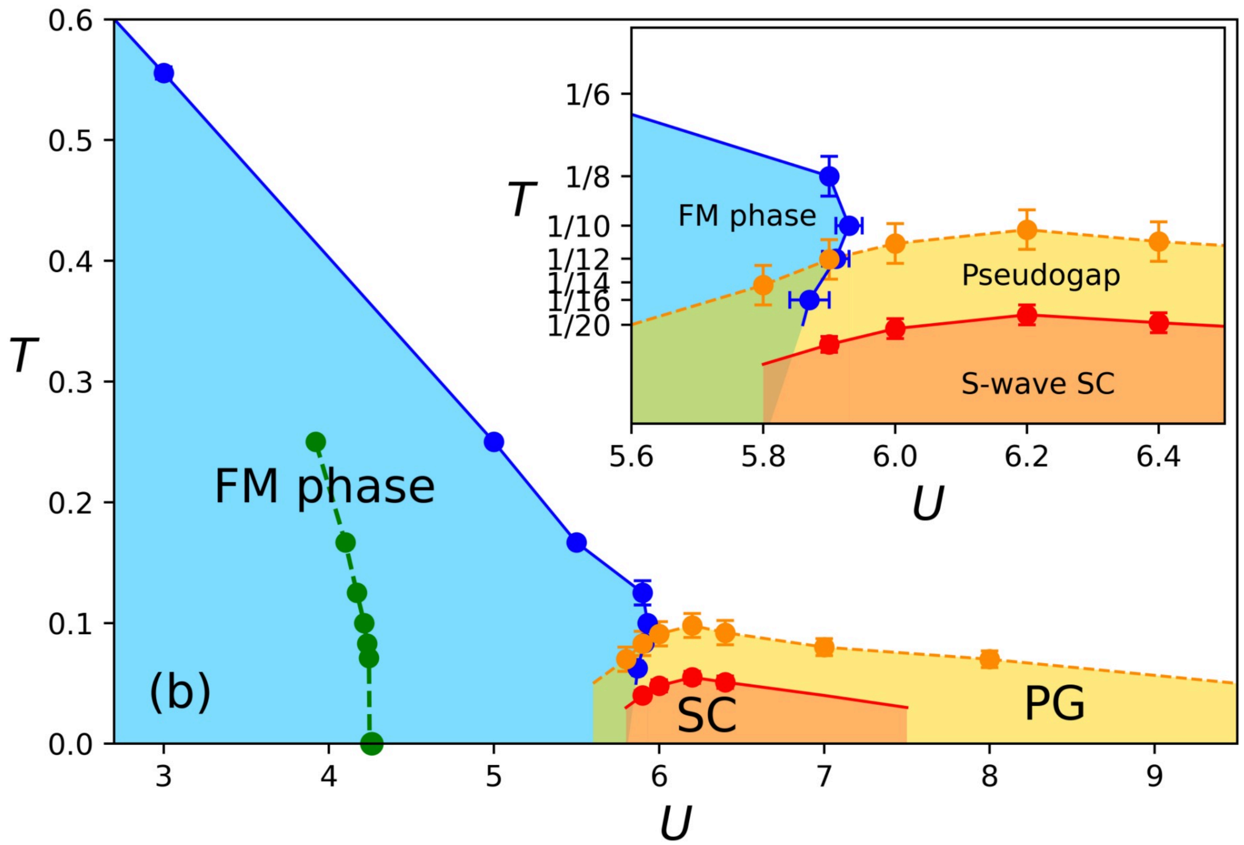
$$\Sigma_Q(\omega_n) \sim (\omega_n)^{1/2} f(\omega_n/\omega_c) + \cdots$$

Pseudogap and superconductivity emerging from quantum magnetic fluctuations: a Monte Carlo study

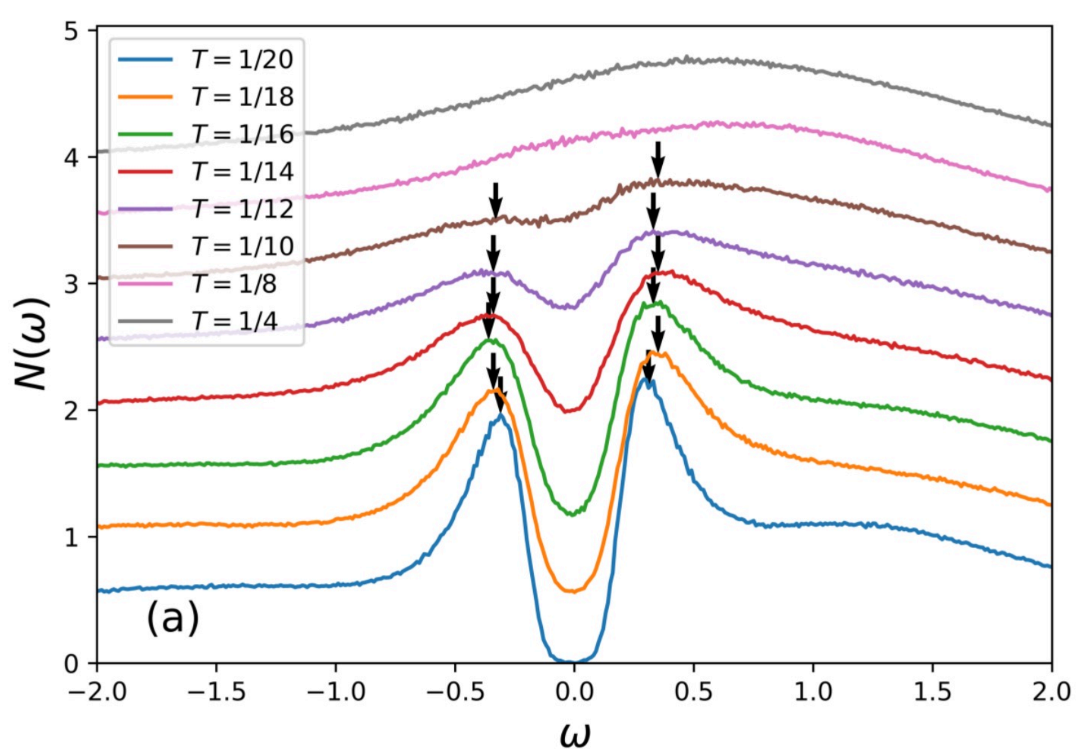
Weilun Jiang,[1,2] Yuzhi Liu,[1,2] Avraham Klein,[3] Yuxuan Wang,[4] Kai Sun,[5] Andrey V. Chubukov,[6] and Zi Yang Meng[7,1,*]

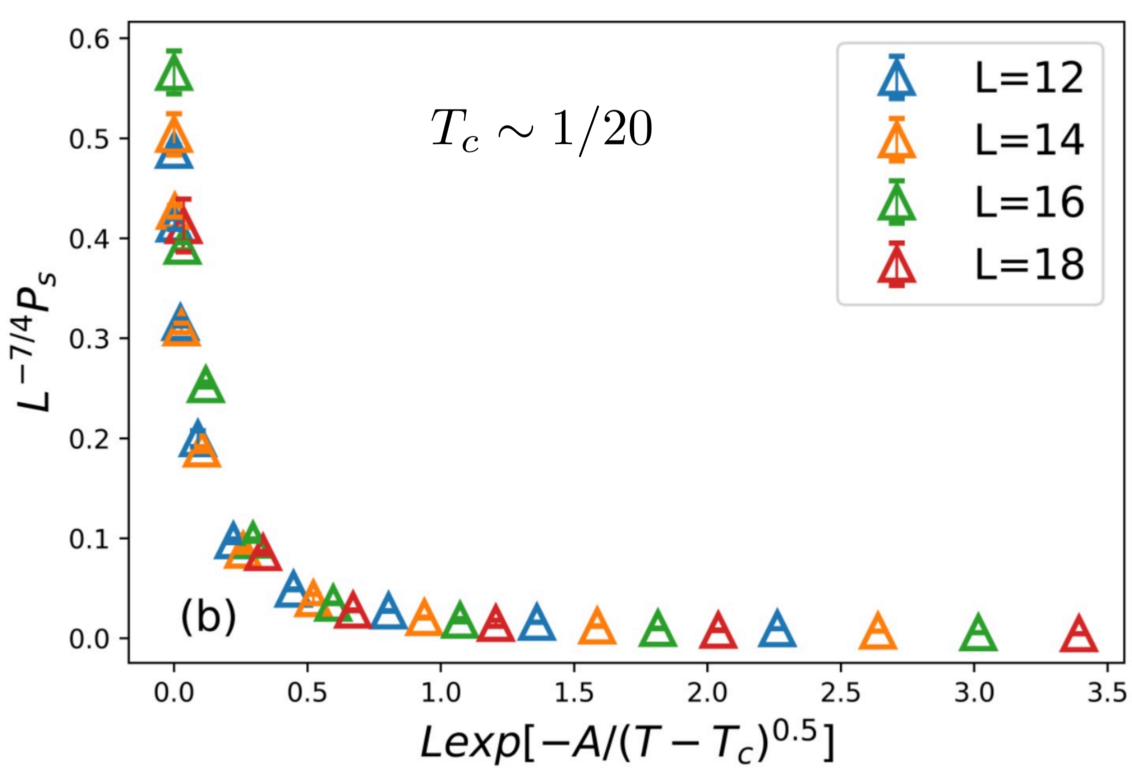
Nat. Comm. 13, 2655 (2022)





- **Pseudogap filling, not BCS**
- **DOS progressively depleted upon lowering T**



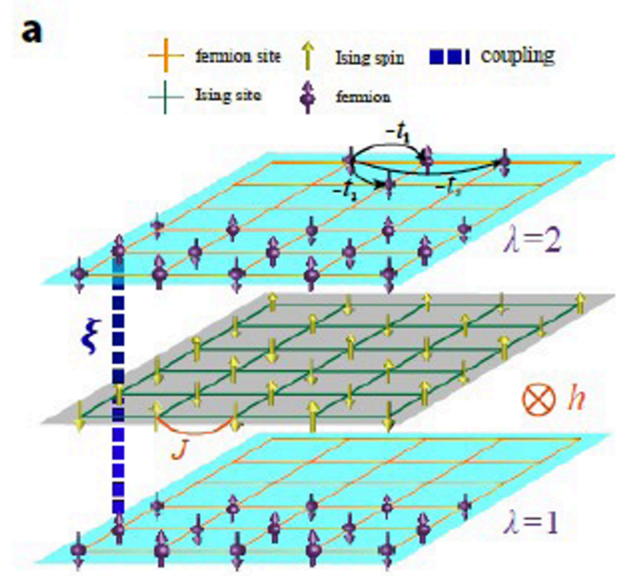


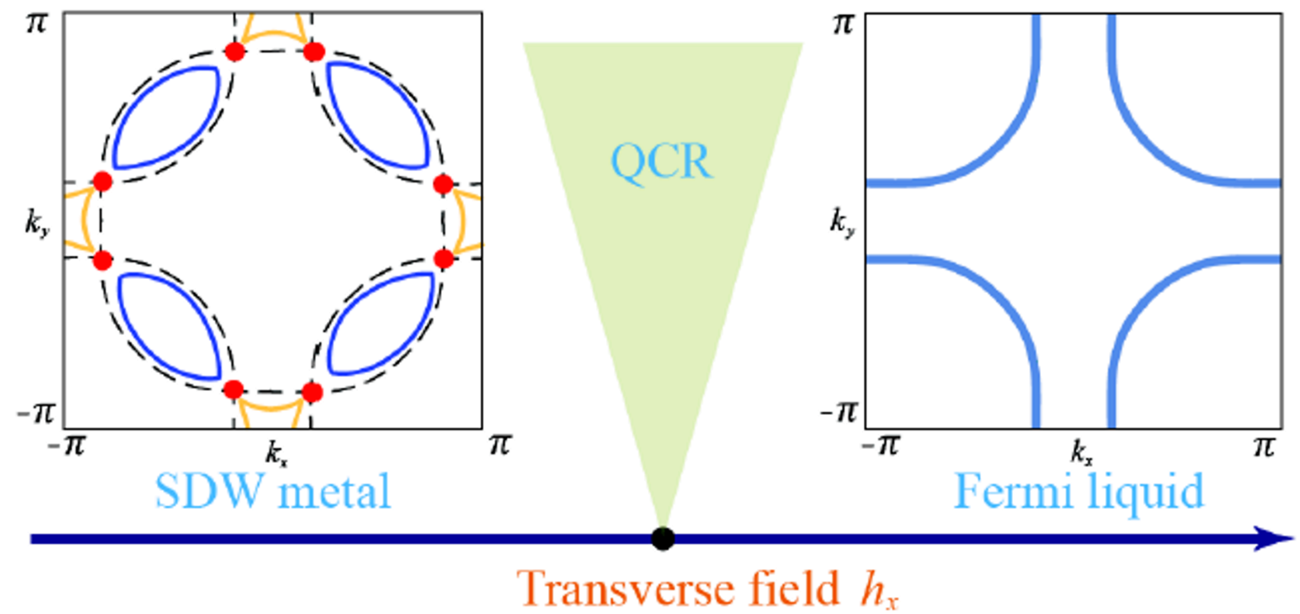
Itinerant quantum critical point with fermion pockets and hotspots

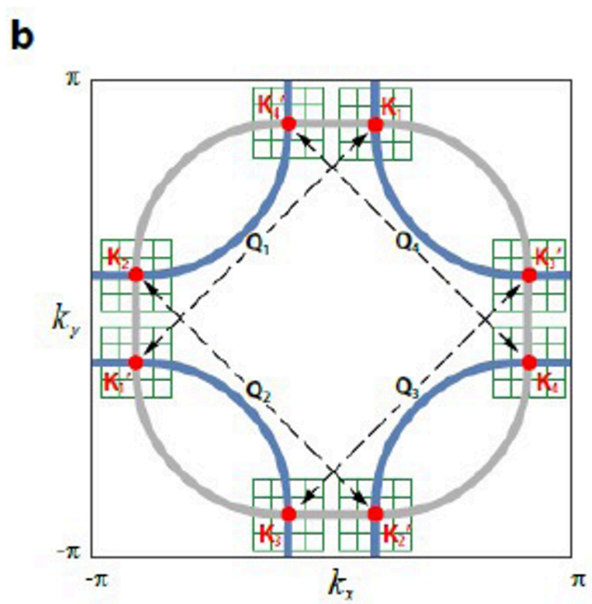
Zi Hong Liu[a,b], Gaopei Pan[a,b], Xiao Yan Xu[c], Kai Sun[d], and Zi Yang Meng[e,a,f,g,h,1]

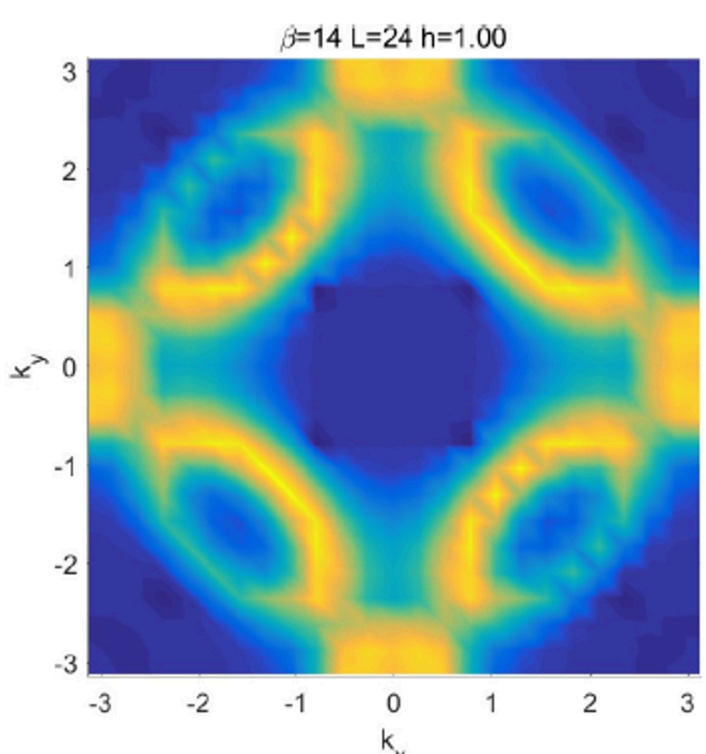
PNAS 116, 16760 (2019)

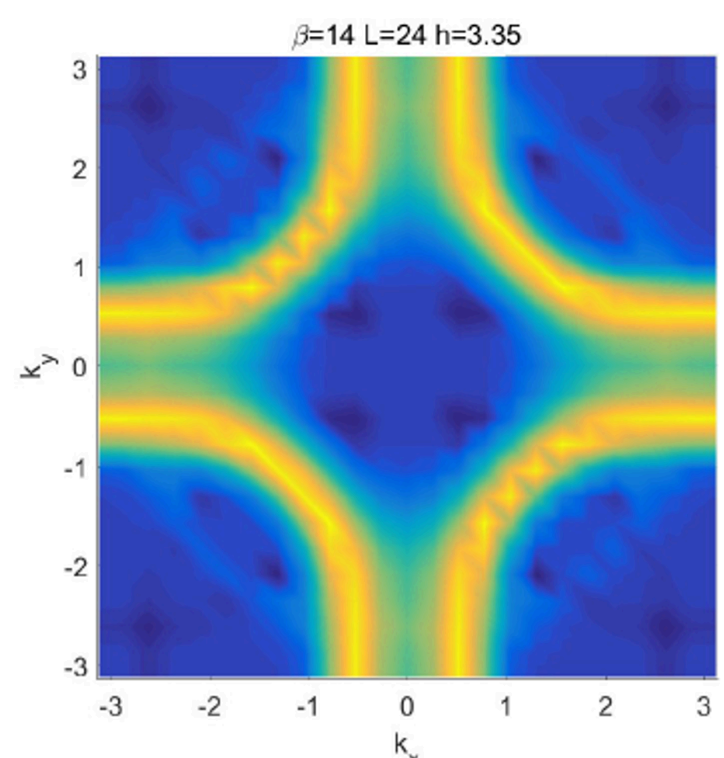
nFL and critical scaling $$\chi(T,h,\mathbf{q},\omega_n) = \frac{1}{c_t T^{a_t}(c_q|\mathbf{q}|^2 + c_\omega \omega)^{1-\eta} + c'_\omega \omega^2} \quad \eta \sim \frac{1}{8}$$











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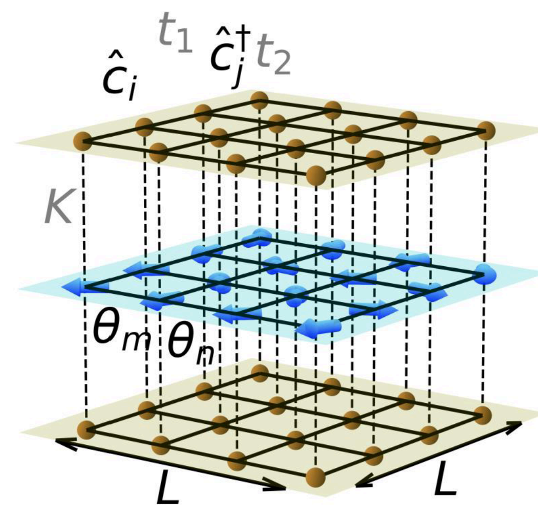

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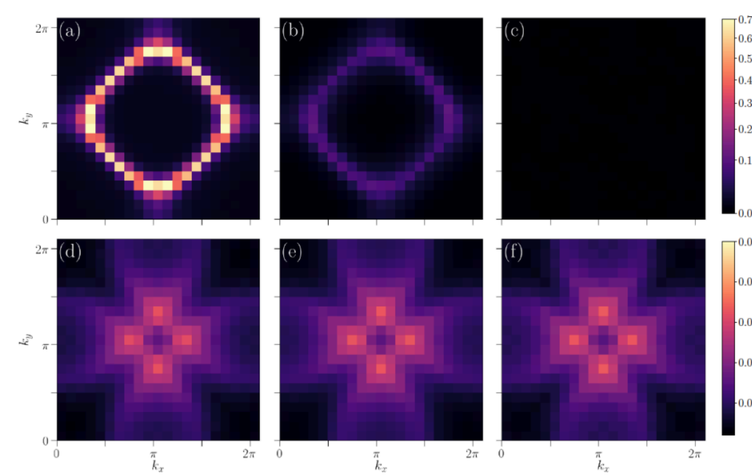

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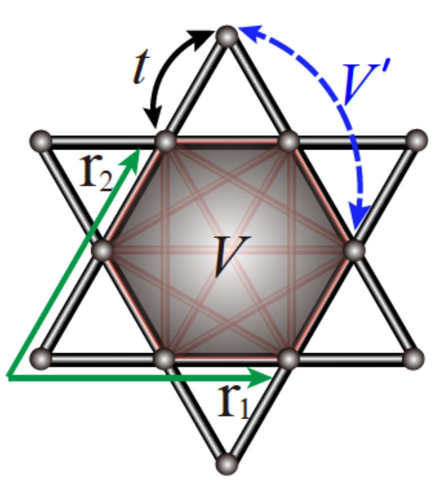

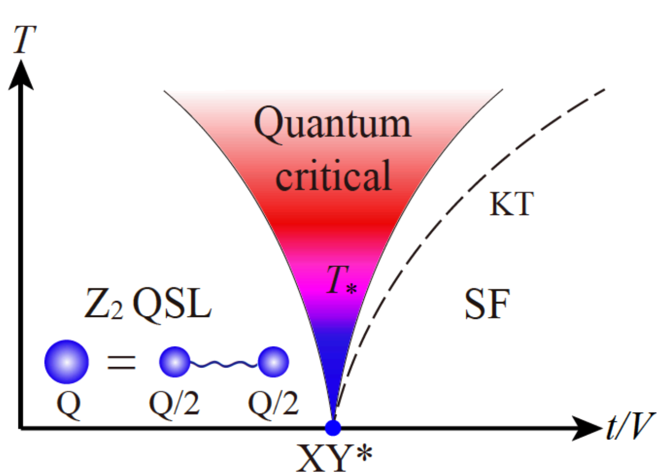

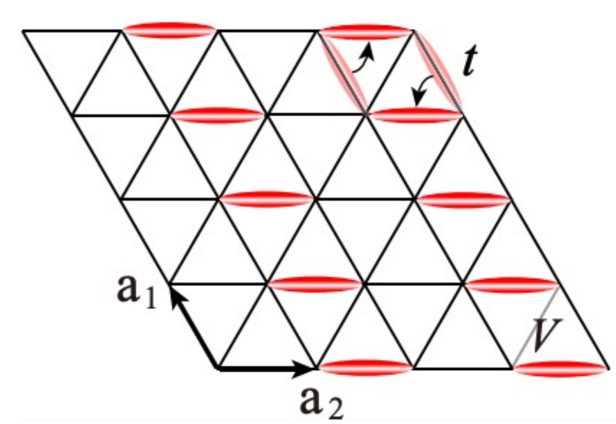

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Metal to Orthogonal Metal Transition *

Chuang Chen(陈闯)[1], Xiao Yan Xu(许霄琰)[2,3], Yang Qi(戚扬)[4,5,6]**, Zi Yang Meng(孟子杨)[7,1,8]**

CPL 37, 047103 (2020) Express Letter

$$H = H_f + H_z + H_g$$

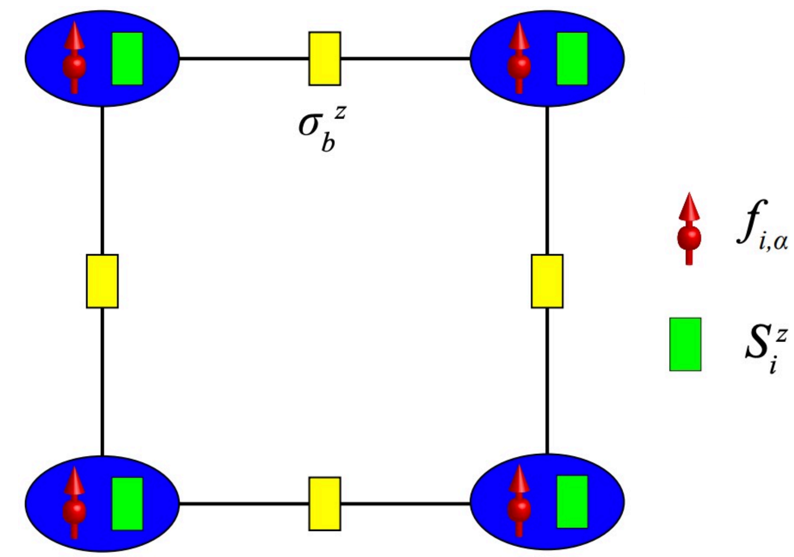
$$H_f = -t\sum_{\langle i,j\rangle}(f^\dagger_{i,\alpha}\sigma^z_{b_{\langle i,j\rangle}}f_{j,\alpha} + h.c.) - \mu\sum_i f^\dagger_{i,\alpha}f_{i,\alpha}, \quad t = 1$$

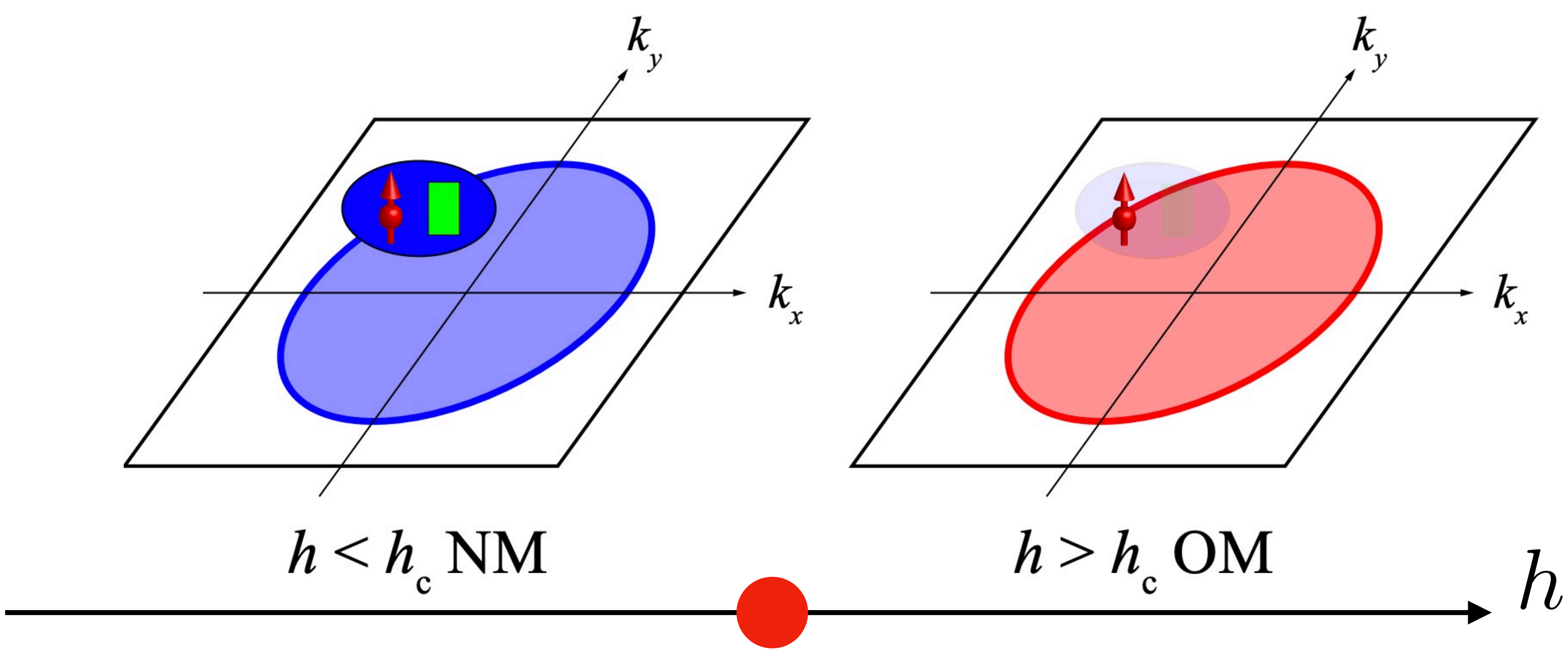
$$H_z = -J\sum_{\langle i,j\rangle}S^z_i\sigma^z_{b_{\langle i,j\rangle}}S^z_j - h\sum_i S^x_i, \quad J = -1$$

$$H_g = -K\sum_{\square}\prod_{b\in\square}\sigma^z_b - g\sum_b \sigma^x_b. \quad K = 1, g = 0.5$$

zero-flux

composite fermions: $c_{i,\alpha} = f_{i,\alpha}S^z_i$



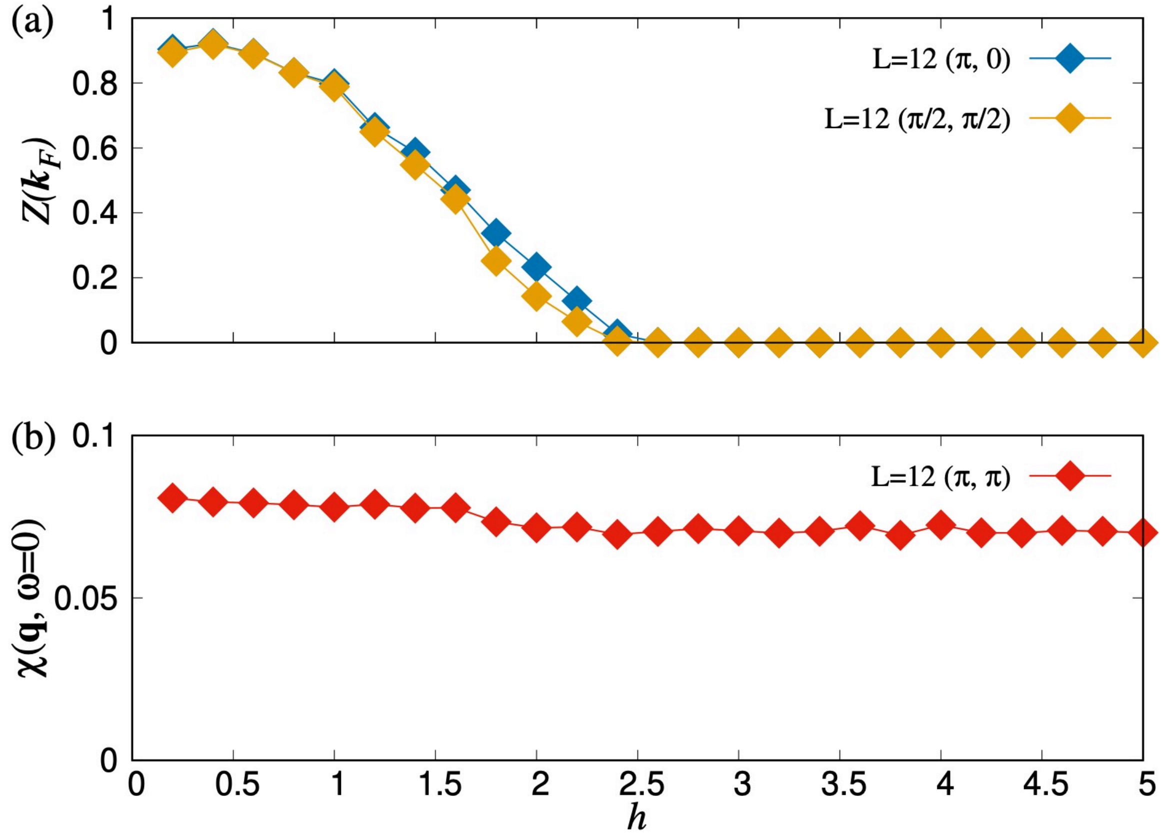


Z2 gauge field couples to matter fields

- Nandkishore, Metlitski, Senthil, PRB 86, 045128 (2012)
- Hohenadler, Assaad, PRL 121, 086601 (2018)
- Gazit, Assaad, Sachdev, Vishwanath, Wang, PNAS 115, E6987 (2018)
- Hohenadler, Assaad, PRB 100, 125133 (2019)
- Chuang Chen et al., CPL 37, 047103 (2020)
- Gazit, Assaad, Sachdev, PRX 10, 041057 (2020)
- Chuang Chen et al., PRB 103, 165131 (2021)

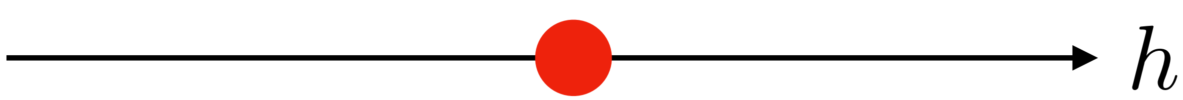
Z2 gauge field couples to matter field

Continuous phase transition (Higgs) between NM and OM without symmetry breaking



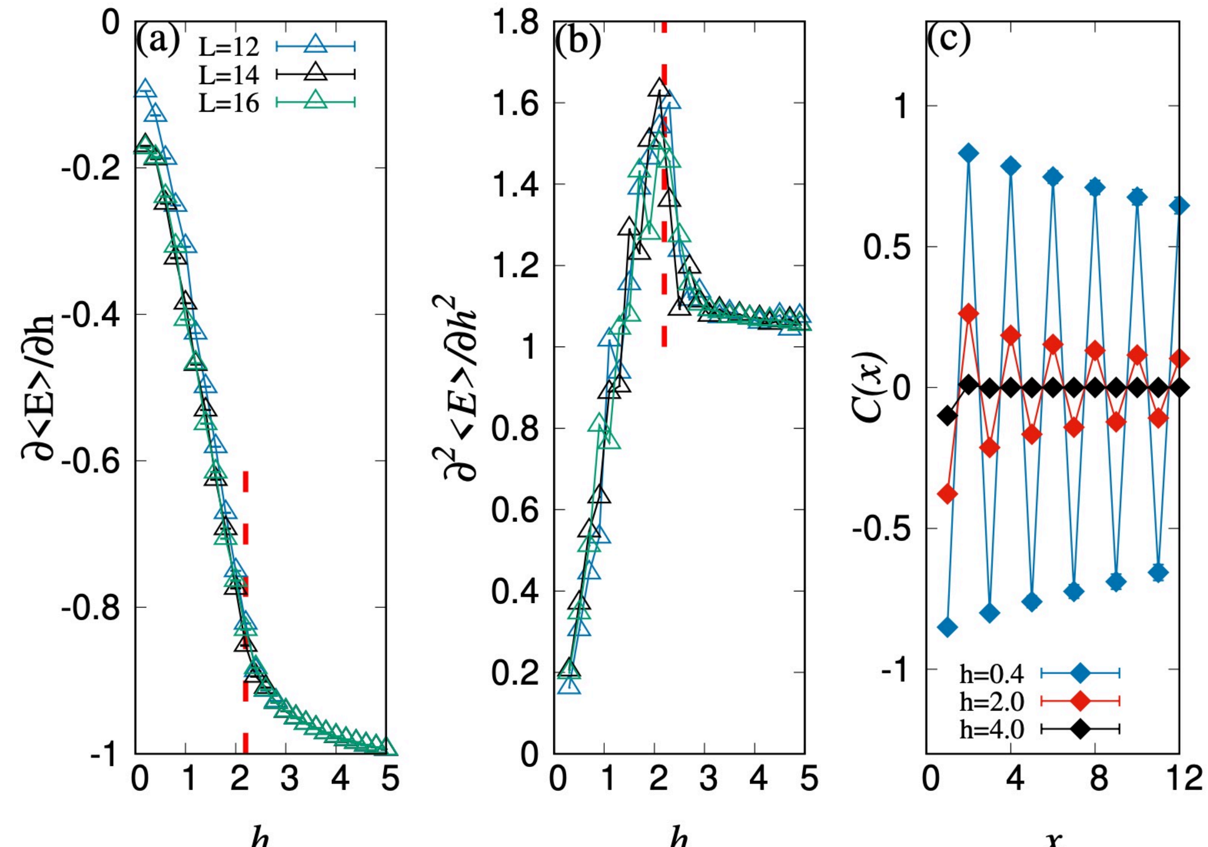
Gauge-invariant string operator

$$C(\mathbf{r}) = \langle S_i^z \prod_i^{i+\mathbf{r}} \sigma^z_{b\in\hat{x}} S^z_{i+\mathbf{r}} \rangle$$



Normal metal

Orthogonal metal



Z2 gauge field confined

Z2 gauge field deconfined

Chuang Chen et al., CPL 37, 047103 (2020)

Z2 gauge field couples to matter field

Chuang Chen et al., CPL 37, 047103 (2020)

$G(\mathbf{k},\tau)\;=$

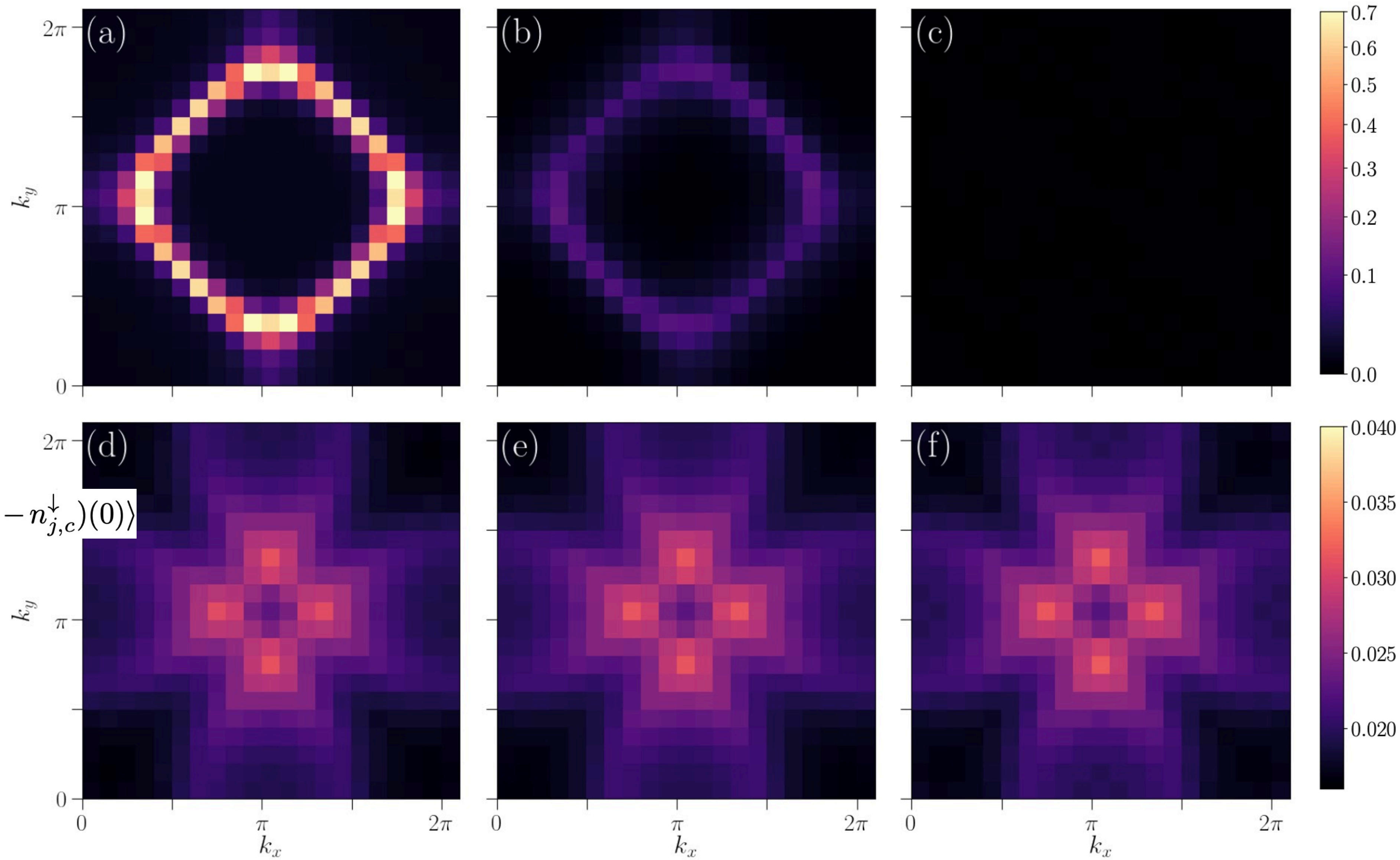
$\frac{1}{N}\sum_{i,j,\alpha} e^{i\mathbf{k}\cdot\mathbf{r}_{ij}}\langle c^{\dagger}_{i,\alpha}(\tau)c_{j,\alpha}(0)\rangle$

$A(\mathbf{k},\omega=0)\propto G(\mathbf{k},\beta/2)$

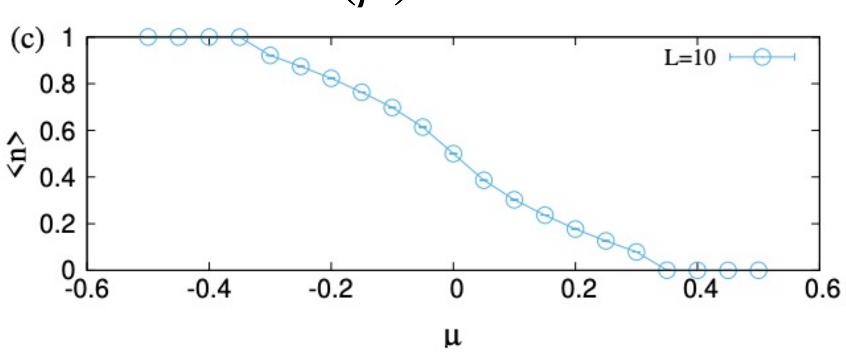
$\chi(\mathbf{q},\omega=0)\;=$

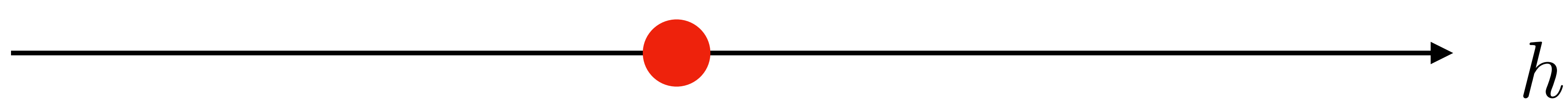
$\frac{1}{\beta N}\int_0^{\beta} d\tau \sum_{i,j} e^{i\mathbf{q}\cdot\mathbf{r}_{ij}}\langle (n^{\uparrow}_{i,c}-n^{\downarrow}_{i,c})(\tau)(n^{\uparrow}_{j,c}-n^{\downarrow}_{j,c})(0)\rangle$

$\langle n_c\rangle=\langle n_f\rangle=0.7$



$n(\mu)\,@\,h=4$





$h=0.5$ $\quad h_c\approx 2$ $\quad h=4$

Normal metal $\quad$ Orthogonal metal

Fermi arcs and pseudogap in a lattice model of a doped orthogonal metal

Chuang Chen,[1] Tian Yuan,[2,3] Yang Qi,[2,3,4,*] and Zi Yang Meng[5,†]

PRB 103, 165131 (2021)

$$H = H_f + H_z + H_g + H_c$$

$$H_f = -\sum_{\langle i,j\rangle}(f^\dagger_{i,\alpha}\sigma^z_{b_{\langle i,j\rangle}} f_{j,\alpha} + h.c.) - \mu\sum_i f^\dagger_{i,\alpha} f_{i,\alpha}$$

$$H_z = -J\sum_{\langle i,j\rangle} S^z_i \sigma^z_{b_{\langle i,j\rangle}} S^z_j - h\sum_i S^x_i,$$

$$H_g = K\sum_{\square}\prod_{b\in\square}\sigma^z_b - g\sum_b \sigma^x_b.$$

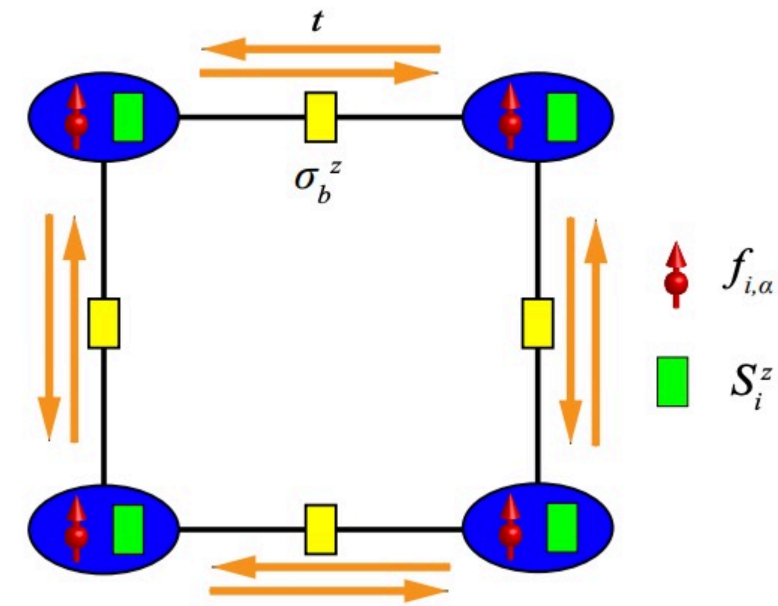
$$H_c = -t\sum_{\langle i,j\rangle} f^\dagger_{i,\alpha} S^z_i f_{j,\alpha} S^z_j + h.c.$$

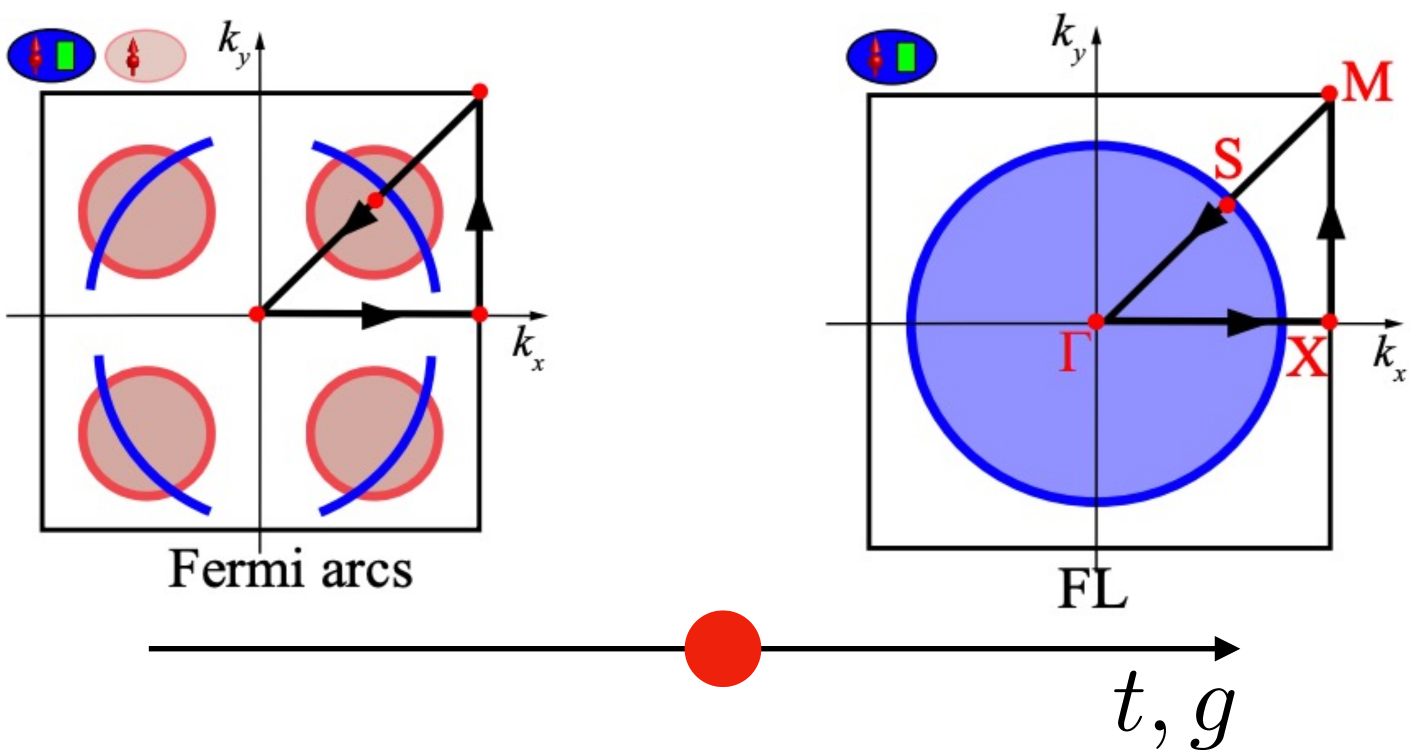
composite fermions: $c_{i,\alpha} = f_{i,\alpha} S^z_i$

$\mu = 1.2, \langle n_f\rangle = 1.12(1)$

$J = 0.1, h = 0.25$

$K = 1$ pi-flux





Nandkishore, Metlitski, Senthil, PRB 86, 045128 (2012)
Hohenadler, Assaad, PRL 121, 086601 (2018)
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Chuang Chen et al., CPL 37, 047103 (2020)
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Chuang Chen et al., PRB 103, 165131 (2021)

Fermi arcs and pseudogap in a lattice model of a doped orthogonal metal

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PRB 103, 165131 (2021)

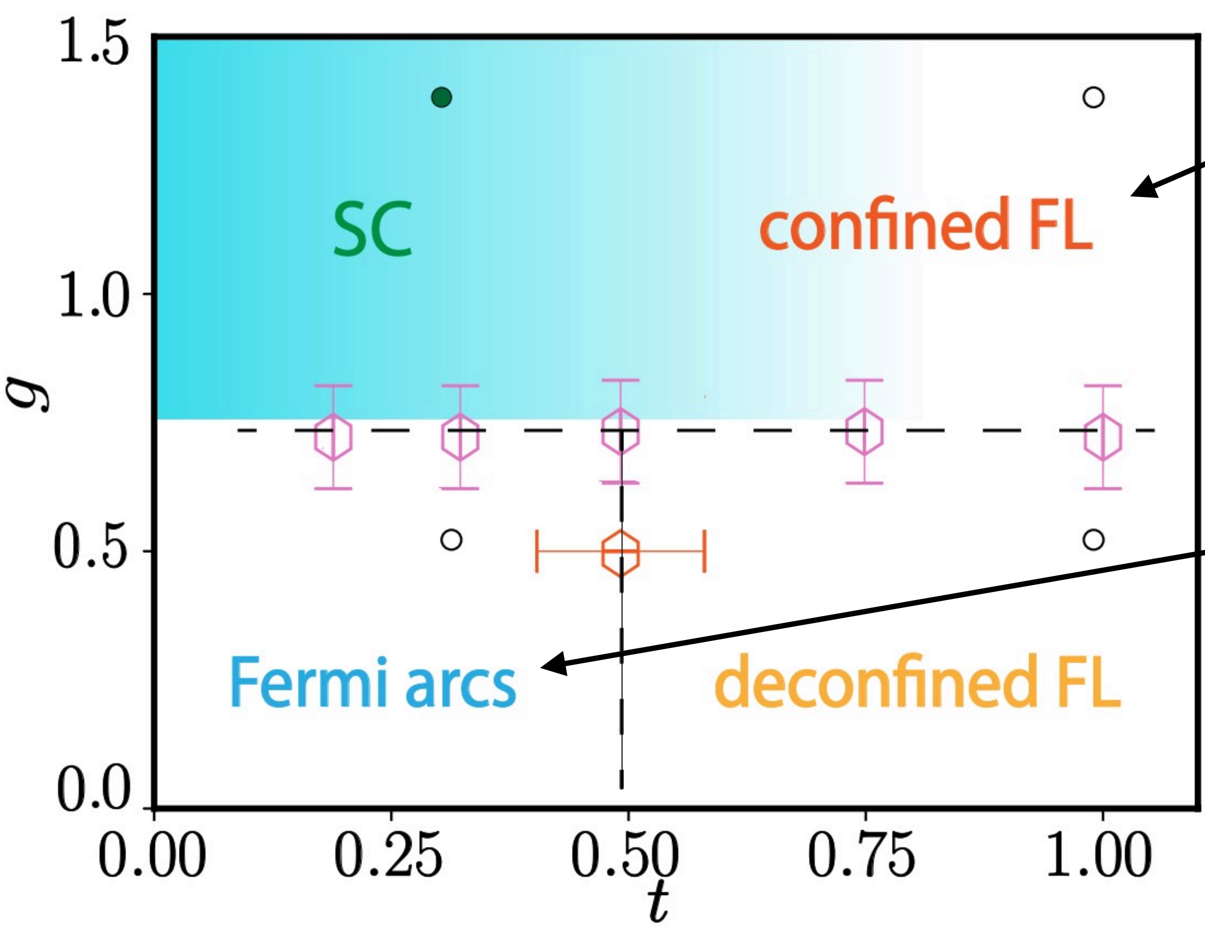
$$H = H_f + H_z + H_g + H_c$$

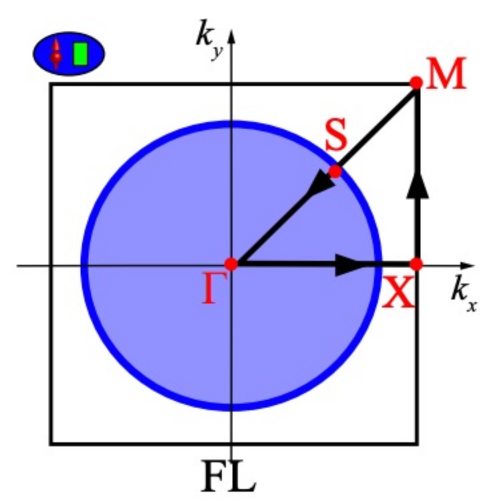
$$H_f = -\sum_{\langle i,j\rangle}(f^\dagger_{i,\alpha}\sigma^z_{b_{\langle i,j\rangle}} f_{j,\alpha} + h.c.) - \mu\sum_i f^\dagger_{i,\alpha} f_{i,\alpha} \qquad \mu = 1.2, \langle n_f\rangle = 1.12(1)$$

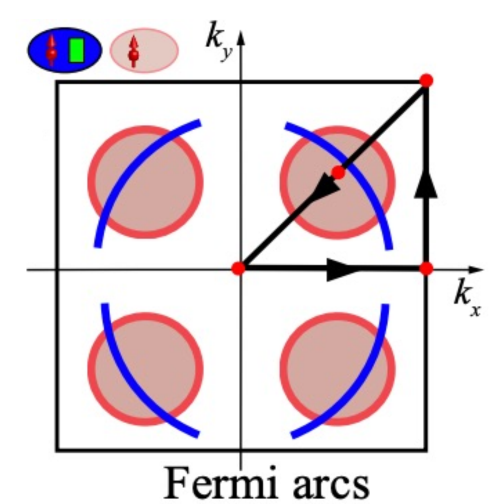
$$H_z = -J\sum_{\langle i,j\rangle} S^z_i \sigma^z_{b_{\langle i,j\rangle}} S^z_j - h\sum_i S^x_i, \qquad J = 0.1, h = 0.25$$

$$H_g = K\sum_{\square}\prod_{b\in\square}\sigma^z_b - g\sum_b \sigma^x_b. \qquad K = 1 \quad \text{pi-flux}$$

$$H_c = -t\sum_{\langle i,j\rangle} f^\dagger_{i,\alpha} S^z_i f_{j,\alpha} S^z_j + h.c.$$

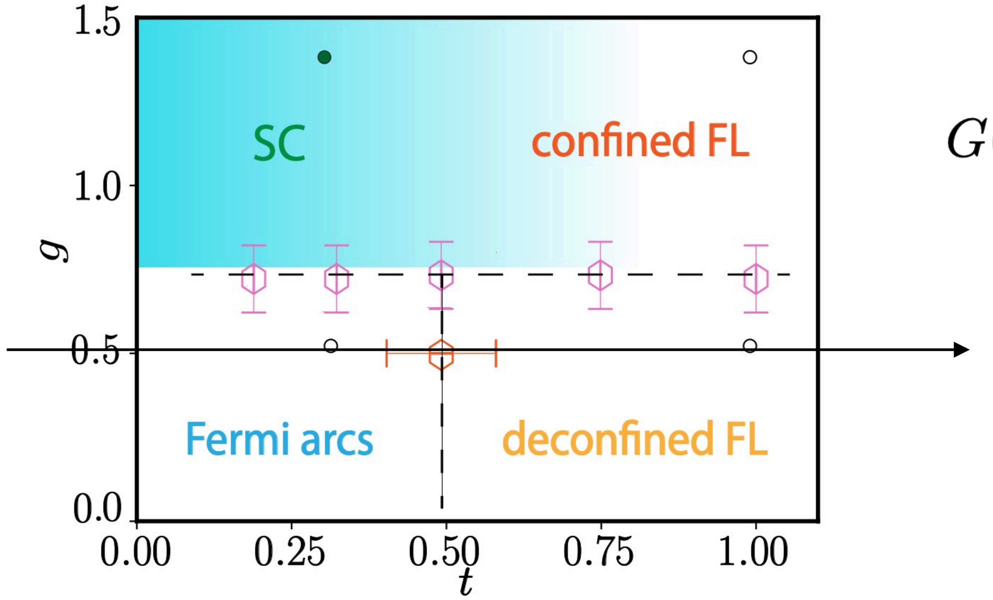






Fermi arcs and pseudogap in a lattice model of a doped orthogonal metal

Chuang Chen,[1] Tian Yuan,[2,3] Yang Qi,[2,3,4,*] and Zi Yang Meng[5,†]



PRB 103, 165131 (2021)

$$G(\mathbf{k},\tau) = \frac{1}{N}\sum_{i,j,\alpha} e^{i\mathbf{k}\cdot\mathbf{r}_{ij}}\langle c^\dagger_{i,\alpha}(\tau)c_{j,\alpha}(0)\rangle$$

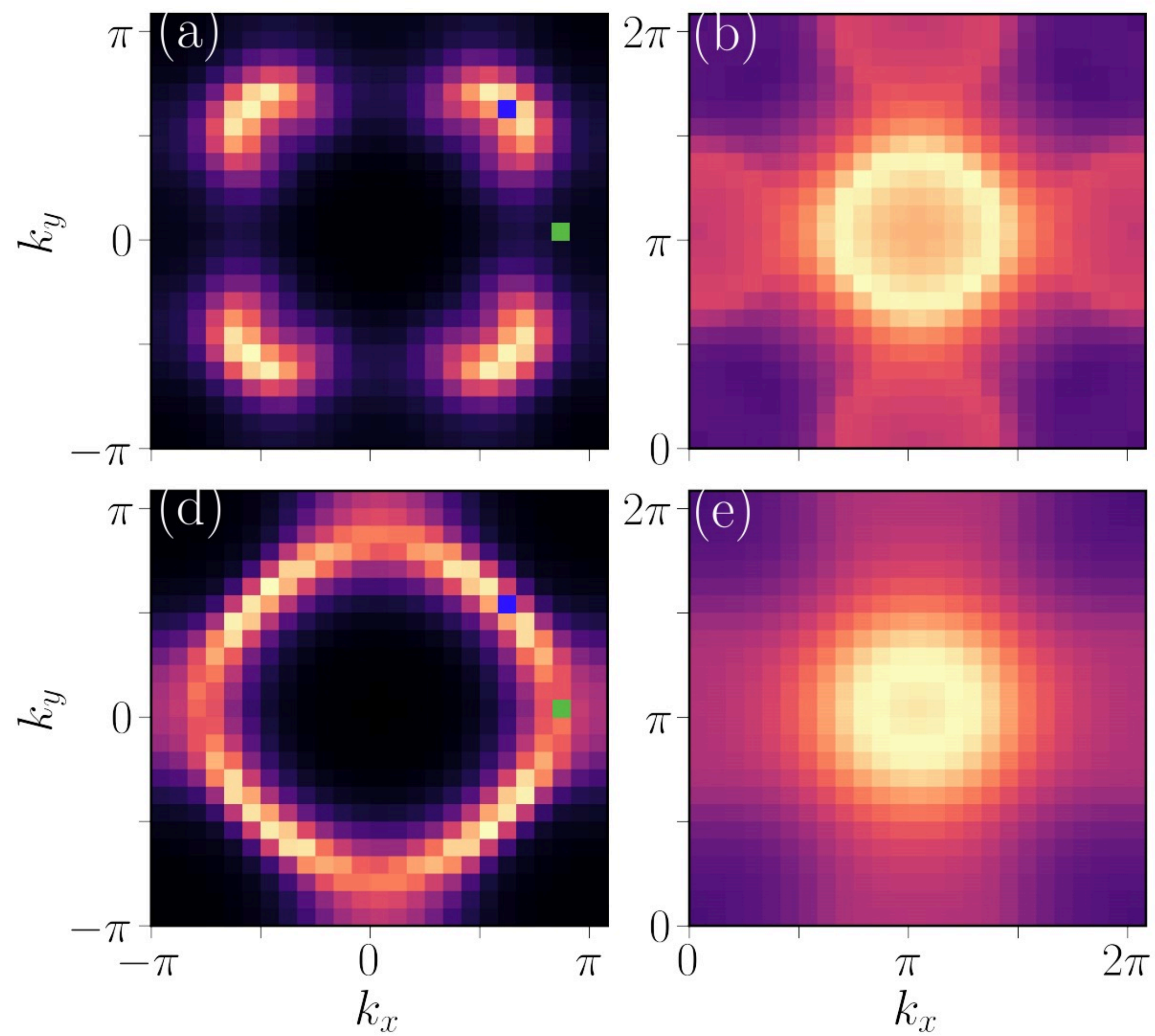
$$A(\mathbf{k},\omega=0) \propto G(\mathbf{k},\beta/2)$$

$$\chi(\mathbf{q},\omega=0) = \frac{1}{\beta N}\int_0^\beta d\tau \sum_{i,j} e^{i\mathbf{q}\cdot\mathbf{r}_{ij}}\langle (n^\uparrow_{i,c}-n^\downarrow_{i,c})(\tau)(n^\uparrow_{j,c}-n^\downarrow_{j,c})(0)\rangle$$

$L = 24, T = 0.05$

$\langle n_f\rangle = 1.12$ Fermi arc $t = 0.3, g = 0.5$

$\langle n_f\rangle = 1.12$ respects Luttinger $t = 1, g = 0.5$



Fermi arcs and pseudogap in a lattice model of a doped orthogonal metal

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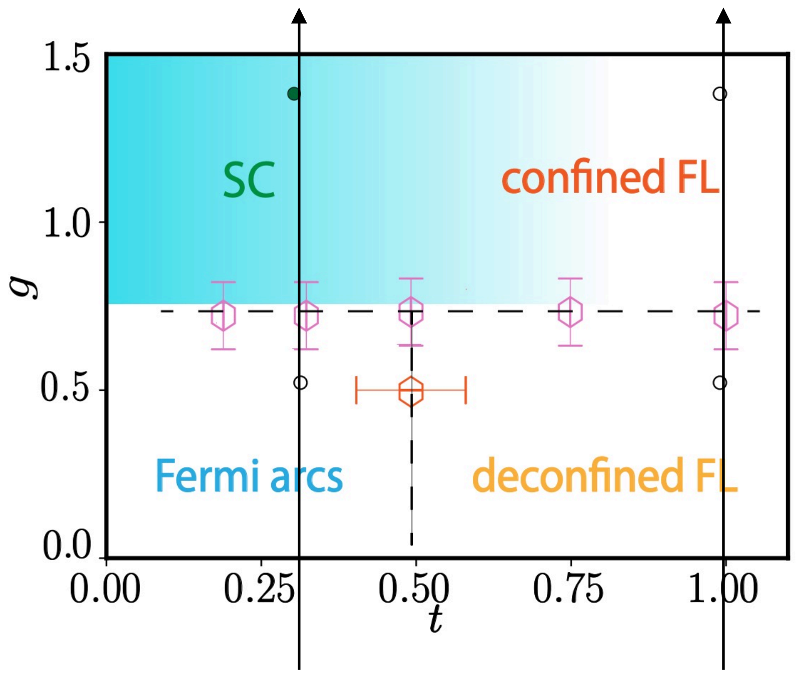
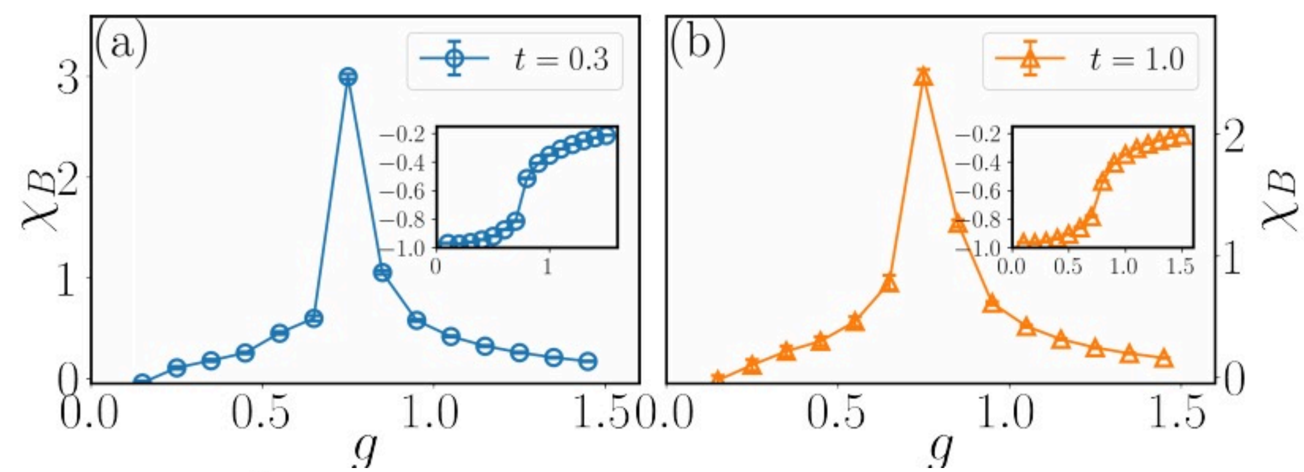
PRB 103, 165131 (2021)



average Z2 flux per plaquette $B = \frac{1}{N}\sum_{\square}\prod_{b\in\square}\sigma_b^z$

Z2 flux susceptibility $\chi_B = \partial\langle B\rangle/\partial g$

$L = 20, T = 0.1$



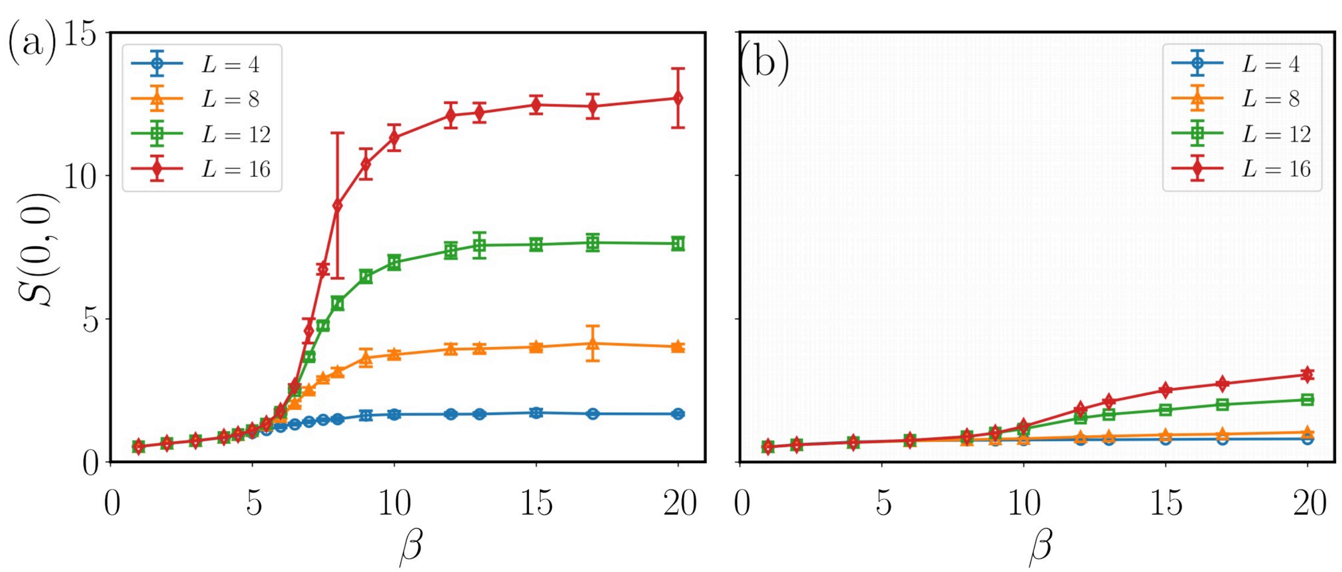
Superconductivity in FL

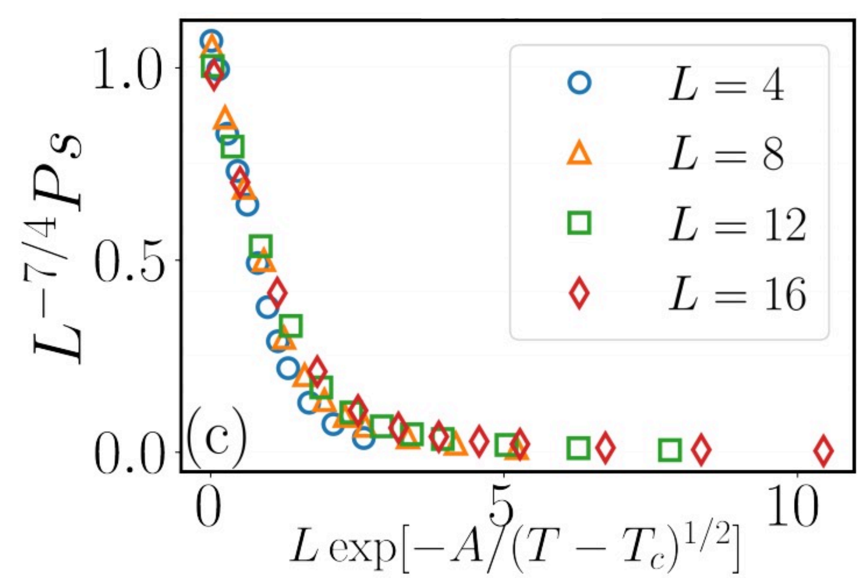
$$S(\mathbf{k}) = \frac{1}{L^2}\sum_{i,j} e^{-i\mathbf{k}\cdot r_{ij}}\left\langle \Delta_i^\dagger \Delta_j\right\rangle, \text{ with } \Delta_i = c_{i\uparrow}c_{i\downarrow}$$

$$P_s = \frac{1}{L^2}\int_0^\beta d\tau \left\langle \Delta(\tau)\Delta^\dagger(0) + h.c.\right\rangle$$

$$P_s = L^{2-\eta} f\left(L\cdot \exp\left(-\frac{A}{(T-T_c)^{1/2}}\right)\right)$$

$\eta = 1/4$ $T_c = 0.12$





Fermi arcs and pseudogap in a lattice model of a doped orthogonal metal

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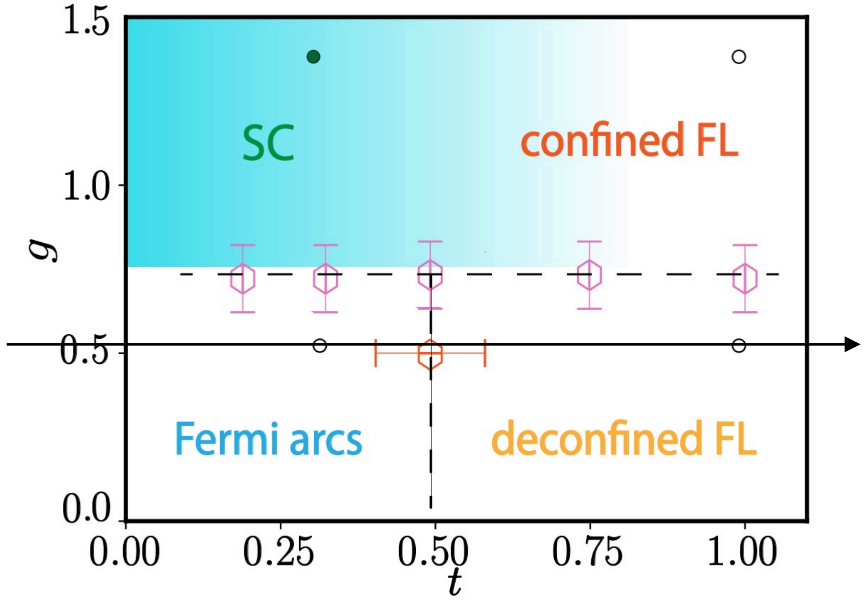
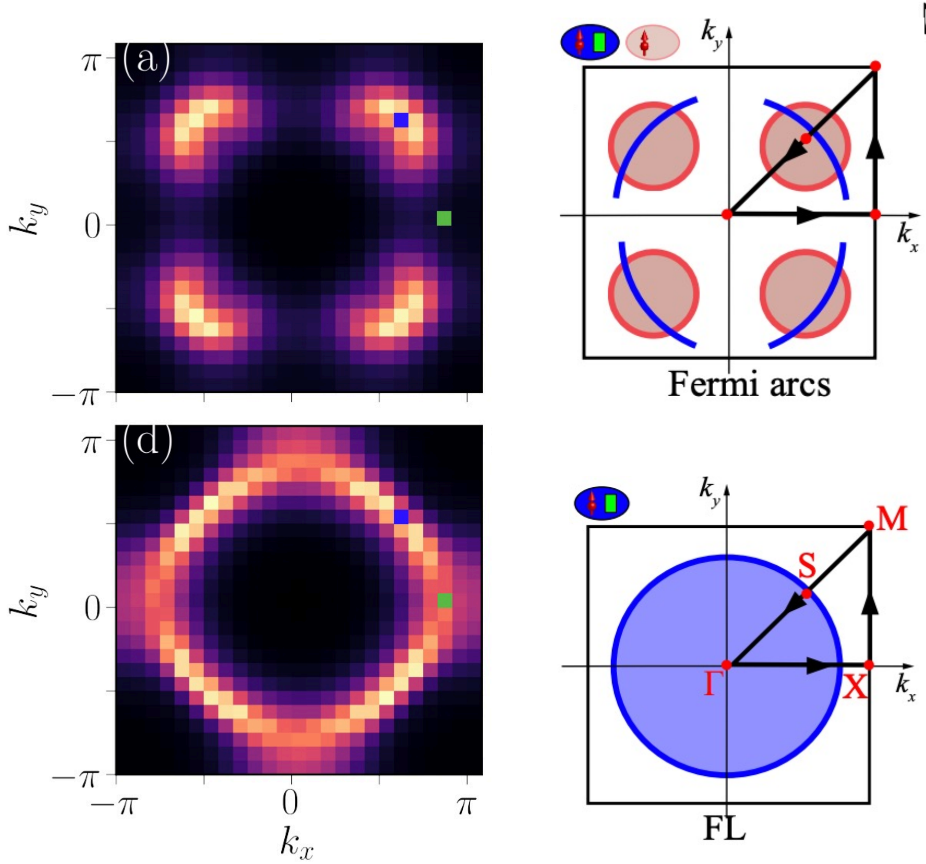
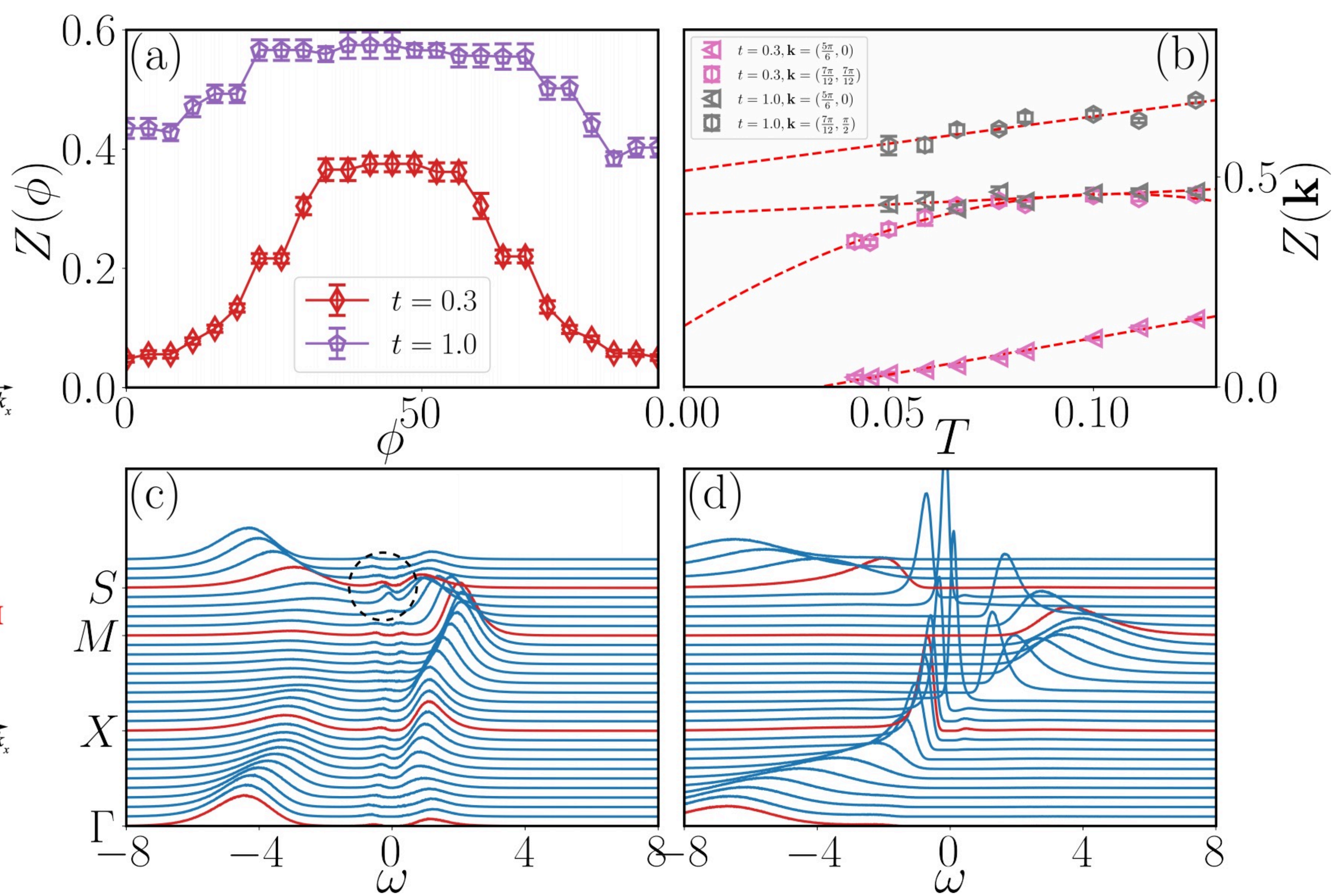
PRB 103, 165131 (2021)



$$Z(\mathbf{k}) \sim \beta G(\mathbf{k}, \beta/2)$$

$$G(\mathbf{k},\tau) = \int d\omega \frac{e^{-\omega\tau}}{1+e^{-\beta\omega}} A(\mathbf{k},\omega)$$





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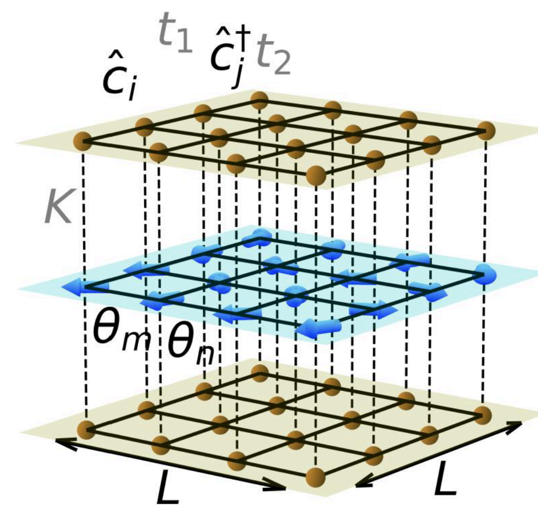
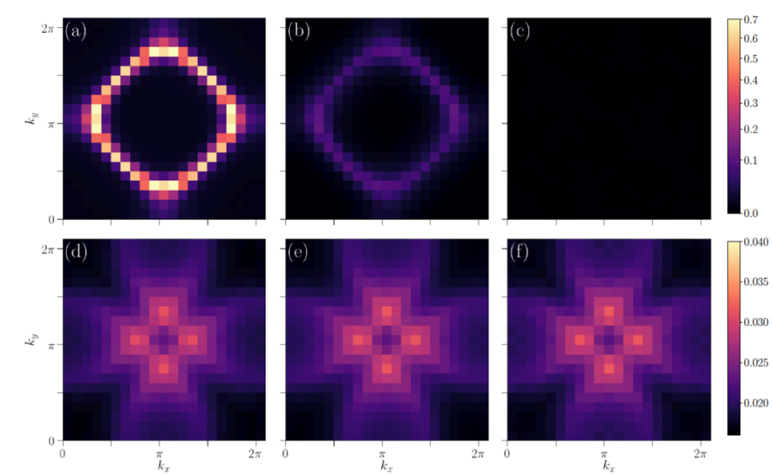
   Quantum critical metals
   Luttinger's theorem
   Matter fields coupled to gauge fields



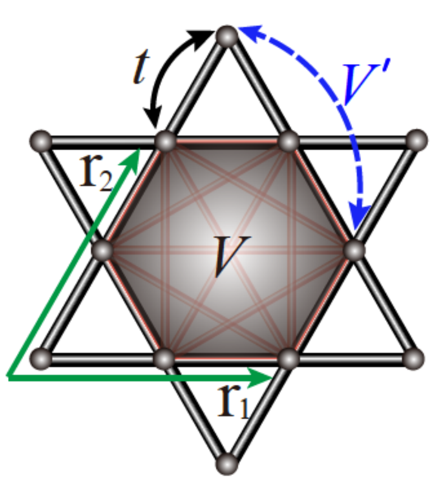
- PRX 7, 031058 (2017)
- PNAS 116 (34), 16760 (2019)
- npj Quantum Materials 5, 65 (2020)
- PRB 105, L041111 (2022)
- Nat. Comm. 13, 2655 (2022)
- ......

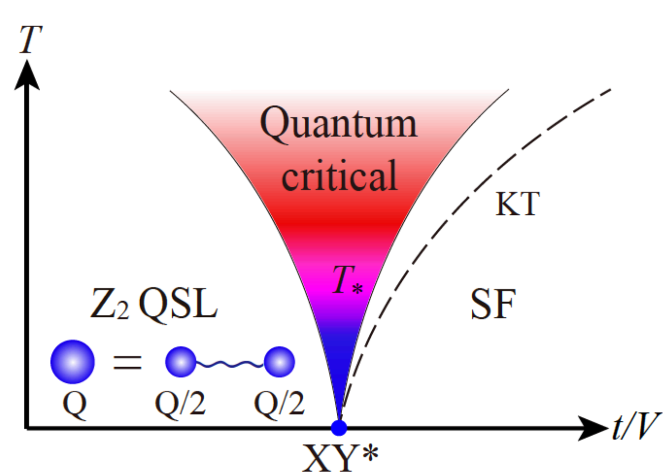


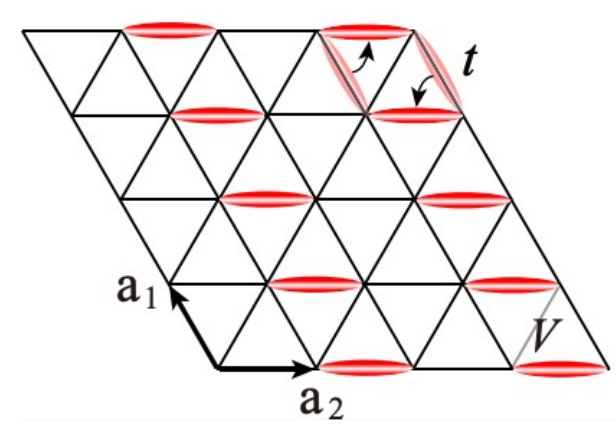
- PRX 9, 021022 (2019)
- PRB 101, 235118 (2020)
- CPL 37, 047103 (2020)
- PRB 103, 165131 (2021)
- ......

2. Fractionalisation, topological order in frustrated magnets
   Quantum dimer models

- PRL 121, 077201 (2018)
- PRL 121, 057202 (2018)
- Nat. Comm. 12, 5347 (2021)
- npj Quantum Materials 6, 39 (2021)
- arXiv: 2202.11100
- arXiv: 2205.04472
- ......







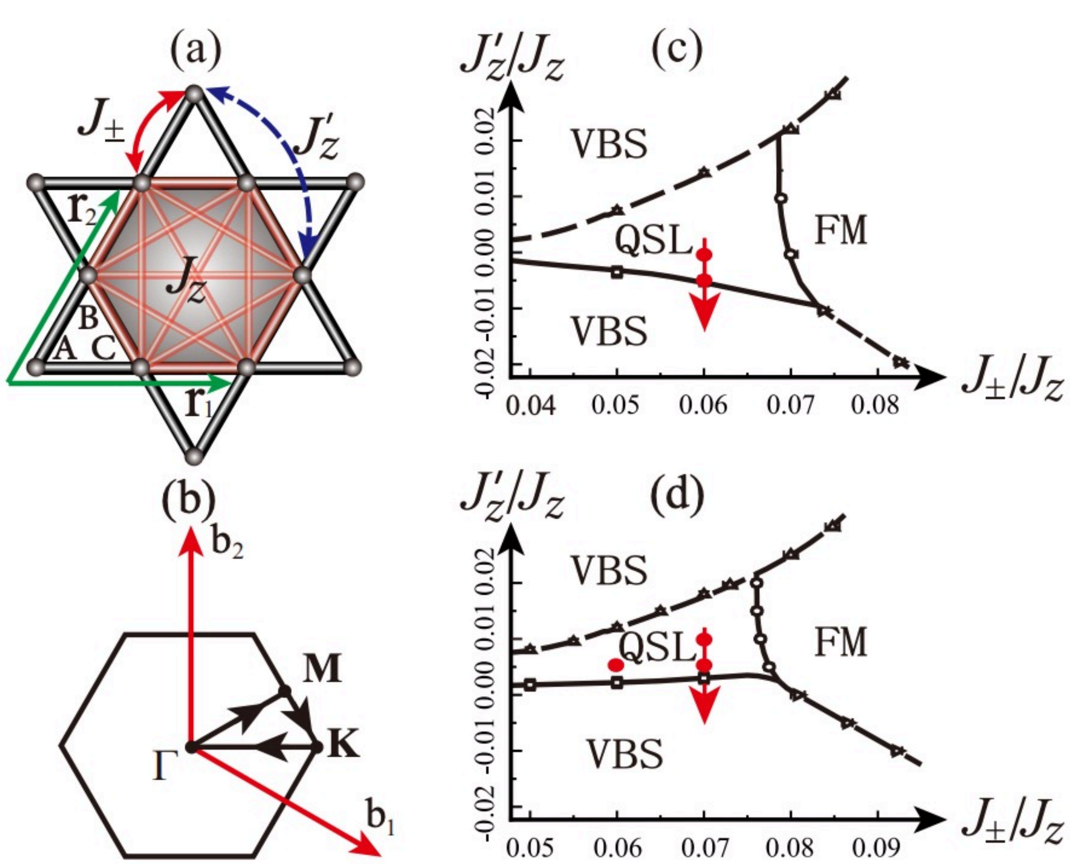
Dynamical Signature of Symmetry Fractionalization in Frustrated Magnets

Guang-Yu Sun,[1,2] Yan-Cheng Wang,[3] Chen Fang,[1,4] Yang Qi,[5,6,7] Meng Cheng,[8] and Zi Yang Meng[1,4]

PRL 121, 077201 (2018)
PRL 121, 057202 (2018)

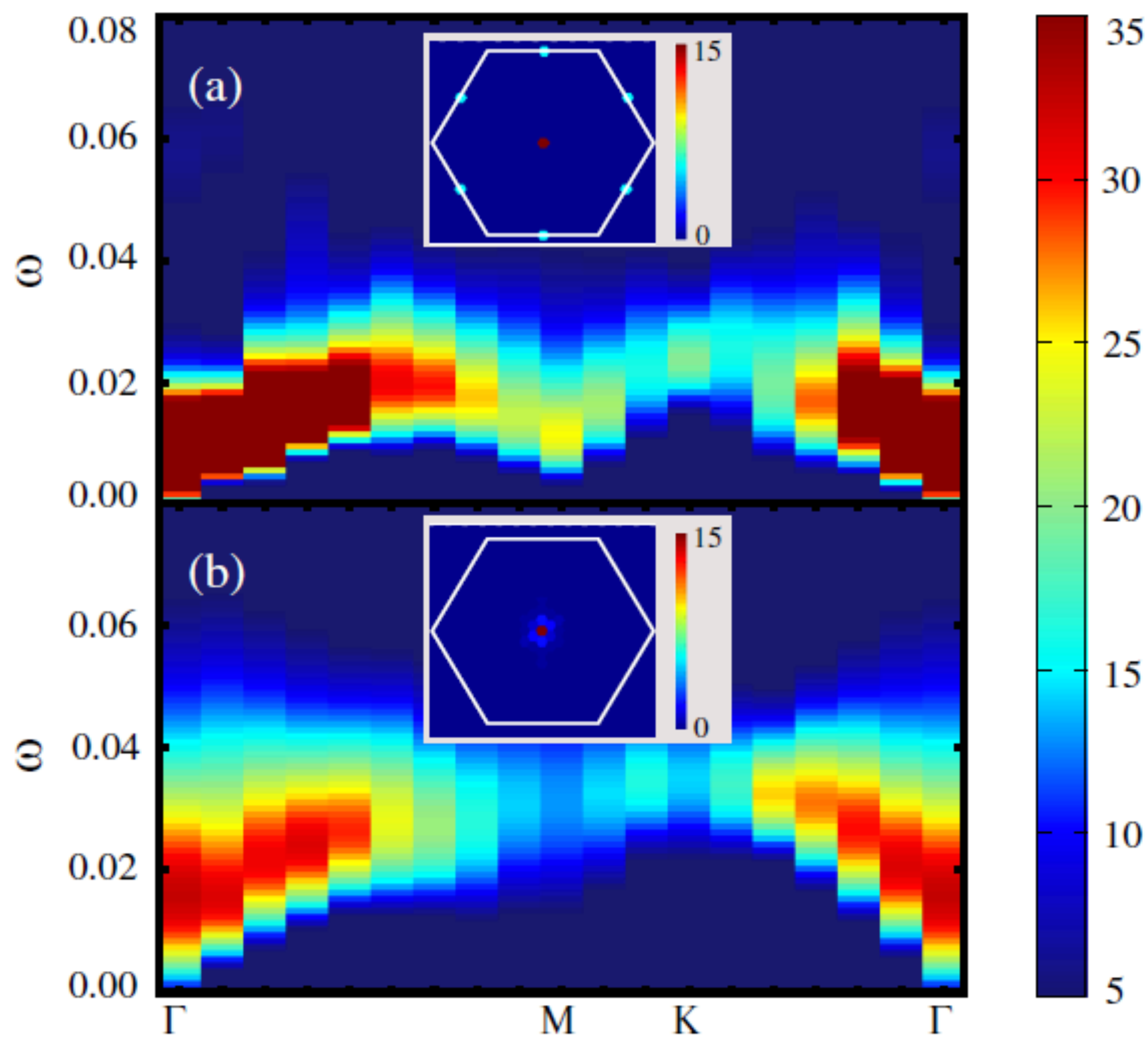
$$H = -J_{\pm}\sum_{\langle i,j\rangle}(S_i^+S_j^- + \mathrm{h.c.}) + \frac{J_z}{2}\sum_{\hexagon}\Big(\sum_{i\in\hexagon}S_i^z\Big)^2 + J_z'\sum_{\langle i,j\rangle'}S_i^zS_j^z - h\sum_i S_i^z$$

$$H = -t\sum_{\langle i,j\rangle}(b_i^\dagger b_j + \mathrm{h.c.}) + V\sum_{\hexagon}\Big(\sum_{i\in\hexagon}n_i\Big)^2 + V'\sum_{\langle i,j\rangle'}n_in_j + \mu\sum_i n_i$$



$h = 0$

$h = 2J_z$



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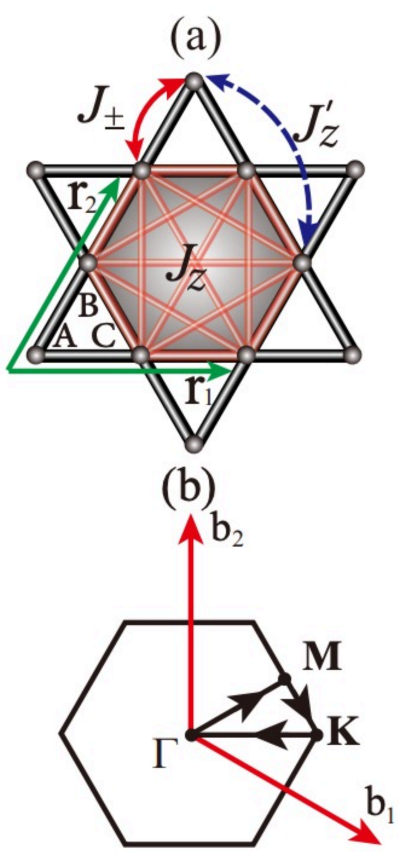
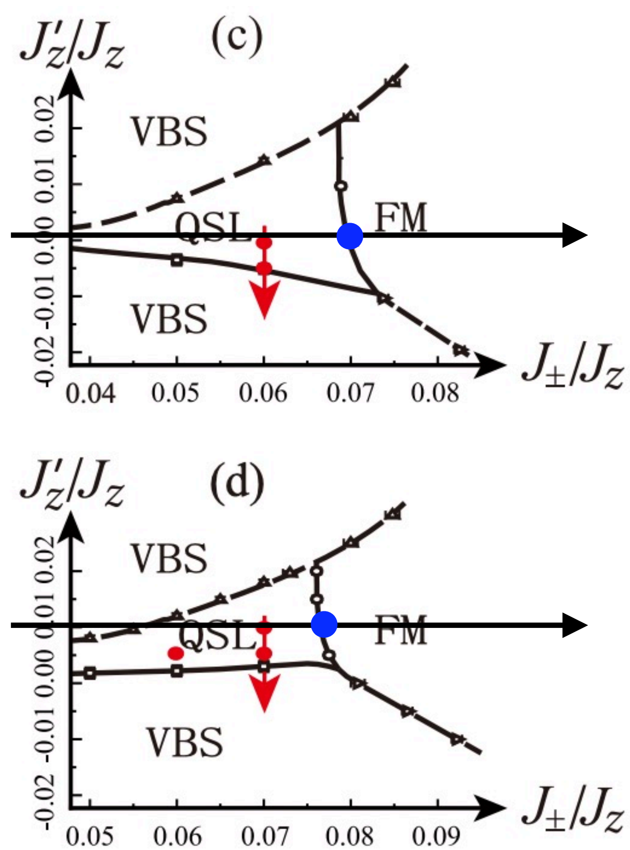
$$H = -t\sum_{\langle i,j\rangle}(b_i^\dagger b_j + \text{h.c.}) + V\sum_{\hexagon}\Big(\sum_{i\in\hexagon}n_i\Big)^2 + V'\sum_{\langle i,j\rangle'}n_in_j + \mu\sum_i n_i$$





$h = 0$

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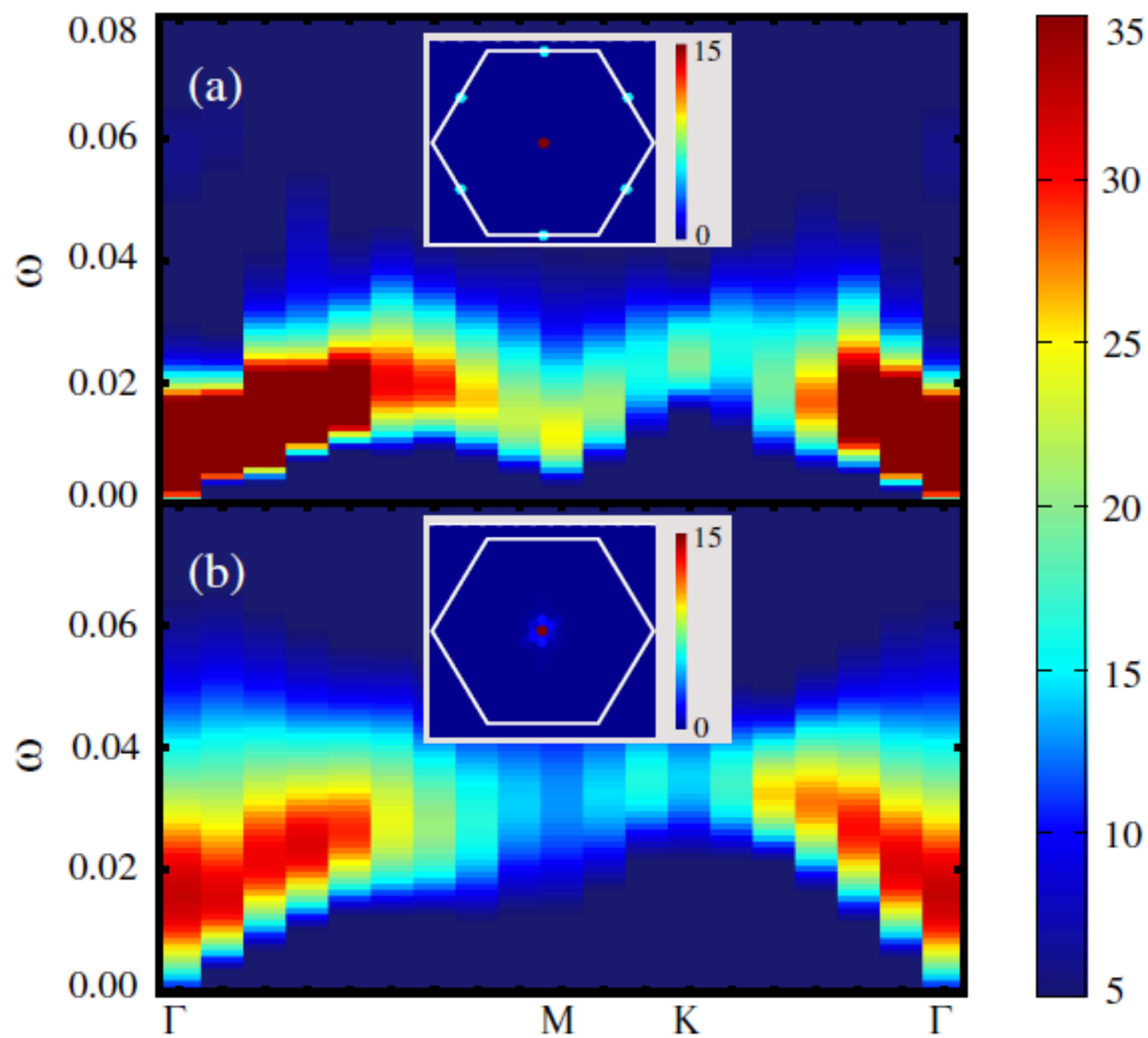
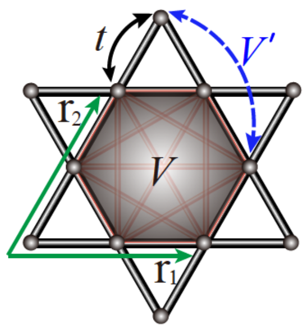


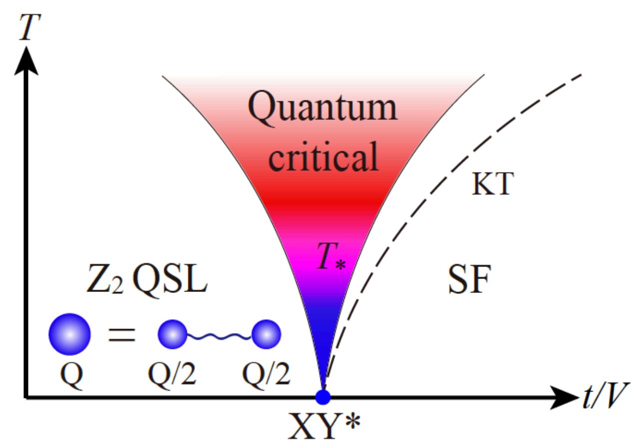
Fractionalized conductivity and emergent self-duality near topological phase transitions

Yan-Cheng Wang[1], Meng Cheng[2], William Witczak-Krempa[3,4] & Zi Yang Meng[5]

Nat. Comm. 12, 5347 (2021)

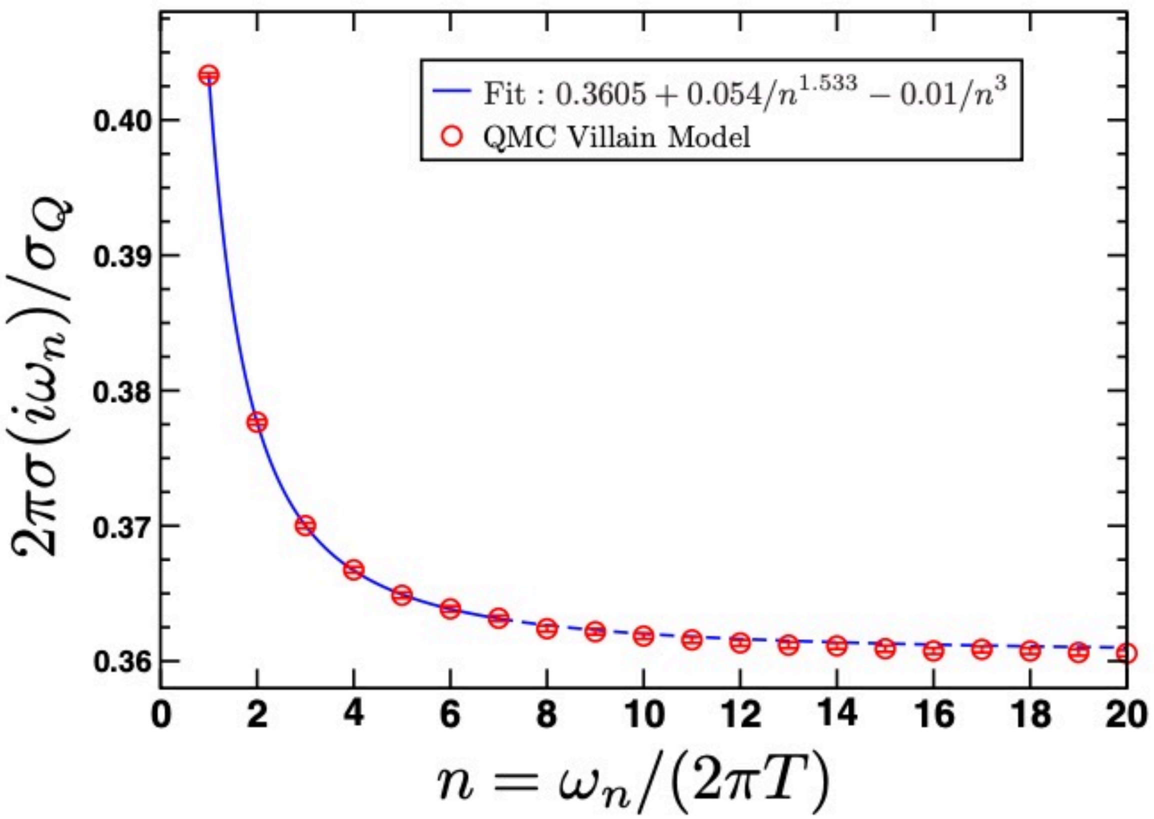
$$H = -t\sum_{\langle i,j\rangle}(b_i^\dagger b_j + \mathrm{h.c.}) + V\sum_{\hexagon}\Big(\sum_{i\in\hexagon} n_i\Big)^2 + V'\sum_{\langle i,j\rangle'} n_i n_j + \mu\sum_i n_i$$





$$\sigma(i\omega_n) = -\frac{i}{\omega_n}\langle J_x(\omega_n)J_x(-\omega_n)\rangle$$

$$\sigma(i\omega_n) = \sigma_\infty + b_1\left(\frac{T}{\omega_n}\right)^{3-\frac{1}{\nu}} + b_2\left(\frac{T}{\omega_n}\right)^3 + \cdots$$



PHYSICAL REVIEW B **90**, 245109 (2014)

Conformal field theories at nonzero temperature: Operator product expansions, Monte Carlo, and holography

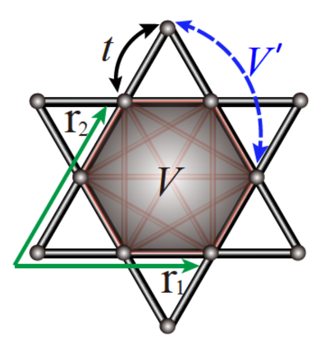
Emanuel Katz,[1] Subir Sachdev,[2,3] Erik S. Sørensen,[4] and William Witczak-Krempa[3]

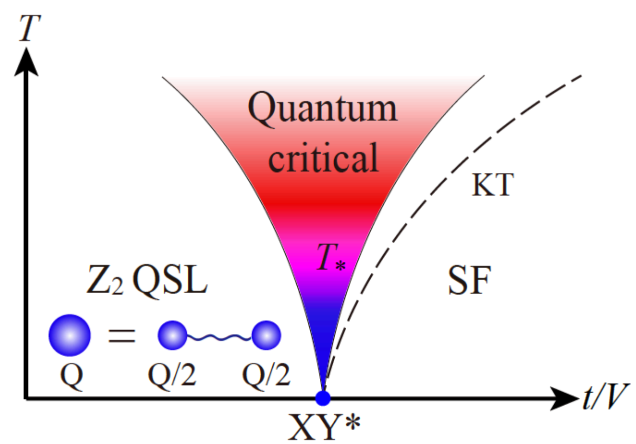
Fractionalized conductivity and emergent self-duality near topological phase transitions

Yan-Cheng Wang[1], Meng Cheng[2], William Witczak-Krempa[3,4] & Zi Yang Meng[5]✉

Nat. Comm. 12, 5347 (2021)

$$H = -t\sum_{\langle i,j\rangle}(b_i^\dagger b_j + \text{h.c.}) + V\sum_{\hexagon}\Big(\sum_{i\in\hexagon} n_i\Big)^2 + V'\sum_{\langle i,j\rangle'} n_i n_j + \mu\sum_i n_i$$

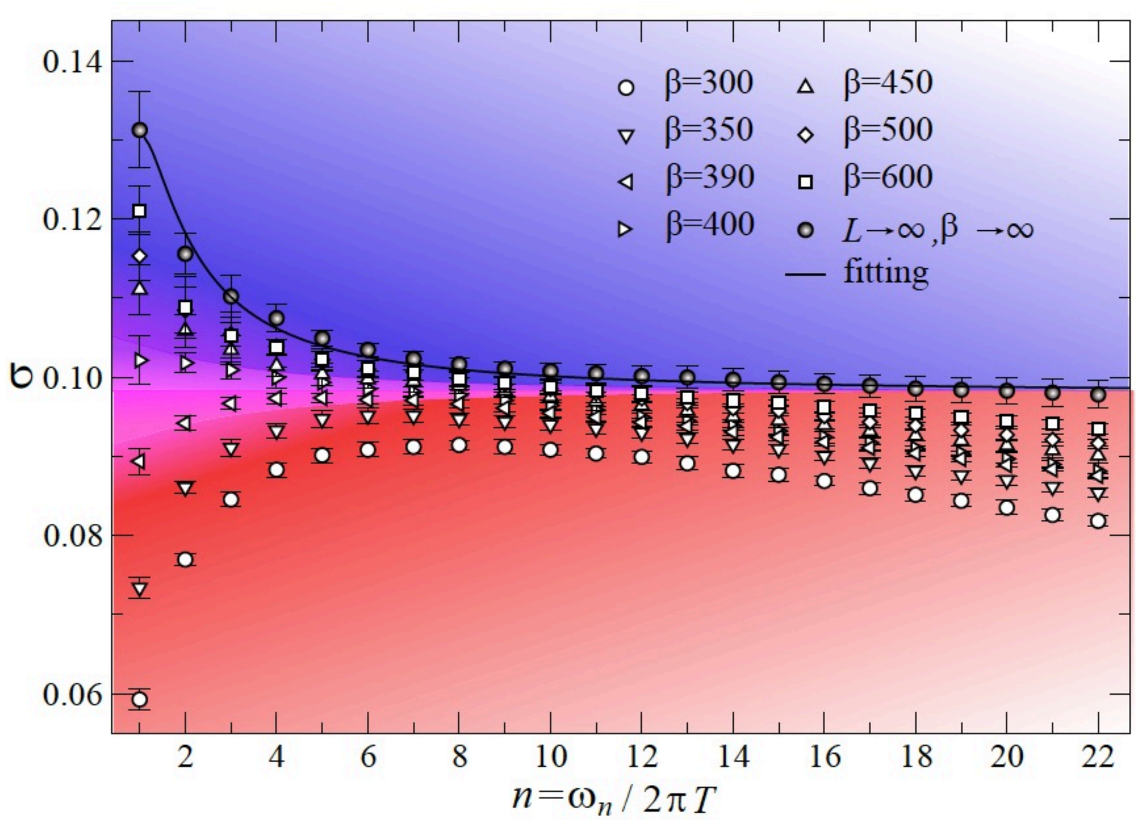


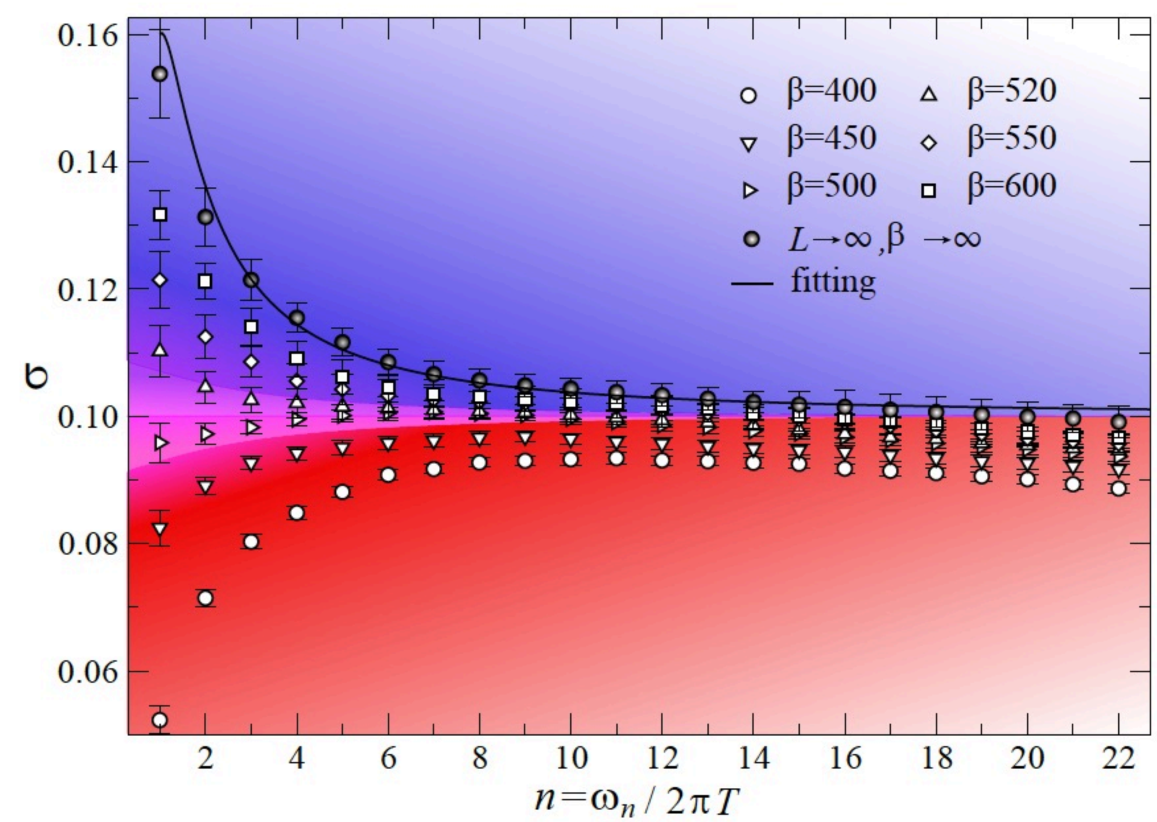


$$\sigma(i\omega_n) = -\frac{i}{\omega_n}\langle J_x(\omega_n)J_x(-\omega_n)\rangle$$

$$\sigma(i\omega_n) = \sigma_\infty + b_1\Big(\frac{T}{\omega_n}\Big)^{3-\frac{1}{\nu}} + b_2\Big(\frac{T}{\omega_n}\Big)^3 + \cdots$$

$$\sigma_{XY^*}(\infty) = \frac{1}{4}\sigma_{XY}(\infty)$$





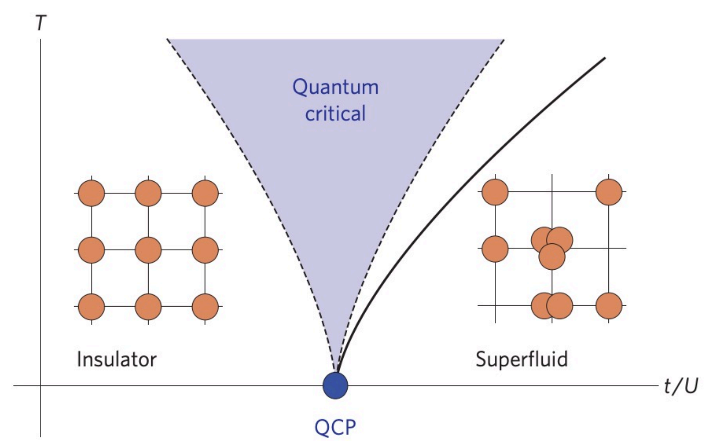
$\sigma_{XY^*}(\infty) = 0.098(9)$ $\sigma_{XY^*}(\infty) = 0.100(13)$

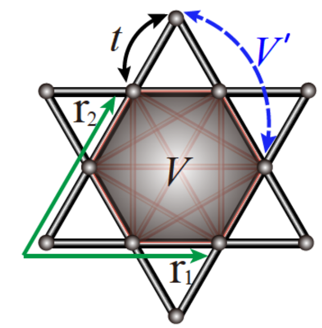
Fractionalized conductivity and emergent self-duality near topological phase transitions

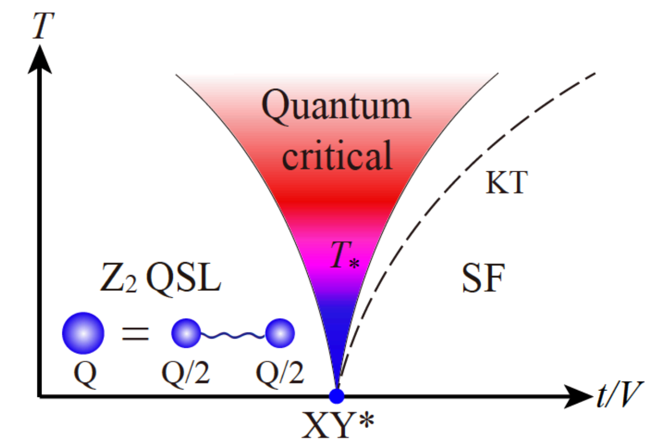
Yan-Cheng Wang[1], Meng Cheng[2], William Witczak-Krempa[3,4] & Zi Yang Meng[5]✉

Nat. Comm. 12, 5347 (2021)

$$H = -t \sum_{\langle i,j \rangle} (b_i^\dagger b_j + \mathrm{h.c.}) + V \sum_{\hexagon} \Big(\sum_{i \in \hexagon} n_i \Big)^2 + V' \sum_{\langle i,j \rangle'} n_i n_j + \mu \sum_i n_i$$

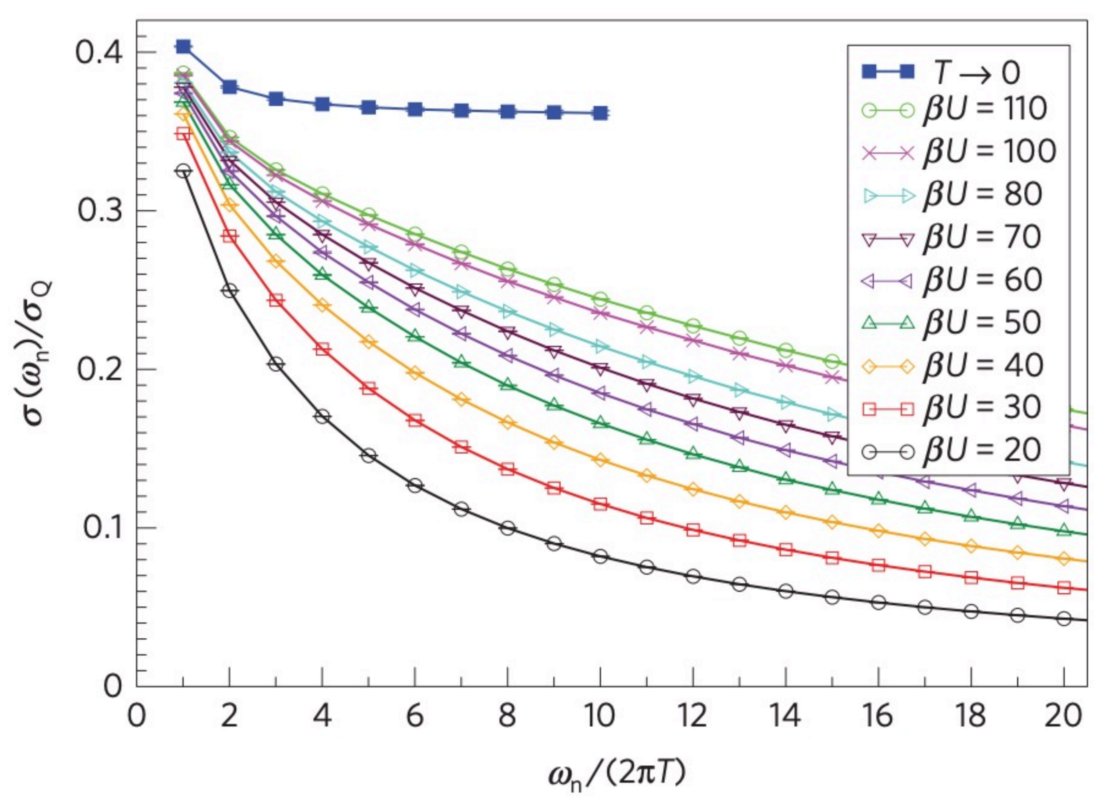


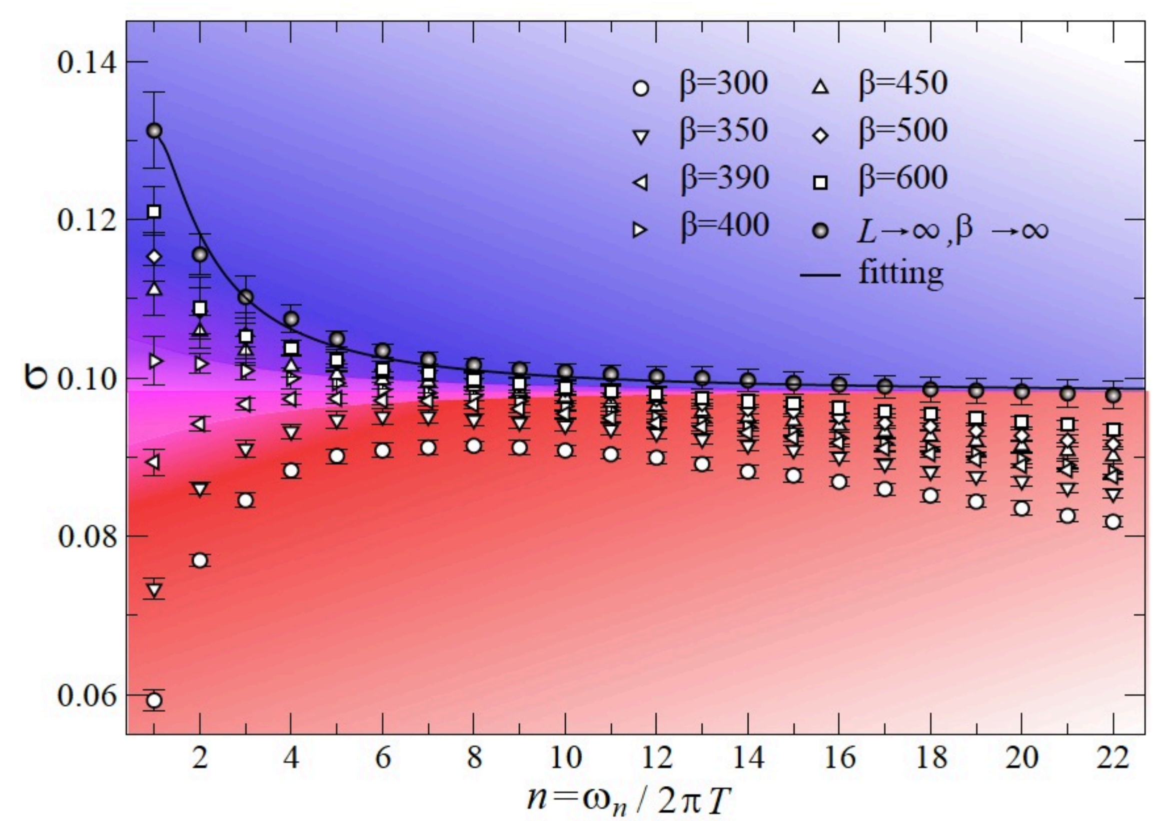




Particle-like conductivity

Particle-like conductivity
Vortex-like conductivity
Particle-Vortex duality at the scale of T*





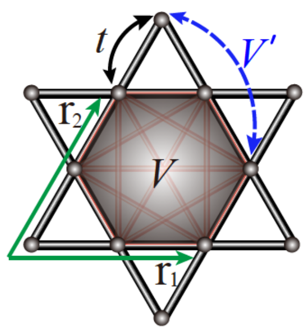
Witczak-Krempa, Sørensen, Sachdev, Nat. Phys. 10, 361 (2014)

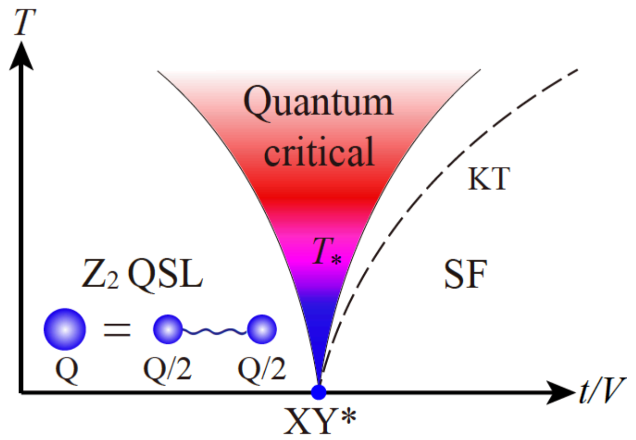
Fractionalized conductivity and emergent self-duality near topological phase transitions

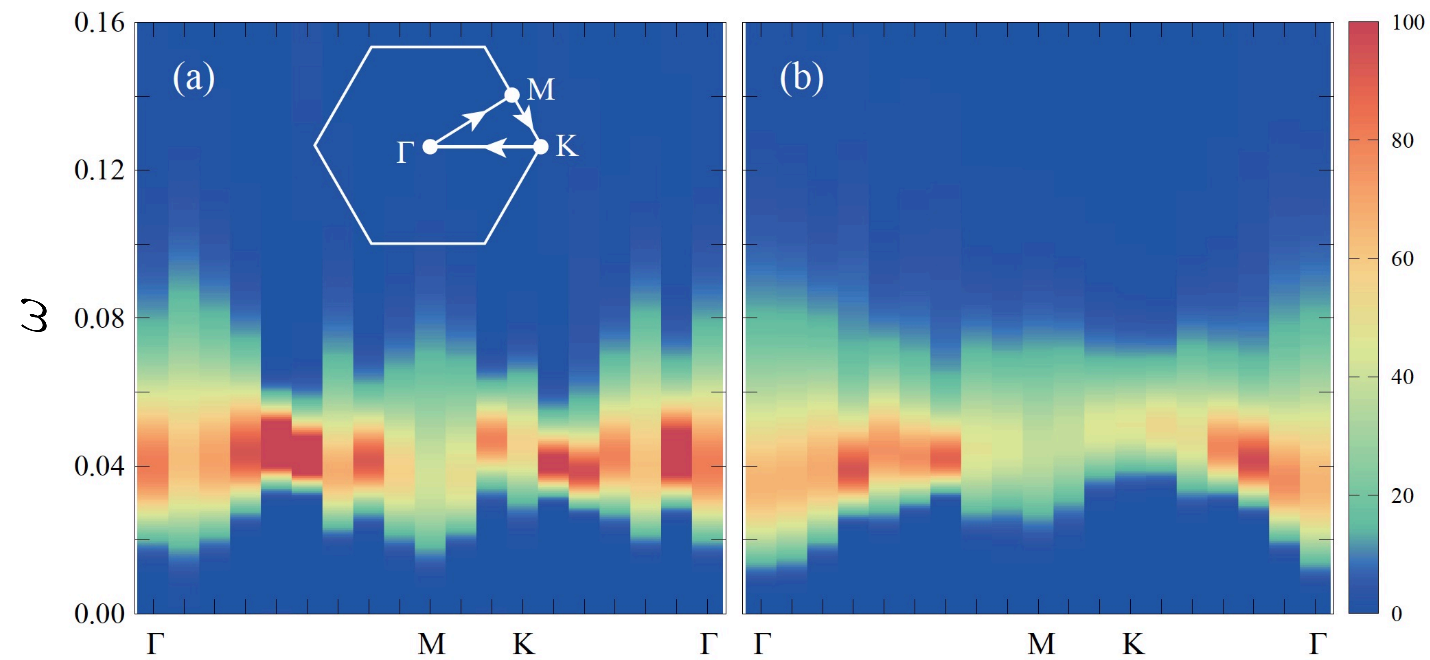
Yan-Cheng Wang[1], Meng Cheng[2], William Witczak-Krempa[3,4] & Zi Yang Meng[5]

Nat. Comm. 12, 5347 (2021)

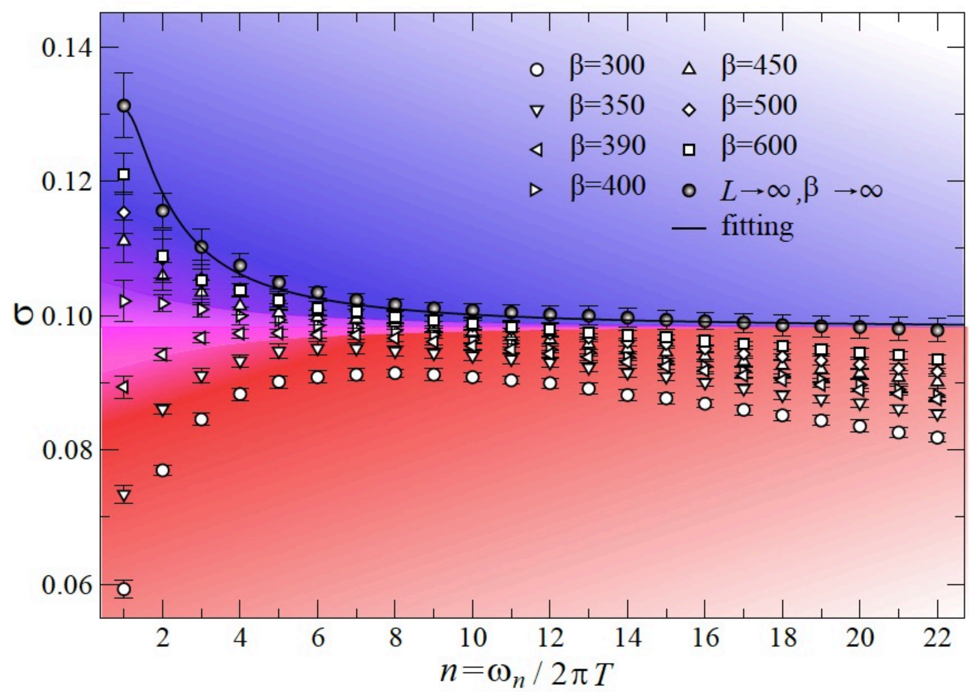
$$H = -t\sum_{\langle i,j\rangle}(b_i^\dagger b_j + \text{h.c.}) + V\sum_{\hexagon}\Big(\sum_{i\in\hexagon} n_i\Big)^2 + V'\sum_{\langle i,j\rangle'} n_i n_j + \mu\sum_i n_i$$

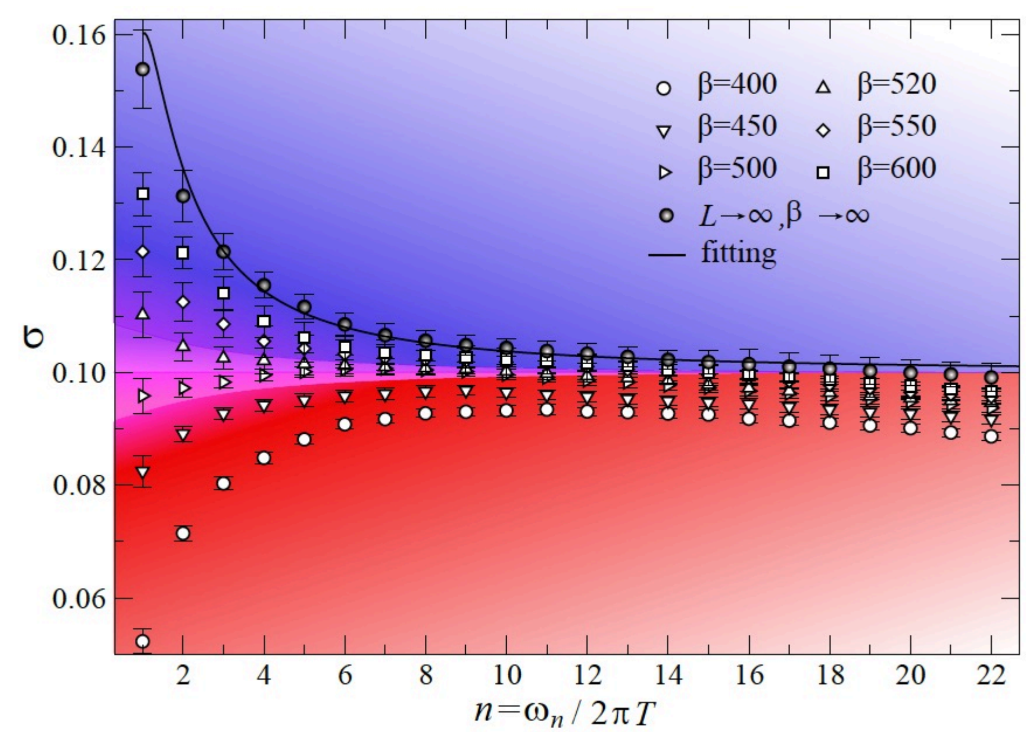






Dynamically self-duality at the scale of T*
Thermally excited visions

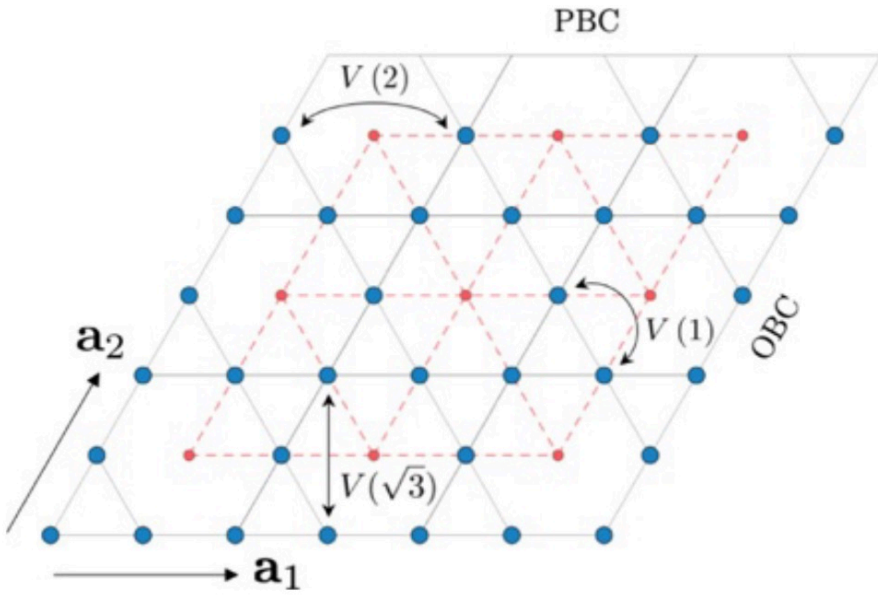




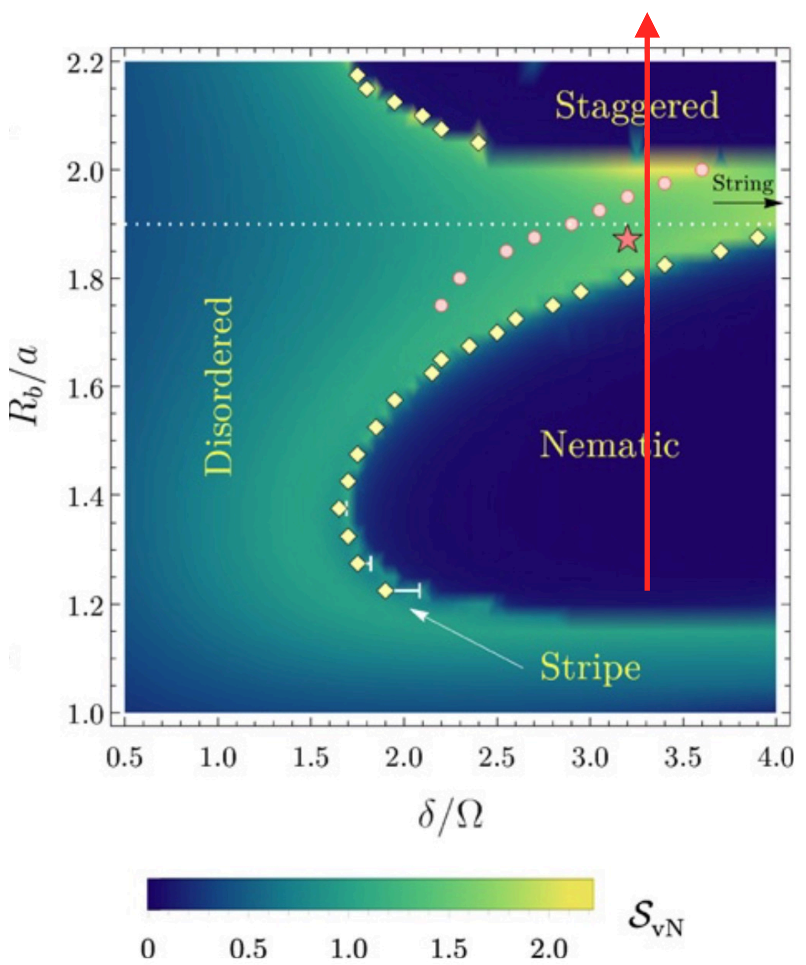
Quantum phases of Rydberg atoms on a kagome lattice

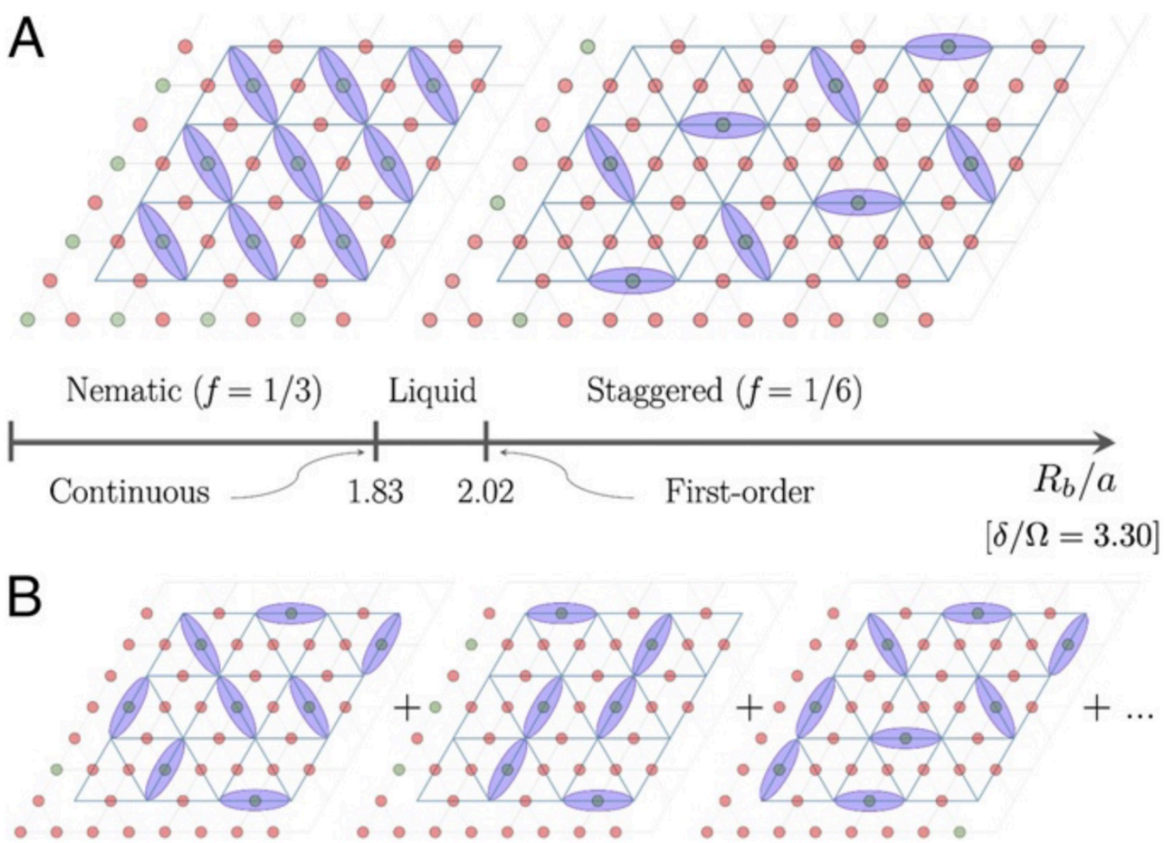
Rhine Samajdar[a,1], Wen Wei Ho[a,b], Hannes Pichler[c,d], Mikhail D. Lukin[a], and Subir Sachdev[a,1]

Kagome and its medial triangle



PNAS 118, e2015785118 (2021)





Maps to quantum dimer models on triangular lattice with varying density

Constrained quantum lattice models are hard to solve

Sweeping cluster quantum Monte Carlo method

Zheng Yan et al., PRB 99, 165135 (2019)

Zheng Yan

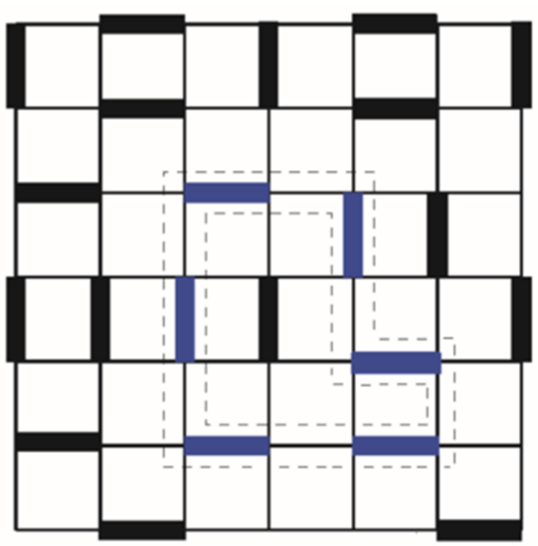
$$H = -t\sum_{\text{plaq}}\left(|\,\|\,\rangle\langle = | + \text{H.c.}\right) + V\sum_{\text{plaq}}\left(|\,\|\,\rangle\langle\,\|\,| + |=\rangle\langle=|\right)$$

$$Z = \sum_{\alpha}\sum_{S_M}\frac{\beta^n (M-n)!}{M!}\left\langle \alpha \left| \prod_{i=1}^{M} H_{a_i,p_i} \right| \alpha \right\rangle$$

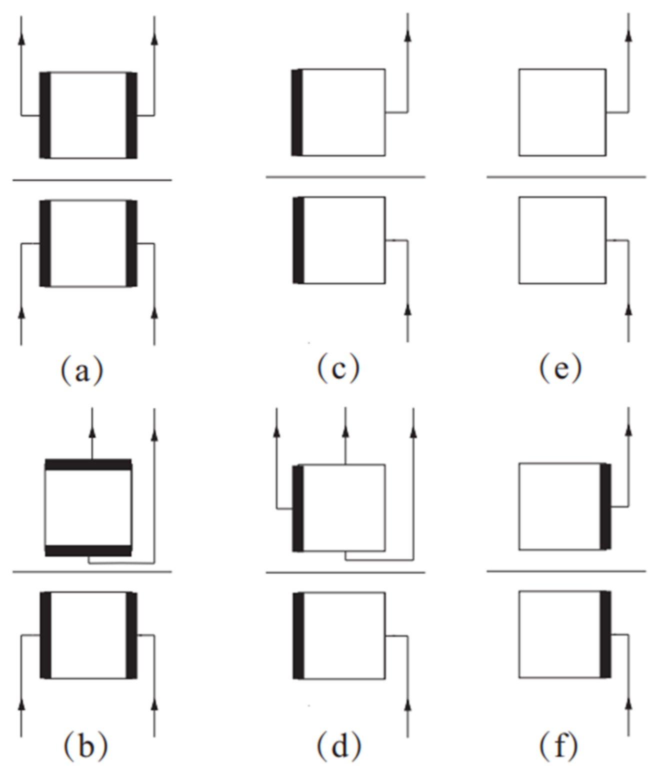
$$\langle\,\|\,|H_{1,p}|\,\|\,\rangle = \langle = |H_{1,p}| = \rangle = 1,$$
$$\langle\,\|\,|H_{2,p}| = \rangle = \langle = |H_{2,p}|\,\|\,\rangle = 1,$$
$$\langle \text{others}|H_{1,p}|\text{others}\rangle = 1 + V;$$

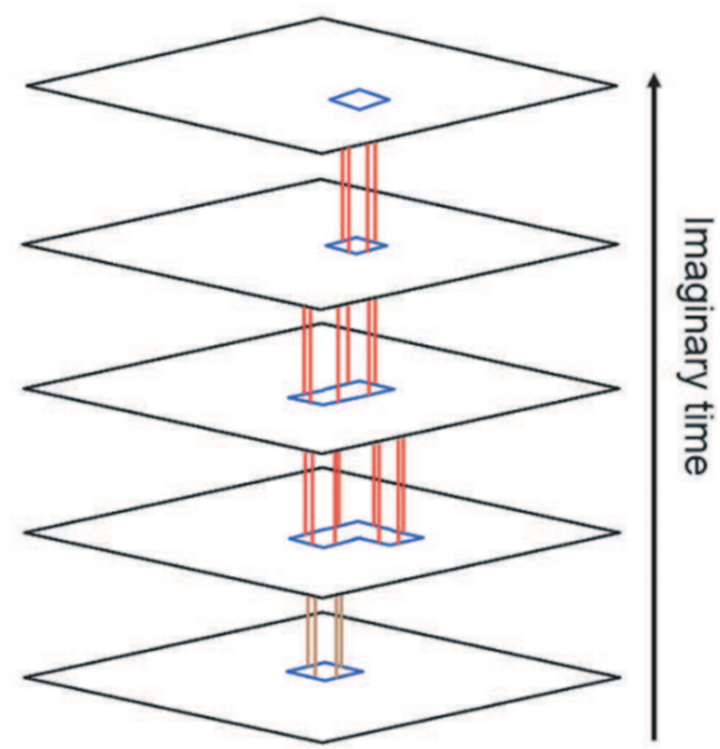
define the matrix elements in time evolution

quantum loop update in the path-integral



loop update for classical dimer model





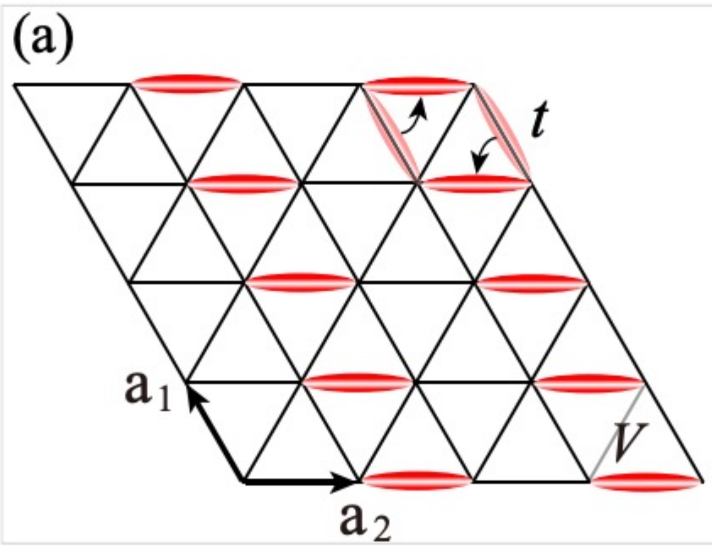
Zheng Yan, global scheme sampling topological sectors, arXiv:2011.08457

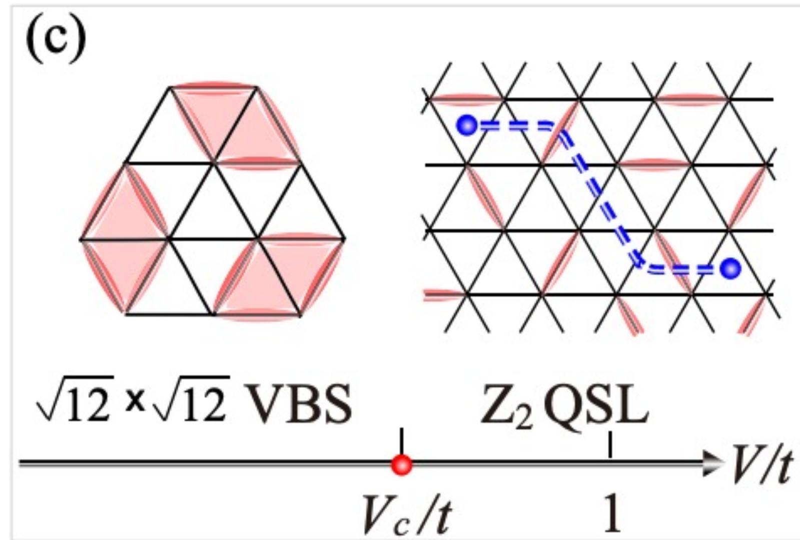
Zheng Yan et al., square lattice mixed phase, PRB 103, 094421 (2021)

Topological phase transition and single/multi anyon dynamics of Z_2 spin liquid

Zheng Yan[1], Yan-Cheng Wang[2], Nvsen Ma[3], Yang Qi[4,5,6] and Zi Yang Meng[1]

npj Quantum Materials 6, 39 (2021)



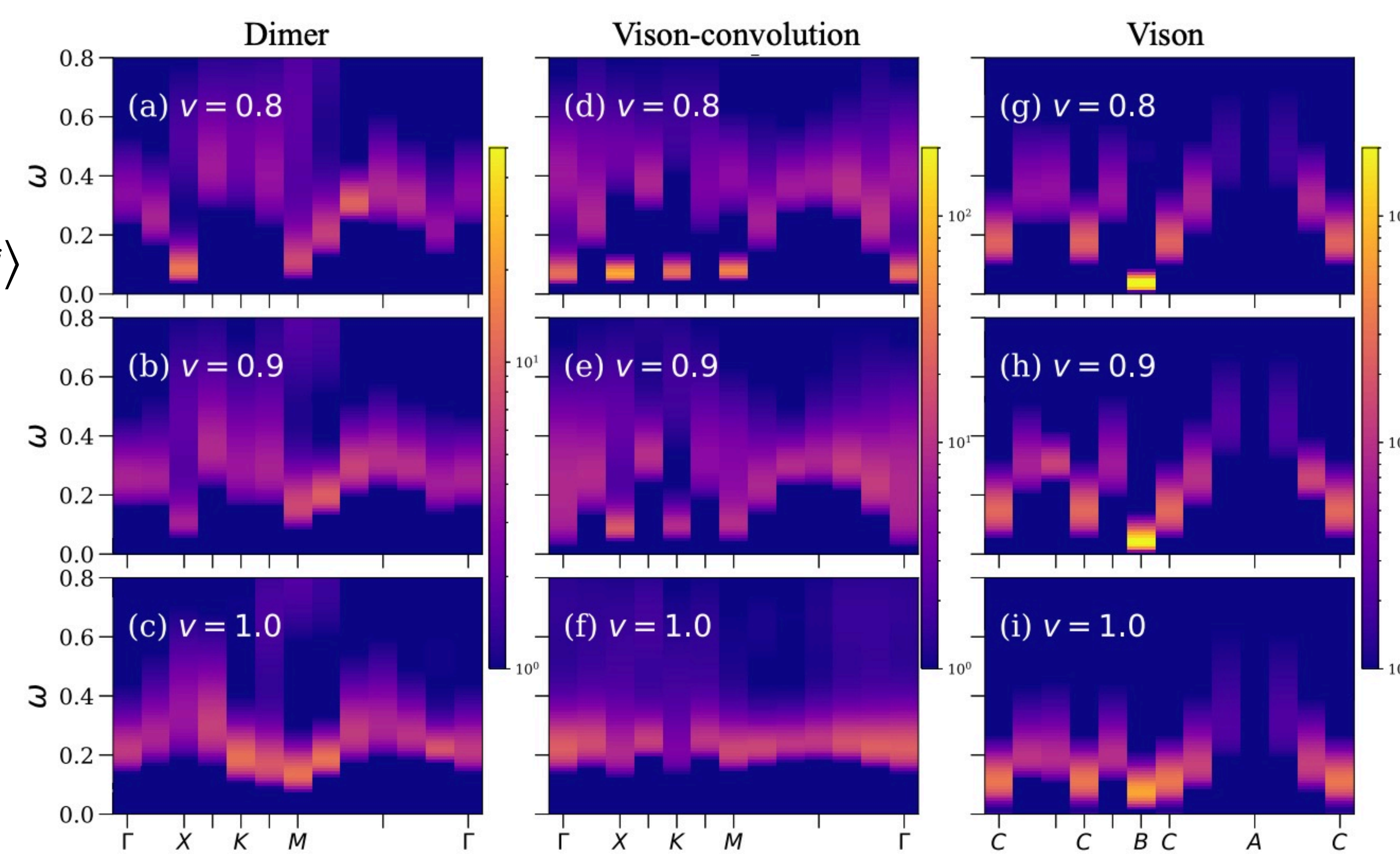


$N_{P_{ij}}$ # dimers along path from plaq i to j

$$C_d(r_{ij},\tau) = \sum_{i,j} \langle D_i(\tau)D_j(0)\rangle - \langle D_i\rangle\langle D_j\rangle$$

$$C_V(r_{ij},\tau) = \sum_{i,j} \langle V_i(\tau)V_j(0)\rangle = \sum_{i,j} \langle (-1)^{N_t + N_{P_{ij}}}\rangle$$

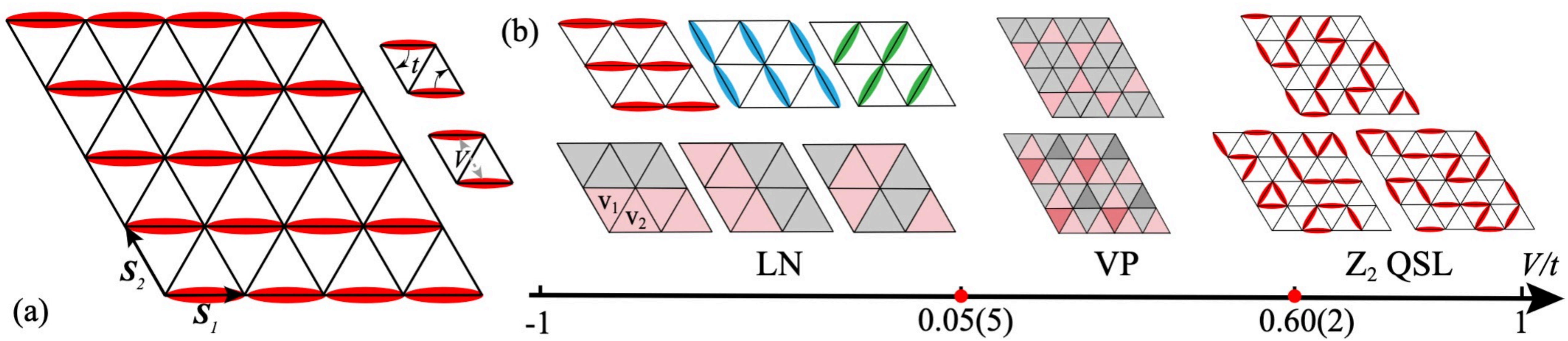
- Bound state of vison pair inside QSL
- Symmetry fractionalisation at transition



Quantum loop model on triangular lattice: Hidden Vison Plaquette phase and Cubic phase transitions

Zheng Yan,[1,2,*] Xiaoxue Ran,[1,*] Yan-Cheng Wang,[3] Rhine Samajdar,[4]
Junchen Rong,[5] Subir Sachdev,[4,6] Yang Qi,[2,7,8,†] and Zi Yang Meng[1,‡]

arXiv: 2205.04472



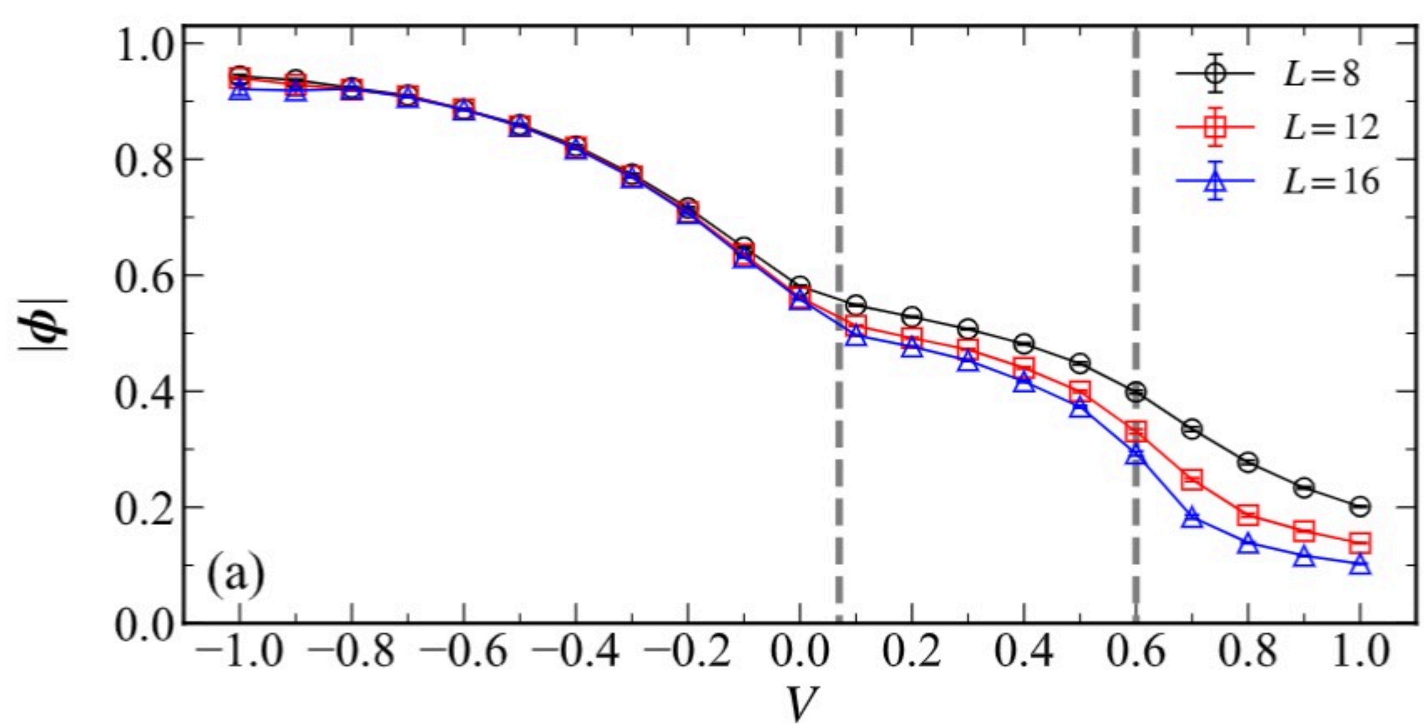
O(3) vison order parameter

$$\phi_j = \sum_{\mathbf{r}} (v_{1,\mathbf{r}}, v_{2,\mathbf{r}}) \cdot \mathbf{u}_j e^{i\mathbf{M}_j \cdot \mathbf{r}}, \quad j = 1, 2, 3$$

Previous literatures disagree on phase diagram

Assume direct LN-QSL transition with emergent O(3)

- Roychowdhury et al., PRB 92, 075141(2015), ED
- Plat et al., PRB 92, 174402 (2015), projection QMC

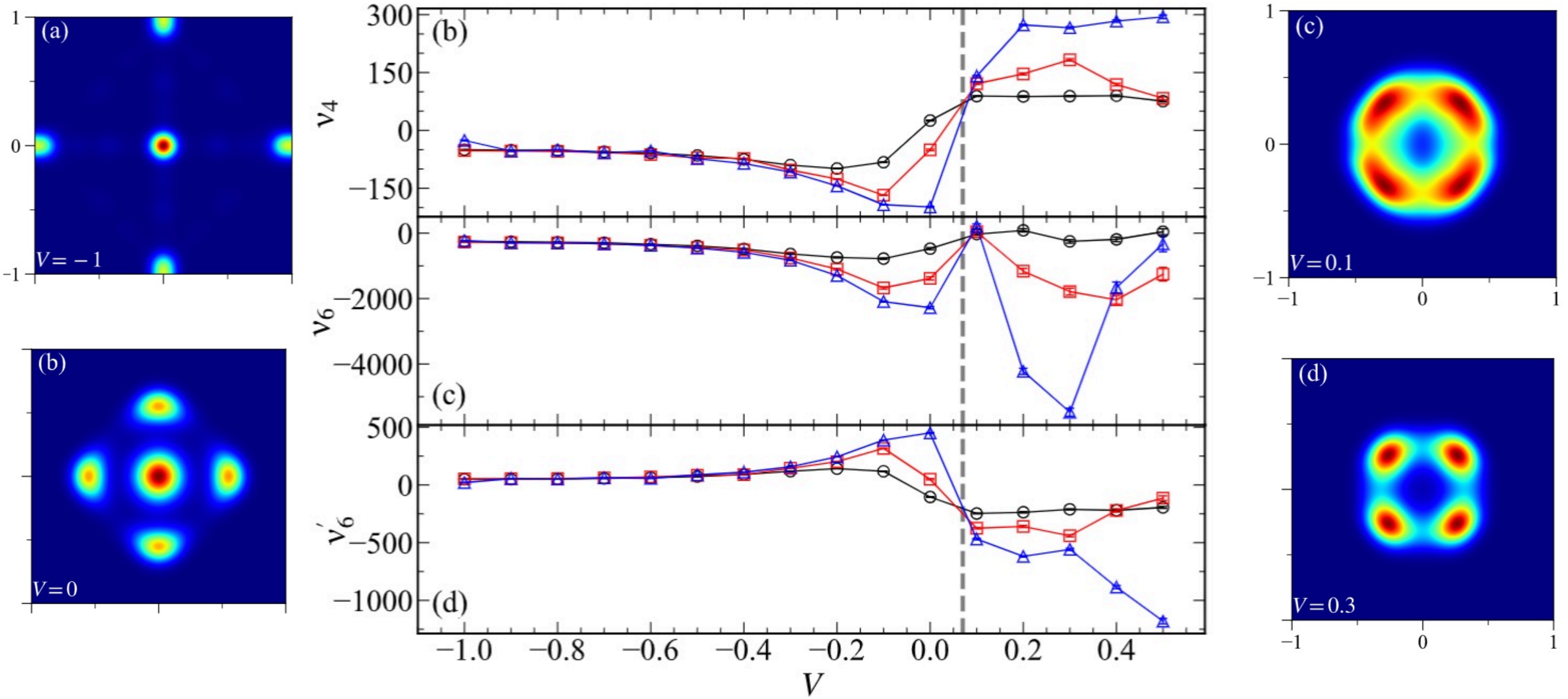


arXiv: 2205.04472

$$L = \sum_{i=1}^{3} (\partial_\mu \phi_i)^2 + r \sum_{i=1}^{3} \phi_i^2 + \mu (\sum_{i=1}^{3} \phi_i \phi_i)^2 + \nu_4 \sum_{i=1}^{3} (\phi_i)^4 + \mu_6 (\sum_{i=1}^{3} \phi_i^2)^3 + \nu_6 (\phi_1 \phi_2 \phi_3)^2 + \nu_6' (\sum_{i=1}^{3} \phi_i^2)(\sum_{i=1}^{3} \phi_i^4)$$

Chester et al., PRD 104, 105013 (2021): **O(3) conformal fixed point is unstable against cubic anisotropy**

(ϕ_1, ϕ_2, ϕ_3) order parameter Monte Carlo histogram

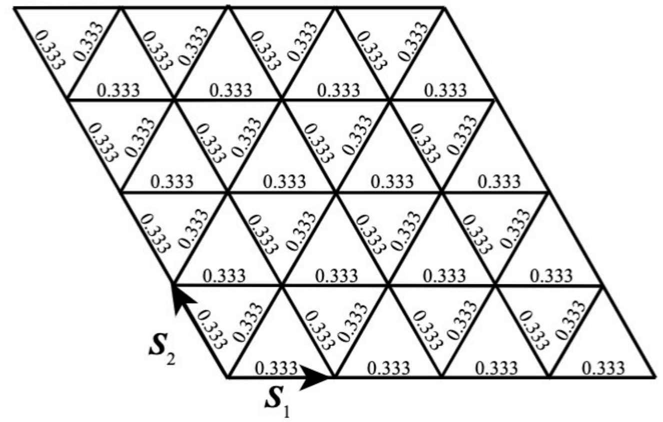


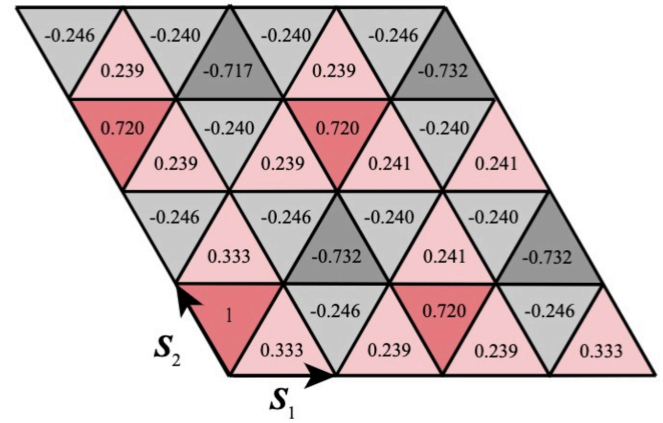
First order transition from face-cubic (nematic) to corner cubic (vison plaquette)

Hidden Vison Plaquette phase and Cubic phase transitions

arXiv: 2205.04472

4x4 ED





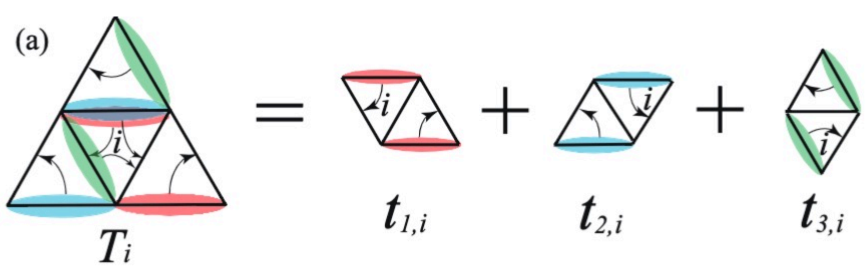
LN

VP

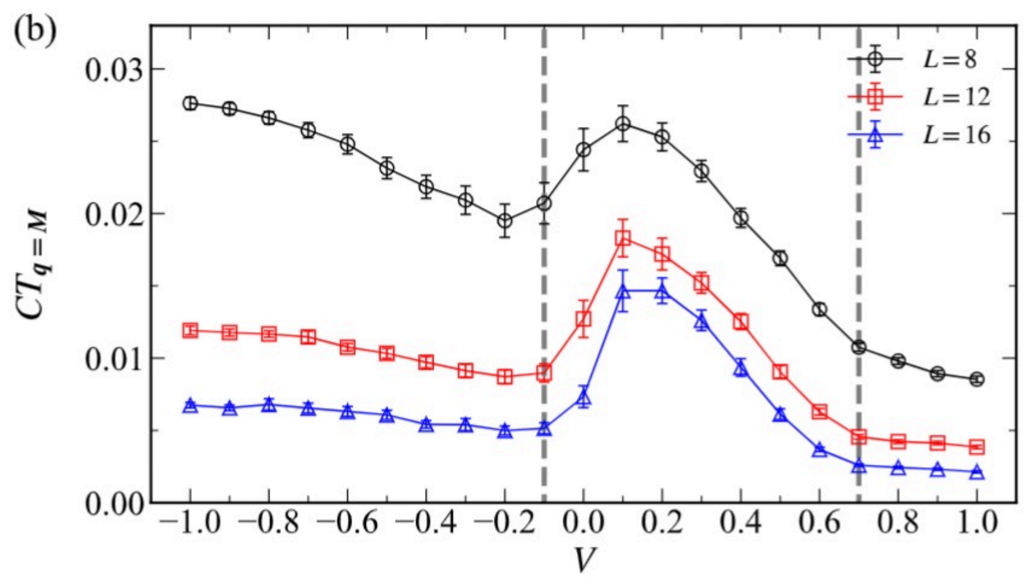
Z2 QSL

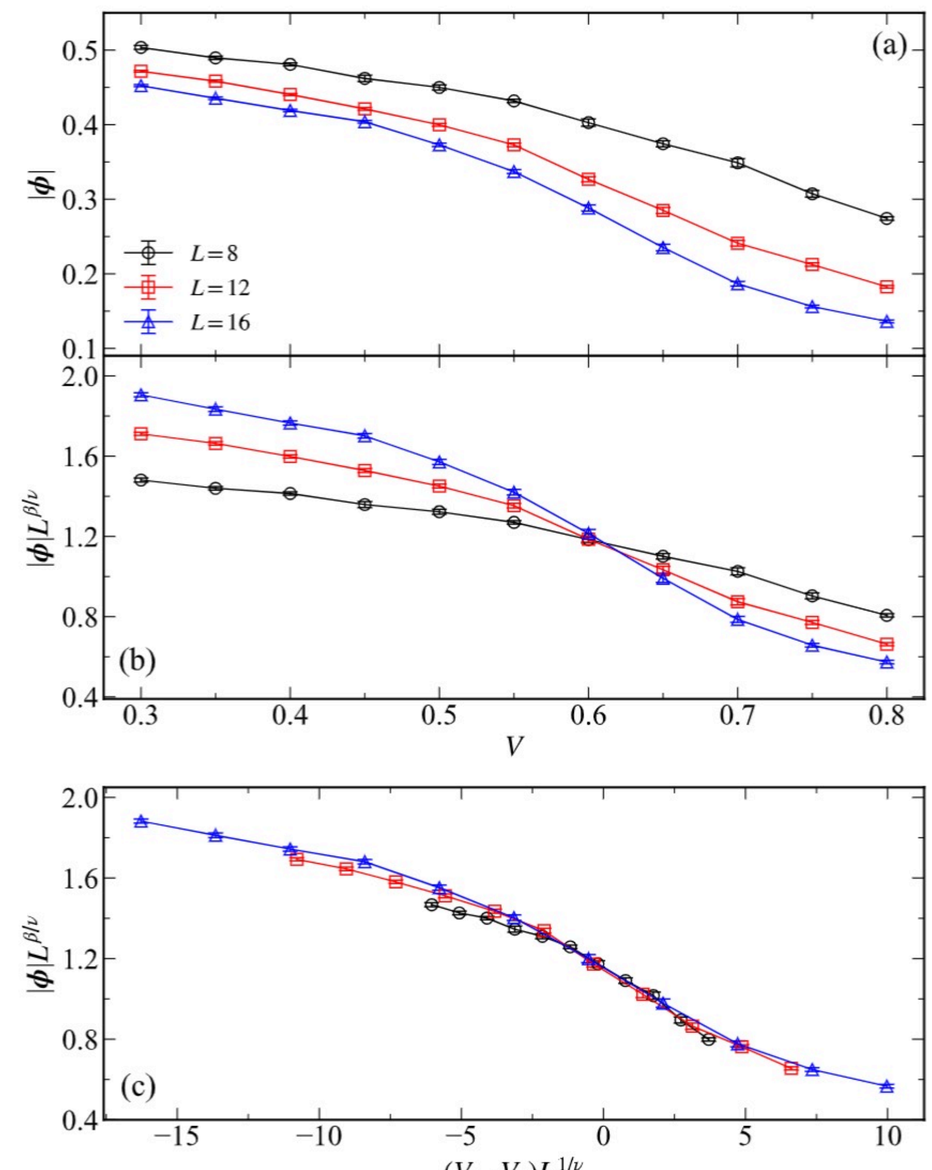
Cubic* transition

Off-diagonal order



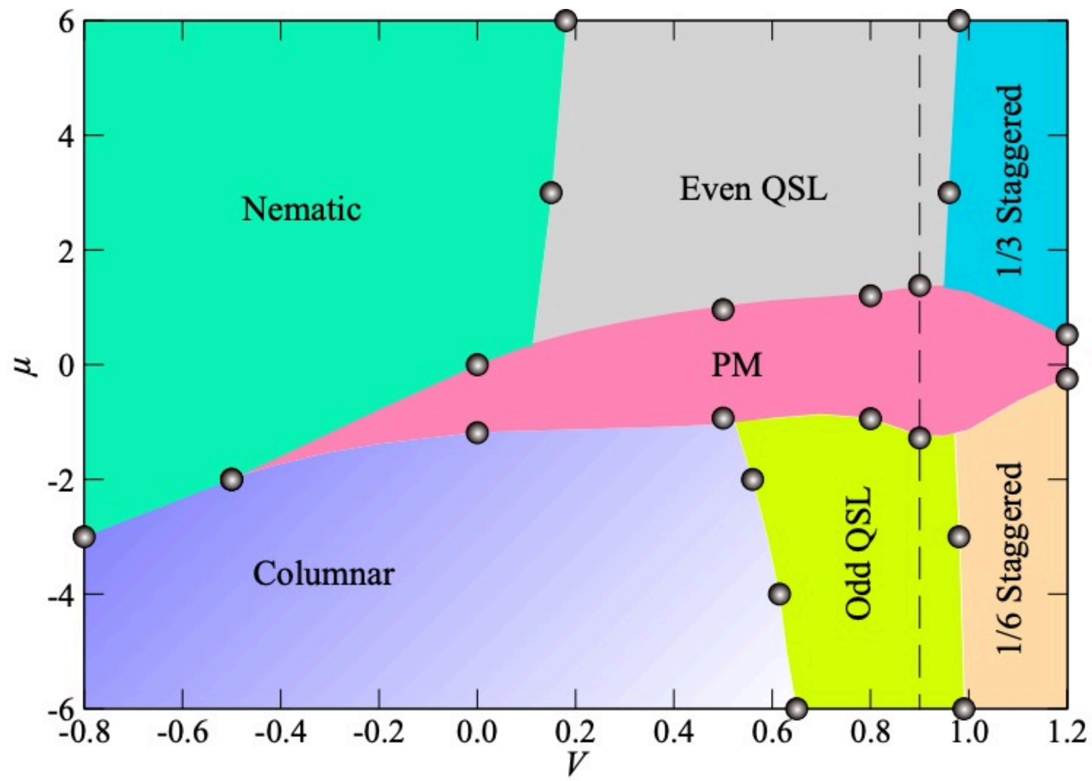
$$CT = \sum_{ij} \langle T_i T_j \rangle$$

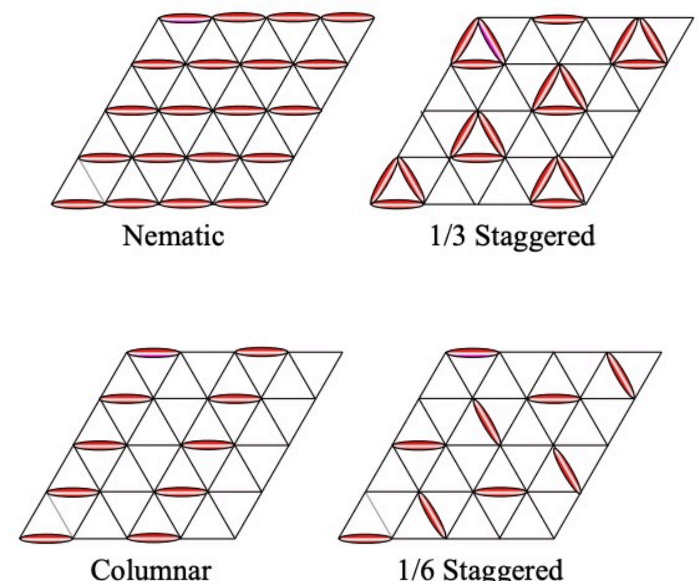




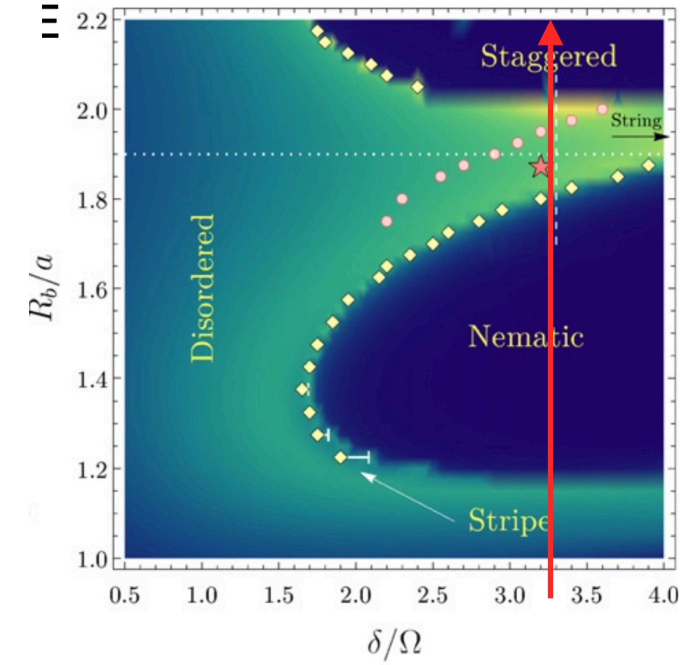
Triangular lattice quantum dimer model with variable dimer density

Zheng Yan,[1] Rhine Samajdar,[2] Yan-Cheng Wang,[3] Subir Sachdev,[2,4,*] and Zi Yang Meng[1,†]

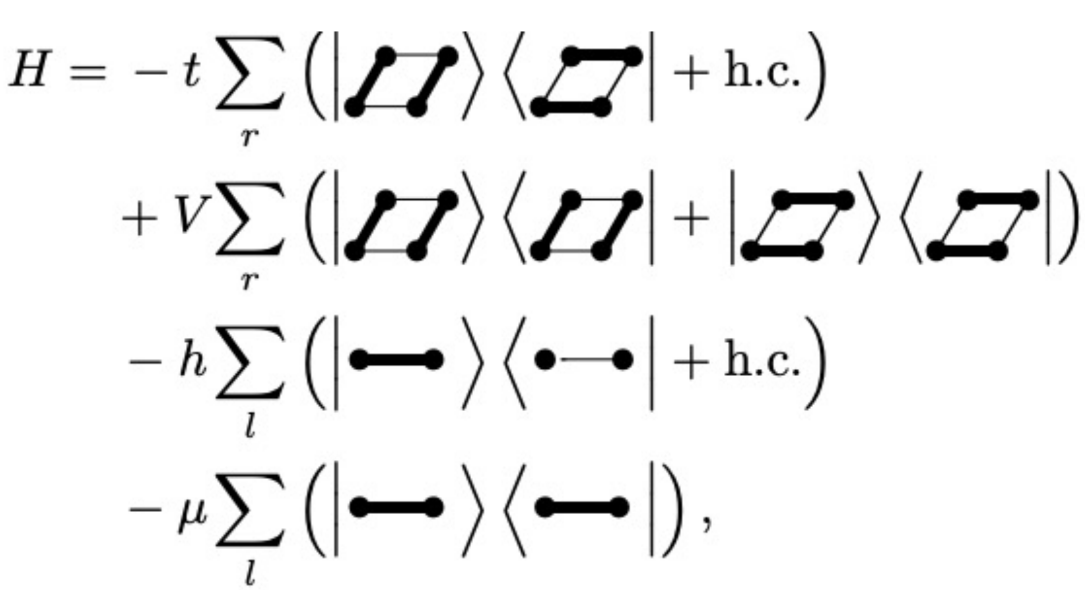


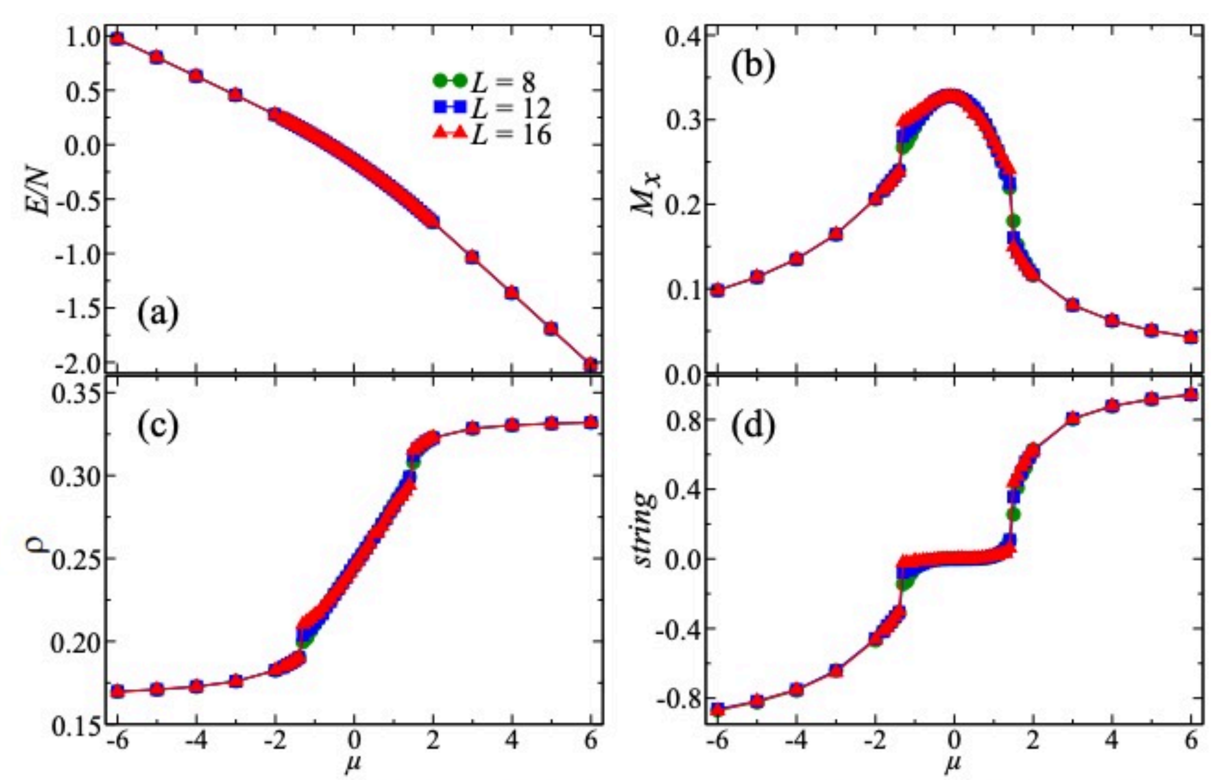


arXiv:2202.11100



$t = 1, h = 0.4$

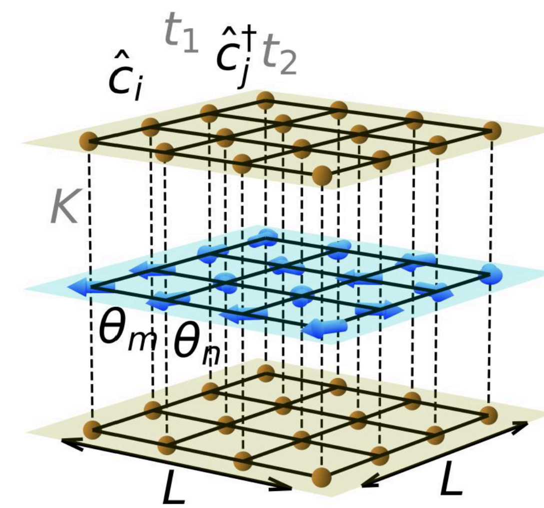




bridging QDM with Fendley, Sengupta, Sachdev

$\langle string \rangle = \langle (-1)^{\#\, dimer} \rangle$

Content



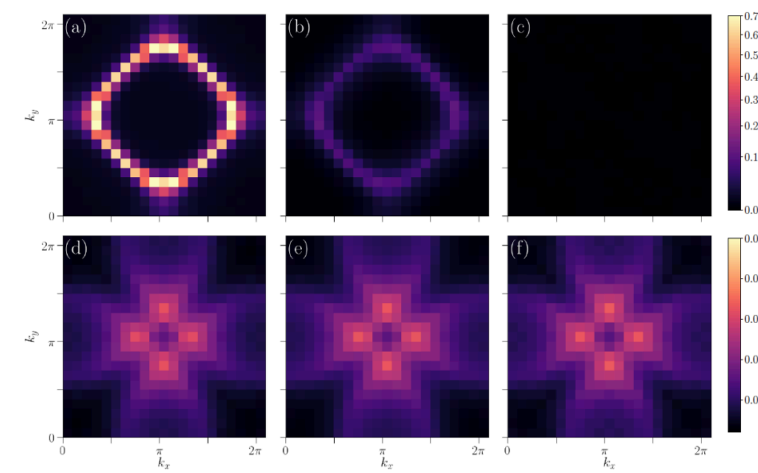
- PRX 7, 031058 (2017)
- PNAS 116 (34), 16760 (2019)
- npj Quantum Materials 5, 65 (2020)
- PRB 105, L041111 (2022)
- Nat. Comm. 13, 2655 (2022)
- ......

1. Non-Fermi-Liquid

   Quantum critical metals

   Luttinger's theorem

   Matter fields coupled to gauge fields



- PRX 9, 021022 (2019)
- PRB 101, 235118 (2020)
- CPL 37, 047103 (2020)
- PRB 103, 165131 (2021)
- ......

2. Fractionalisation, topological order in frustrated magnets

   Quantum dimer models

- PRL 121, 077201 (2018)
- PRL 121, 057202 (2018)
- Nat. Comm. 12, 5347 (2021)
- npj Quantum Materials 6, 39 (2021)
- arXiv: 2202.11100
- arXiv: 2205.04472
- ......