Transmon-based quantum computers from a many-body perspective

Christoph Berke

PhD defense, 15.02.2023

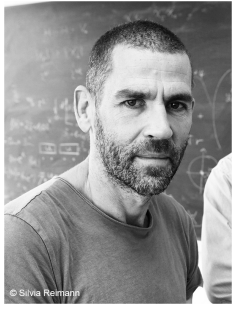
CRC183
ENTANGLED STATES OF MATTER

University of Cologne

Team Transmon

Cologne

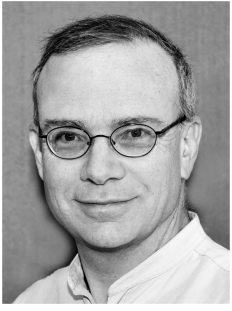
Simon Trebst



Alex Altland

Simon Börner

Aachen / Jülich

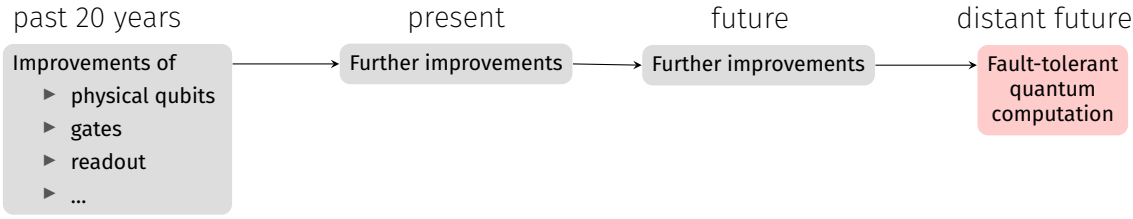


David DiVincenzo

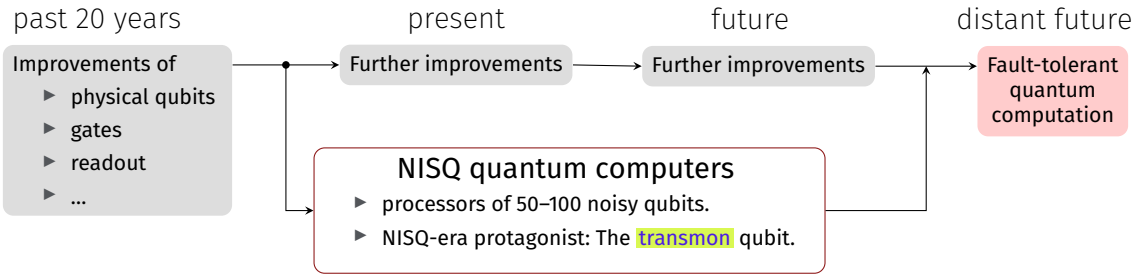
Evangelos Varvelis

ML4Q
MATTER AND LIGHT FOR QUANTUM COMPUTING

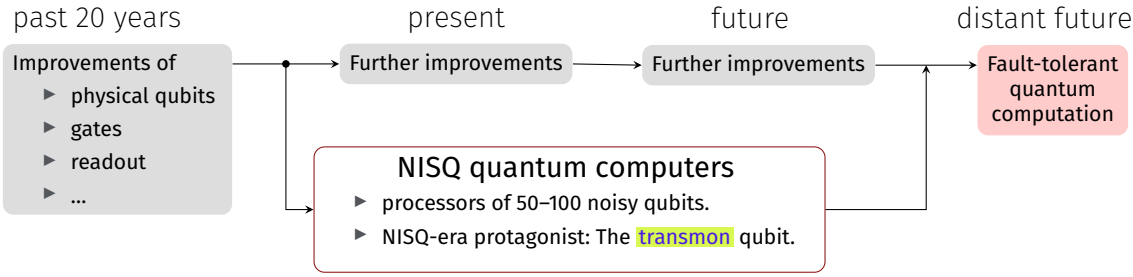
NISQ era & transmon milestones



NISQ era & transmon milestones



NISQ ERA & TRANSMON MILESTONES



SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

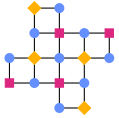
Realization of a discrete time crystal on 57 qubits of a quantum computer

Philipp Frey and Stephan Rachel*

University of Melbourne,
IBM Manhattan

Realizing repeated quantum error correction in a distance-three surface code

S. Krinner et al.
Nature 2022
ETH Zürich



TOPOLOGICAL MATTER

Realizing topologically ordered states on a quantum processor

K.J.Satzinger et al.
Science 2021,
Google's Sycamore

More transmons = New problems?

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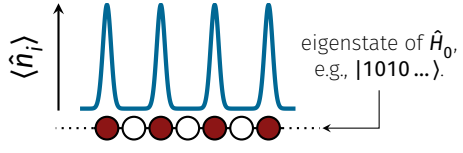

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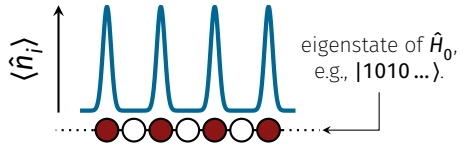
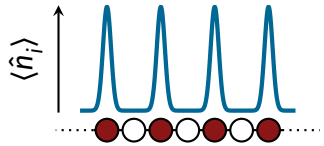


Fate under unitary dynamics $e^{-i\hat{H}t/\hbar}$?

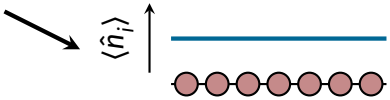
$\hat{H} \neq \hat{H}_0$

More transmons = New problems?



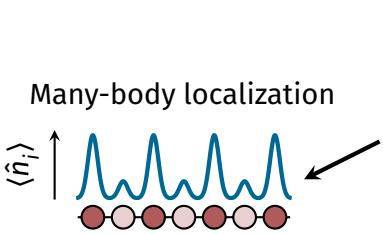
Fate under unitary dynamics $e^{-i\hat{H}t/\hbar}$?

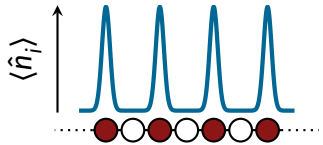
Thermalization/Quantum Chaos



- Subsystems exchange energy.

More transmons = New problems?





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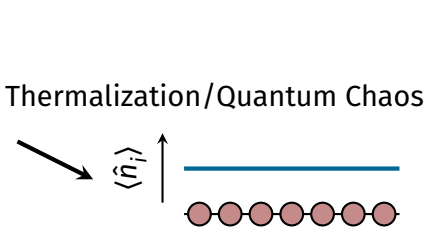
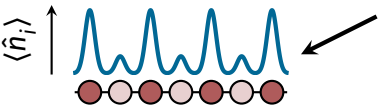
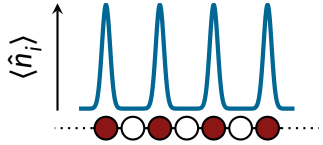


- Requires strong disorder.
- Subsystems exchange energy.

More transmons = New problems?

Many-body localization





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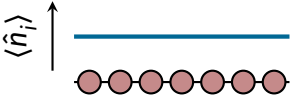

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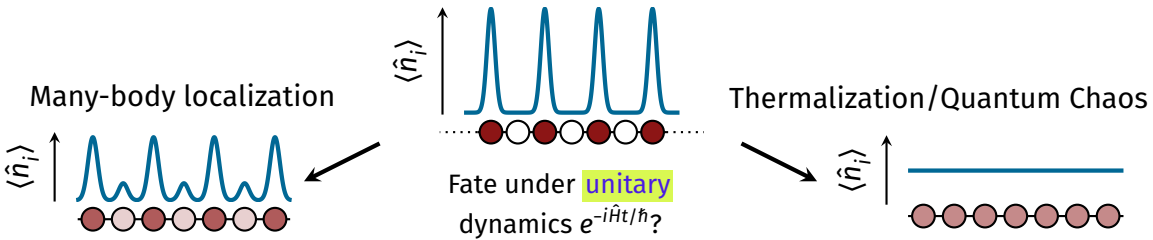

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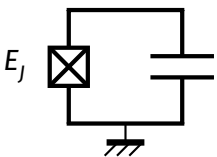
Potential quantum computer.

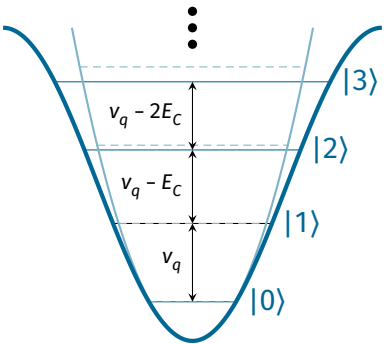
A quantum computer's nemesis.

The transmon qubit

$$\hat{H} = 4E_C\hat{n}^2 - E_J \cos\hat{\varphi}$$

- A transmon is a nonlinear oscillator.





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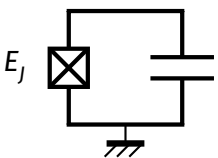
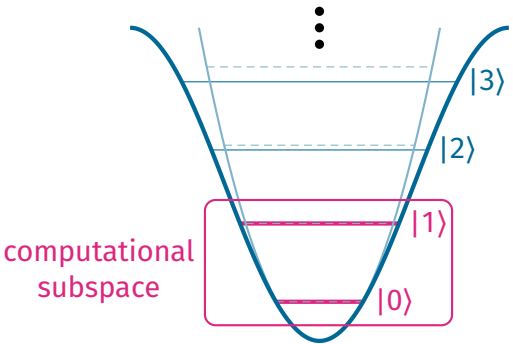


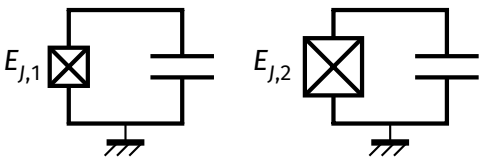


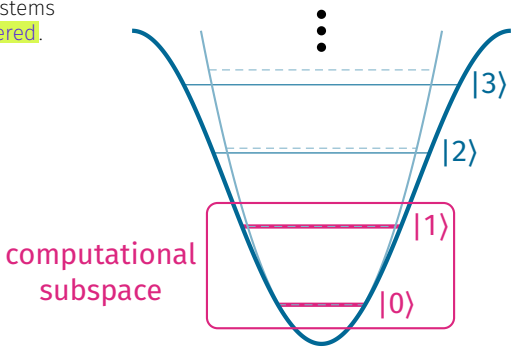
The transmon qubit

$$\hat{H} = 4E_C\hat{n}_1^2 - E_{J,1}\cos\hat{\varphi}_1$$
$$+ 4E_C\hat{n}_2^2 - E_{J,2}\cos\hat{\varphi}_2$$

transmon systems are disordered.

- A transmon is a nonlinear oscillator.





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$$+ T\hat{n}_1\hat{n}_2$$

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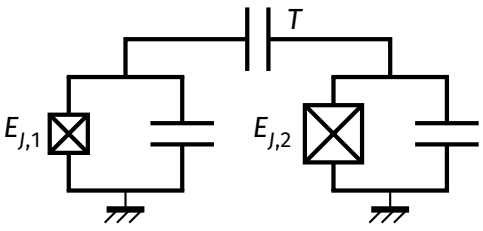

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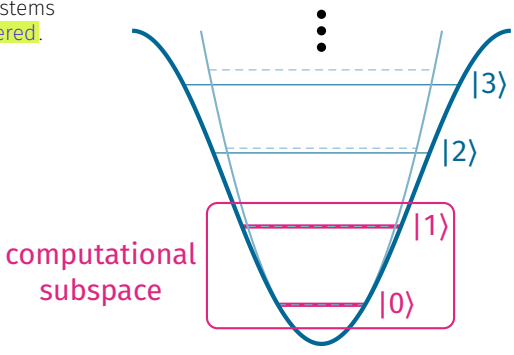
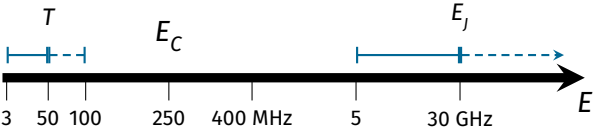


The many-transmon problem

$$\hat{H} = \sum_i \left(4E_C \hat{n}_i^2 - E_{J,i} \cos \hat{\varphi}_i\right) + T \sum_{\langle i,j \rangle} \hat{n}_i \hat{n}_j$$



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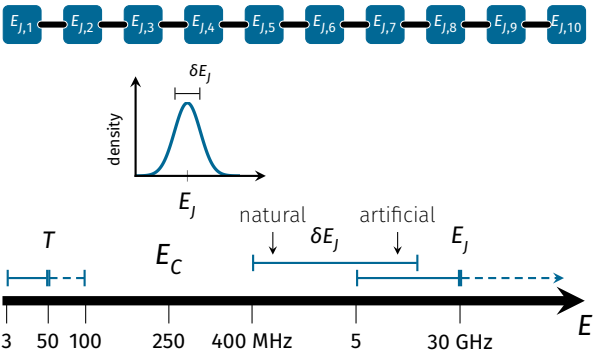

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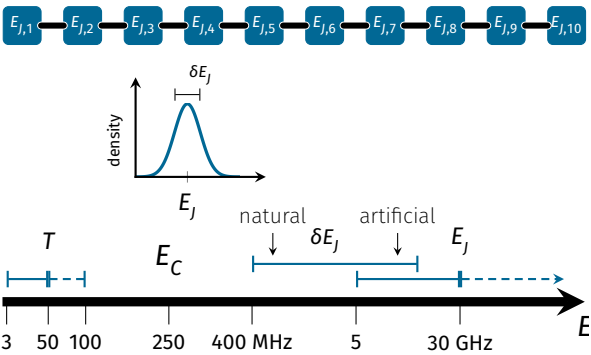

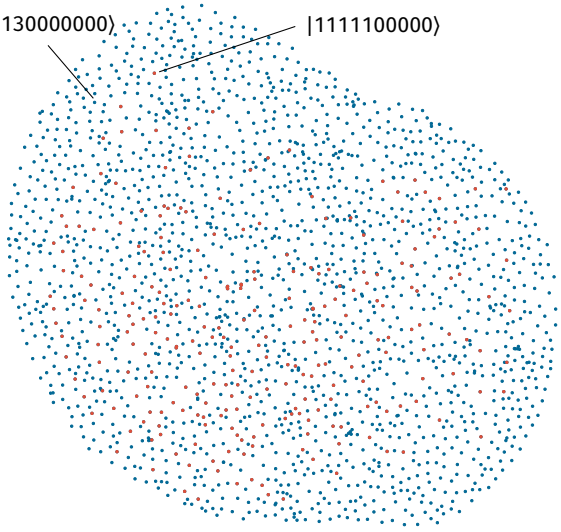

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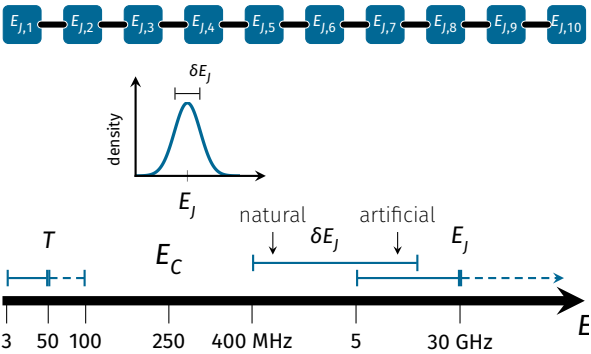
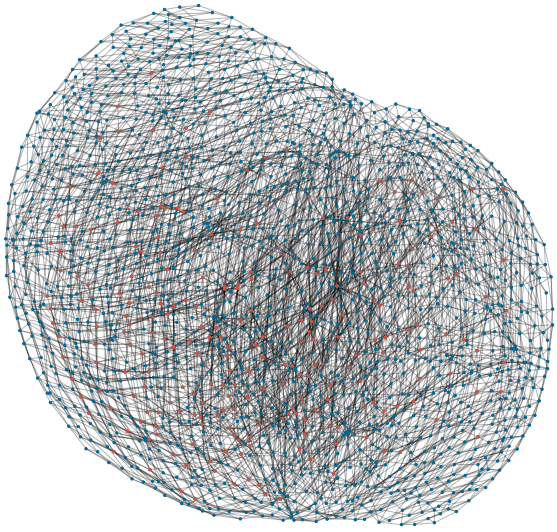
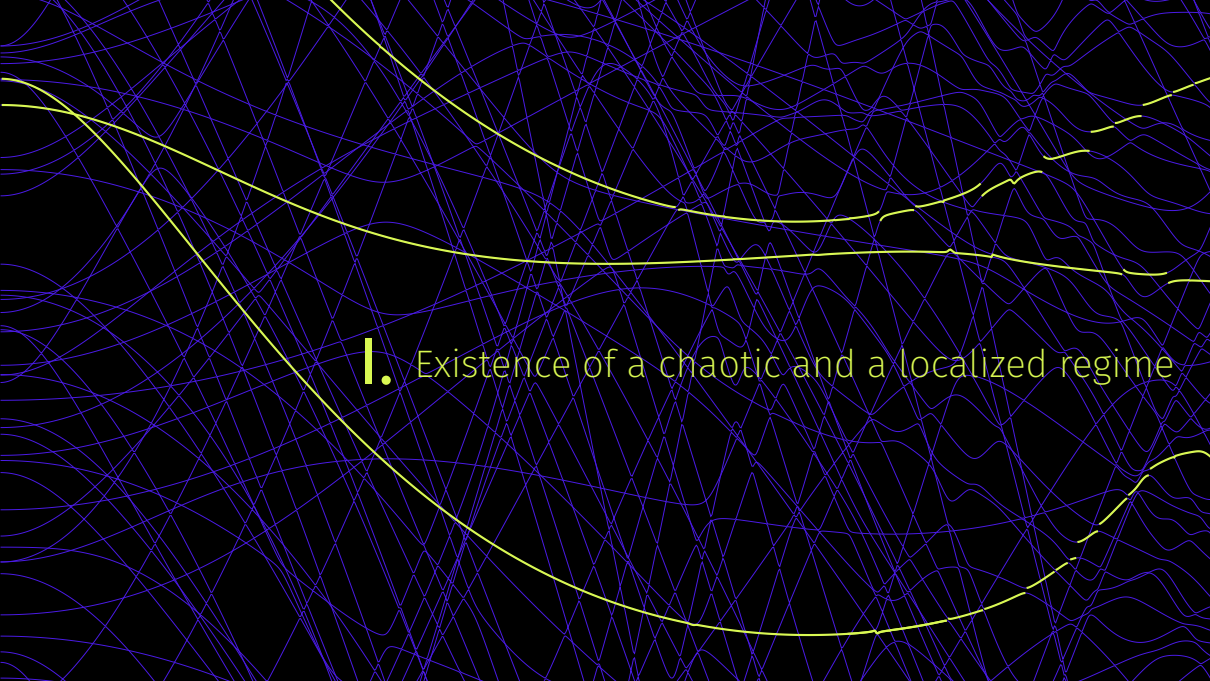
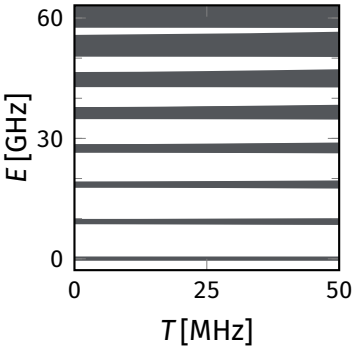





I. Existence of a chaotic and a localized regime

Level Repulsion



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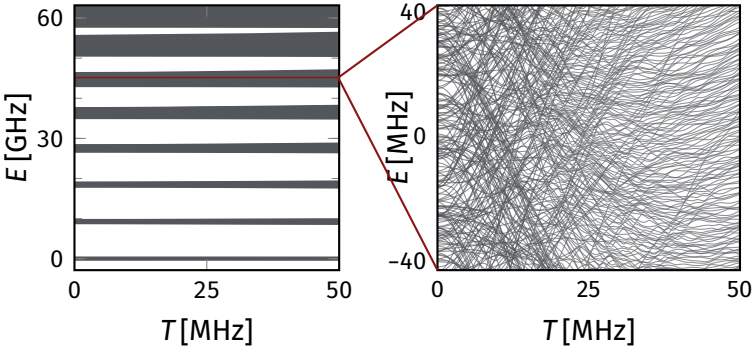

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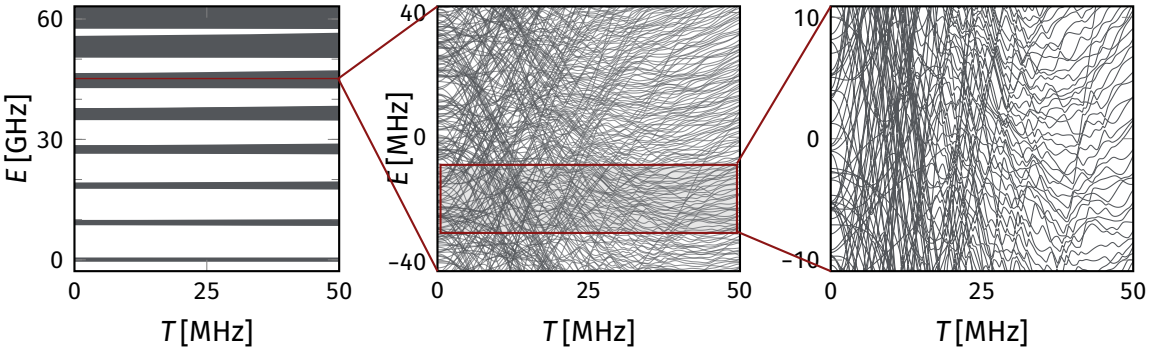

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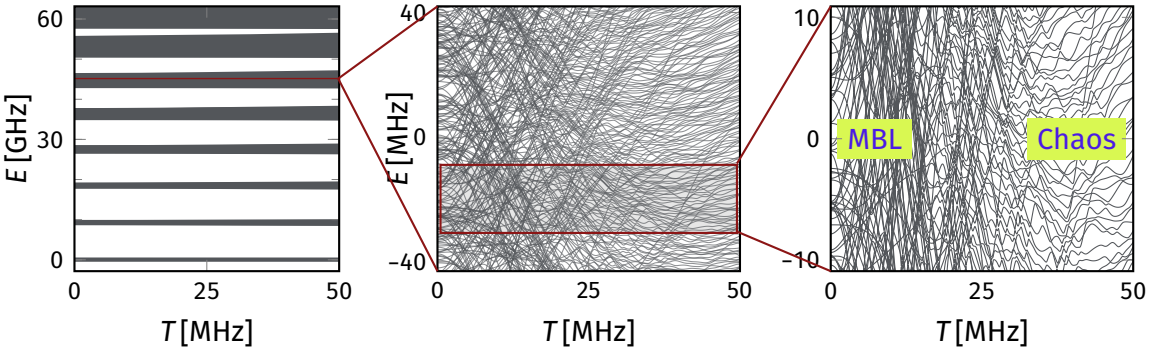
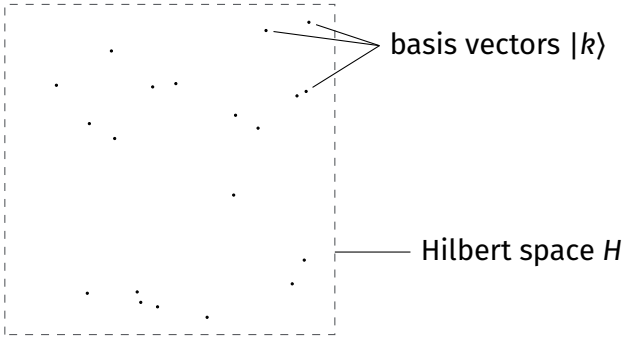


Wave functions

- Delocalization of wave function $|\psi\rangle = \sum_k c_k |k\rangle$.



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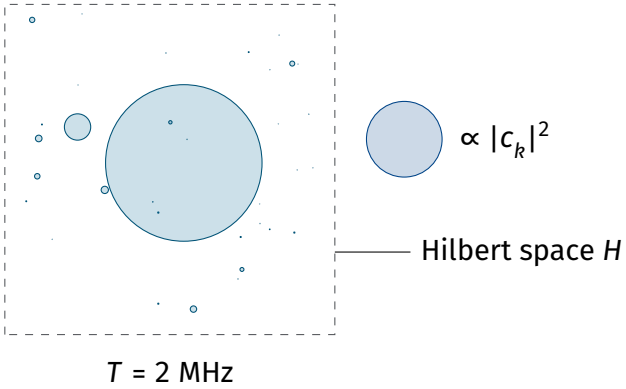

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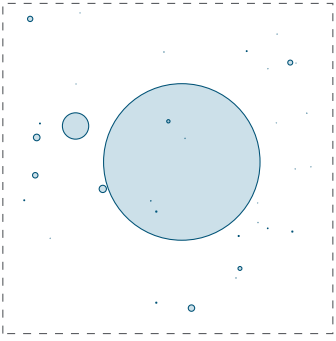
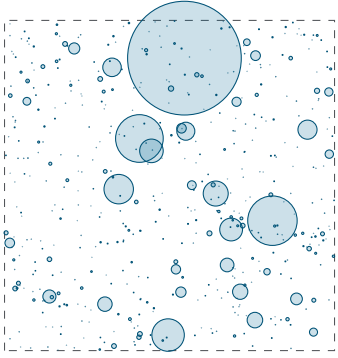


T = 2 MHz



T = 15 MHz

Wave functions

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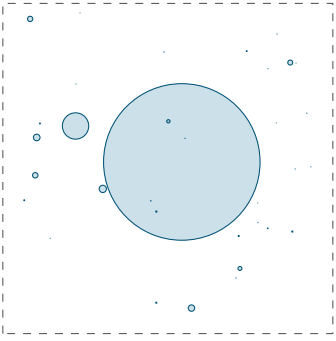

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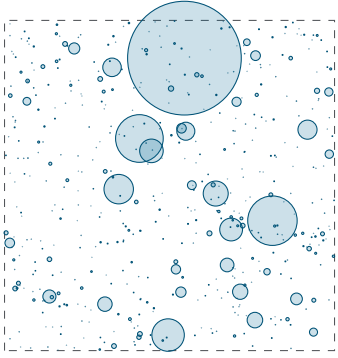

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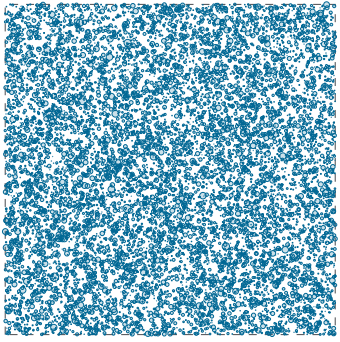

T = 70 MHz

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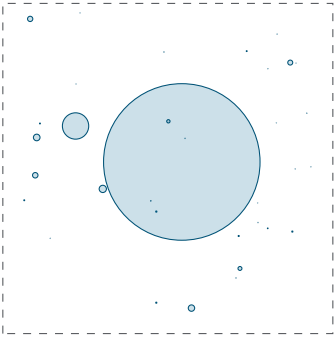
- **I**nverse **p**artition **r**atio: IPR = $\sum_k |c_k|^4$



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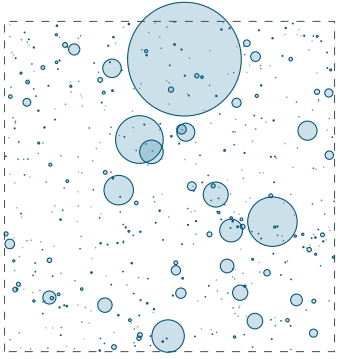

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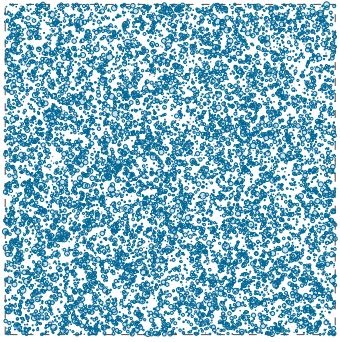

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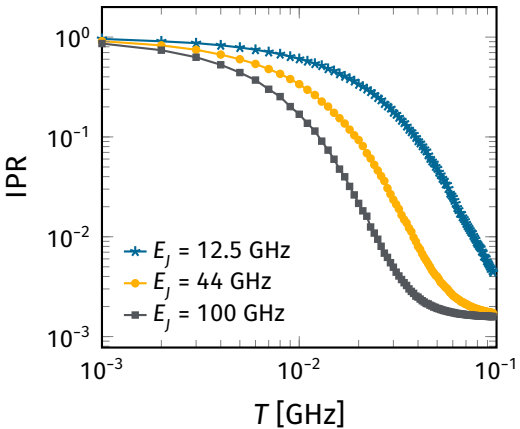
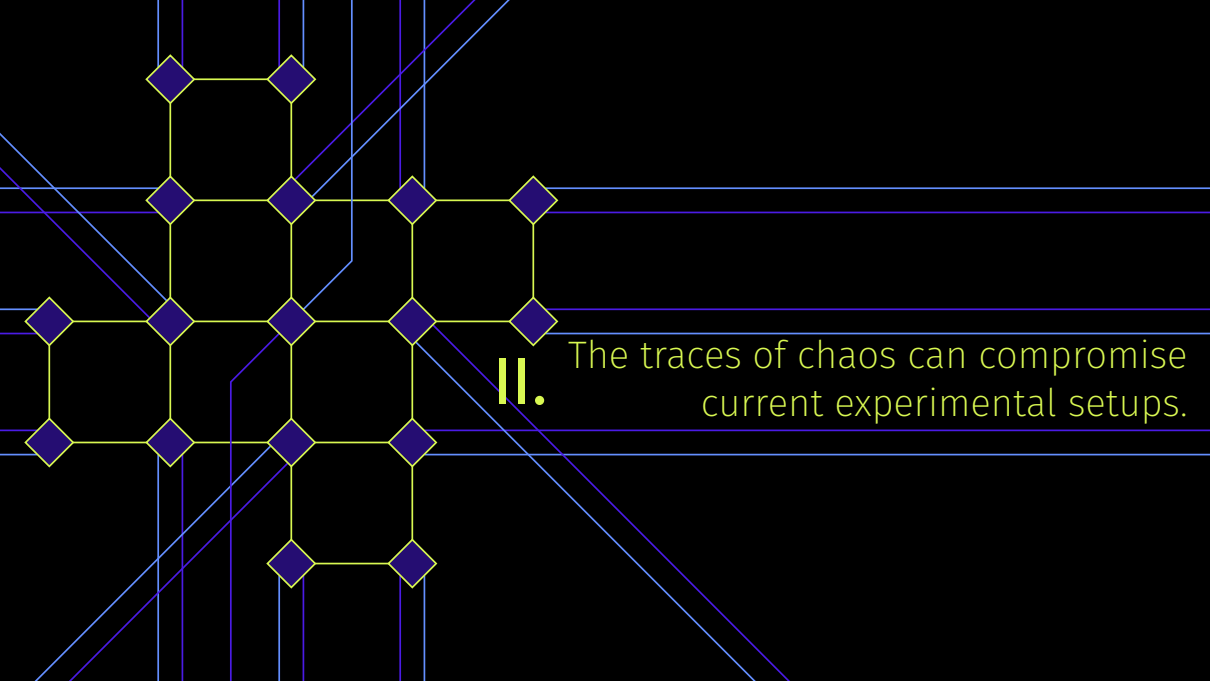
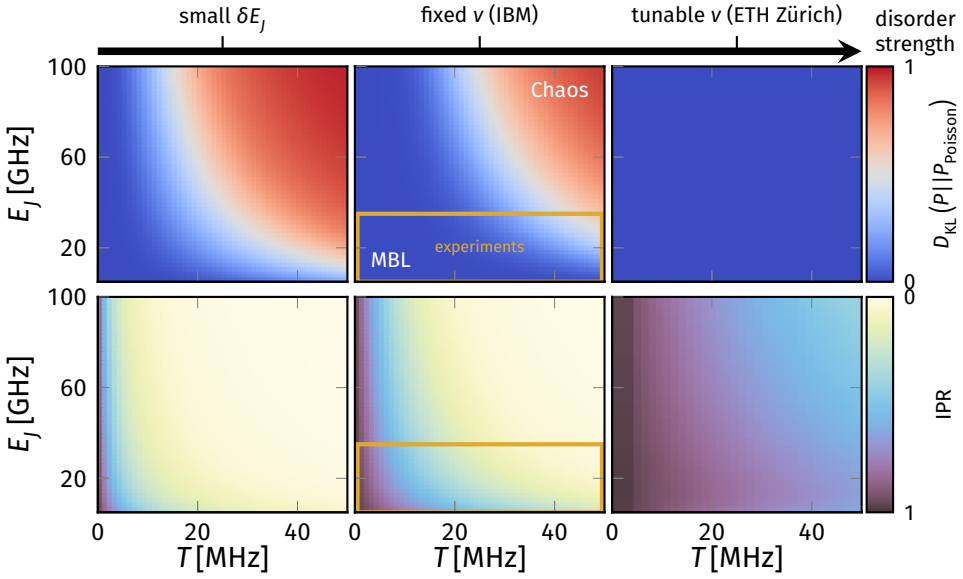


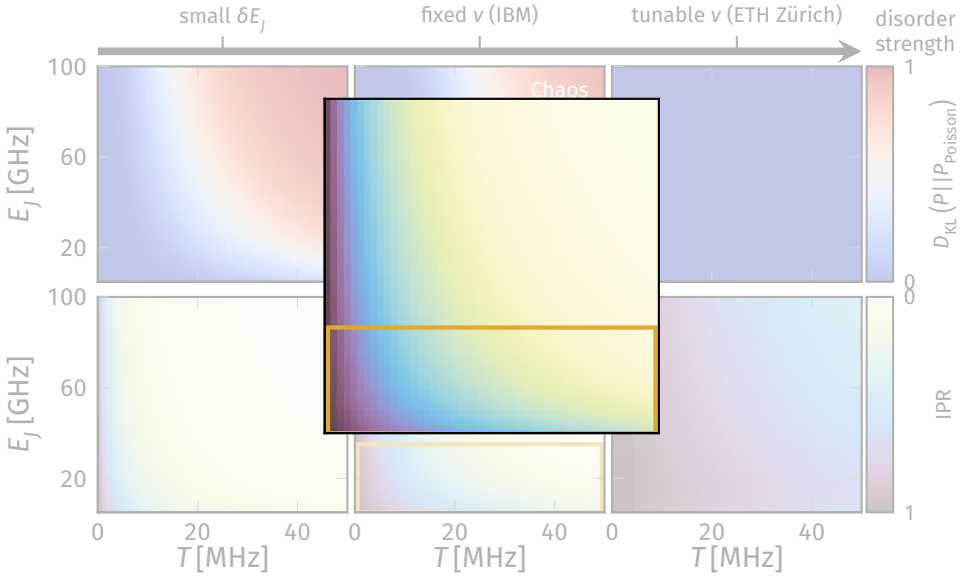


II. The traces of chaos can compromise current experimental setups.

Prevalent transmon architectures



Prevalent transmon architectures



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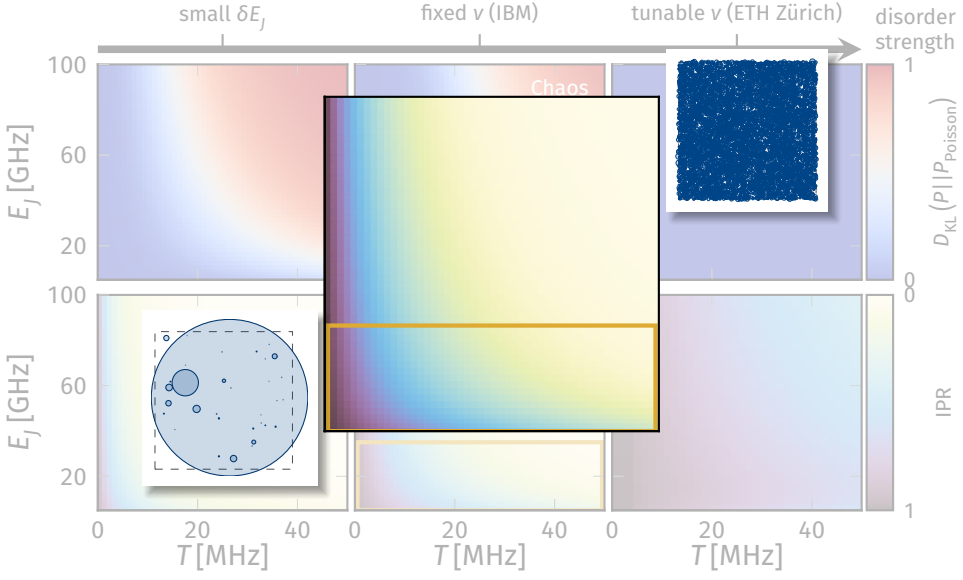
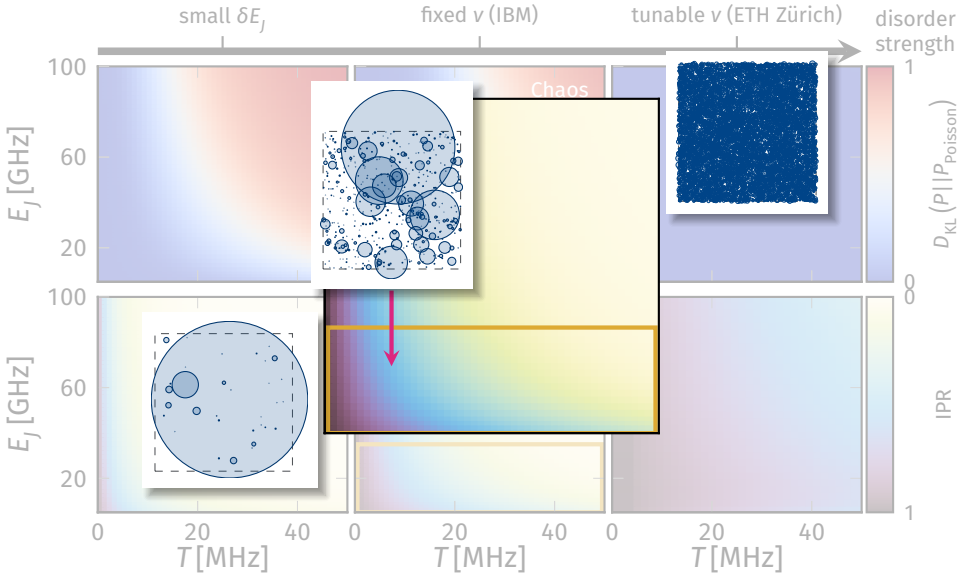
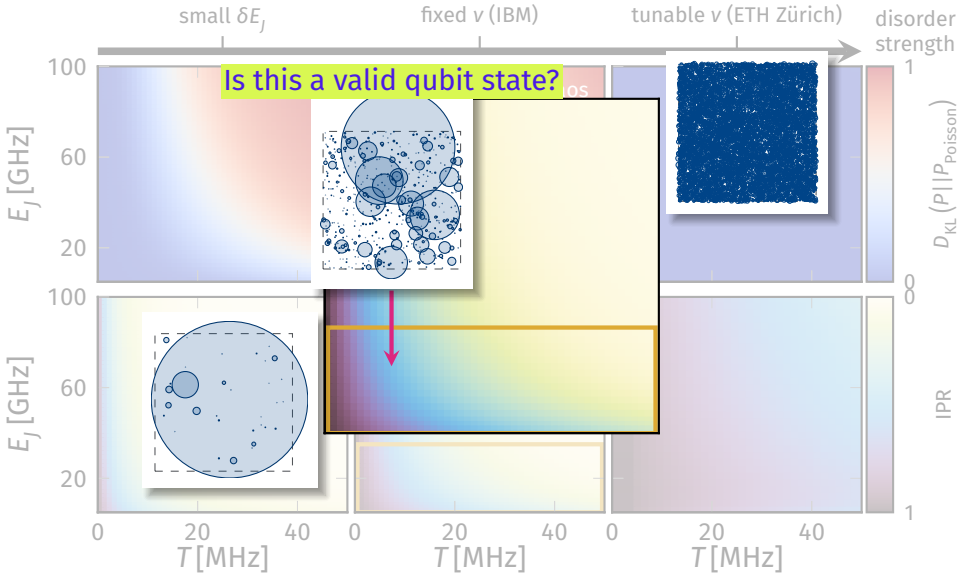


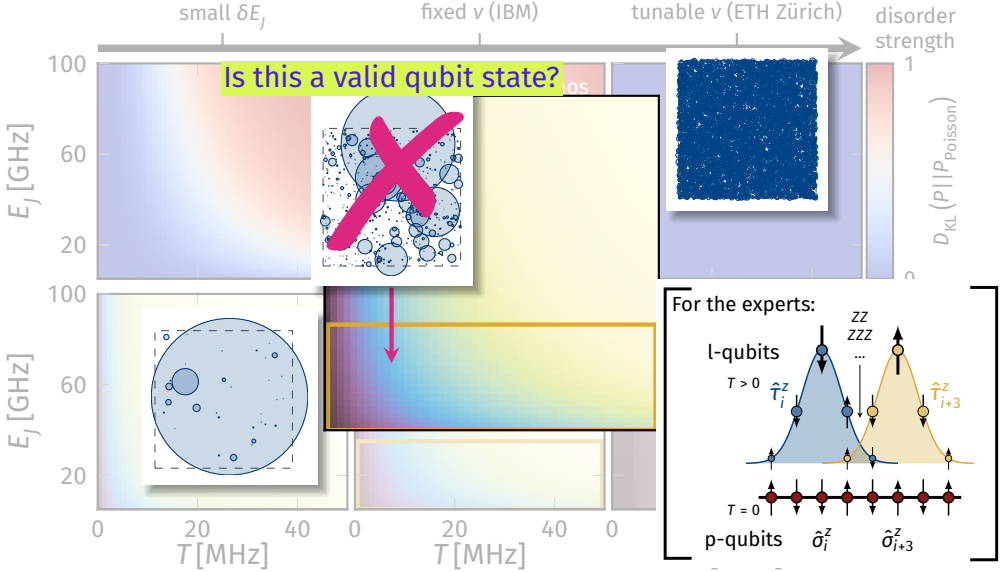
Prevalent transmon architectures



Prevalent transmon architectures

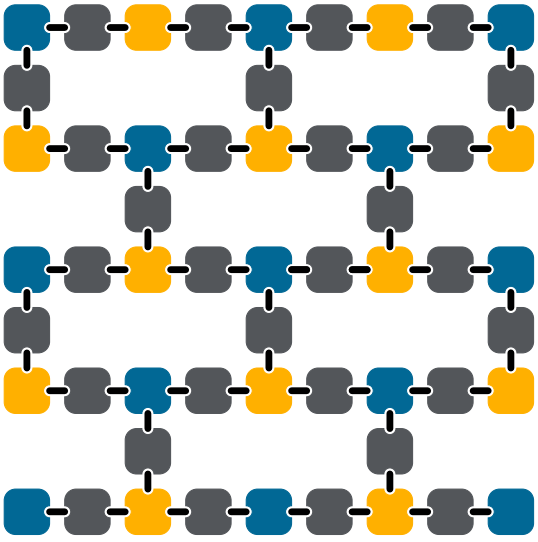


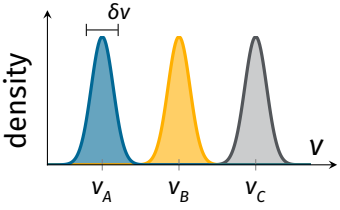
Prevalent transmon architectures



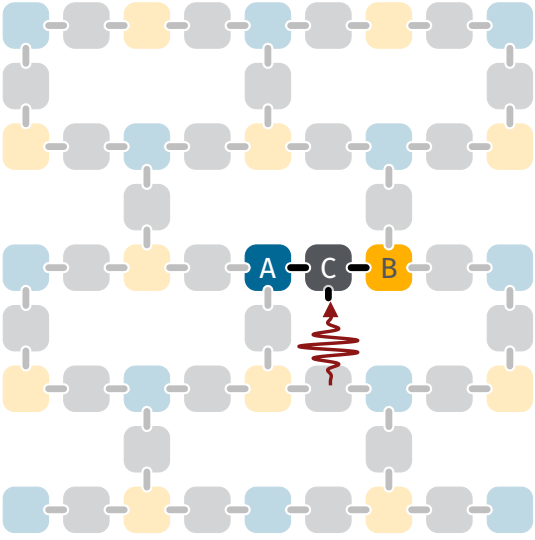
III. Insights from the many-body perspective

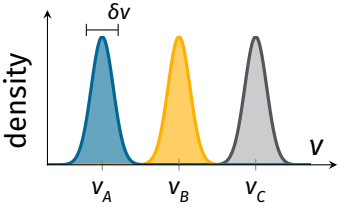
Frequency Patterns





Frequency Patterns





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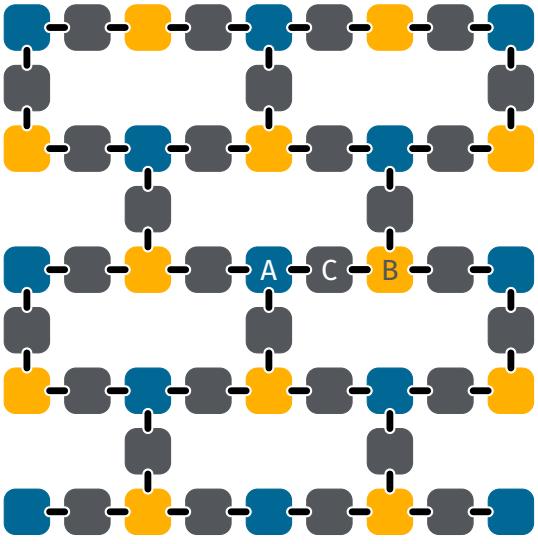
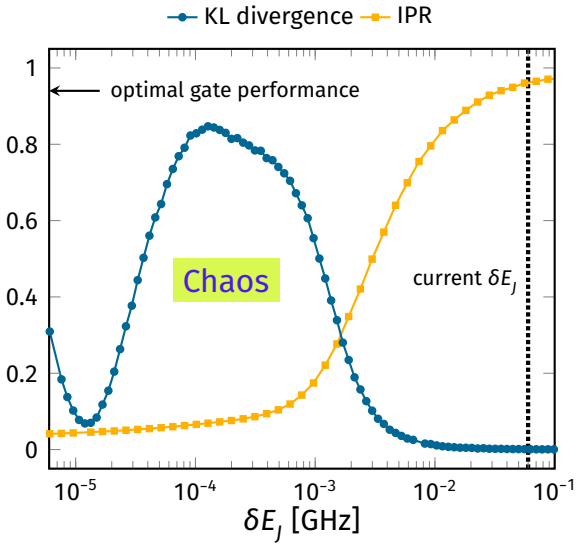
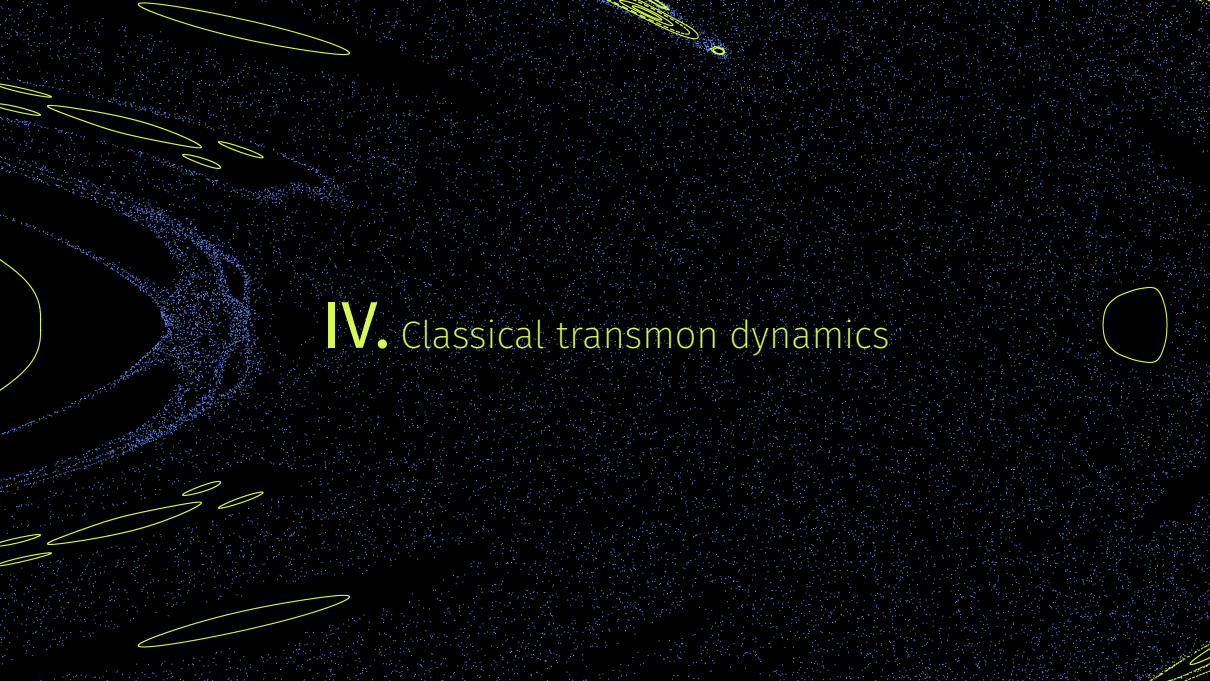
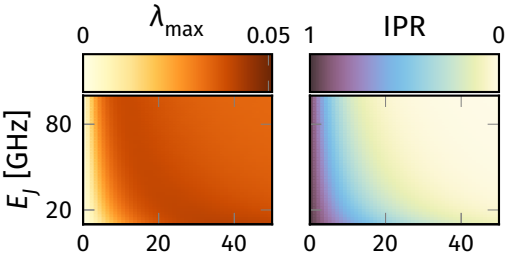






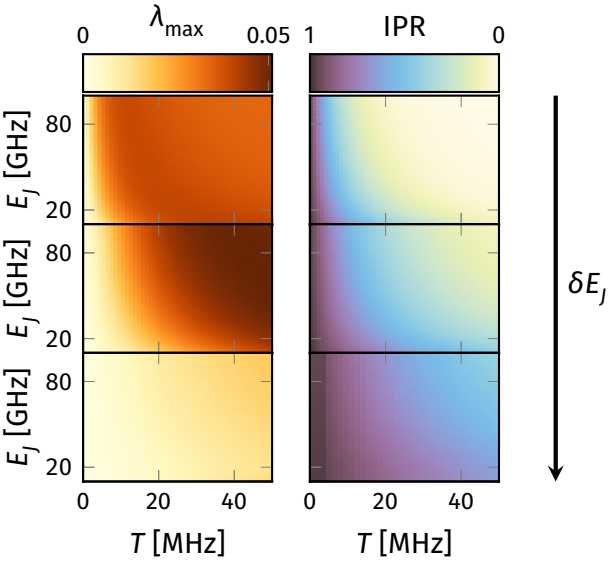
IV. Classical transmon dynamics

Classical Dynamics

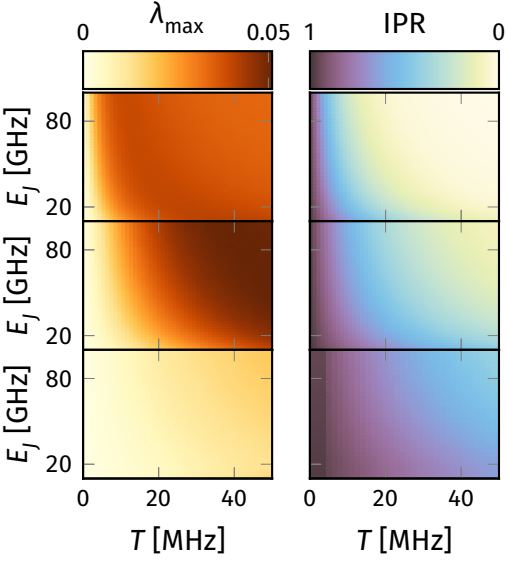


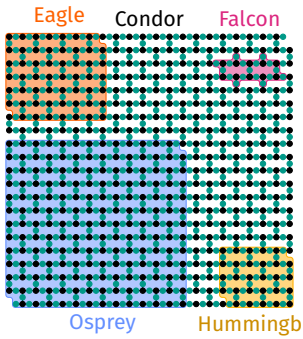
classical to quantum correspondence

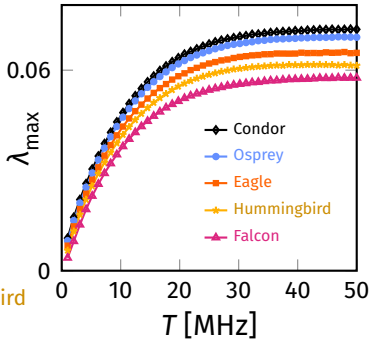
Classical Dynamics



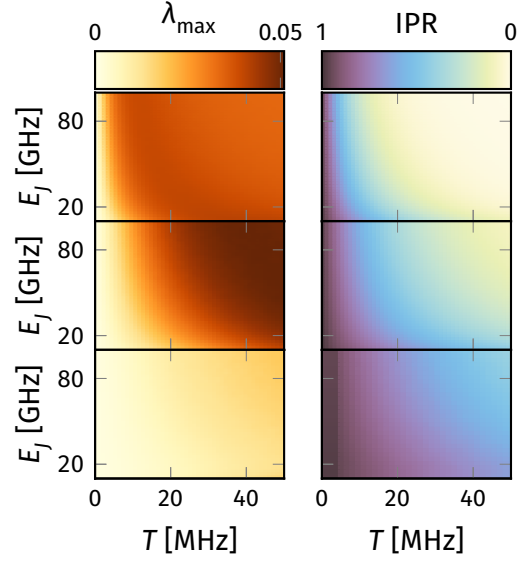
Classical Dynamics

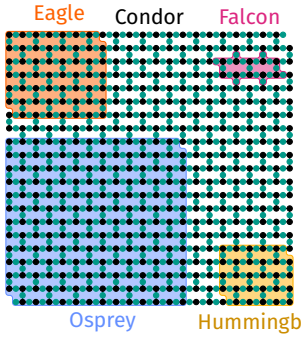


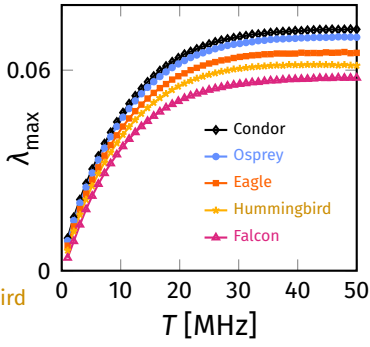




Classical Dynamics







Can classical analysis optimize parameters for quantum computer?

Summary

- Qubits need disorder → protection vs. operation dilemma.

C.B., E.V., S.T., A.A., & D.D.
Nature Comm. 13 (1), 2495, 2022
Editors Highlights

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

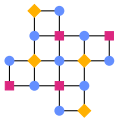
Realization of a discrete time crystal on 57 qubits of a quantum computer

Philipp Frey and Stephan Rachel*

University of Melbourne,
IBM Manhattan

Realizing repeated quantum error correction in a distance-three surface code

S. Krinner et al.
Nature 2022
ETH Zürich



TOPOLOGICAL MATTER

Realizing topologically ordered states on a quantum processor

K.J.Satzinger et al.
Science 2021,
Google's Sycamore

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C.B., E.V., S.T., A.A., & D.D.
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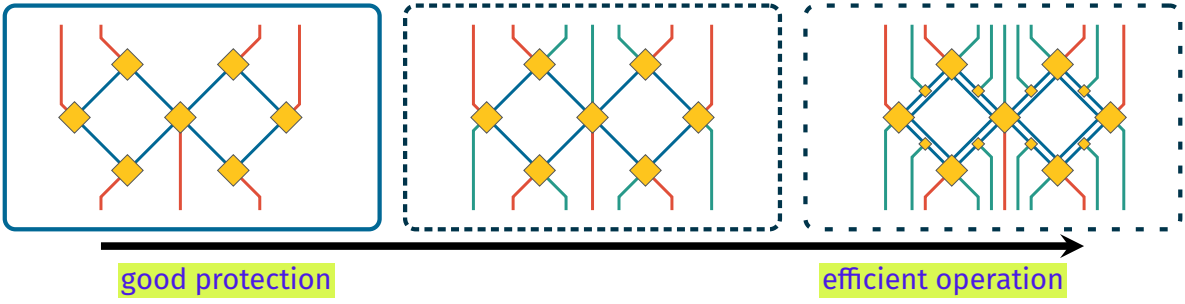

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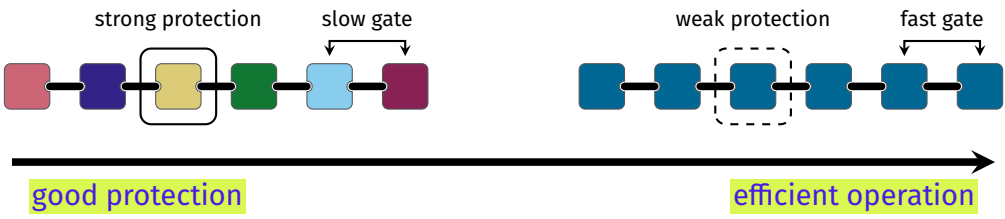

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- Many-body perspective can help identifying the optimal spot between localization / protection and chaos.

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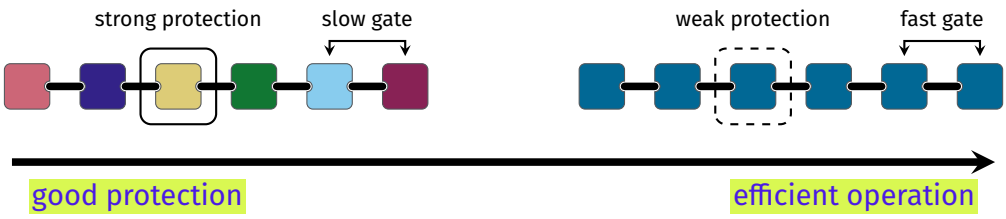

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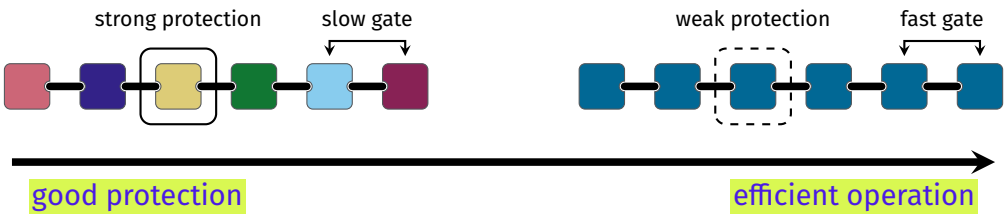

I. Existence of a chaotic regime ...

II. ...that affects relevant parameter regions.

III. MBL perspective offers new insights.

IV. Classical analysis might be a useful tool.

Field-driven effects in Kitaev spin liquids

Ciarán Hickey

C.B., S.T., C.H., PRB 101 (21), 214442 (2020)
C.H., M.Gohlke, **C.B.** , S.T., PRB 103 (6), 064417 (2021)
C.H., **C.B.**, et al., PRR 2 (2), 023361 (2020)

CRC 1238
Control and Dynamics of Quantum Materials

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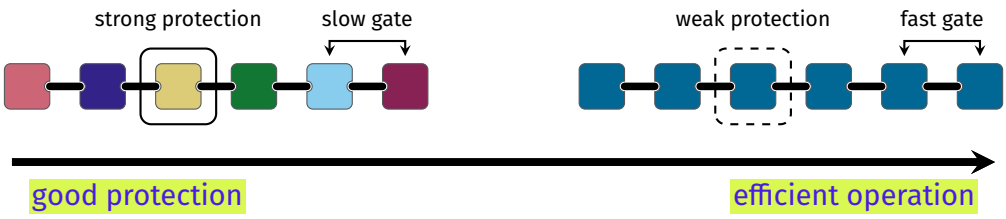


I. Existence of a chaotic regime ...

II. ...that affects relevant parameter regions.

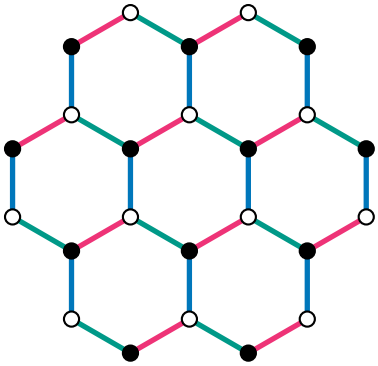
III. MBL perspective offers new insights.

IV. Classical analysis might be a useful tool.

V. In *B* fields, AFM KSL show richer physics than FM KSL.

Thank You!

Field-driven effects in Kitaev spin liquids



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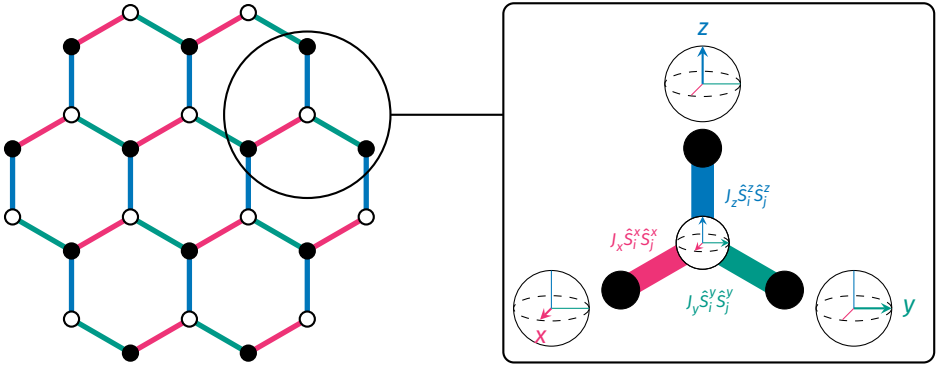

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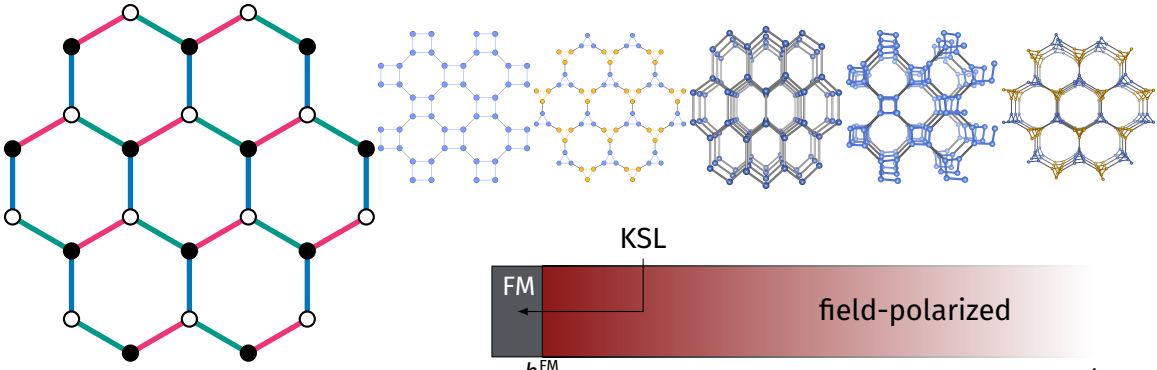

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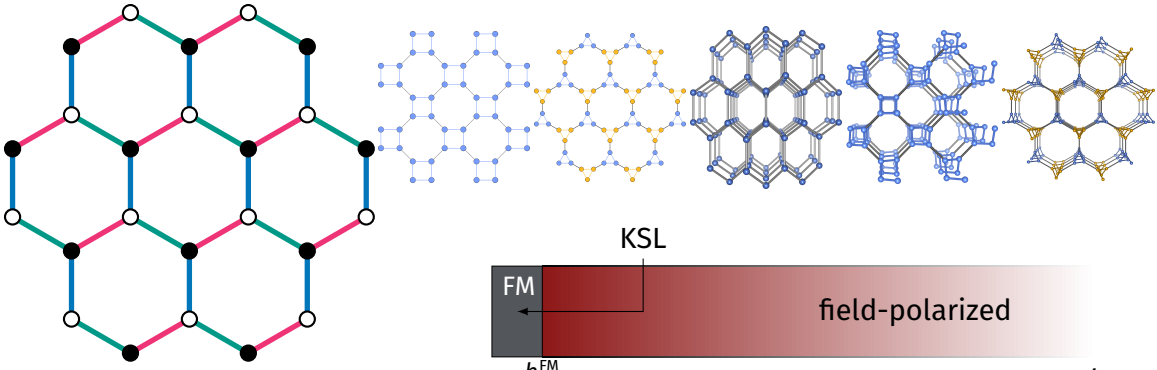

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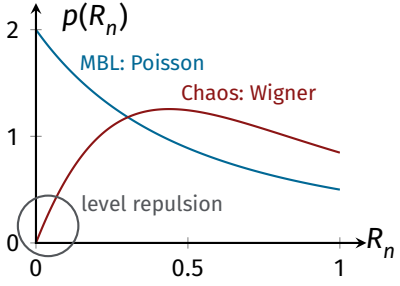
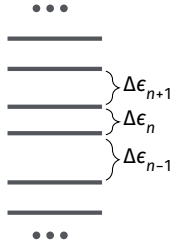
Quantifying chaos: Level statistics

- Statistics for $r_n = \Delta\epsilon_{n+1}/\Delta\epsilon_n$.





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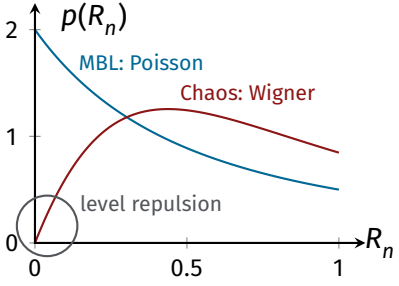
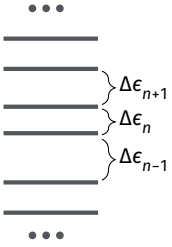
$$D_{\mathrm{KL}}(P||Q) = \sum_k p_k \log\left(\frac{p_k}{q_k}\right)$$

data — theory





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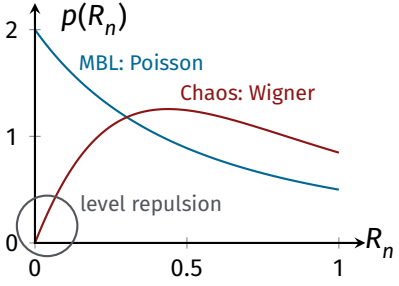

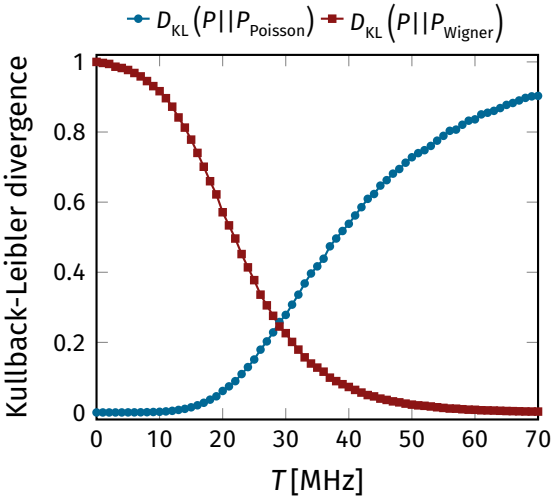

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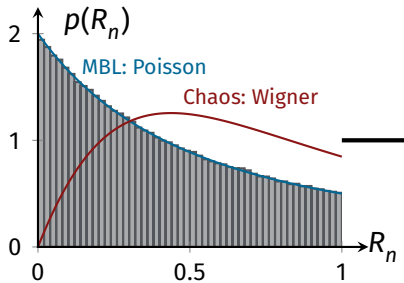

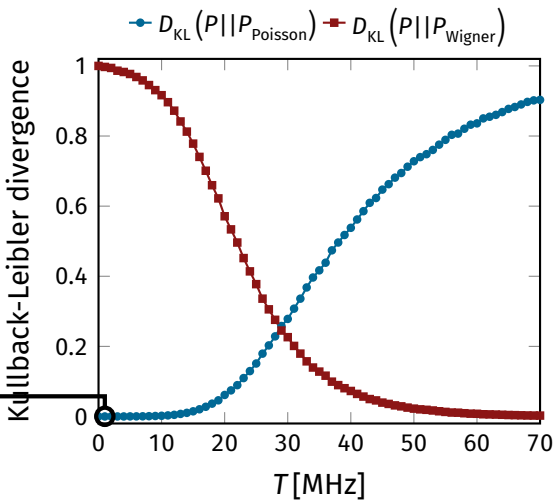

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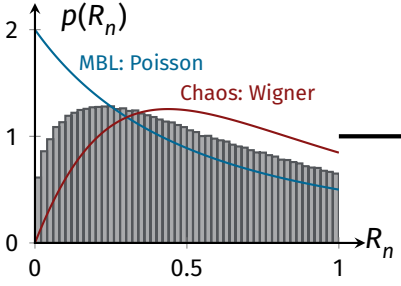

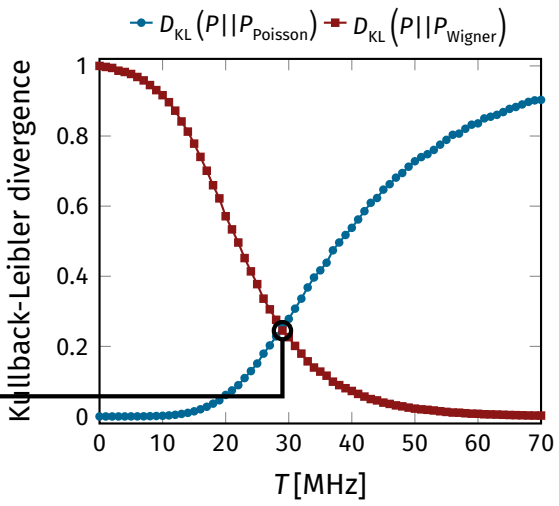

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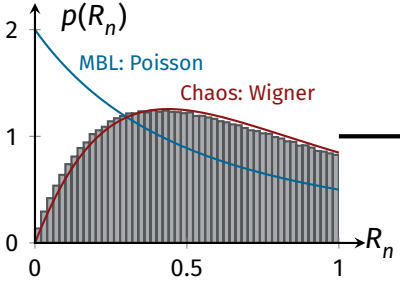
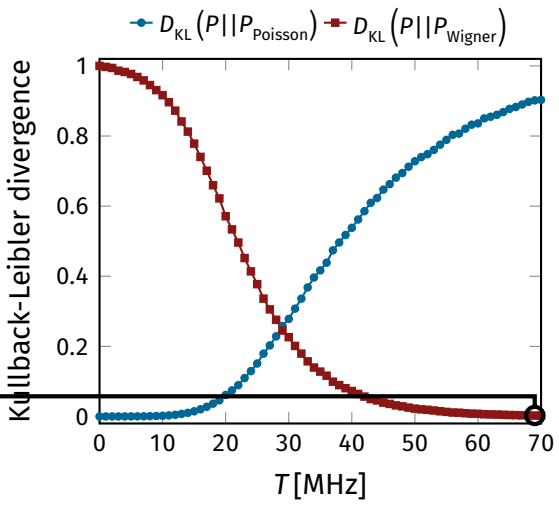
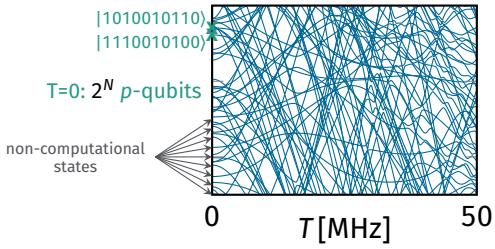




L-BIT CORRELATIONS



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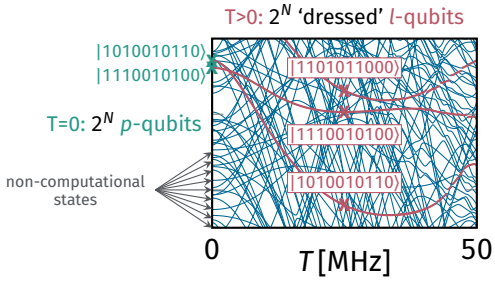

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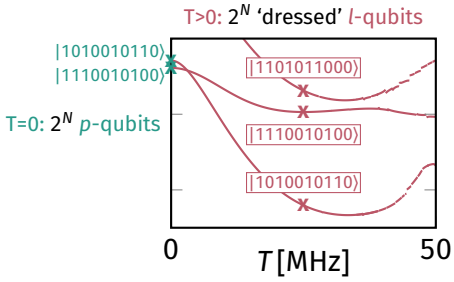


L-BIT CORRELATIONS

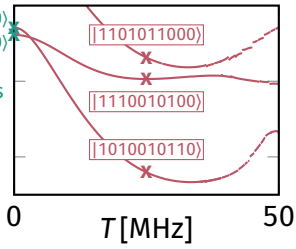
$$H = \begin{bmatrix} E_{00000} & & & \\ & E_{00001} & & \\ & & \ddots & \\ & & & E_{11111} \end{bmatrix} = \sum_i h_i \tau_i + \sum_{ij} J_{ij} \tau_i \tau_j + \sum_{ijk} K_{ijk} \tau_i \tau_j \tau_k + \ldots$$

Walsh transformation

correlations between *l*-bits

T>0: 2^N 'dressed' *l*-qubits

T=0: 2^N *p*-qubits



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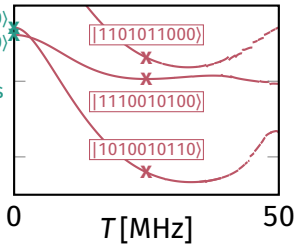
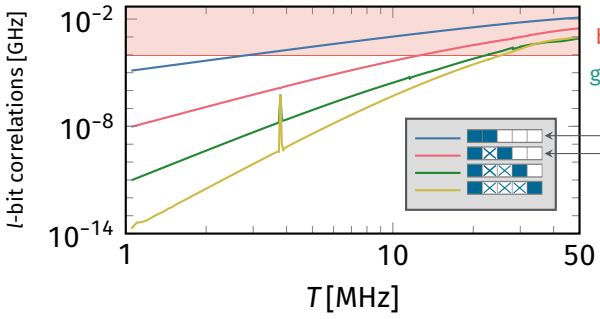




bad

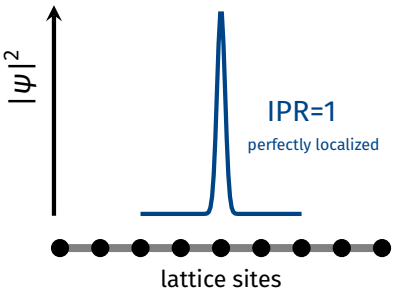
good

ZZ correlations: $J_{12}, J_{23}, \ldots$ ("well established").

$J_{13}, J_{24}, K_{123}, \ldots$
hardly considered, but dangerously large.

Quantifying chaos: Wave function statistics

$$\mathrm{IPR} = \int \mathrm{d}x |\langle x|\psi\rangle|^4$$



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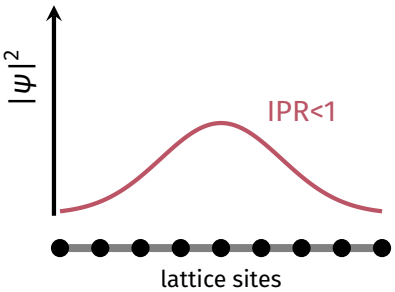

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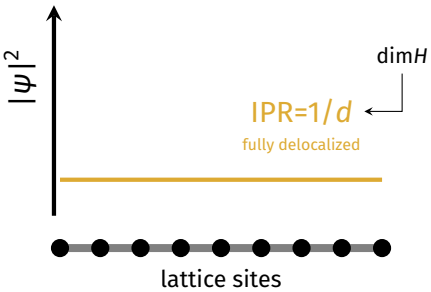

Quantifying chaos: Wave function statistics

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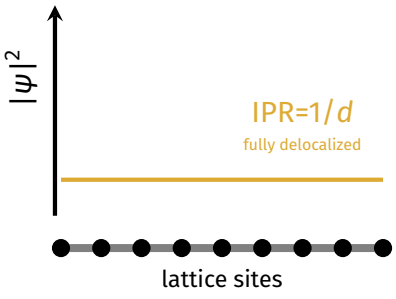
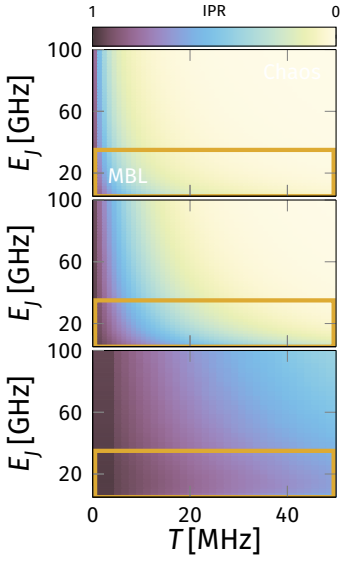
small δE_J

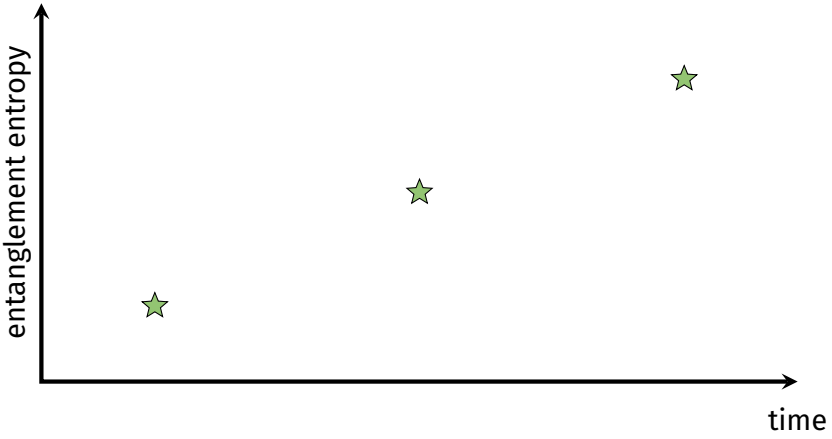
IBM

Delft





The second law of thermodynamics



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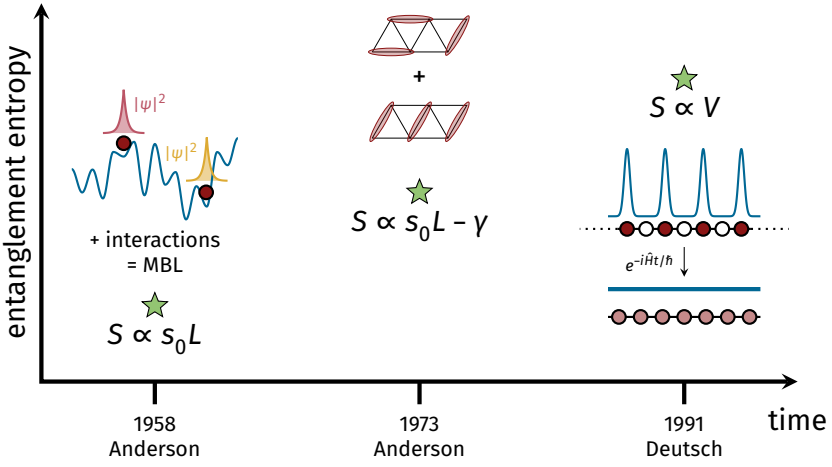
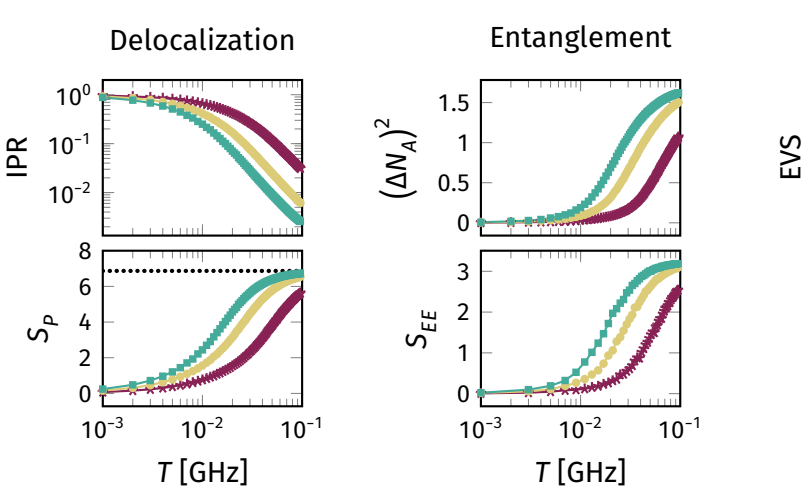


More wave function metrics



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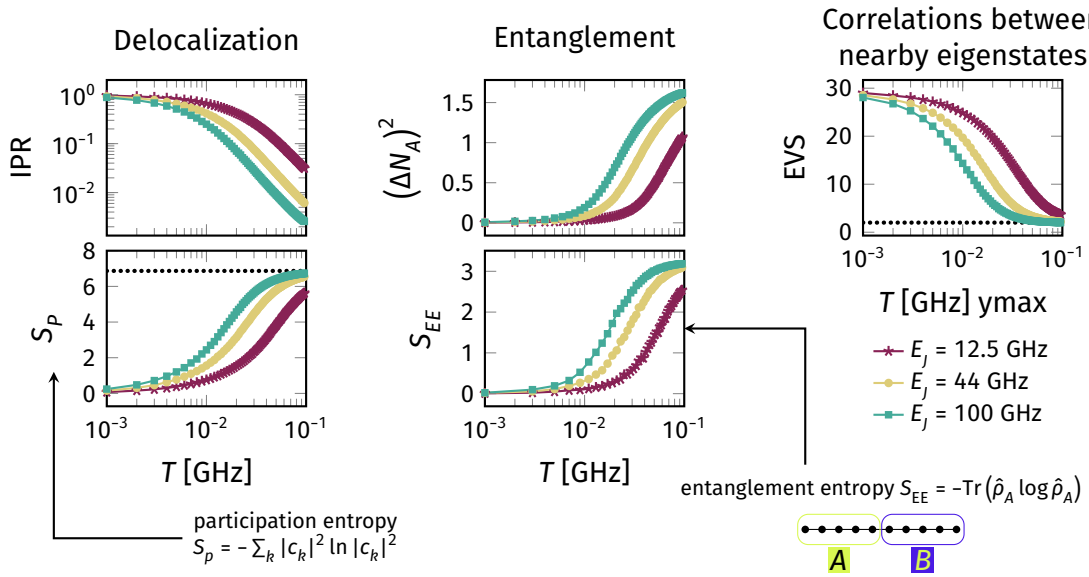
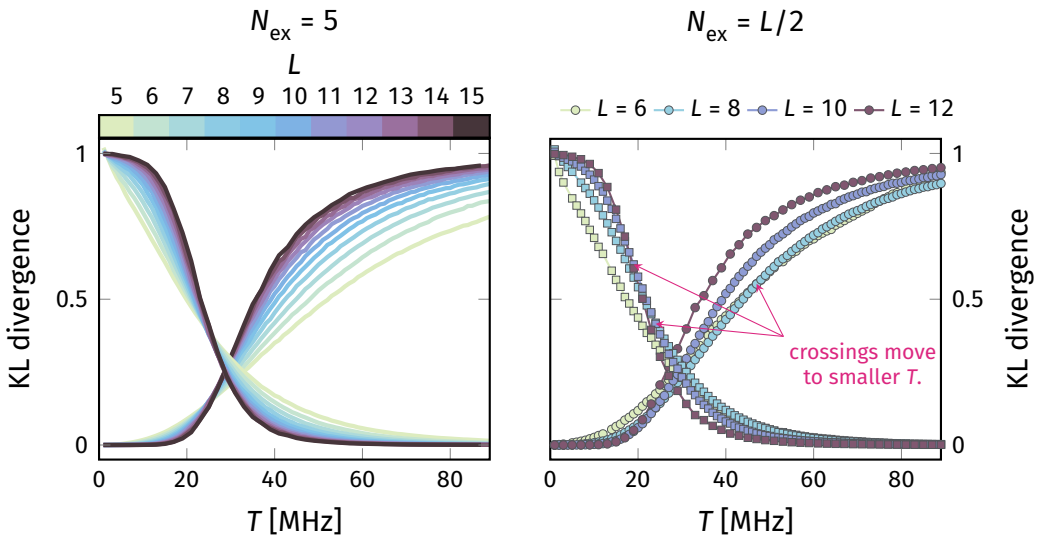
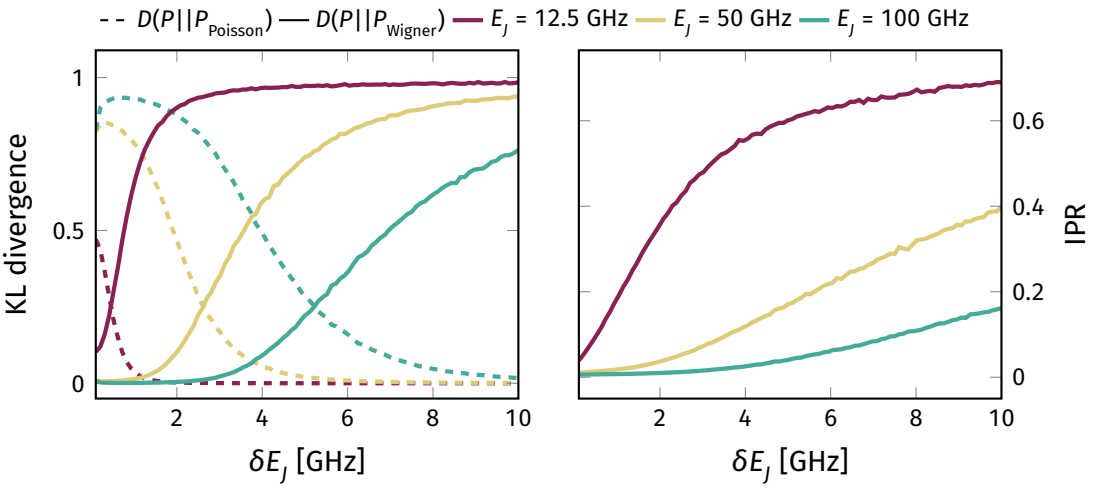


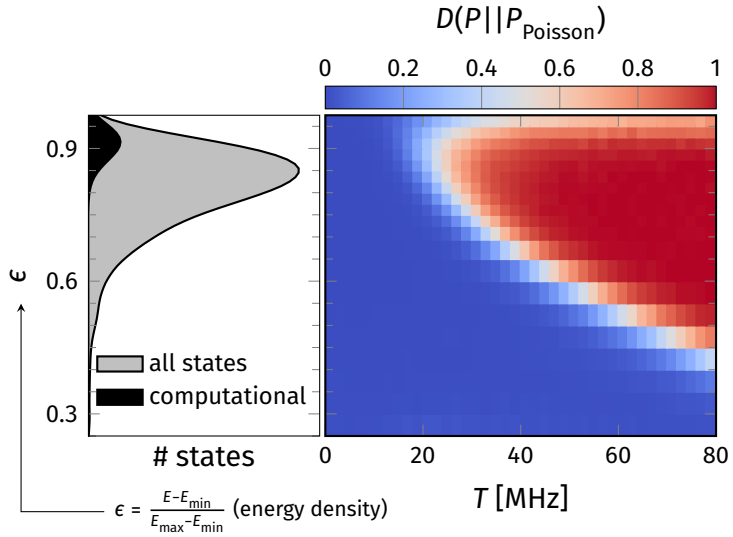
Varying the system size



Varying the disorder strength



Many-body mobility edge



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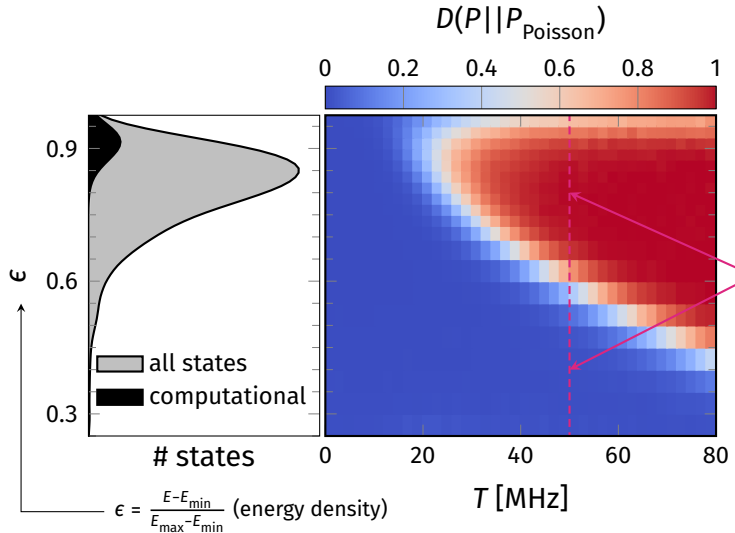
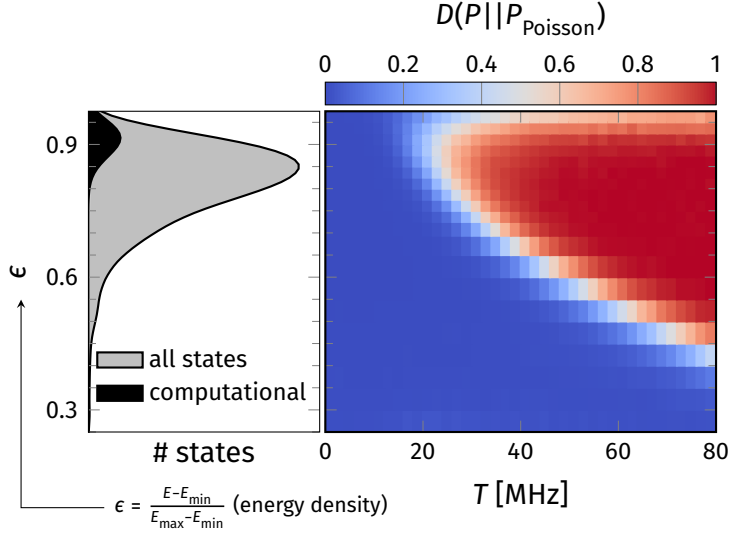
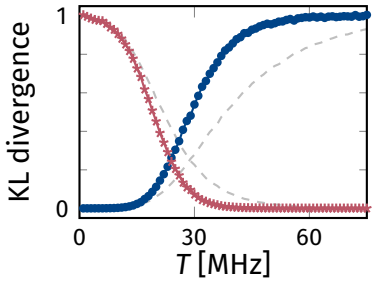
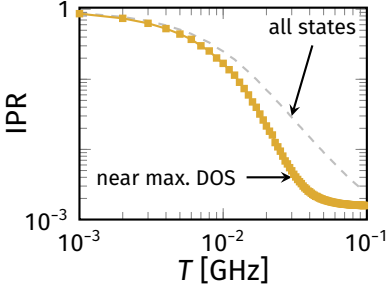


Coexistence of ergodic and localized states.

Many-body mobility edge







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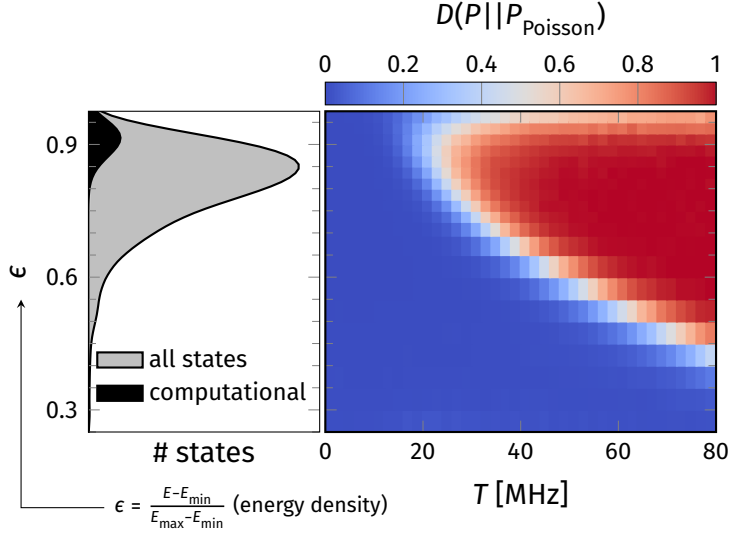
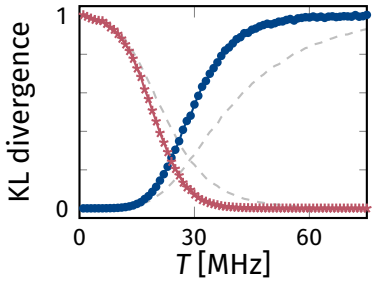
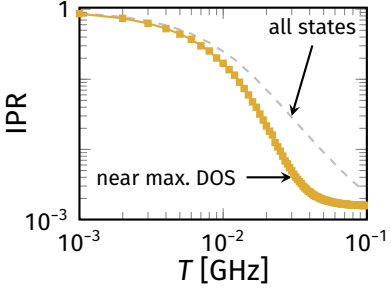
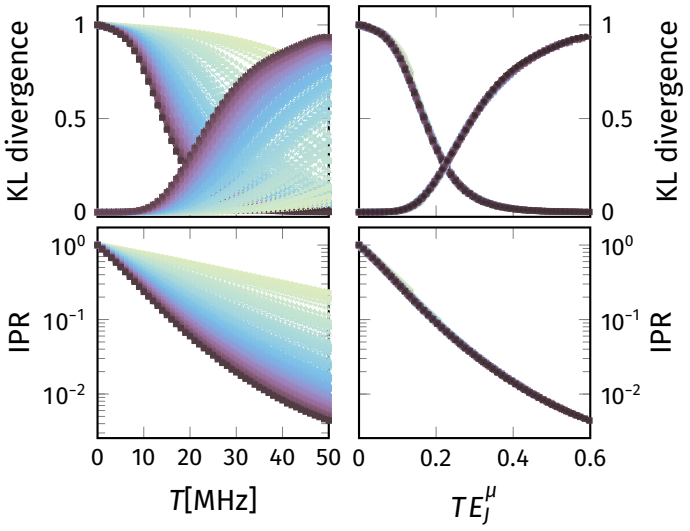






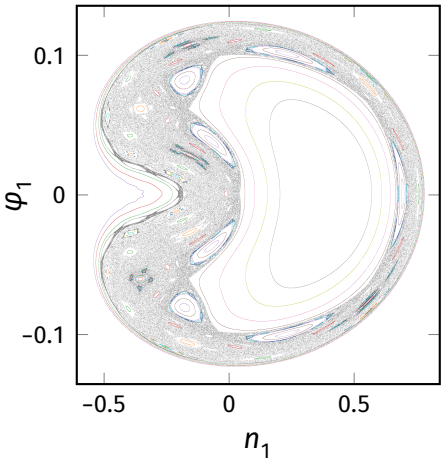
Data collapse

- Which parameter drives the MBL↔chaos transition?
- Compare $\Delta\epsilon_{m,n}$ and $t_{m,n}$ (Energy difference and coupling of Fock states)
- Here: $\frac{t_{m,n}}{\Delta\epsilon_{m,n}} \propto TE_J^{1/2}$.
- Data collapse for rescaling $T \to TE_J^{0.54}$



Poincaré Sections

- Stroboscopic view: Poincaré sections in φ_1–n_1 plane.



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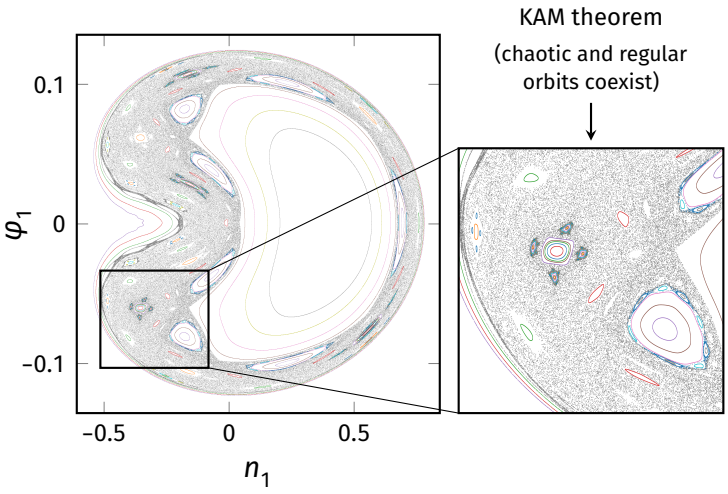

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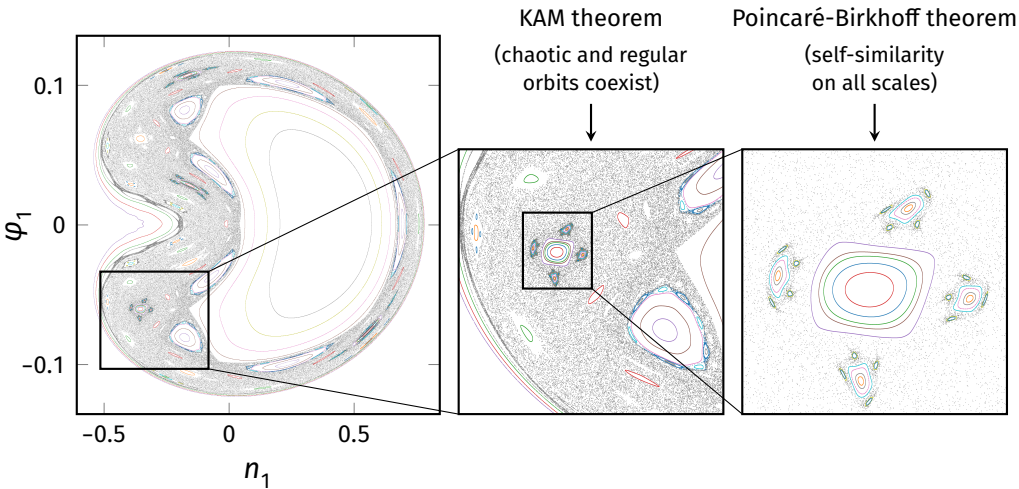
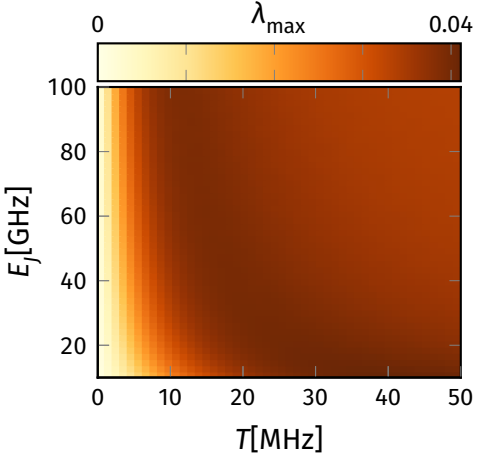


Classical transmon memory

- Is information on initial state $|101010\ldots\rangle$ preserved?



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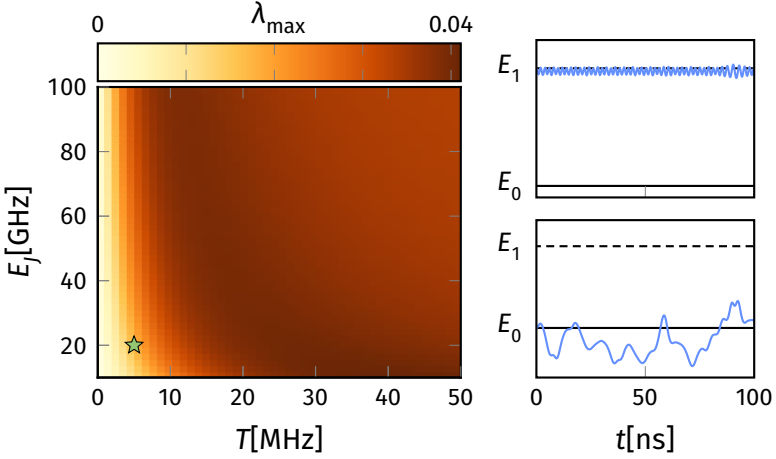

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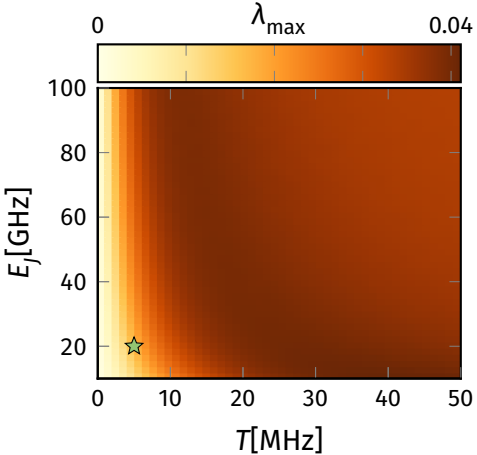

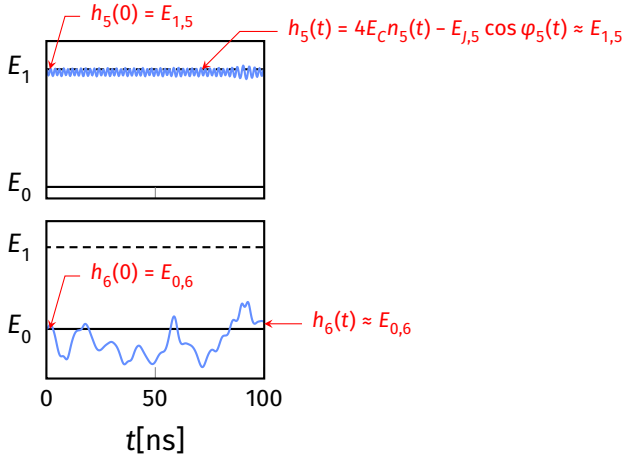

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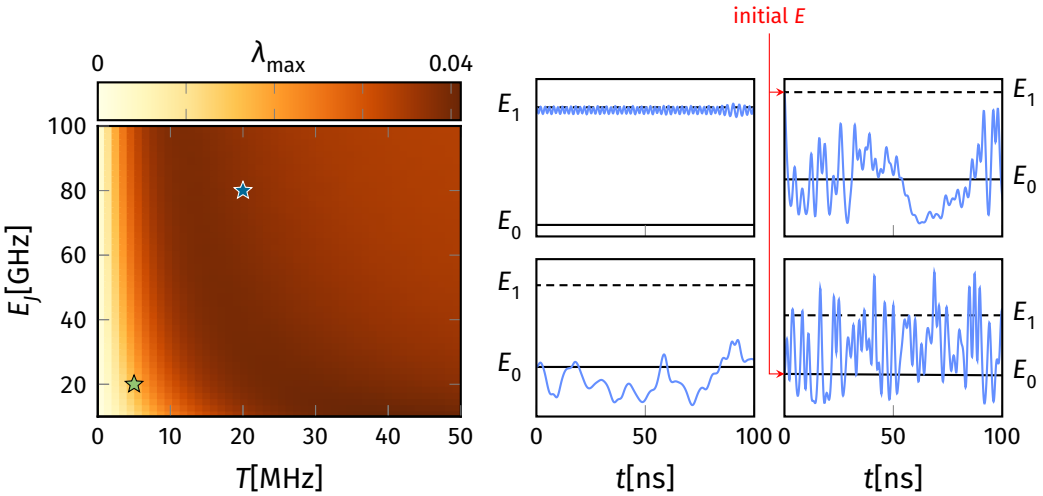
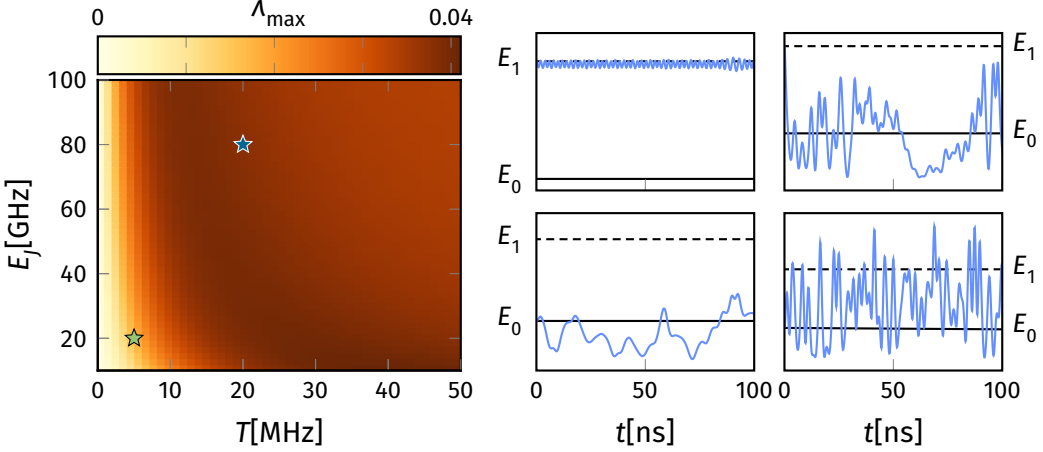


Classical transmon memory

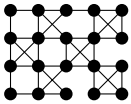
- Is information on initial state $|101010\ldots\rangle$ preserved?
- λ_{max} serves as a quality indicator for the classical 'transmon storage device'.



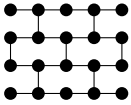
Solving the frequency-crowding problem

Step 1: optimize the geometry. ✔

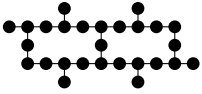
connectivity



Penguin v2,
2018



Penguin v4,
2019



Since **2020**:
Heavy-hexagon lattice,
Falcon and successors.

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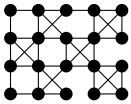

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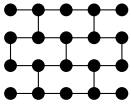

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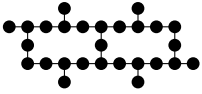

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Low connectivity is not for free!

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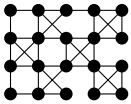

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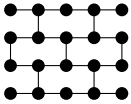

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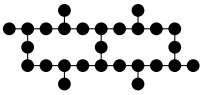

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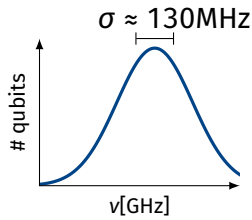
Step 2: frequency patterns.

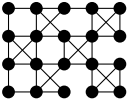
As-fabricated frequency spread:
p(collision-free Falcon) = 0.1%



Solving the frequency-crowding problem

Step 1: optimize the geometry. ✔

connectivity



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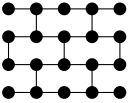

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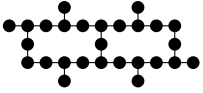

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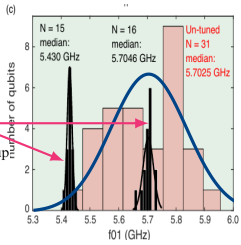

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Step 1: optimize the geometry. ✔

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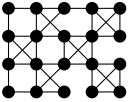

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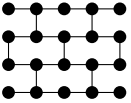

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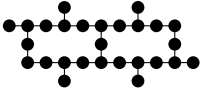

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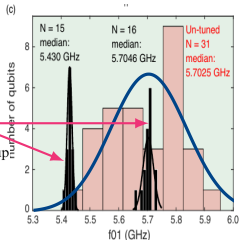

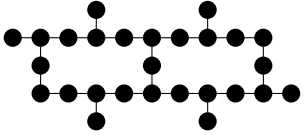

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Step 1: optimize the geometry. ✔

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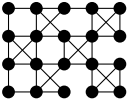

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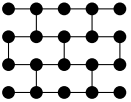

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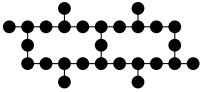

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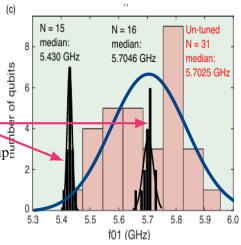
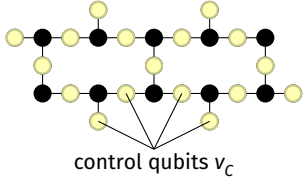
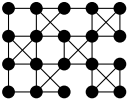




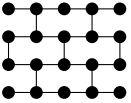
Solving the frequency-crowding problem

Step 1: optimize the geometry. ✔

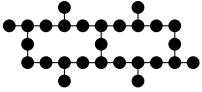
connectivity



Penguin v2,
2018



Penguin v4,
2019



Since **2020**:
Heavy-hexagon lattice,
Falcon and successors.

Step 2: frequency patterns.

As-fabricated frequency spread:
p(collision-free Falcon) = 0.1%

LASIQ-tuned frequency spread:

Laser-annealing Josephson junctions for yielding scaled-up superconducting quantum processors

Jared B. Hertzberg[1,2], Eric J. Zhang[1], Sami Rosenblatt[1], Easwar Magesan[1], John A. Smolin[1], Jeng-Bang Yau[1], Vivekananda P. Adiga[1], Martin Sandberg[1], Markus Brink[1], Jerry M. Chow[1] and Jason S. Orcutt[1]

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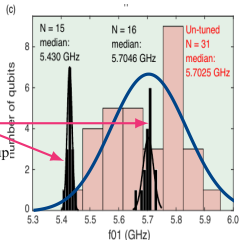

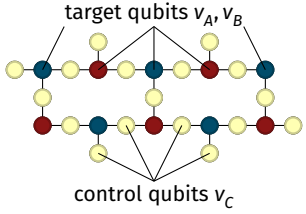

Solving the frequency-crowding problem

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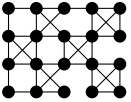

Penguin v2,
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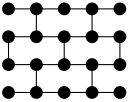
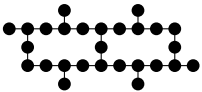


Penguin v4,
2019



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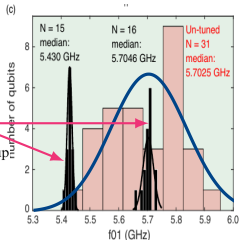
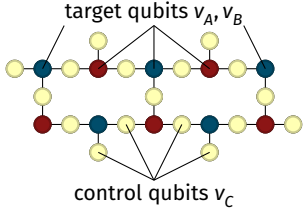
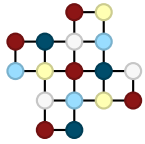
npj Quantum Information 2021



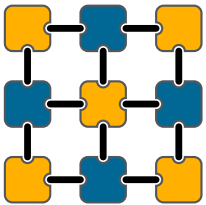


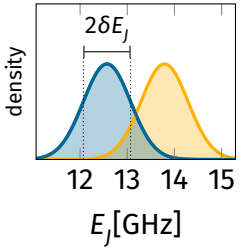
p(c-f Falcon) = 70%



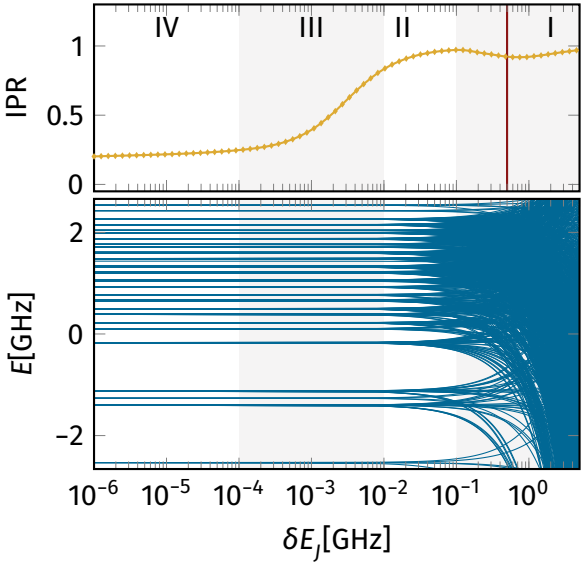
p(c-f Surface 17) = 6%

Frequency engineering - part I

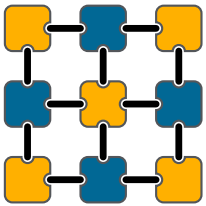


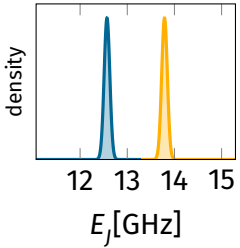


- $\delta E_J \equiv$ LASIQ tuning precision.



Frequency engineering - part I





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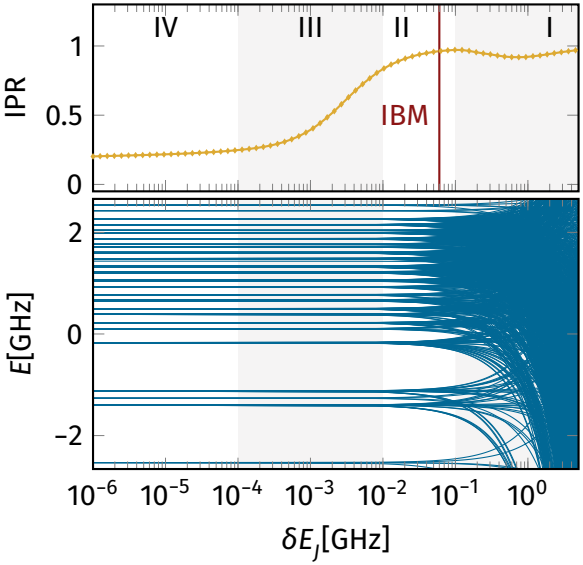
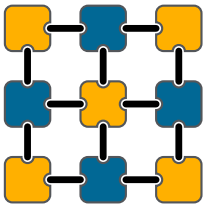
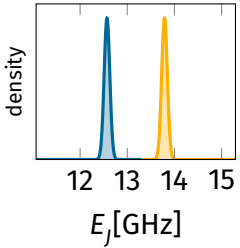
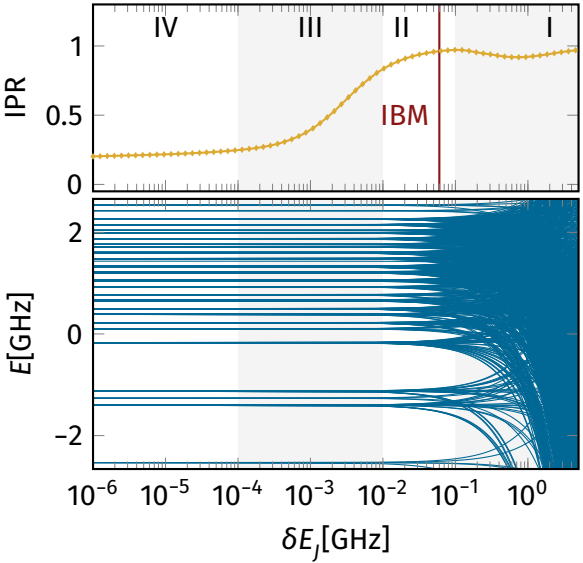


Frequency engineering - part I

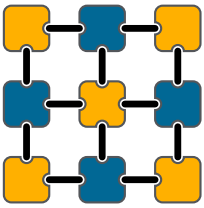


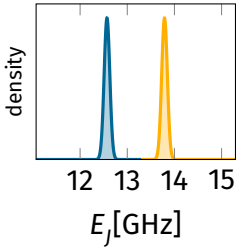


- $\delta E_J \equiv$ LASIQ tuning precision.
- Four different disorder regimes:
  - I: global MBL phase.
  - II: Restructuring of Hilbert space: Permutation **multiplets**.



Frequency engineering - part I





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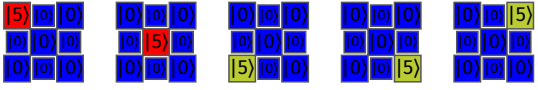
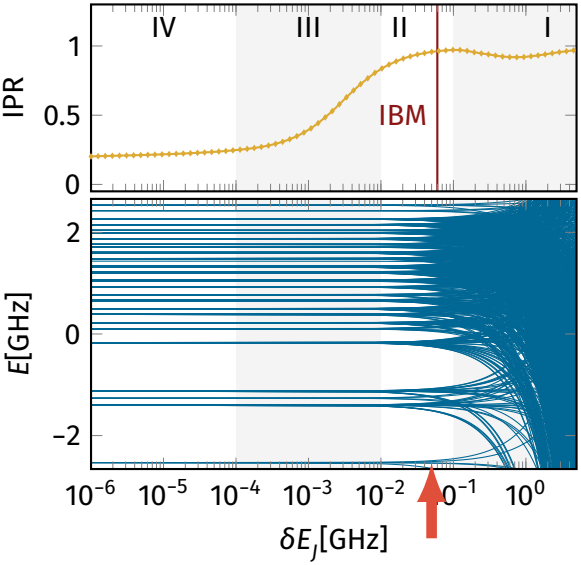
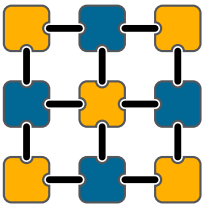
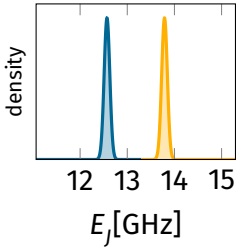




Frequency engineering - part I





- $\delta E_J \equiv$ LASIQ tuning precision.
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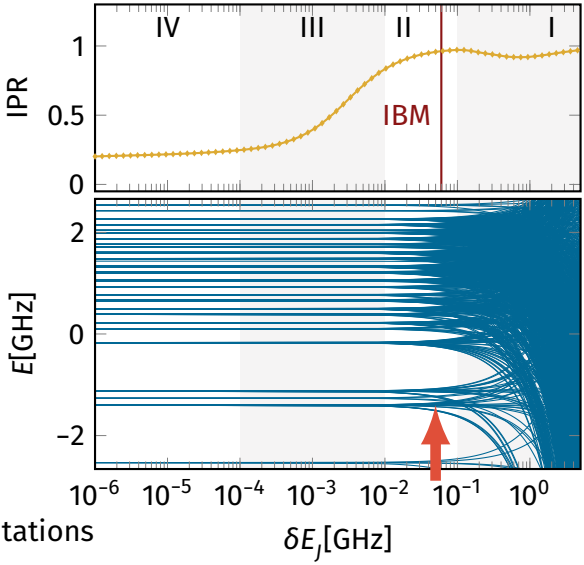
+ 17 other permutations



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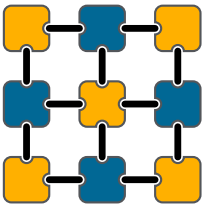

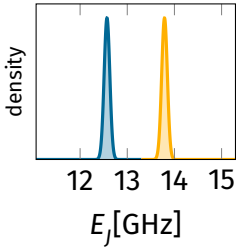

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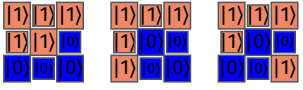
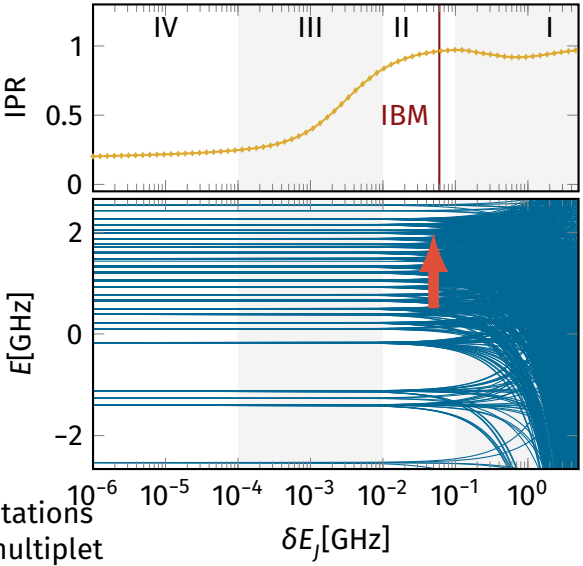
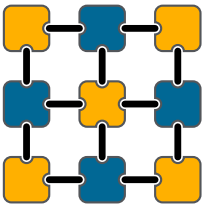
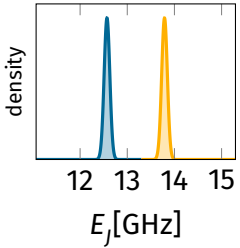


+ 57 other permutations
Computational multiplet



Frequency engineering - part I





- $\delta E_J \equiv$ LASIQ tuning precision.
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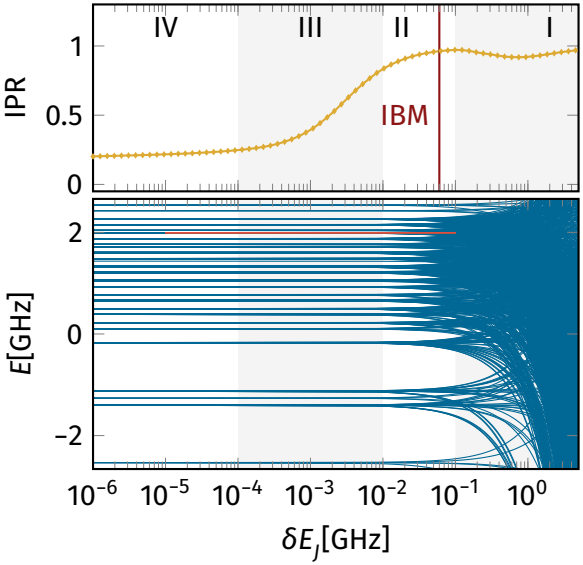
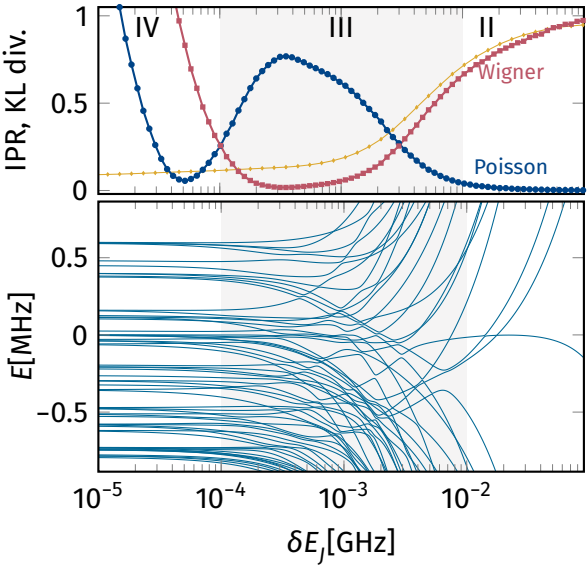
  - III & IV: Zoom in on next slide.



Frequency engineering - part II

- II: Restructuring + Localization.



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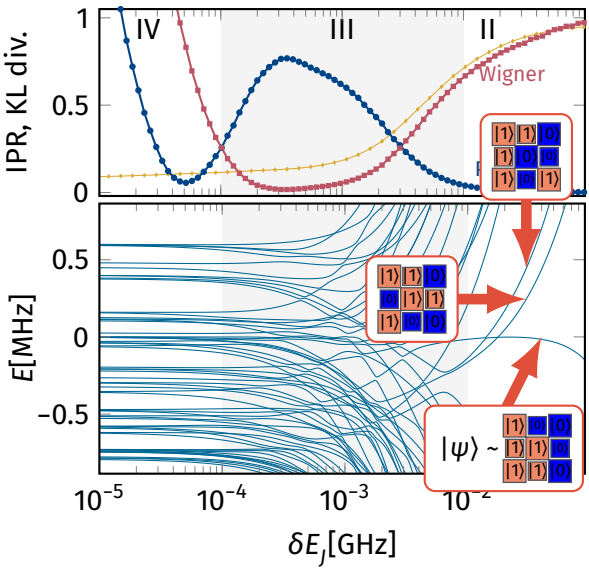
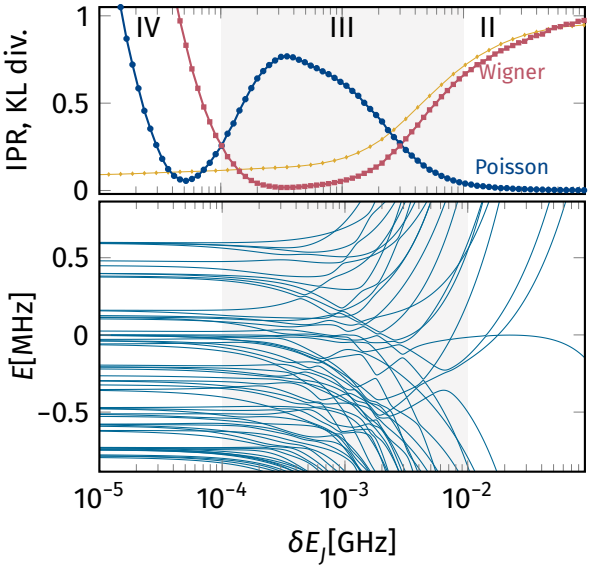


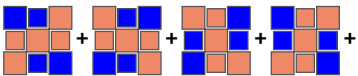
Frequency engineering - part II

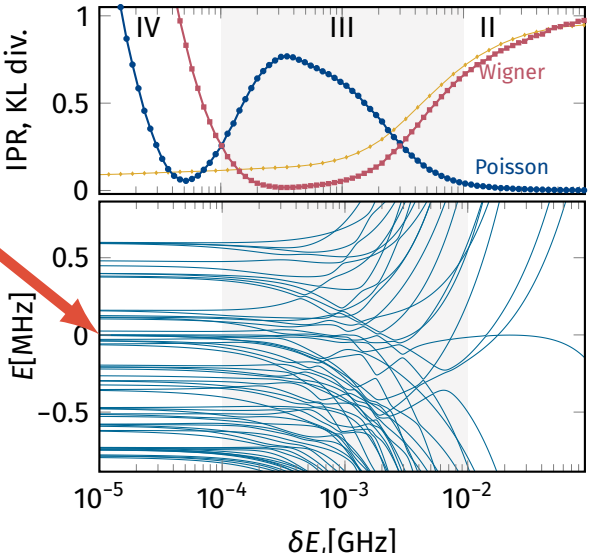
- II: Restructuring + Localization.
- III: Delocalization within multiplets.



Frequency engineering - part II

- II: Restructuring + Localization.
- III: Delocalization within multiplets.
- IV: Symmetries: Molecular multiplets.

$|\psi\rangle =$  + ...



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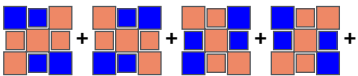
$|\psi\rangle =$  $+ \ldots$

- Scaling: $t_{\text{eff}}/\Delta\nu \longrightarrow \delta E_J \sim T^2$.