Trapping Centers at the Superfluid–Mott-insulator Criticality: Transition between Charge-quantized States

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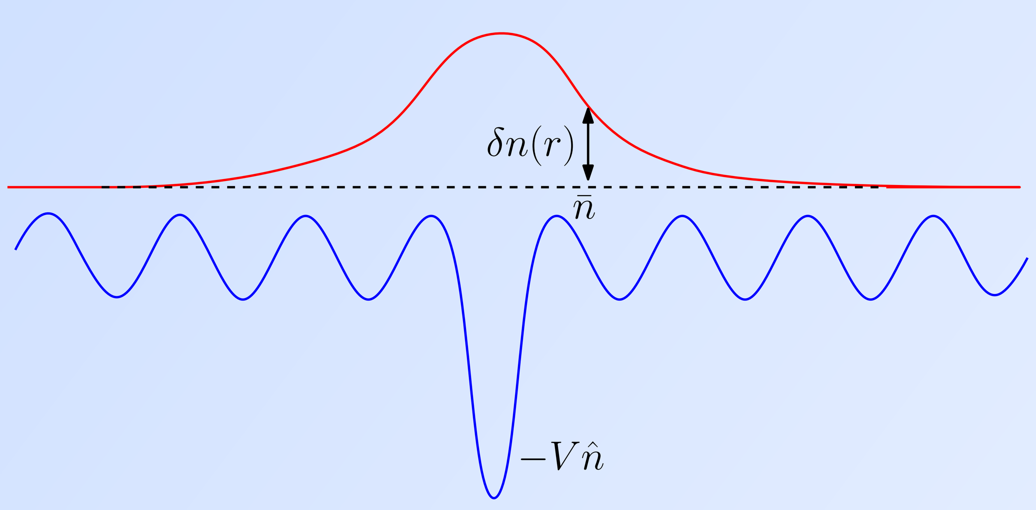
Under the conditions of superfluid–Mott-insulator criticality in two dimensions, the trapping centers are generically characterized by an integer charge corresponding to the number of trapped particles or holes. Varying the strength of the center leads to a transition between two competing ground states with charges differing by ±1. The hallmark of the transition scenario is a splitting of the number density distortion into a half-integer core and a large halo carrying the complementary charge of ±1/2. The sign of the halo changes across the transition and the radius of the halo diverges on the approach to the critical strength of the center.

Charge of the Center at SF-MI Criticality: Quantized or not?

Charge properties of impurities in bosonic systems

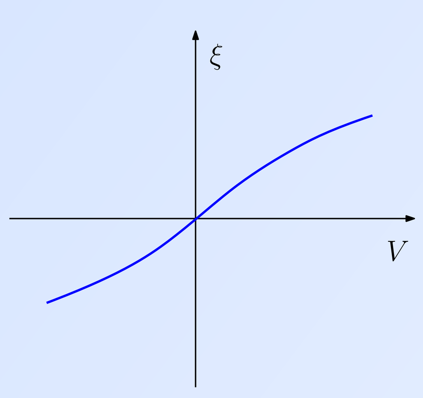
Massive impurities $\Longrightarrow$ static potential



Charge quantization:

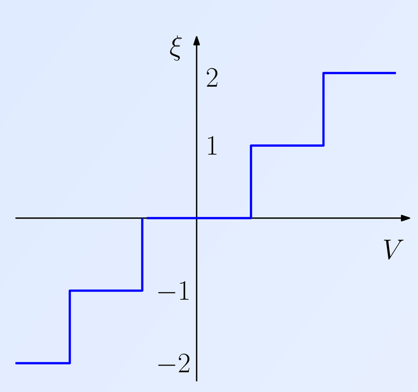
$\xi \equiv \int d^d\mathbf{r}\delta n(\mathbf{r})$ is integer

Superfulid



compressible
no quantization

Mott-insulator



gapped
quantized

SF-MI quantum criticality in d>1:

- incompressible
- no gap

Method

Worm-algorithm path-integral quantum Monte Carlo method for Bose Hubbard model at 2D

$$H = -\sum_{\langle ij\rangle} b_i^\dagger b_j + \frac{U}{2}\sum_i n_i(n_i-1) - \mu\sum_i n_i + V n_0$$

Generic Quantization

Asymptotic behavior far away from the center

$$\delta n(r) \propto \chi(\mathbf{r}) \qquad (r\to\infty)$$

dictated by the linear-response function

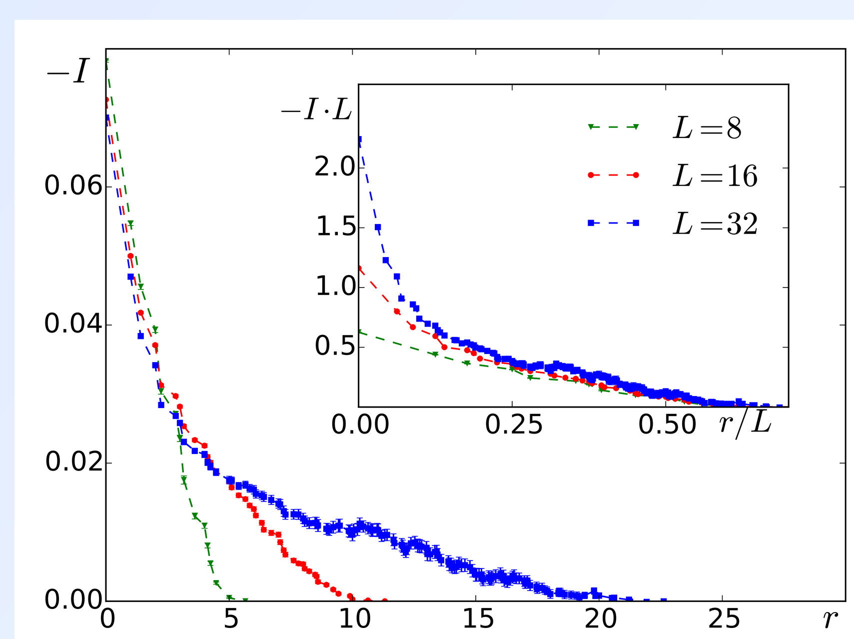
$$\chi(\mathbf{r}) = \int_0^\beta d\tau[\langle n(\mathbf{0},0)n(\mathbf{r},\tau)\rangle - |\langle n(\mathbf{0},0)\rangle|^2]$$

featuring the universal critical behavior

$$\chi(r) \propto \frac{1}{r^3}$$

The integral of distorted density profile

$$I(r) \equiv \sum_{r_i\le r}(n_i-1) = \xi \pm \frac{\text{const}}{r} \qquad (r\to\infty)$$



Numerical result for V=3.5 at QCP in canonical ensemble with total particle number N=L²

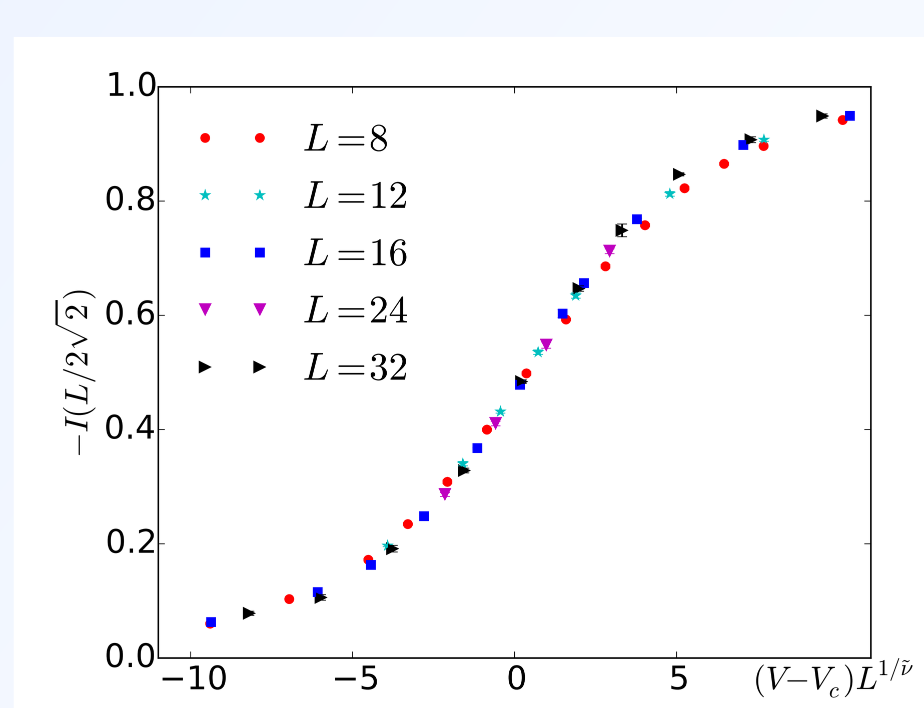
Continuous Transition

Continuous quantum phase transition between two states with different quantized charge

The healing length r_0 diverges as

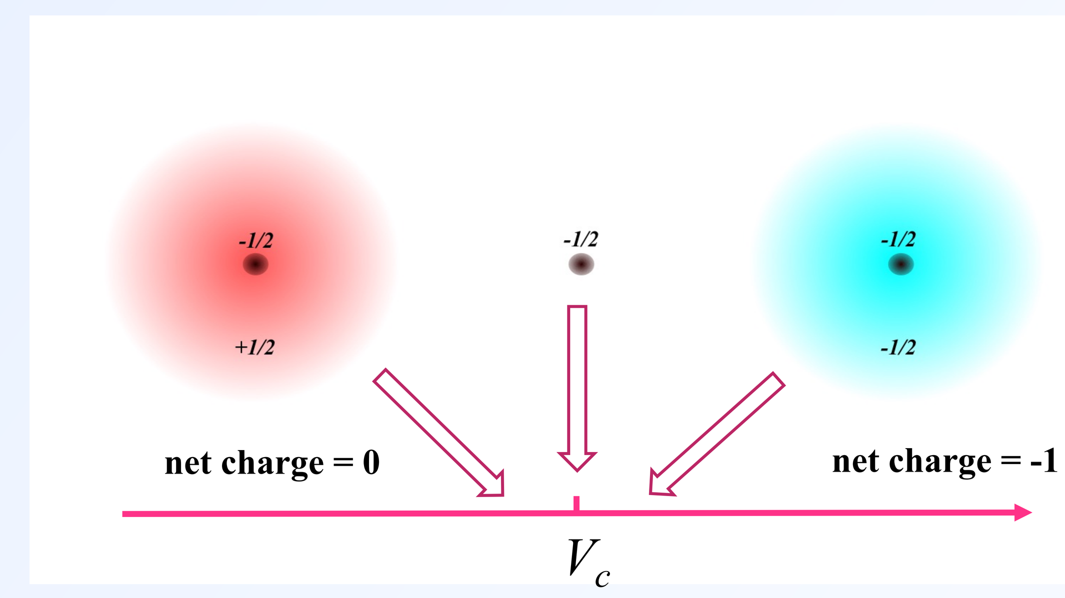
$$r_0 \sim |V-V_c|^{-\tilde{\nu}} \qquad \tilde{\nu} = 2.33(5)$$

Use the integral of density profile I(r) over a certain macroscopic range as an observable

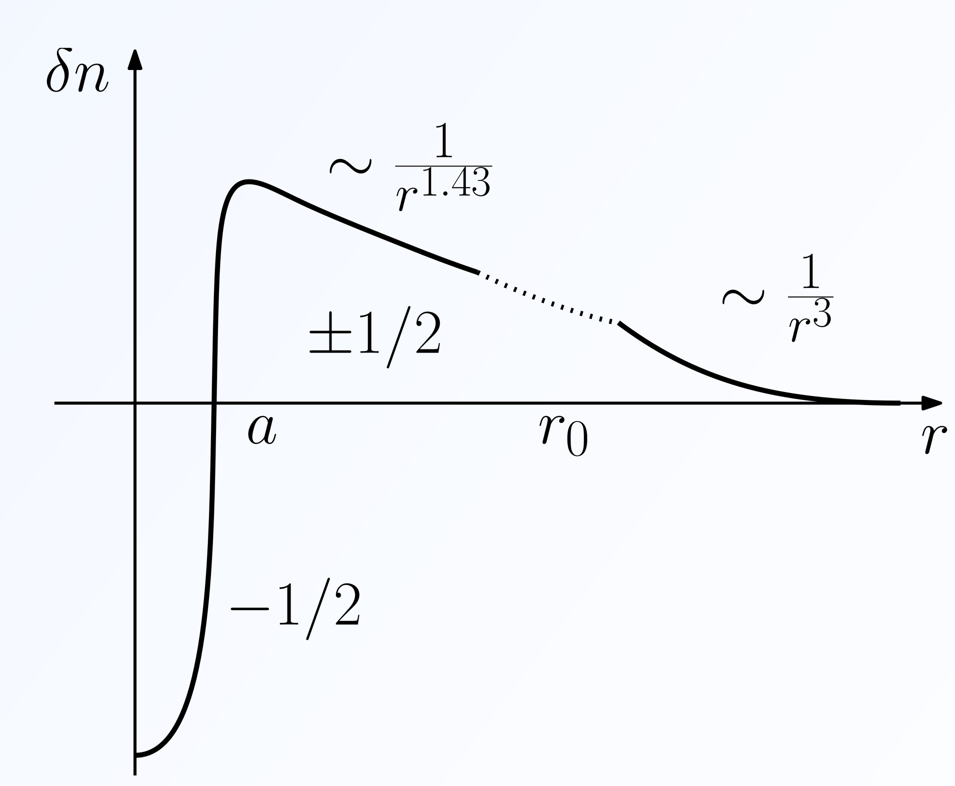


The integral $I(L/2\sqrt{2})$ in the Hubbard model as a function of rescaled strength of the center at different system sizes. The simulation is performed in the grand canonical ensemble.

Transition Between Different Integer States



As approaching the transition point, the density profile develops bimodal distribution including a half-integer charged core and a macroscopic halo with charge ±1/2.
The size of halo is characterized by r_0.



Conclusion

- generic charge quantization at 2D SF-MI criticality
- continuous transition between different charged states
  - half-integer charge at the transition point
  - bimodal distribution at the critical regime: half-integer core surrounded by half-integer halo with diverging radius
- halo with divergent size will induce non-pairwise long range interactions which can be utilized to engineer new quantum phases out of impurity gas