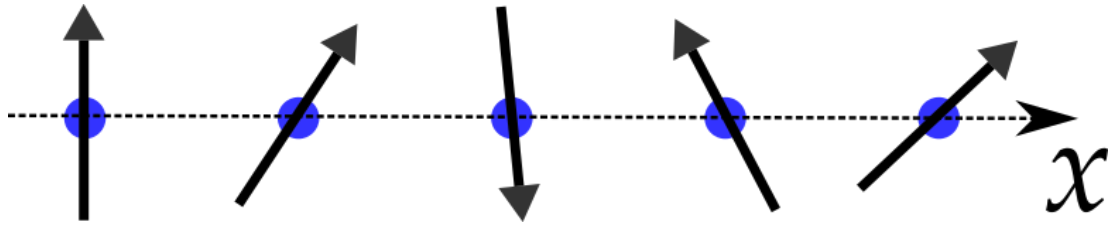
Multi-spin cat state in small arrays of large dipolar spins

Youssef Trifa[1] & Tommaso Roscilde[1]
youssef.trifa@ens-lyon.fr

[1] Laboratoire de Physique de l'ENS de Lyon, CNRS UMR 5672, France

Dipolar Hamiltonian

- XXZ model (Δ= -2) for a 1D Spin chain with dipolar coupling ($J_{ij} = \frac{J_0}{|i-j|^3}$)

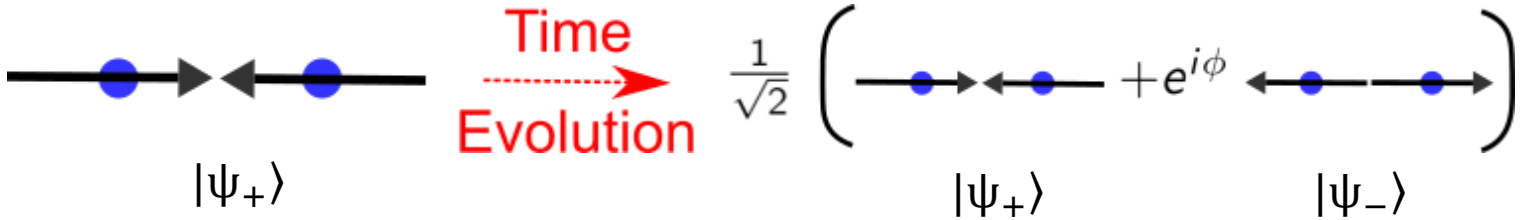


$$\mathcal{H} = -\sum_{i \neq j} \frac{J_{ij}}{2} \left(S_i^x S_j^x + S_i^y S_j^y - 2 S_i^z S_j^z \right) + B_q \sum_i (S_i^z)^2$$

- Quadratic zeeman field (which can be fine tuned using both magnetic fields and lasers [1][2]) coupled to a One Axis Twisting term

- Expected time evolution:

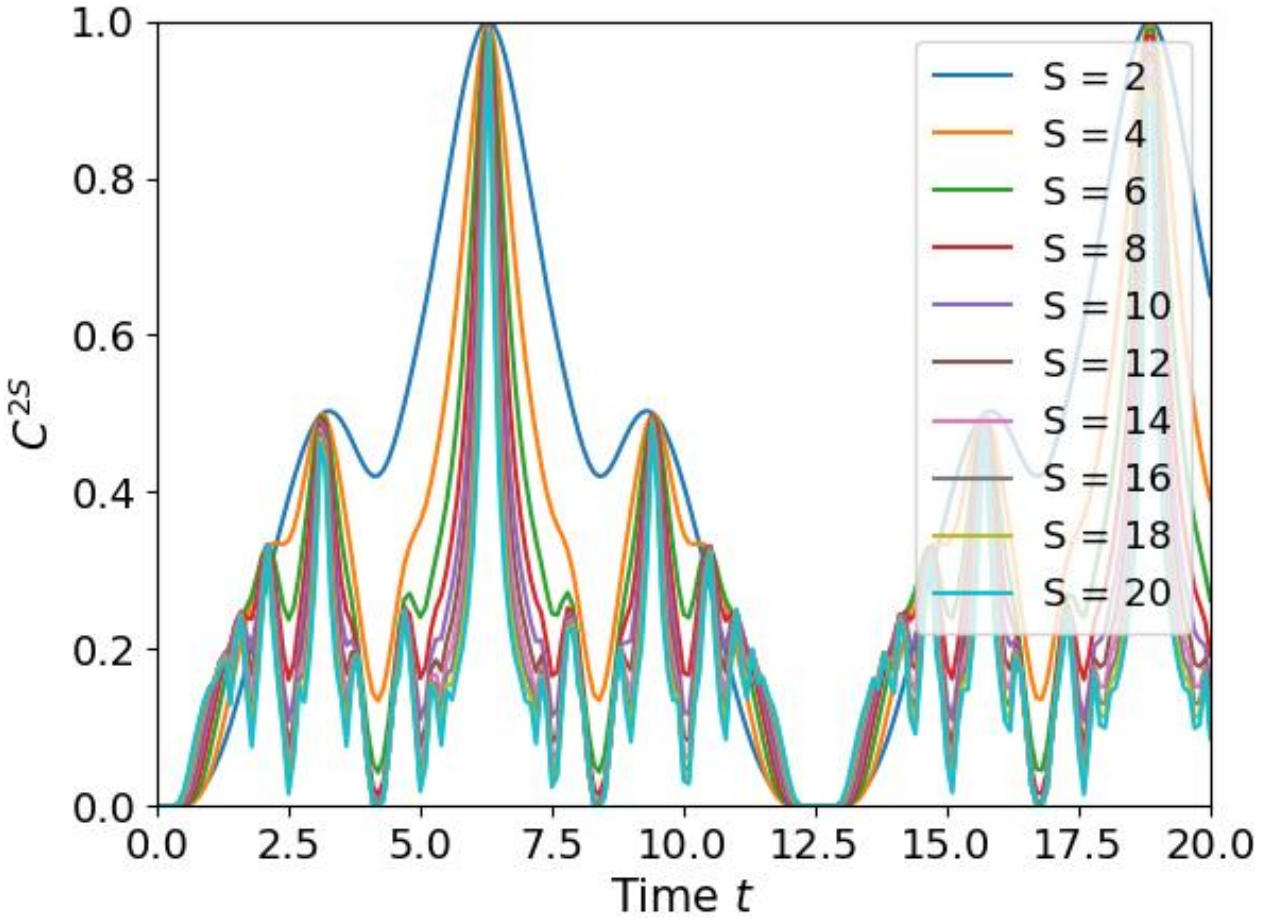
Staggered state along *x*



Cat State

[1] 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)
[2] Chalopin, T., Bouazza, C., Evrard, A. *et al. Nat Commun* **9,** 4955 (2018).

Cat states with 2 spins



- $C^{2S} = 2|\langle\psi(t)|\psi_+\rangle\langle\psi(t)|\psi_-\rangle|$: cat-state correlation function
- Exact result for $B_q = 0.25$:

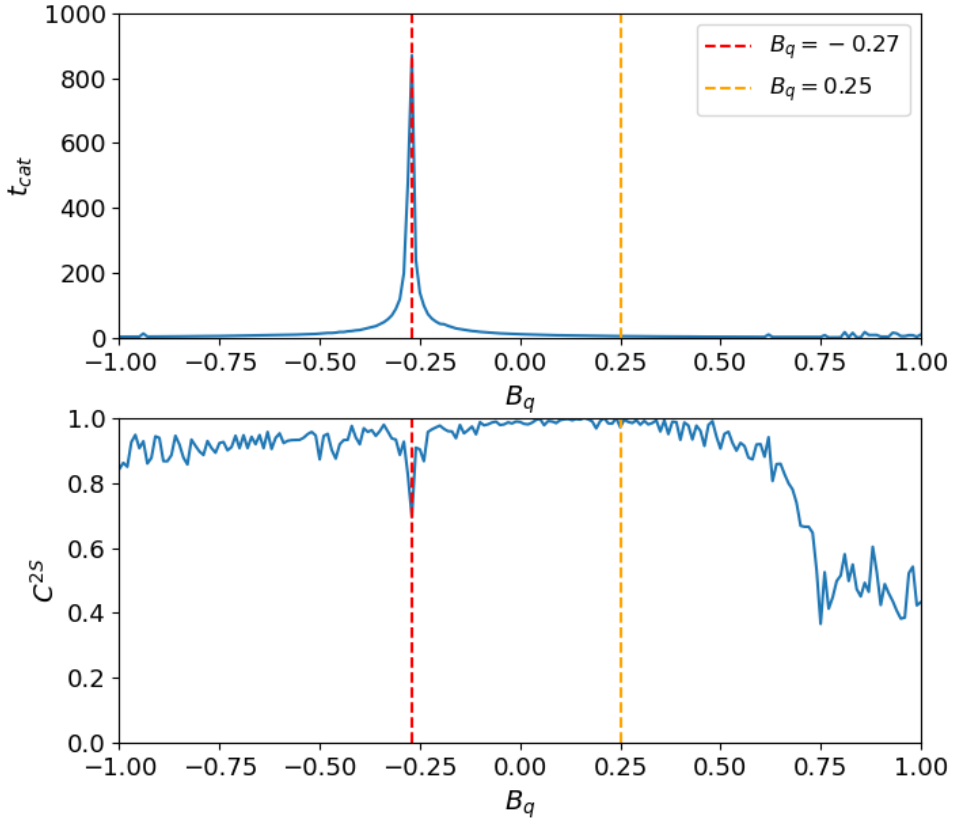
$$\mathcal{H} = \frac{1}{4}J_{stag}^2 - \frac{S(S+1)}{2} + \frac{1}{4}\left(J^z\right)^2$$

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

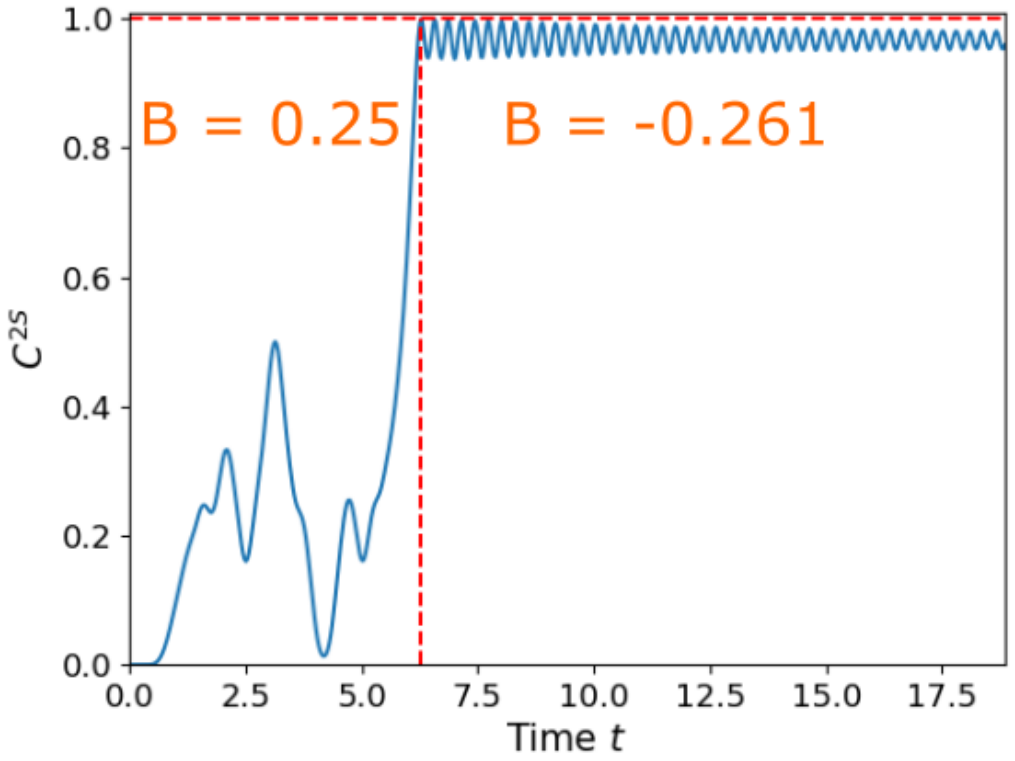
- Cat state at $t = 2\pi$ for any S: possibility to realize a cat state with Cr, Er or Dy atoms [3]
- Even possible with two BECs as two giant spins [4]

[3] Lepoutre, S., Schachenmayer, J., Gabardos, L. *et al. Nat Commun* **10,** 1714 (2019)

[4] 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)



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

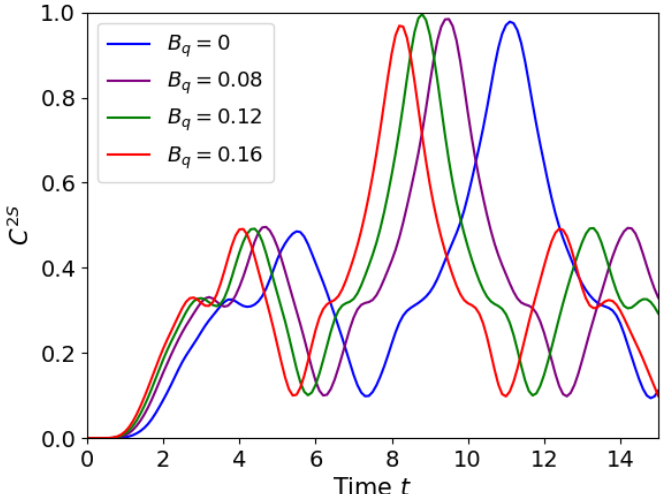


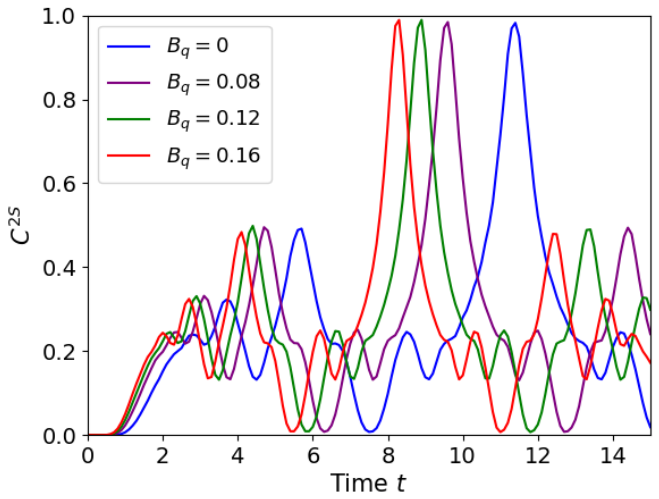
Evolution of C^{2S} in time for 2 spins 8

- Best cat state for $B_q = 0.25$
- Slowest dynamics for $B_q \approx -0.27$
- Robust phenonemon, especially for $B_q < 0$

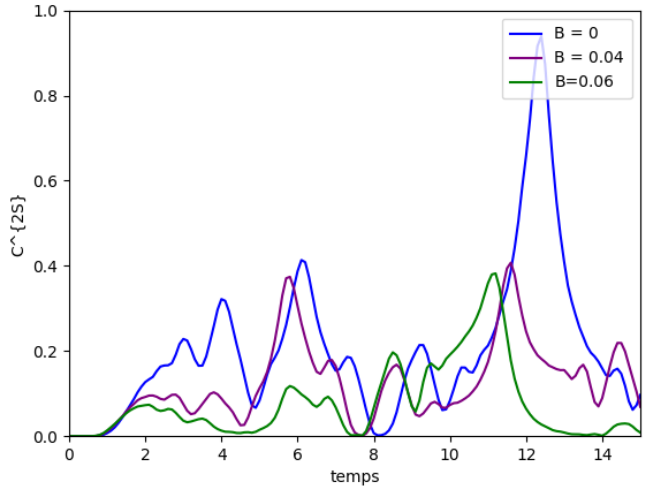
- Use both for a long-lived cat state
- Cat state maximizes the variance of J^x_{stag}
- Maximal sensitivity to an external magnetic field along x

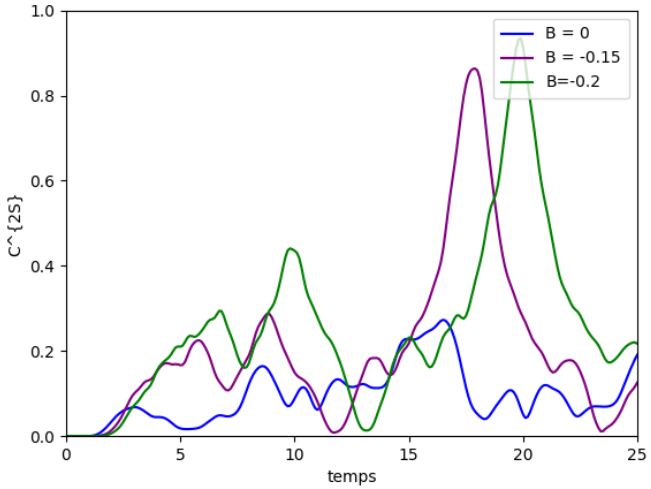
Cat states with 3 or more spins





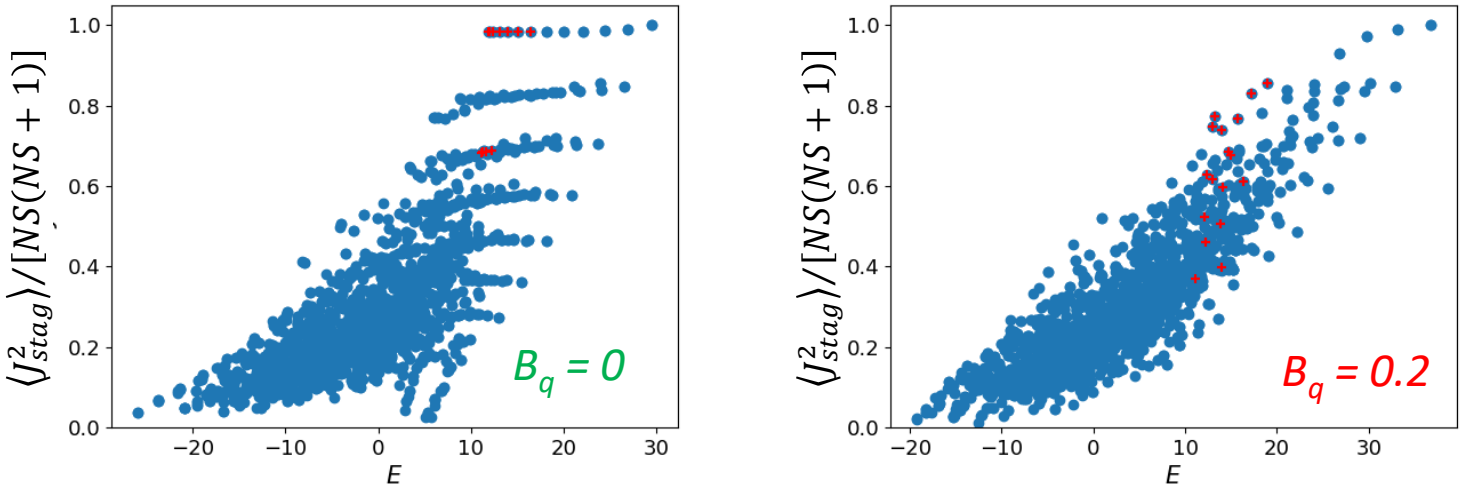
Cat state formation for 3 spins 3 (left) and 6 (right)





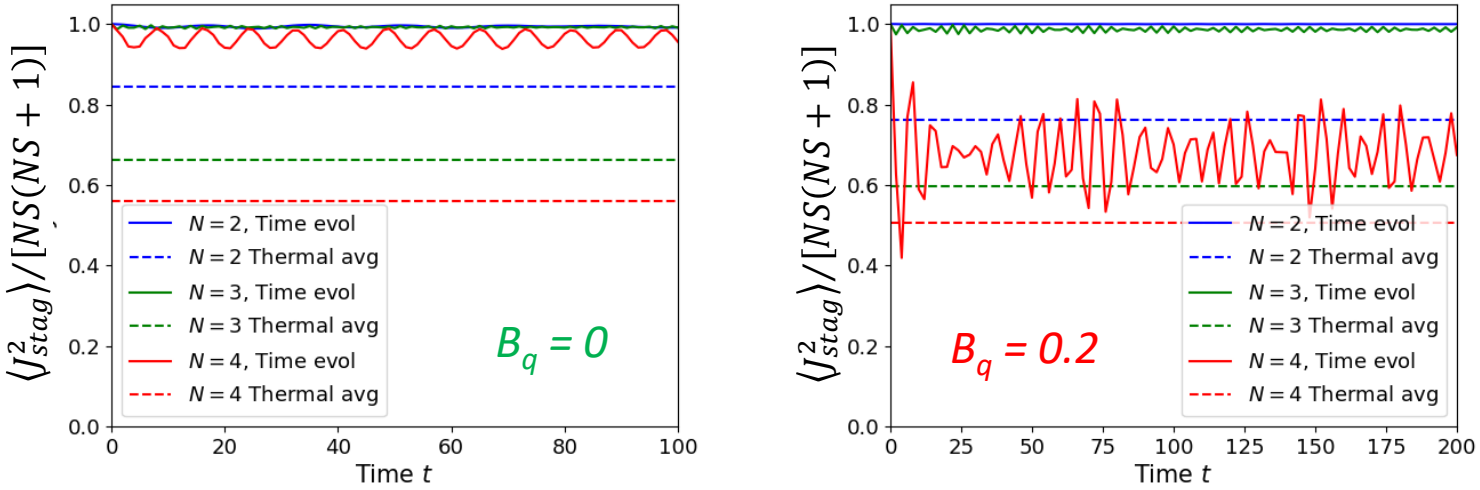
Cat state formation for 4 spins 6 (left) and 5 spin 3 (right)

Hamiltonian spectrum & Quantum Scars



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

- Red dots corresponds to 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



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

- Thermal average obtained with the expected temperature of the initial state
- For $B_q = 0$, $\langle J^2_{stag}\rangle$ almost conserved: dynamics confined in a tiny subspace of the Hilbert Space : Weak Ergodicity Breaking
- For $B_q = 0.2$, explore a much larger number of states: almost No Ergodicity Breaking

Outlook

- Possible to prepare cat states with magnetic atoms as Cr, Er and Dy with already known experimental methods
- Robust phenomenon, with the possibility to tune B_q from -5 to +0.5 (in units of the constant coupling J_0) for 2 spins
- Robustness due to weak ergodicity breaking in the Hamiltonian spectrum, leading to a quasi conservation of J^2_{stag}
- Possible implementation with two giant spins using two condensates, allowing for huge metrologic improvements as cat states sensitivity scales with their size $N \times S$