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Nonequilibrium quantum criticality of interacting Dirac fermions

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Background

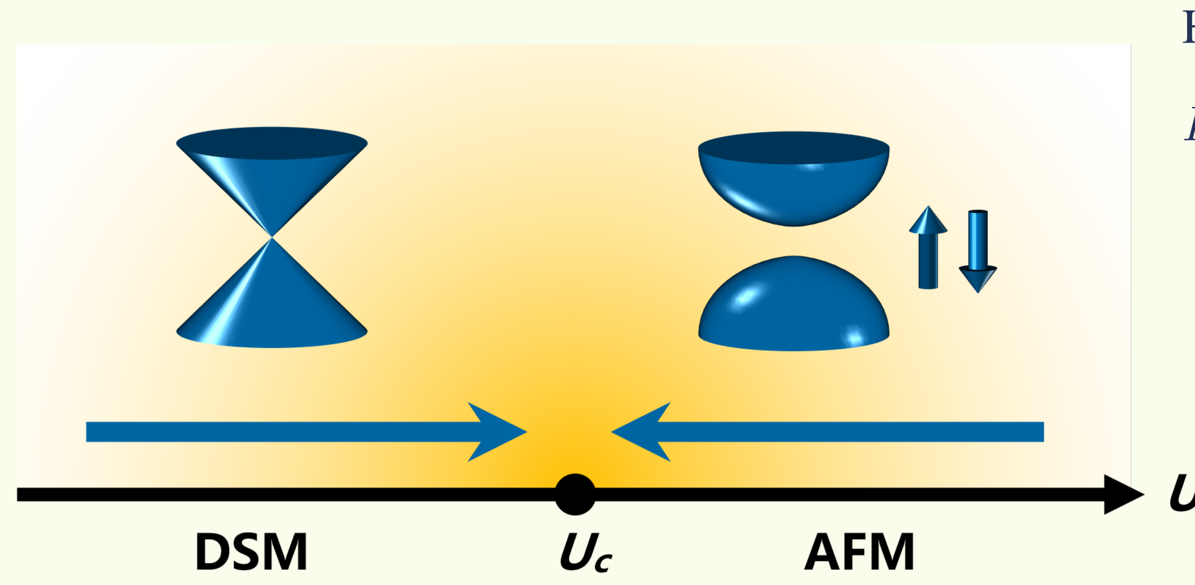
Current status in this field

- Nonequilibrium scaling has been developed in various classical or quantum systems, but rarely studied in strongly interacting fermionic systems[1–3].
- Dirac fermions with linear dispersion matter in phase transition widely in graphene, Weyl/Dirac semimetal, surface of topological insulator[4, 5].

This work

- For the first time, we demonstrate the nonequilibrium dynamics of chiral Heisenberg universality class for Dirac fermions.

Model and protocol



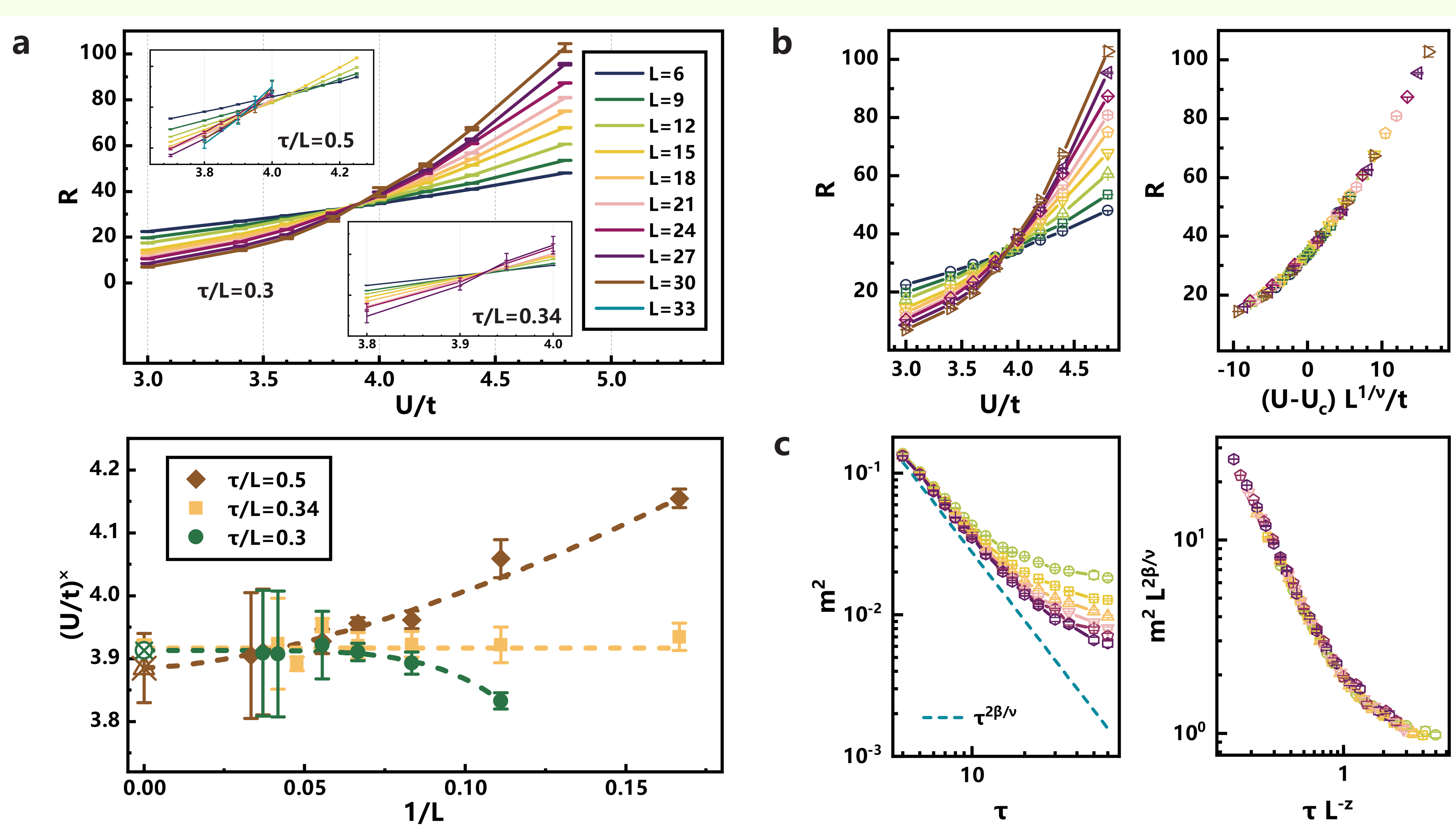
Half-filled honeycomb Hubbard model ($t=1$)

$$H=-t\sum_{\langle ij\rangle,\sigma}c^{\dagger}_{i\sigma}c_{j\sigma}+U\sum_i\left(n_{i\uparrow}-\frac{1}{2}\right)\left(n_{i\downarrow}-\frac{1}{2}\right).$$

Steps

- Prepare initial states of DSM and AFM.
- Quench them to the quantum critical point (QCP) U_c.
- Explore the imaginary-time relaxation by determinant quantum Monte Carlo[6].

Imaginary-time relaxation dynamics with the AFM ordered initial state



We are concerned about these observable quantities:

AFM structure factor $S(\boldsymbol{q})=\frac{1}{L^2}\sum_{i,j}e^{i\boldsymbol{q}\cdot(\boldsymbol{r}_i-\boldsymbol{r}_j)}\langle m_i^{(z)}m_j^{(z)}\rangle$,

AFM order parameter $m^2=S(\boldsymbol{0})$,

Correlation ratio $R=S(\boldsymbol{0})/S(\Delta\boldsymbol{q})$.

Imaginary-time correlation $A=\frac{1}{L^2}\sum_i\langle m_i^{(z)}(0)\,m_i^{(z)}(\tau)\rangle$.

a. Estimation of quantum critical point U_c

$$R(g,\tau,L)=f_R\left(gL^{1/\nu},\tau^{-1}L^z\right).$$

Fixed $\tau^{-1}L^z$, curves intersect at $g=U-U_c=0$.

$\Rightarrow$ QCP: $U/t=3.91\pm0.03$.

b. Fitting for ν

Fixing $\tau^{-1}L^z=0.3$, $R(g)=f_R\left(gL^{1/\nu}\right)$,

$\Rightarrow\ \nu=1.17\pm0.07$.

c. Fitting for β/ν

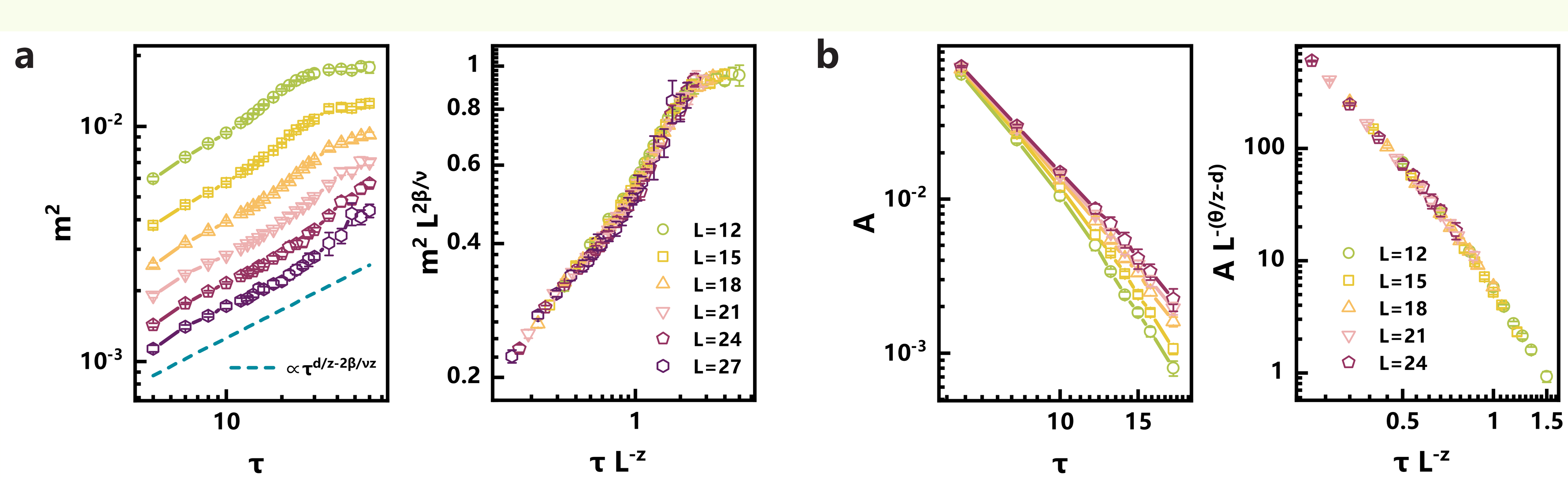
Saturated AFM initialized, $g=0$ set,

$$m^2=\tau^{-2\beta/\nu z}f_{m^2}\left(\tau^{-1}L^z\right),$$

$\Rightarrow\ \beta/\nu=0.80\pm0.03$.

Limit $\tau L^{-z}\to0$, $m^2\sim\tau^{-2\beta/\nu z}+\tau^{-2\beta/\nu z}\mathcal{O}(\tau L^{-z})$.

Imaginary-time relaxation dynamics with the disordered initial state



a. Examination for β/ν

Initial DSM at $g=0$. Here we take $\beta/\nu=0.80$,

$$m^2=L^{-d}\tau^{d/z-2\beta/\nu z}f_{m^2}\left(\tau^{-1}L^z\right).$$

Compare with zero-order approximation $m^2\sim\tau^{d/z-2\beta/\nu z}$.

b. Fitting for θ

Random initial state at $g=0$,

$$A=L^{\theta z-d}f_A\left(\tau^{-1}L^z\right).$$

$\Rightarrow\ \theta=-0.84\pm0.04$.

Discussion and conclusion

Comparison with previous works

model	method	U_c/t	β/ν	θ
honeycomb	QMC (present)	3.91(3)	0.80(3)	−0.84(4)
honeycomb	QMC[5]	3.85(2)	0.75(2)	-
honeycomb	QMC[4]	3.77(4)	0.8(1)	-
Gross-Neveu	$4-\epsilon$ (1st order)[7]	-	0.945	-
Gross-Neveu	$4-\epsilon$ (2nd order)[7]	-	0.985	-
Gross-Neveu	FRG[8]	-	1.008	-

Conclusion

- A negative critical initial slip exponent $\theta=-0.84(4)$ for chiral Heisenberg universality class.
- An efficient dynamic QMC method to determine the critical point and critical exponents.
- A new avenue for numerical studies on nonequilibrium quantum criticality of fermionic systems.

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