Multimer subradiant states in multilevel waveguide QED

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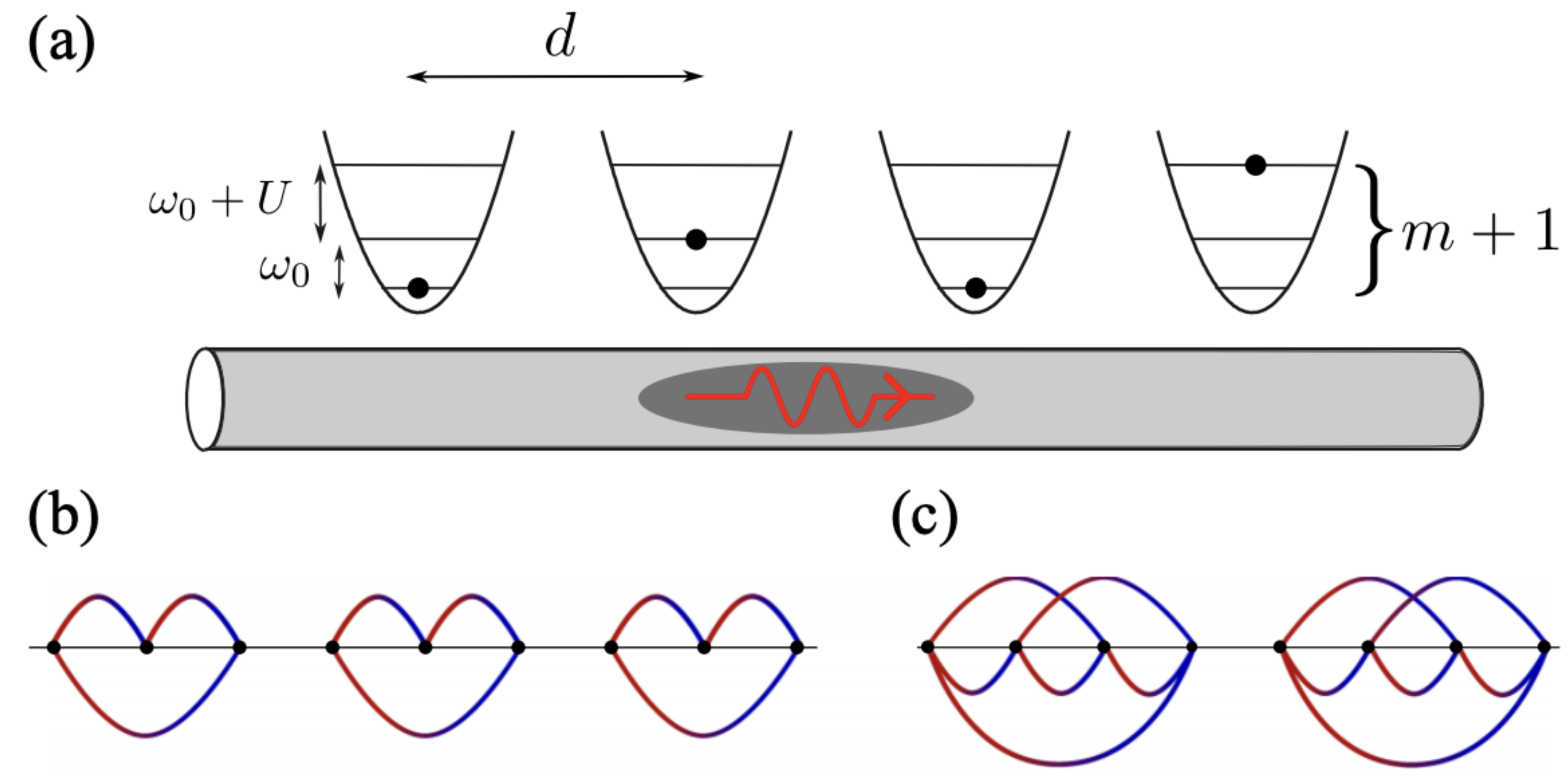
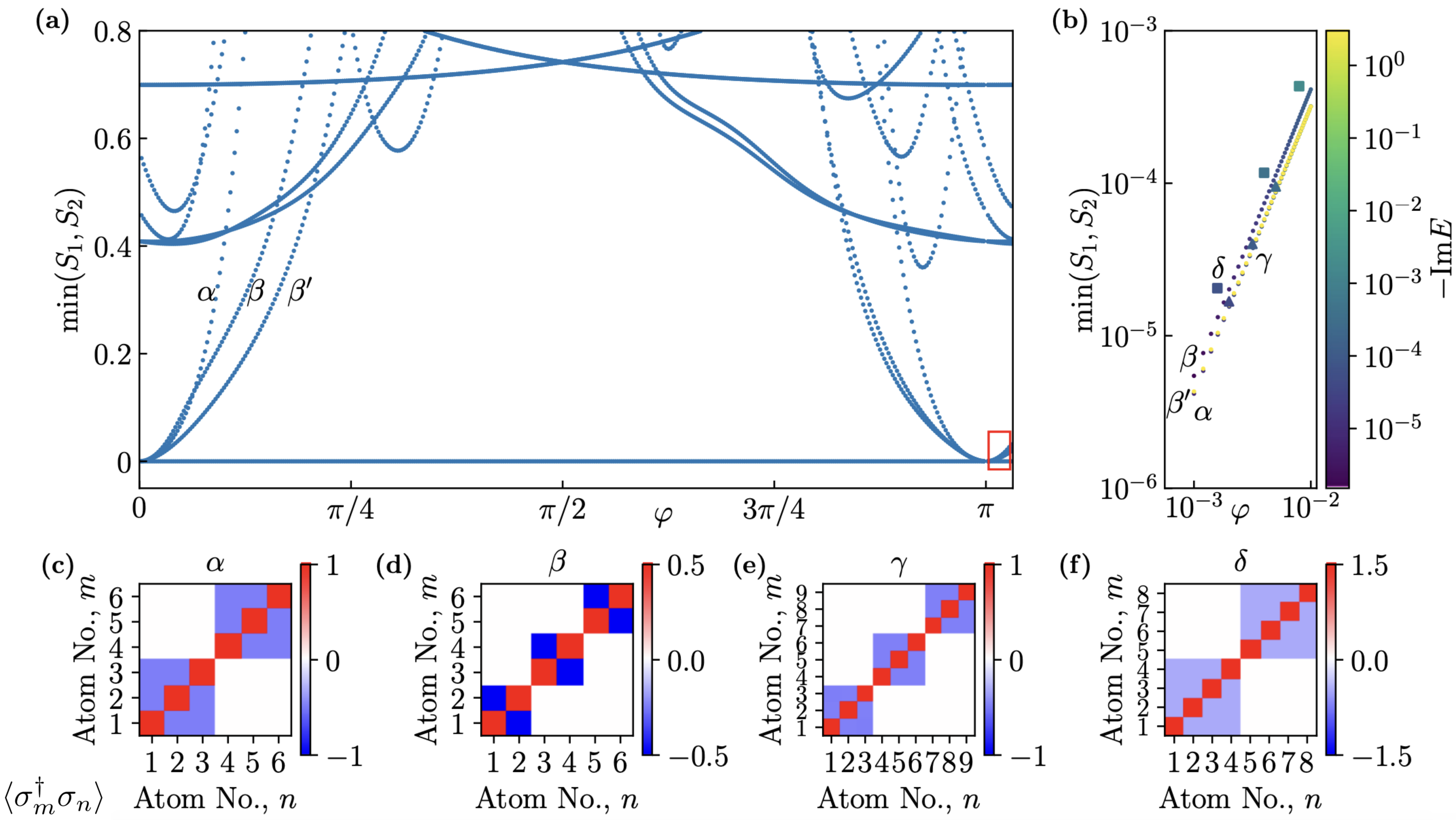
Problem:
We study the spatial structure of the multiple-excited subradiant states in a waveguide QED setup with multilevel atoms.

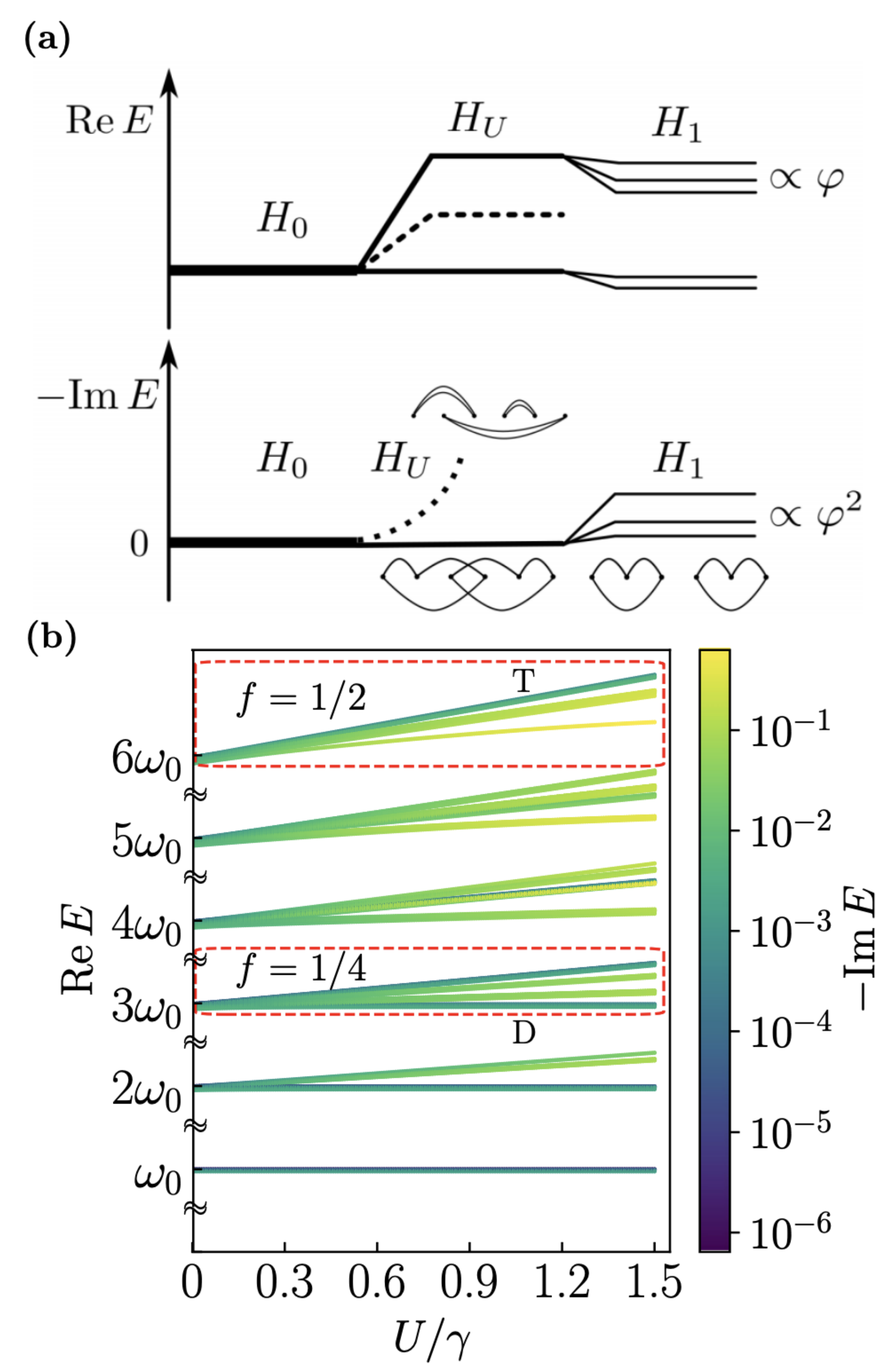
Summary of results:
- Subradiant states are fully composed of dimer operators, and only exist below half-filling.
- The existence of multimer subradiant states depends on the number of atoms in the array, number of levels per atom and the fill factor. Below half-filling, multimer states, if exist, are the most subradiant states in their energy branches.

Setup

An equidistant array of multilevel atoms coupled via photons in a waveguide.







$$H = \omega_0 \sum_{j=1}^{N} \sigma_j^\dagger \sigma_j + \frac{U}{2} \sum_{j=1}^{N} \sigma_j^\dagger \sigma_j (\sigma_j^\dagger \sigma_j - 1)$$

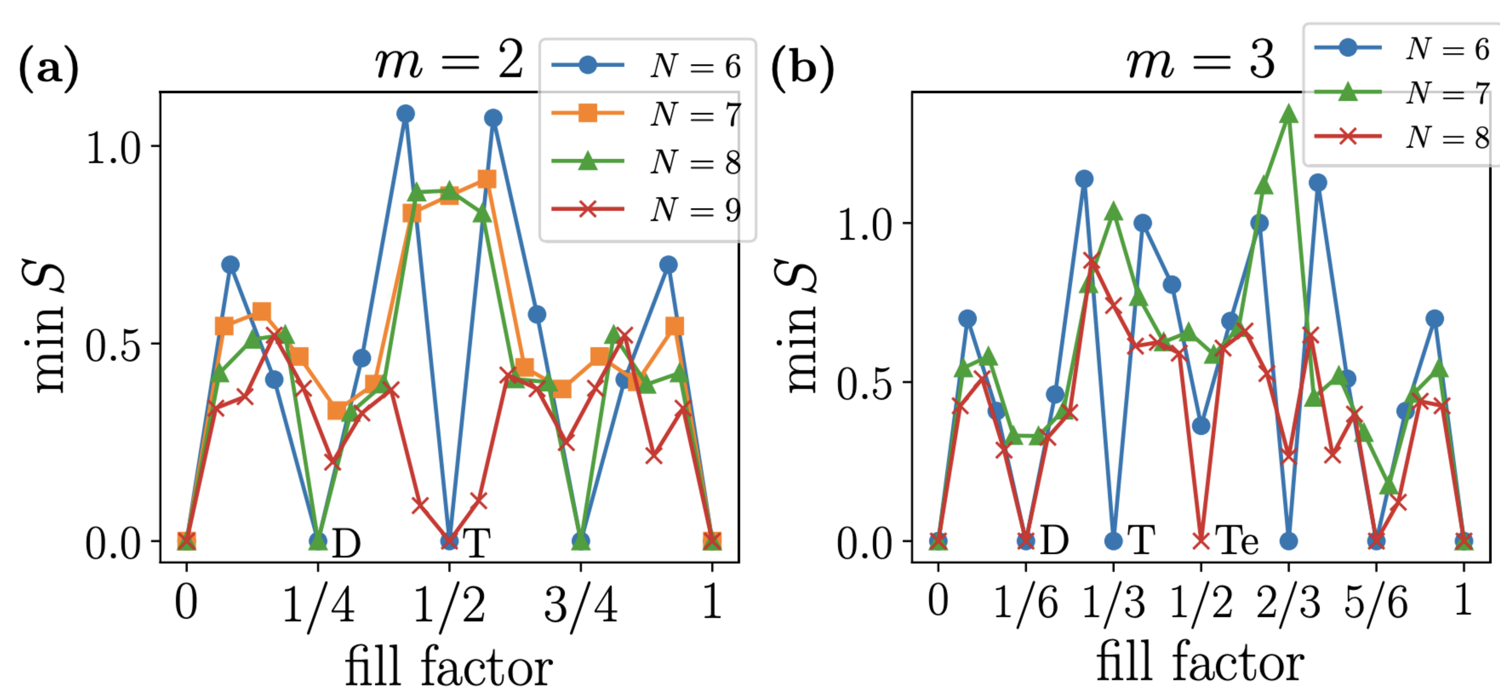
$$- \mathrm{i}\gamma_{1\mathrm{D}} \sum_{i,j=1}^{N} \mathrm{e}^{\mathrm{i}\omega_0 |z_i - z_j|/c} \sigma_i^\dagger \sigma_j.$$

$$-\mathrm{i} \sum_{i,j=1}^{N} \sigma_i^\dagger \sigma_j \mathrm{e}^{\mathrm{i}\varphi|i-j|} \approx -\mathrm{i}H_0 - \varphi H_1 - \frac{\mathrm{i}\varphi^2}{2} H_2,$$

where

$$H_0 = \sum_{i,j=1}^{N} \sigma_i^\dagger \sigma_j, \quad H_1 = -\sum_{i,j=1}^{N} \sigma_i^\dagger \sigma_j |i-j|,$$

$$H_2 = -\sum_{i,j=1}^{N} \sigma_i^\dagger \sigma_j |i-j|^2.$$



Dependence of the minimum value of entanglement entropy on fill factor f. D, T, Te represent dimer, trimer and tetramer states.

Multimer states

Dimer state:

$$(\sigma_1^\dagger - \sigma_2^\dagger)(\sigma_3^\dagger - \sigma_4^\dagger)(\sigma_5^\dagger - \sigma_6^\dagger)|0\rangle$$

Trimer state:

$$(\sigma_1^\dagger - \sigma_2^\dagger)(\sigma_2^\dagger - \sigma_3^\dagger)(\sigma_3^\dagger - \sigma_1^\dagger)$$
$$\times (\sigma_4^\dagger - \sigma_5^\dagger)(\sigma_5^\dagger - \sigma_6^\dagger)(\sigma_6^\dagger - \sigma_4^\dagger)|0\rangle$$

Tetramer state:

$$(\sigma_1^\dagger - \sigma_2^\dagger)(\sigma_2^\dagger - \sigma_3^\dagger)(\sigma_3^\dagger - \sigma_4^\dagger)$$
$$(\sigma_1^\dagger - \sigma_3^\dagger)(\sigma_2^\dagger - \sigma_4^\dagger)(\sigma_1^\dagger - \sigma_4^\dagger)|0\rangle$$