# Quantum computing “al dente”

**Simon Trebst**
University of Cologne

Entangled States of Matter
Berlin, May 2022

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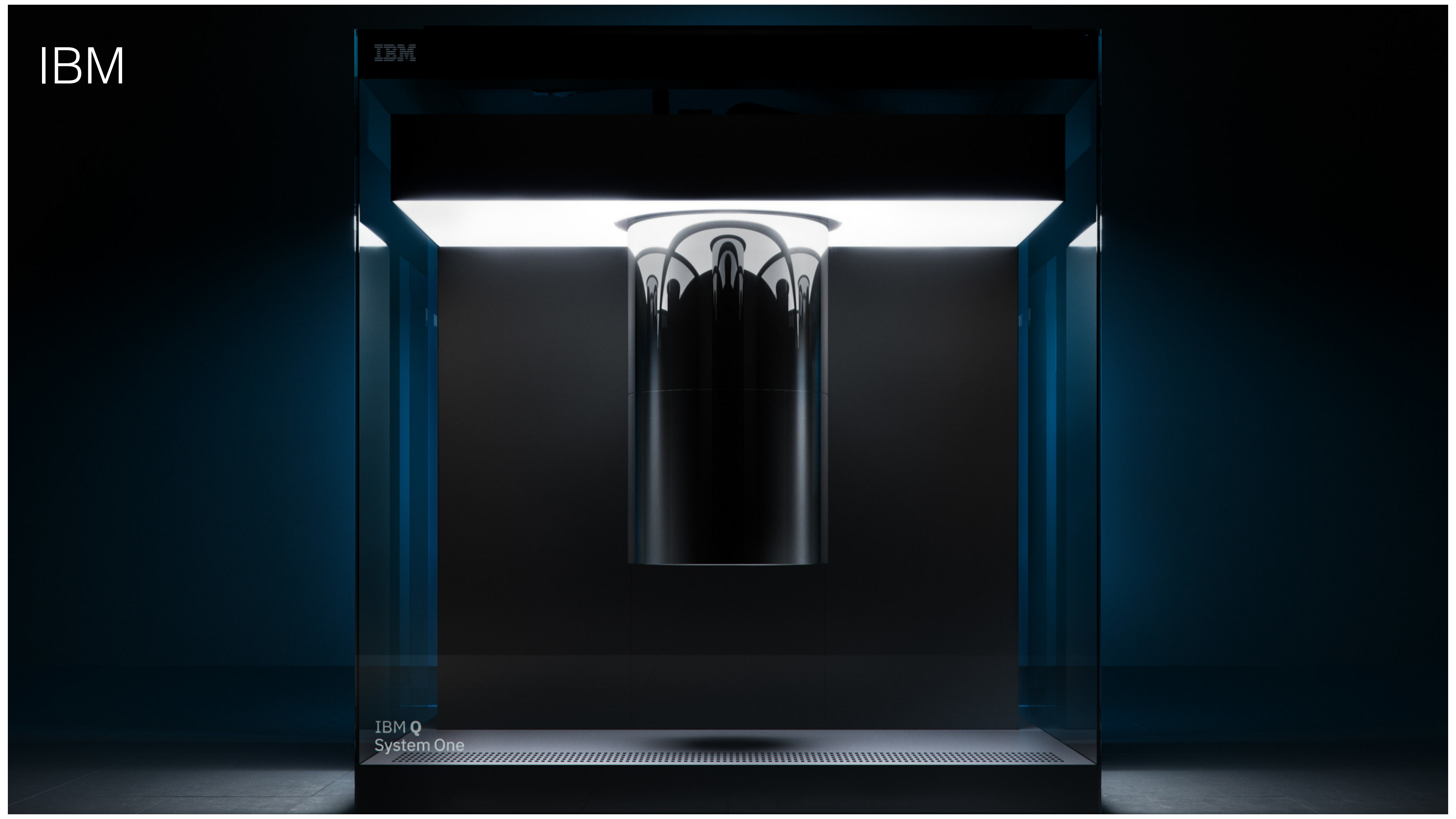
MATTER AND LIGHT FOR QUANTUM COMPUTING

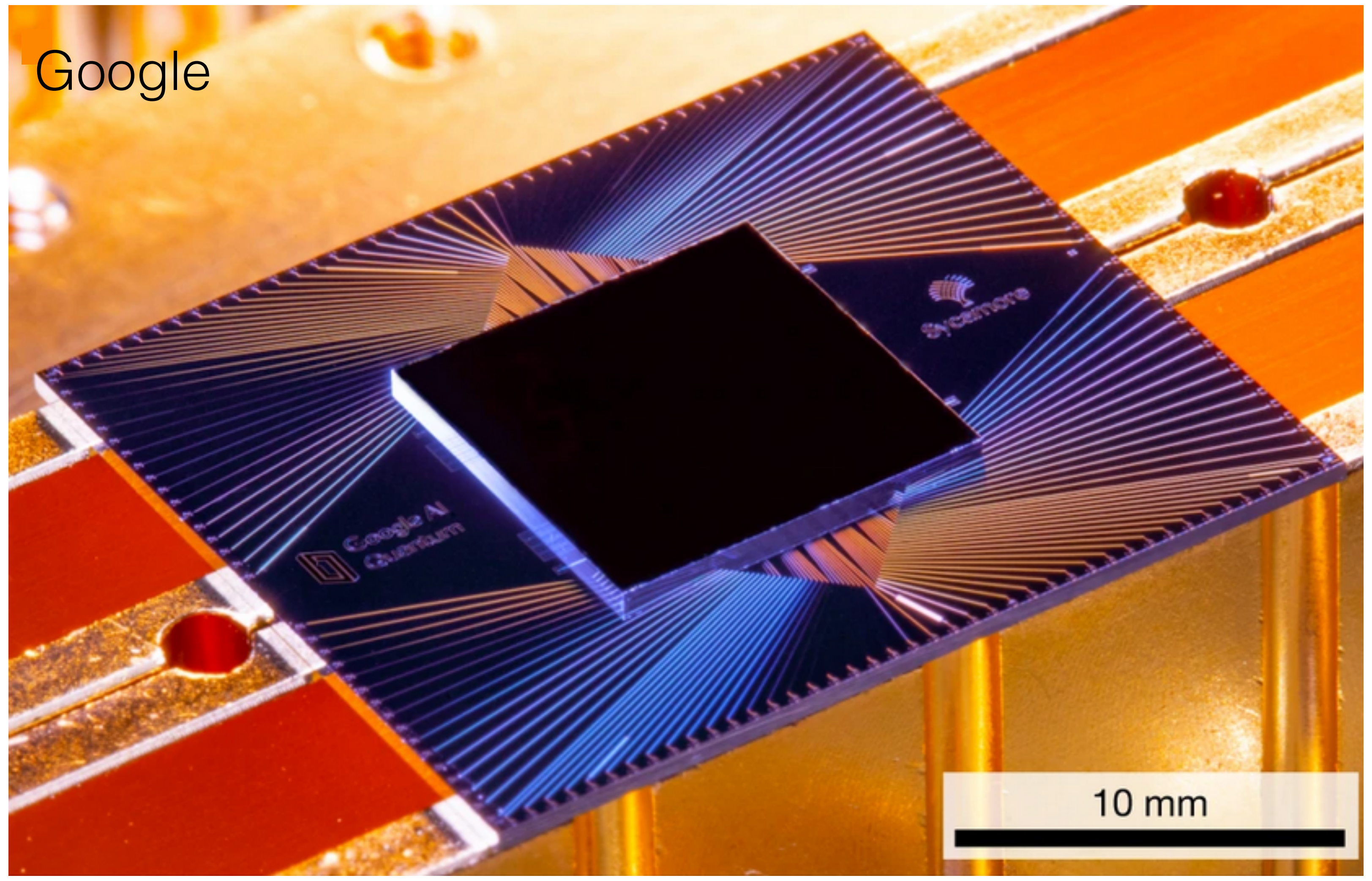
# Quantum Computing in the NISQ era

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

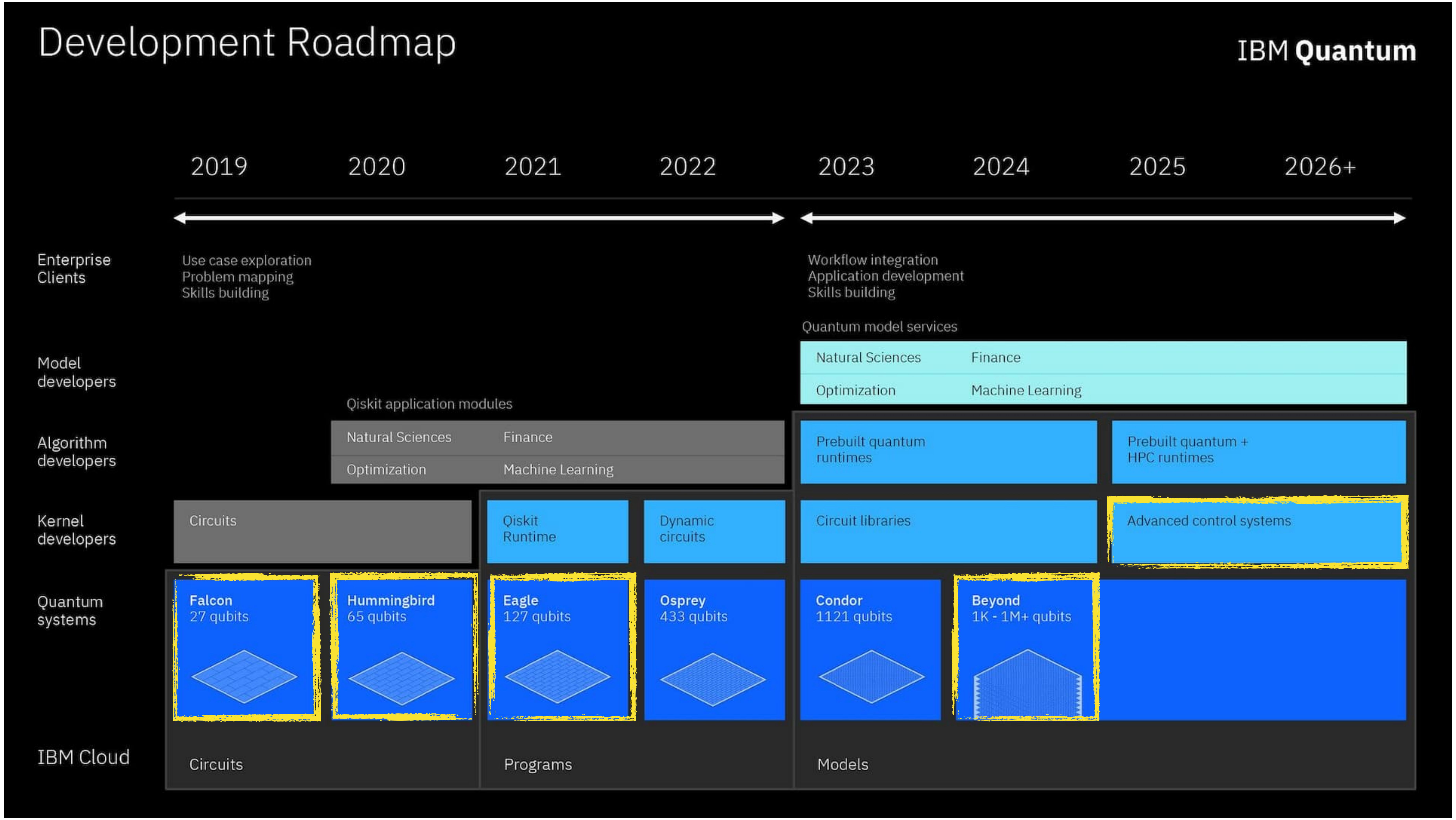



Eagle generation — 127 qubits




Sycamore chip — 53 qubits

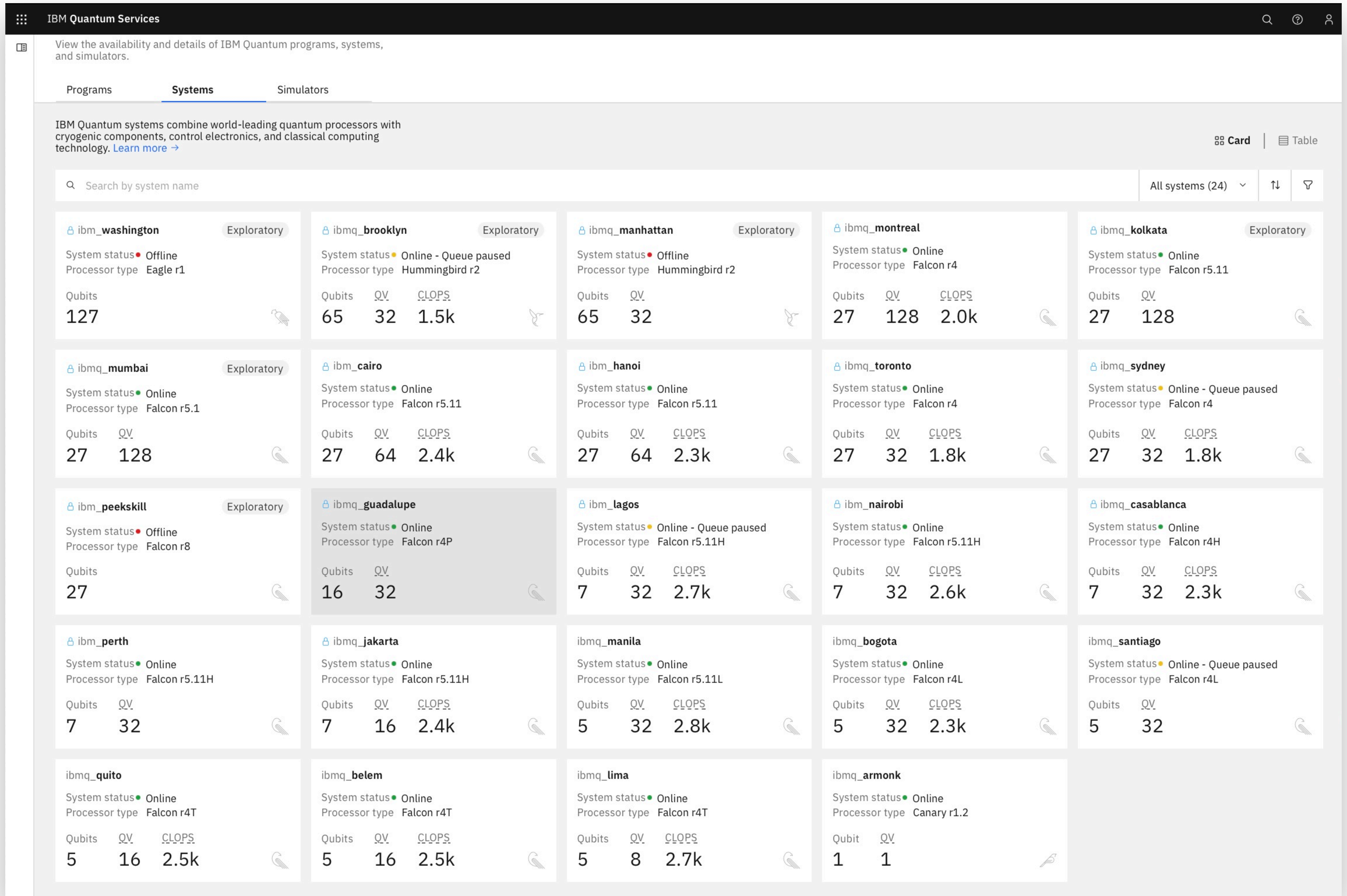
# Quantum Computing in the NISQ era

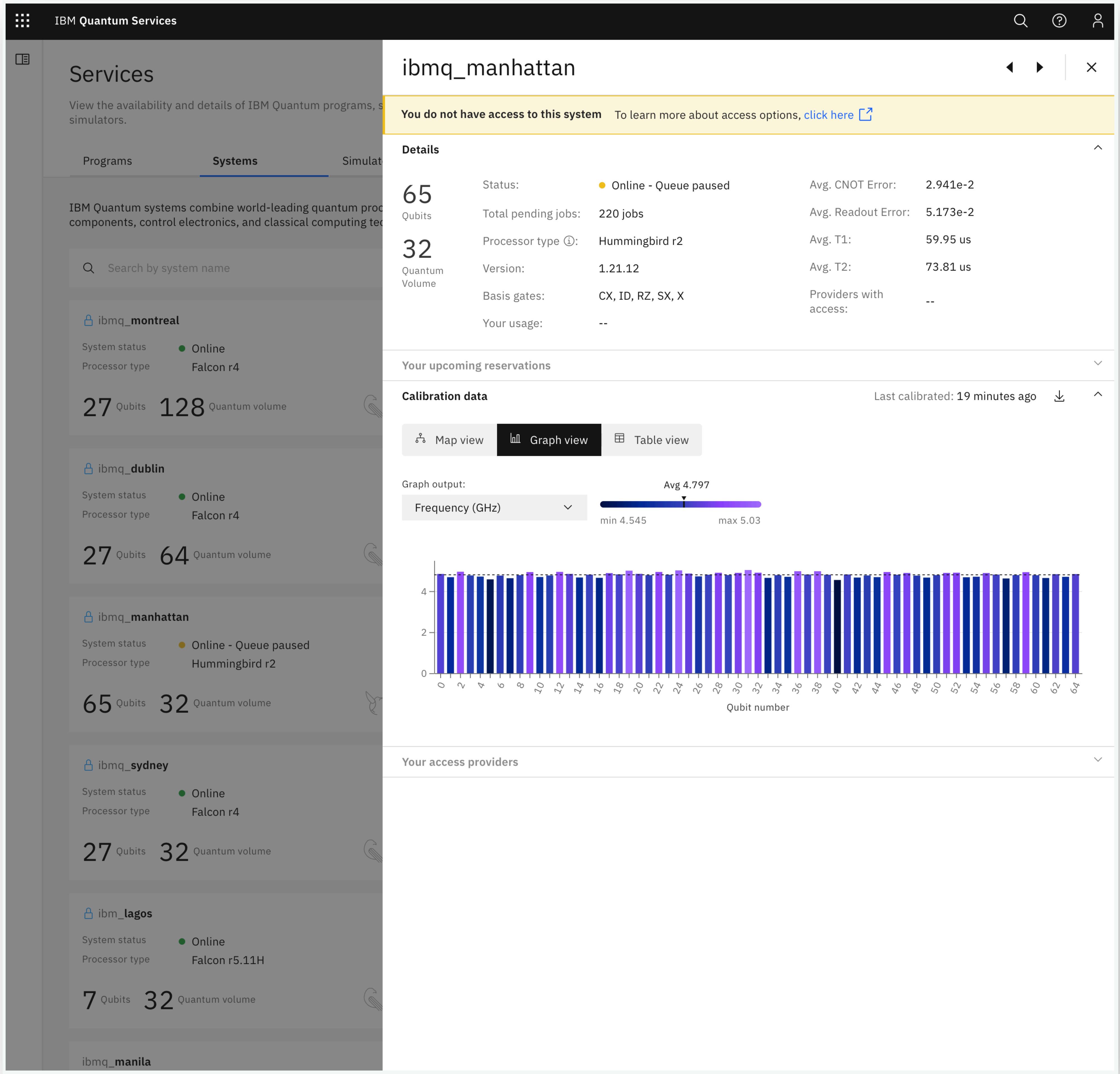



https://research.ibm.com/blog/quantum-development-roadmap

# Quantum Computing in the NISQ era

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

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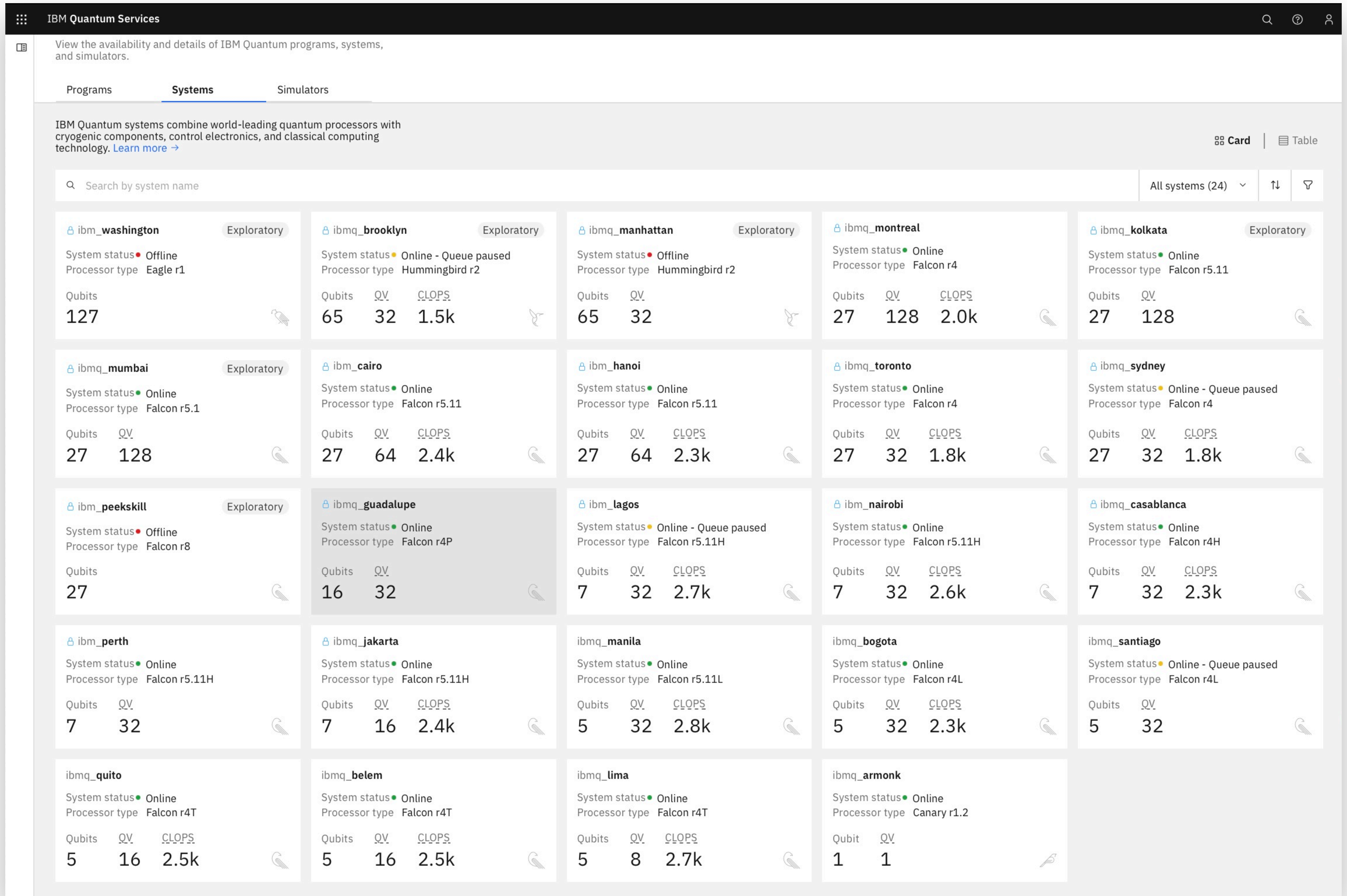
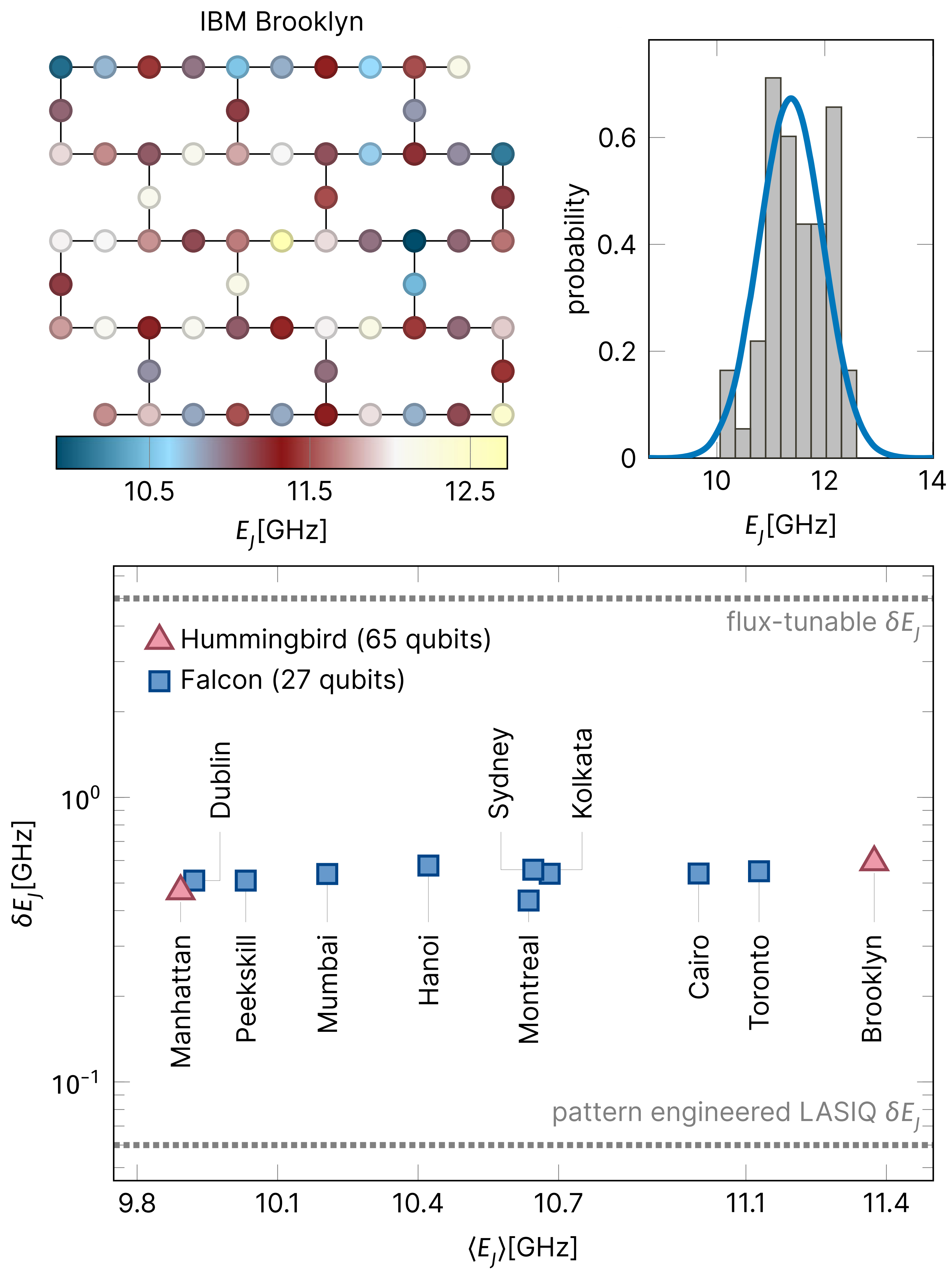
# Quantum Computing in the NISQ era

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



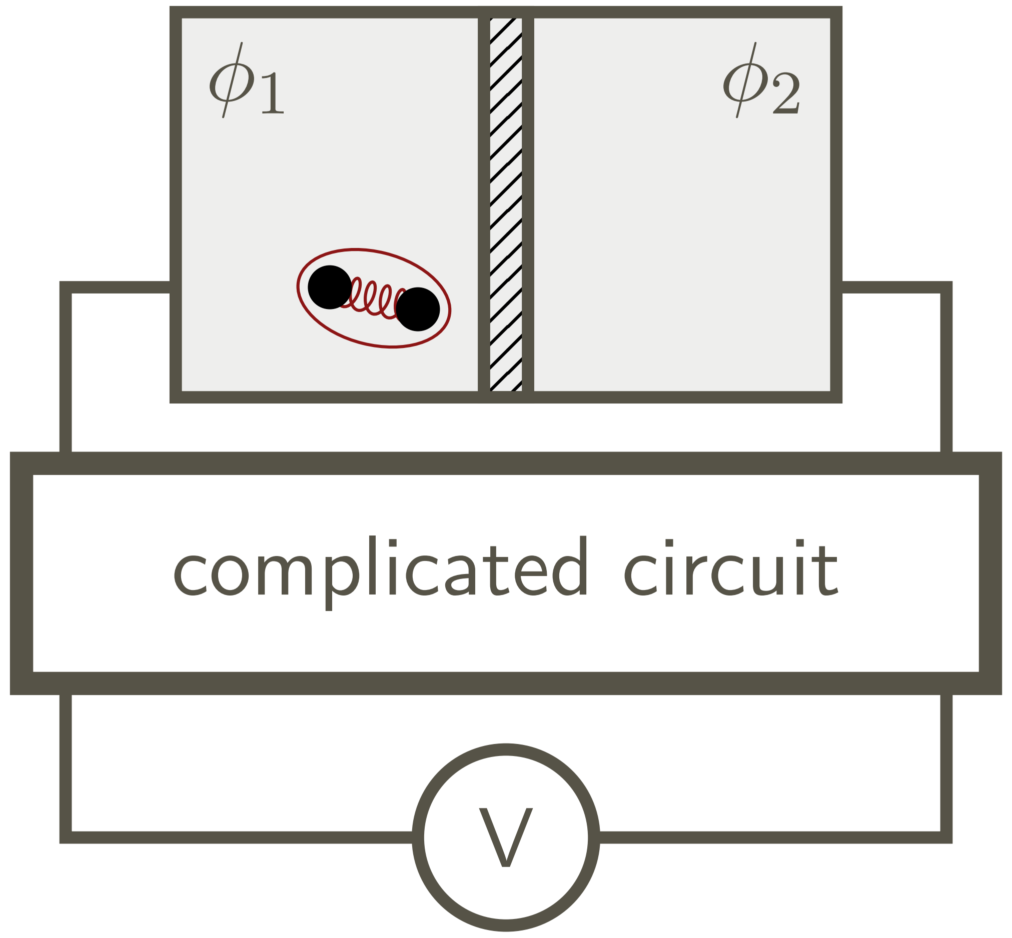



# single transmon qubit

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

charging energy

Josephson tunneling

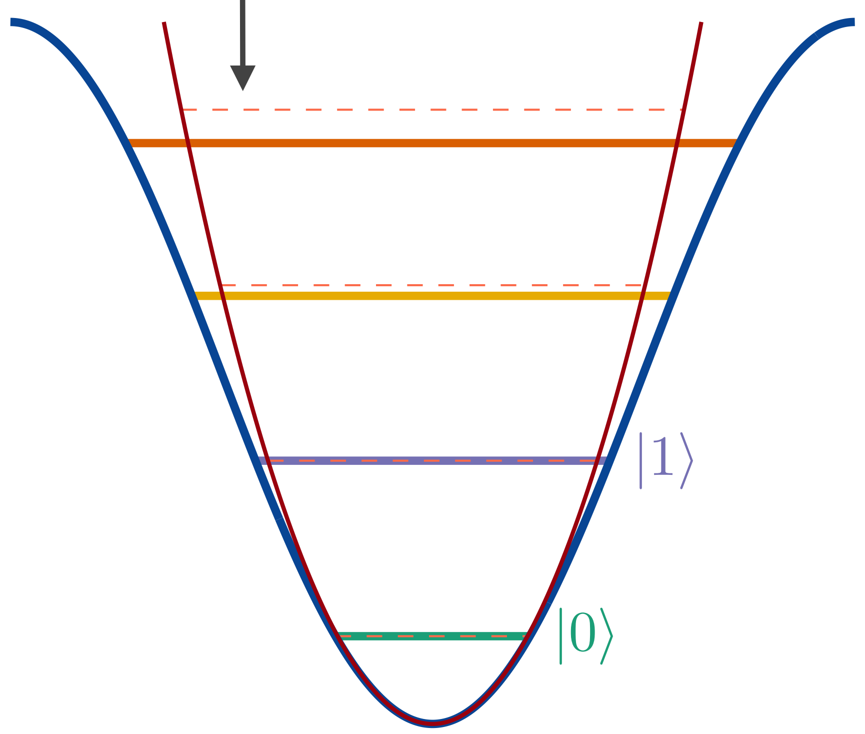


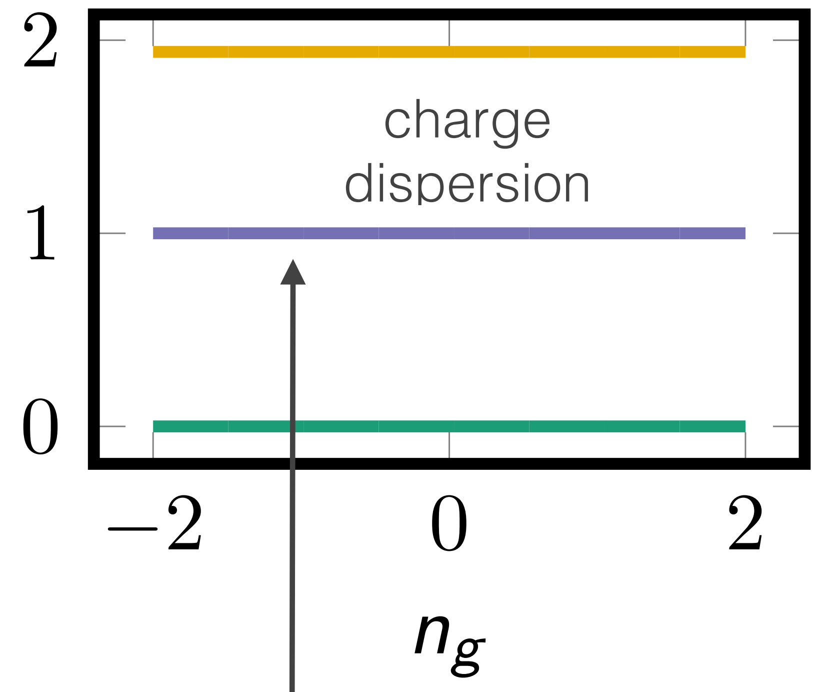

**charge insensitive**

cooper pair box

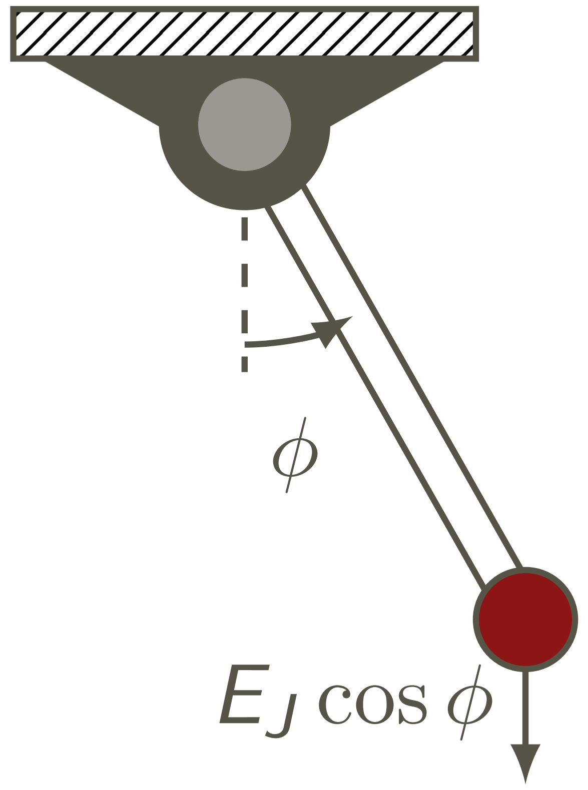
**anharmonicity**

level spacings converge **algebraically** to equidistance



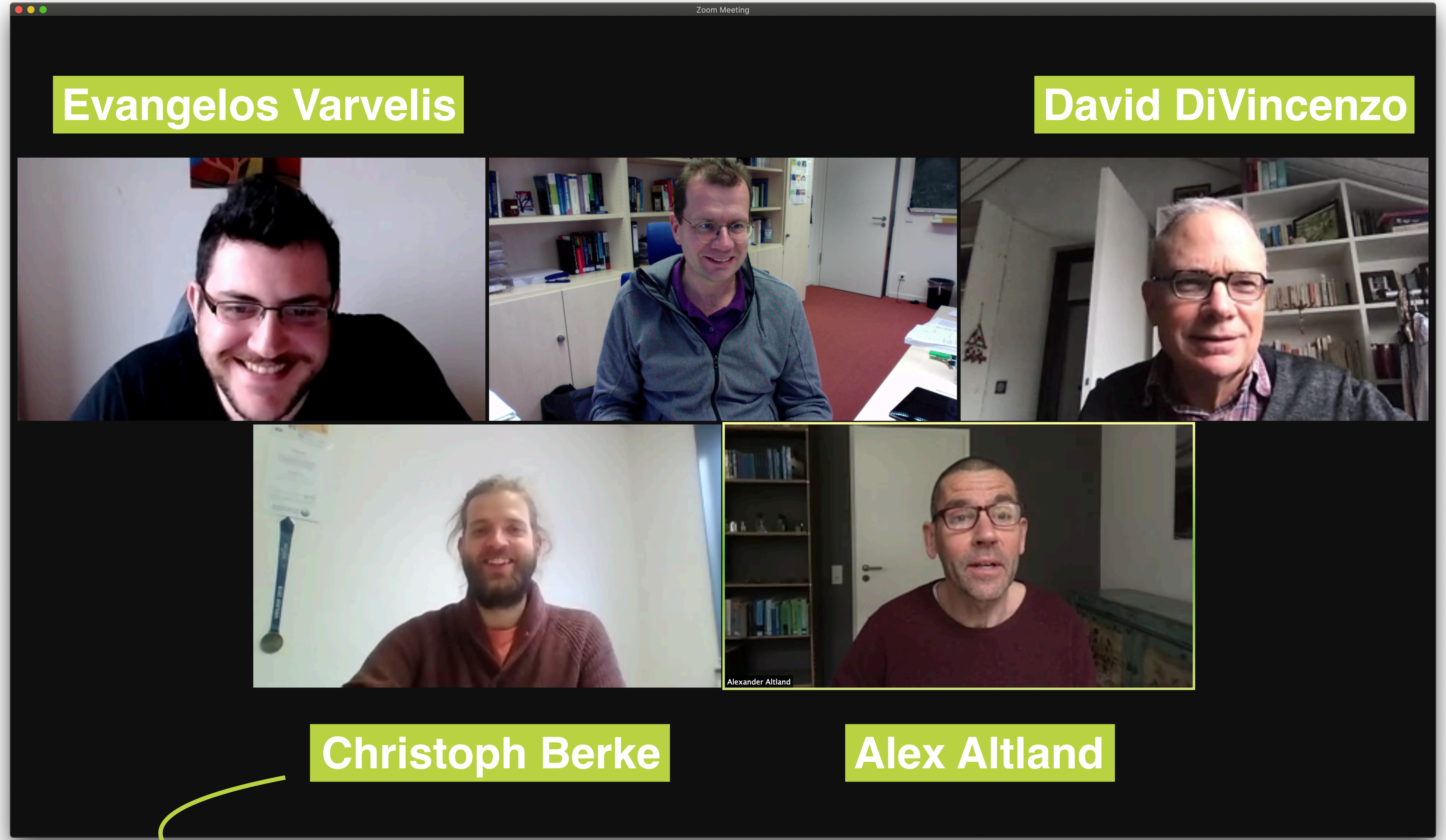




charge sensitivity decays **exponentially**




**anharmonic oscillator**

# meet the team

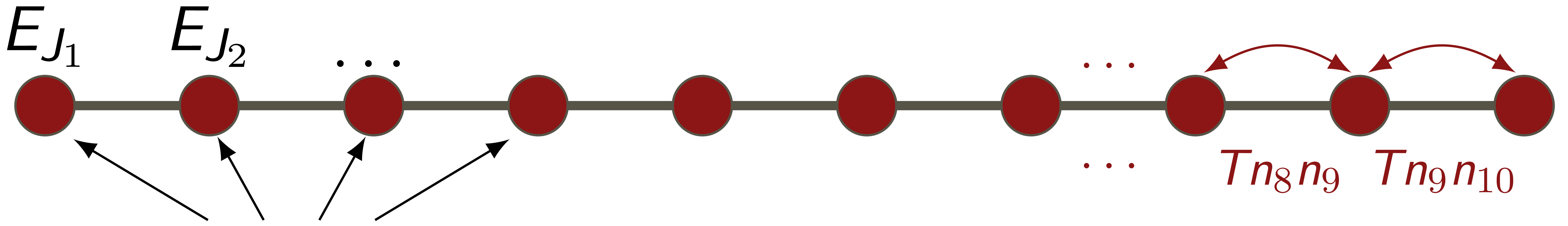



Christoph also prepared many (LaTeX) originals for the slides of this talk.

# many transmon qubits

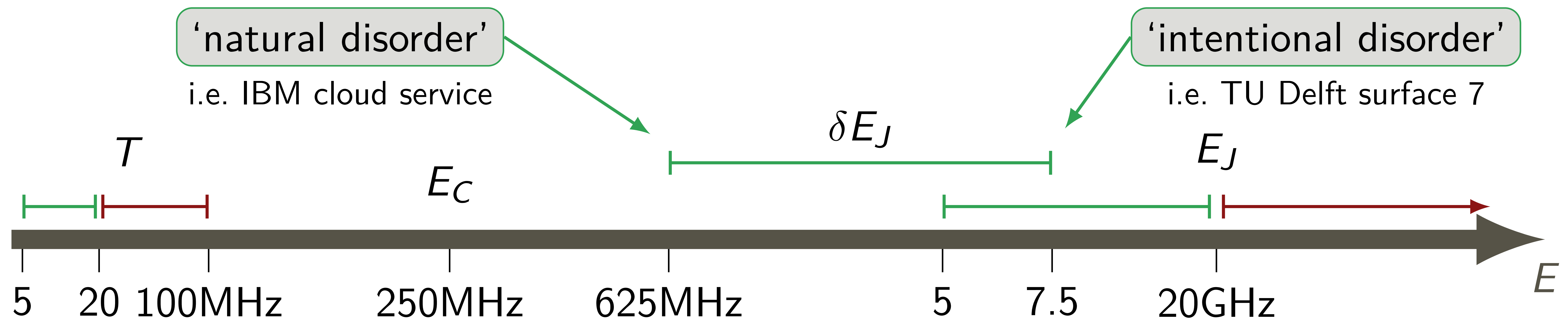
$$H = 4E_C \sum_i n_i^2 - \sum_i E_{J_i} \cos\phi_i + T \sum_{<i,j>} n_i n_j$$

Capacitive coupling

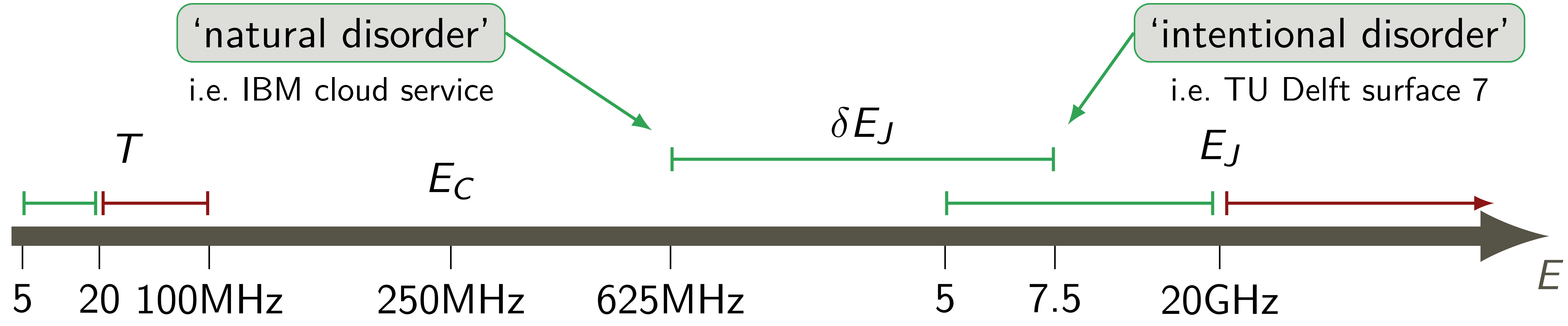


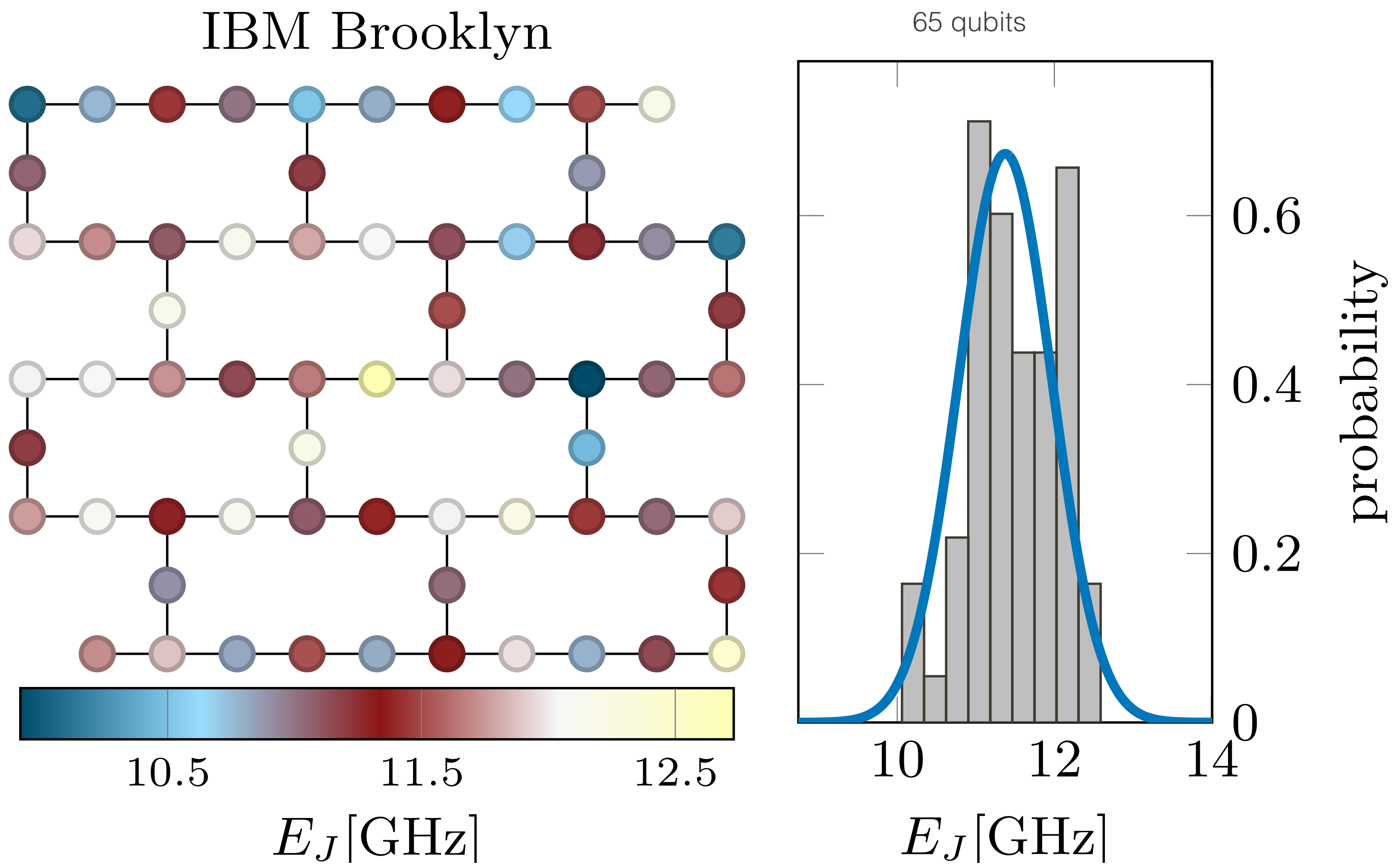

different $E_J$: disorder $\delta E_J$

relevant **energy scales**



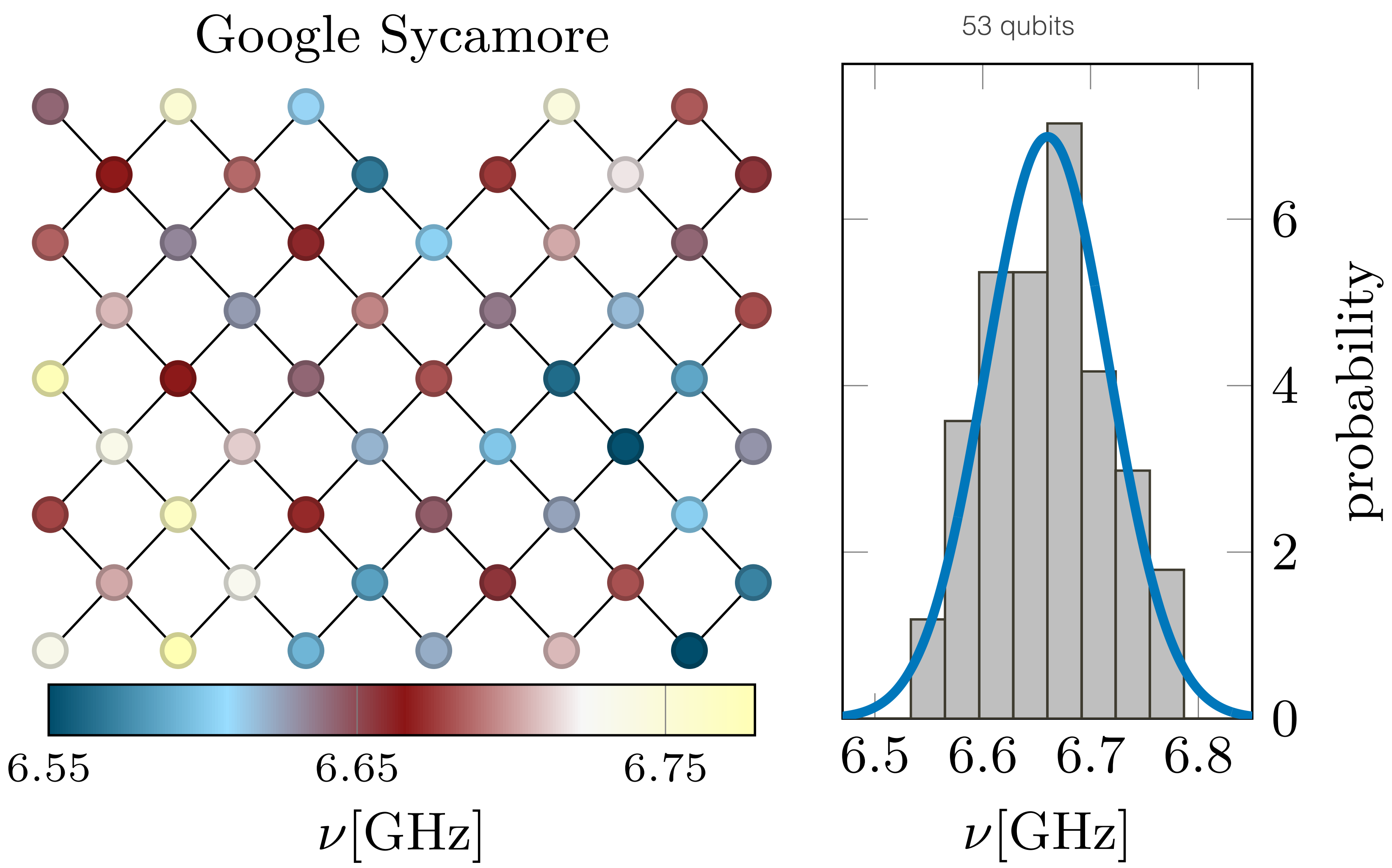
# disorder / experimental settings




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

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



# many-body perspective

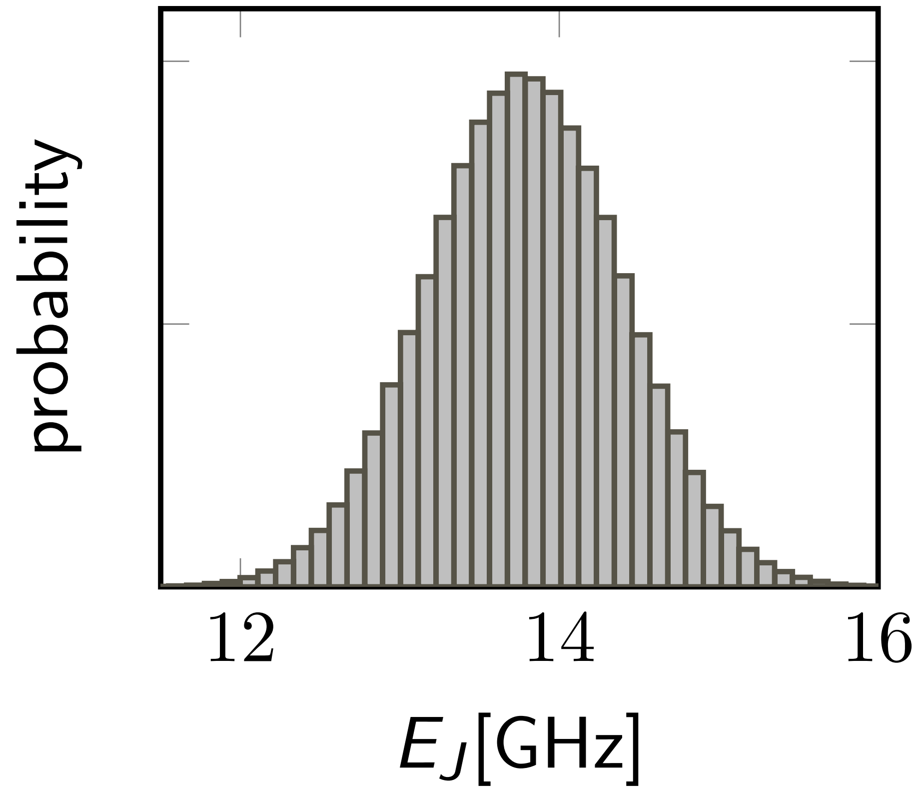
$$H = 4E_C \sum_i n_i^2 - \sum_i E_{J_i} \cos\phi_i \; + T \sum_{<i,j>} n_i n_j$$

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

$$\nu_i = \sqrt{8 E_{J_i} E_C} \quad \xrightarrow[\text{large} \qquad \text{small}]{} \quad t_{ij} = \frac{T}{4\sqrt{2E_C}} \sqrt[4]{E_{J_i} E_{J_j}}$$




**plus disorder**
via variations of Josephson energy $E_J$

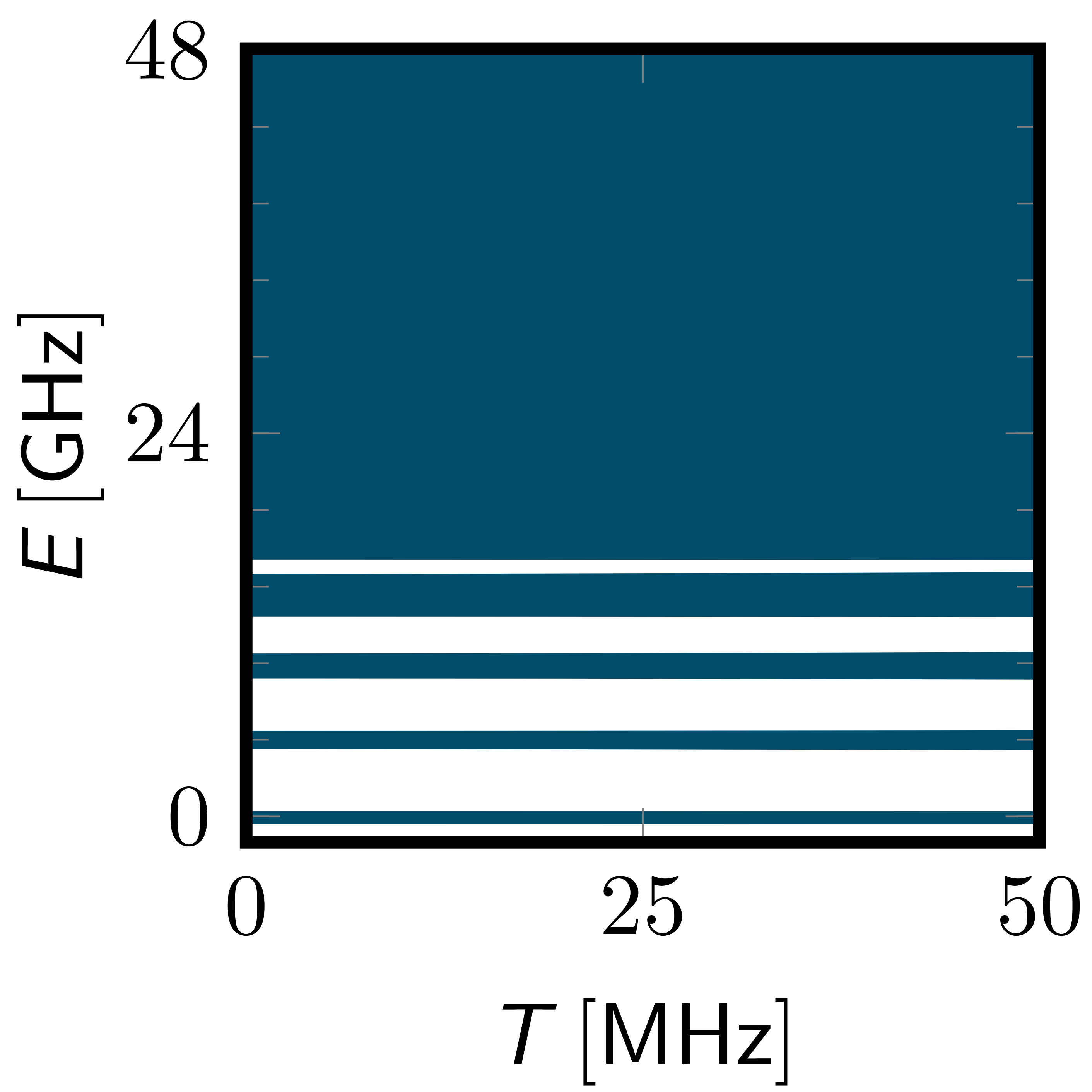
**Reference model** for bosonic
**many-body localization**

# 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)



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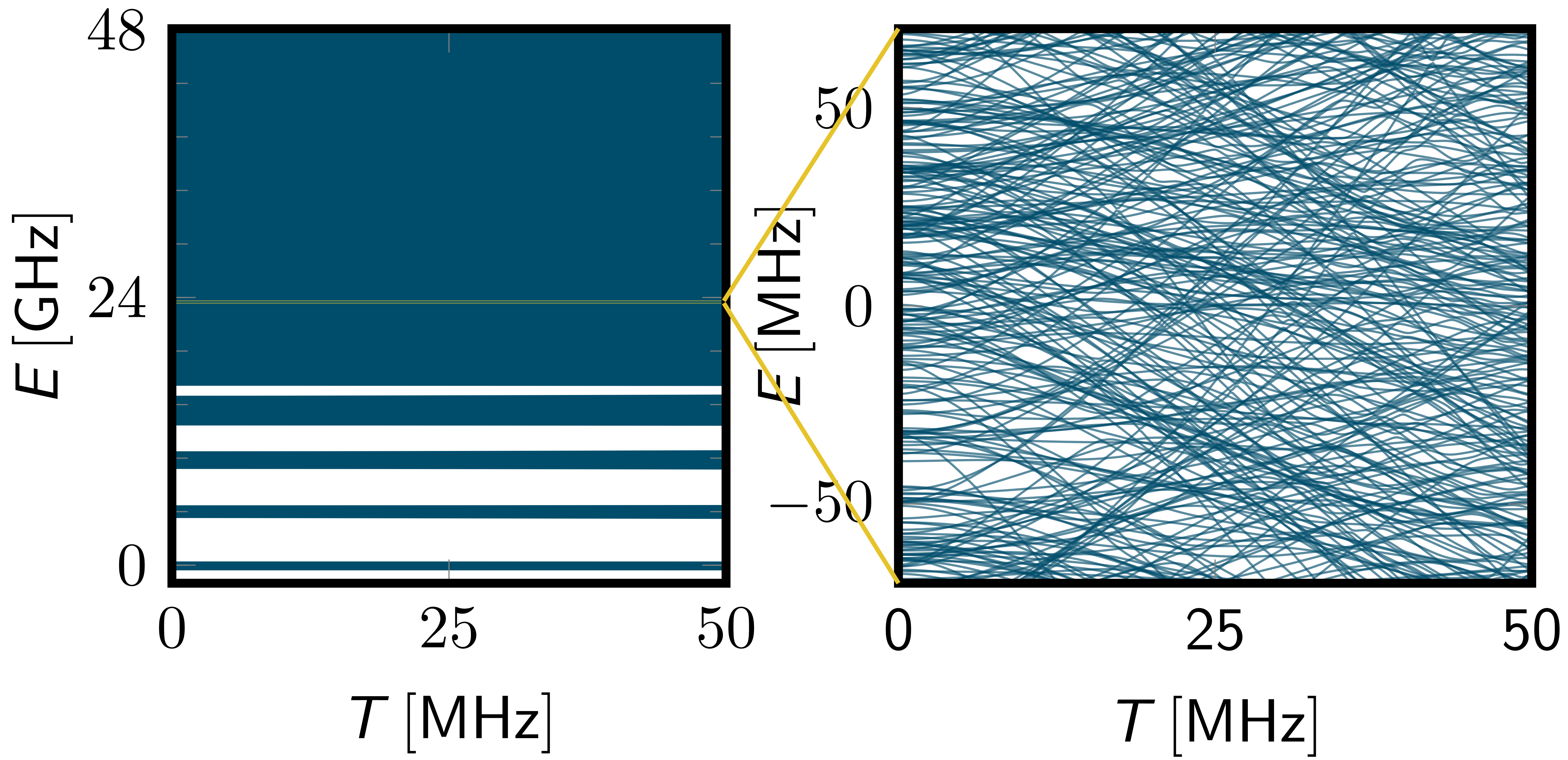

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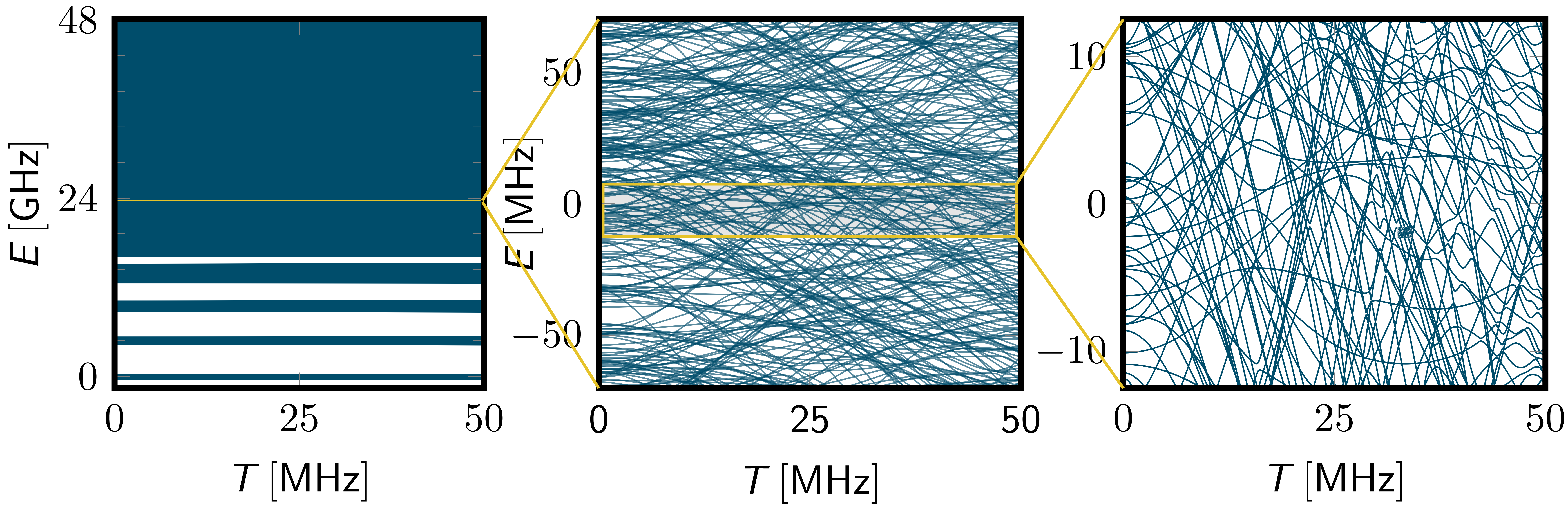
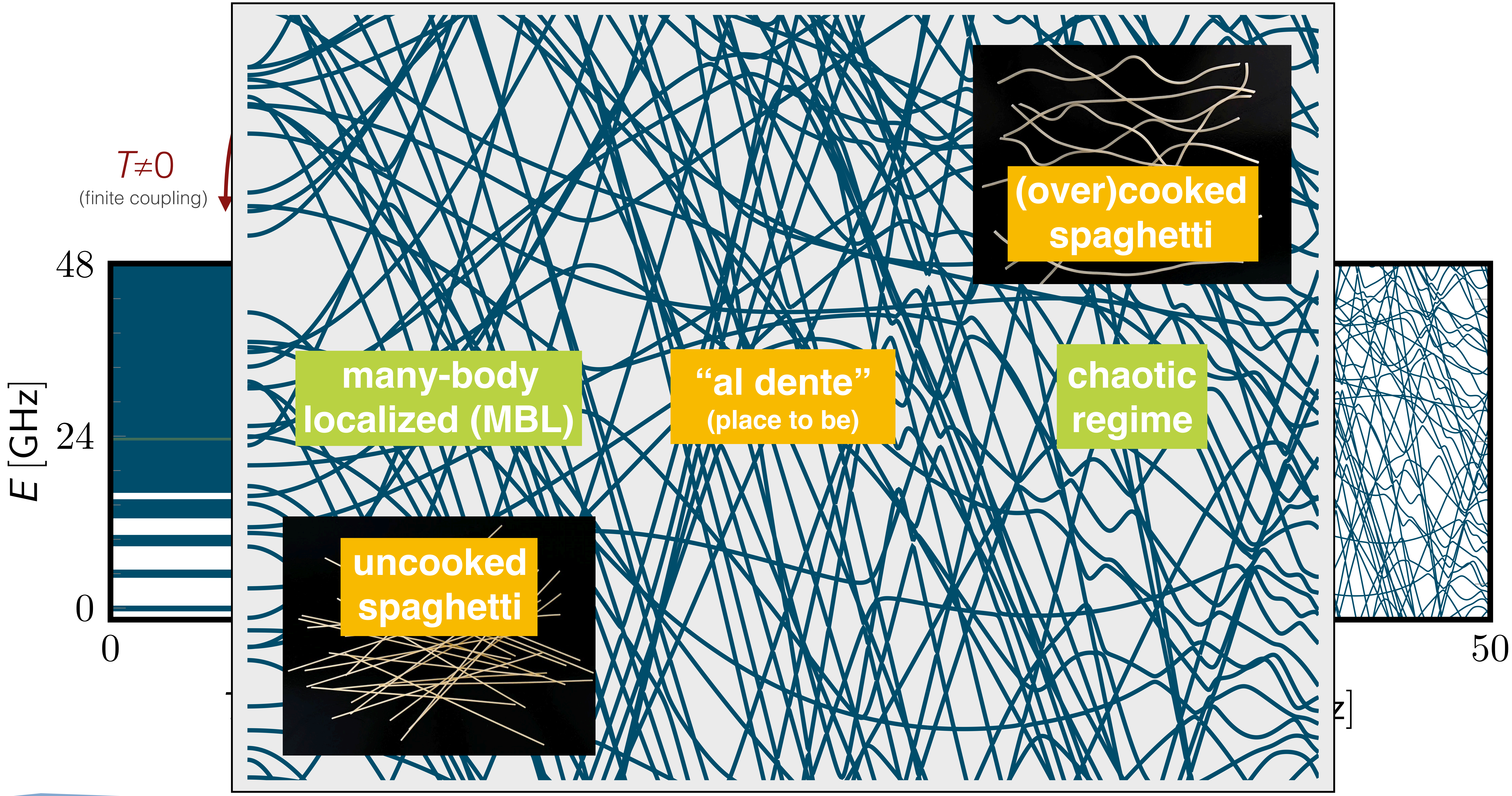


# energy spectra – spaghetti plots



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

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

$\Delta\epsilon_{n+1}$

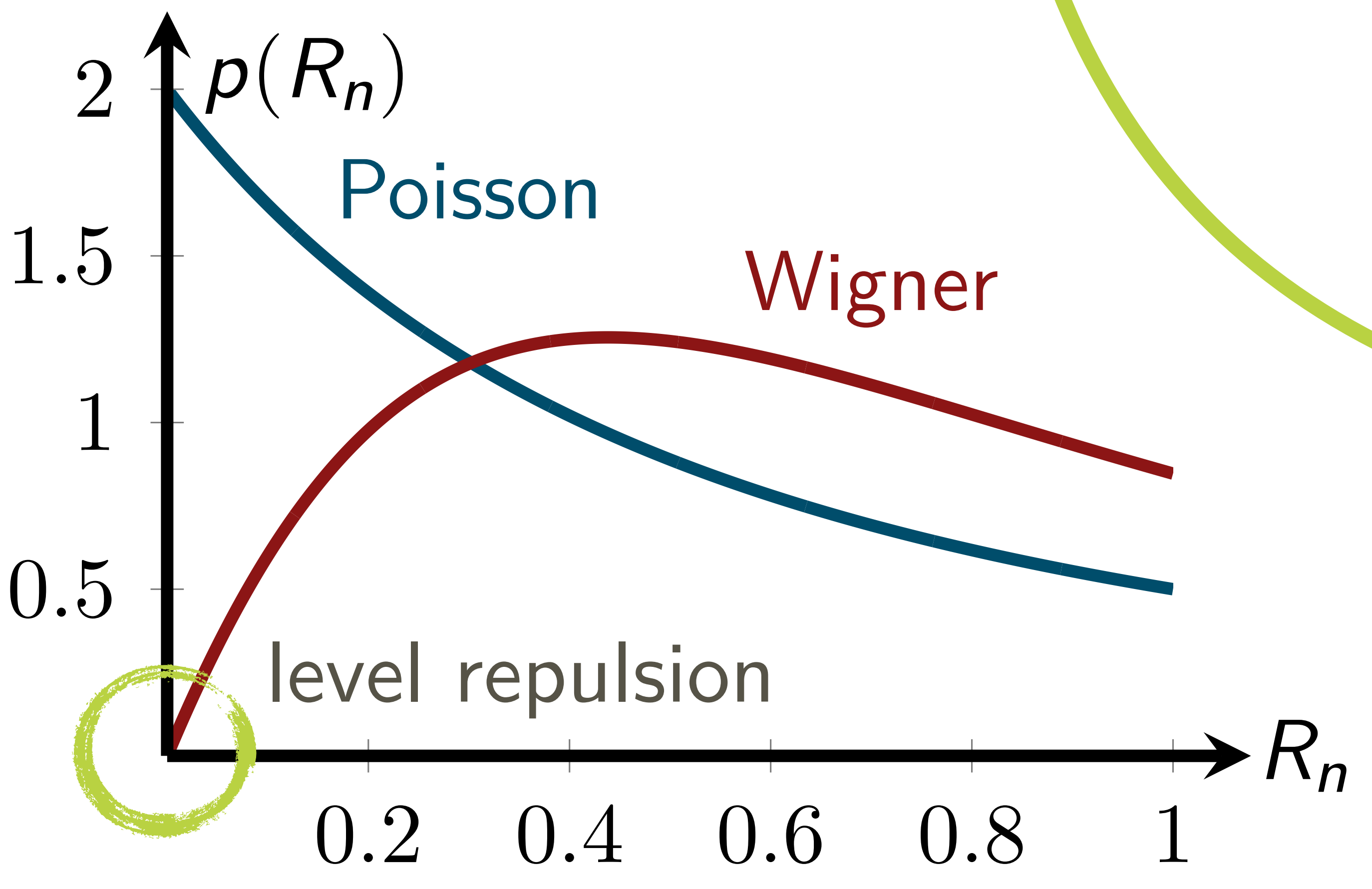
$\Delta\epsilon_n$

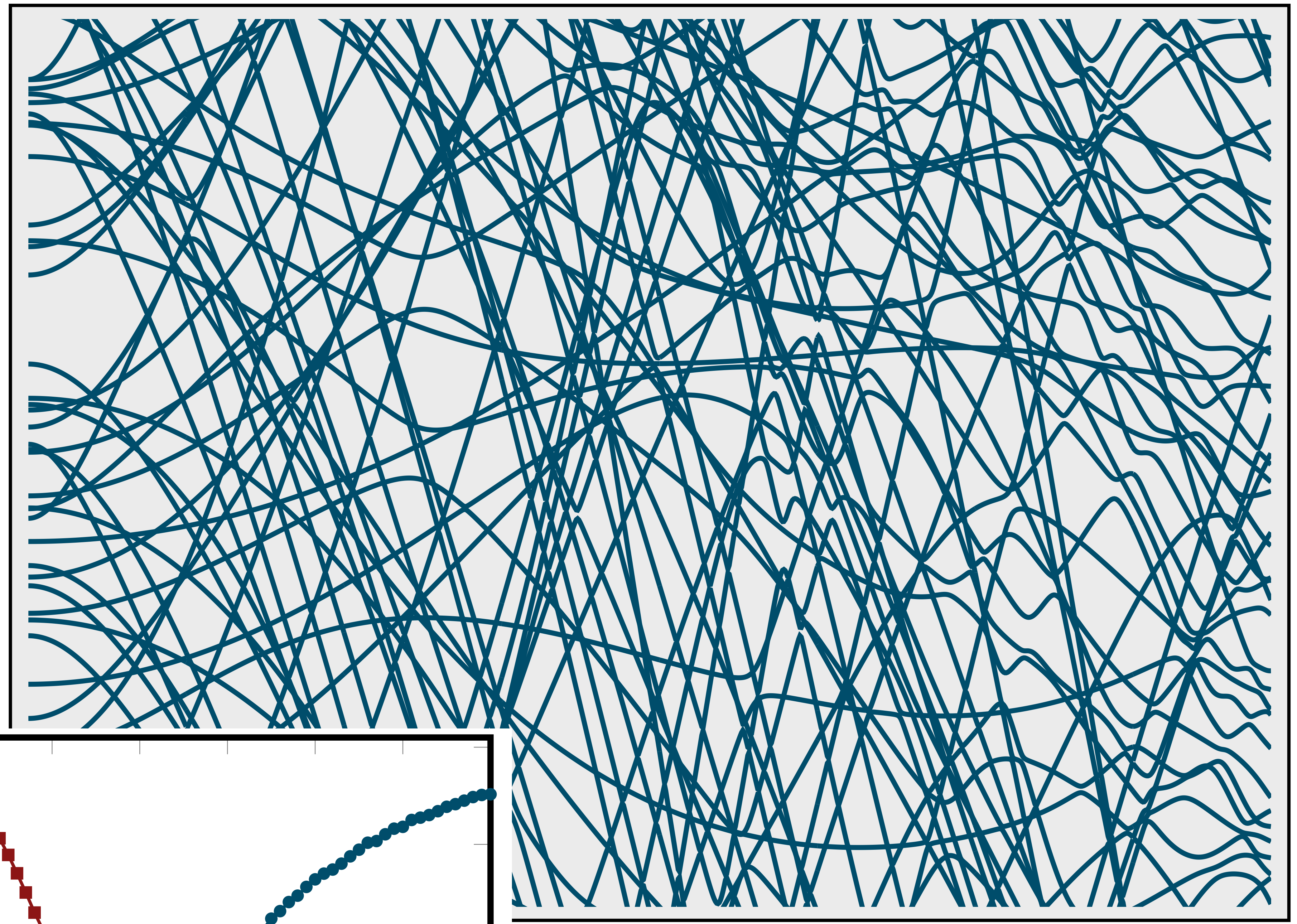
Kullback-Leiber divergence

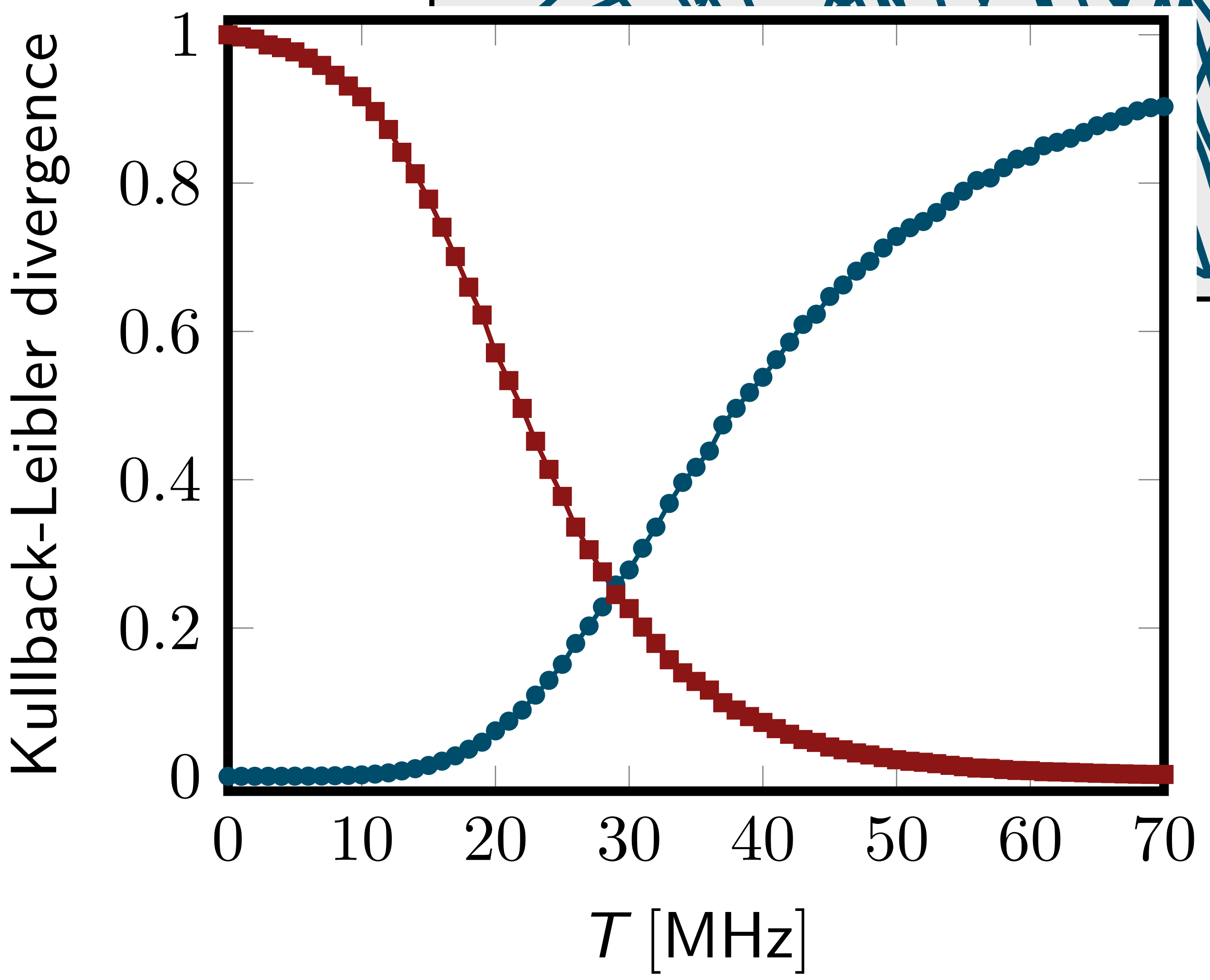
$$D_{\mathrm{KL}}(P||Q) = \sum_k p_k \log\left(\frac{p_k}{q_k}\right)$$

data

theory



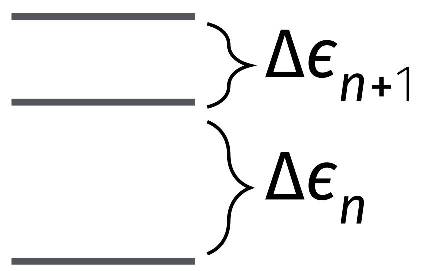


# quantifying chaos

## spectral statistics

level statistics

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



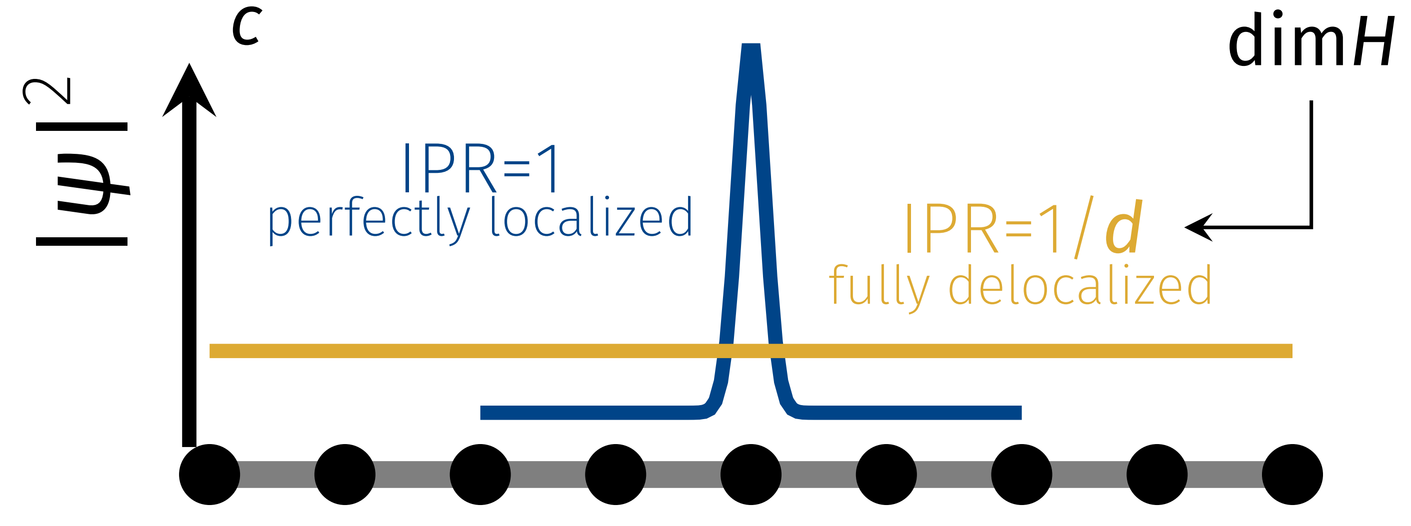

Kullback-Leiber divergence

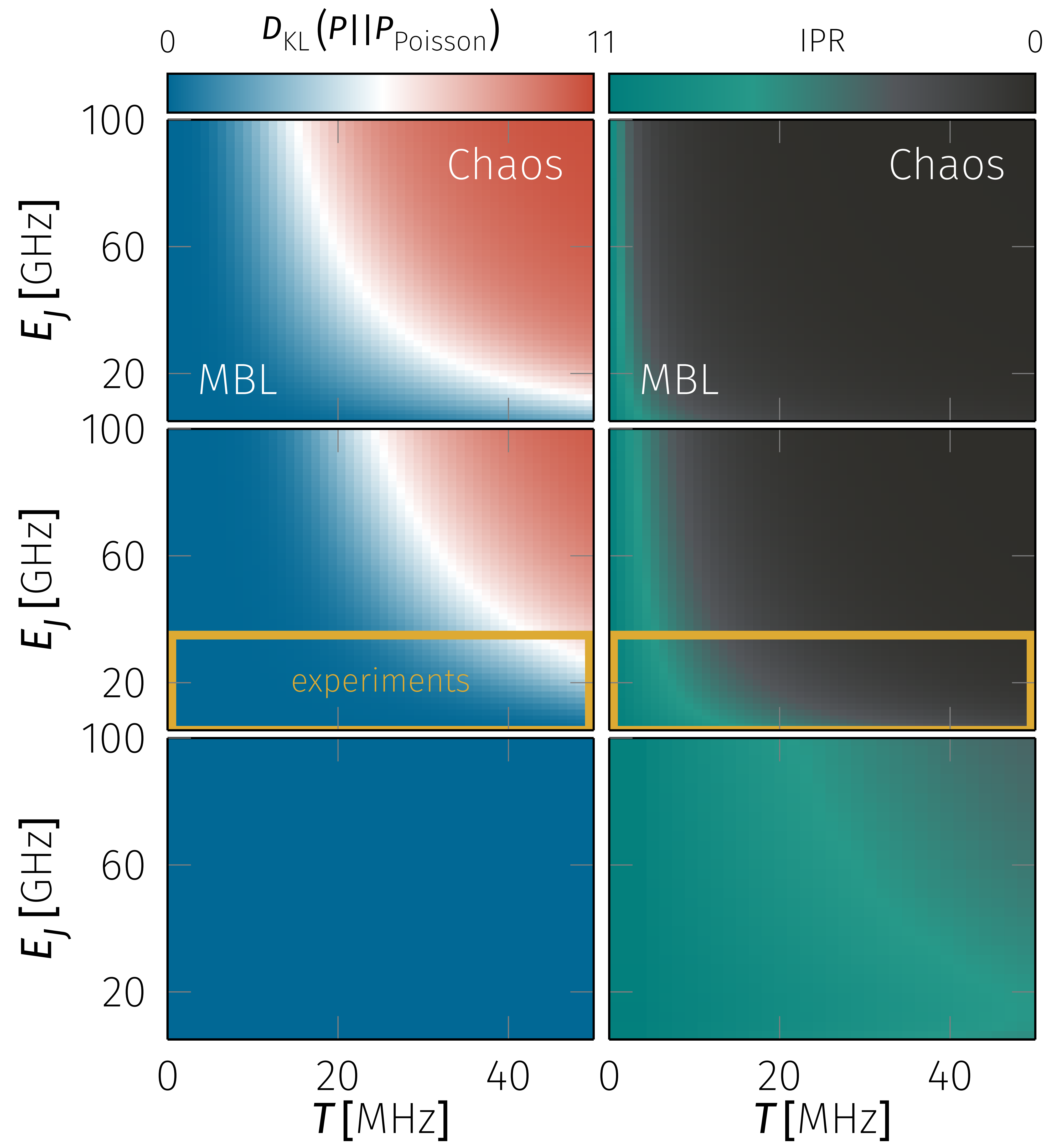
$$D_{\mathrm{KL}}(P||Q) = \sum_k p_k \log\left(\frac{p_k}{q_k}\right)$$

data → $p_k$; theory → $q_k$

## wavefunction statistics

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



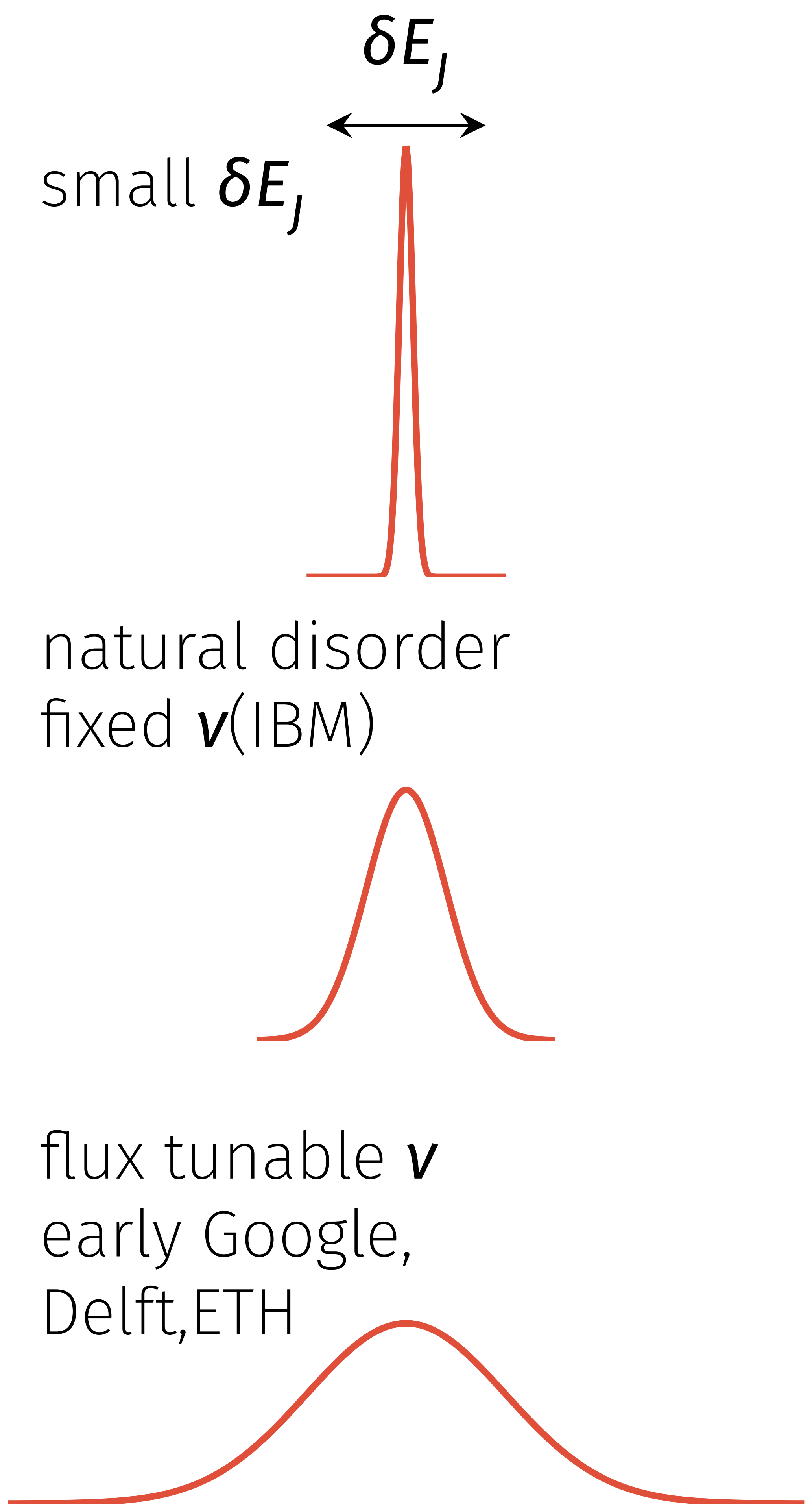



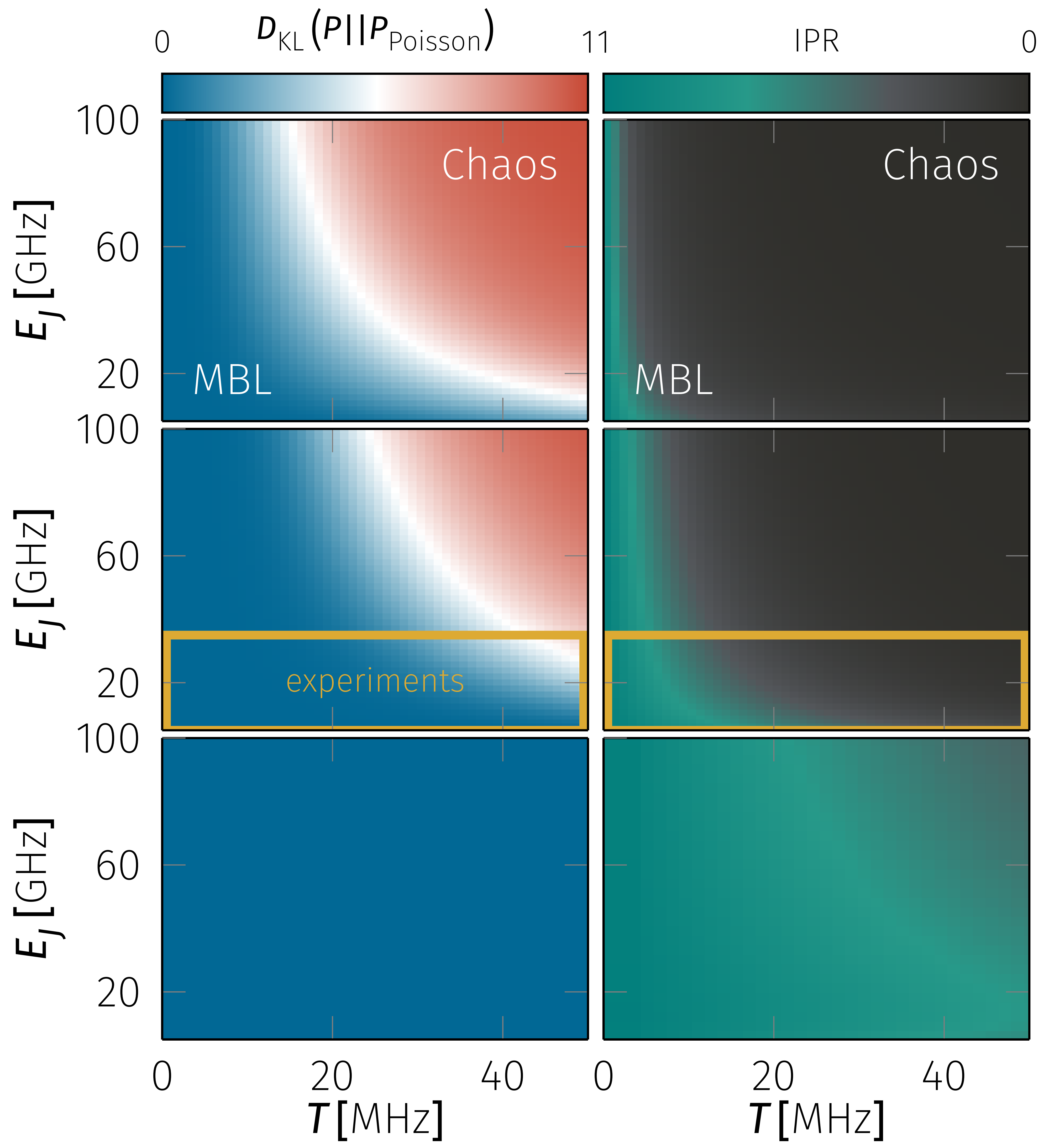
# quantifying chaos

**patterned disorder**

**natural disorder**

**tunable disorder**



# quantifying chaos

**ZZ couplings & more**

**p**-qubits and **l**-qubits

**τ - Hamiltonian**

of many-body localization

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

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

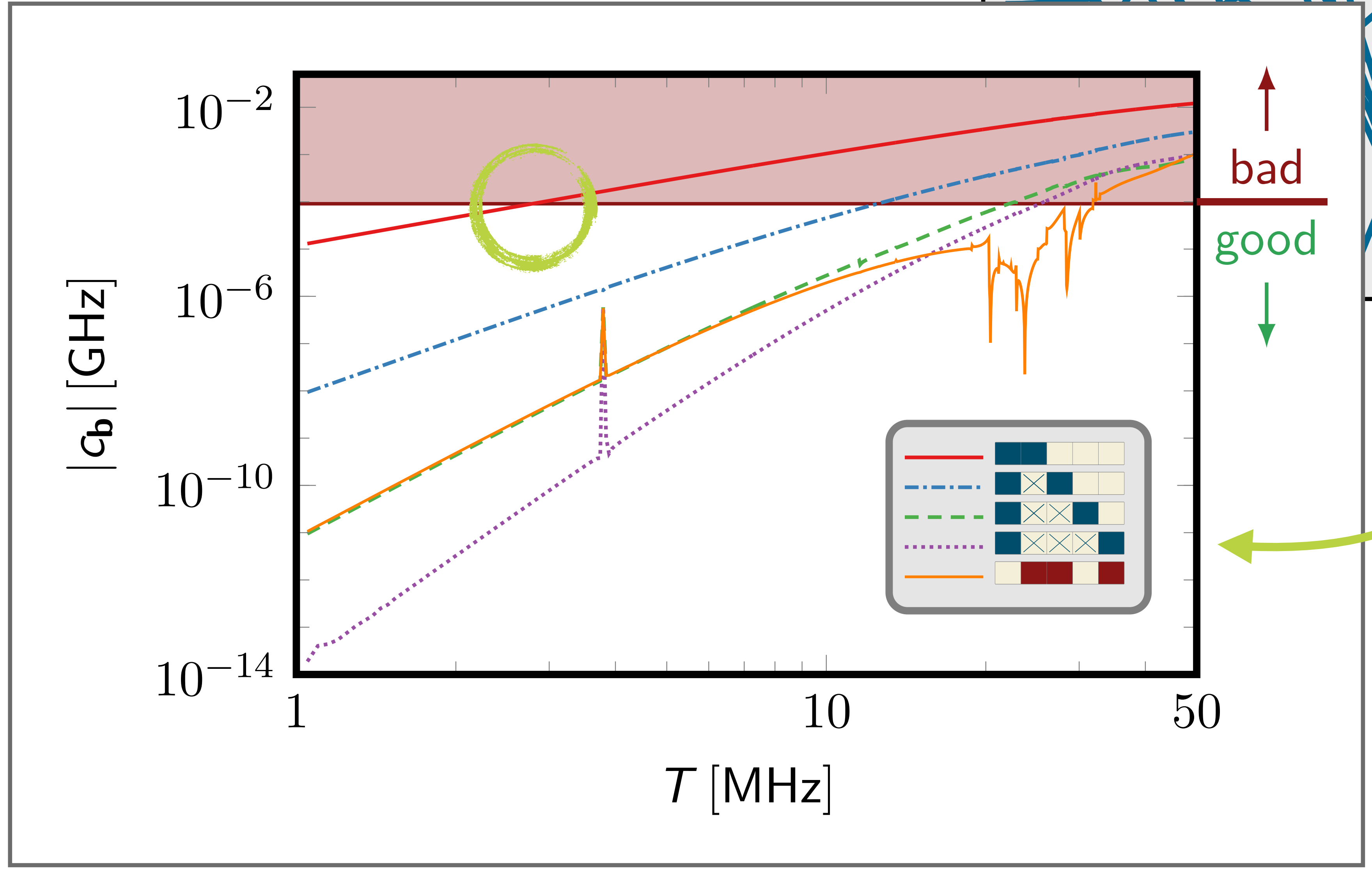
**Phenomenology of fully many-body-localized systems**

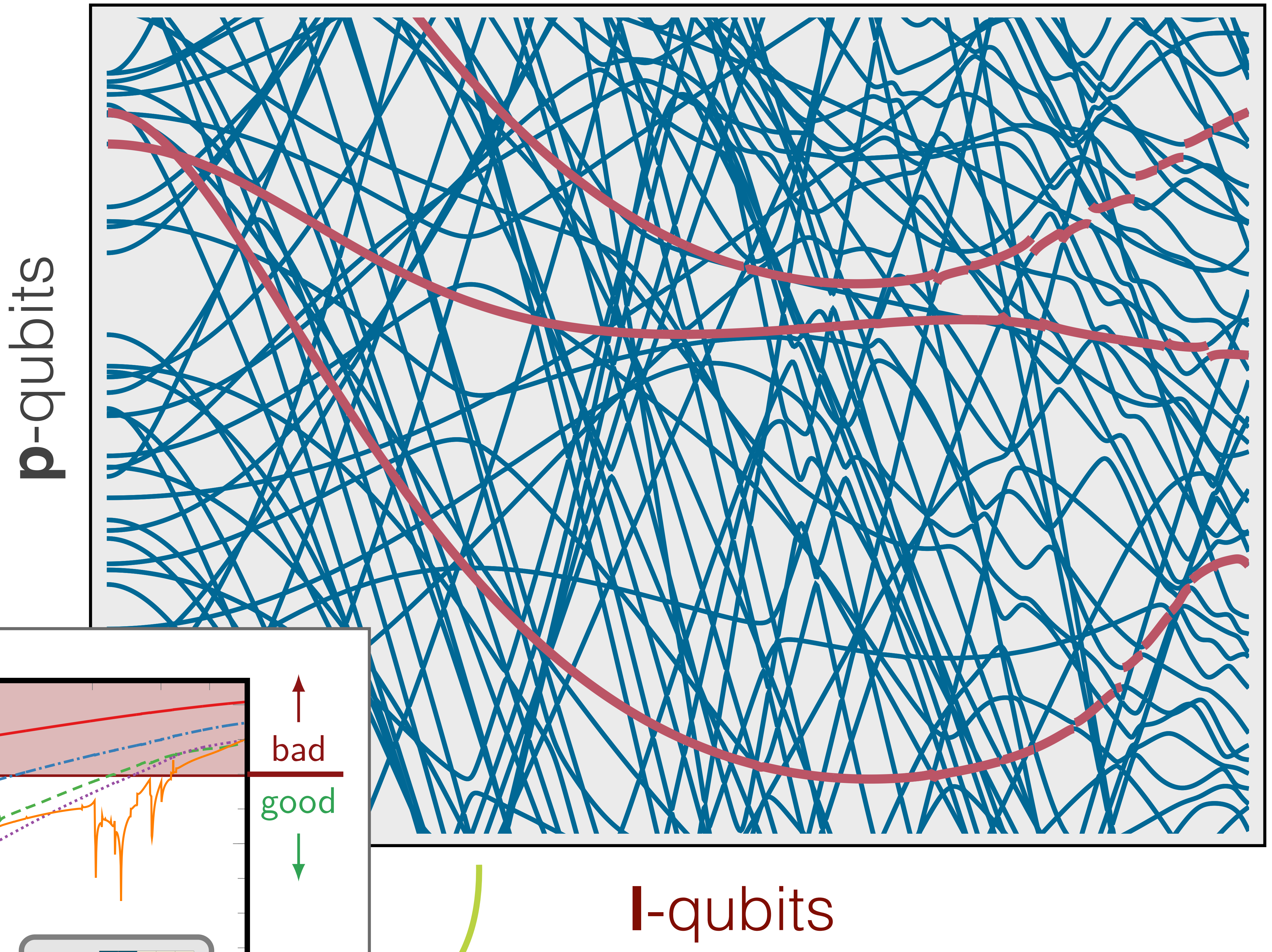
David A. Huse,[1] Rahul Nandkishore,[2] and Vadim Oganesyan[3,4]
[1]*Physics Department, Princeton University, Princeton, New Jersey 08544, USA*
[2]*Princeton Center for Theoretical Science, Princeton University, Princeton, New Jersey 08544, USA*
[3]*Department of Engineering Science and Physics, College 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,*]
[1]*Department of Physics, Syracuse University, Syracuse, New York 13244, USA*
[2]*Peter Grünberg Institute, Forschungszentrum Jülich, Jülich 52428, Germany*
[3]*Jülich-Aachen Research Alliance (JARA), Fundamental of Future Information Technologies, Jülich 52428, Germany*
[4]*IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, New York 10598, USA*
(Received 8 April 2020; accepted 2 September 2020; published 11 November 2020)

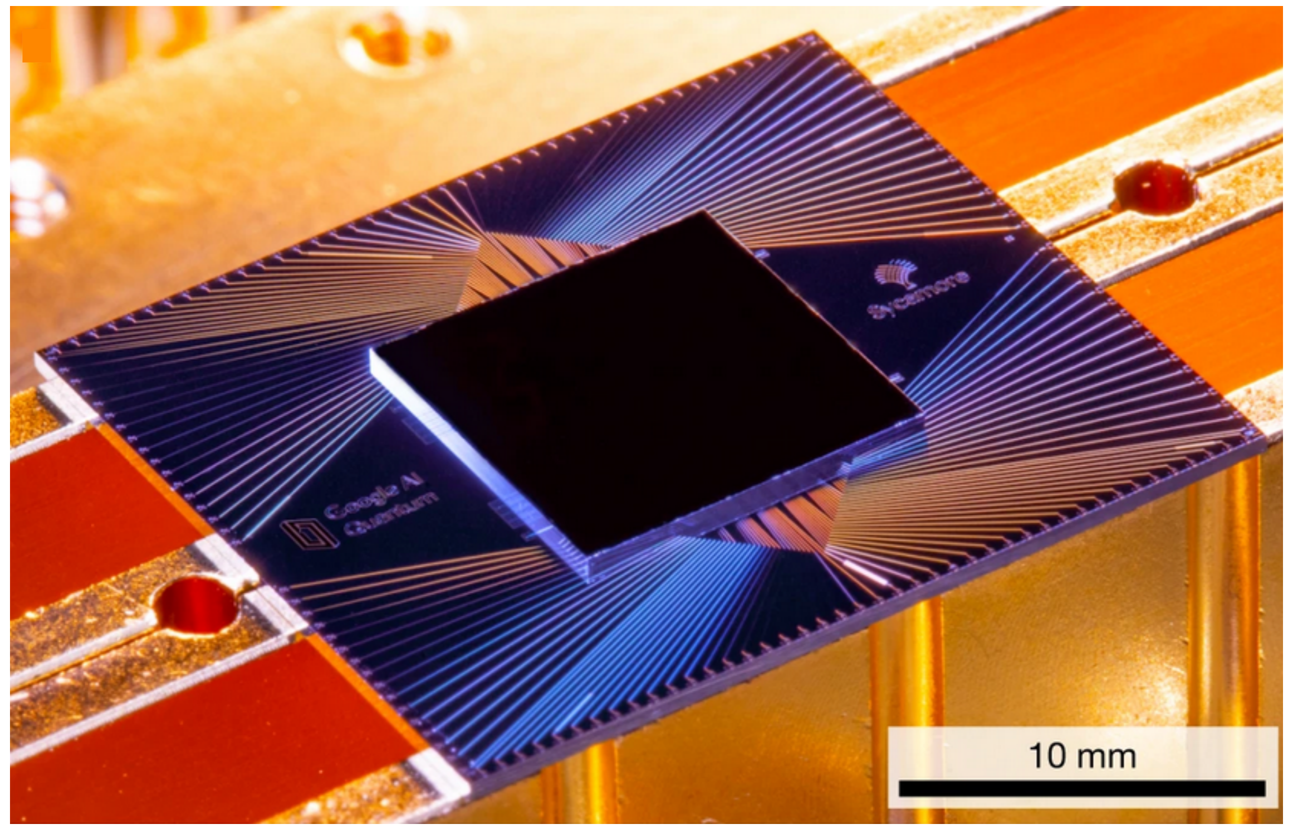


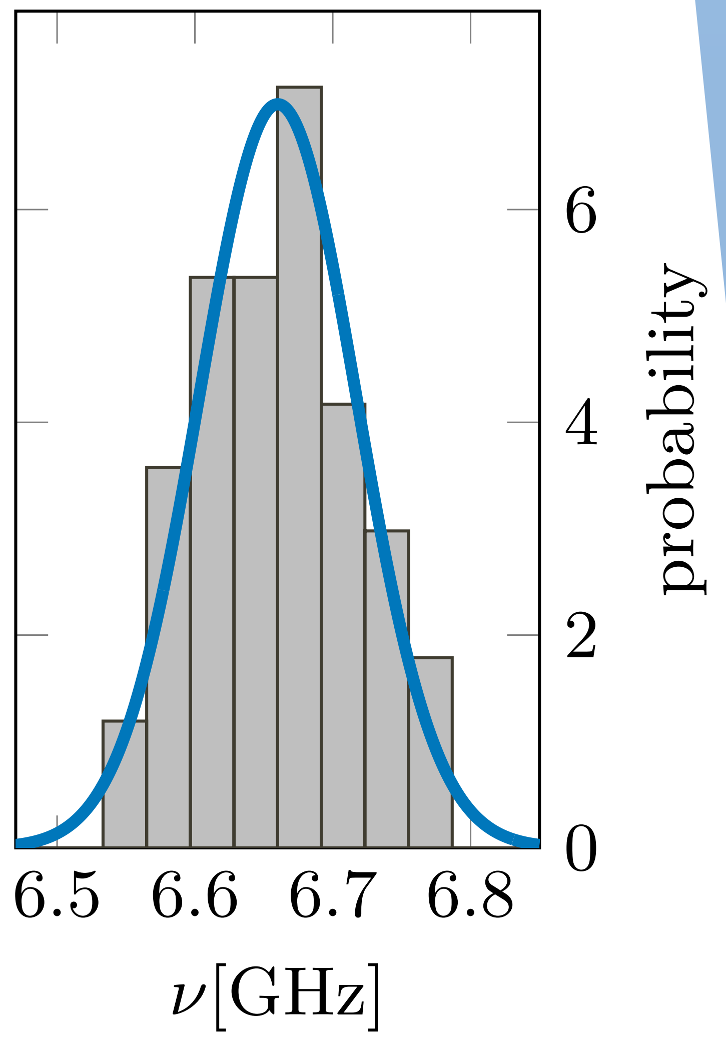

**Walsh transform**

# disorder engineering

# Google quantum processor




Google's **frequency engineering**



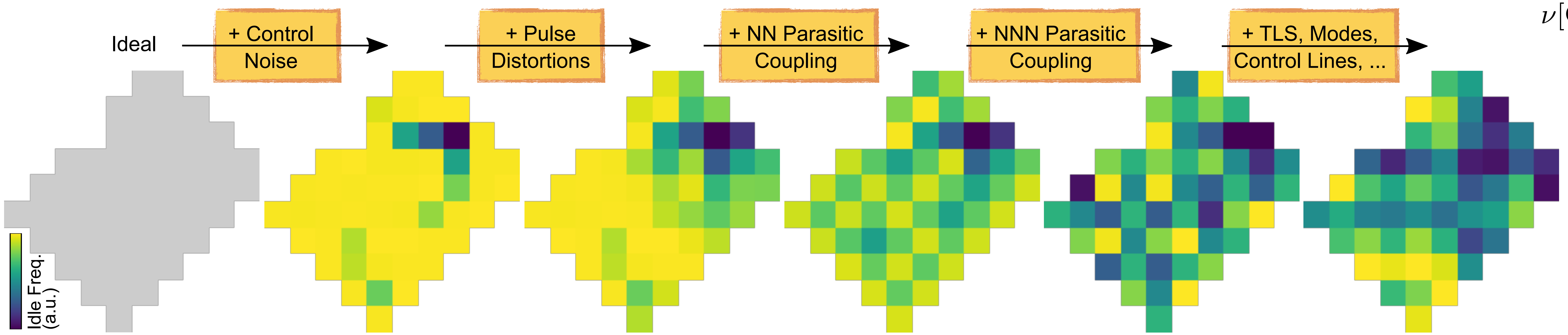



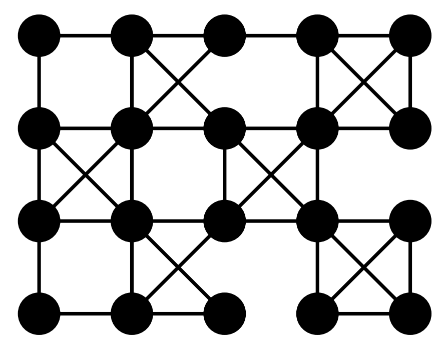

FIG. S12. **Idle frequency solutions found by our Snake optimizer with different error mechanisms enabled.** The optimizer makes increasingly complex tradeoffs as more error mechanisms are enabled. These tradeoffs manifest as a transition from a structured frequency configuration into an unstructured 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

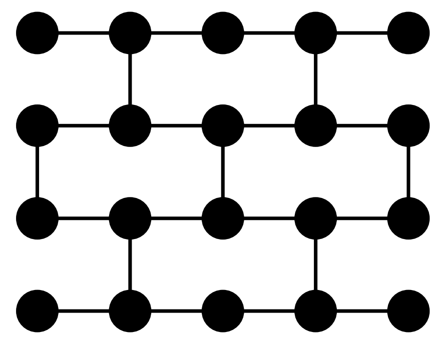
IBM's strategy to avoid

**frequency crowding**

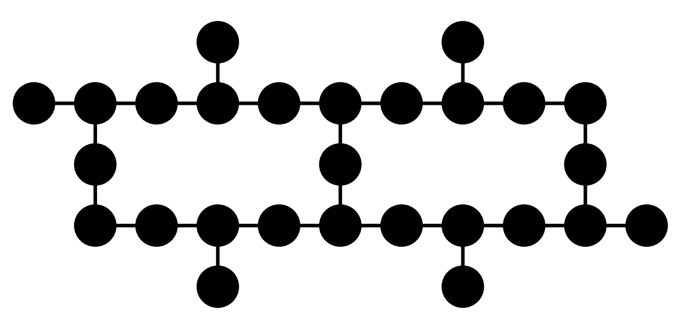
- optimize device geometry



2018

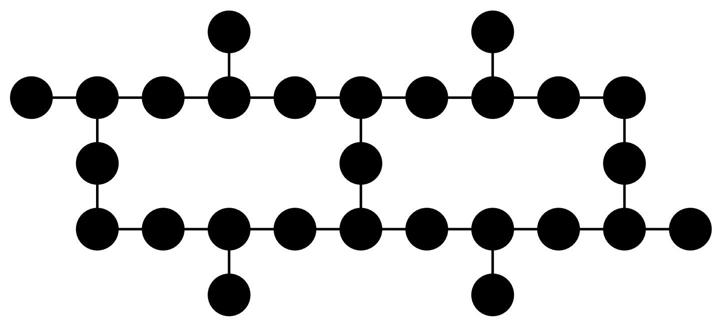


2019

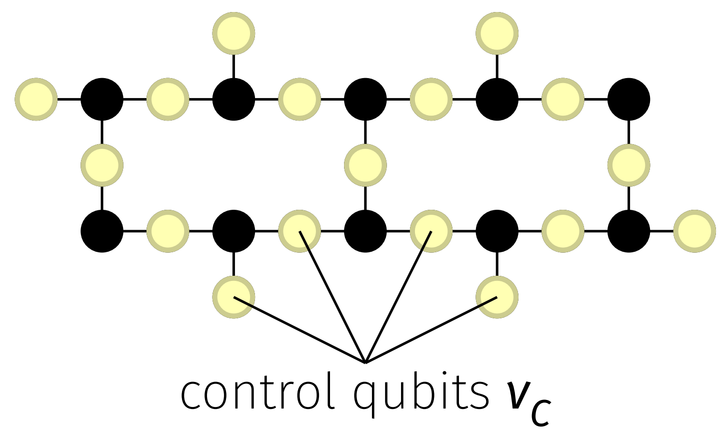


2020

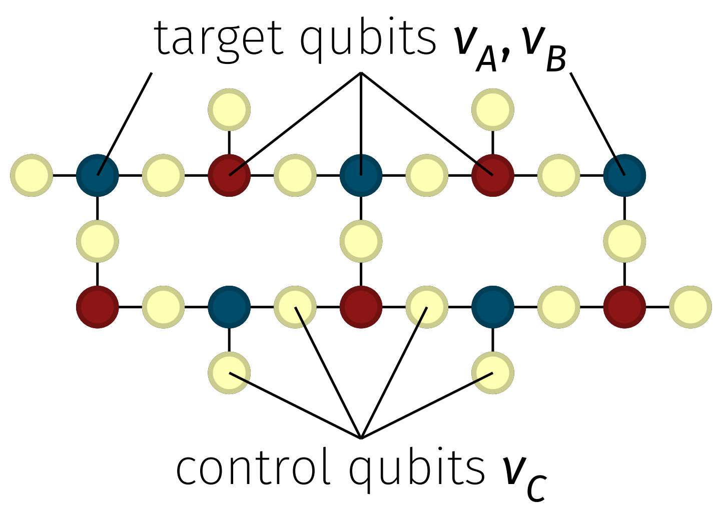
- frequency patterns



uniform



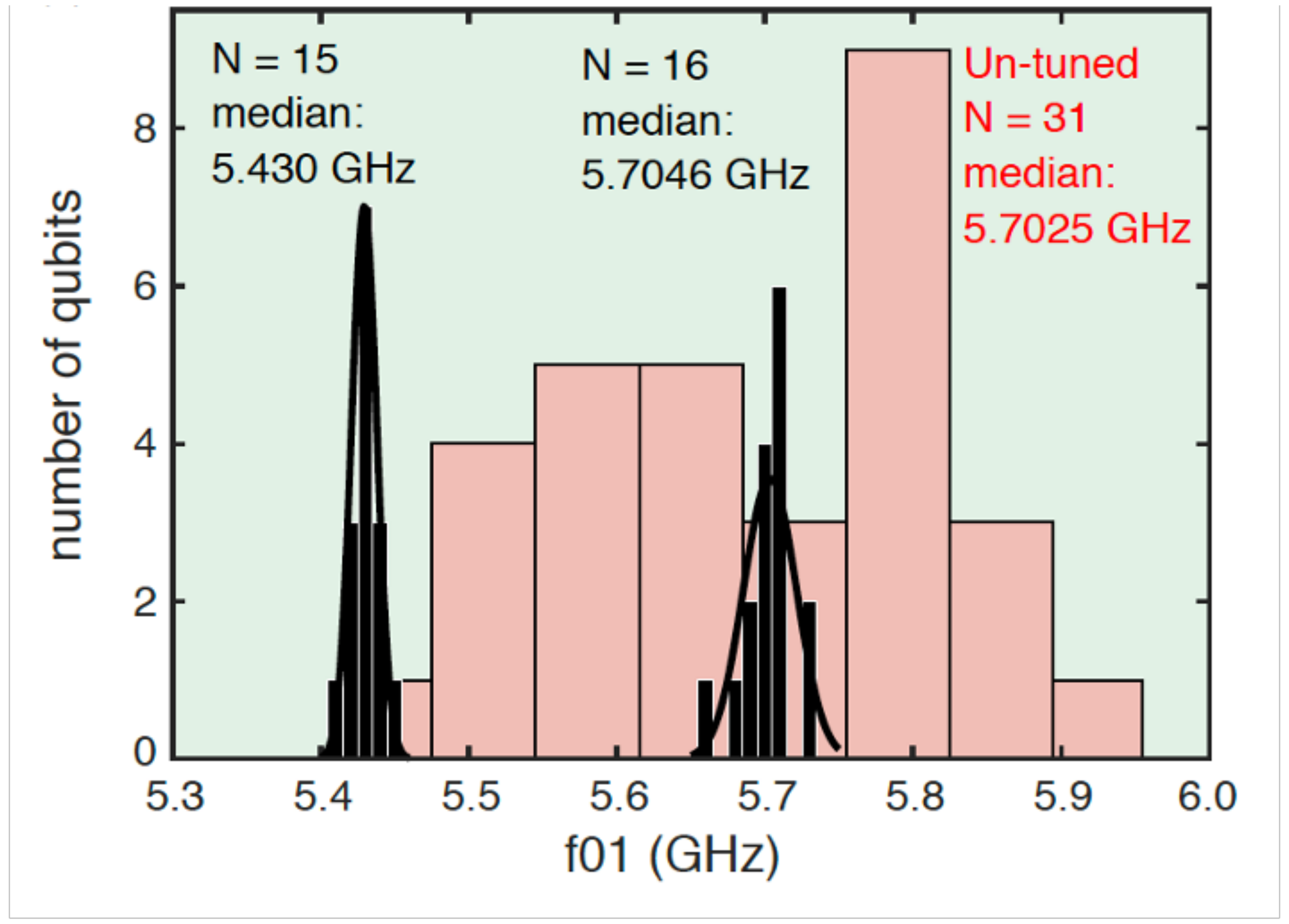

A – B




A – B – C

**pattern engineering**

via laser annealing




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

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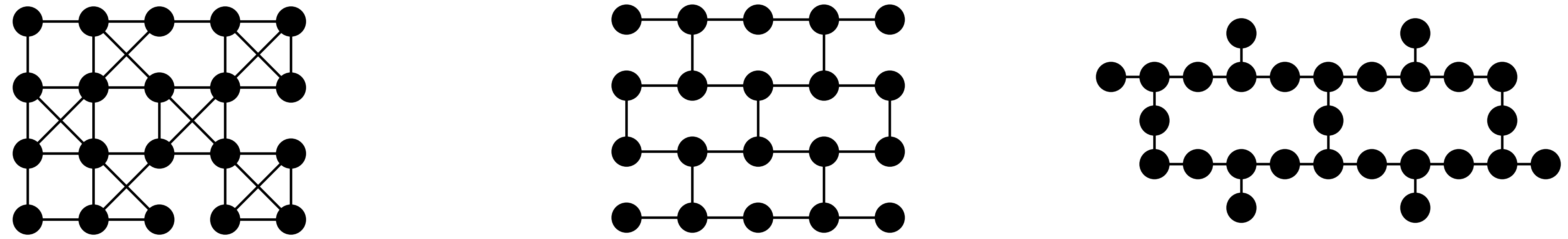
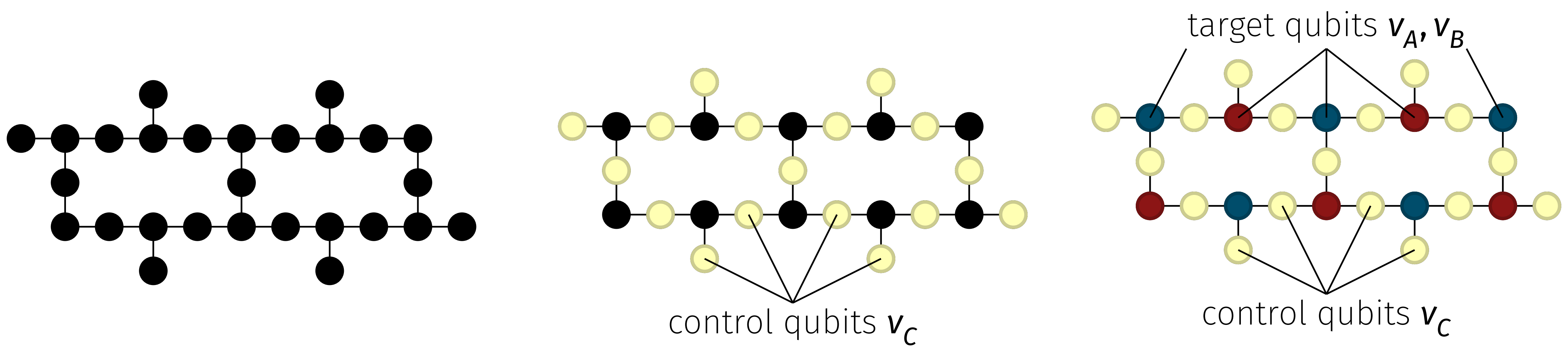
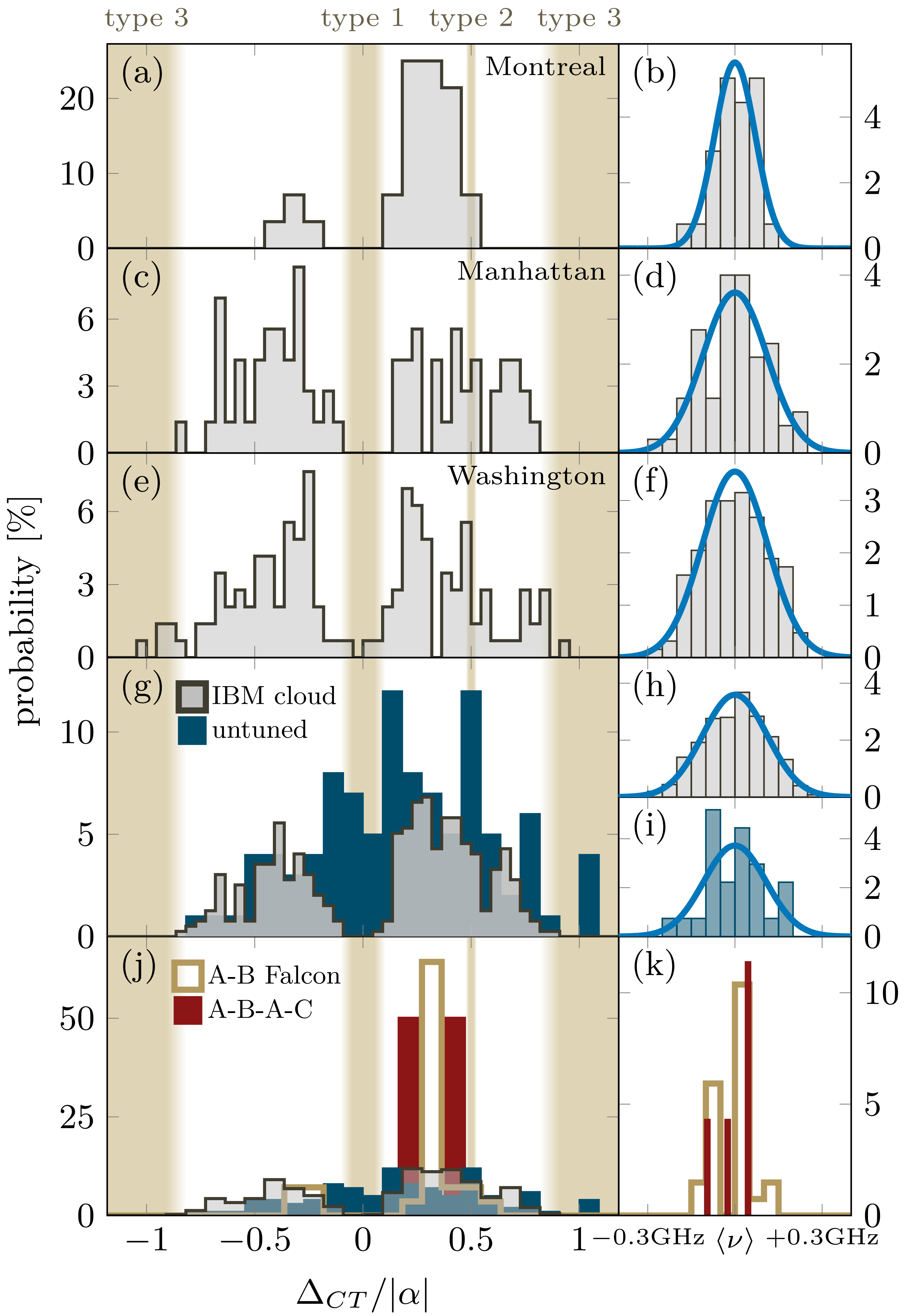


2018 2019 2020

- frequency patterns




uniform A – B A – B – C




**27**-qubit
"Falcon"

**65**-qubit
"Hummingbird"

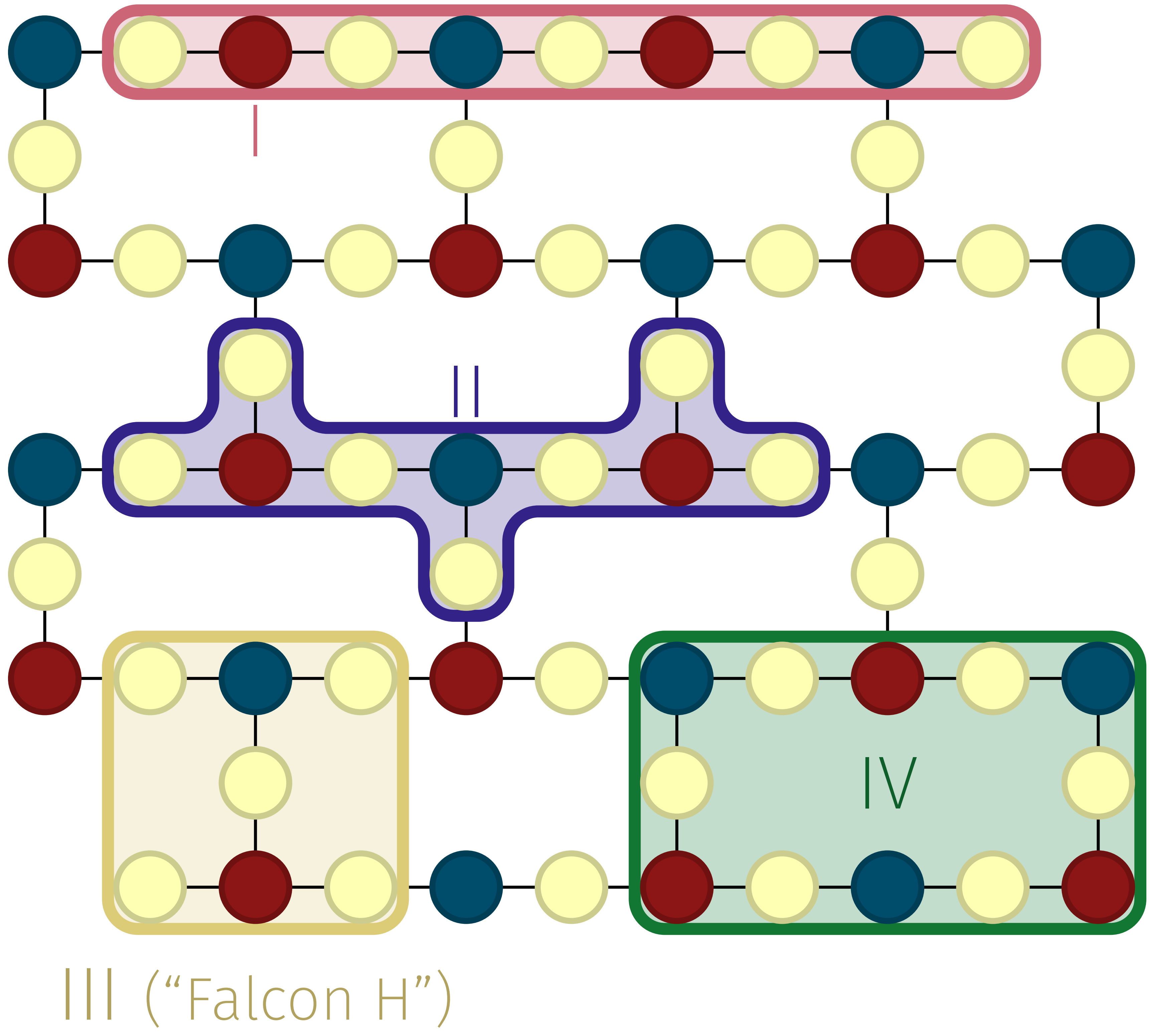
**127**-qubit
"Eagle"

device
**average**

**targeted**
device

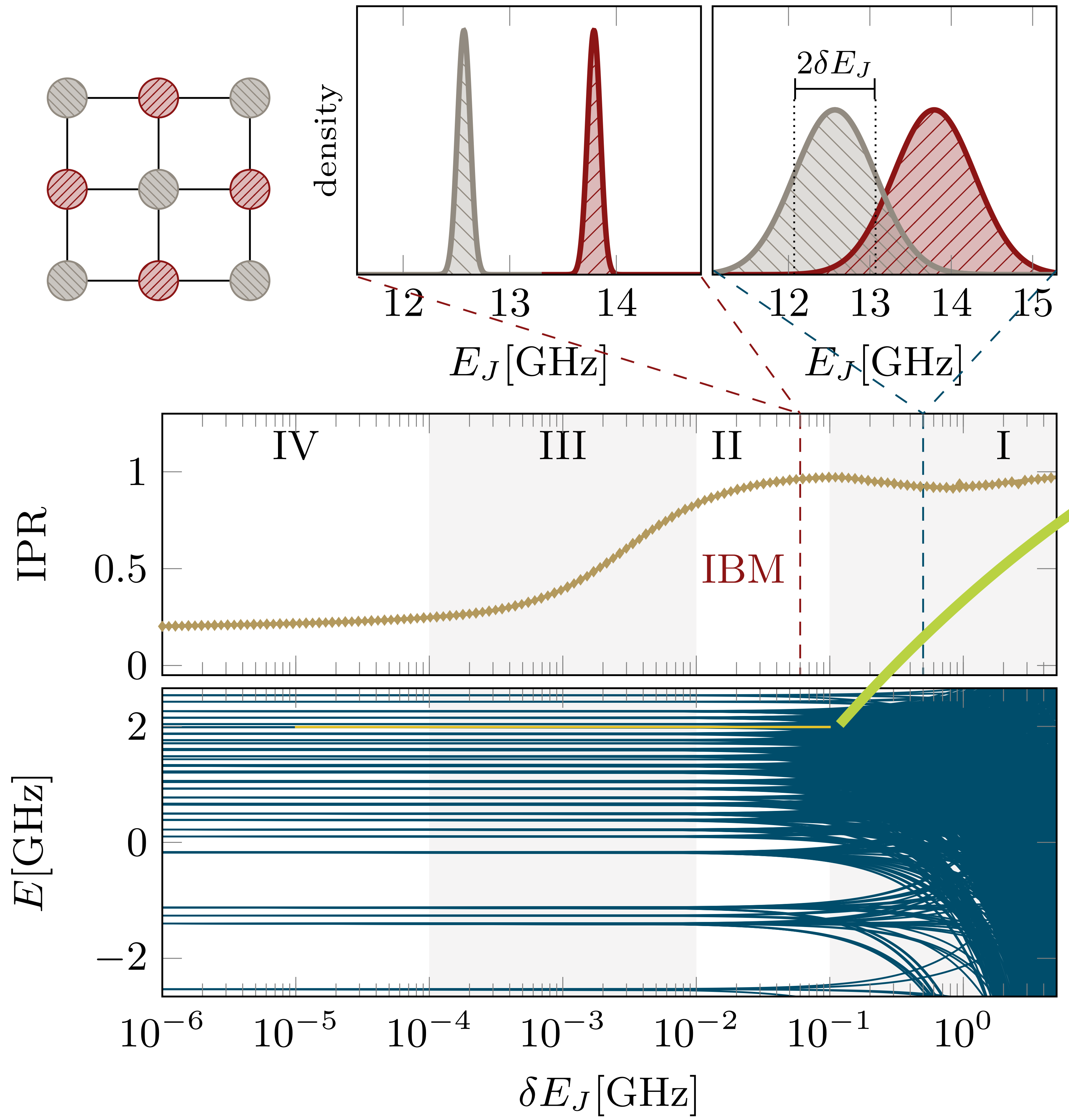
# A – B – C frequency patterns

device layouts



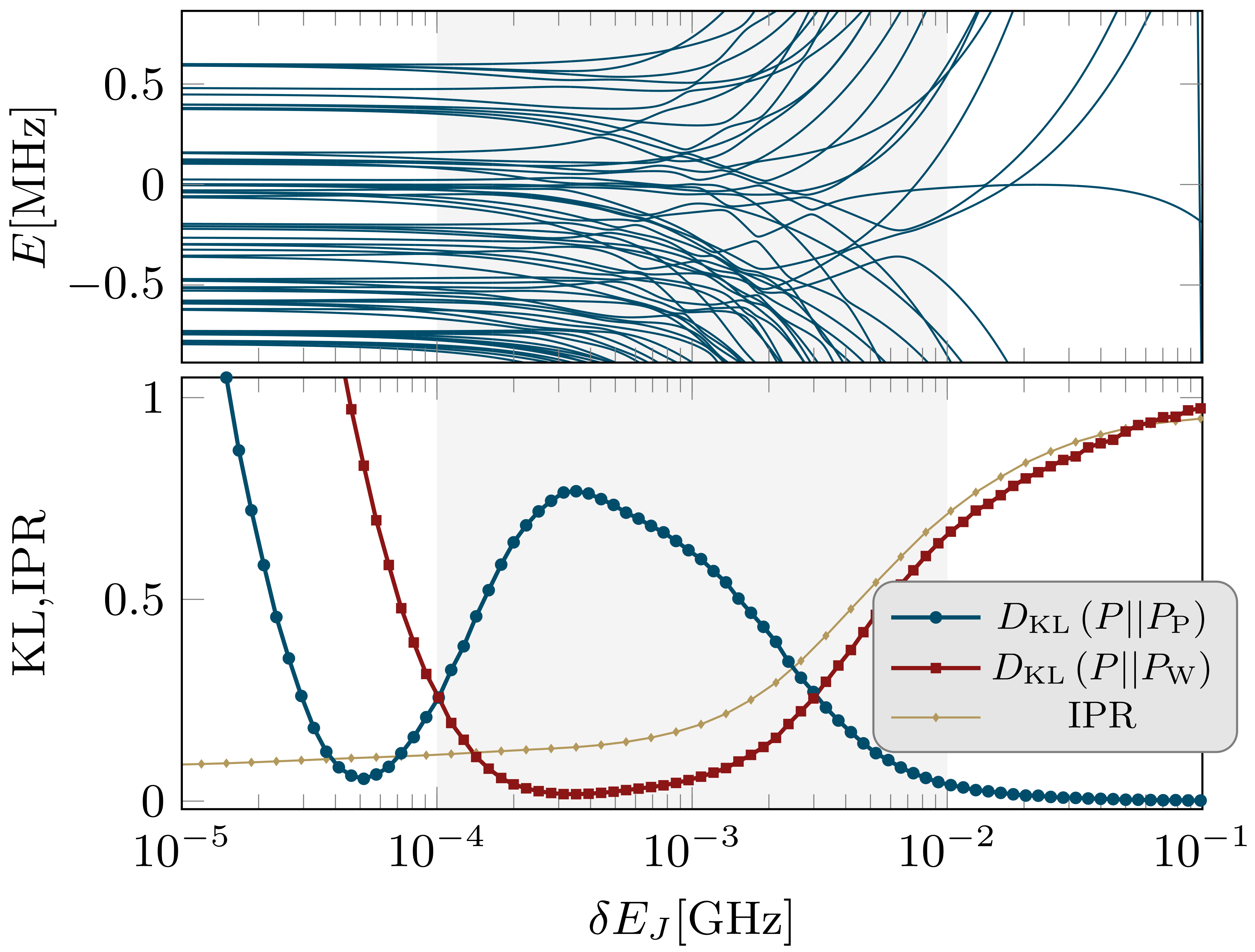

inverse participation ratio

# extreme disorder engineering




**staggered** disorder regimes

evolution of **5-excitation** bundle




**reentrant chaotic behavior**

(multiplet delocalization)

# Where to go from here?

# summary

Nature Comm. (2022)

Take-away messages

- Transmon qubit architectures need to balance **intentional disorder** and **non-linear couplings** to stay away from an **MBL - chaos transition**.
- Some **current experimental setups** in fact lie dangerously close to chaos transition.
- Highly connected **two dimensional** chips will be even more susceptible to chaos.

Outlook

- **Disorder engineering** needs to explore more complex staggering pattern than currently done.
- Dynamical **qubit operations** will need delicate stabilization.