Quantum computing
“al dente”

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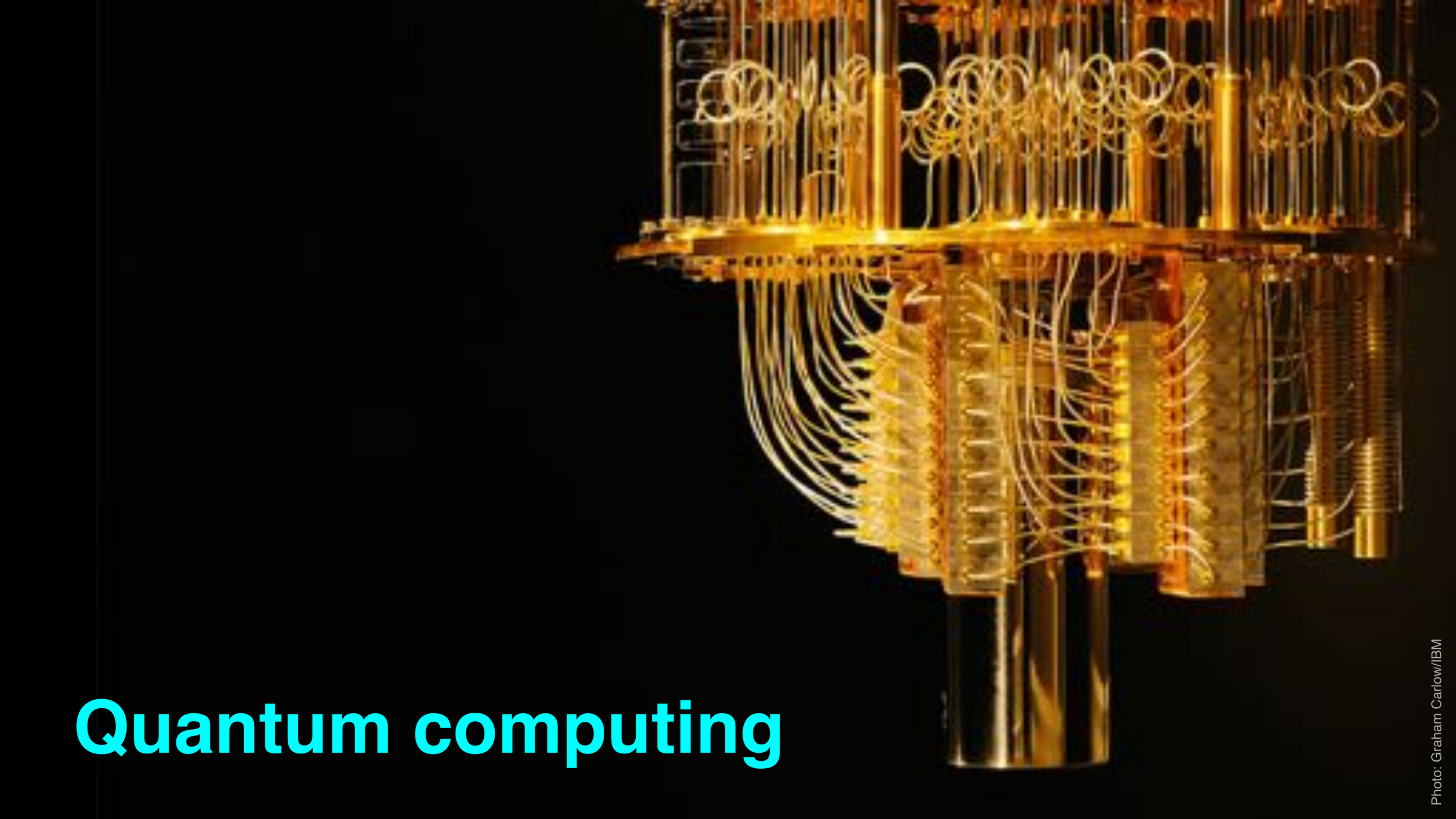
University of Cologne

CRC183
ENTANGLED STATES OF MATTER

Flatiron Institute
New York, July 2022

ML4Q
MATTER AND LIGHT FOR
QUANTUM COMPUTING



Quantum computing

Photo: Graham Carlow/IBM


analog
devices

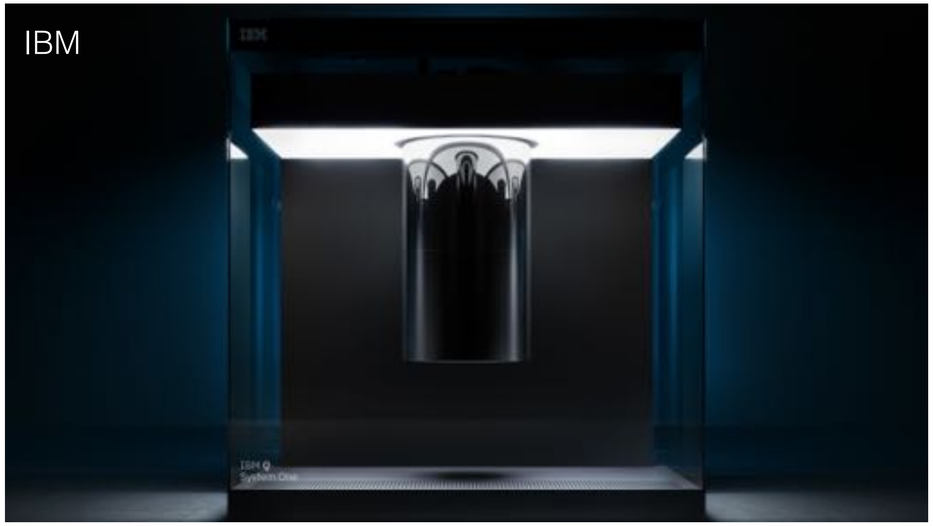
2020's: the NISQ era

An experimental pivot from of a **few pristine qubits**

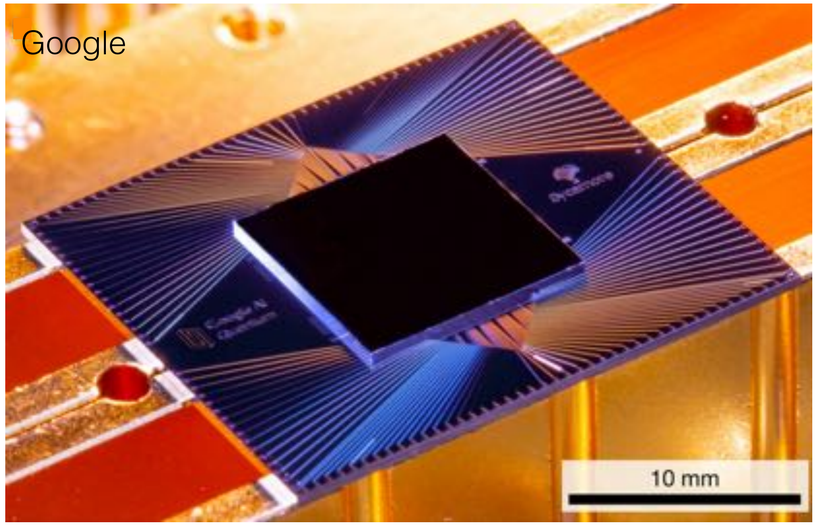
to the realization of circuit architectures of **50-100 qubits**

but tolerating a significant level of **imperfections.**

noisy intermediate scale quantum
devices

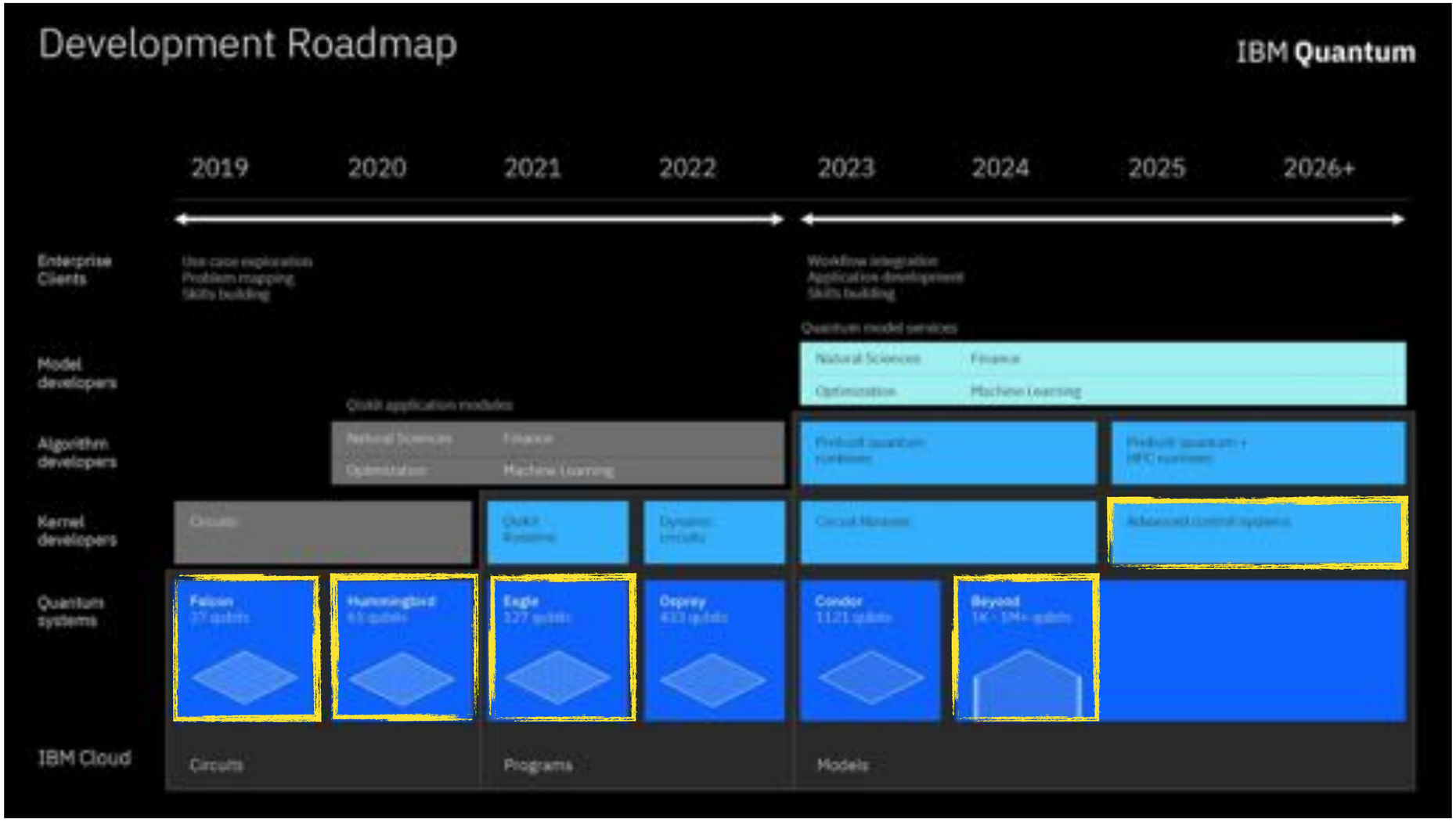


Eagle generation — 127 qubits



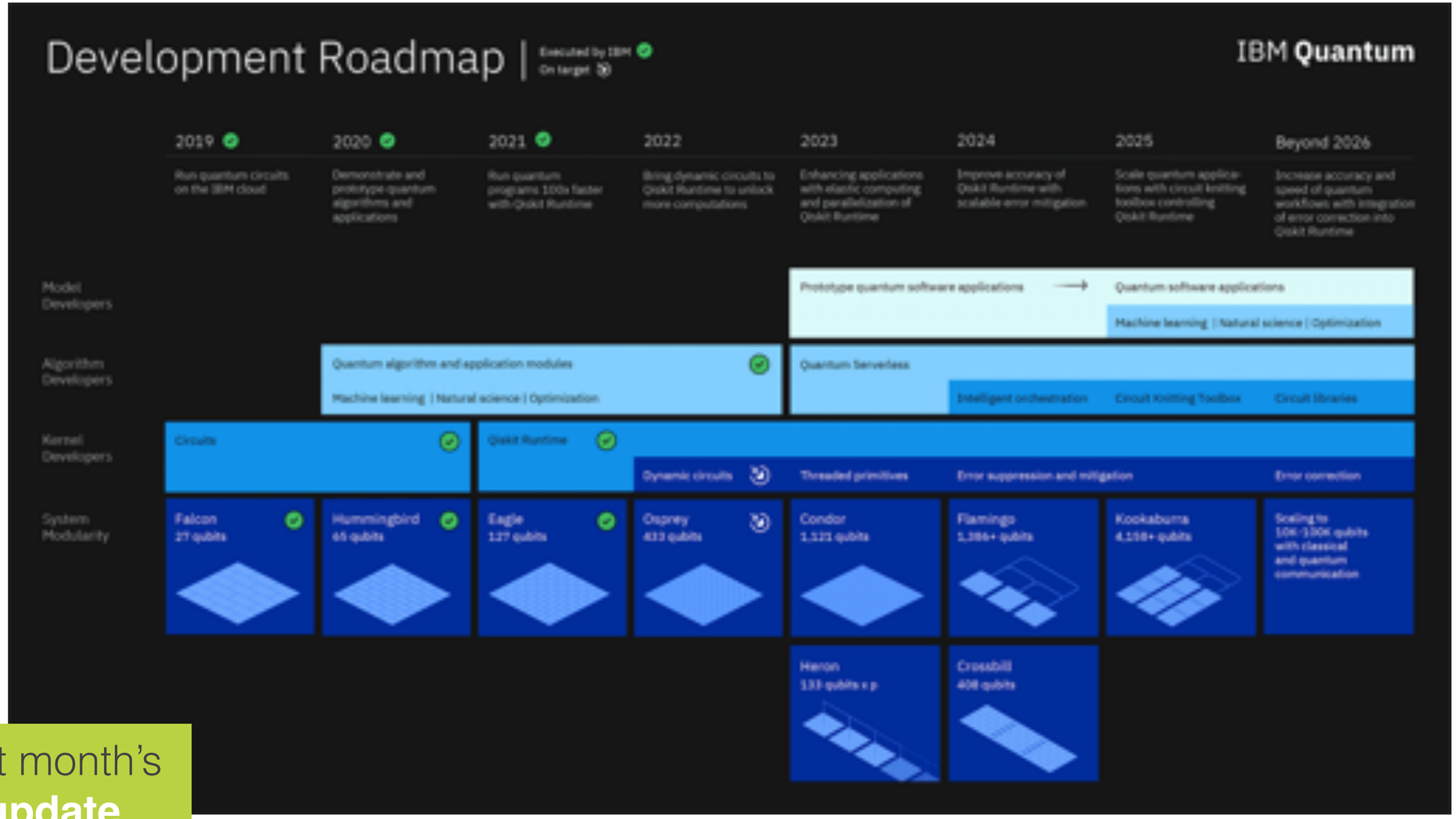
Sycamore chip — 53 qubits

Quantum Computing in the NISQ era



https://research.ibm.com/blog/quantum-development-roadmap

Quantum Computing in the NISQ era

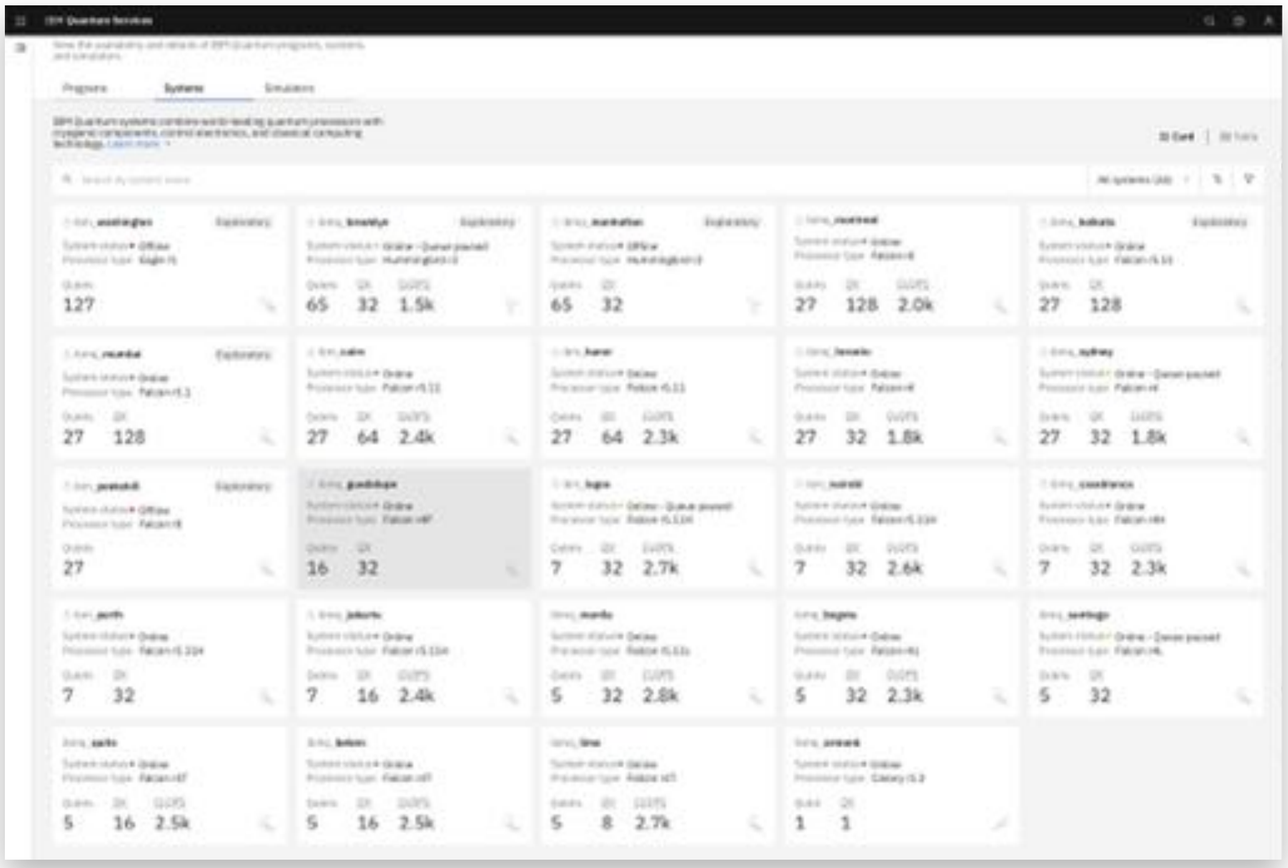


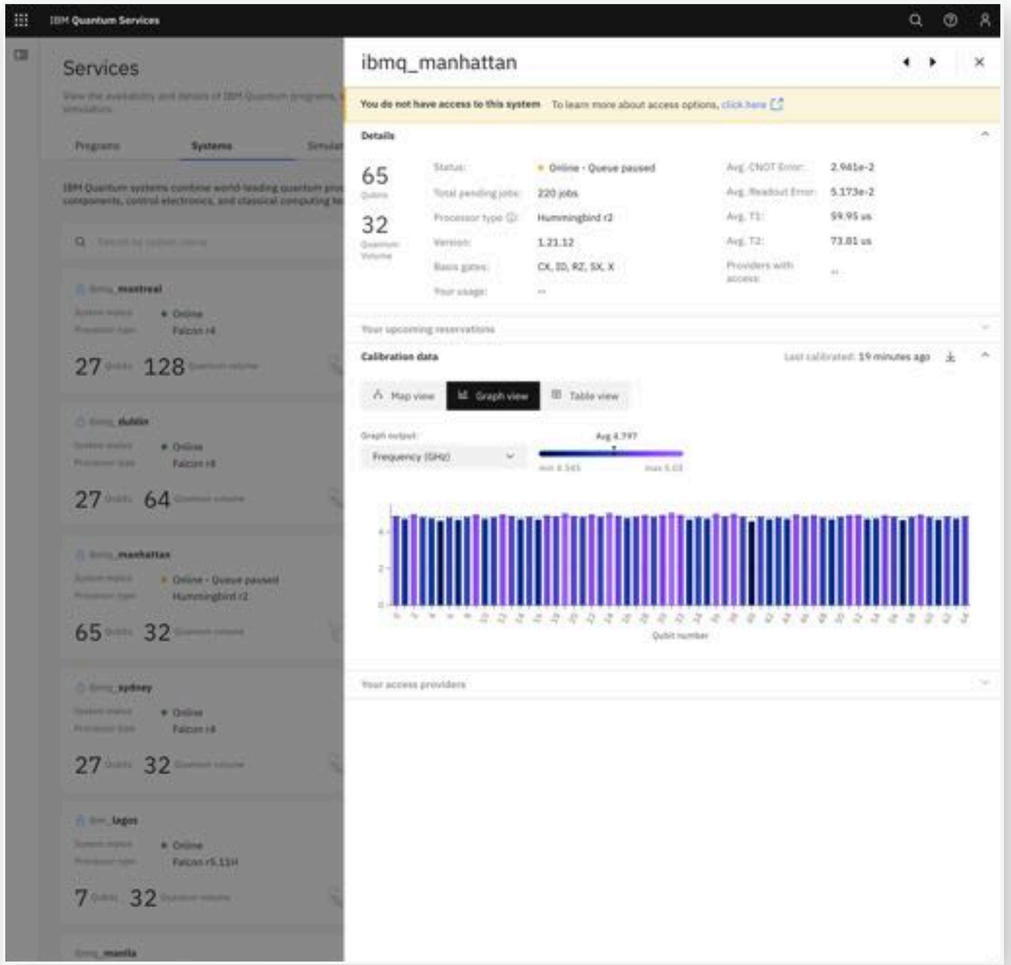
last month's **update**

https://research.ibm.com/blog/quantum-development-roadmap

digital quantum processors

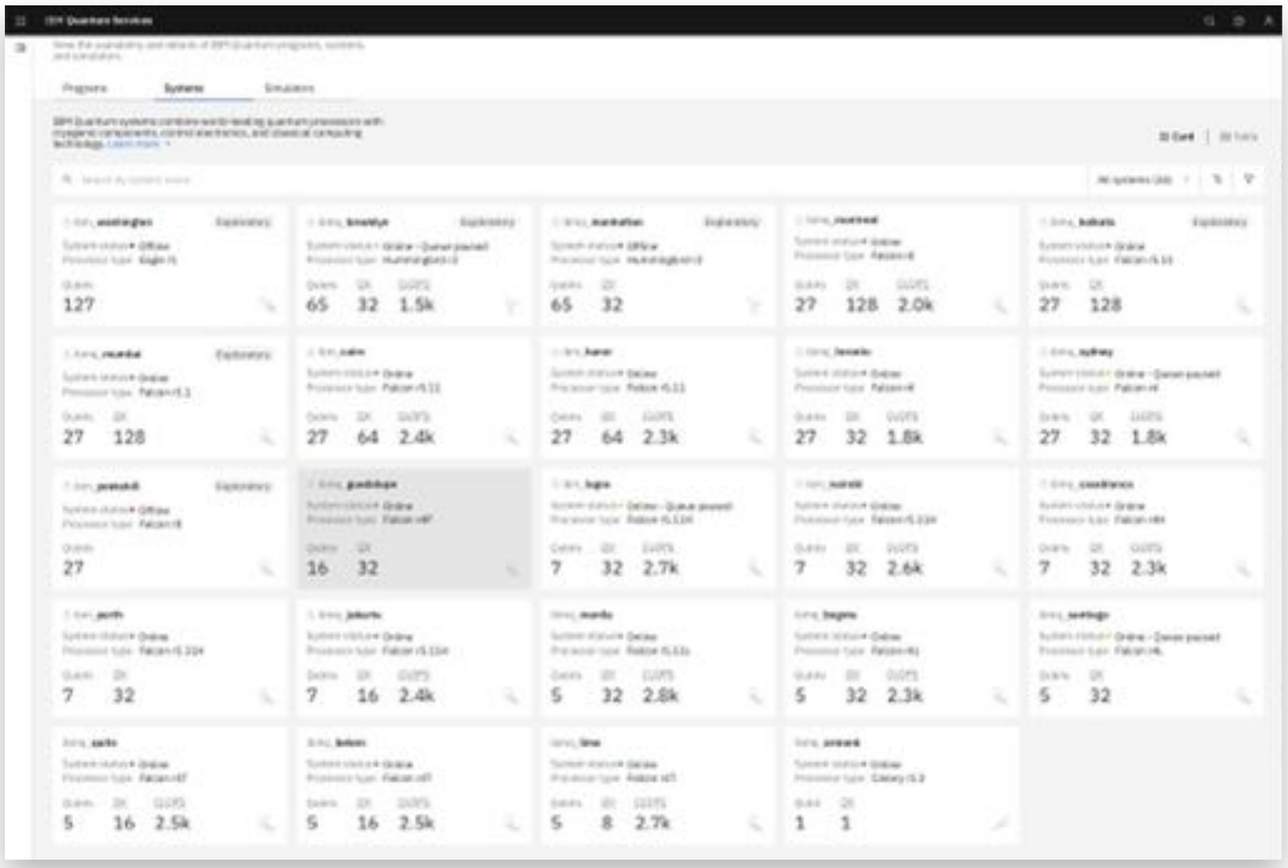
IBM quantum cloud devices with **5-127 qubits**

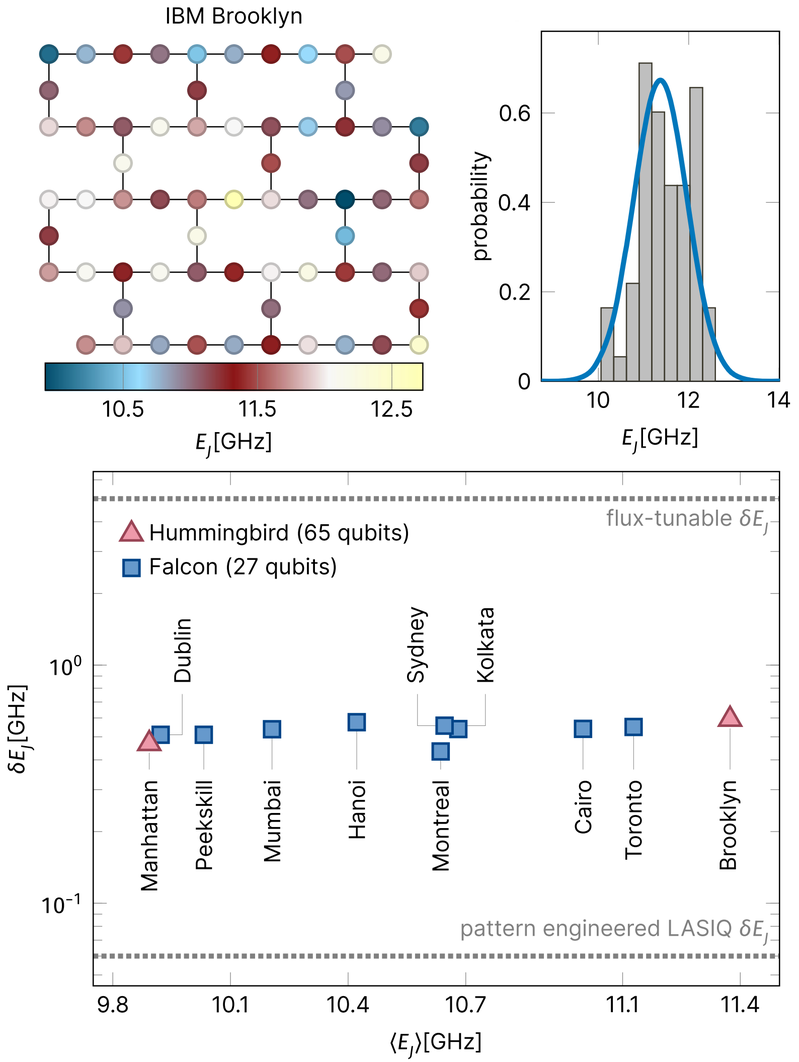




digital quantum processors

IBM quantum cloud devices with **5-127 qubits**



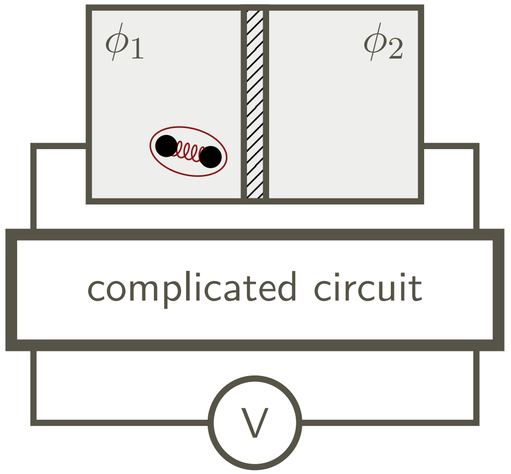


single transmon qubit

$$\hat{H}_{\mathrm{ST}} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\phi}$$

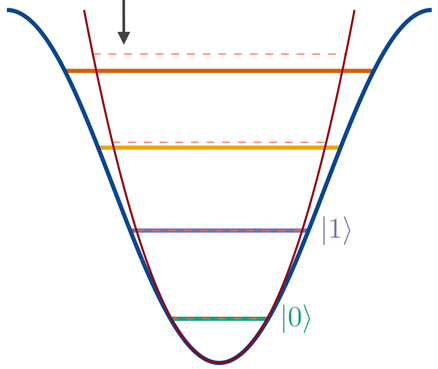
charging energy

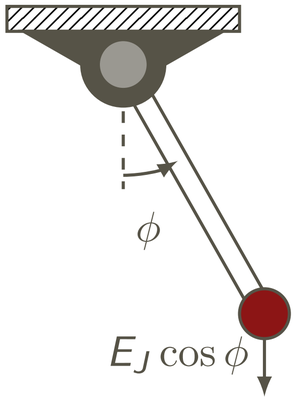
Josephson tunneling



anharmonicity

level spacings converge **algebraically** to equidistance

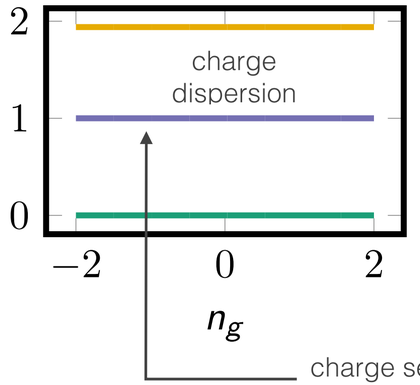




anharmonic oscillator

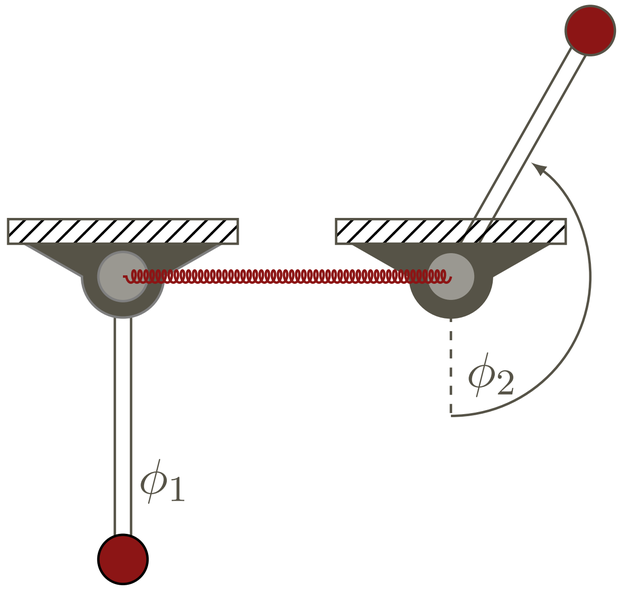
charge insensitive

cooper pair box

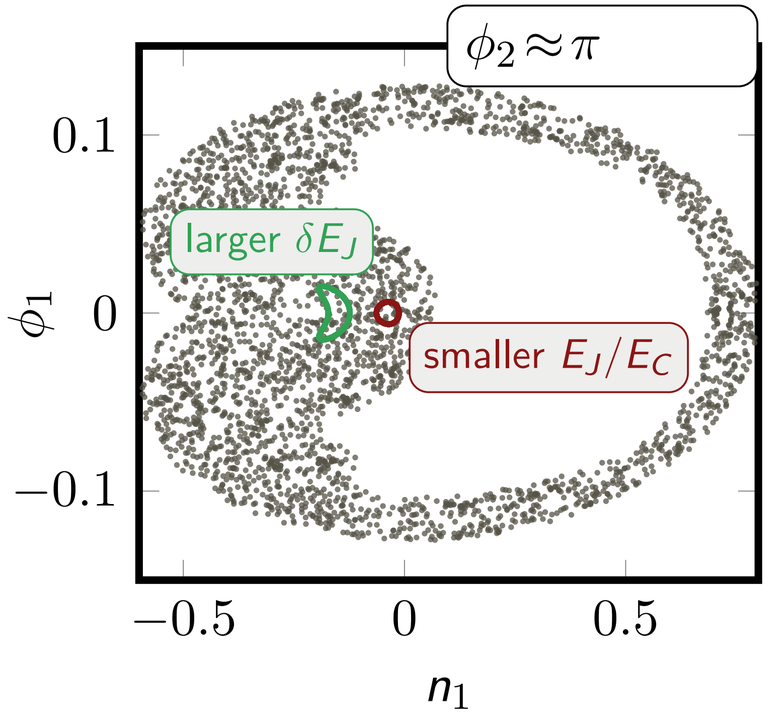


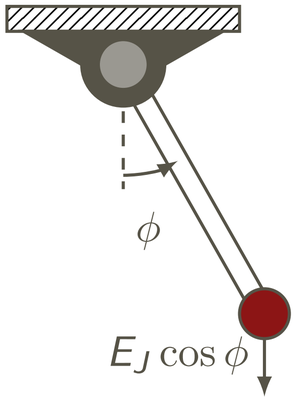
charge sensitivity decays **exponentially**

two classical transmon qubits



coupled oscillators

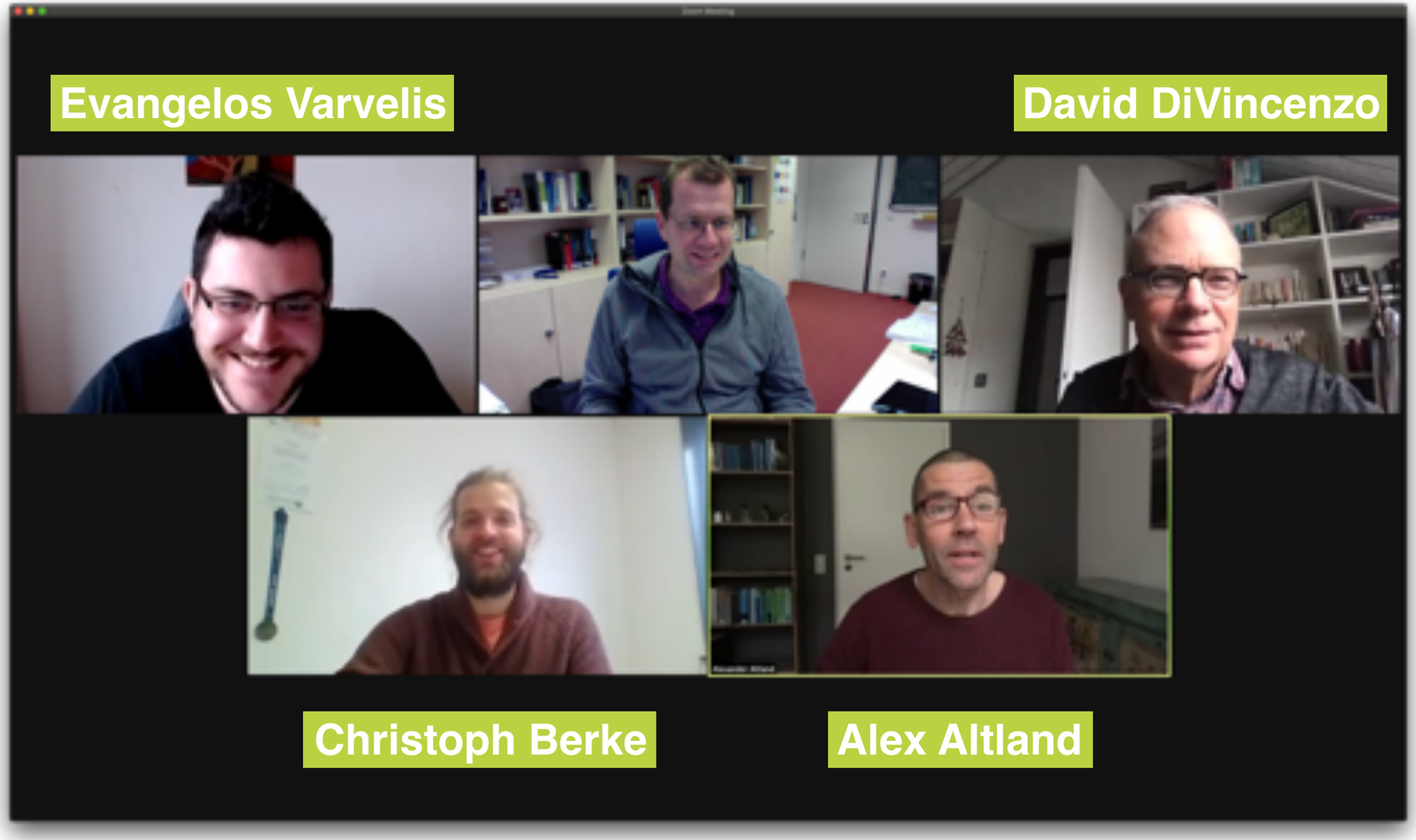




anharmonic oscillator

More quantitative analysis for 10 transmons (BSc thesis S. Börner, 2020)
Classical chaos on time scales way **below the typical coherence times**.

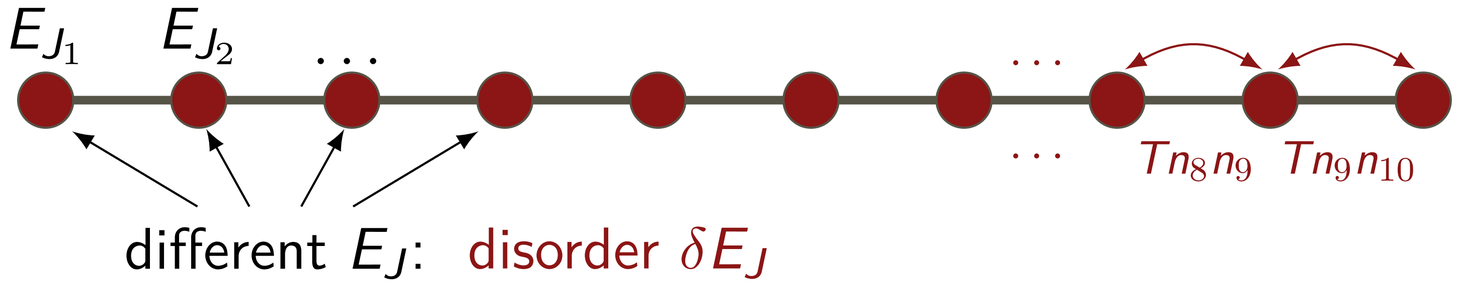
meet the team



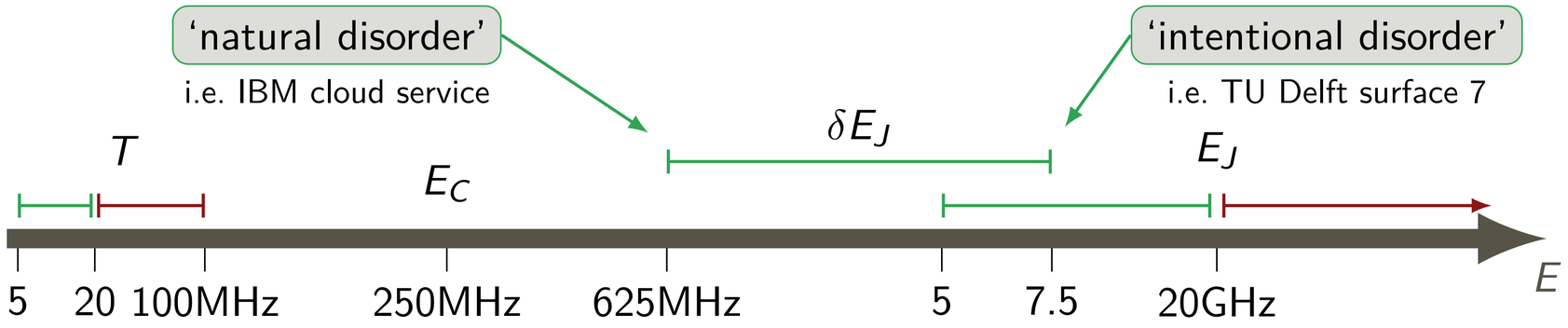
many transmon qubits

$$H = 4E_C \sum_i n_i^2 - \sum_i E_{J_i} \cos\phi_i \; + T \sum_{<i,j>} n_i n_j$$

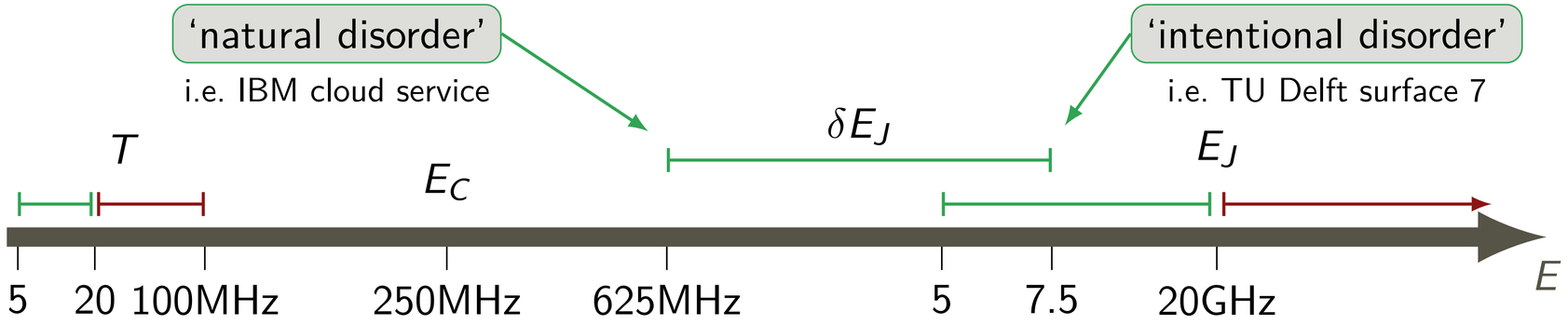
Capacitive coupling

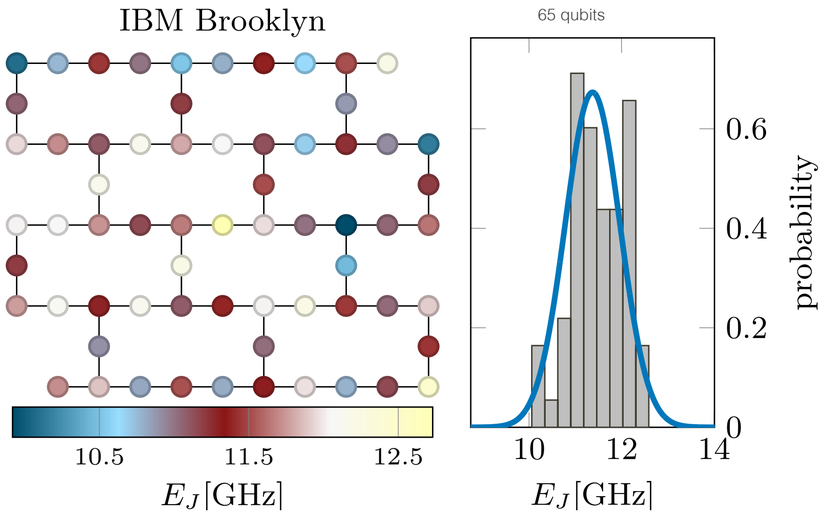


relevant **energy scales**



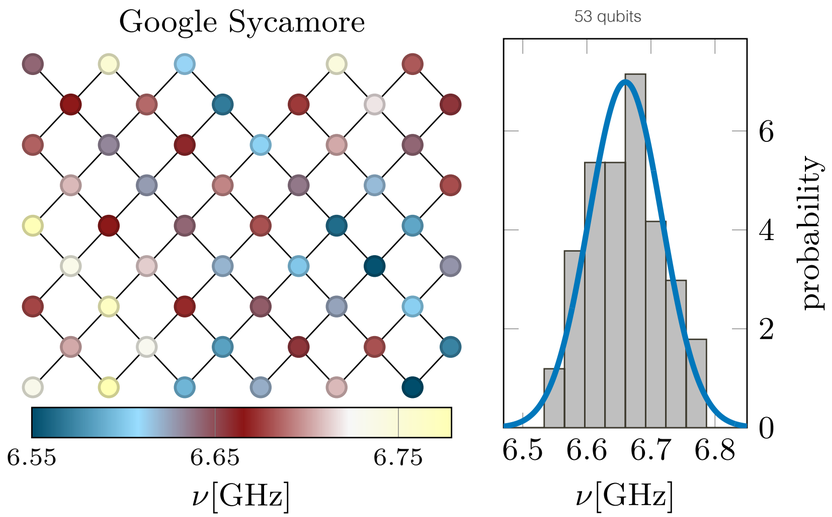
disorder / experimental settings





natural disorder **IBM** $\delta\nu \approx E_C/2$

Google/Delft $\delta\nu \approx 6E_C$ intentional disorder



many-body perspective

$$H = 4E_C \sum_i n_i^2 - \sum_i E_{J_i} \cos\phi_i \; + T \sum_{<i,j>} n_i n_j$$

series expansions
random-wave approximation

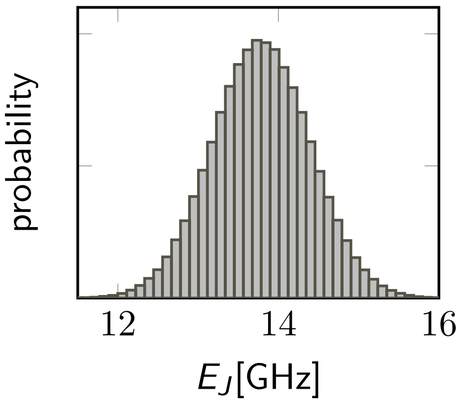
$$H = \sum_i \nu_i \, a_i^\dagger a_i - \frac{E_C}{2} \sum_i a_i^\dagger a_i (a_i^\dagger a_i + 1) + \sum_{\langle i,j \rangle} t_{ij} (a_i a_j^\dagger + a_i^\dagger a_j)$$

attractive **Bose-Hubbard** model

$$\nu_i = \sqrt{8 E_{J_i} E_C}$$

large → small

$$t_{ij} = \frac{T}{4\sqrt{2E_C}} \sqrt[4]{E_{J_i} E_{J_j}}$$



plus disorder
via variations of Josephson energy E_J

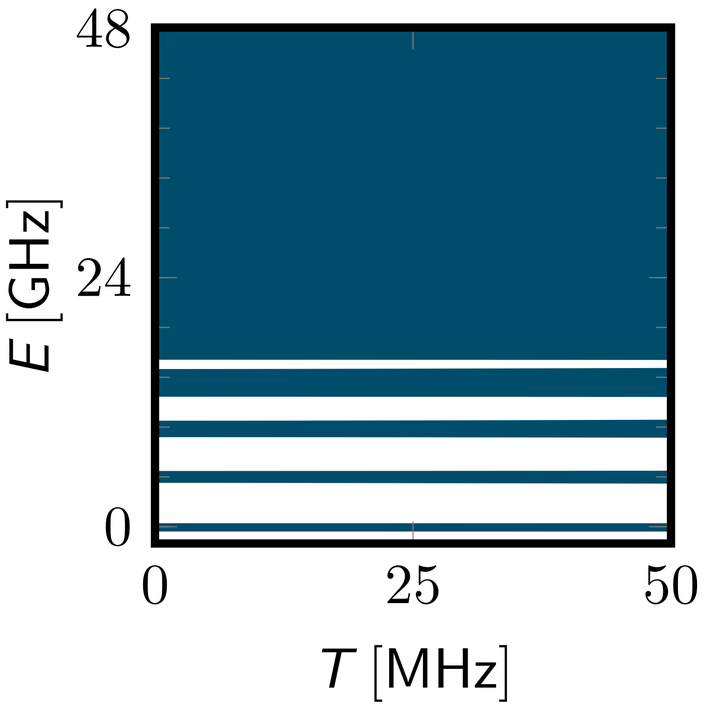
reference model for bosonic
many-body localization

energy spectra – spaghetti plots

$$H = 4E_C \sum_i n_i^2 - \sum_i E_{J_i} \cos\phi_i \; + T \sum_{<i,j>} n_i n_j$$

Capacitive coupling

$T \neq 0$
(finite coupling)



energy spectra – spaghetti plots

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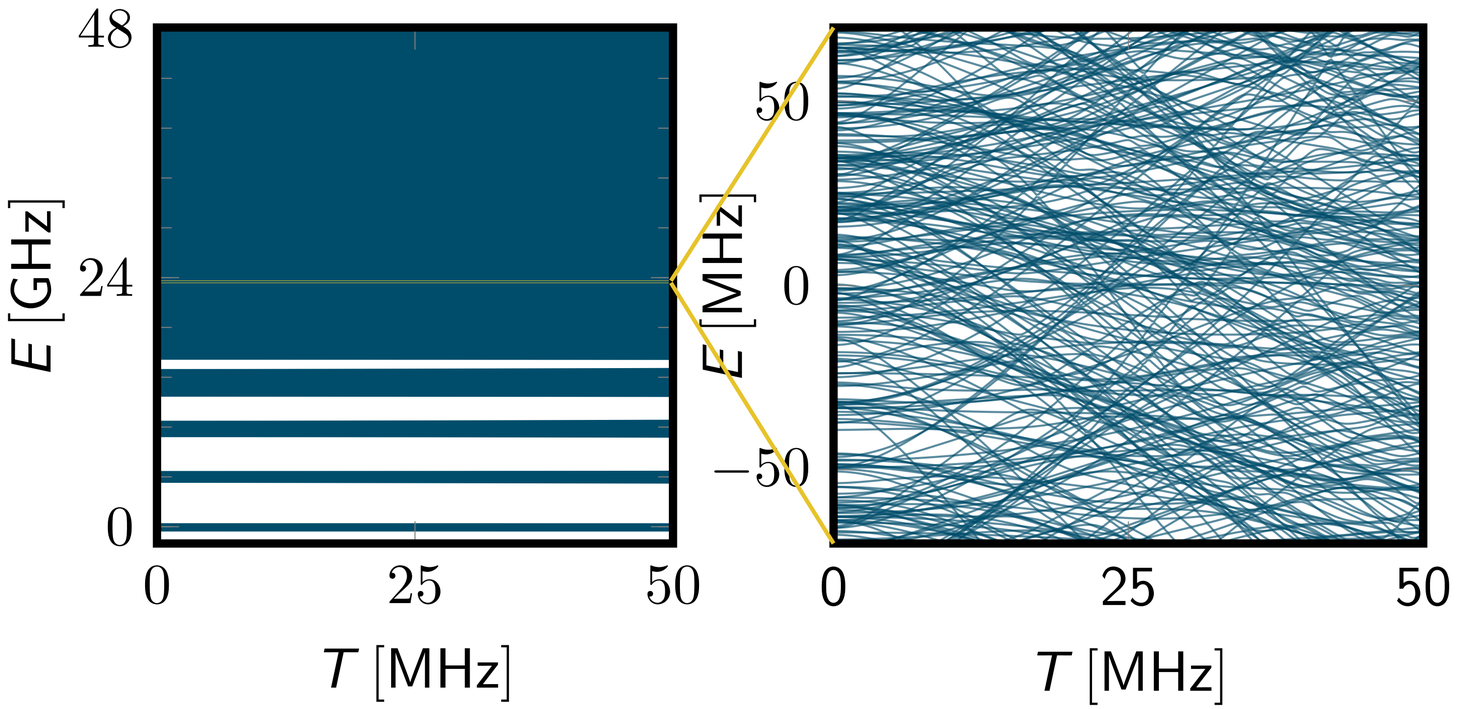

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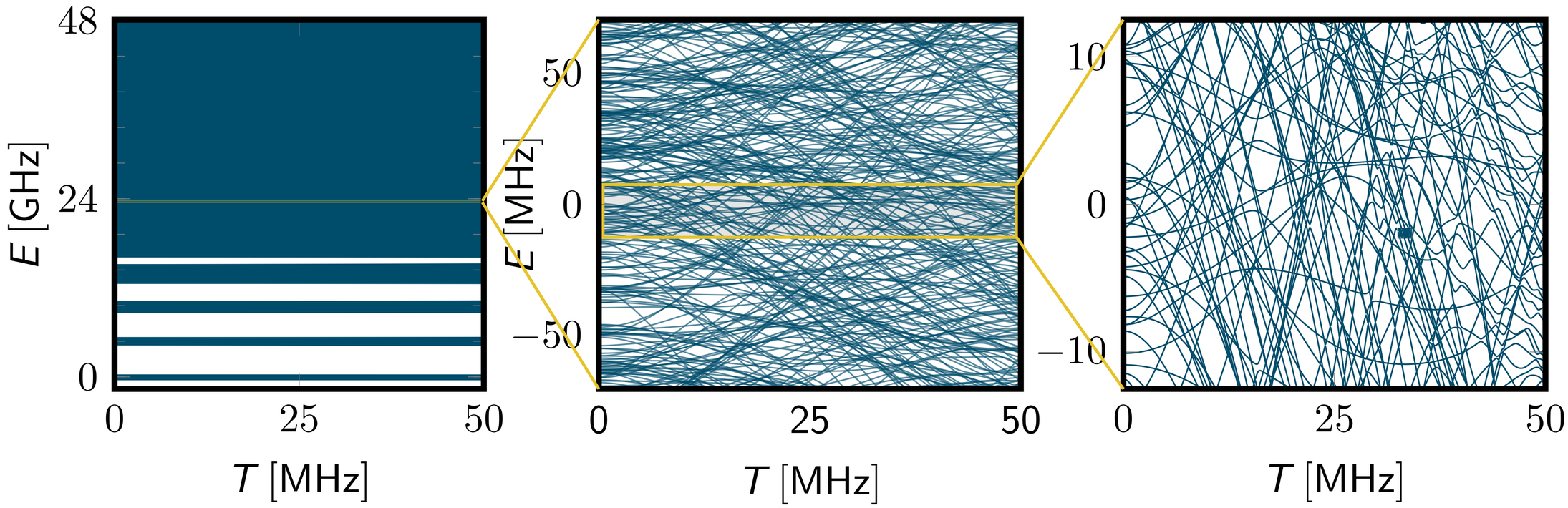
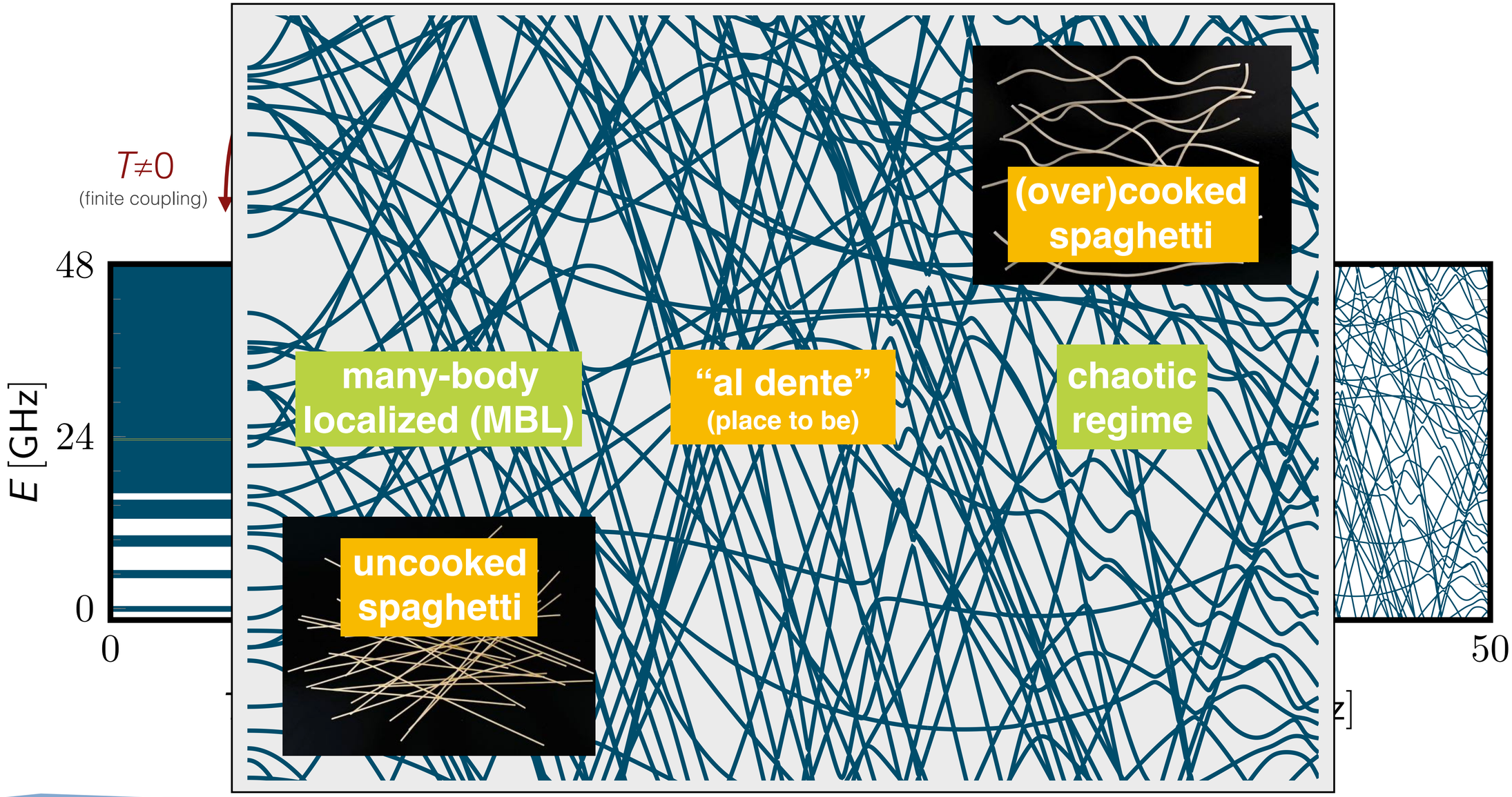


energy spectra – spaghetti plots



We need to find a **subtle balance**

– disorder can **protect qubits**,

but **entangling / coupling qubits** in its

presence might lead to quantum chaos.

quantifying chaos

spectral statistics

level statistics

$r_n = \Delta\epsilon_{n+1}/\Delta\epsilon_n$

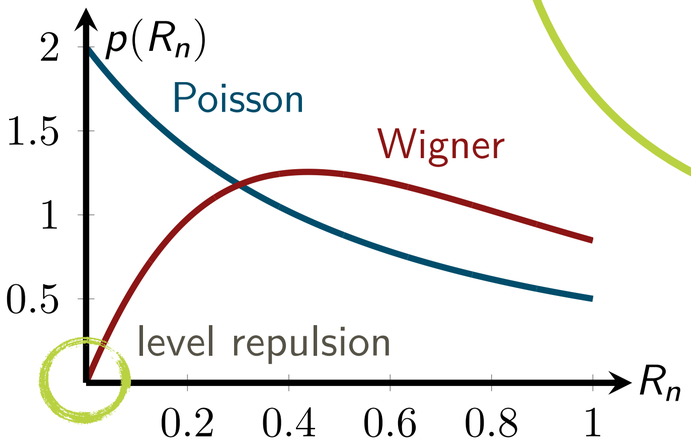
$\Delta\epsilon_{n+1}$

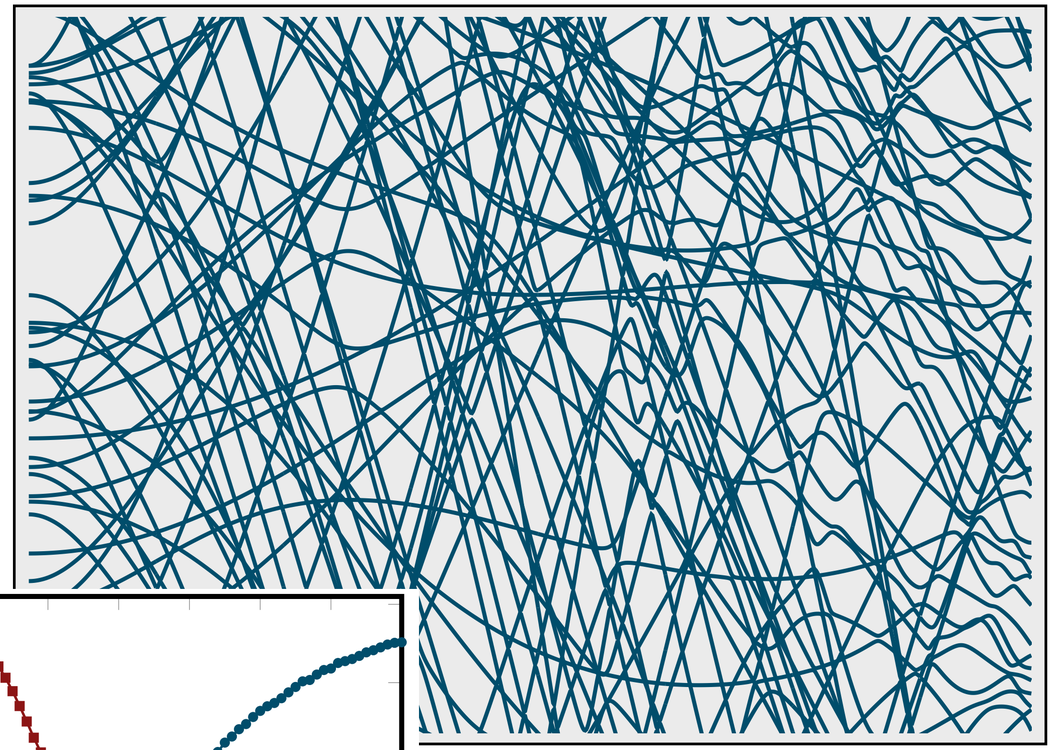
$\Delta\epsilon_n$

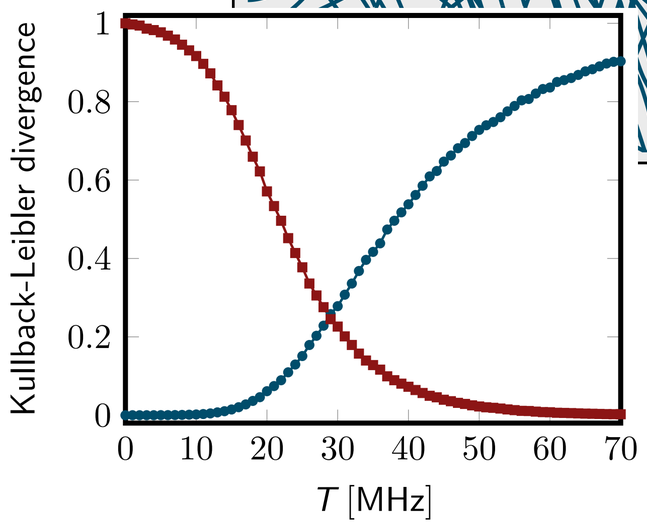
Kullback-Leiber divergence

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

data — theory







quantifying chaos

spectral statistics

level statistics

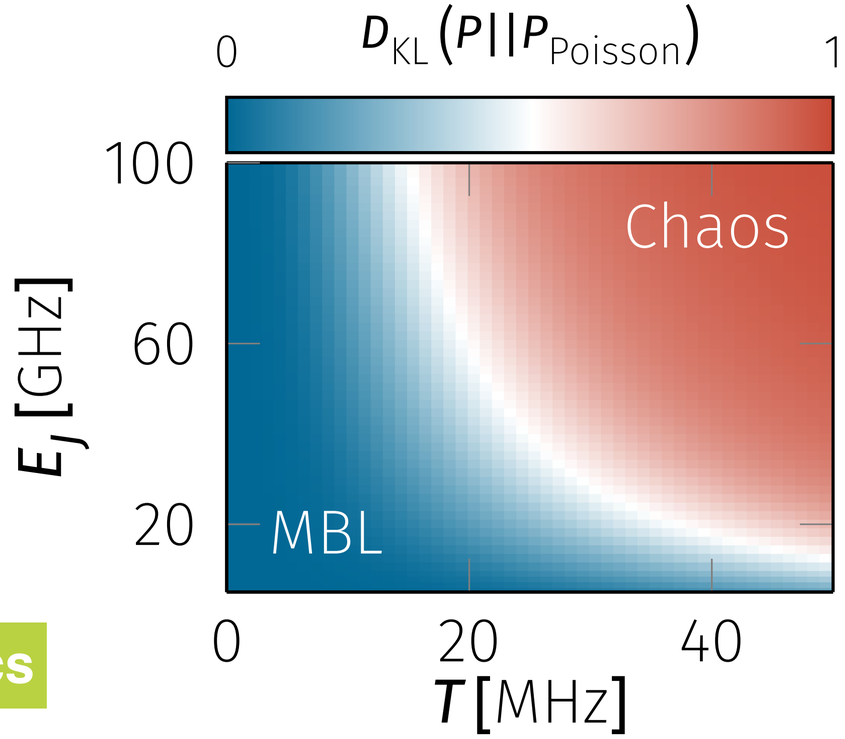
$r_n = \Delta\epsilon_{n+1}/\Delta\epsilon_n$

$\Delta\epsilon_{n+1}$, $\Delta\epsilon_n$

Kullback-Leiber divergence

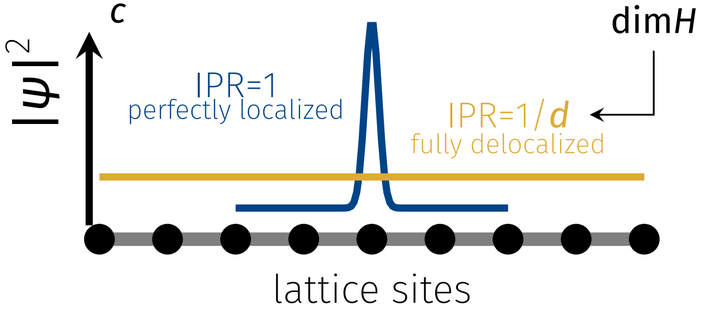
$$D_{KL}(P||Q) = \sum_k p_k \log\left(\frac{p_k}{q_k}\right)$$

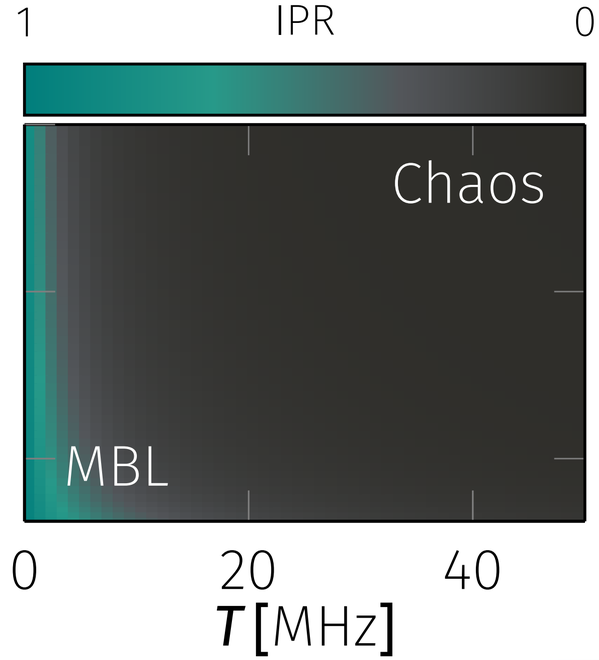
data, theory



wavefunction statistics

$$IPR = \sum_c |\langle c|\psi\rangle|^4$$



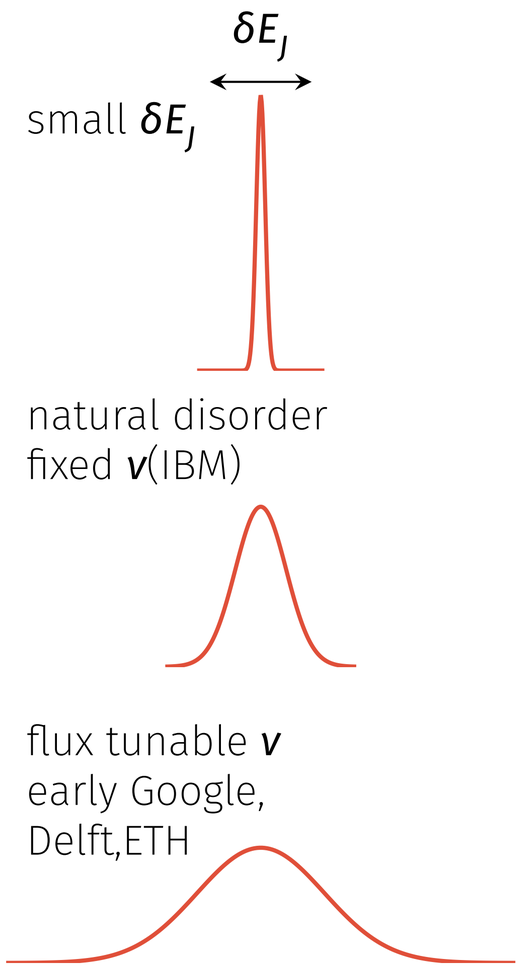


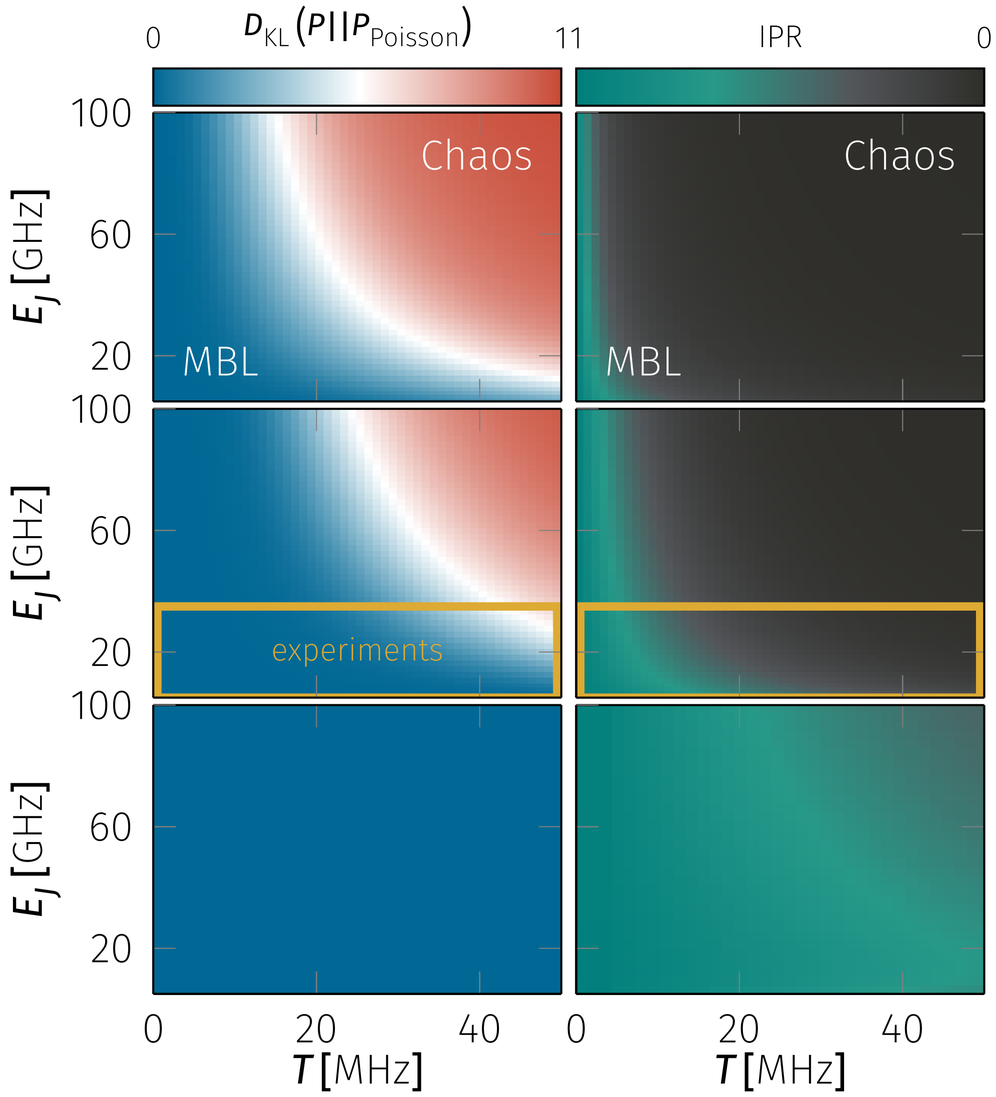
quantifying chaos

patterned disorder

natural disorder

tunable disorder



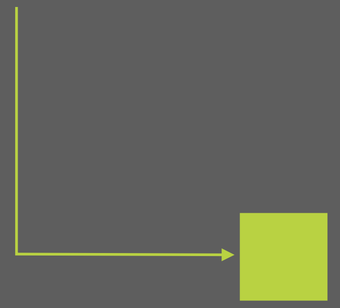


computational states

non-computational subspace

$$\dim \mathcal{H} \approx 8 \cdot 10^8$$

$$\dim \mathcal{H}_{\mathrm{cs}} \approx 3 \cdot 10^6$$



computational subspace

correlations

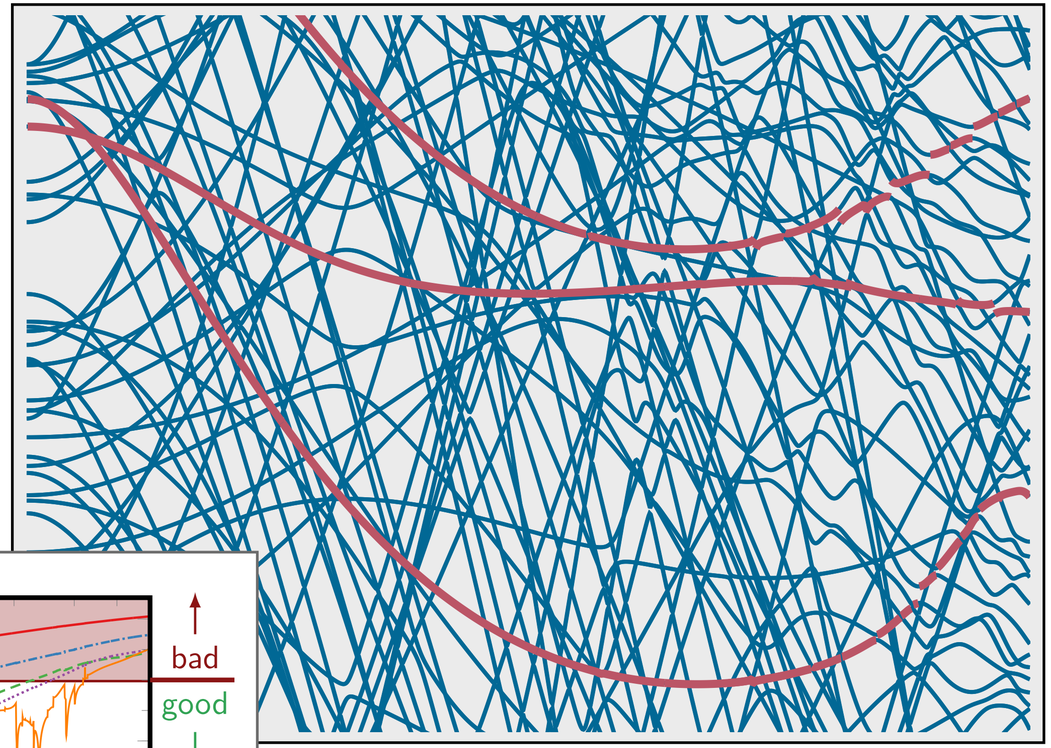
ZZ couplings & more

p-qubits and **I**-qubits

τ - Hamiltonian

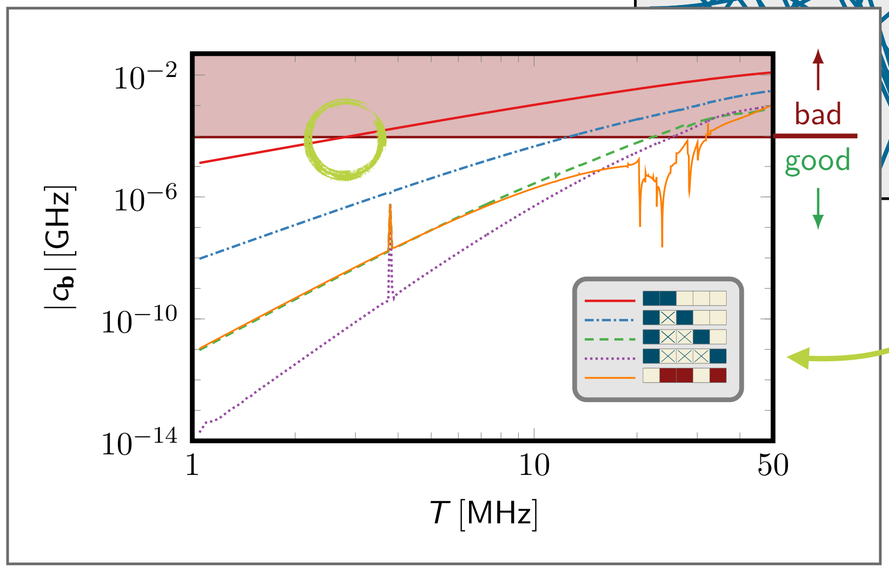
of many-body localization

$$H = \sum_i h_i \tau_i^z + \sum_{ij} J_{ij} \tau_i^z \tau_j^z + \sum_{ijk} K_{ijk} \tau_i^z \tau_j^z \tau_k^z + \cdots$$



I-qubits

Walsh transform



PHYSICAL REVIEW B **90**, 174202 (2014)

Phenomenology of fully many-body-localized systems

David A. Huse,[1] Rahul Nandkishore,[2] and Vadim Oganesyan[3,4]
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[2]*Princeton Center for Theoretical Science, Princeton University, Princeton, New Jersey 08544, USA*
[3]*Department of Engineering Science and Physics, College of Staten Island, CUNY, Staten Island, New York 10314, USA*
[4]*Initiative for the Theoretical Sciences, The Graduate Center, CUNY, New York, New York 10016, USA*
(Received 27 August 2014; published 13 November 2014)

PHYSICAL REVIEW LETTERS **125,** 200504 (2020)

Suppression of Unwanted *ZZ* Interactions in a Hybrid Two-Qubit System

Jaseung Ku,[1] Xuexin Xu,[2,3] Markus Brink,[4] David C. McKay,[4] Jared B. Hertzberg,[4] Mohammad H. Ansari,[2,3] and B. L. T. Plourde[1,*]
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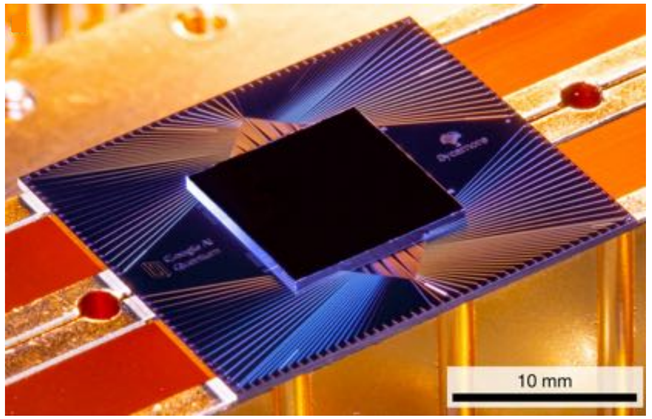
(Received 8 April 2020; accepted 2 September 2020; published 11 November 2020)

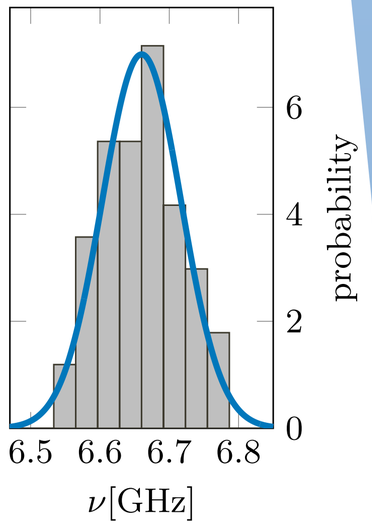
disorder engineering

or how much imperfection should we really tolerate?

Google quantum processor



Google's **frequency engineering**



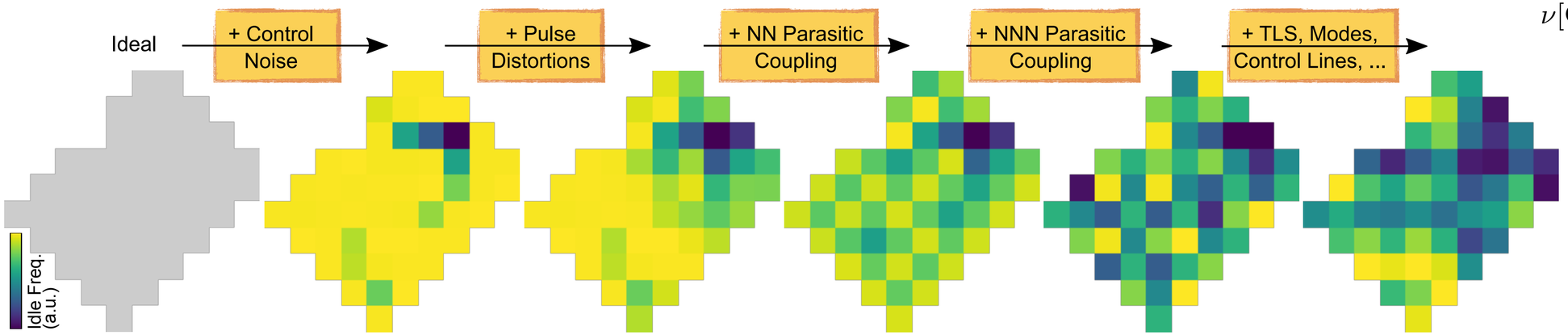


FIG. S12. **Idle frequency solutions found by our Snake optimizer with different error mechanisms enabled.** The optimizer makes increasingly complex tradeoffs as more error mechanisms are enabled. These tradeoffs manifest as a transition from a structured frequency configuration into an unstructured one. Similar tradeoffs are simultaneously made in optimizing interaction and readout frequencies. Optimized idle and interaction operating frequencies are shown in Figure S13 and optimized readout frequencies are shown in Figure S20. Color scales are chosen to maximize contrast. Grey indicates that

IBM quantum processors

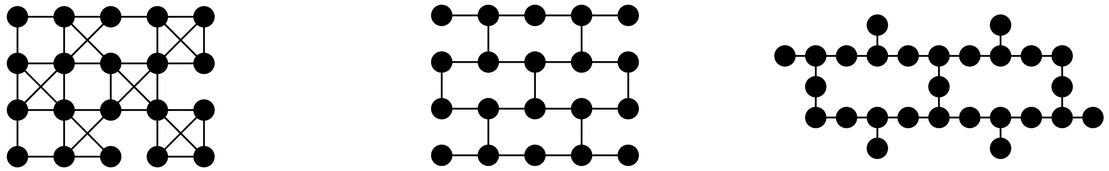
IBM's strategy to avoid

frequency crowding

pattern engineering

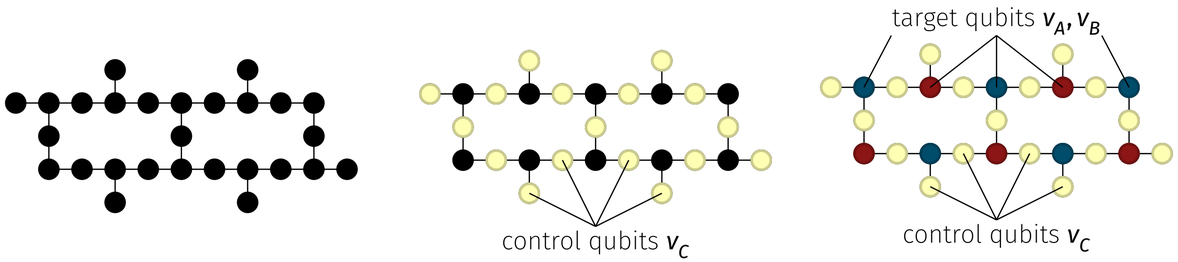
via laser annealing

- optimize device geometry

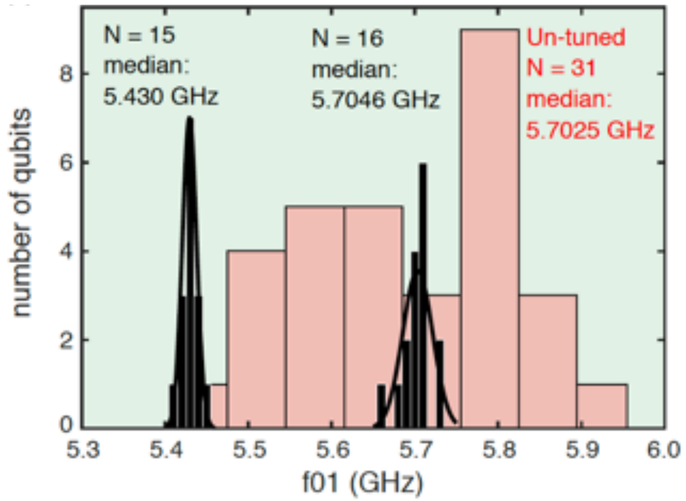


2018 2019 2020

- frequency patterns



uniform A – B A – B – C



npj | Quantum Information 19 August 2021

ARTICLE OPEN

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

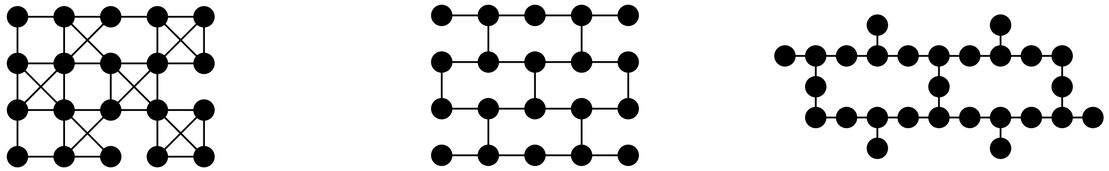
Jared B. Hertzberg[1✉], Eric J. Zhang[1], Sami Rosenblatt[1], Easwar Magesan[1], John A. Smolin[1], Jeng-Bang Yau[1], Vivekananda P. Adiga[1], Martin Sandberg[1], Markus Brink[1], Jerry M. Chow[1] and Jason S. Orcutt[1]

IBM quantum processors

IBM's strategy to avoid

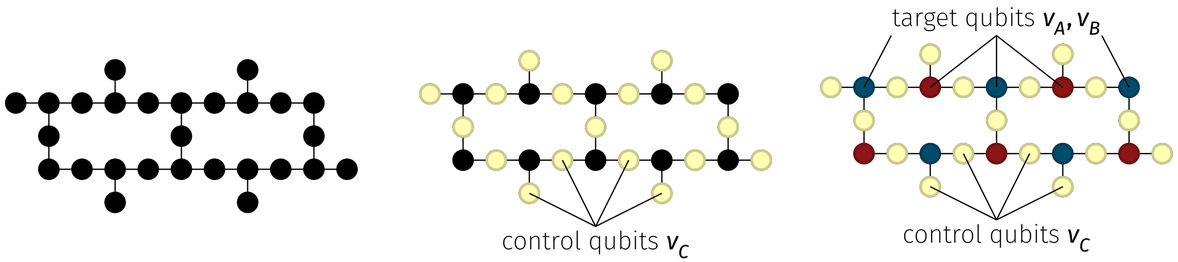
frequency crowding

- optimize device geometry

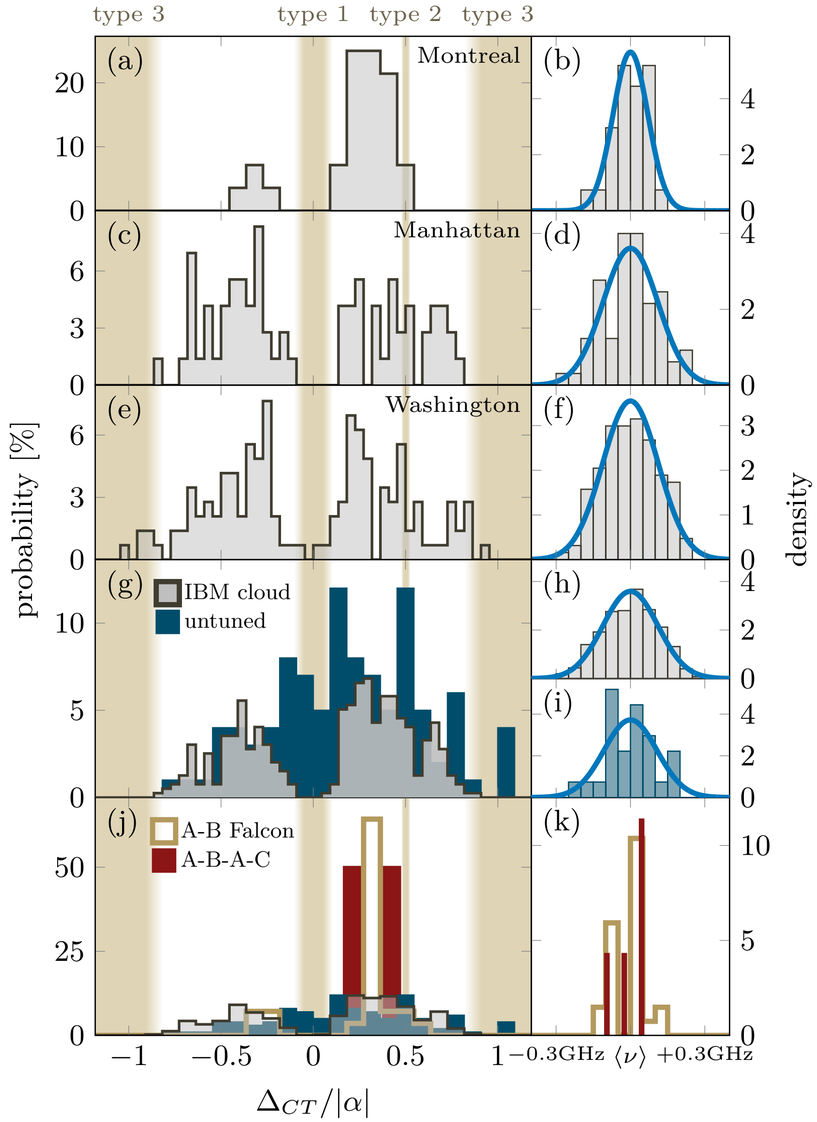


2018 2019 2020

- frequency patterns



uniform A – B A – B – C



27-qubit "Falcon"

65-qubit "Hummingbird"

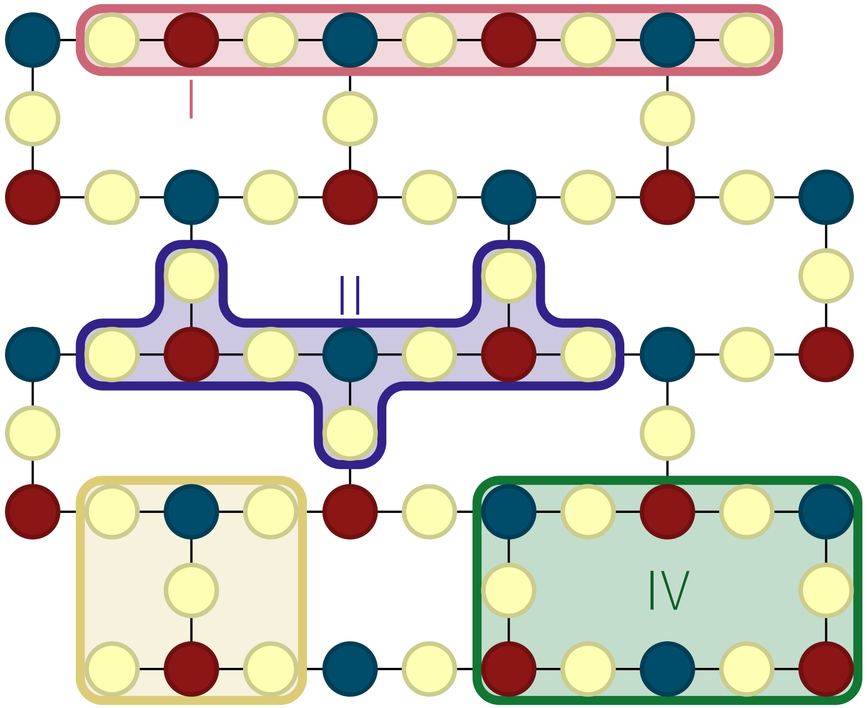
127-qubit "Eagle"

device **average**

targeted device

A – B – C frequency patterns

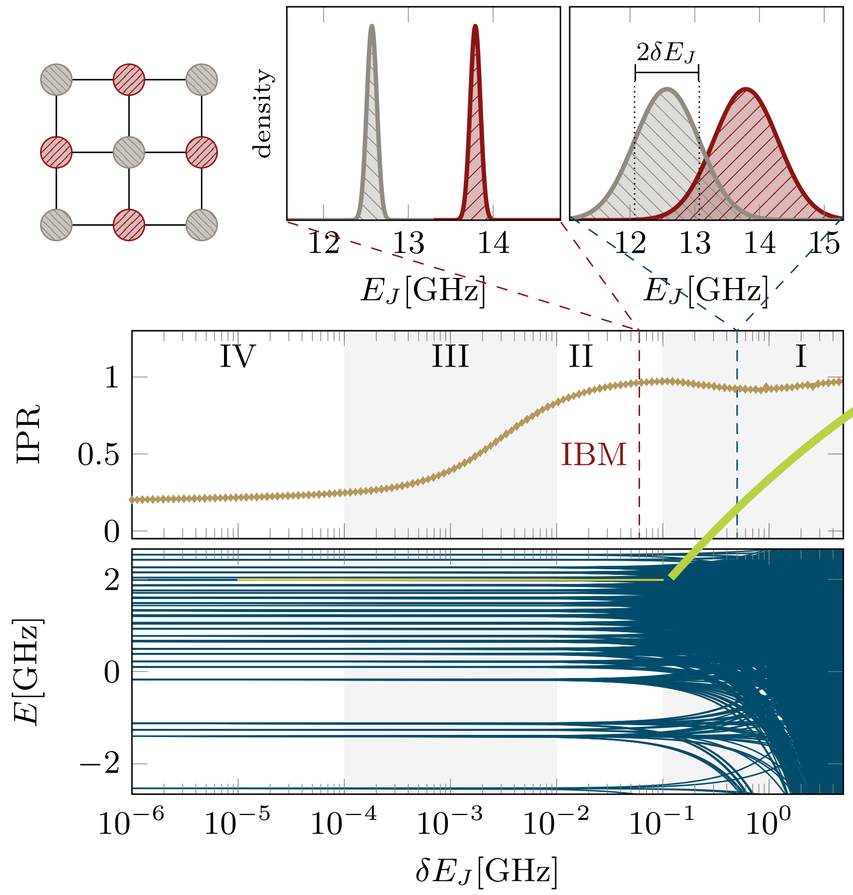
device layouts



III (“Falcon H”)

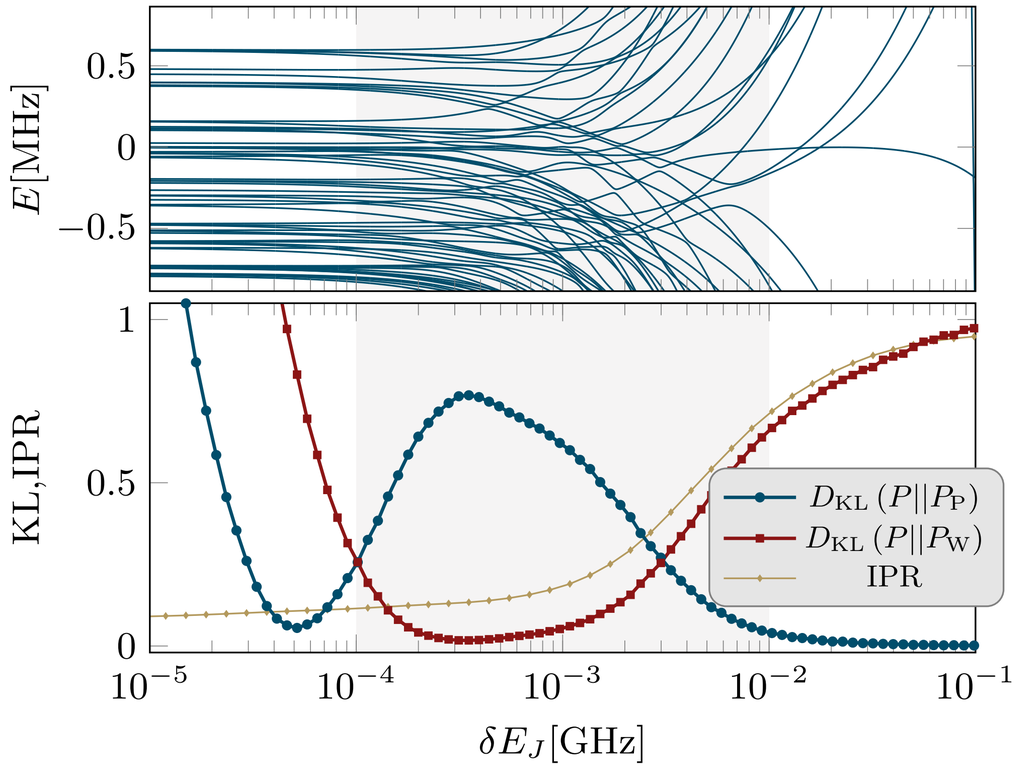
inverse participation ratio

extreme disorder engineering



staggered disorder regimes

evolution of **5-excitation** bundle



reentrant chaotic behavior

(multiplet delocalization)

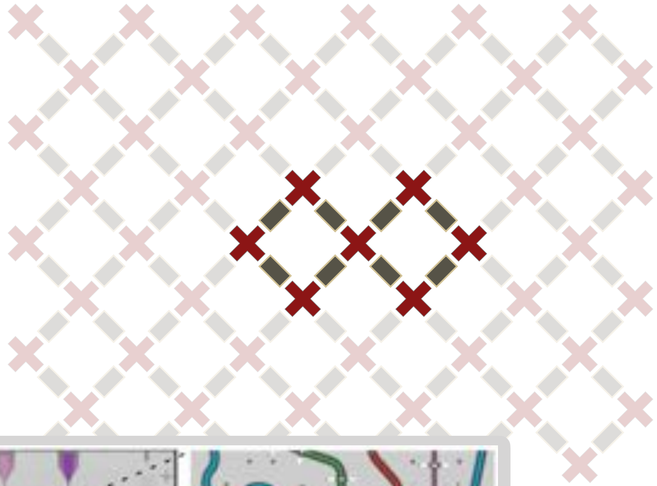
2D geometries

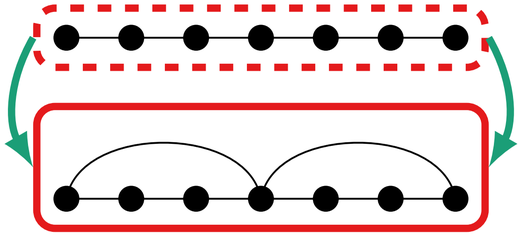
surface codes

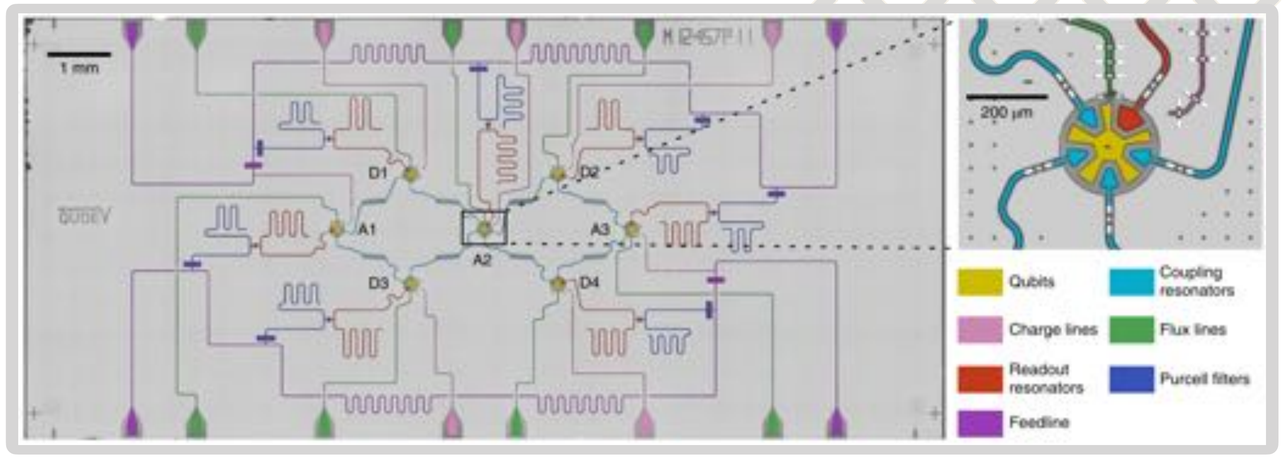
Google's

sycamore processor

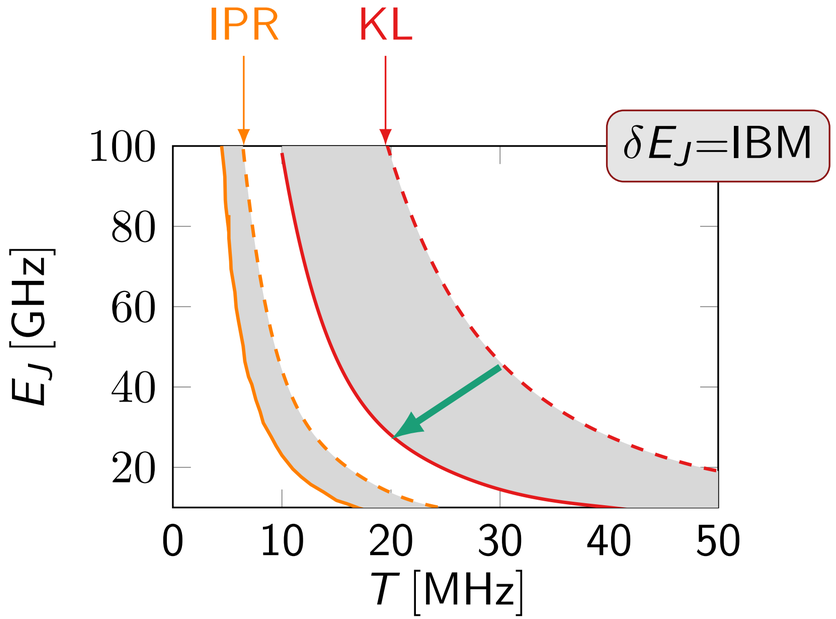
surface 7







C. Andersen et al., Nature Physics (2020)

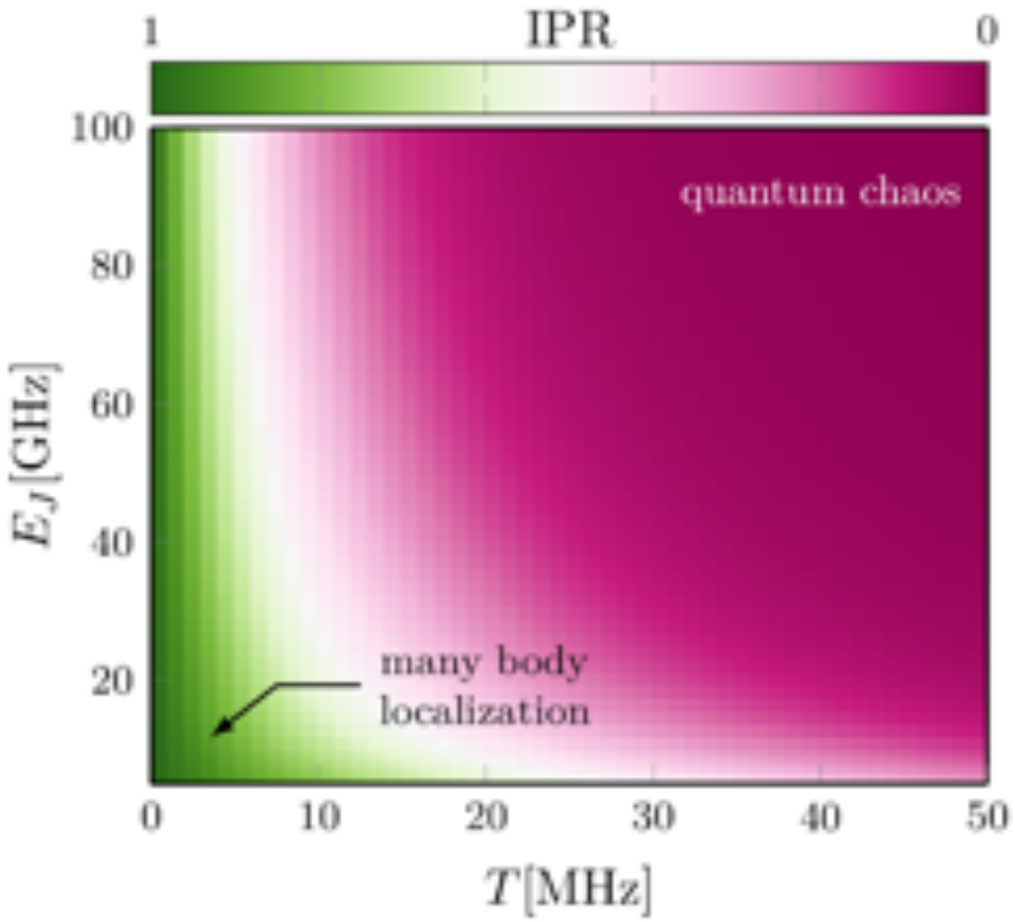


design simulations

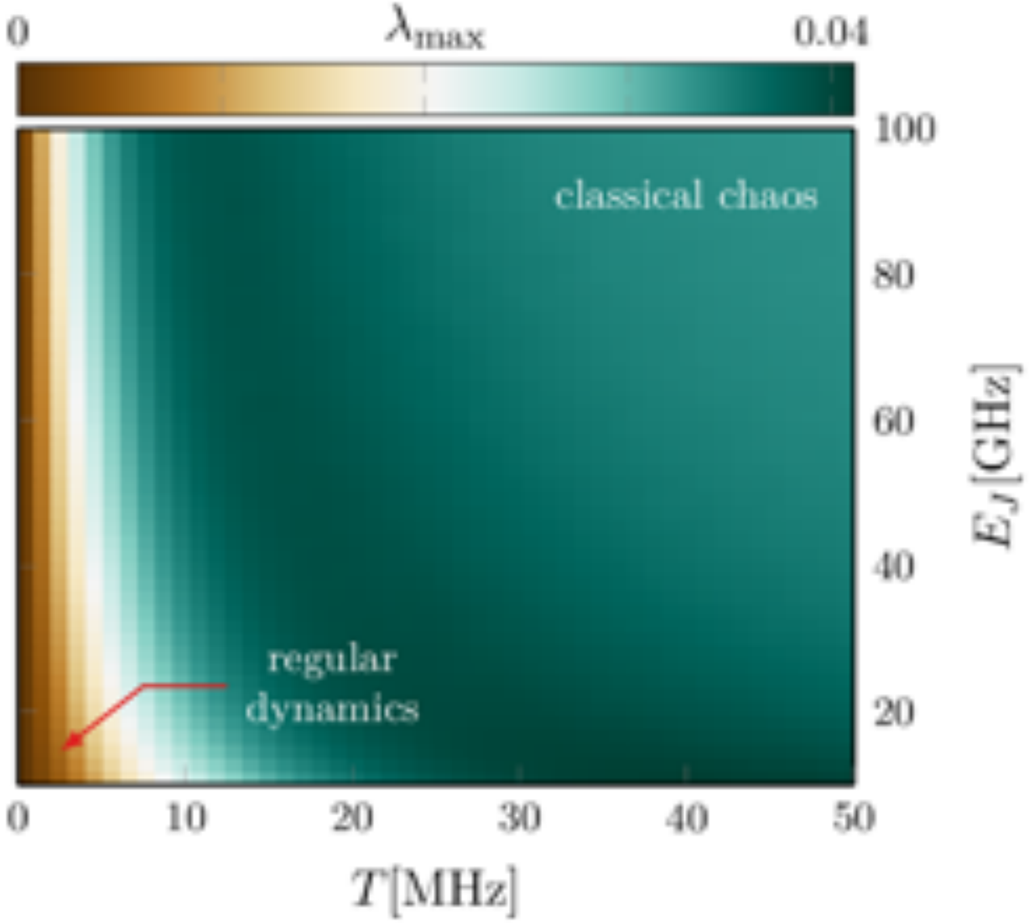
or how can we help avoiding chaos?

many-body numerics to the rescue

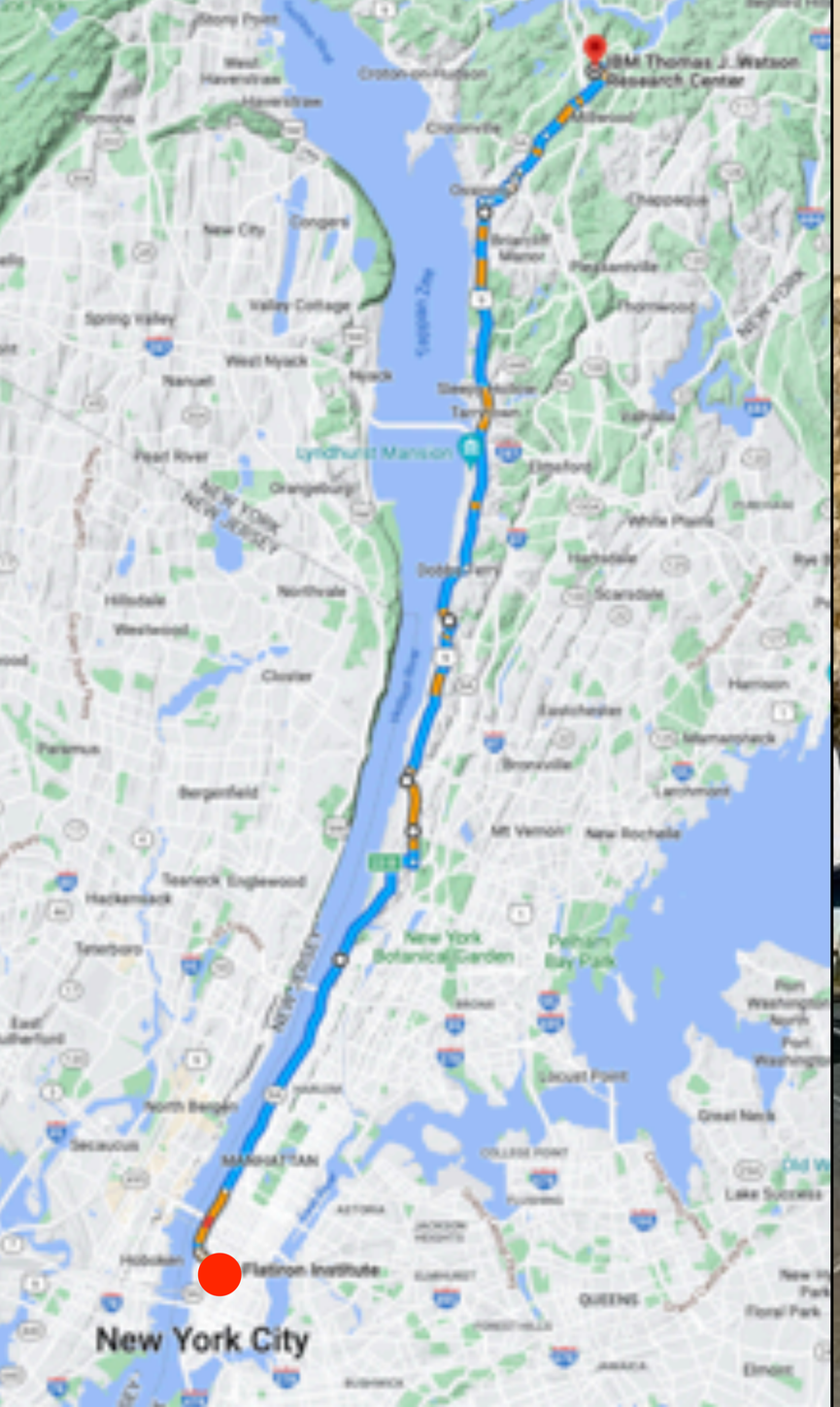
quantum simulations

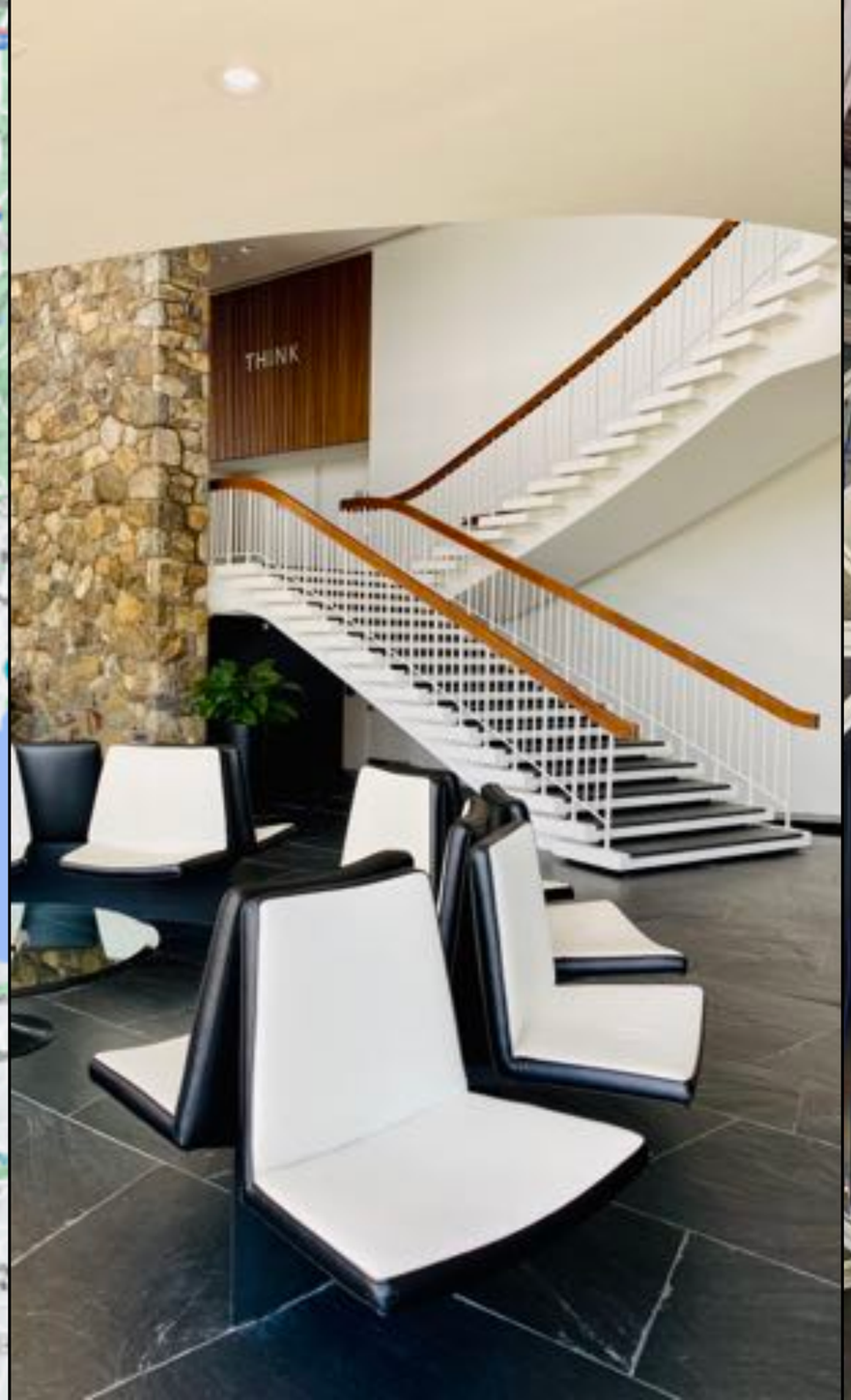


classical simulations



Where to go from here?


IBM Thomas J. Watson Research Center
Flatiron Institute
New York City


THINK

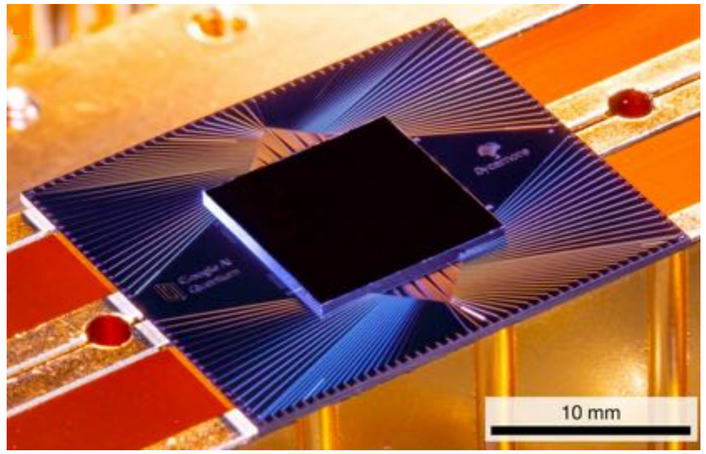

IBM Quantum

summary

Nature Comm. (2022)

Take-away messages

- The transition to **digital quantum computing** has been ushered in by “noisy intermediate-scale quantum” **NISQ devices**.
- **Tolerating imperfections** has been a key **guiding principle**.
- **Transmon qubit architectures** need to balance **intentional disorder** and **non-linear couplings**.
- **Quantum many-body perspective** – stay close to **many-body localization** and away from **chaos**.



Quantum Computing
“al dente”

Thanks!