Eigenstate Thermalization, random matrices and Behemoths

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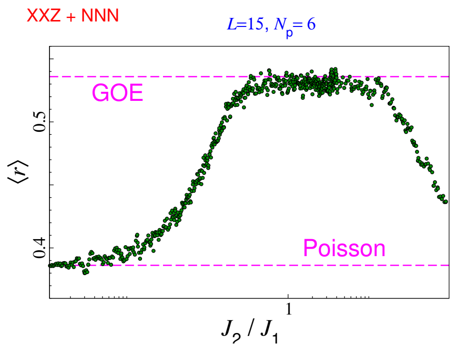
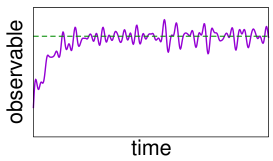
Eigenstate thermalization scaling

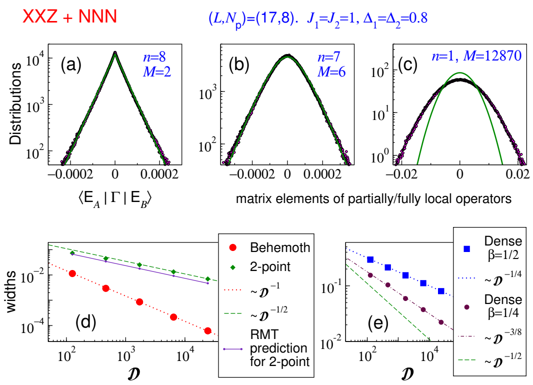
Many-body Hamiltonians are random matrices (?!?)

Eigenstate thermalization hypothesis (which observables?)

E.T.H. Scaling — local, less local & Behemoth operators







References

Beugeling, Moessner, Haque, P.R.E (2014)
Finite-size scaling of eigenstate thermalization

Beugeling, Andreanov, Haque, JSTAT (2015)
Entanglement & participation ratios, all eigenstates

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Off-diagonal matrix elements

Beugeling, Bäcker, Moessner, Haque, P.R.E (2018)
Eigenstate amplitudes (coefficients)

Haque and McClarty, P.R.B (2019)
ETH in Sachdev-Ye-Kitaev models

Khaymovich, Haque, McClarty, P.R.L. (2019)
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Bäcker, Haque, Khaymovich, P.R.E (2019)
Multifractal dimensions

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Entanglement in mid-spectrum states

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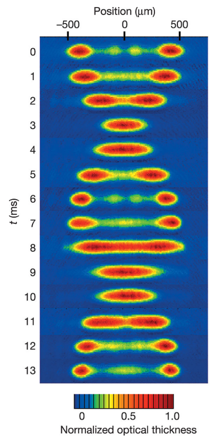
Context

Non-equilibrium dynamics of isolated quantum systems

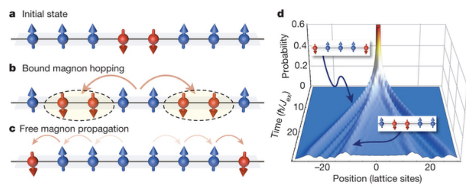
Increasing # of experiments in the limit of "isolation":

time of measurement	$<<$	time scale of environment effects

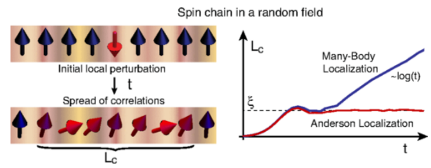
- Ultracold trapped atoms/ions
- NMR quantum computing
- Ultrafast pump-probe spectroscopy



Weiss group, Nature 2006



Bloch group, Nature Phys 2013



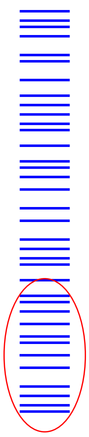
Wei, Ramanathan, Cappellaro, PRL 2018

The Many-Body Eigenspectrum

Standard many-body quantum physics

⇓

low-lying parts of the many-body spectrum.

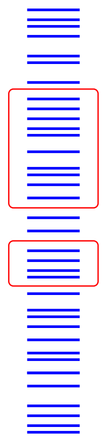


Dynamics in isolation

⇓

No tendency toward ground state

Any part of spectrum can be important!



Motivates study of eigenstates in the middle of the many-body spectrum.

Mid-spectrum eigenstates are (often) somewhat ‘random’

Random matrices

Relevant classes:

GOE and GUE

GOE

Symmetric matrix

Real elements

Elements random & gaussian-distributed

GUE

Hermitian matrix

Complex elements

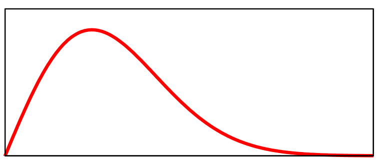
Real & imaginary parts are random and gaussian-distributed

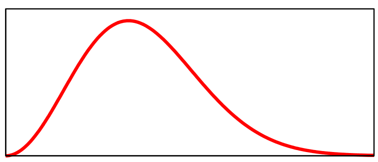
Properties

Eigenstates: coefficients are gaussian-distributed

Eigenvalues: level spacings ($s_i = E_{i+1} - E_i$) have Wigner-Dyson statistics

$$P_{\text{GOE}}(s) \propto s e^{-\alpha_1 s^2} \qquad P_{\text{GUE}}(s) \propto s^2 e^{-\alpha_2 s^2}$$





Eigenvalues display level repulsion: $P(0) = 0$

Many-Body Hamiltonians...

This talk: $\longrightarrow$ lattice systems, finite Hilbert space

Eigenspectrum has a bottom and a top

Typically N_p particles in L sites

Particles $\longrightarrow$ fermions, bosons, or up-spins

Thermodynamic limit: $L \to \infty$, $N_p \to \infty$, constant N_p/L

Many-Body Hamiltonians: random-matrix behavior?

Typical many-body Hamiltonian, with few-body, local interactions:

Hamiltonian matrix is sparse

Elements are not random

Many-Body Hamiltonians: random-matrix behavior?

Typical many-body Hamiltonian, with few-body, local interactions:

Hamiltonian matrix is sparse

Elements are not random

Example:

$$\begin{pmatrix}
0.4 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 \\
0.5 & -0.4 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 \\
0 & 0.5 & 0.4 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.5 & 0 & -0.4 & 0.5 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 \\
0 & 0 & 0.5 & 0.5 & -0.4 & 0.5 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.5 & 0.4 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.5 & 0 & 0 & -0.4 & 0.5 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0.5 \\
0 & 0 & 0 & 0 & 0.5 & 0 & 0.5 & -0.4 & 0.5 & 0 & 0 & 0.5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0.5 & -0.4 & 0.5 & 0 & 0 & 0.5 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.4 & 0 & 0 & 0 & 0.5 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0.4 & 0.5 & 0 & 0 & 0 \\
0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & -0.4 & 0.5 & 0 & 0 \\
0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & -0.4 & 0.5 & 0 \\
0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & -0.4 & 0.5 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.4
\end{pmatrix}$$

XXZ chain,
$\Delta = 0.8$ ($L = 6$ sites, $N_p = 2$ $\uparrow$-spins)

Many-Body Hamiltonians: random-matrix behavior?

Typical many-body Hamiltonian, with few-body, local interactions:

Hamiltonian matrix is sparse

Elements are not random

Nevertheless

Eigenstate coefficients:

usually Gaussian-distributed

Energy eigenvalues:

usually Wigner-Dyson statistics

Exceptions:

- integrable systems
- very large interactions
- spectral edges

Coefficients of many-body eigenstates

$$|\mathsf{E}_A\rangle = \sum_{\boldsymbol{n}} c_{\boldsymbol{n}} \, |\boldsymbol{n}\rangle$$

$|\boldsymbol{n}\rangle$'s $\longrightarrow$ many-body configurations

$$H \;=\; J_1 \sum_{i=1}^{L-1} \left(S_i^+ S_{i+1}^- + S_i^- S_{i+1}^+ + \Delta_1 S_i^z S_{i+1}^z \right) \;+\; J_2 \sum_{i=2}^{L-2} \left(S_i^+ S_{i+2}^- + S_i^- S_{i+2}^+ + \Delta_2 S_i^z S_{i+2}^z \right)$$

$J_2 = 0 \longrightarrow$ integrable XXZ chain

$J_2 \approx J_1 \longrightarrow$ non-integrable
('chaotic' or 'ergodic')

$|\boldsymbol{n}\rangle$'s $\longrightarrow$

$|\downarrow\downarrow\downarrow\downarrow\uparrow\uparrow\uparrow\uparrow\rangle$

$|\downarrow\downarrow\downarrow\uparrow\downarrow\uparrow\uparrow\uparrow\rangle$

$|\downarrow\downarrow\downarrow\uparrow\uparrow\downarrow\uparrow\uparrow\rangle$

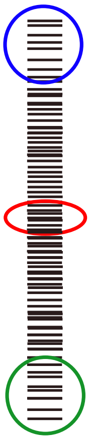
$\vdots$

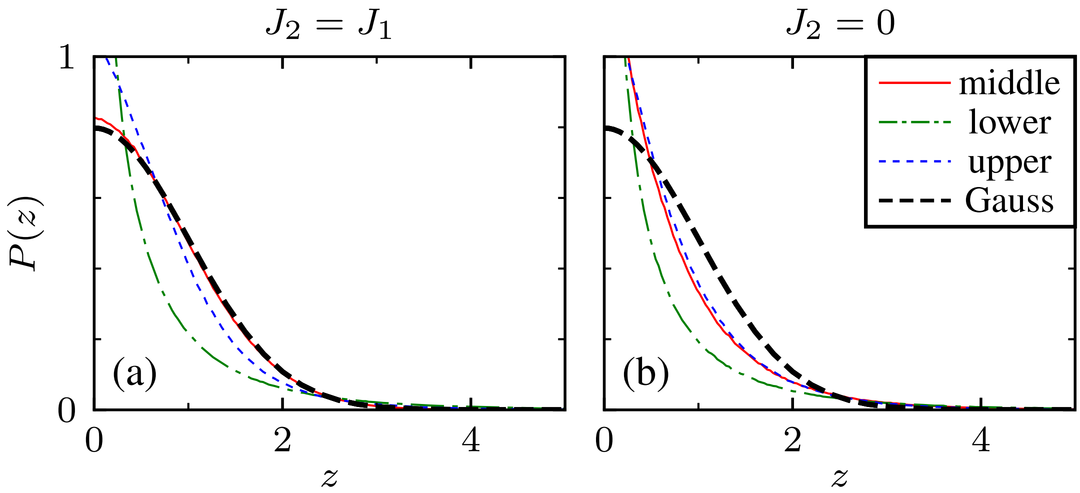
Coefficients of many-body eigenstates

$|\mathsf{E}_A\rangle = \sum_{n} c_n |n\rangle$ $\qquad z = c_n\sqrt{\mathcal{D}},$ $\qquad \mathcal{D} =$ Hilbert space dimension

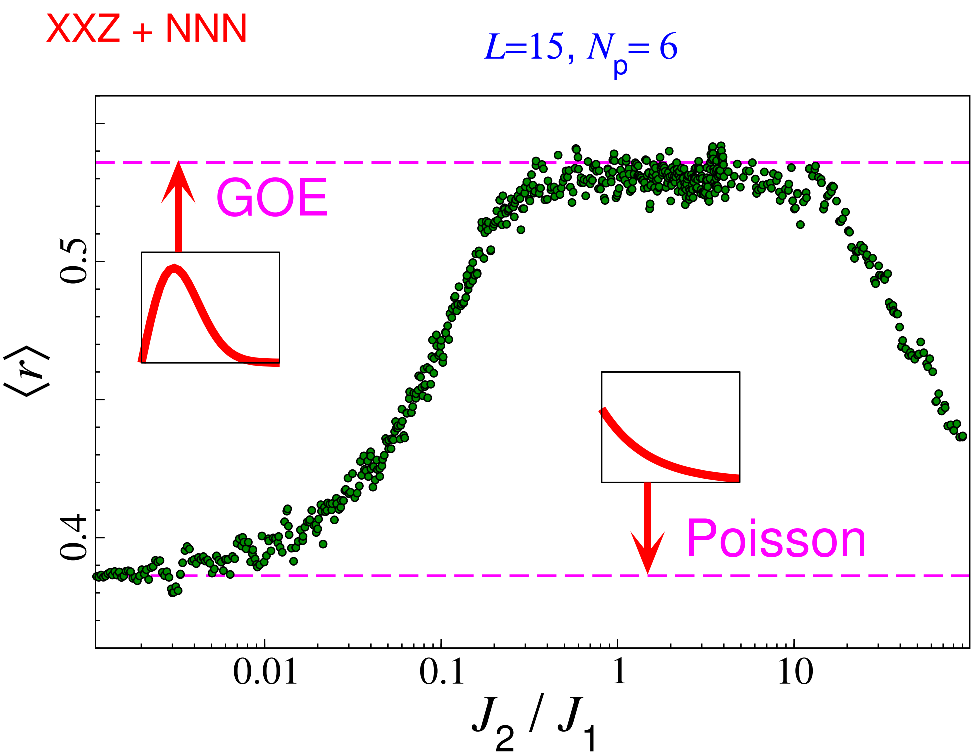
Beugeling, Moessner, Bäcker, Haque, P.R.E (2018)

NON-INTEGRABLE $\qquad$ INTEGRABLE





Level statistics of many-body spectra



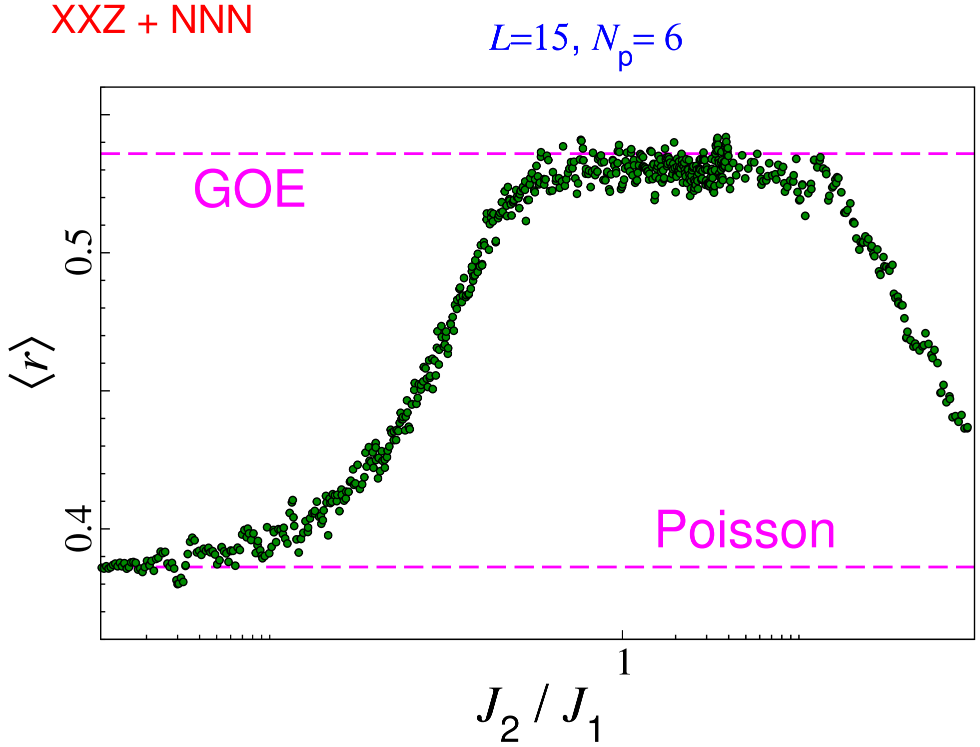
$\langle r \rangle$ distinguishes GOE, GUE, Poisson

$$r_i = \min\left(\frac{s_{i+1}}{s_i}, \frac{s_i}{s_{i+1}}\right)$$

Integrable systems usually have Poisson statistics

Level statistics of many-body spectra

XXZ + NNN



$\langle r \rangle$ distinguishes GOE, GUE, Poisson

$$r_i = \min\left(\frac{s_{i+1}}{s_i}, \frac{s_i}{s_{i+1}}\right)$$

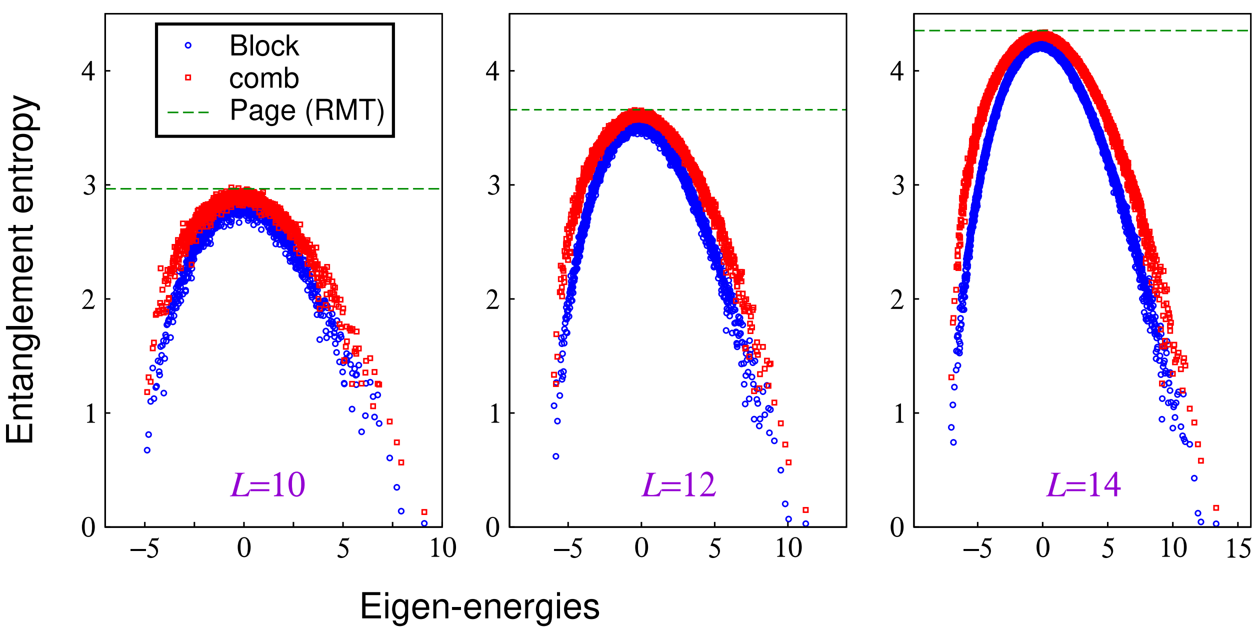
Integrable systems usually have Poisson statistics

Entanglement entropy of many-body eigenstates

XYZ + NNN

(both: $\eta = 0.5$, $\Delta = 0.9$)
+ h_x-field (0.8) + h_z-field (0.2)

Haque, McClarty, Khaymovich, arXiv:2008



Only the middle of the spectrum?

Only the middle of the spectrum?

Introduce temperature: $\Big($pretend: system is described by canonical $e^{-\beta H}\Big)$

$$E_{\text{TOTAL}} = \frac{\mathrm{tr}\left(e^{-\beta H} H\right)}{\mathrm{tr}\left(e^{-\beta H}\right)} = \frac{1}{Z(\beta)} \sum_A e^{-\beta E_A} E_A$$

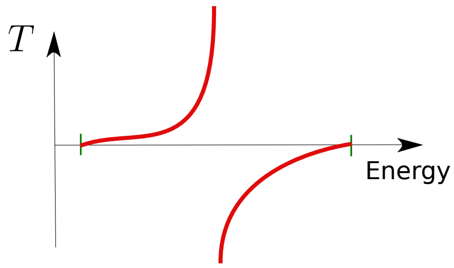
with $$Z(\beta) = \mathrm{tr}\left(e^{-\beta H}\right) = \sum_A e^{-\beta E_A}$$

$|E_A\rangle$, $E_A \rightarrow$ eigenstates, eigenenergies

$\longrightarrow$ provides a temperature $\leftrightarrow$ energy map, also for a finite system!

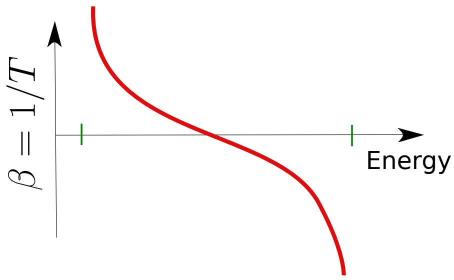
Based on eigenvalues alone.

NOT JUST THE MIDDLE OF THE SPECTRUM



mid-spectrum eigenstates $\equiv$ infinite-temperature states

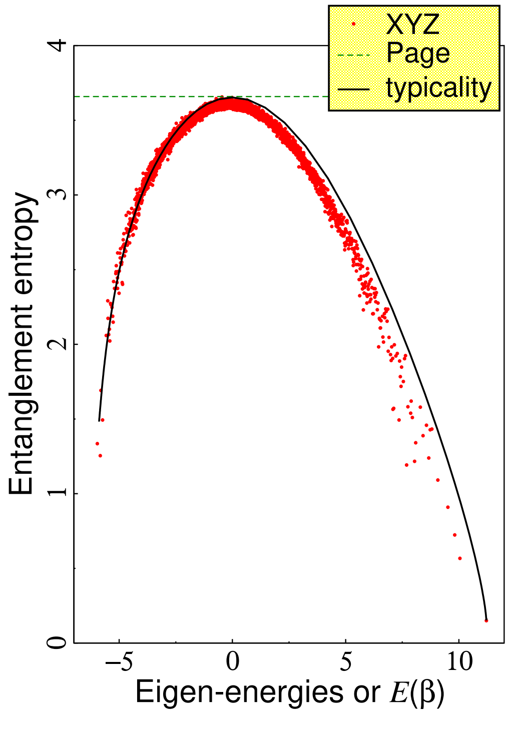
Negative temperatures!



Mid-spectrum eigenstates
$\longrightarrow$ well-described by $|\psi_{\text{rand}}\rangle$

Finite-temperature eigenstates
$\longrightarrow$ well-described by $\exp\left[-\frac{\beta}{2}H\right]|\psi_{\text{rand}}\rangle$

Not just the middle of the spectrum



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$\longrightarrow$ well-described by $|\psi_{\text{rand}}\rangle$

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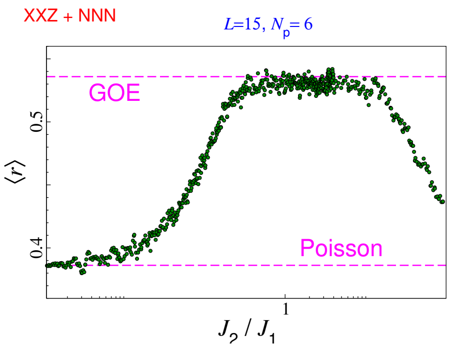
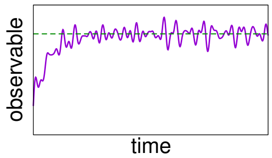
Eigenstate thermalization scaling

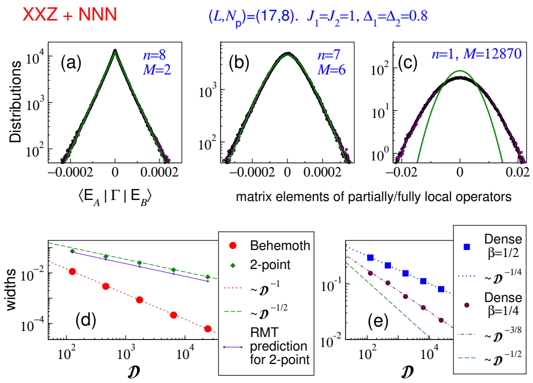
Many-body Hamiltonians are random matrices (?!?)

Eigenstate thermalization hypothesis (which observables?)

E.T.H. Scaling — local, less local & Behemoth operators





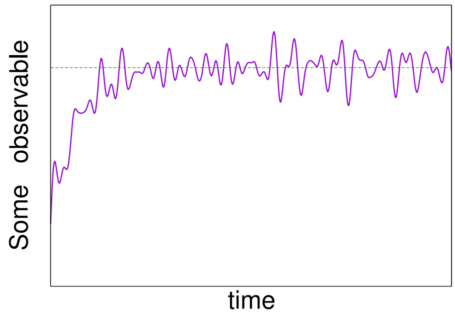


Thermalization in isolated systems

Generic (non-integrable) isolated system

driven out of equilibrium

$\Longrightarrow$ many observables thermalize



An observable thermalizes

$\Longrightarrow$ relaxes to value dictated by thermal ensemble

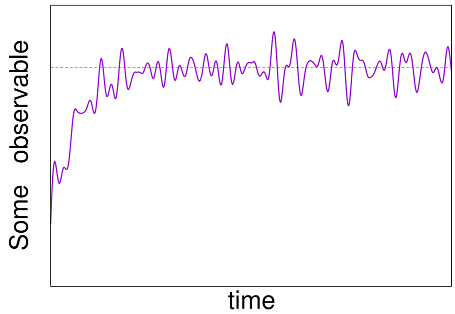
Thermalization in isolated systems

An observable thermalizes

$\Longrightarrow$ relaxes to value dictated by thermal ensemble

If initial state is $|\psi(0)\rangle = \sum_A c_A |\mathsf{E}_A\rangle$, relaxes to

$$\langle O(t)\rangle \;=\; \langle\psi(t)|\,\hat{O}\,|\psi(t)\rangle \;\xrightarrow{t\to\infty,\ \langle\cdot\rangle}\; \sum_A |c_A|^2 \langle \mathsf{E}_A|\,\hat{O}\,|\mathsf{E}_A\rangle$$



$|\mathsf{E}_A\rangle$, $E_A \rightarrow$ eigenstates, eigenenergies

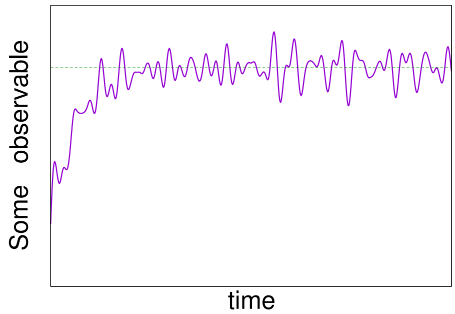
Thermalization in isolated systems

An observable thermalizes

$\Longrightarrow$ relaxes to value dictated by thermal ensemble

$$\langle O\rangle_{\text{therm}} = \frac{1}{Z(\beta)}\sum_A e^{-\beta E_A}\langle \mathsf{E}_A|\,\hat{O}\,|\mathsf{E}_A\rangle$$

β defined by energy: $$E_{\text{TOTAL}} = \frac{1}{Z(\beta)}\sum_A e^{-\beta E_A} E_A$$



$|\mathsf{E}_A\rangle$, $E_A \rightarrow$ eigenstates, eigenenergies

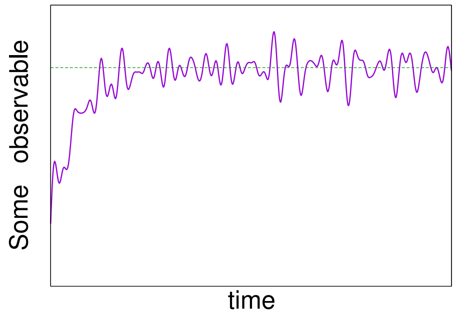
Thermalization in isolated systems

An observable thermalizes

$\Longrightarrow$ relaxes to value dictated by thermal ensemble

$$\sum_A |c_A|^2 \langle \mathsf{E}_A | \widehat{O} | \mathsf{E}_A \rangle \;=\; \frac{1}{Z(\beta)} \sum_A e^{-\beta E_A} \langle \mathsf{E}_A | \widehat{O} | \mathsf{E}_A \rangle$$

Crucial: Eigenstate expectation values $\langle \mathsf{E}_A | \widehat{O} | \mathsf{E}_A \rangle$



$|\mathsf{E}_A\rangle$, E_A $\rightarrow$ eigenstates, eigenenergies

THERMALIZATION IN ISOLATED SYSTEMS

Mechanism for thermalization: Eigenstate Thermalization Hypothesis

$\langle E_A | \hat{O} | E_A \rangle$'s are smooth functions of E_A

$\longrightarrow$ 'implies' thermalization

Deutsch, P.R.A (1991); Srednicki, P.R.E (1994)

Rigol, Dunjko, Olshanii, Nature (2008)

.... + many others

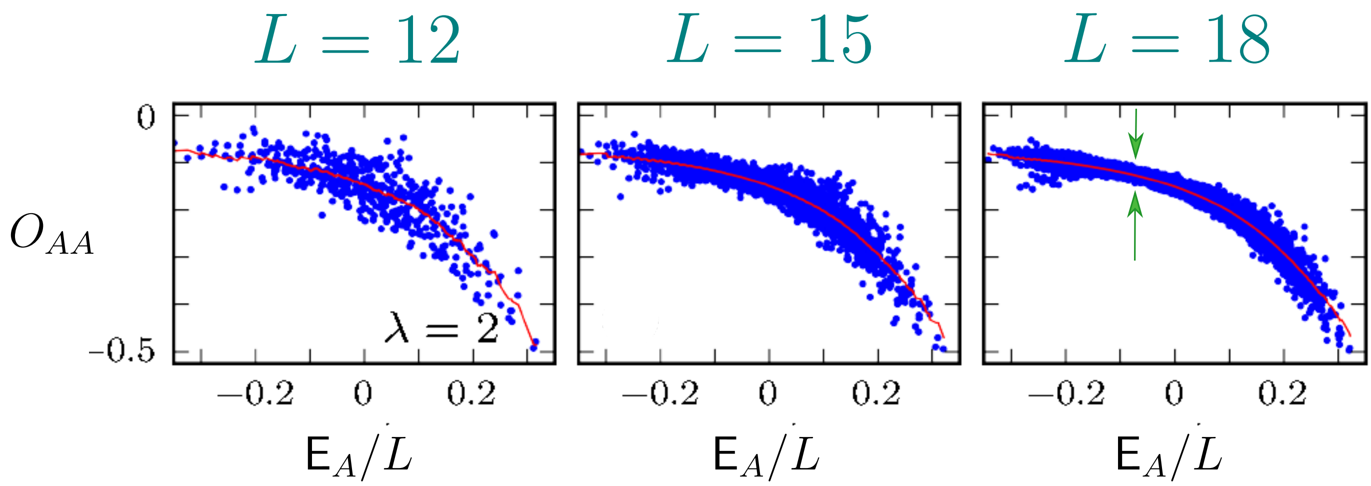
Beugeling, Moessner, Haque, P.R.E (2014)

Finite-Size Scaling of ETH

E.T.H. Scaling

$$H = H_{XXZ} + \lambda \sum_i (i - i_0)^2 S^z_j$$

$$O_{AA} = \langle \mathsf{E}_A | \hat{O} | \mathsf{E}_A \rangle = \langle \mathsf{E}_A | S^z_{\text{middle}} | \mathsf{E}_A \rangle$$



Scaling of E.T.H. fluctuations: $\sigma \sim \mathcal{D}^{-1/2} \sim e^{-\alpha L}$

$\mathcal{D} =$ dimension of Hilbert space

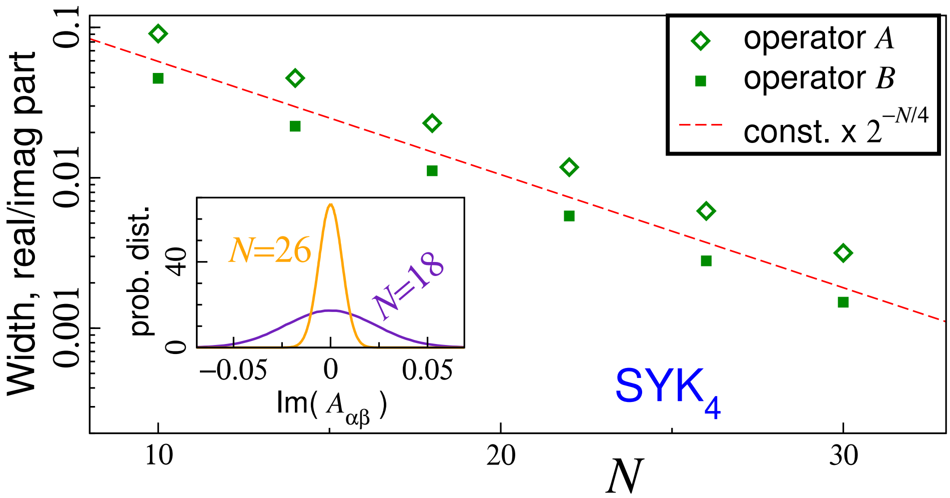
Beugeling, Moessner, Haque, P.R.E (2014)

E.T.H. Scaling: Off-diagonal matrix elements

$O_{AB} = \langle \mathsf{E}_A | \hat{O} | \mathsf{E}_B \rangle$

Sachdev-Ye-Kitaev model

(N Majorana fermions)



Haque & McClarty
P.R.B (2019)

$\sigma \sim \mathcal{D}^{-1/2} \sim 2^{-N/4}$

A standard statement of E.T.H.

Srednicki, 1999

$$\langle \mathsf{E}_A |\, \hat{O}\, | \mathsf{E}_B \rangle \;=\; \delta_{AB}\, f^{(1)}(\bar{\mathsf{E}}) \;+\; e^{-S(\bar{\mathsf{E}})/2}\, f^{(2)}(\bar{\mathsf{E}}, \omega)\, R_{AB}$$

$$\bar{\mathsf{E}} = (1/2)(\mathsf{E}_A + \mathsf{E}_B)$$

$$\omega = \mathsf{E}_B - \mathsf{E}_A$$

$R_{AB} \longrightarrow$ a gaussian random variable; $f^{(1,2)} \longrightarrow$ smooth functions.

$S \sim \log \mathcal{D}$ is the entropy $\Longrightarrow$ Distribution width $\sim \mathcal{D}^{-1/2}$

Local operators $\longrightarrow$

diagonal matrix elements, off-diagonal matrix elements

both distributions have width $\sim \mathcal{D}^{-1/2}$

$\mathcal{D} \equiv$ Hilbert space dimension

WHICH OPERATORS OBEY $\sim \mathcal{D}^{-1/2}$ SCALING?

Khaymovich, Haque, McClarty, P.R.L. (2019)

Eigenstate Thermalization,
Random Matrix Theory
and Behemoths

EIGENSTATE THERMALIZATION SCALING

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Eigenstate thermalization hypothesis (which observables?)

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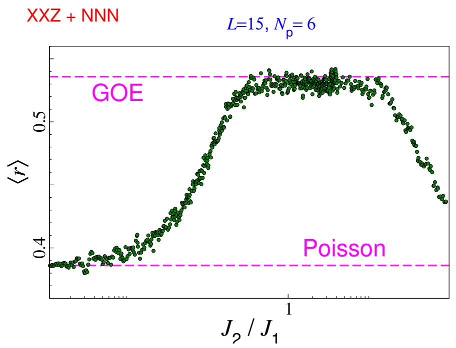
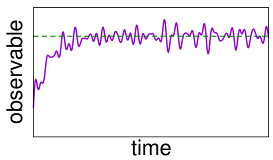
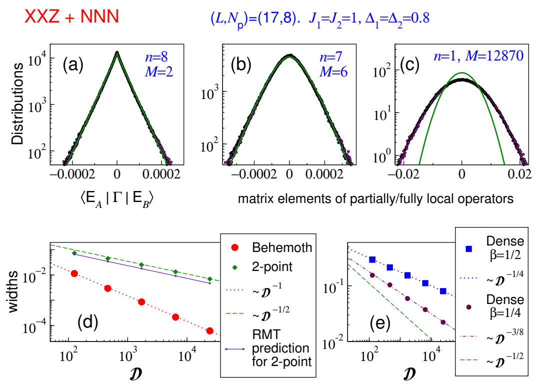






Operators in RMT and many-body physics

Could interpret random matrix as:

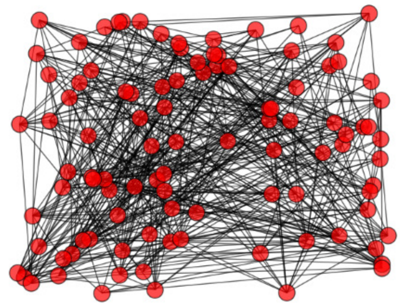
Hamiltonian of a single particle

on a fully-connected graph

with random hoppings

$$H = \sum_{ij} h_{ij}\, \hat{d}_i^\dagger \hat{d}_j$$

$$\begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} & \dots & h_{1N} \\ h_{21} & h_{22} & h_{23} & h_{24} & \dots & h_{2N} \\ h_{31} & h_{32} & h_{33} & h_{34} & \dots & h_{3N} \\ h_{41} & h_{42} & h_{43} & h_{44} & \dots & h_{4N} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ h_{N1} & h_{N2} & h_{N3} & h_{N4} & \dots & h_{NN} \end{pmatrix}$$



OPERATORS IN RMT AND MANY-BODY PHYSICS

Hamiltonian of a single particle on a fully-connected graph

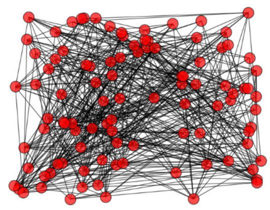
Not many interesting observables, except:

$$\widehat{\omega}_{ij} \equiv \widehat{d}_i^\dagger \widehat{d}_j = |i\rangle\langle j|$$

Node-node correlation function

For $i = j$: node occupancy

$$\begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} & \cdots & h_{1N} \\ h_{21} & h_{22} & h_{23} & h_{24} & \cdots & h_{2N} \\ h_{31} & h_{32} & h_{33} & h_{34} & \cdots & h_{3N} \\ h_{41} & h_{42} & h_{43} & h_{44} & \cdots & h_{4N} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ h_{N1} & h_{N2} & h_{N3} & h_{N4} & \cdots & h_{NN} \end{pmatrix}$$



$$H = \sum_{ij} h_{ij}\, \widehat{d}_i^\dagger \widehat{d}_j$$

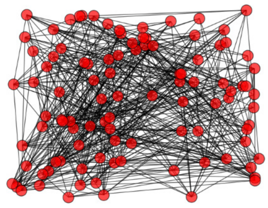
Operators in RMT and many-body physics

$$\widehat{\omega}_{ij} \equiv \widehat{d}_i^\dagger \widehat{d}_j = |i\rangle\langle j|$$

As a matrix? $\widehat{\omega}_{ij}$ has a single nonzero element.

Hermitian version: $\widehat{\gamma}_{ij} = \widehat{\omega}_{ij} + \widehat{\omega}_{ji}$

$\longrightarrow$ Matrix with two nonzero elements.



$$\begin{pmatrix} 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 0 \end{pmatrix}$$

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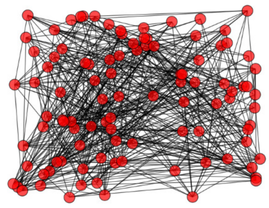


Many-body analogy $\longrightarrow$

a node i $\equiv$ a many-body configuration $|\mathbf{n}\rangle$

Changes one many-body configuration to another.

$$\widehat{\Omega}_{nn'} \equiv |\boldsymbol{n}\rangle\langle \boldsymbol{n}'|$$

Highly nonlocal

Behemoth operators

Operators in RMT and many-body physics

$$\hat{\Omega}_{nn'} \equiv |\boldsymbol{n}\rangle\langle\boldsymbol{n'}|$$

$\hat{\Omega}$ in configuration space $\longrightarrow$

$$\begin{pmatrix} 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 0 \end{pmatrix}$$

Behemoths form a basis for operators.

$\Downarrow$

Any operator is a sum of Behemoths.

(e.g. local observables, 2-point correlators)

From nonlocal to local operators

(Using spinless-fermion language)

Series of operators

$$\widehat{\Omega}_M \equiv \prod_{k=1}^{n} \widehat{c}^{\dagger}_{i_k} \widehat{c}_{j_k} = \sum_{\alpha=1}^{M} \widehat{\Omega}^{(\alpha)}_{\boldsymbol{n}\boldsymbol{n}'}$$

A $(2n)$-point correlator.

M nonzero terms in operator matrix.

Behemoth: $\widehat{c}^{\dagger}_{i_1} \widehat{c}^{\dagger}_{i_1} \ldots \widehat{c}^{\dagger}_{i_{N_\mathsf{p}}} \widehat{c}_{j_1} \widehat{c}_{j_2} \ldots \widehat{c}_{j_{N_\mathsf{p}}}$

$n = N_\mathsf{p}$, $M = 1$ or 2

2-point correlator: $\widehat{c}^{\dagger}_{i_1} \widehat{c}_{j_1}$

$n = 1$, $M = \binom{L-2n}{N_\mathsf{p}-n} \sim O(\mathcal{D})$

Can generalize $\longrightarrow$ spins, bosons, Hubbard, N_p-non-conserving systems, allow overlap between $\boldsymbol{n}$, $\boldsymbol{n}'$ configurations....

Many types of operators covered in this framework.

Width of distributions: scaling with $\mathcal{D}$

Behemoth distribution $\sim K_0(\mathcal{D}x) \longrightarrow$ Width scales as $\sim \mathcal{D}^{-1} \longrightarrow$ super-ETH scaling

Local operators are sums of $M \sim O(\mathcal{D})$ Behemoths.

Using central limit theorem, width $\sim \sqrt{M}\mathcal{D}^{-1} \sim \mathcal{D}^{-1/2} \longrightarrow$ ETH scaling

A 'typical' operator is dense, $M > O(\mathcal{D})$

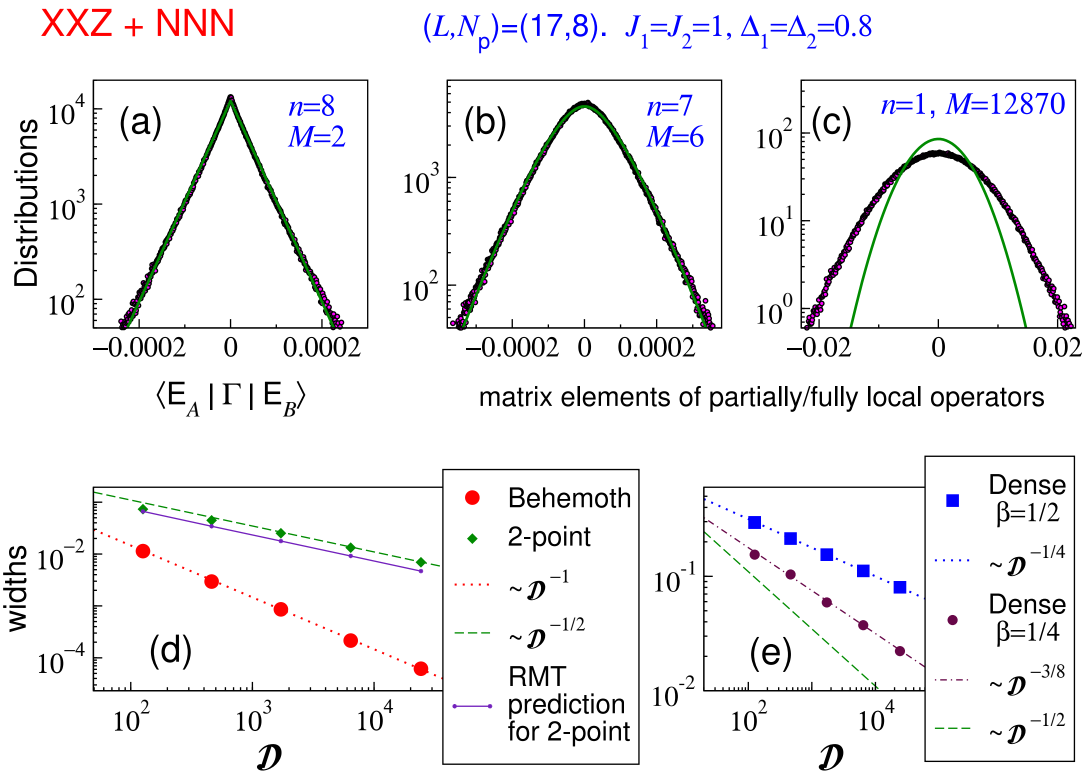
If $M \sim O\left(\mathcal{D}^{1+\beta}\right)$, width (using CLT) $\sim \mathcal{D}^{-1/2+\beta/2} \longrightarrow$ sub-ETH scaling

If $M \sim O\left(\mathcal{D}^{2}\right)$, width $\sim \mathcal{D}^{0}$

ETH works because
physical operators are sparse.

$\mathcal{D}^{-1/2}$ scaling works because
local operators have $M \sim O(\mathcal{D})$

NON-LOCAL TO LOCAL TO TYPICAL



Eigenstate thermalization scaling

Many-body Hamiltonians are random matrices (?!?)

Eigenstate thermalization hypothesis (which observables?)

E.T.H. Scaling — local, less local & Behemoth operators