Observation of the antiferromagnetic phase transition in the fermionic Hubbard model

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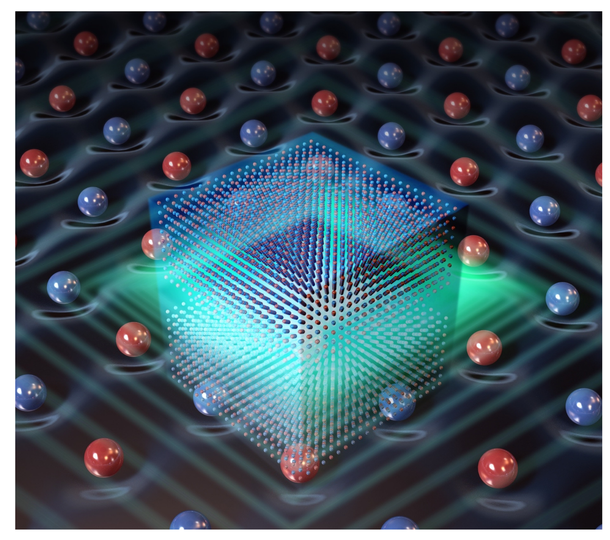
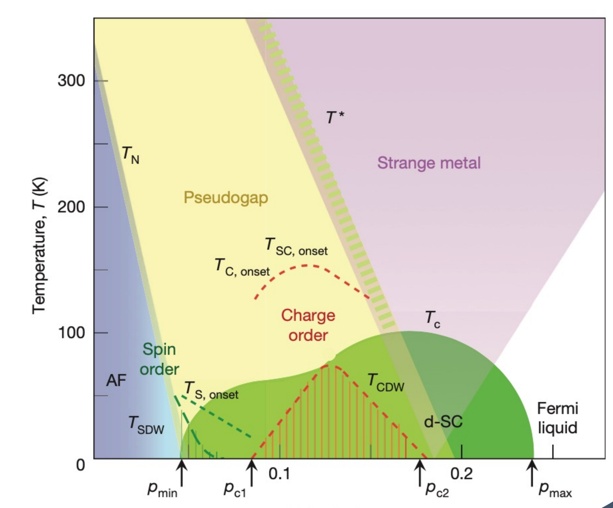
Motivation

- Build a fermionic Hubbard model (FHM) quantum simulator with ultracold fermions in optical lattices.

$$H = -t\sum_{\langle i,j\rangle,\sigma}(c^{+}_{i\sigma}c_{j\sigma} + \text{H.C.}) + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

- Realizing the antiferromagnetic phase transition and reaching the ground state of the FHM at half-filling.
- Explore the low-temperature phase diagram of the FHM, potentially offer solutions to the high-T_c superconductivity problem.





B. Keimer, et al., Nature 518, 7538 (2015)

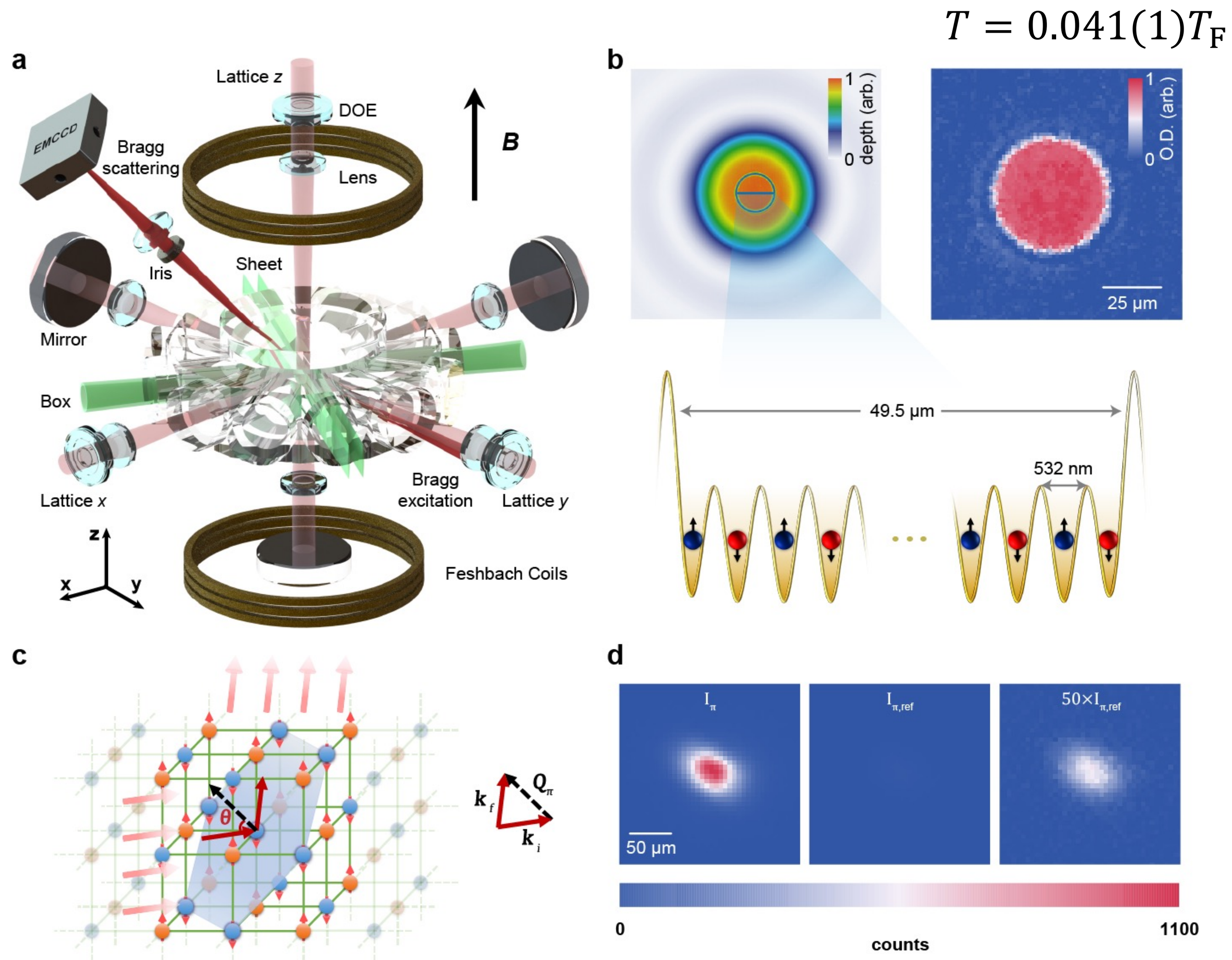
Experimental scheme

- Preparing homogeneous Fermi gases in a box trap: low entropy per particle/less density redistribution during lattice loading.
- Loading Fermi gases into a flat-top optical lattices: guarantee the uniformity of Hubbard parameters across the system.

$\rho \simeq 6.64\times10^{12}/cm^3$

$s = 0.216(2)k_B$

$T = 0.041(1)T_F$



- Measurement of S_π with spin-sensitive Bragg scattering of light
  - Spin structure factor: $S_\pi = \frac{4}{N}\sum_{i,j} e^{i\pi\cdot(\boldsymbol{R}_i-\boldsymbol{R}_j)}\langle \hat{S}^z_i \hat{S}^z_j\rangle$
  - Scattered intensity in lattice (lattice depth: 20E_r):

$$I_\pi \propto \left[e^{-2W_\pi}(S_\pi - 1) + \frac{4\delta^2 + s_0}{4\delta^2}\right]$$

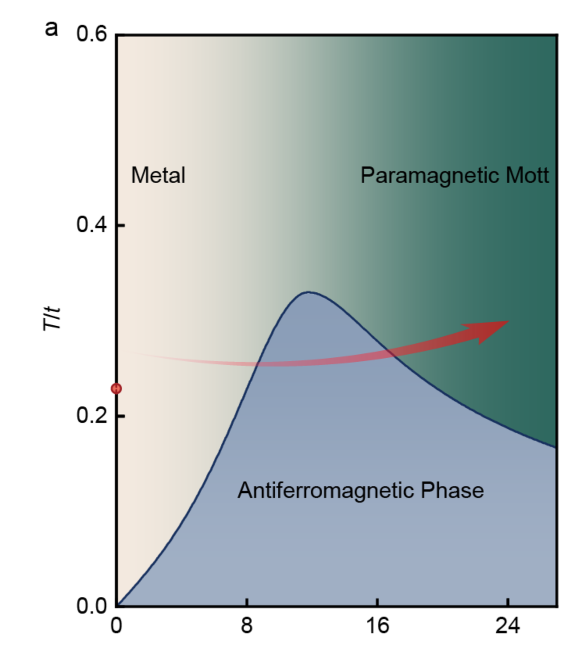
  - Scattered intensity after free expansion: $I_{\pi,\mathrm{ref}} \propto \frac{4\delta^2+s_0}{4\delta^2}$

We obtain: $$S_\pi = e^{2W_\pi}\left(1+\frac{s_0}{4\delta^2}\right)\left(\frac{I_\pi}{I_{\pi,\mathrm{ref}}} - 1\right) + 1$$

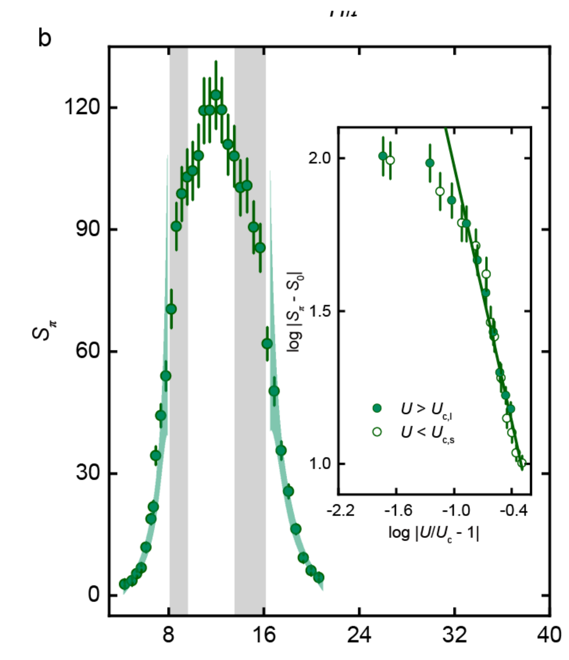
where $\delta \simeq 13.7, s_0 \simeq 30.6 \to \zeta \simeq e^{2W_\pi}\left(1+\frac{s_0}{4\delta^2}\right) \simeq 1.531$

Experimental results

Experimental phase diagram of 3D FHM at half filling

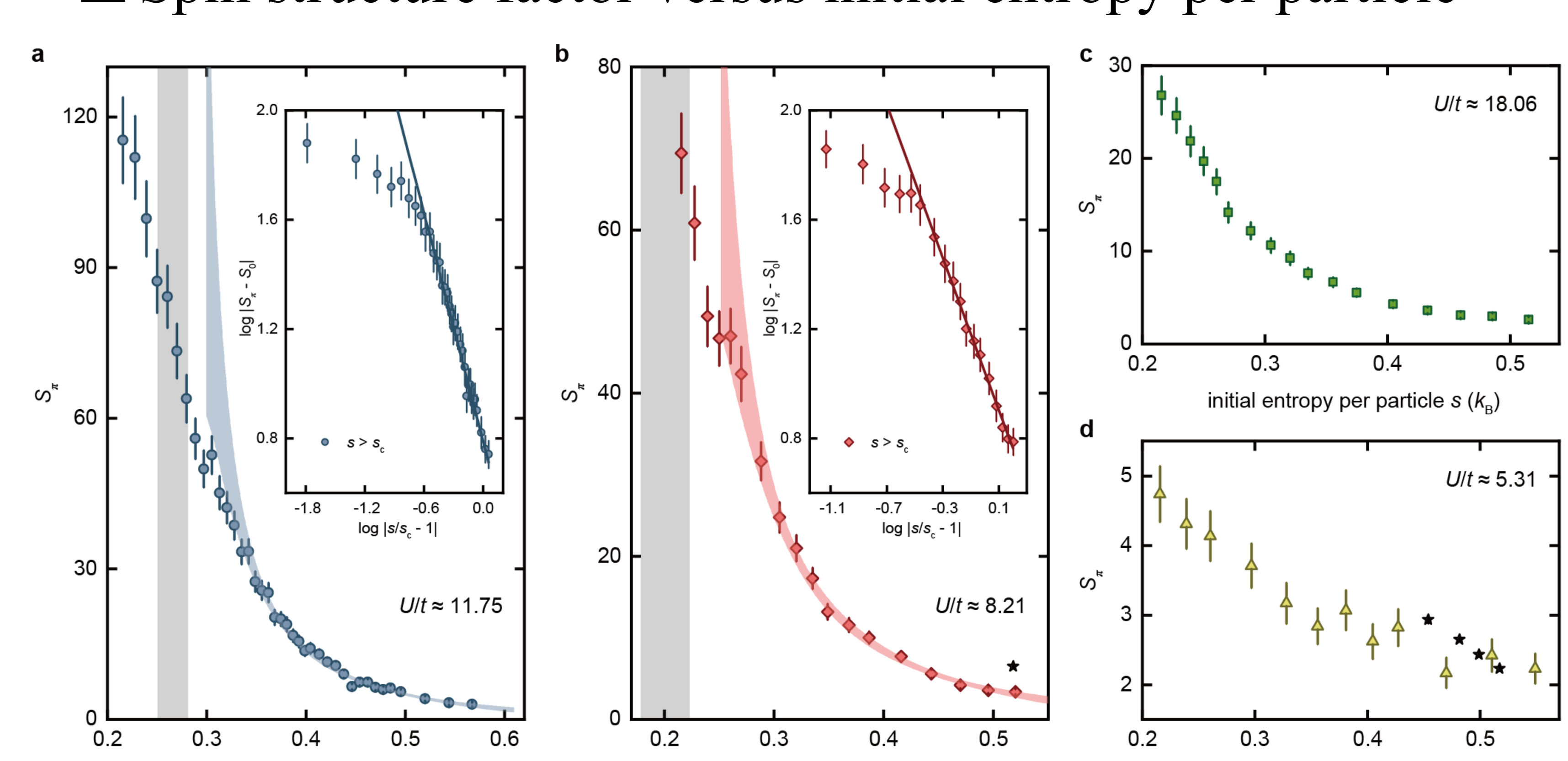


- The achieved low temperature allows us to cross the AFM phase boundary twice by increasing the on-site interactions.
- Optimal $U_{\mathrm{opt}}\sim 11.75t$ due to being away from half filling near the system boundary and residual disorder in the lattice potential.
- Approximately 20% heating due to the weak nonadiabaticity during lattice loading.



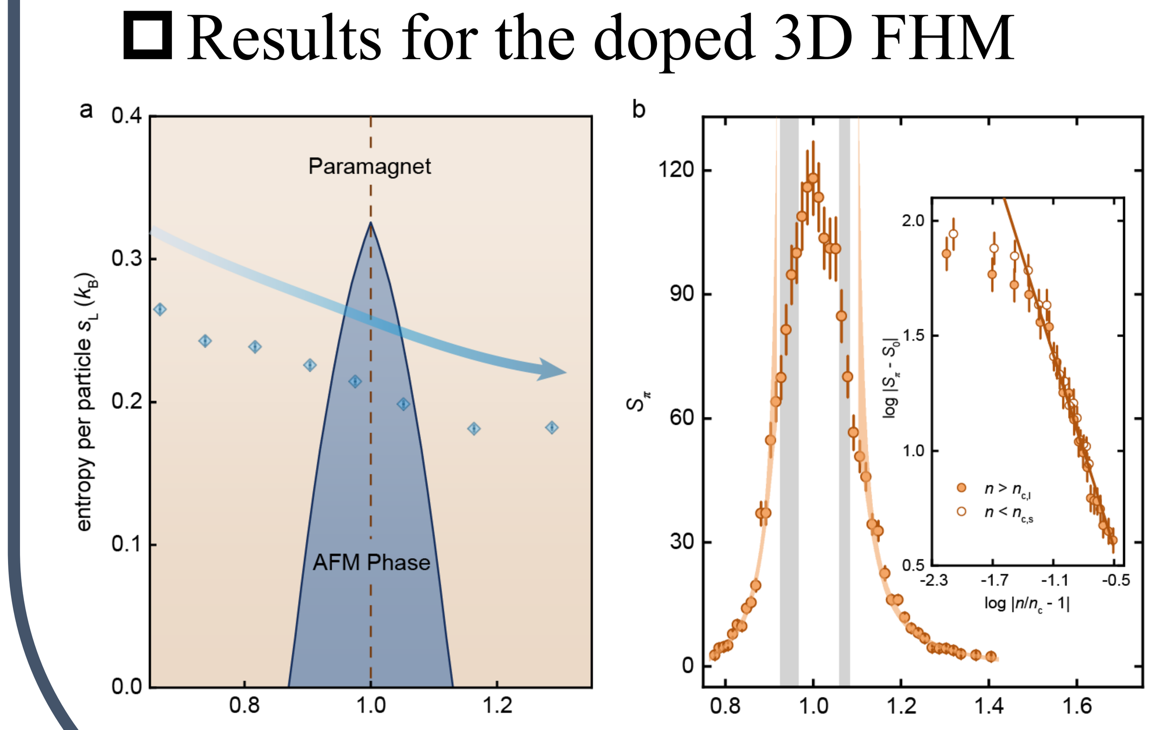
- Averaged $S_\pi = 123(8)$ at $U \simeq 12t$ and $S_\pi > 300$ for single measurements due to critical fluctuations.
- Néel transition points $U_{c,s} = 8.84(33)$, $U_{c,l} = 14.86(48)$.
- $S_\pi - S_0 \propto |U - U_c|^{-\gamma}, \gamma = 1.396$ is the critical exponent from Heisenberg university class.

Spin structure factor versus initial entropy per particle



- Critical points for $U/t = 11.75$ and 8.21: $s_c = 0.27(1)k_B$ and $0.20(1)k_B$, respectively. / $S_\pi - S_0 \propto |s - s_c|^{-\gamma}, \gamma = 1.396$.
- Agree with DQMC results at high temperature and small interactions.

Results for the doped 3D FHM



- The system remains in the AFM phase for $0.95(1) < n < 1.07(1)$.
- $S_\pi - S_0 \propto |n - n_c|^{-\gamma}$, where $\gamma = 1.396$, suggesting the consistency with 3D Heisenberg universality class.

Reference: arxiv:2402.14605 (*Nature*, in Press)

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Innovation Program for Quantum Science and Technology

The Anhui Initiative in Quantum Information Technologies

Shanghai Municipal Science and Technology Major Project