Entangled states of dipolar magnetic atoms in multimode traps

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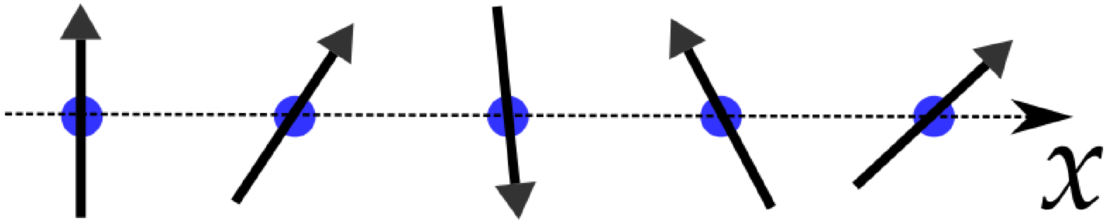
Dipolar Hamiltonian

- Hamiltonian for magnetic atomes (Cr, Er, Dy) in a strong Zeeman Field[1, 2]:
  XXZ model for a 1D Spin chain with dipolar coupling ($J_{ij} = \frac{J_0}{|i-j|^3}$)

$$\mathcal{H} = -\sum_{i \neq j} \frac{J_{ij}}{2} \left(S_i^x S_j^x + S_i^y S_j^y - 2 S_i^z S_j^z \right) + B_q \sum_i (S_i^z)^2$$

- Quadratic zeeman field (tunable via both magnetic fields and lasers [3, 4])



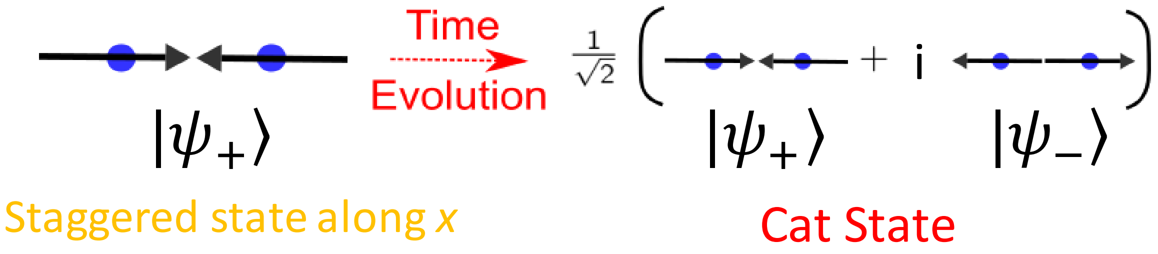
[1] Lepoutre, S., Schachenmayer, J., Gabardos, L. *et al. Nat Commun* **10,** 1714 (2019).
[2] A. de Paz, B. Naylor, J. Huckans, A. Carrance, O. Gorceix, E. Maréchal, P. Pedri, B. Laburthe-Tolra, and L. Vernac Phys. Rev. A **90**, 043607 (2014).
[3] A. Patscheider, B. Zhu, L. Chomaz, D. Petter, S. Baier, A.-M. Rey, F. Ferlaino, and M. J. Mark Phys. Rev. Research **2**, 023050 (2020).
[4] Chalopin, T., Bouazza, C., Evrard, A. *et al. Nat Commun* **9,** 4955 (2018).

Cat states with 2 spins

- Exact result for B_q = *0.25*: one axis twisting model

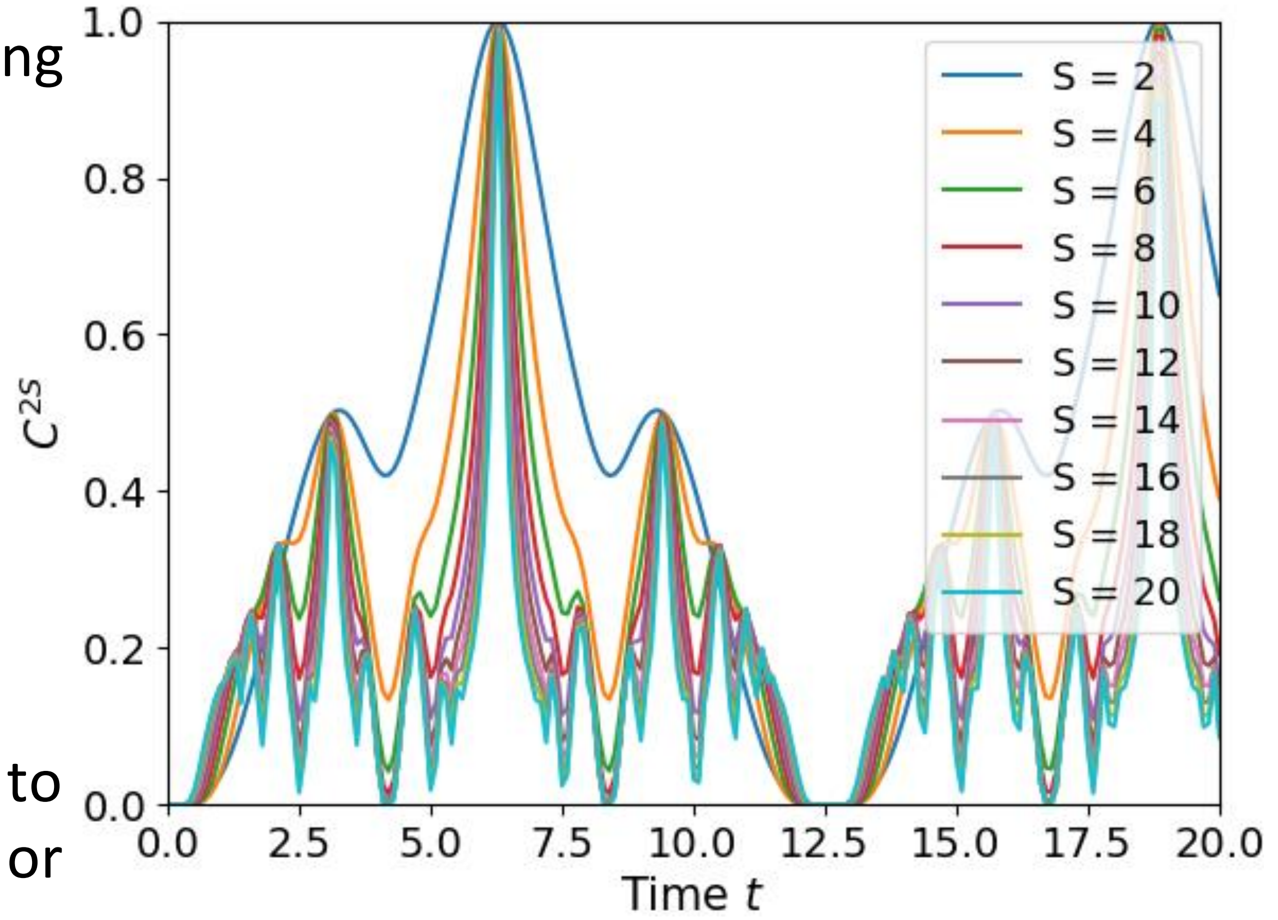
$$\mathcal{H} = \frac{1}{4} J_{stag}^2 - \frac{S(S+1)}{2} + \frac{1}{4}\left(J^z\right)^2$$

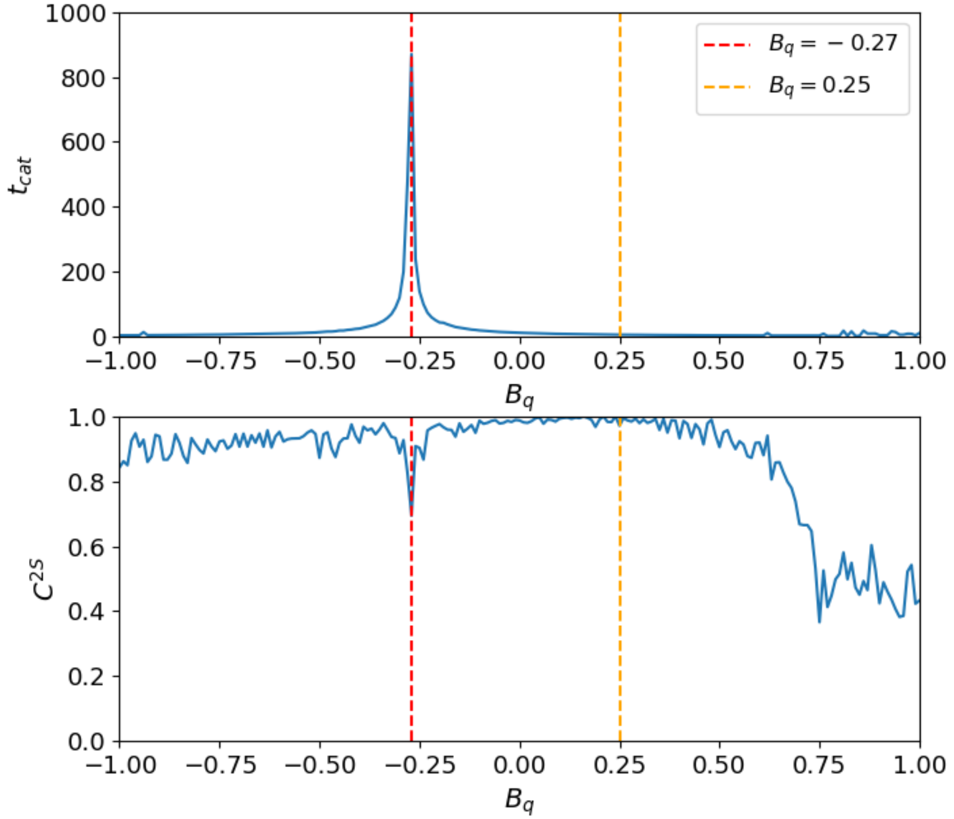
where $J_{stag}^2 = \left(J_{stag}^x\right)^2 + \left(J_{stag}^y\right)^2 + (J^z)^2$



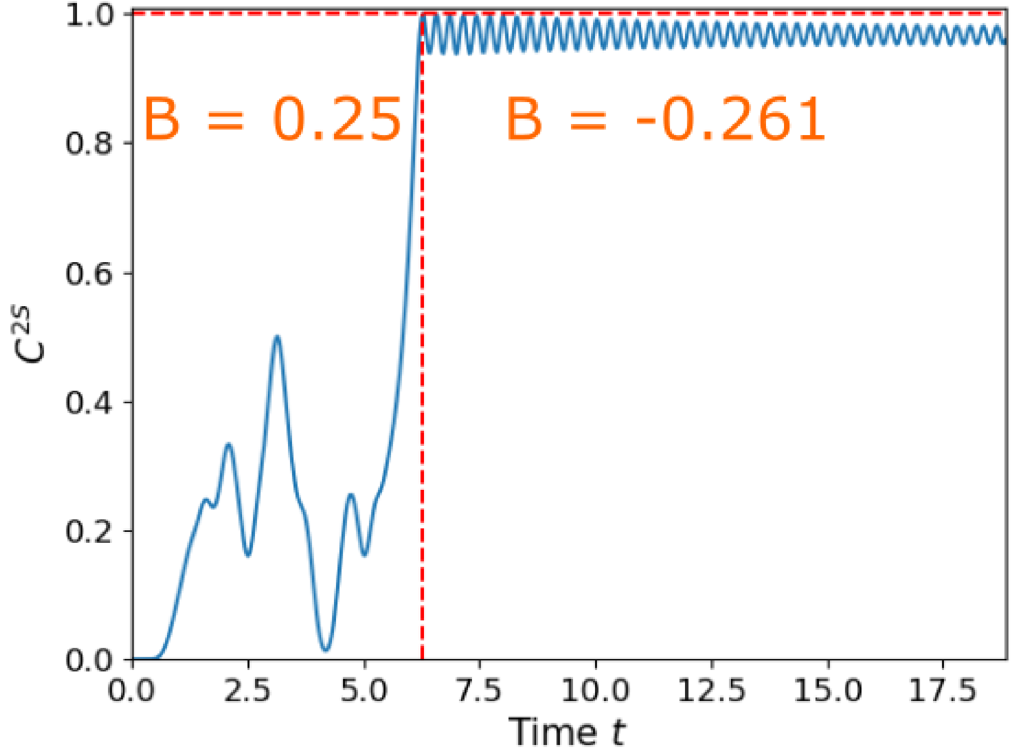
- Cat state at $t = 2\pi$ for any S: possibility to realize a cat state with Cr, Er or Dy atoms [1] or two BECs as two giant spins [2]
- Cat-state correlation function:

$$C^{2S} = 2|\langle\psi(t)|\psi_+\rangle\langle\psi(t)|\psi_-\rangle|$$





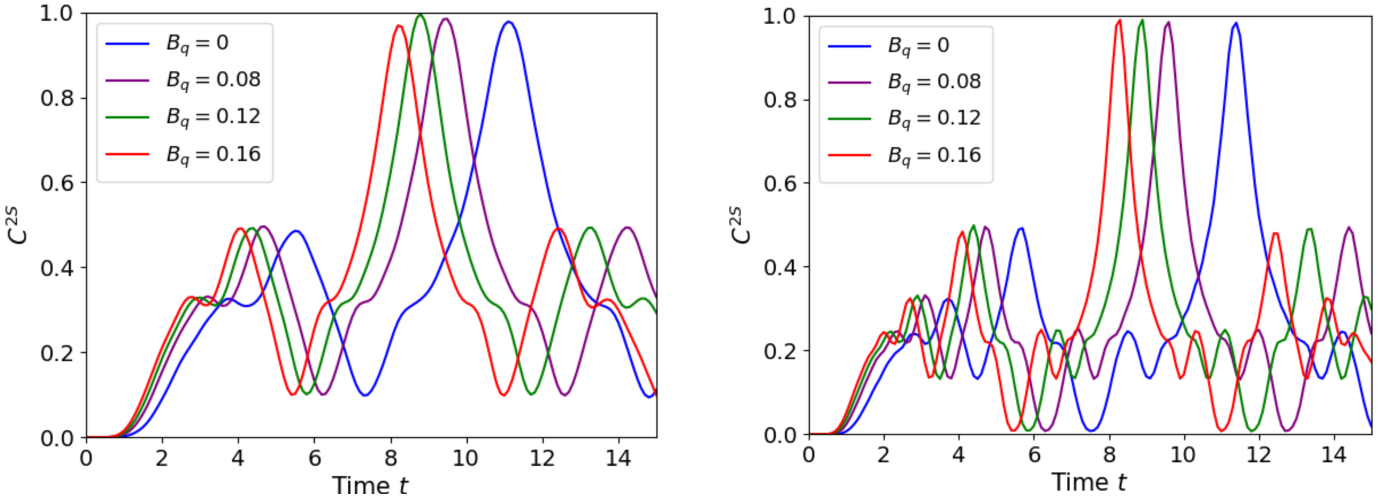
Evolution of t_{cat} and $C^{2S}{}_{\max}$ with B_q for N=2 spins S=6



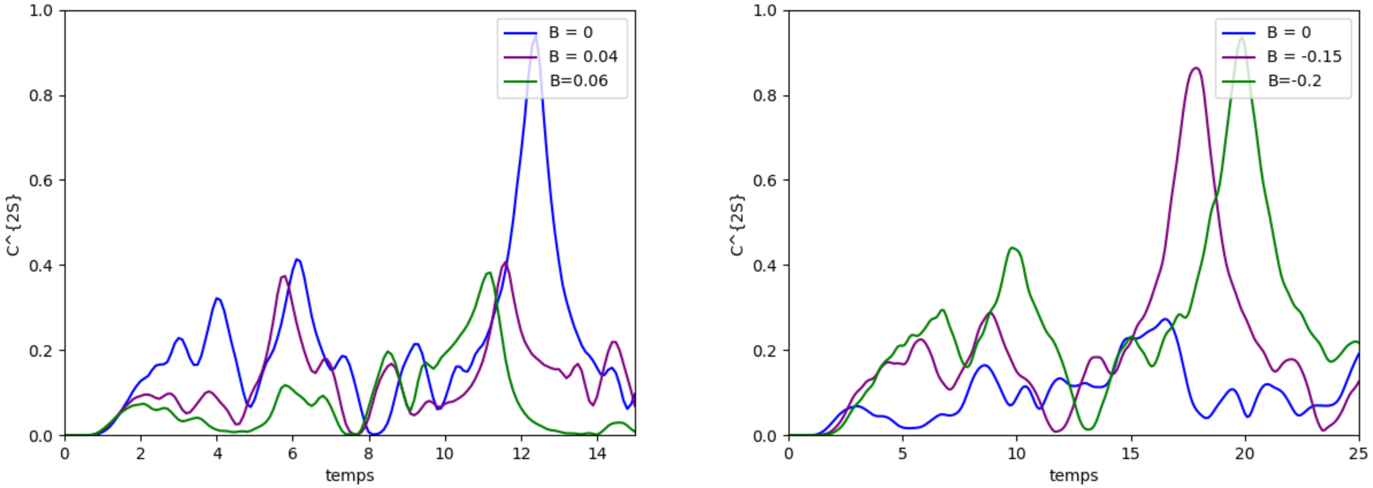
Evolution of C^{2S} in time for N=2 spins S=8

- Best cat state for $B_q = 0.25$ & Slowest dynamics for $B_q \approx -0.27$. We can use both properties to prepare a long-lived cat state by switching the value of Bq at the right time.
- Robust phenonemon, especially for $B_q < 0$
- Cat state maximizes the variance of J^x_{stag} ➡ maximal sensitivity to an external magnetic field along x.

Cat states with 3 or more spins

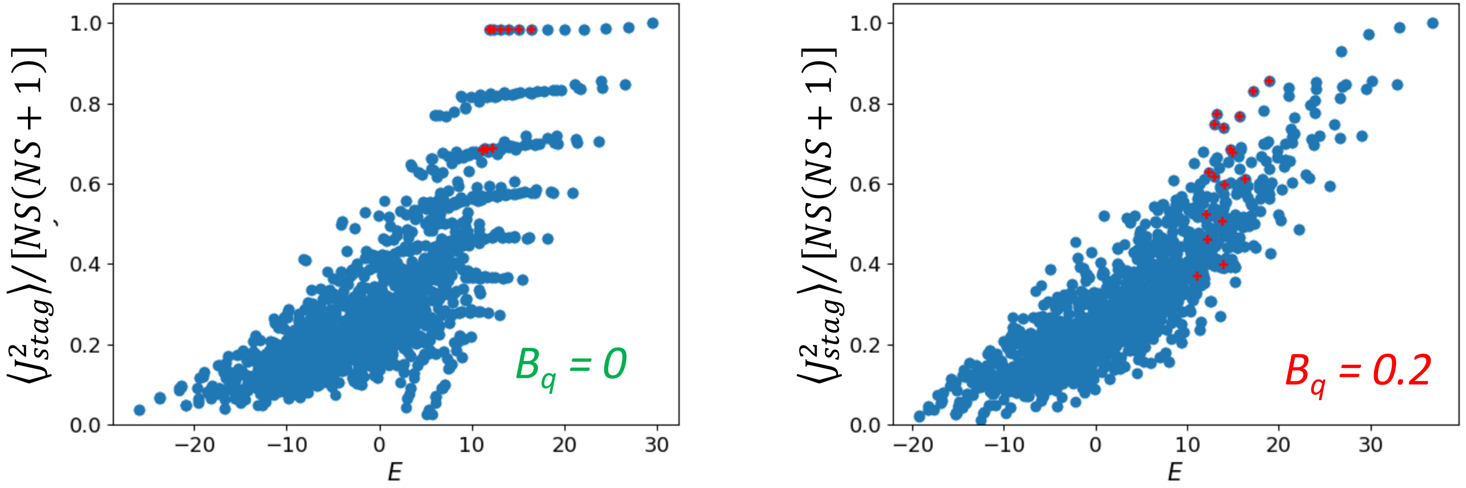


Cat state formation for N=3 spins S=3 (left) and S=6 (right)

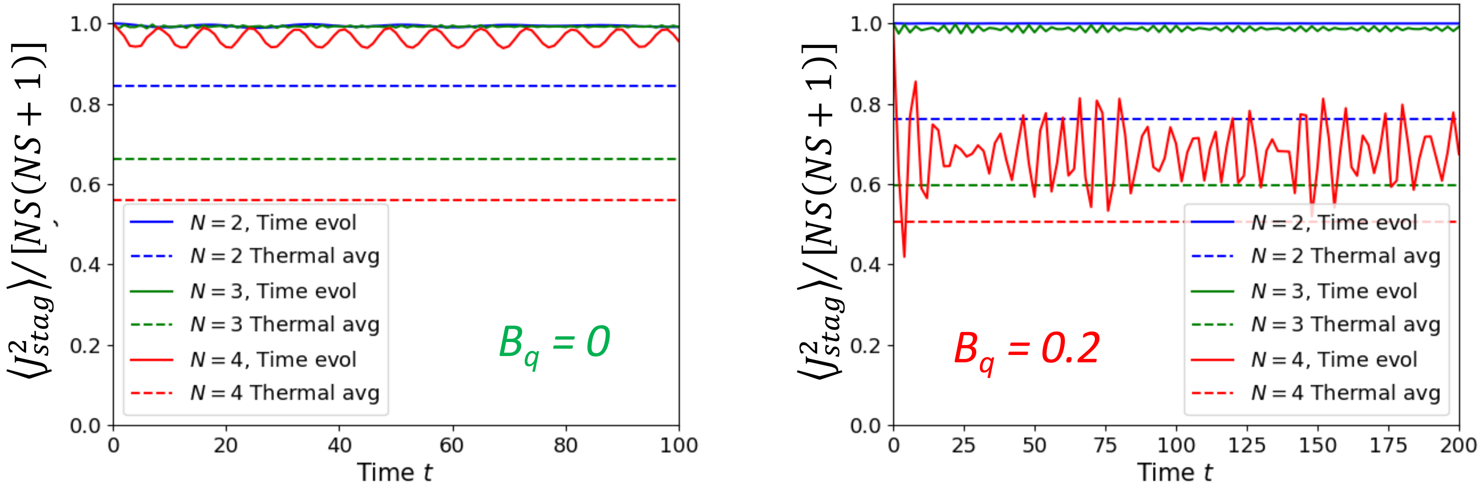


Cat state formation for N=4 spins S=6 (left) and N=5 spin S=3 (right)

Hamiltonian spectrum & Quantum Scars



Total spin and energy associated to the Hamiltonian eigenvectors for 4 spins 3



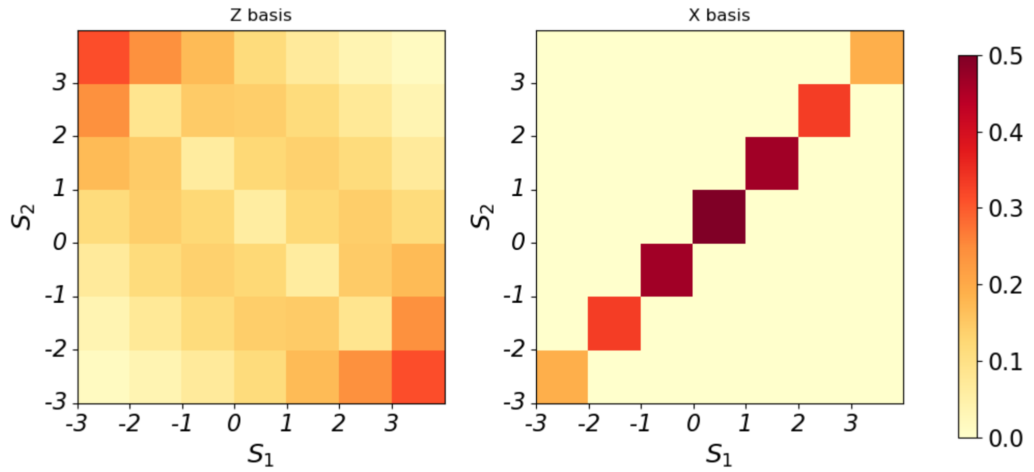
Variation in time of the mean total spin compared to its statistical mean value

- Red dots: overlap with the staggered initial state
- For $B_q = 0$, the band at $J_{stag} = NS$ forms a well separated eigenspace of $\mathcal{H}$
- For $B_q = 0.2$, these states are mixed in the bulk of other states

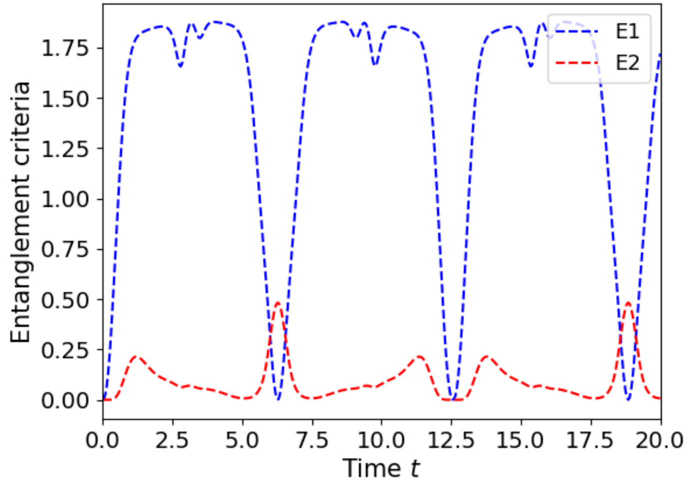
- Thermal average at the temperature corresponding to the energy of the initial state
- For $B_q = 0$, $\langle J^2_{stag} \rangle$ almost conserved: dynamics confined in a subspace of the Hilbert Space : Weak Ergodicity Breaking.
- For $B_q = 0.2$, Ergodicity is nearly restored.

Twin Spin states for 2 spins

- Initial state fully polarized along x. After *t = 2π* and with B_q = 0.25, appearance of a highly entangled state : $|\psi_{twin}\rangle = \sum_{m=-S}^{S} c_m |m, m\rangle_x$
- The $|c_m|^2$ follow a Gaussian distribution of standard deviation $\sigma \approx 0{,}85\sqrt{S}$



Wavefunction density in the X and Z basis.



Entanglement criterion versus time

- This state satisfies a bipartite entanglement criterion, $E_1 < E_2$ [5], around *t = 2π* :

$$E_1 = \mathrm{Var}\left(J_1^x - g_x J_2^x\right) \mathrm{Var}\left(J_1^y - g_y J_2^y\right) \quad E_2 = \frac{\langle J_1^z J_2^z \rangle^4}{4} \left(\frac{1}{\langle (J_2^z)^2 \rangle J_1} + \frac{|g_x g_y|}{\langle (J_1^z)^2 \rangle J_2} \right)^2 \quad g_a = \mathrm{cov}\left(J_1^a, J_2^a\right) / \mathrm{Var}\left(J_2^a\right)$$

[5] I. Frérot, T. Roscilde, in preparation.