Non-ergodic Quantum Dynamics in Highly Excited States of a Kinematically Constrained Rydberg Chain

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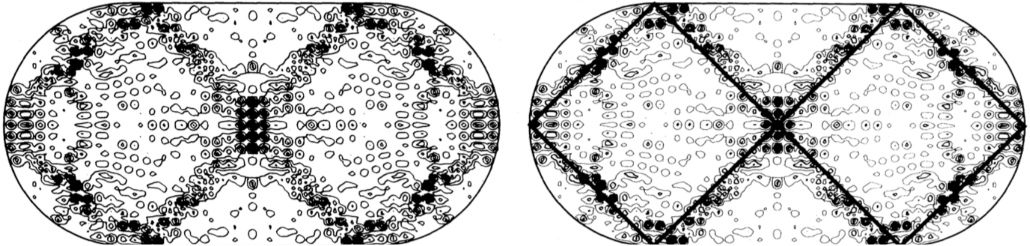
Quantum scars



- Unstable periodic orbits of the classical stadium billiards (right) imprint upon a wavefunction (left) after quantisation[2].
- This is surprising! One might expect unstable classical period orbits to be lost in the transition to quantum mechanics as the particle becomes "blurred".
- Not all chaotic systems were created equivalent[3]. Think eigenstate thermalisation for all vs. *almost* all eigenstates.

[2] Heller 1984.
[3] Hassell 2010.

ARTICLE

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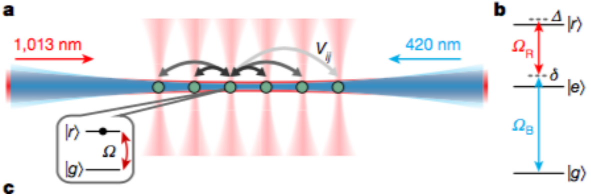
Probing many-body dynamics on a 51-atom quantum simulator

Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

This experiment[4] reports on a Rydberg chain with individual control over interactions. The Hamiltonian is

$$H = \sum_j \left(\frac{\Omega_j}{2} X_j - \Delta_j n_j \right) + \sum V_{ij} n_i n_j \qquad (1)$$

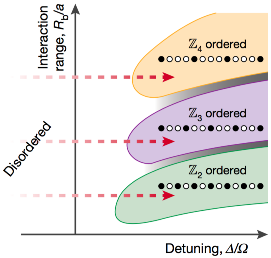
where couplings Ω is the Rabi frequency, Δ is a laser detuning and $V_{i,j} \sim C/r_{i,j}^6$ are replusive van der Waals interactions.

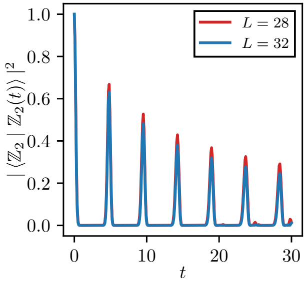


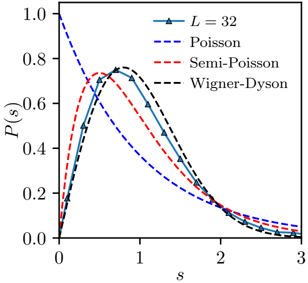
[4]See also another recent experiment Zhang et al. 2017 claiming 53 qubits

Quantum revivals

- For homogeneous couplings and in the limit $V_{j,j+1} \gg \Omega \gg \Delta$ periodic quantum revivals were observed.
- This is especially surprising considering that the system is non-integrable as evidenced by the level statistics.





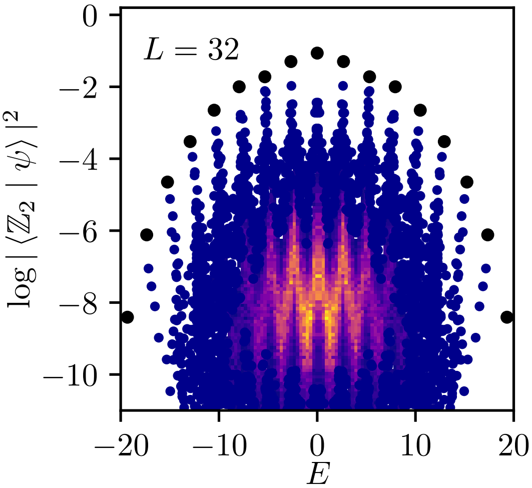


$$H = \sum_j P_j X_j P_j$$

(effective model of Fibonacci anyons Lesanovsky et al. 2012)

$$P = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

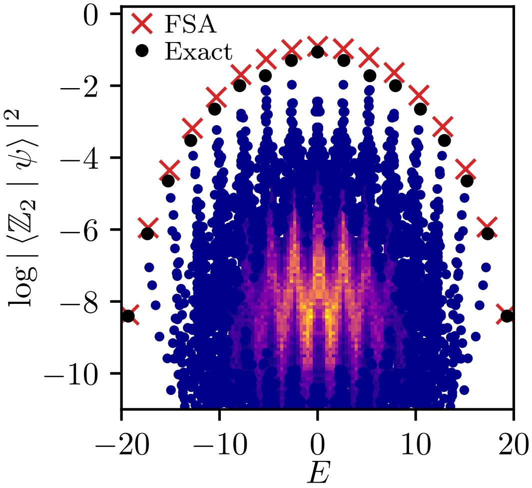
From dynamics to eigenvalues



- A band of special states which account for most of the Néel state.
- These have approximately equally spaced eigenvalues, and converging with system size.
- Explains the oscillatory dynamics.

Goal: Find or otherwise explain these special states.

Forward-scattering approximation

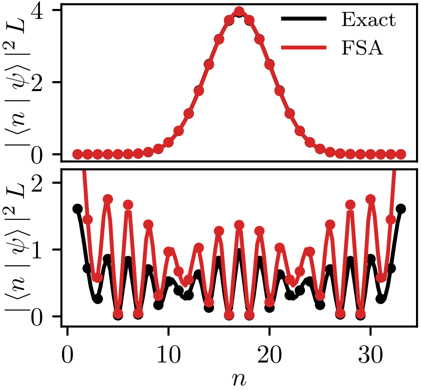


- We have developed a polynomial (in L) algorithm to approximate these most important states.
- Successfully identifies the important states for explaining the oscillations.
- For $L = 32$ the eigenvalue error $\Delta E/E \approx 1\%$.
- Error in each step decreases with increasing L.

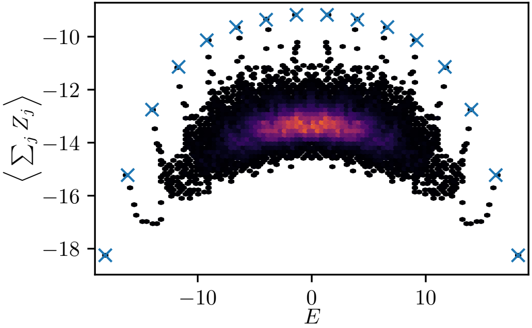
Quantum many-body scars

But what's *scarring* got to do with it?

- The forward-scattering quasi-modes imprint upon the eigenstates forming a *many-body quantum scar*.



- Matrix elements of local observables in the energy basis are not smooth w.r.t. energy. Eigenstate thermalisation is violated.



Conclusions

To recap:-

- Non-integrable many-body system which displays periodic quantum revivals despite being ergodic.
- Approximate eigenvalues and eigenstate (quasi-modes) can be found which explain this effect.
- Further these quasi-modes scar the exact eigenstates signalling a failure of a strong eigenstate thermalisation hypothesis, i.e. *almost all* but not all the eigenstates are homogeneous, even in the middle of the band.

Also of interest:-

- Number of zero energy states that grows with the Fibonacci numbers. Can be used for storing quantum information. (See also Schecter et al. arXiv:1801.03101)
- Many-body localisation (Chen et al. arXiv:1709.04067)