Fluctuating antiferromagnetism and the pseudogap metal

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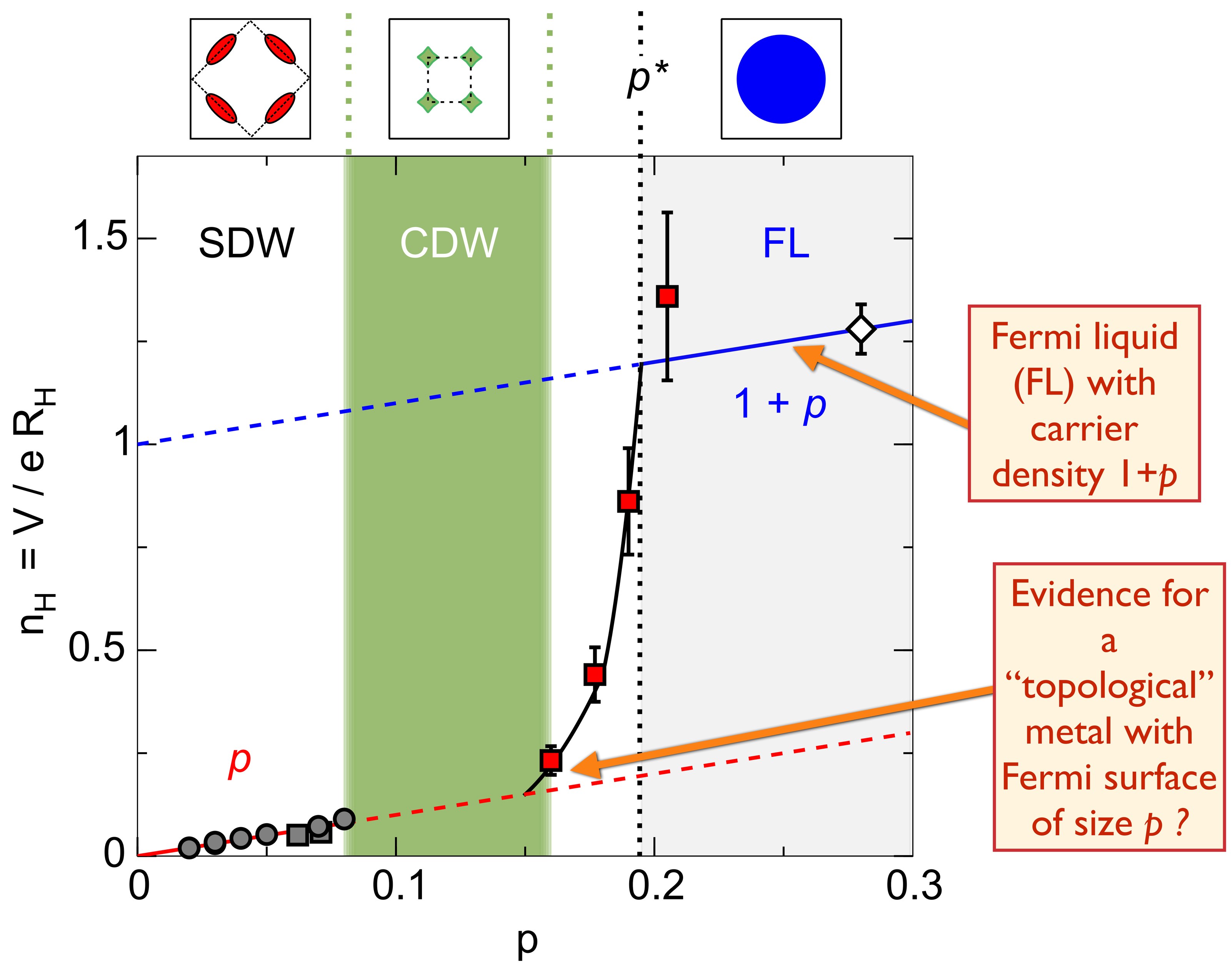
Hall effect measurements in YBCO



Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

Hall effect with spiral magnetic order

$$H_{\rm MF} = \sum_{\boldsymbol{k}} \left(c^\dagger_{\boldsymbol{k}\uparrow}, c^\dagger_{\boldsymbol{k}+\boldsymbol{Q}\downarrow} \right) \begin{pmatrix} \xi_{\boldsymbol{k}} & -A \\ -A & \xi_{\boldsymbol{k}+\boldsymbol{Q}} \end{pmatrix} \begin{pmatrix} c_{\boldsymbol{k}\uparrow} \\ c_{\boldsymbol{k}+\boldsymbol{Q}\downarrow} \end{pmatrix},$$

where $\xi_{\boldsymbol{k}} = -2t(\cos k_x + \cos k_y) - 4t' \cos k_x \cos k_y - \mu$ is the fermionic dispersion, A the antiferromagnetic gap and $\boldsymbol{Q} = (\pi - 2\pi\eta, \pi)$ the ordering wave vector.

The average of the spin density obeys

$$\left\langle c^\dagger_{i\alpha} \sigma^\ell_{\alpha\beta} c_{i\beta} \right\rangle = \Phi_{i\ell}\, e^{i\boldsymbol{Q}\cdot\boldsymbol{r}_i} + \text{c.c.}$$

where Φ_ℓ, $\ell = x, y, z$, are complex order parameters for the spiral order.

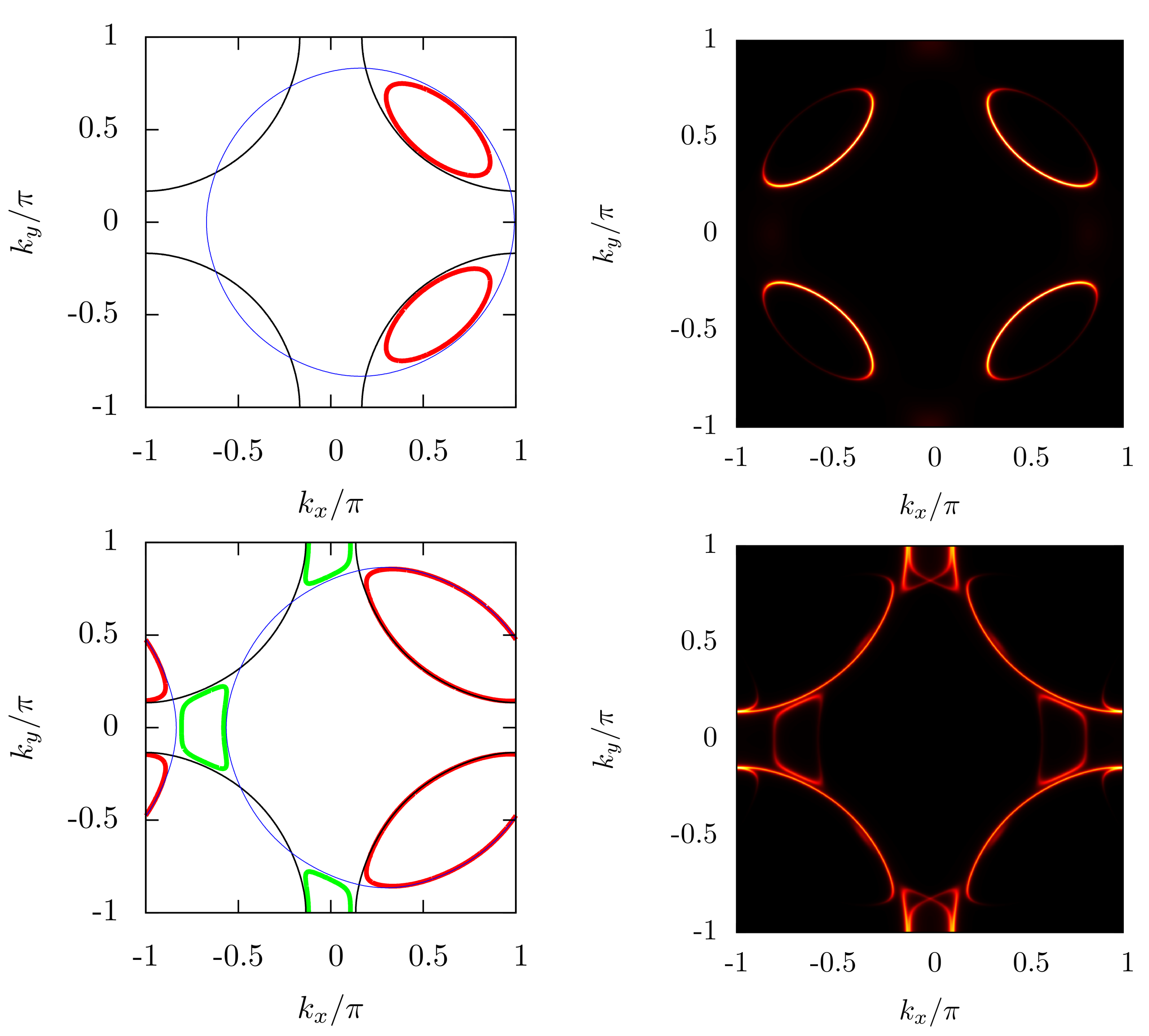
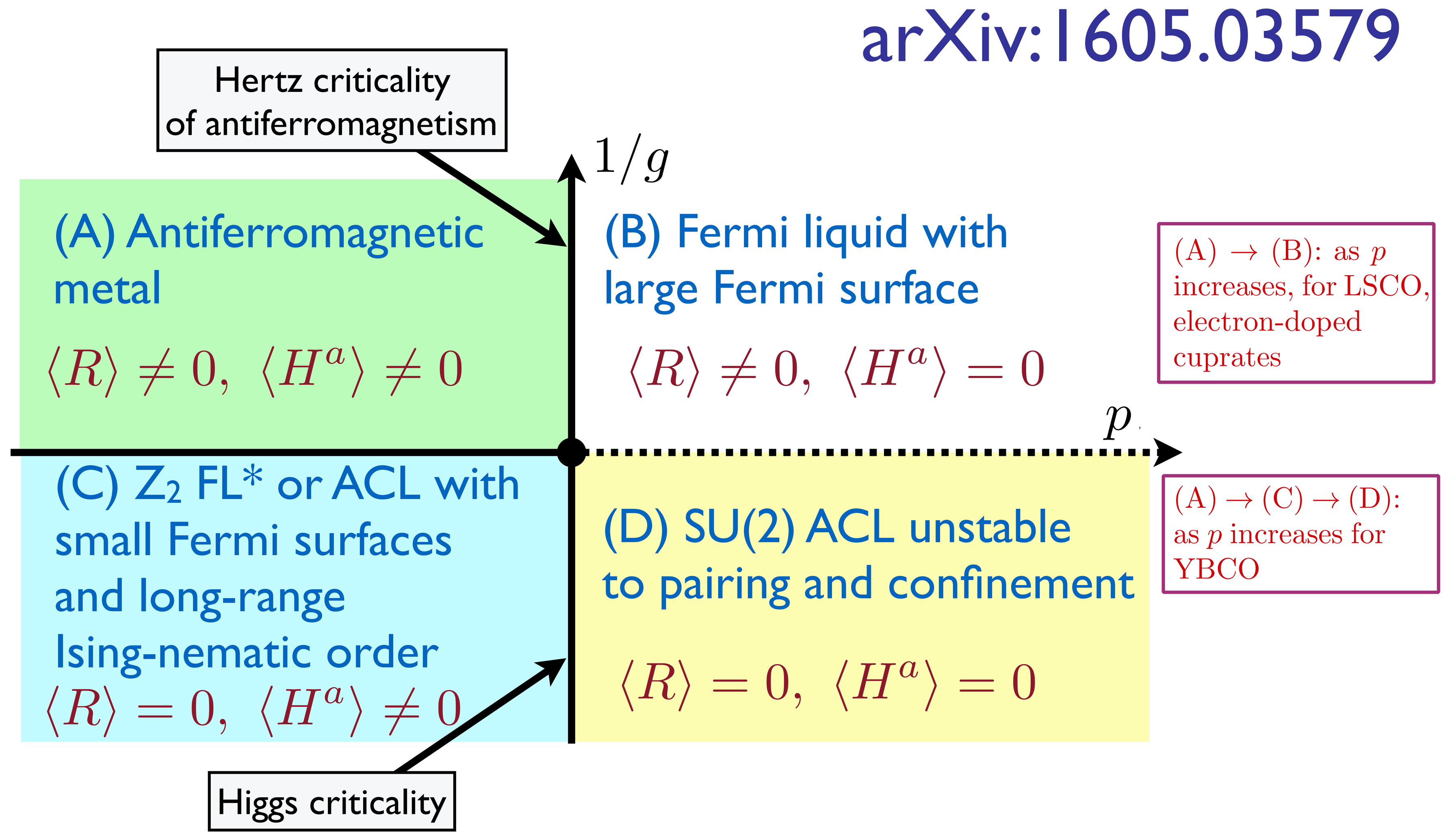


Figure 1: Quasi-particle Fermi surfaces (left) and single-electron spectral functions (right) of spiral anti-ferromagnetic states for $p = 0.08$, $A = 0.63$ (top) and $p = 0.15$, $A = 0.23$ (bottom), where $t' = -0.35$ and $\eta = p$. Hole and electron pockets in the left panels are marked in red and green, respectively, while the thin lines indicate the bare (black) and the $\boldsymbol{Q}$ shifted (blue) unreconstructed Fermi surfaces.

Same Hall effect in a "topological metal" with fluctuating antiferromagnetism and Z_2 topological order

arXiv:1605.03579



The key step is to transform the electrons to a rotating reference frame along the local magnetic order, using a SU(2) rotation R_i and (spinless-)fermions $\psi_{i,s}$ with $s = \pm$,

$$\begin{pmatrix} c_{i\uparrow} \\ c_{i\downarrow} \end{pmatrix} = R_i \begin{pmatrix} \psi_{i,+} \\ \psi_{i,-} \end{pmatrix},$$

where $R_i^\dagger R_i = R_i R_i^\dagger = 1$. This introduces a SU(2) gauge invariance (distinct from the global SU(2) spin rotation)

$$\begin{pmatrix} \psi_{i,+} \\ \psi_{i,-} \end{pmatrix} \to U_i(\tau) \begin{pmatrix} \psi_{i,+} \\ \psi_{i,-} \end{pmatrix}, \quad R_i \to R_i U_i^\dagger(\tau),$$

under which the original electronic operators remain invariant, $c_{i\alpha} \to c_{i\alpha}$; here $U_i(\tau)$ is a SU(2) gauge-transformation acting on the $s = \pm$ index. So the ψ_s fermions are SU(2) gauge fundamentals, carrying electromagnetic global U(1) charge, but not the SU(2) spin of the electron: they are the fermionic "chargons" of this theory, and the density of the ψ_s is the same as that of the electrons. The bosonic R fields also carry the global SU(2) spin (corresponding to left multiplication of R) but are electrically neutral: they are the bosonic "spinons". After transforming to the rotating reference frame, the spiral order parameter becomes a SO(3) Higgs field given by the complex vector H^a with

$$H^a = \frac{1}{2} \Phi_\ell \operatorname{Tr}\left[\sigma^\ell R \sigma^a R^\dagger\right]$$

Condensation of the Higgs field breaks the SU(2) gauge invariance down to Z_2, leading to a topological metal: a fractionalized Fermi liquid (FL*) or an algebraic charge liquid (ACL). It also reconstructs the Fermi surfaces of the spinless chargons ψ, while the Hall effect is the same as that for electrons, c, in the presence of antiferromagnetic order Φ_ℓ.

arXiv:1607.06087

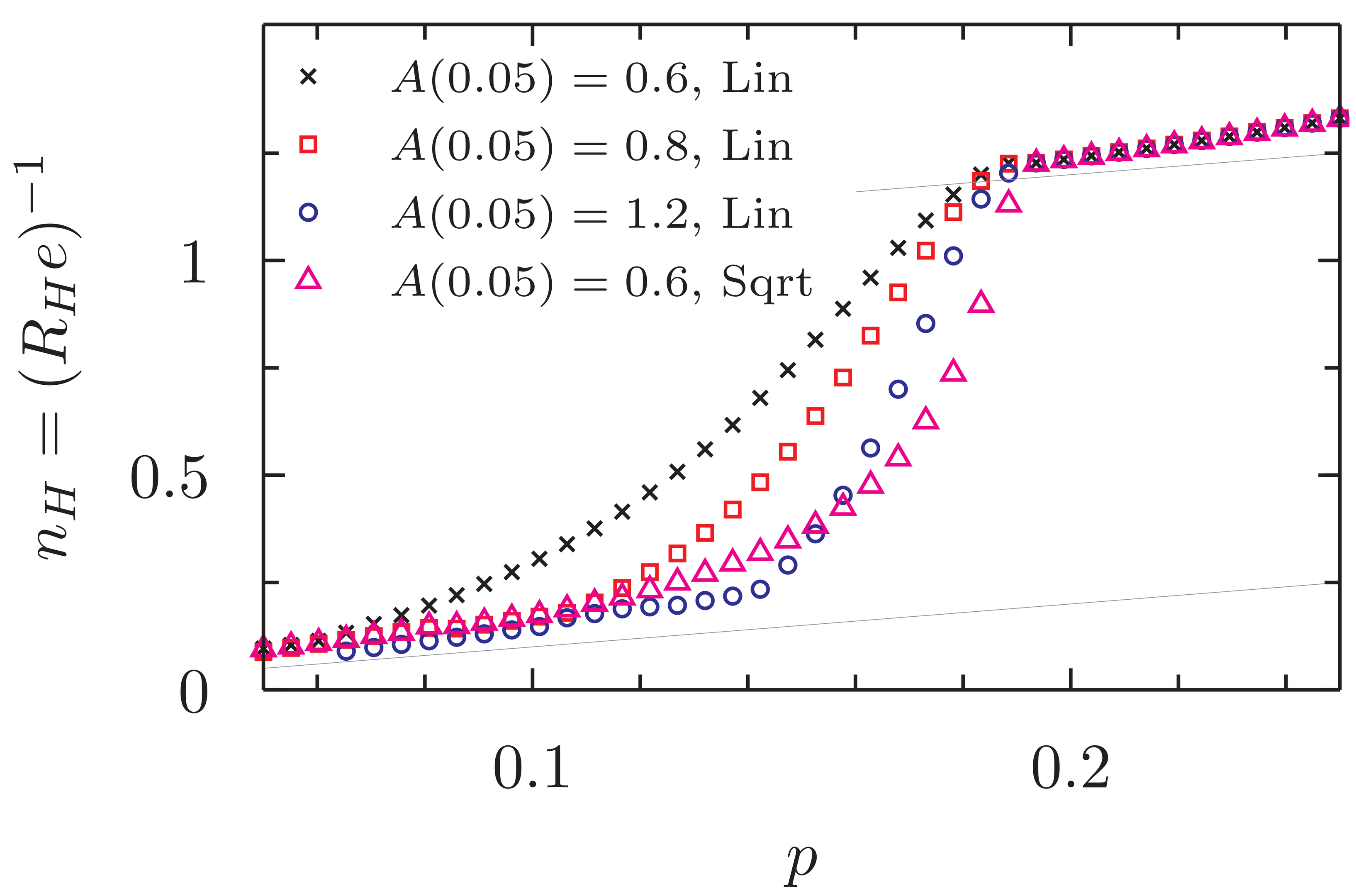


Figure 2: Hall number n_H as a function of doping for $t' = -0.35$. Results for a linear dependence, $A(p) \sim (p^* - p)$, and a square root dependence, $A(p) \sim \sqrt{p^* - p}$, where $p^* = 0.19$ in both cases, are labeled as "Lin" and "Sqrt", respectively.