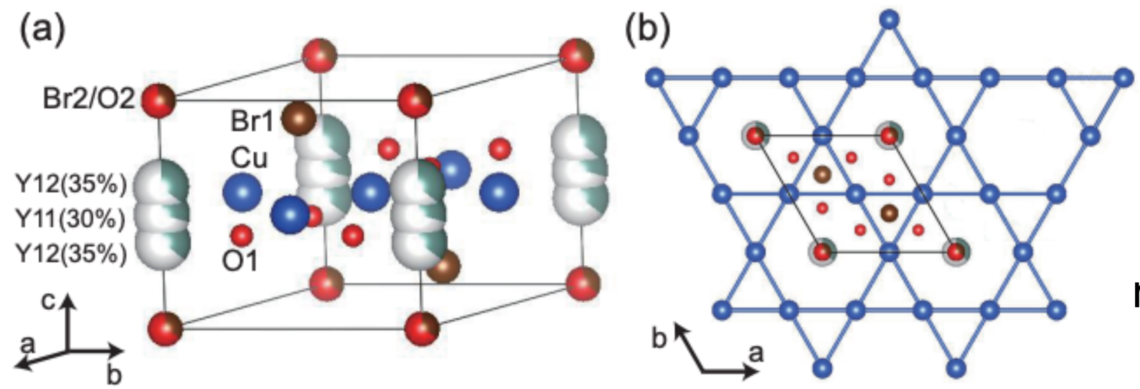
QED3, Entanglement Computation, …

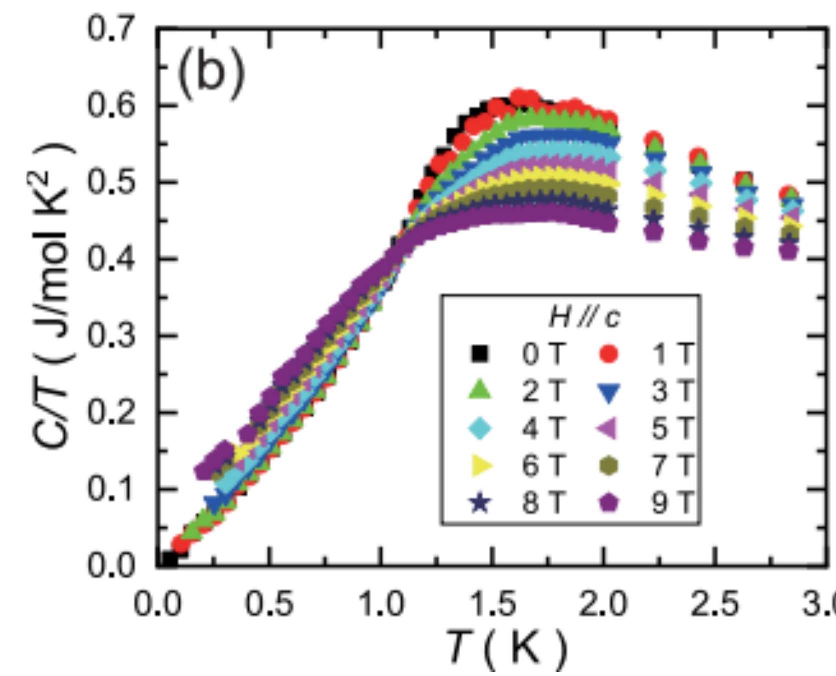
ZI YANG MENG
孟子楊
https://quantummc.xyz/

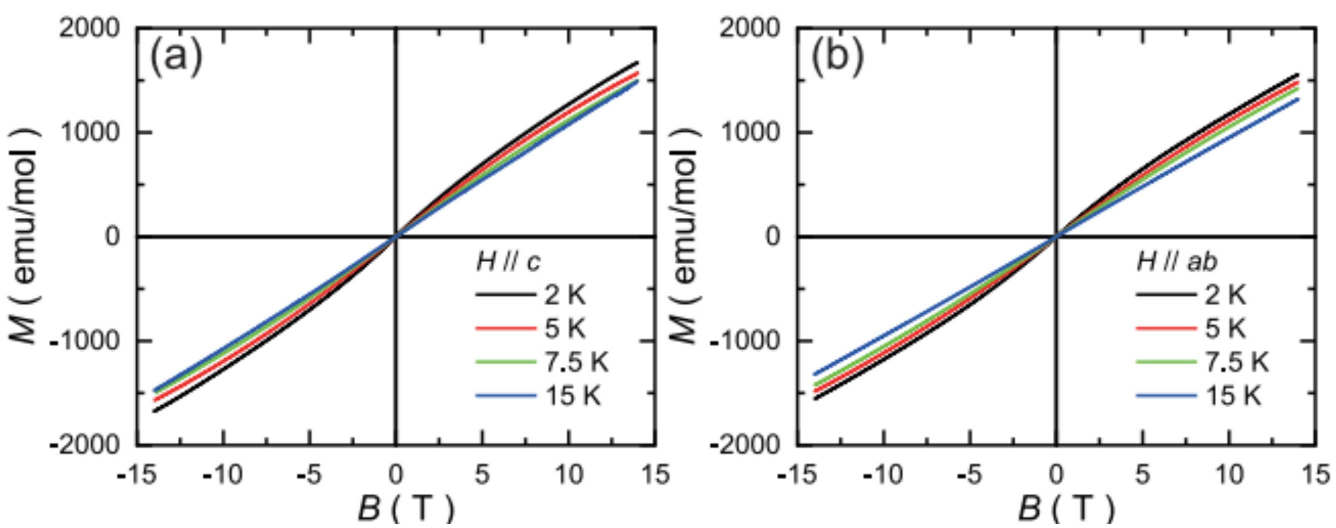
$YCu_3(OH)_6Br_2[Br_x(OH)_{1-x}]$ (YCu_3-Br)



no mag. order

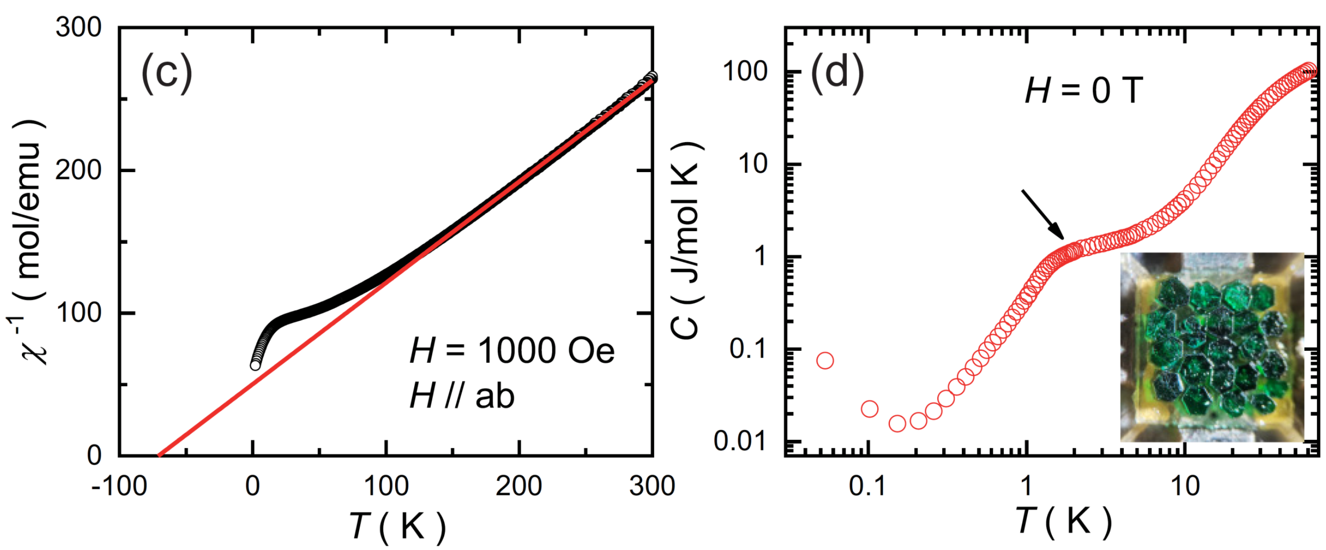
$0.05K$

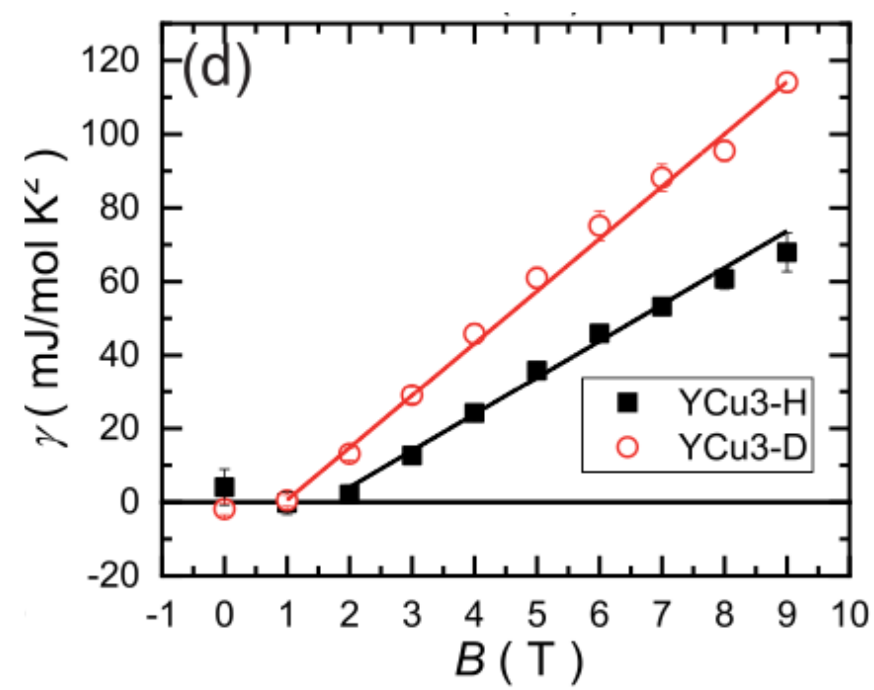




$C/T = \gamma + \alpha T$

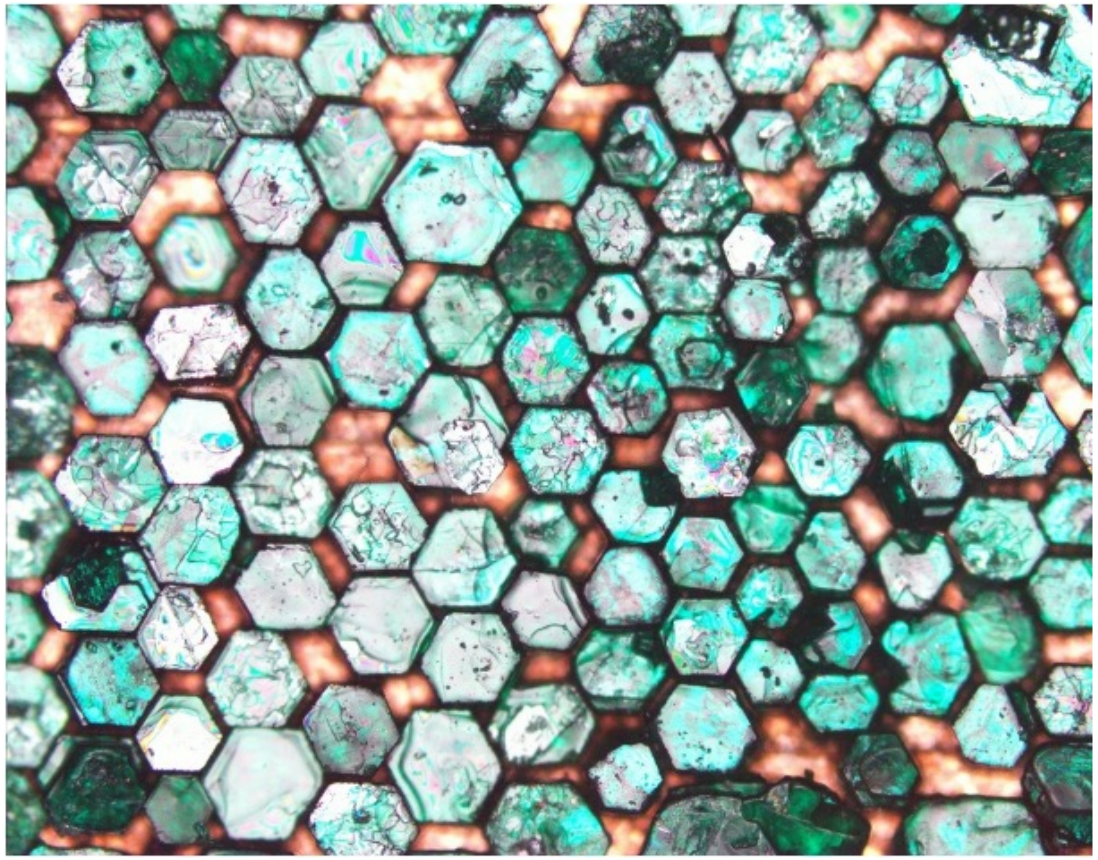
$k_B T \ll \mu_B B$

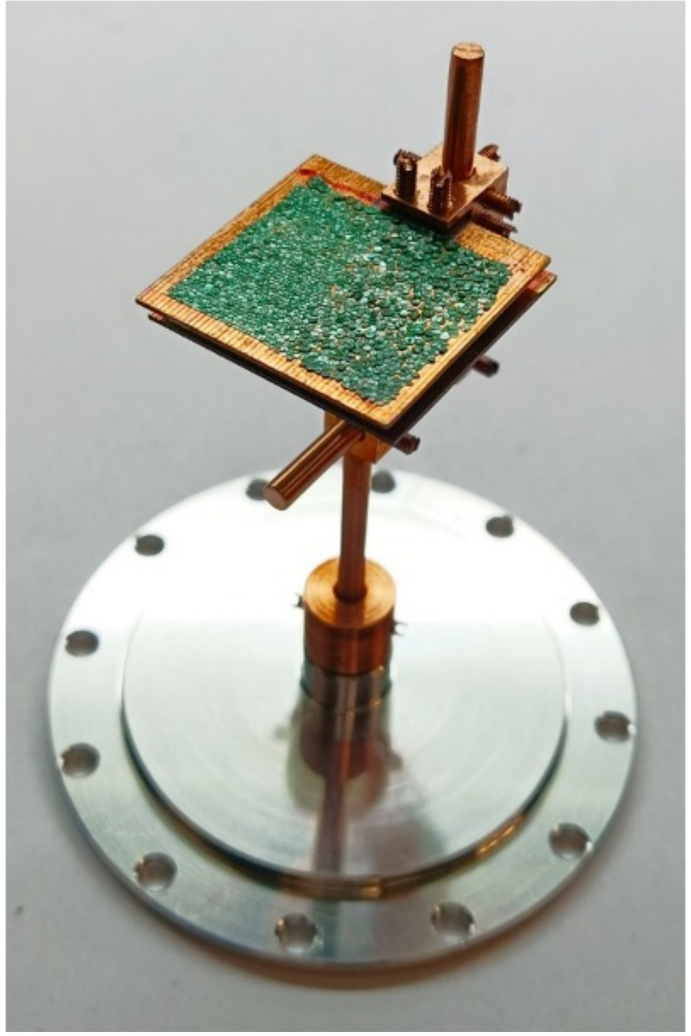




Possible Dirac quantum spin liquid in a kagome quantum antiferromagnet YCu3(OH)6Br2[Brx(OH)1−x], Zeng, Ma, …, ZYM, Shiliang Li, [Phys. Rev. B 105, L121109 (2022)]

$YCu_3(OH)_6Br_2[Br_x(OH)_{1-x}]$ (YCu_3-Br)



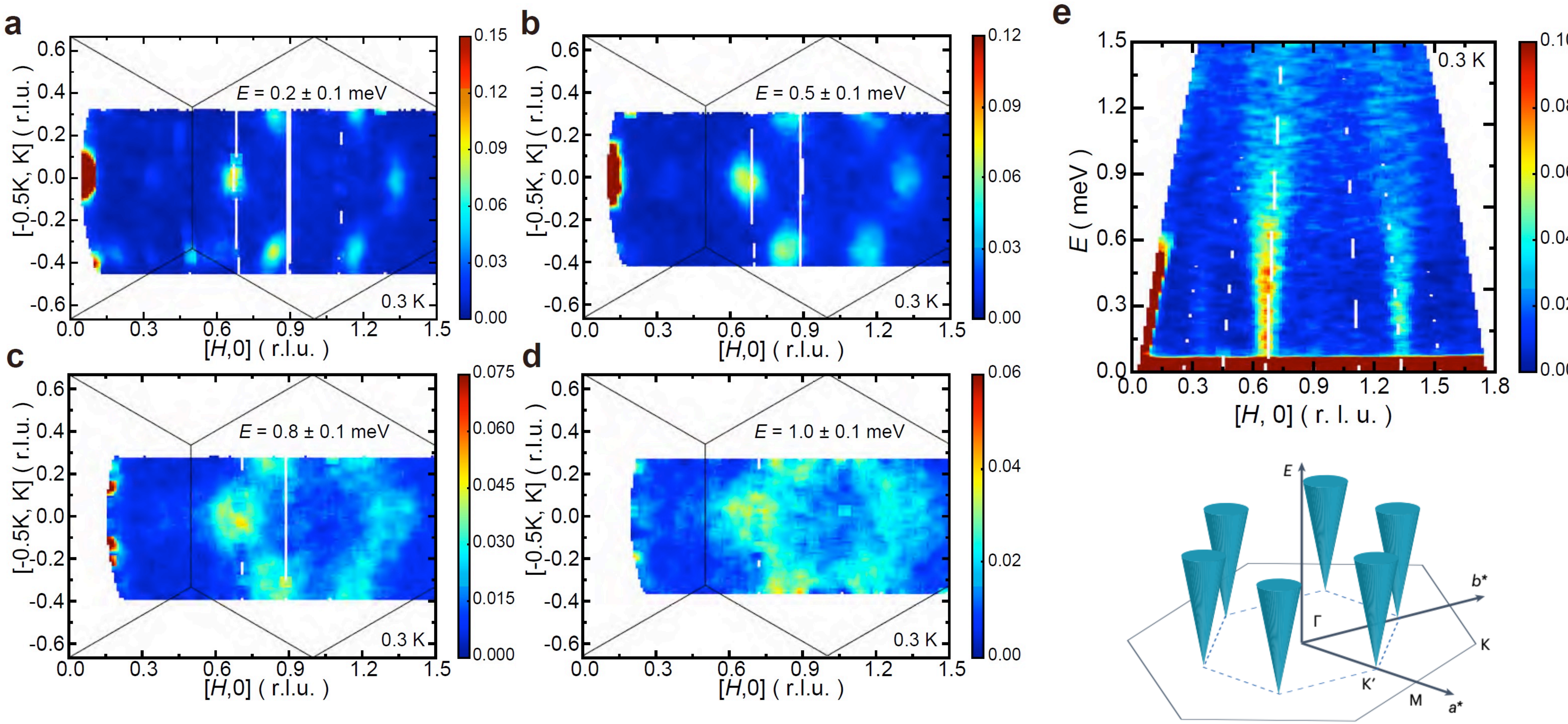


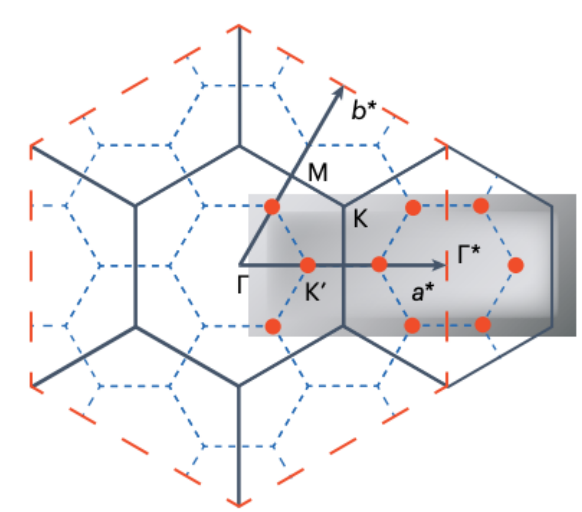
Sample #1: ~ 5000 single crystals, ~ 0.5 g @ AMATERAS, J-Parc

Sample #2: ~ 800 single crystals, ~ 0.5 g @ AMATERAS, J-Parc & THALES, ILL

📍 Spectral evidence for Dirac spinons in a kagome lattice antiferromagnet,
Zeng, Zhou, …, ZYM, Shiliang Li,
Nat. Phys. 20, 1097 (2024)

$YCu_3(OH)_6Br_2[Br_x(OH)_{1-x}]$ (YCu_3-Br or YCOB)





Spectral evidence for Dirac spinons in a kagome lattice antiferromagnet,
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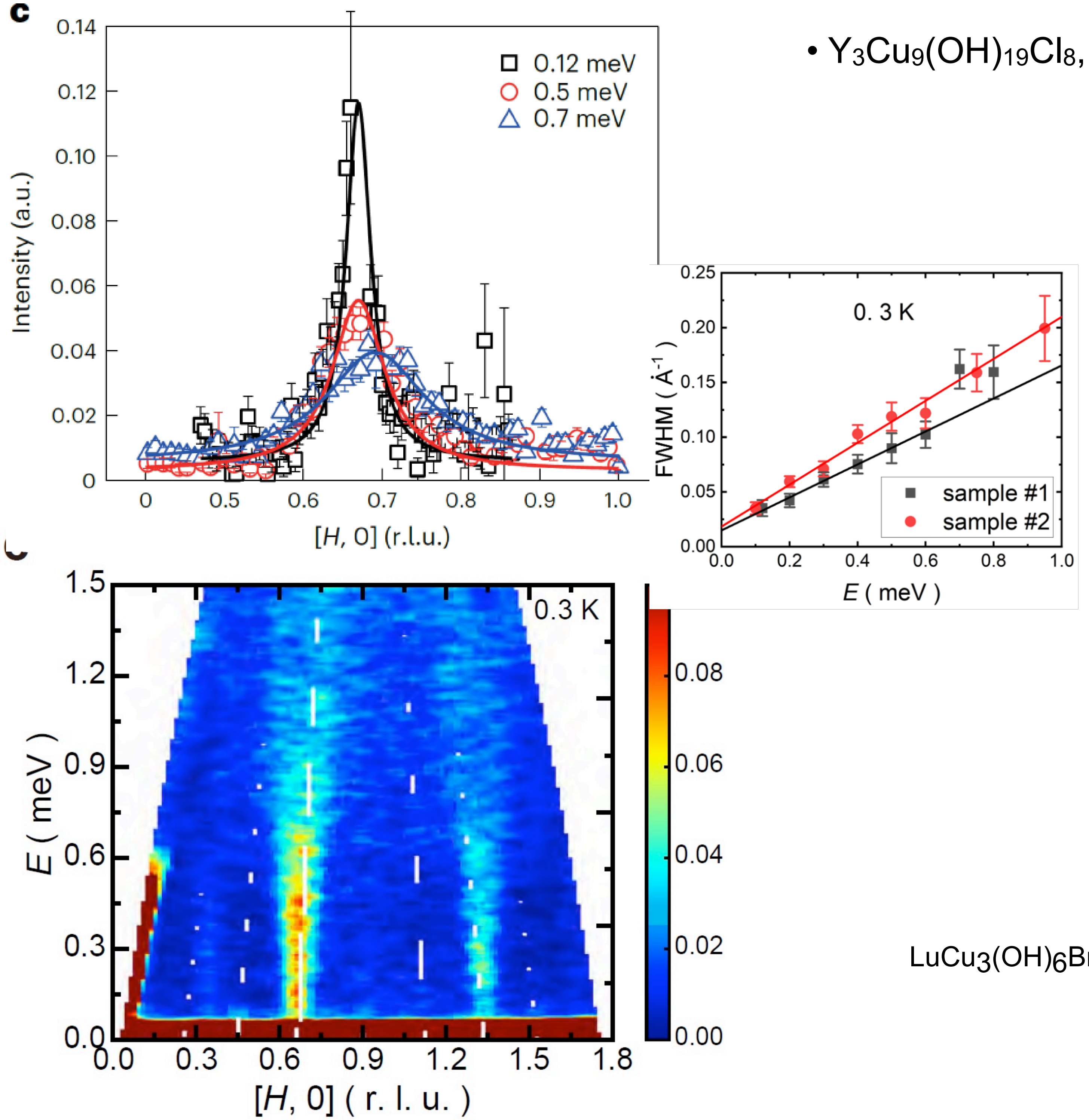
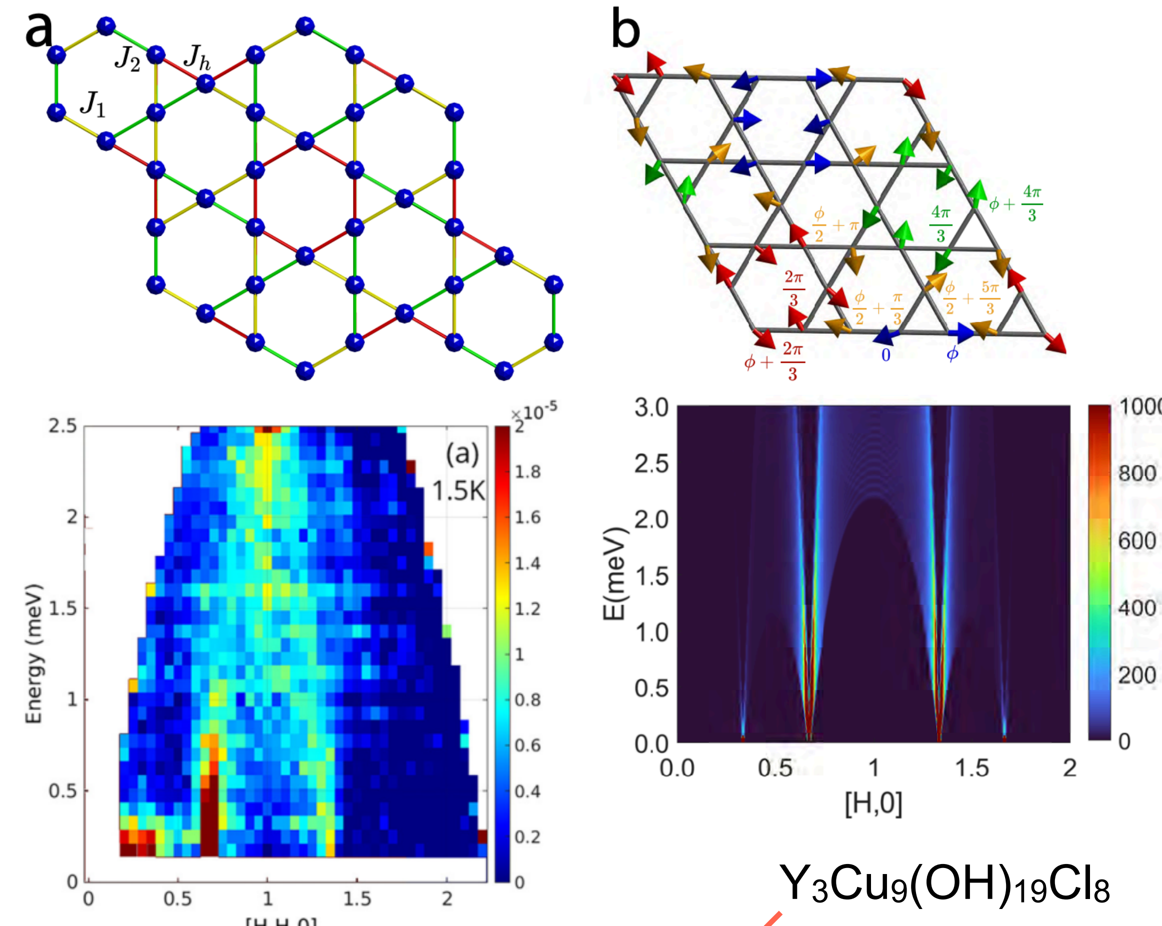
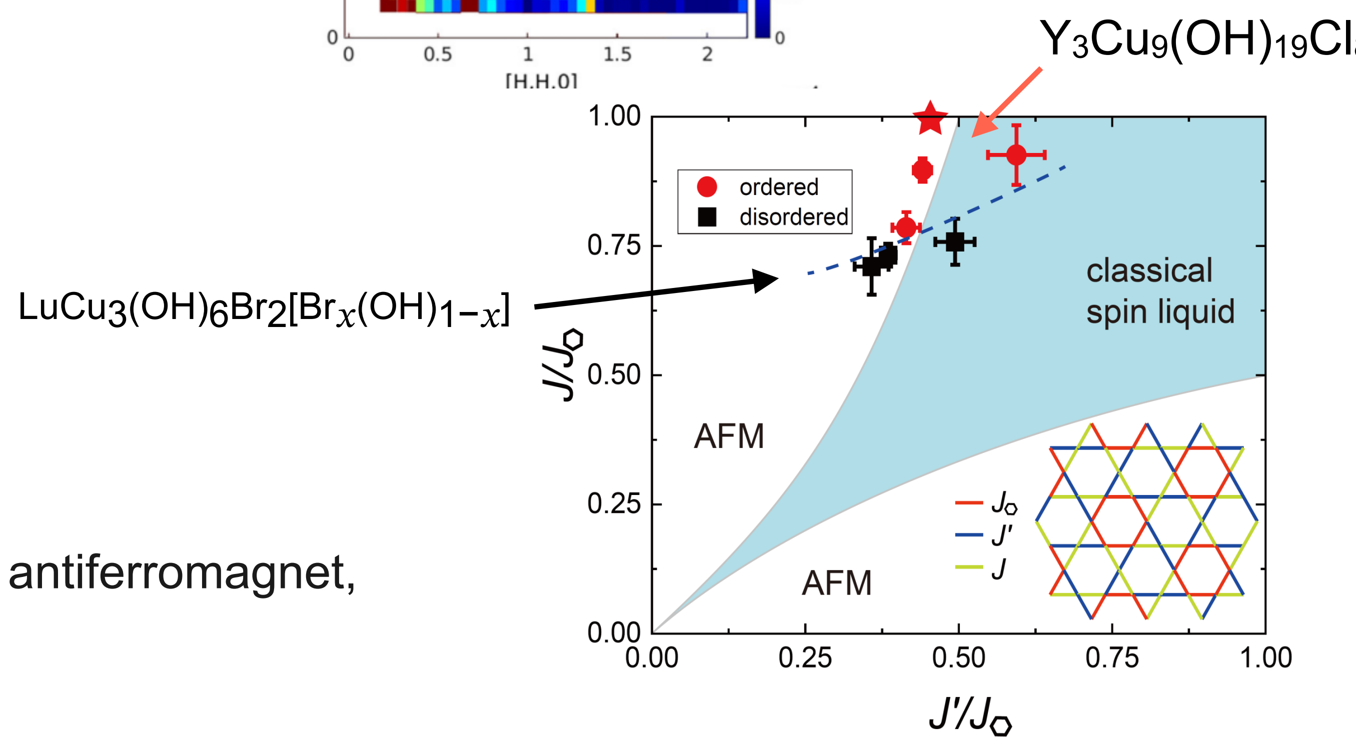


• $Y_3Cu_9(OH)_{19}Cl_8$, Y-kapellasite, Phys. Rev. B 107, 125156 (2023)





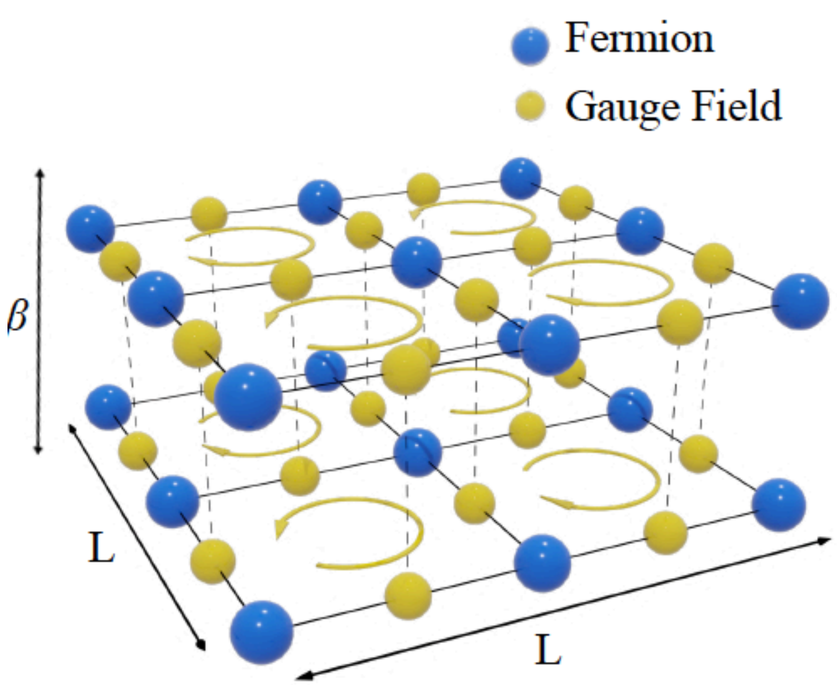
Spectral evidence for Dirac spinons in a kagome lattice antiferromagnet, Zeng, Zhou, …, ZYM, Shiliang Li, [Nat. Phys. 20, 1097 (2024)]

Antiferromagnetic Order and Possible Quantum Spin Liquid in $LuCu_3(OH)_6Br_2[Br_x(OH)_{1-x}]$, Z. Li, …, Shiliang Li, [Chin. Phys. Lett. 42, 027504 (2025)]

Monte Carlo Study of Lattice Compact Quantum Electrodynamics with Fermionic Matter: The Parent State of Quantum Phases

Xiao Yan Xu,[1,*] Yang Qi,[2–4,†] Long Zhang,[5] Fakher F. Assaad,[6] Cenke Xu,[7] and Zi Yang Meng[8,9,10,11,‡]

Phys. Rev. X 9, 021022 (2019)



$$S = S_B + S_F = \int_0^\beta d\tau \ (L_B + L_F)$$

$i, j \in L \times L$

$L = 16{,}20$

$$L_B^{nc} = \frac{1}{JN_f} \sum_{\langle i,j \rangle} \frac{(\phi_{ij,\tau+1} - \phi_{ij,\tau})^2}{\Delta\tau^2} + K \sum_{\square} \cos\Big(\sum_{\langle i,j \rangle \in \square} \phi_{ij,\tau} \Big)$$

$\sim E^2$ $\qquad (\nabla \times a)^2 \sim B^2$

$\tau \in [0, \ \beta = \frac{1}{T}]$

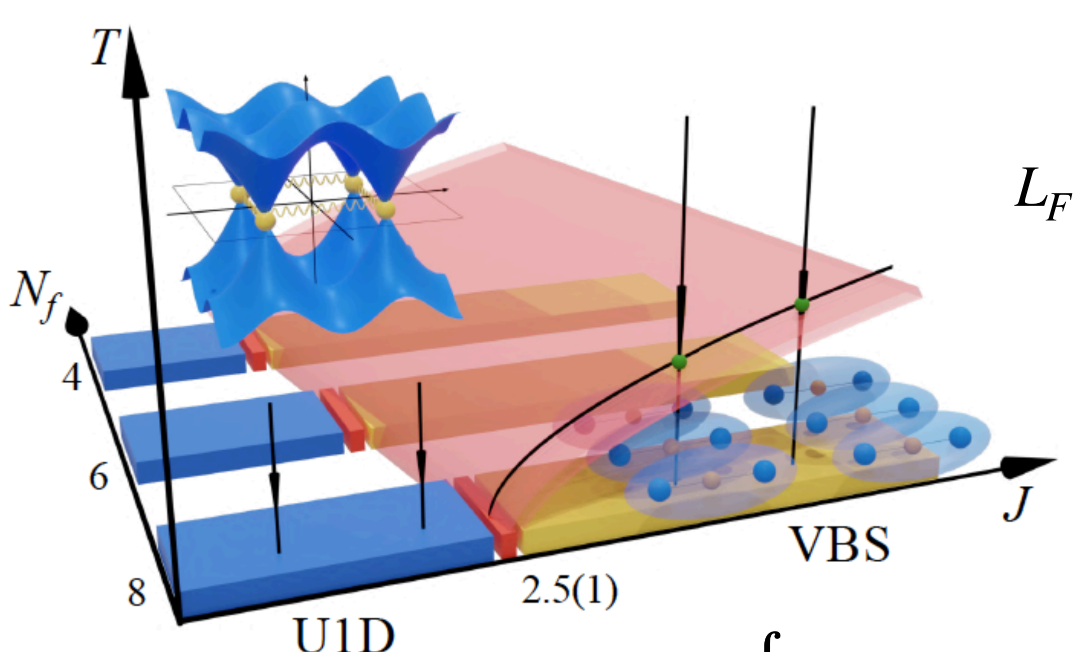
$$L_B^{c} = \frac{1}{JN_f} \sum_{\langle i,j \rangle} \frac{1 - \cos(\phi_{ij,\tau+1} - \phi_{ij,\tau})}{\Delta\tau^2} + K \sum_{\square} \cos\Big(\sum_{\langle i,j \rangle \in \square} \phi_{ij,\tau} \Big)$$

$\beta = 2L, 4L$

$\Delta\tau = 0.1$

$$L_F = \sum_{\langle i,j \rangle, \alpha} \psi^\dagger_{i,\tau,\alpha} (\partial_\tau \delta_{ij} - t e^{i\phi_{ij,\tau}}) \psi_{j,\tau,\alpha} + h.c.$$

$\alpha \in 2, 4, \cdots, N_f$



$O(\beta \times (L \times L)^3) \sim O(L^7)$

$N_f = 2, \cdots, 8, 10$

$$Z = \int D(\phi, \psi^\dagger, \psi) \ e^{-(S_B + S_F)} = \int D\phi \ e^{-S_B} \ \mathbf{Tr}[e^{-S_F}] = \int D\phi \ e^{-S_B} \ [\det(\mathbf{1} + \prod_{\tau=1}^{\beta} B_\tau(\phi_\tau))]^{N_f}$$

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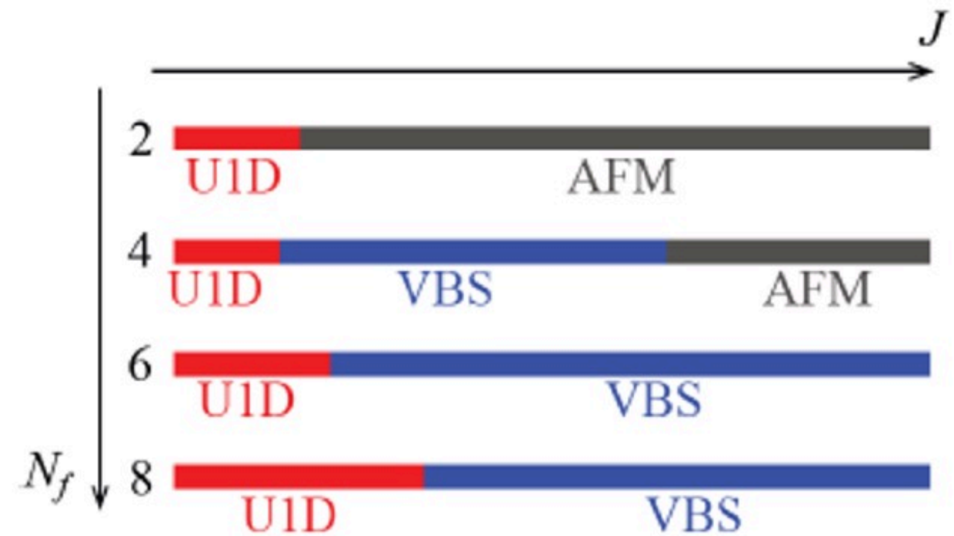
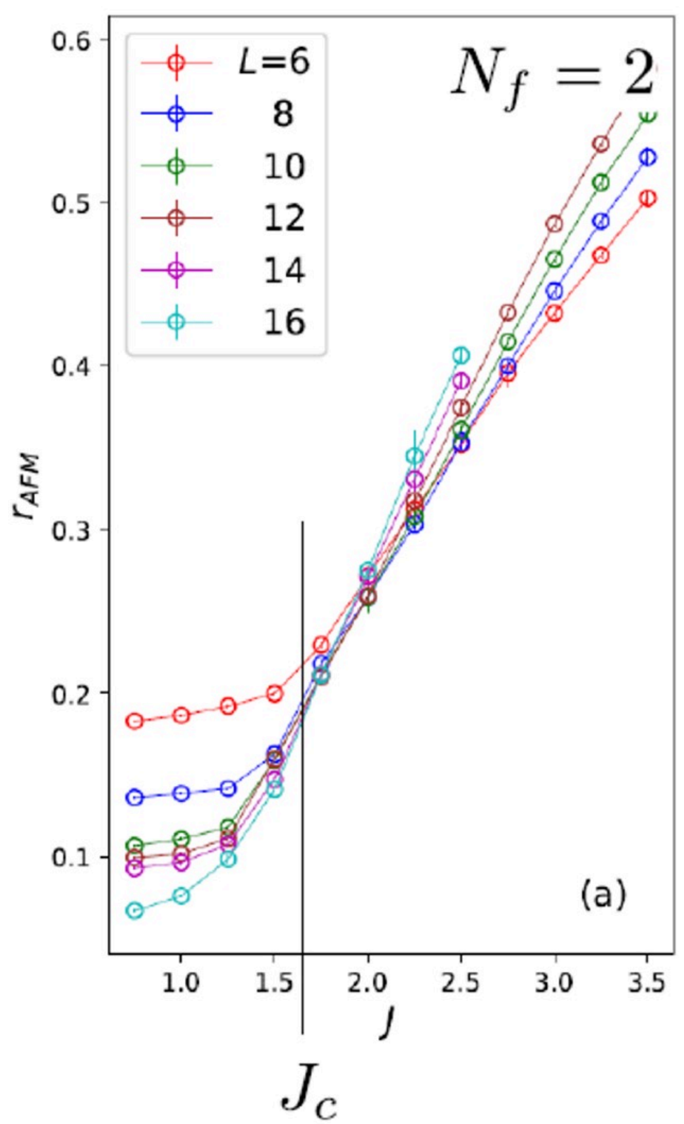
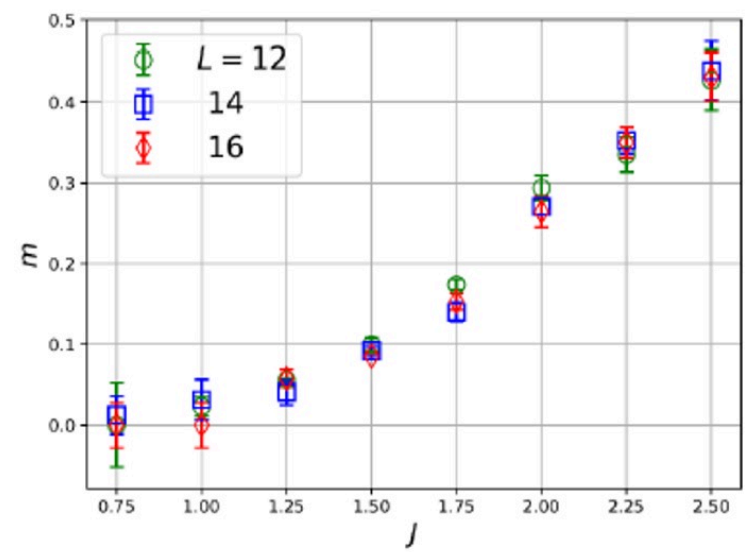
$$S^{\alpha}_{\beta}(i) = \psi^{\dagger}_{i\alpha}\psi_{i\beta} - \frac{1}{N_f}\delta_{\alpha\beta}\sum_{\gamma}\psi^{\dagger}_{i\gamma}\psi_{i\gamma}$$

$$\chi_S(\mathbf{k}) = \frac{1}{L^4}\sum_{ij}\sum_{\alpha\beta}\langle S^{\alpha}_{\beta}(i)S^{\beta}_{\alpha}(j)\rangle e^{i\mathbf{k}\cdot(\mathbf{r}_i-\mathbf{r}_j)}$$

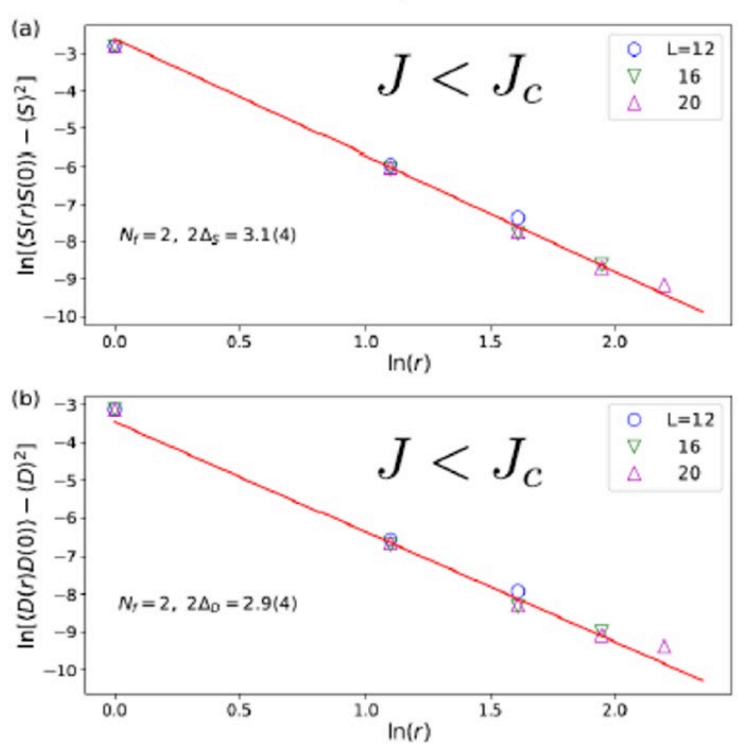
$$r_{\mathrm{AFM}} = 1 - \frac{\chi_S(\mathbf{X}+\delta\mathbf{q})}{\chi_S(\mathbf{X})}$$

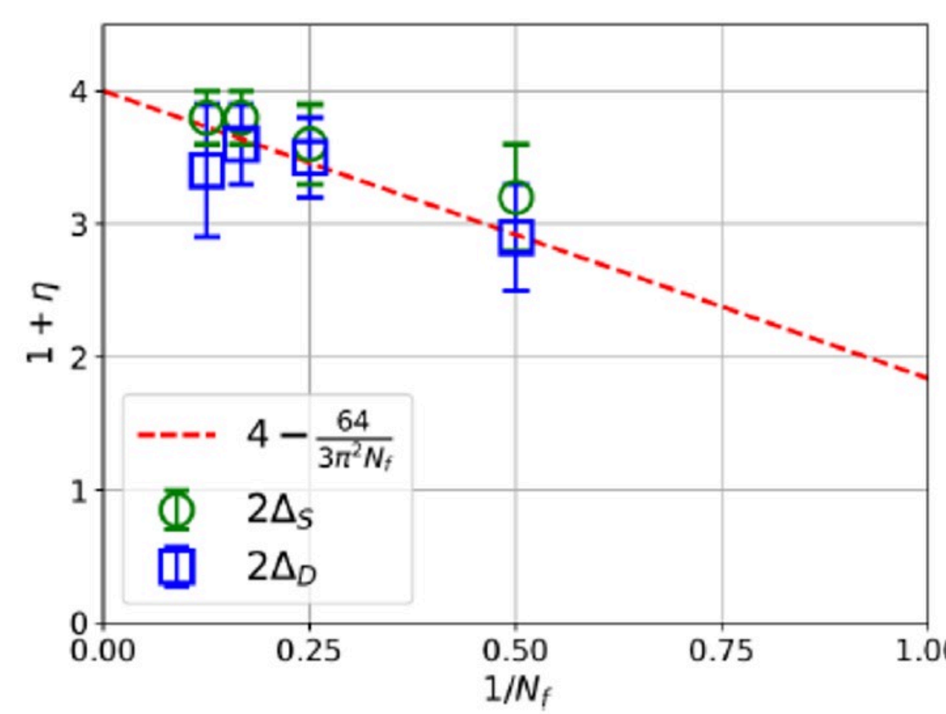






$$C(\tau) = \langle \sin(\sum_{b\in\square}\phi_b(\tau))\cdot\sin(\sum_{b\in\square}\phi_b(0))\rangle \sim \exp(-m\tau)$$





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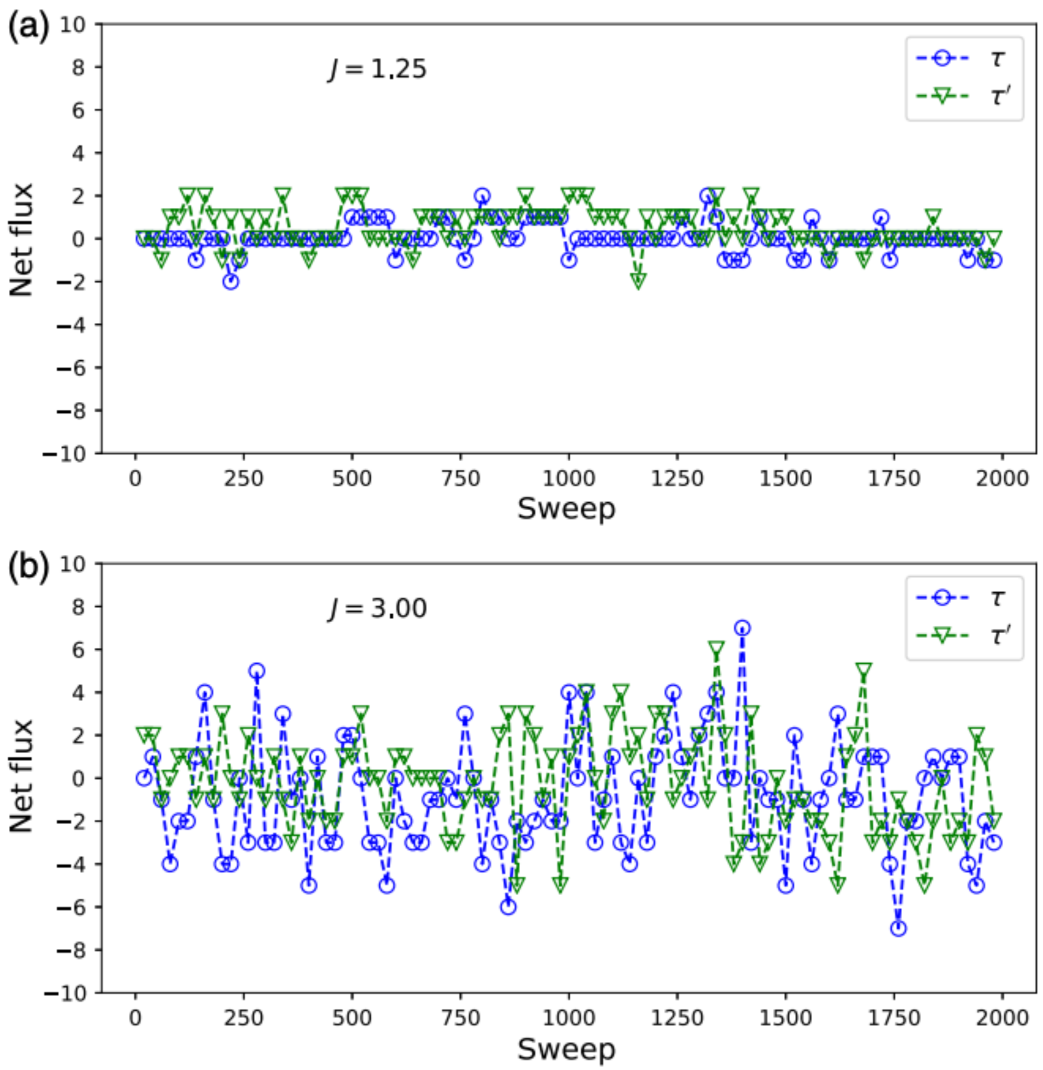
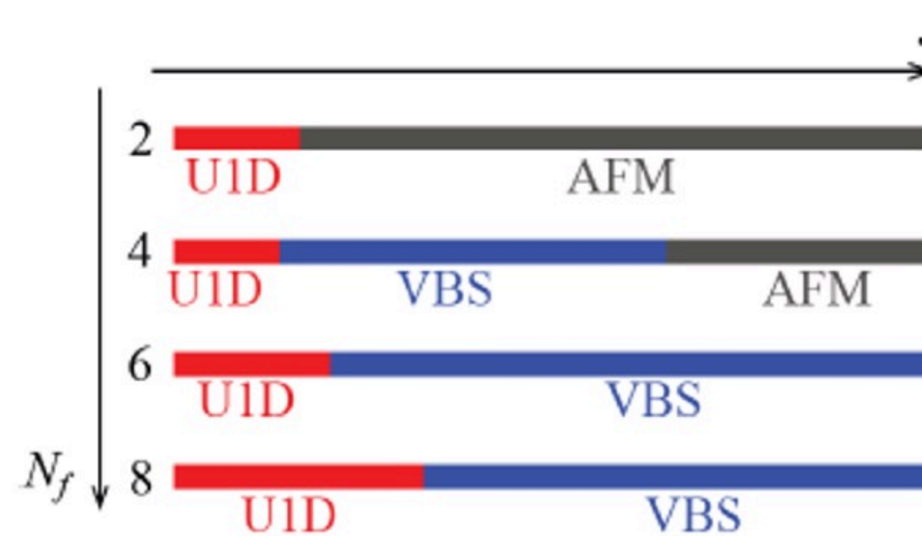
$$\sum_{b\in\square} \phi_b(\tau) = \Phi_\square(\tau) + 2\pi m_\square(\tau) \qquad \Phi_\square(\tau) \in [0,2\pi)$$

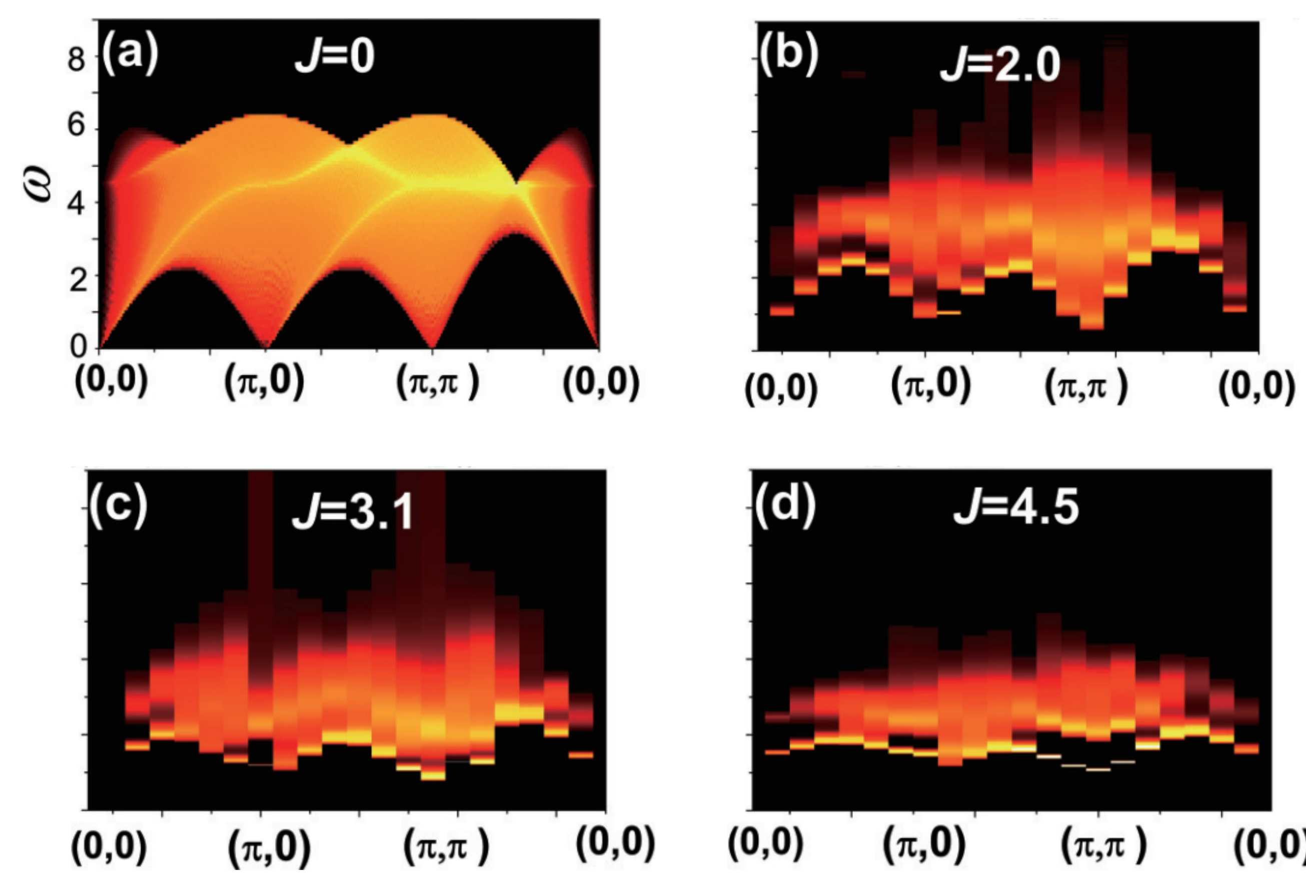
Net flux $\quad M(\tau) = \sum_{\square} m_\square(\tau)$

$N_f = 2, \quad J_c \sim 1.6(2), \quad L = 12, \quad \tau' - \tau = 8\Delta\tau$





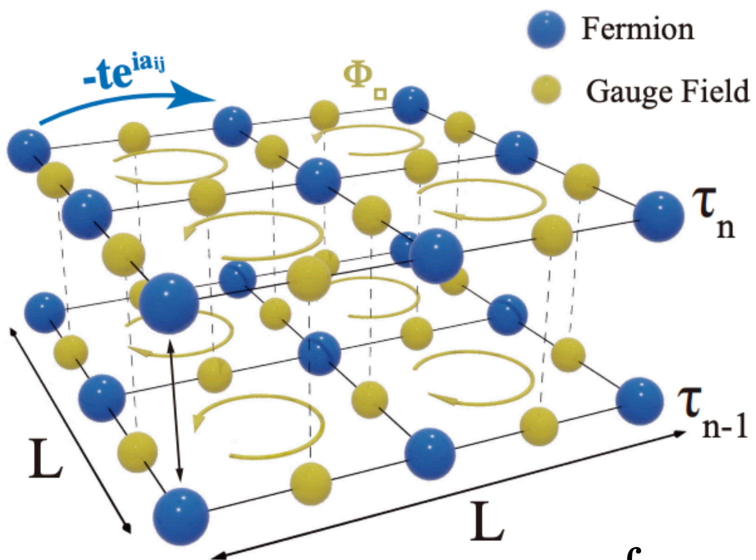
$N_f = 8, \quad J_c \sim 2.5(1), \quad L = 14$



Emergent gauge flux in QED_3 with flavor chemical potential: application to magnetized U(1) Dirac spin liquids

Chuang Chen,[1,2] Urban F. P. Seifert,[3] Kexin Feng,[1] Oleg A. Starykh,[4] Leon Balents,[5,6,7] and Zi Yang Meng[1]

arXiv: 2508.08528



$$S=\sum_{i,n}\left[\psi_i^\dagger(\tau_n)(\psi_i(\tau_n)-\psi_i(\tau_{n-1}))-\frac{1}{2}B\psi_i^\dagger(\tau_n)\sigma^z\psi_i(\tau_n)\right]$$
$$-t\sum_{\langle ij\rangle,n}\left[e^{ia_{ij}(\tau_n)}\psi_i^\dagger(\tau_n)\psi_j(\tau_n)+\text{h.c.}\right]$$
$$+\frac{1}{J}\sum_{\langle ij\rangle,n}\left[a_{ij}(\tau_n)-a_{ij}(\tau_{n-1})\right]^2$$

$i,j\in L\times L$

$L=16{,}20$

$K=0$

$\tau\in[0,\beta=1/T]$

$$Z=\int D(\phi,\psi^\dagger,\psi)\;e^{-(S_B+S_F)}=\int D\phi\;e^{-S_B}\,\mathbf{Tr}[e^{-S_F}]=\int D\phi\;e^{-S_B}\,[\det(\mathbf{1}+\prod_{\tau=1}^{\beta}B_\tau(\phi_\tau,B))]^{N_f}$$

$\beta=2L$

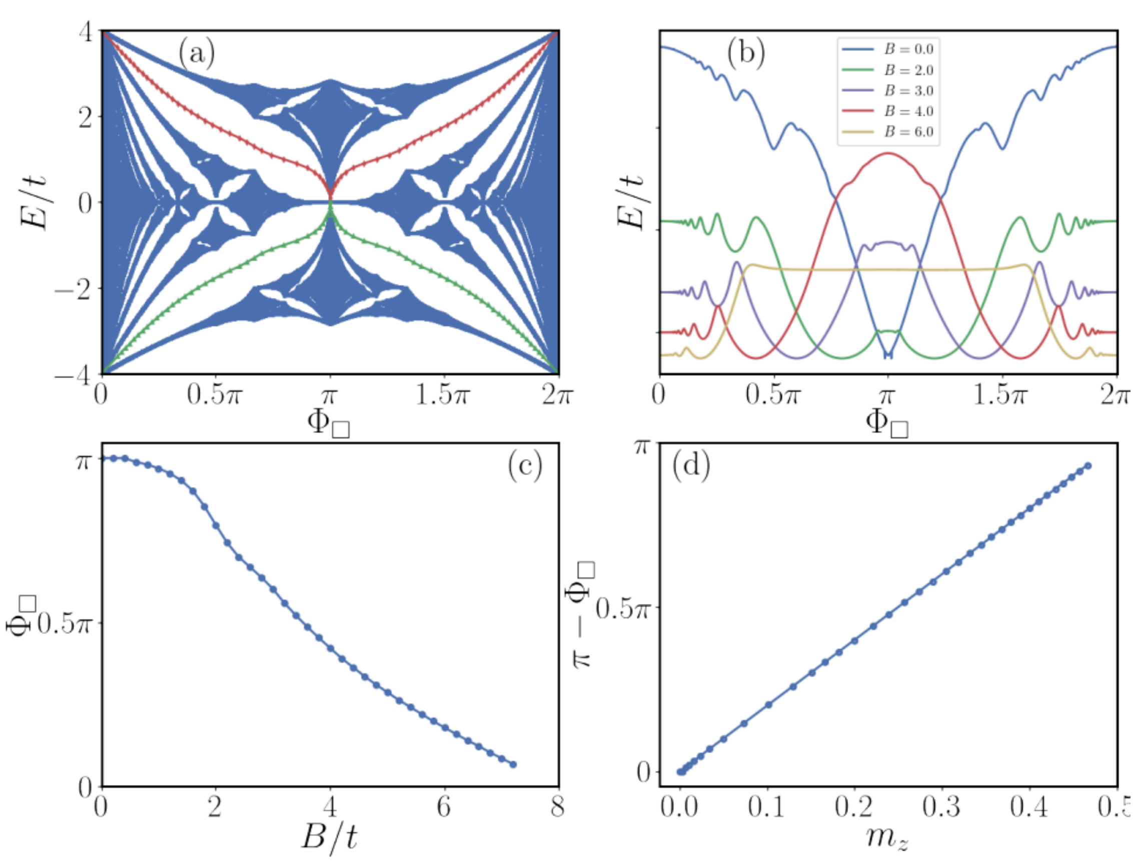
$\Delta\tau=0.1$

$N_f=2$

$O(\beta\times(L\times L)^3)\sim O(L^7)$

$J\to 0$: mean-field limit, temporal gauge fluctuations frozen

$L=32$



$$\Phi_\square(\tau)=\nabla\times a_\square(\tau)=\sum_{b\in\square}\phi_b(\tau)$$

Emergent gauge flux in QED_3 with flavor chemical potential: application to magnetized U(1) Dirac spin liquids

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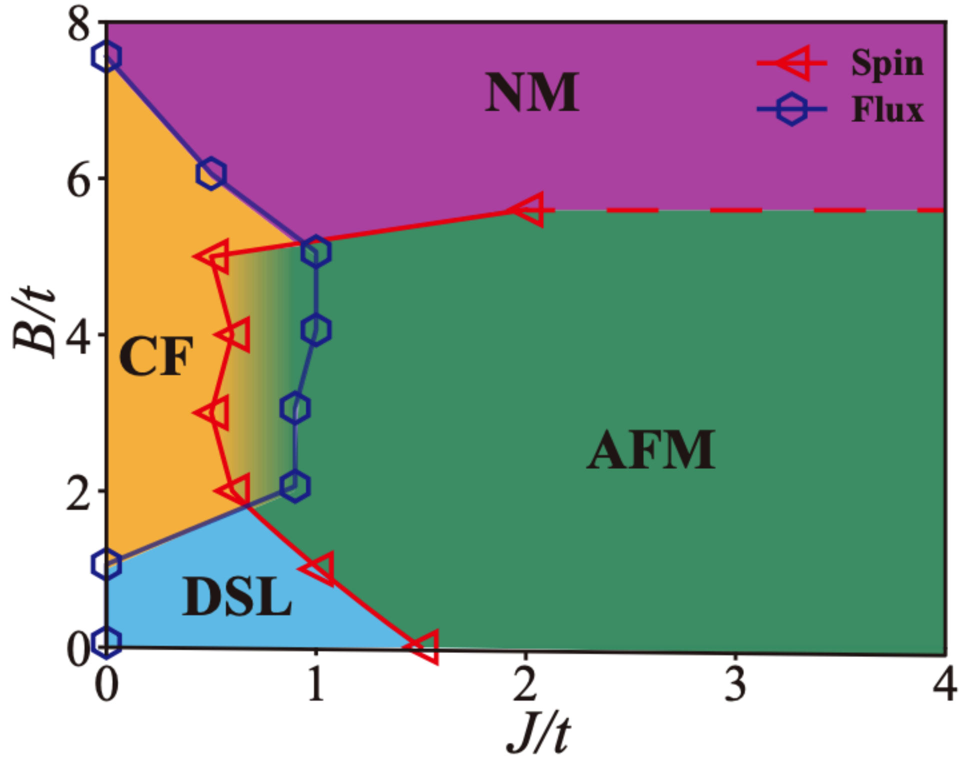


CF: $$\chi = \langle \sin(\sum_{b \in \Box} \phi_b) \rangle = \langle \sin(\nabla \times a) \rangle \neq 0$$

emergent gauge flux

$$S^{\pm}(\mathbf{q}) = \frac{1}{N} \sum_{ij} \langle \sin(\Phi_{\Box,i}) \ \sin(\Phi_{\Box,j}) \rangle \ e^{-i\mathbf{q}\cdot\mathbf{r}_{ij}} \qquad \mathbf{q} = \Gamma$$

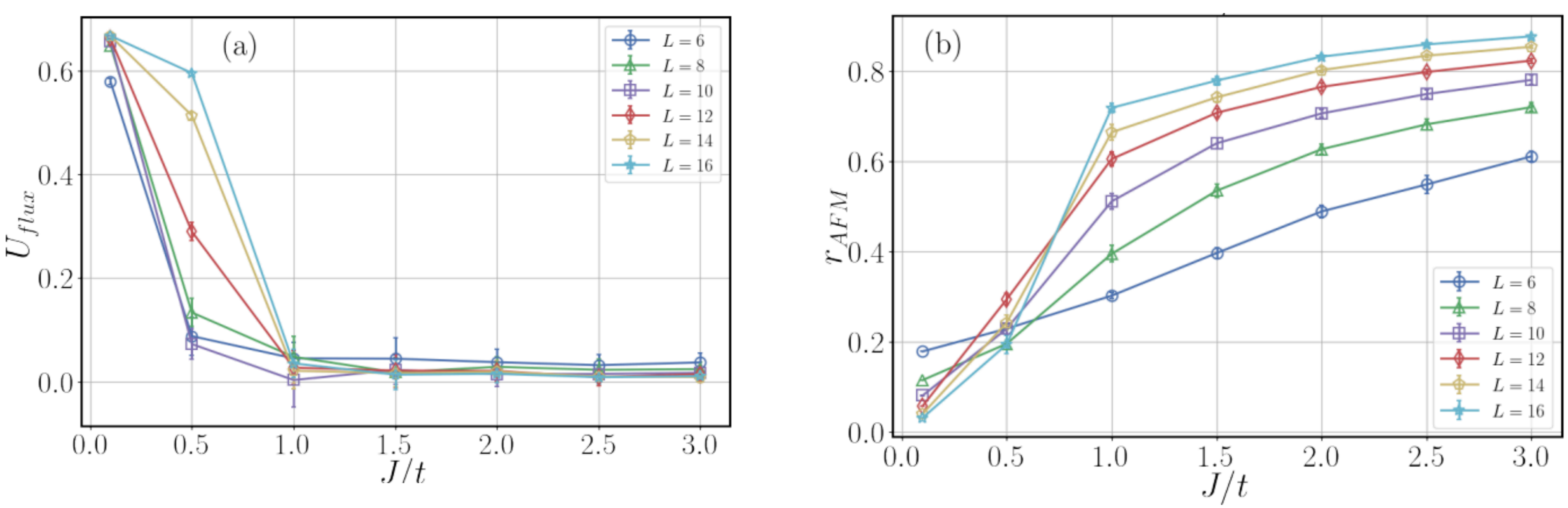
AFM: $$N^{+} = (-1)^{i} \langle \psi_i^{\dagger} \sigma^{+} \psi_i \rangle \neq 0$$

in-plane AFM order

$$S^{\pm}(\mathbf{q}) = \frac{1}{N} \sum_{ij} \langle S_i^{+} S_j^{-} + h.c. \rangle \ e^{-i\mathbf{q}\cdot\mathbf{r}_{ij}} \qquad \mathbf{q} = M = (\pi, \pi)$$

$$N^{+} = \lim_{N \to \infty} \sqrt{\frac{1}{N} S^{\pm}(M)}$$

$B/t = 2$



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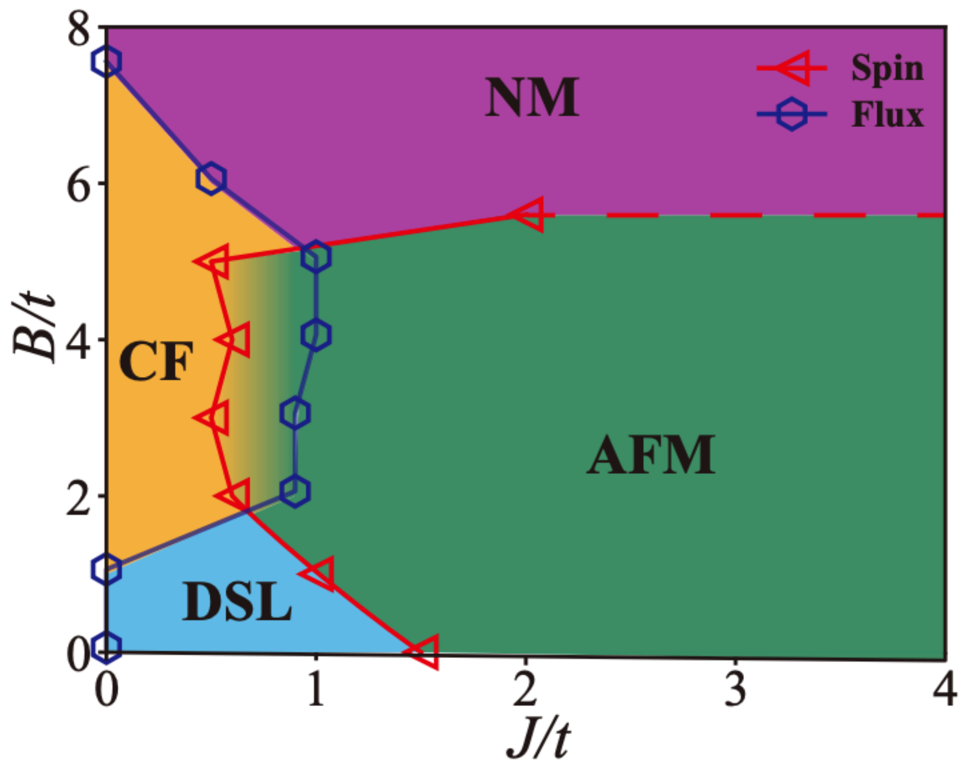


CF: $$\chi = \langle \sin(\sum_{b\in\square} \phi_b)\rangle = \langle \sin(\nabla \times a)\rangle \neq 0$$

emergent gauge flux

AFM: $$N^+ = (-1)^i \langle \psi_i^\dagger \sigma^+ \psi_i \rangle \neq 0$$

in-plane AFM order

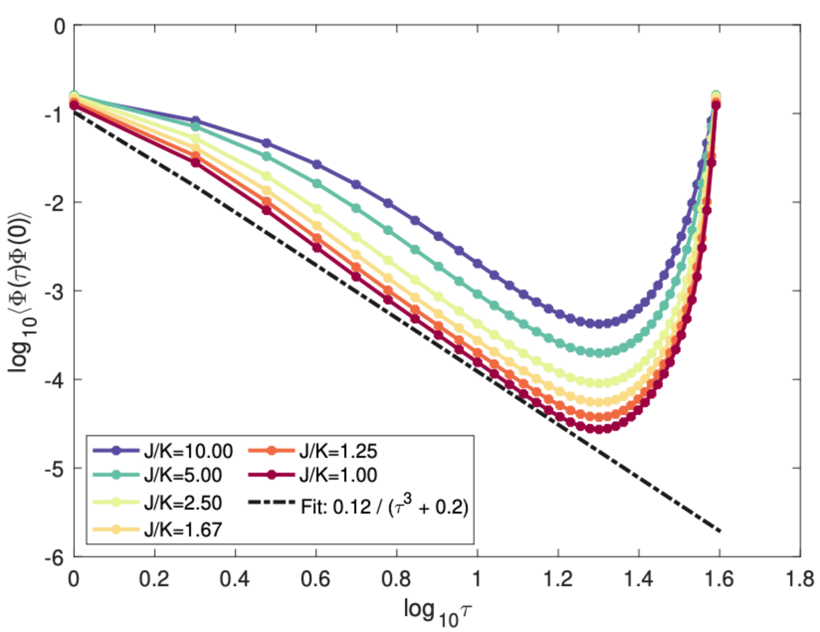
$$C_\chi(\tau) = \frac{1}{N_\square} \sum_\square \langle \sin(\sum_{b\in\square} \phi_b(\tau)) \cdot \sin(\sum_{b\in\square} \phi_b(0))\rangle$$

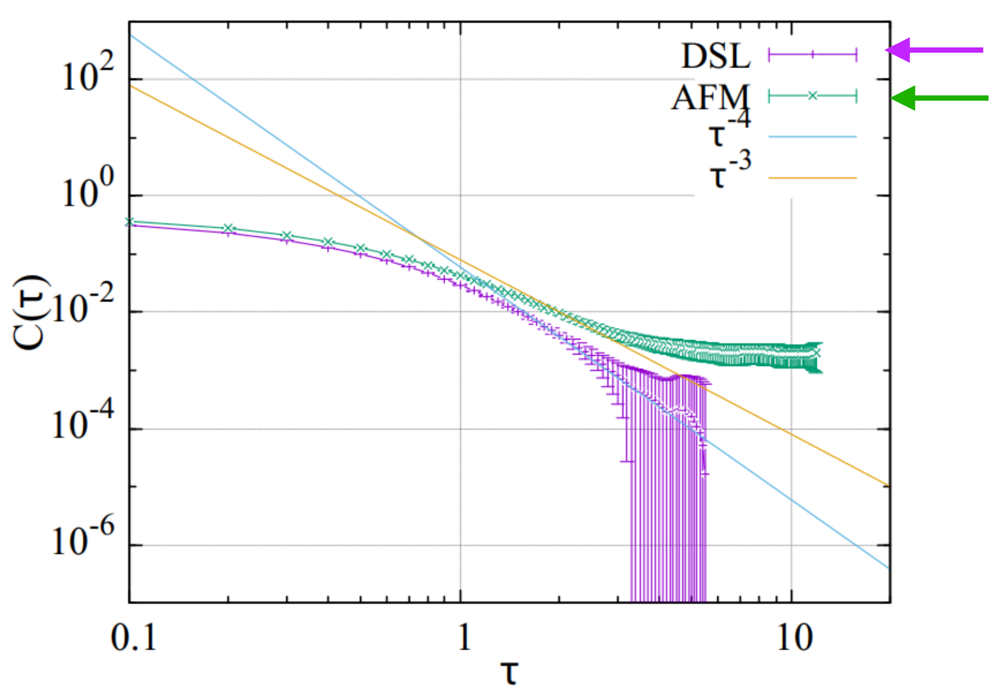
$C_\chi(\tau) \sim \tau^3$

in free photon theory and in AFM

$C_\chi(\tau) \sim \tau^4$

in DSL, conserved currents





$B = 0, J = 3, K = 1, L = 12$

$B = 3, J = 3, K = 0, L = 12$

Emergent gauge flux in QED_3 with flavor chemical potential: application to magnetized U(1) Dirac spin liquids

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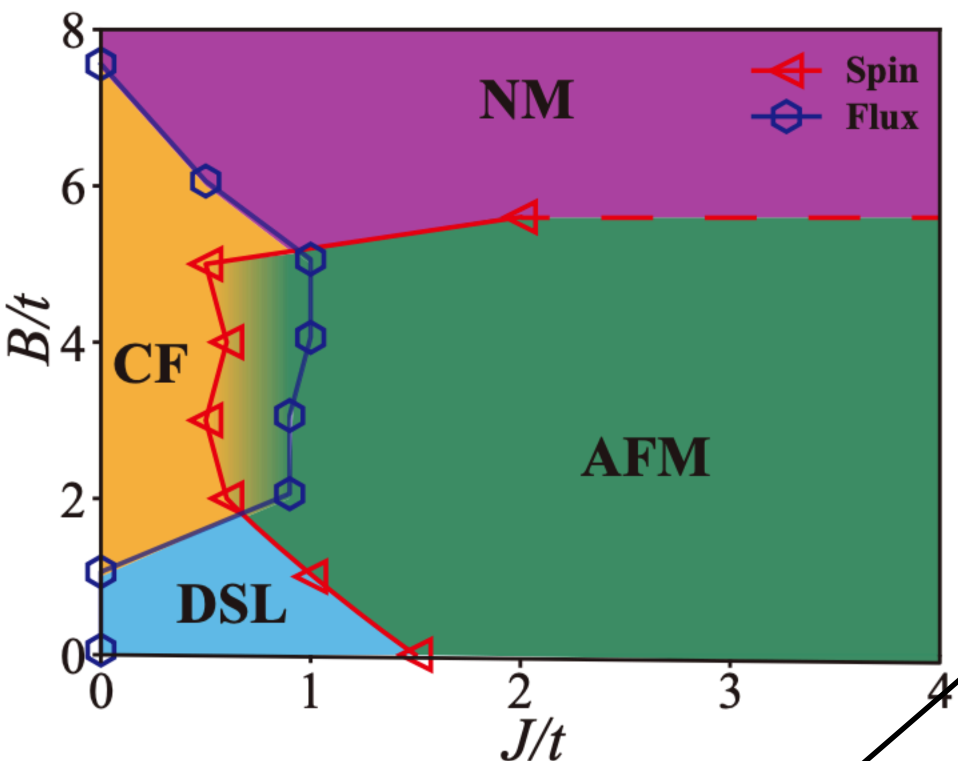
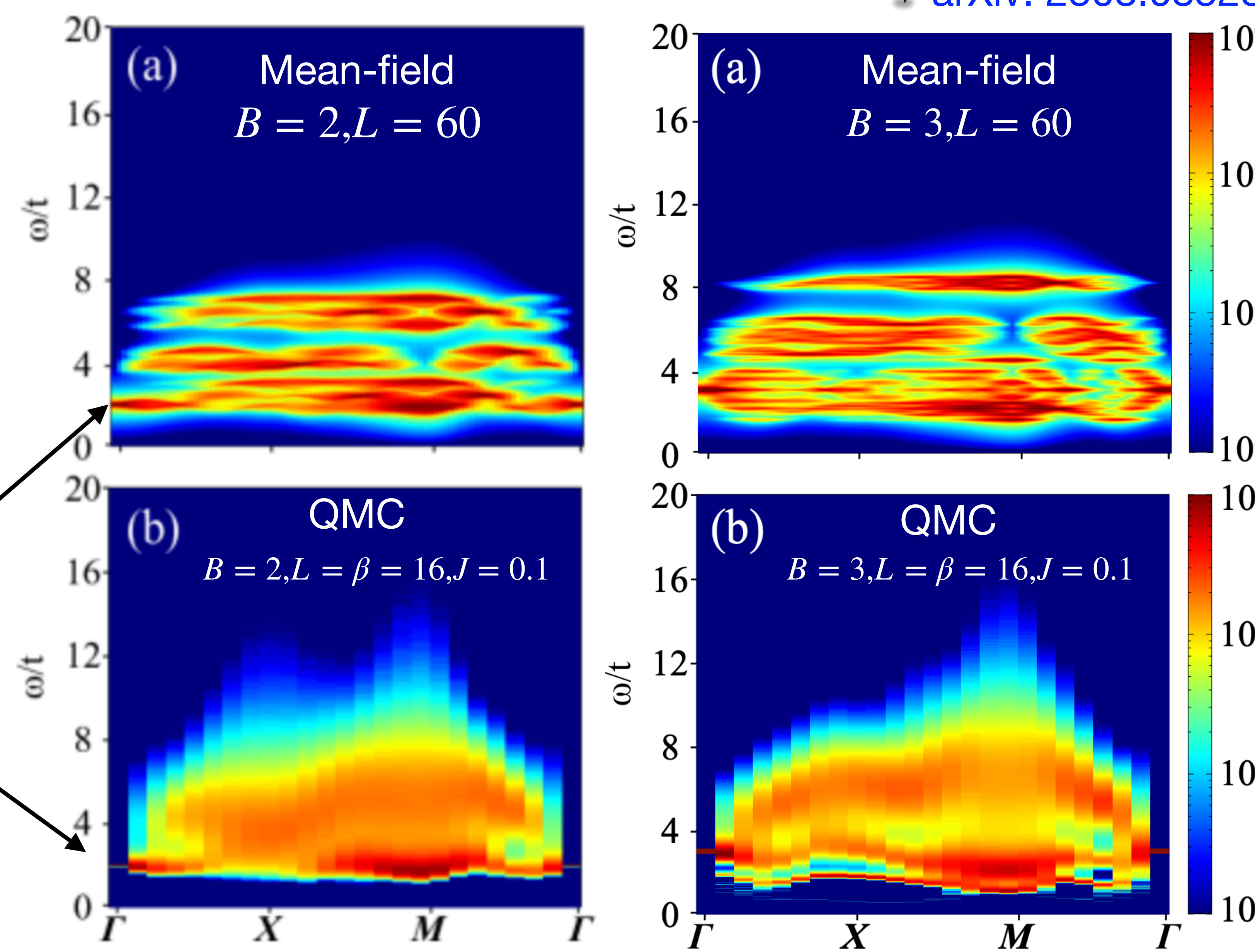
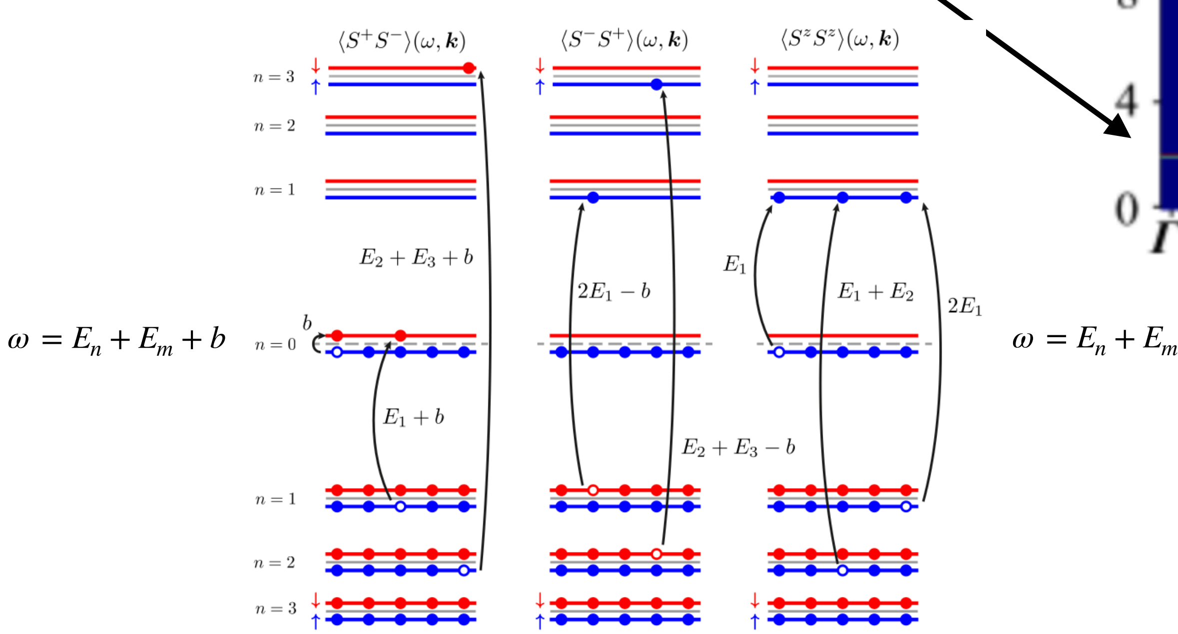


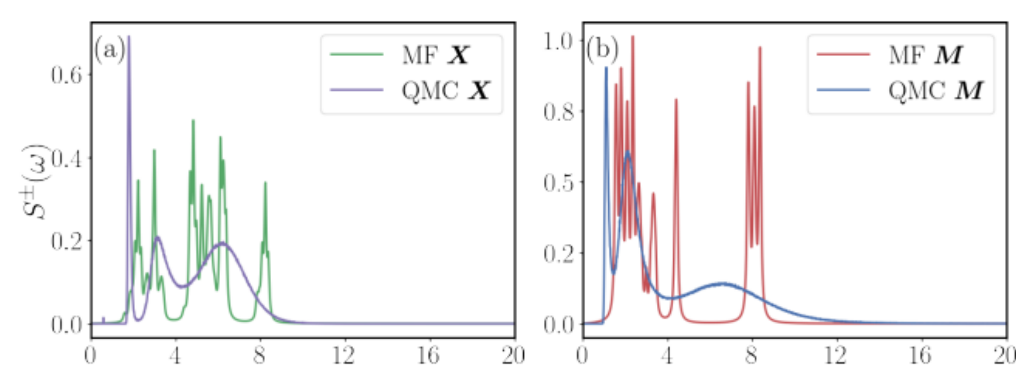
$S^{\pm}(\mathbf{q},\omega)$

Larmor pole at

$\omega = B$







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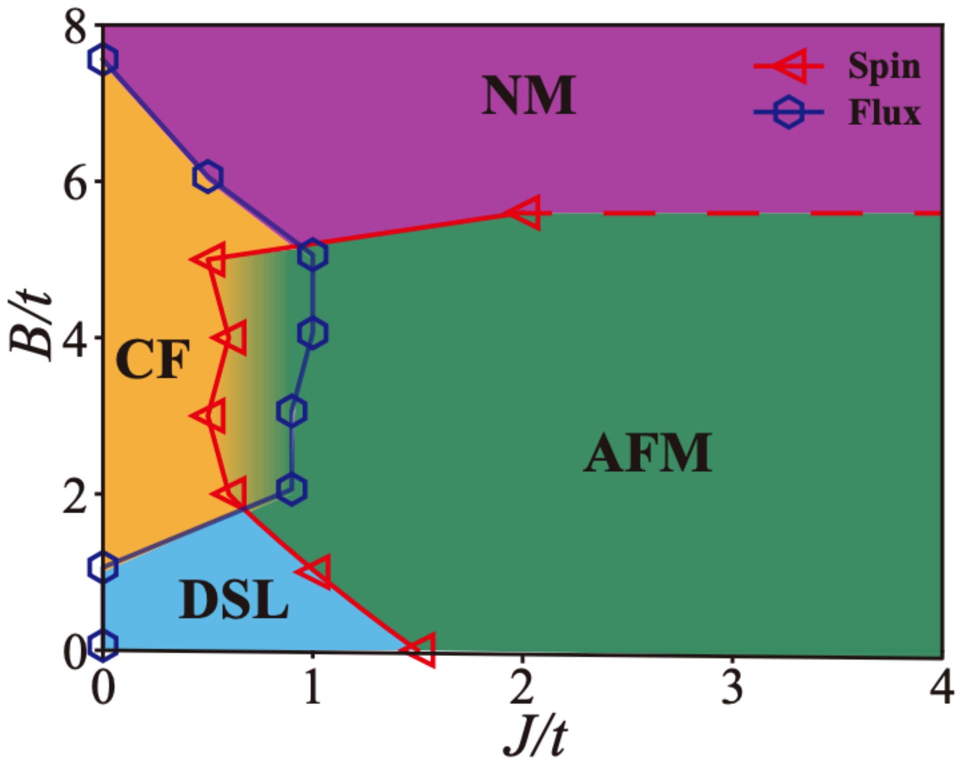


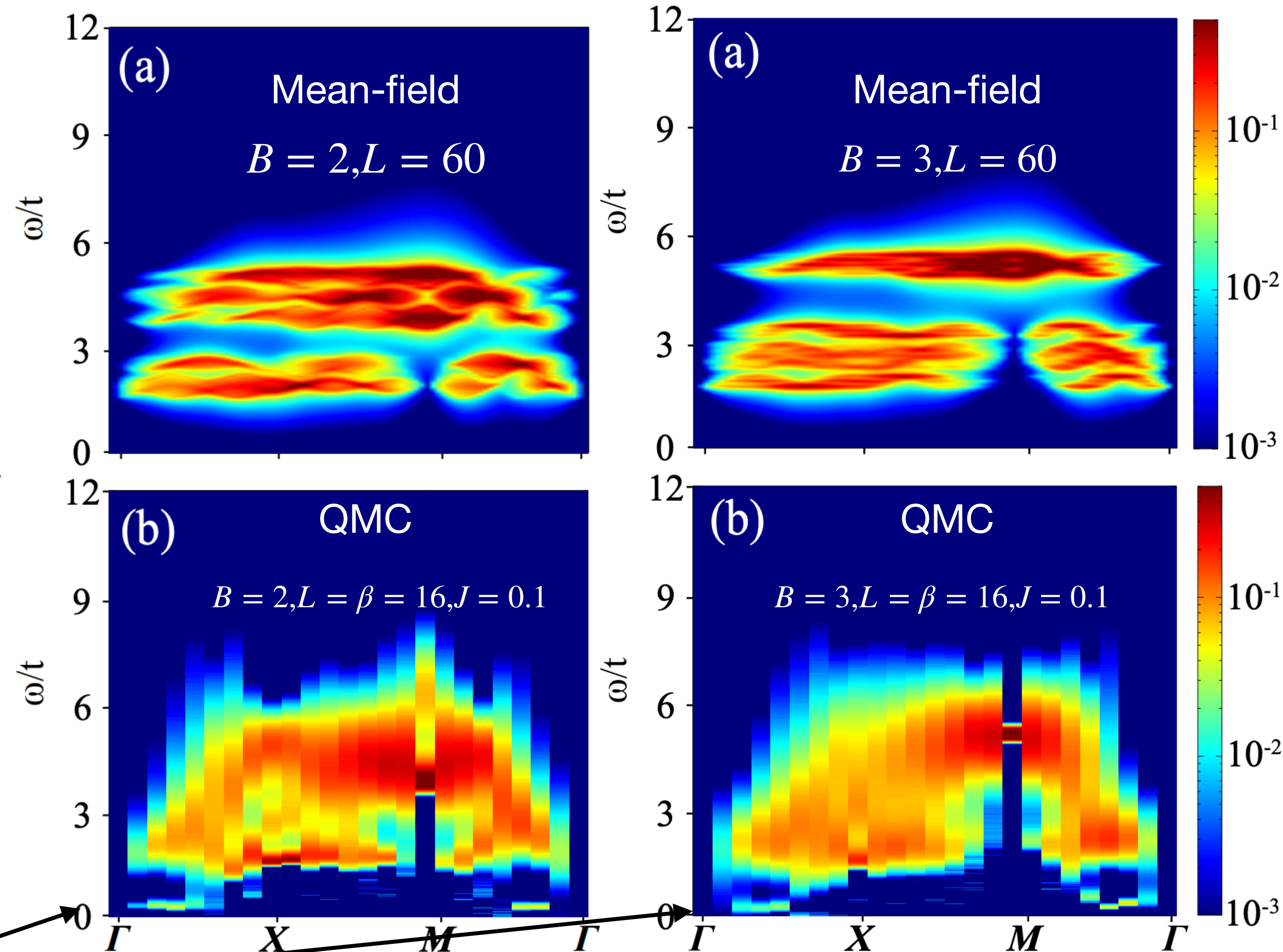
$$S^{zz}(\mathbf{q}, \omega)$$

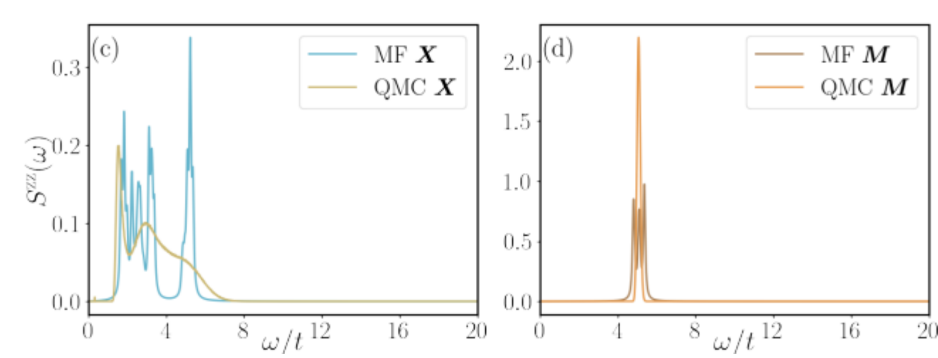
$$S^z \sim \nabla \times a^c$$

$$\langle S^z S^z \rangle_{\omega,\mathbf{q}} \sim \frac{1}{2} \chi c q \delta(\omega - cq)$$

spin corr. probes emergent magnetic flux

gapless gauge photon





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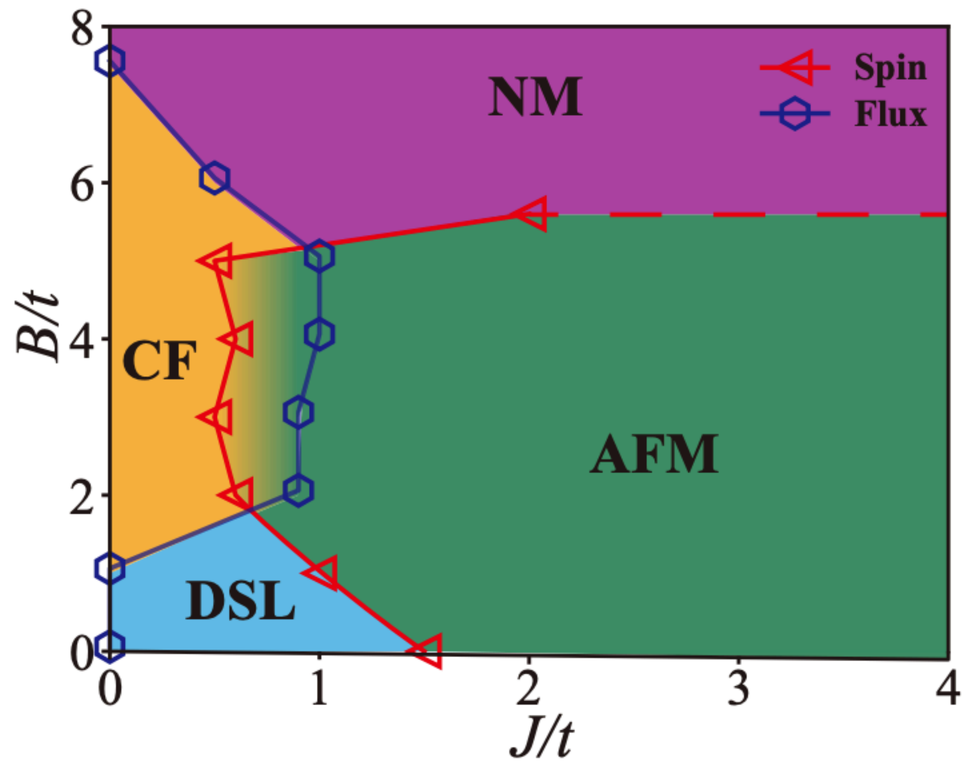
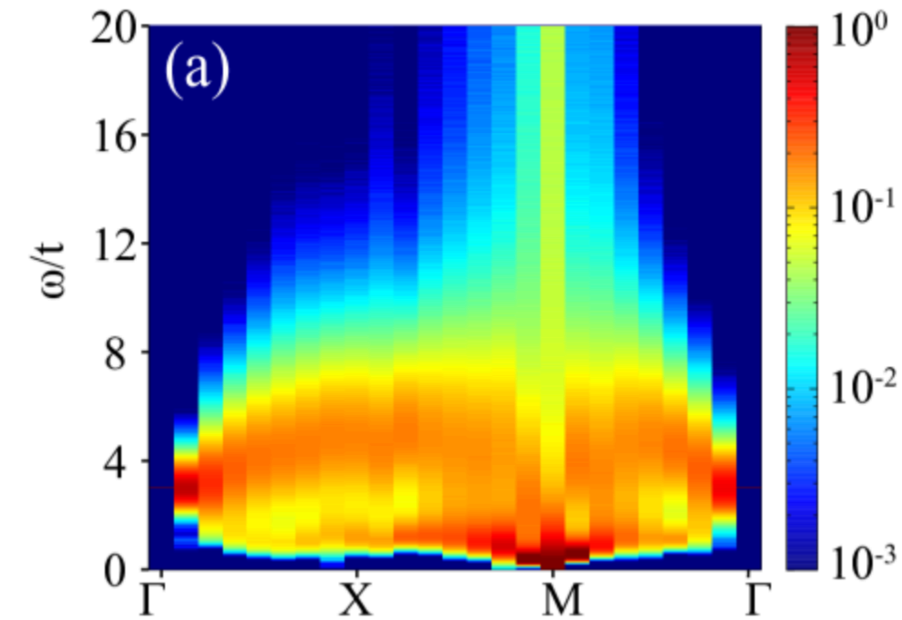


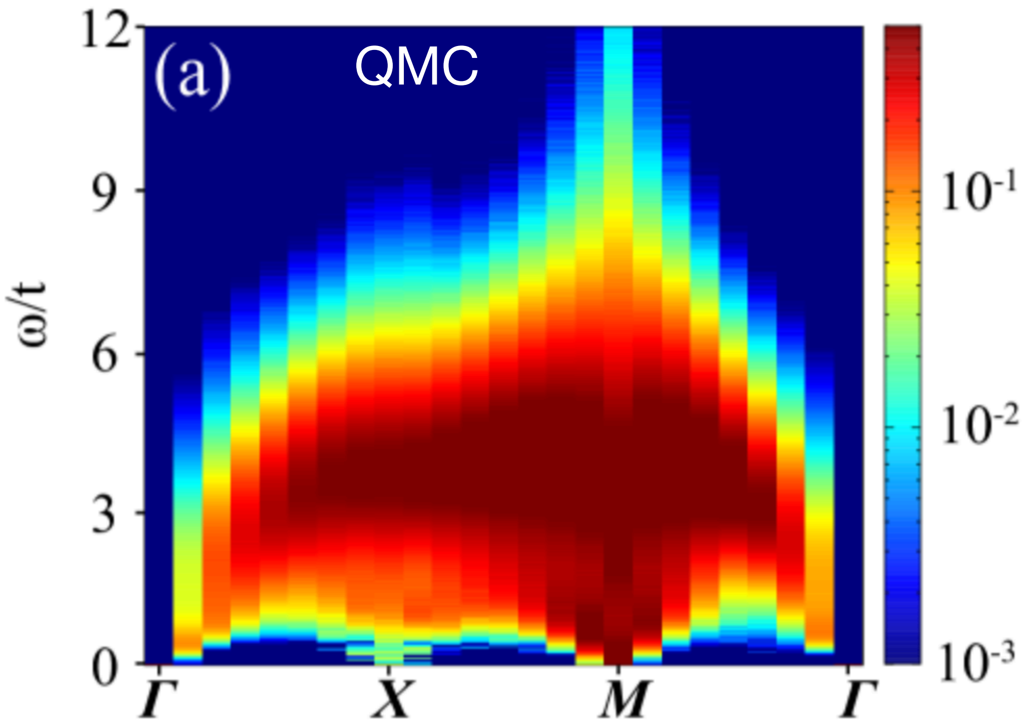
arXiv: 2508.08528

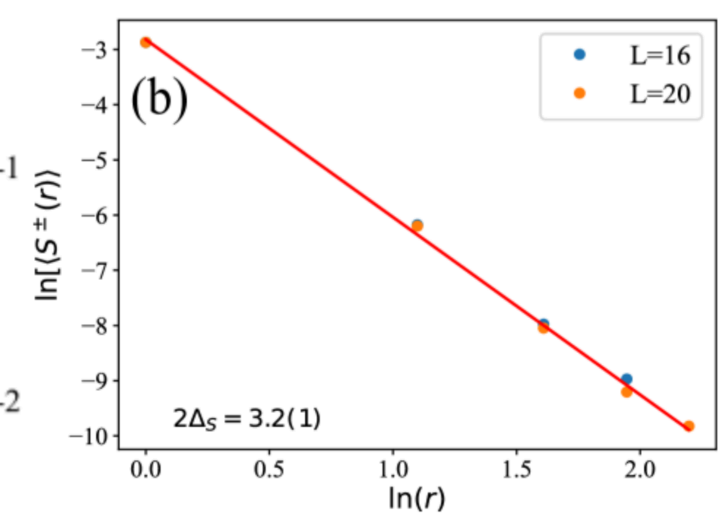
$S^{\pm}(\mathbf{q},\omega)$ $B=3, L=\beta=16, J=3$



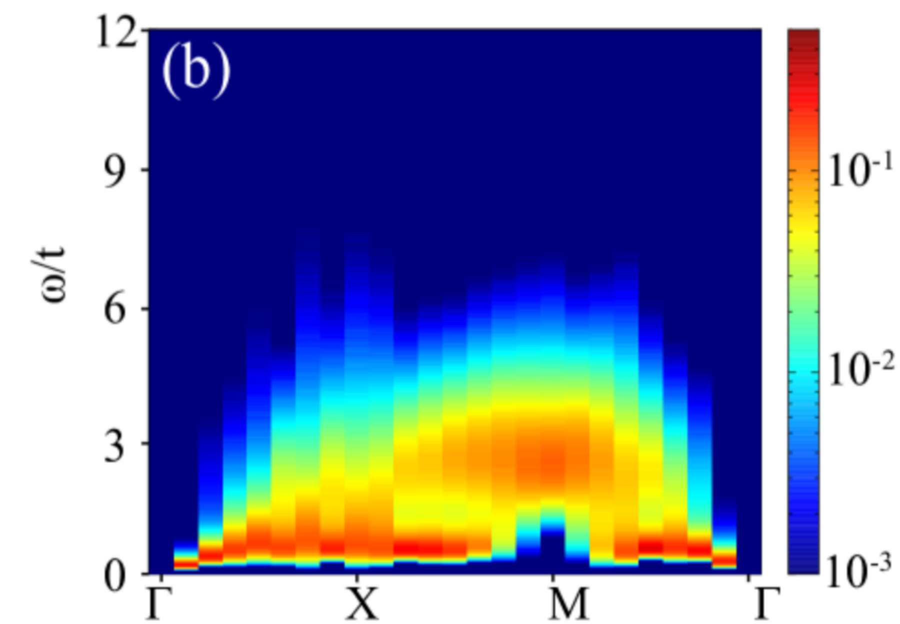
- fermion bilinears or mass terms: a singlet $M_s = \bar{\Psi}\Psi$ and a set of adjoints $M_a = \bar{\Psi}T_a\Psi$, where $a = 1 \ldots 15$ range over the SU(4) generators. *A priori*, these two sets have independent scaling dimensions, Δ_s and Δ_{adj}, respectively. An estimate from Ref. [5] is $\Delta_s \approx 2.3$, $\Delta_{\text{adj}} \in (1.4, 1.7)$.

$S^{\pm}(\mathbf{q},\omega)$ $B=0, L=\beta=16, J=1$





$S^{zz}(\mathbf{q},\omega)$ $B=3, L=\beta=16, J=3$



Quantum Fisher Information as a Thermal and Dynamical Probe in Frustrated Magnets: Insights from Quantum Spin Ice

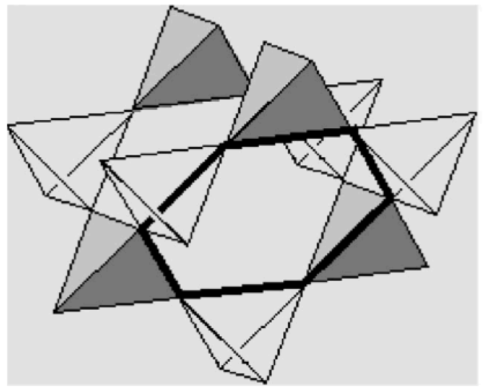
Chengkang Zhou,[1,*] Zhengbang Zhou,[2,*] Félix Desrochers,[2,3] Yong Baek Kim,[2] and Zi Yang Meng[1]

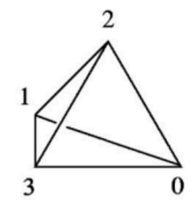
arXiv: 2510.14813

$$\mathcal{H}=\mathcal{H}_I+\mathcal{H}',$$

$$\mathcal{H}_I=\frac{J_z}{2}\sum_t (S_t^z)^2,$$

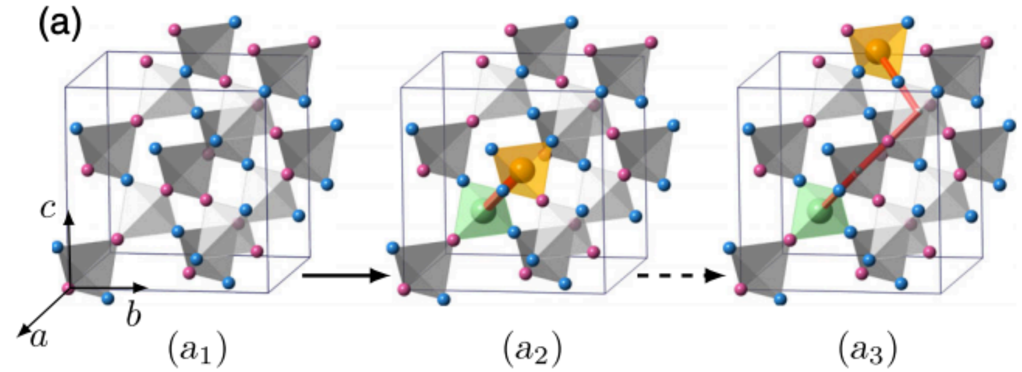
$$\mathcal{H}'=\frac{J_\perp}{2}\sum_{\langle ij\rangle}(S_i^+S_j^- + \text{H.c.}),$$



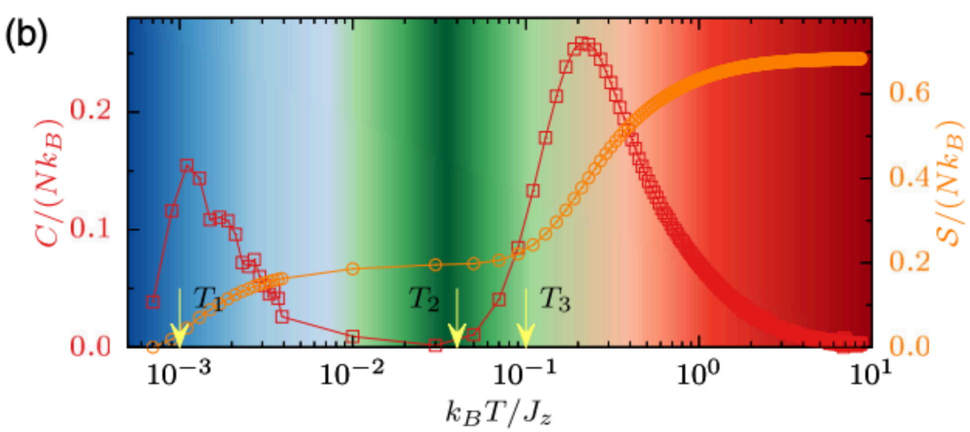


Dynamics of Topological Excitations in a Model Quantum Spin Ice,
Huang, Deng, Wang, Meng, PRL 120, 167202 (2018)

$$\mathcal{H}=\sum_{\langle i,j\rangle} -J_\pm(S_i^+S_j^- + \text{H.c.}) + J_z S_i^z S_j^z.$$



$J_{\pm,c}/J_z = 0.052$



$J_\pm/J_z = 0.046$

$T_1 = 0.001 J_z$

$T_2 = 0.04 J_z$

$T_3 = 0.1 J_z$

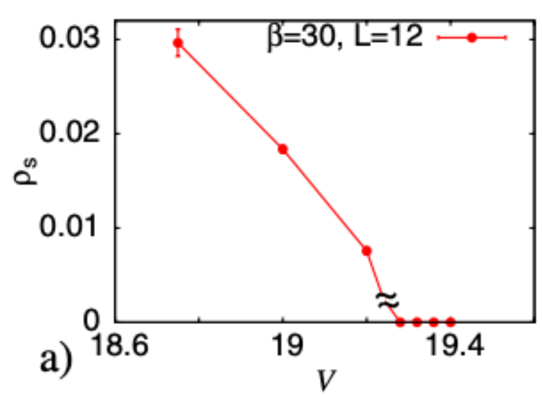
Pyrochlore photons: The U(1) spin liquid in a S=1/2 three-dimensional frustrated magnet,
Hermele, Fisher, Balents, PRB 69, 064404 (2004)

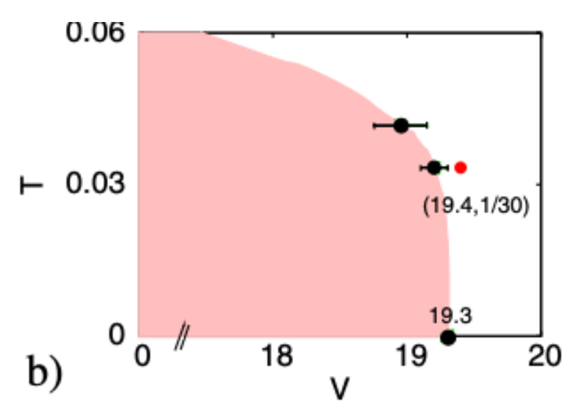
$$\mathcal{H}_p=\frac{U}{2}\sum_{\langle \mathbf{r}\mathbf{r}'\rangle}(n_{\mathbf{r}\mathbf{r}'}-1/2)^2 - K\sum_{\hexagon}\cos(\phi_1-\phi_2+\phi_3-\phi_4+\phi_5-\phi_6).$$

$$\mathcal{H}_p=\frac{U}{2}\sum_{\langle \mathbf{r}\mathbf{r}'\rangle}e^2_{\mathbf{r}\mathbf{r}'} - K\sum_{\hexagon}\cos\left(\sum_{\mathbf{r}\mathbf{r}'\in\hexagon} a_{\mathbf{r}\mathbf{r}'}\right).$$

Unusual Liquid State of Hard-Core Bosons on the Pyrochlore Lattice,
Banerjee, Isakov, Damle, Kim, PRL 100, 047208 (2008)

$$H=\sum_{\langle ij\rangle}[V(n_i-1/2)(n_j-1/2) - t(b_i^\dagger b_j + b_i b_j^\dagger)]$$





Quantum Fisher Information as a Thermal and Dynamical Probe in Frustrated Magnets: Insights from Quantum Spin Ice

Chengkang Zhou,[1,*] Zhengbang Zhou,[2,*] Félix Desrochers,[2,3] Yong Baek Kim,[2] and Zi Yang Meng[1]

arXiv: 2510.14813

Dynamics of Topological Excitations in a Model Quantum Spin Ice, Huang, Deng, Wang, Meng, PRL 120, 167202 (2018)

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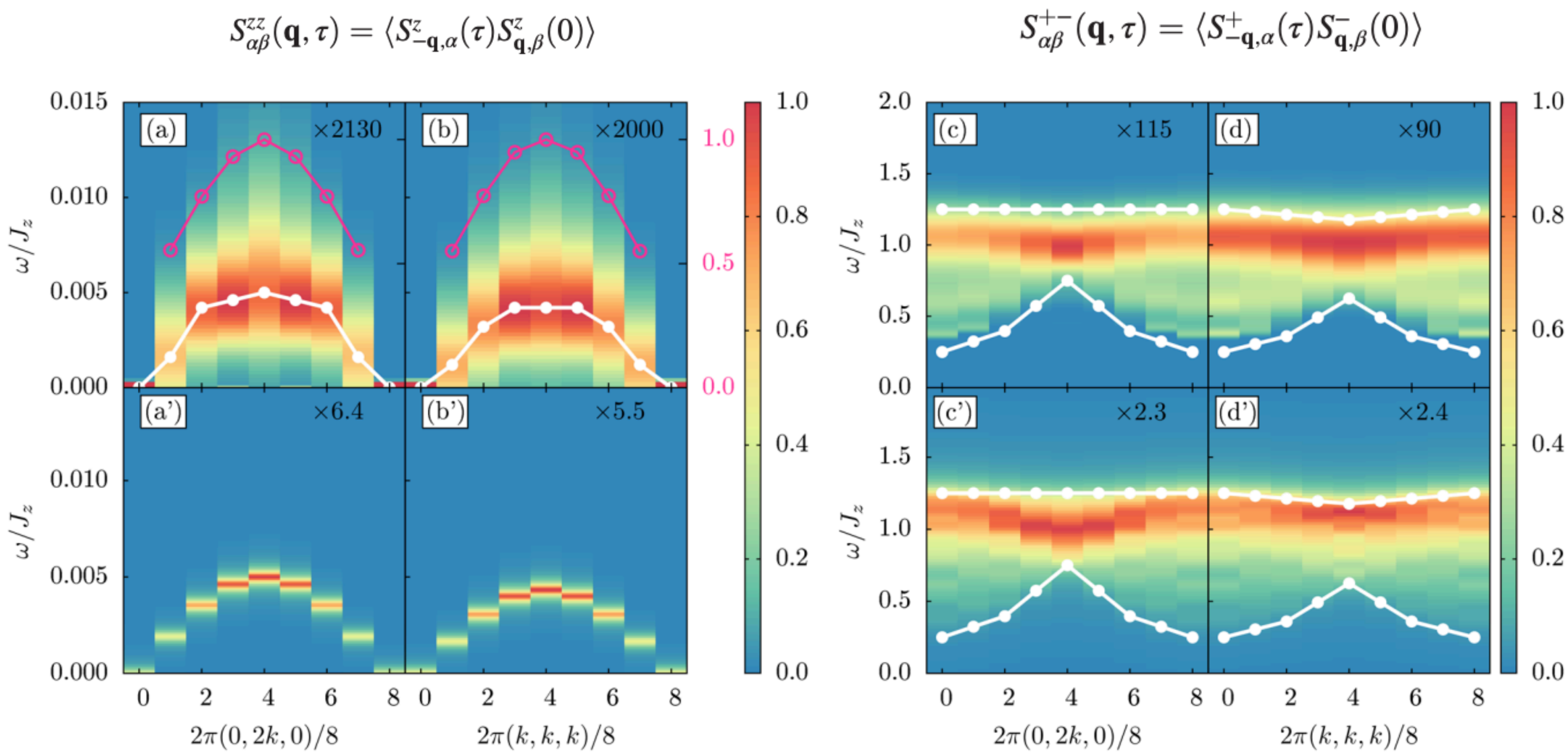

$$J_{\pm}/J_z = 0.046, \quad T_1 = 0.001 J_z, \quad 4\times 8\times 8\times 8$$

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$\rho = \sum_n p_n |n\rangle\langle n|$ $\quad F_Q[\rho, O] = 2\sum_{m,n} \frac{(p_m - p_n)^2}{p_m + p_n} \left|\langle m|O|n\rangle\right|^2$

$O = S^{\alpha}_{\mathbf{q}} := \sum_i S^{\alpha}_{\mathbf{R}_i} e^{i\mathbf{q}\cdot\mathbf{R}_i}$

$f_Q(O) := F_Q[\rho, O]/N, \qquad \Delta\lambda = \lambda_{\max} - \lambda_{\min}$

$$f_Q(S^{\alpha}_{\mathbf{q}}, T) = 4\int_0^{\infty} d\omega \tanh\left(\frac{\omega}{2T}\right)\left(1 - e^{-\omega/T}\right) A^{\alpha}(\mathbf{q}, \omega)$$

$$\mathrm{nQFI}(O) := \frac{f_Q(O)}{(\Delta\lambda)^2} > m \Longrightarrow \text{entanglement depth } \geq m + 1$$

$$A^{\alpha}(\mathbf{q}, \omega) := \frac{1}{2\pi N}\int dt \langle S^{\alpha\dagger}_{\mathbf{q}}(t) S^{\alpha}_{\mathbf{q}}(0)\rangle e^{i\omega t}$$

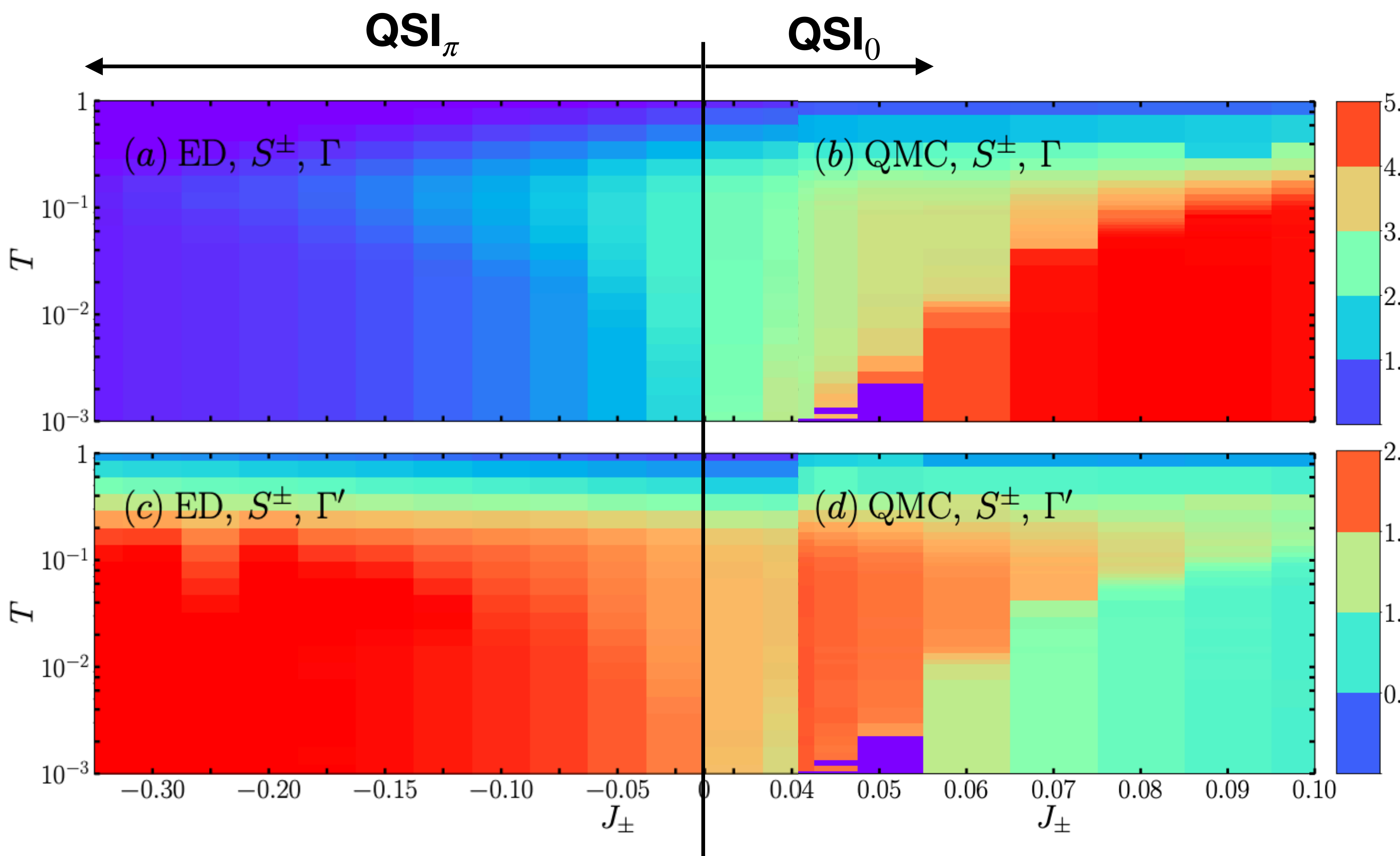
$f_Q(S^{\pm}_q, T)$

$q = \Gamma = (0,0,0)$

ED, 16-site cluster

QMC, 4×4^3 sites

$q = \Gamma' = (4\pi, 4\pi, 0)$



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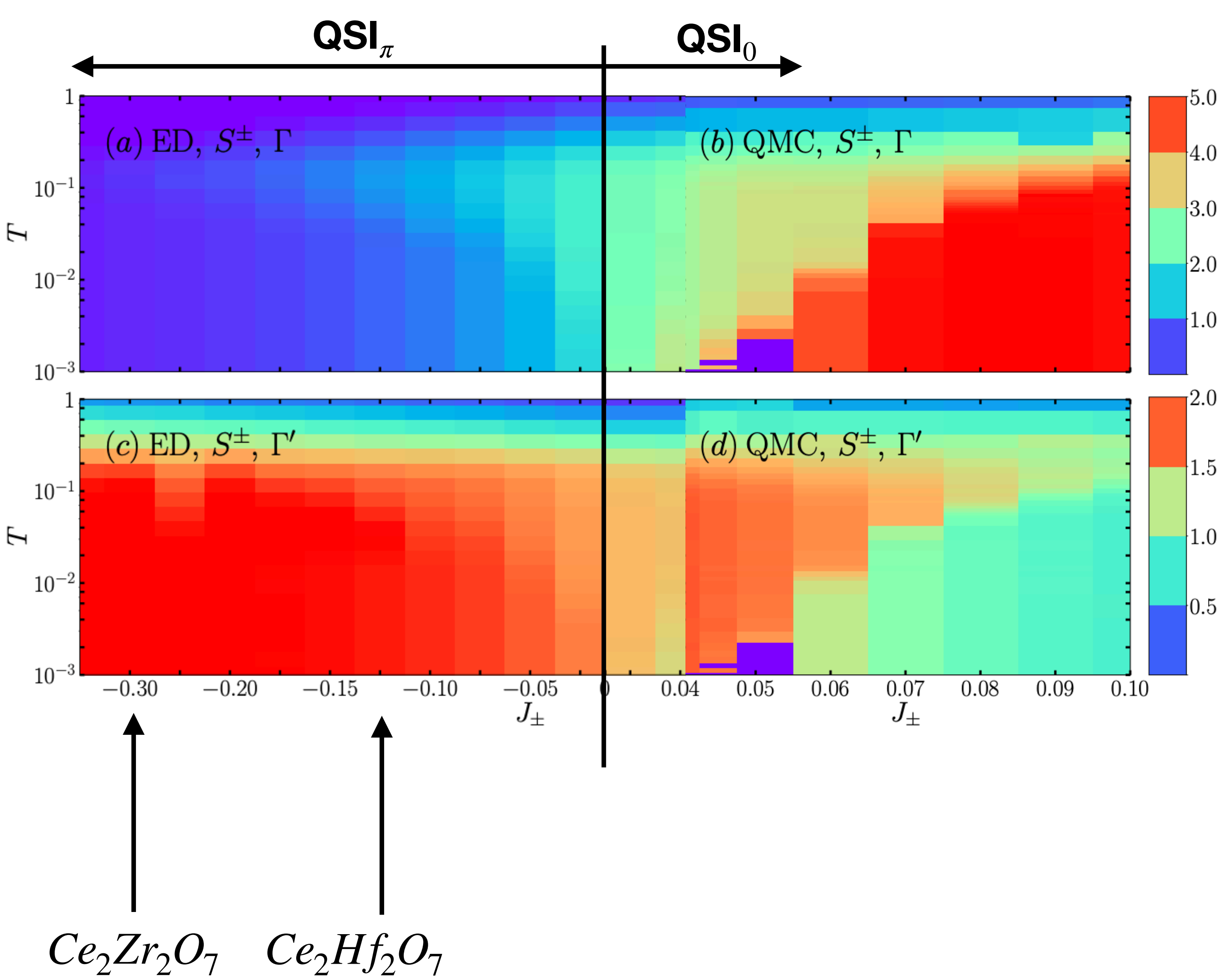

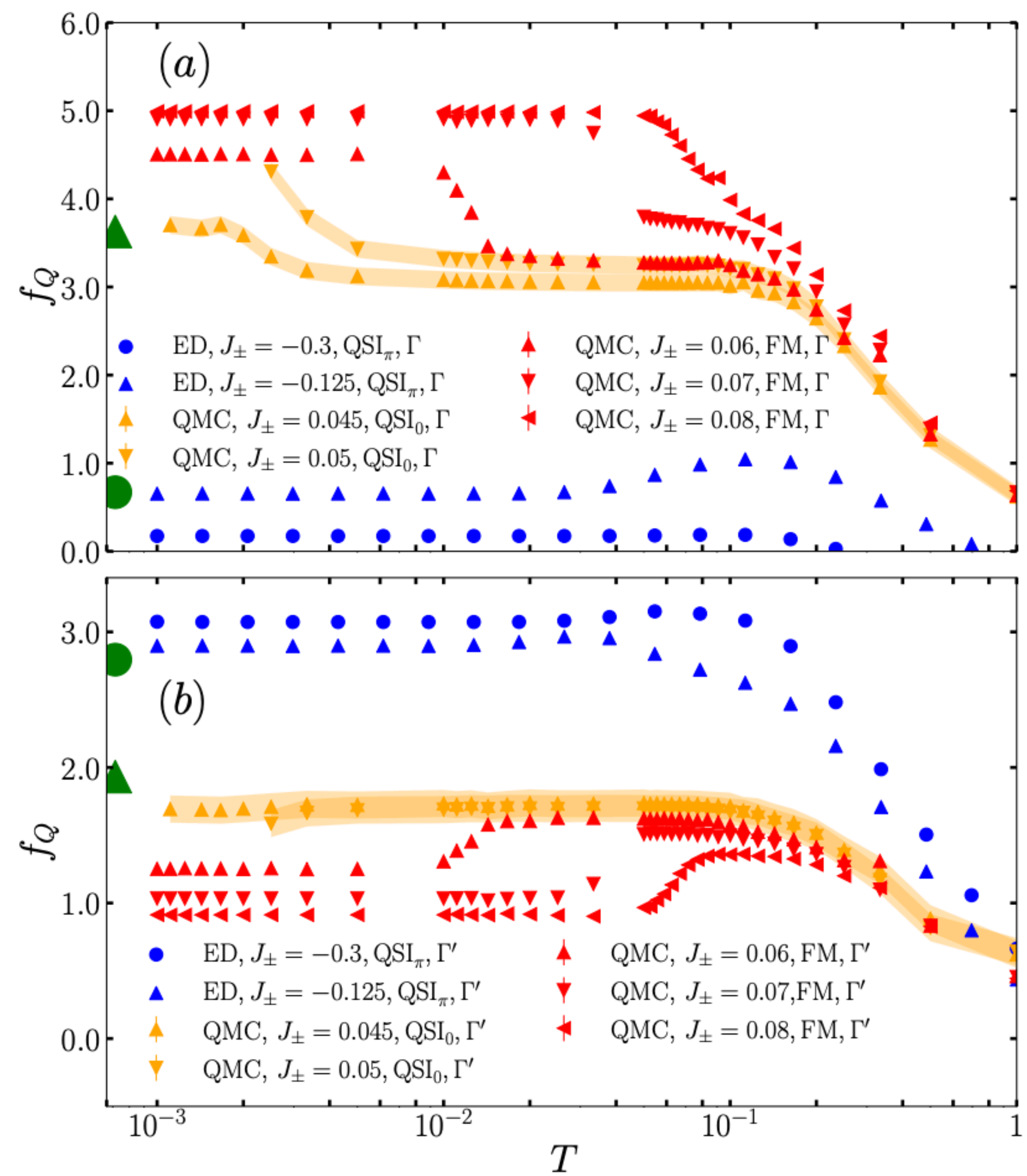

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Ce-based dipolar–octupolar (DO) pyrochlore $Ce_2Zr_2O_7$

neutron scattering couples to dipolar moments $S^{\pm}$

from local to global frame

$$\frac{d^2\sigma}{d\Omega d\omega} \propto \frac{1}{N}\sum_{\mu\nu}\left(\hat{\mathbf{z}}_\mu \cdot \hat{\mathbf{z}}_\nu - \frac{(\hat{\mathbf{z}}_\mu \cdot \mathbf{Q})(\hat{\mathbf{z}}_\nu \cdot \mathbf{Q})}{|\mathbf{Q}|^2}\right)\langle \tau^z_{-\mathbf{q},\mu}(t)\tau^z_{\mathbf{q},\nu}(0)\rangle := A^{\mathrm{DO}}(\mathbf{q},t)$$

$f(S_q^{DO}, T)$ $\quad q = \Gamma' = (4\pi, 4\pi, 0)$

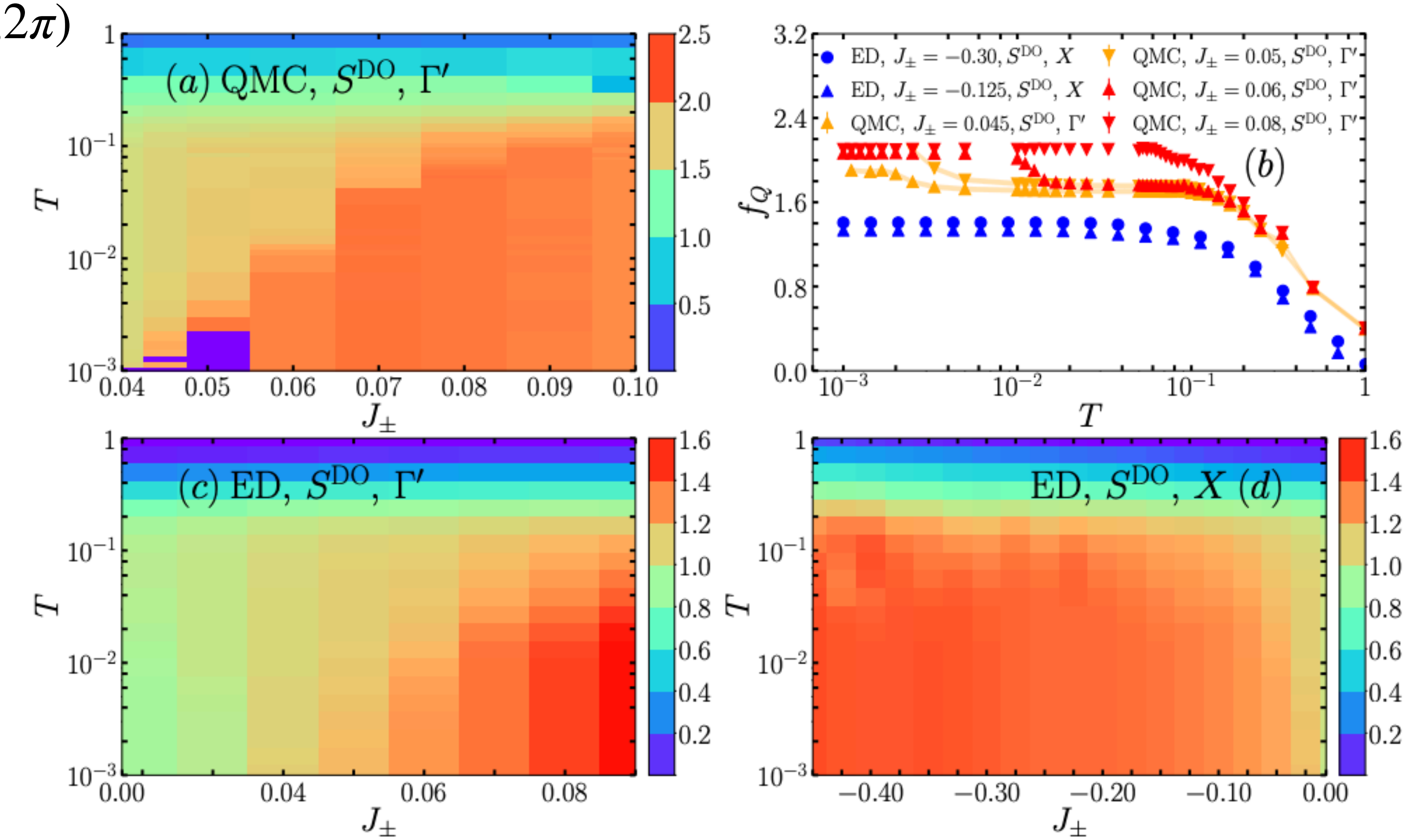
$q = X = (0,0,2\pi)$

$$f_Q(S^\alpha_{\mathbf{q}}, T) = 4\int_0^\infty d\omega \tanh\left(\frac{\omega}{2T}\right)\left(1 - e^{-\omega/T}\right)A^\alpha(\mathbf{q},\omega)$$

$$\mathrm{nQFI}(S^{\mathrm{DO}}_{\mathbf{q}}) = \tfrac{3}{2} f_Q(S^{\mathrm{DO}}_{\mathbf{q}})$$

$$\mathrm{nQFI}(S^{\mathrm{DO}}_{\Gamma'}, T) \gtrsim 2.2$$

QSI$_0$ > 3 partite entangled



$$\mathrm{nQFI}(S^{\mathrm{DO}}_{X}, T) \gtrsim 2.3$$

QSI$_\pi$ > 3 partite entangled