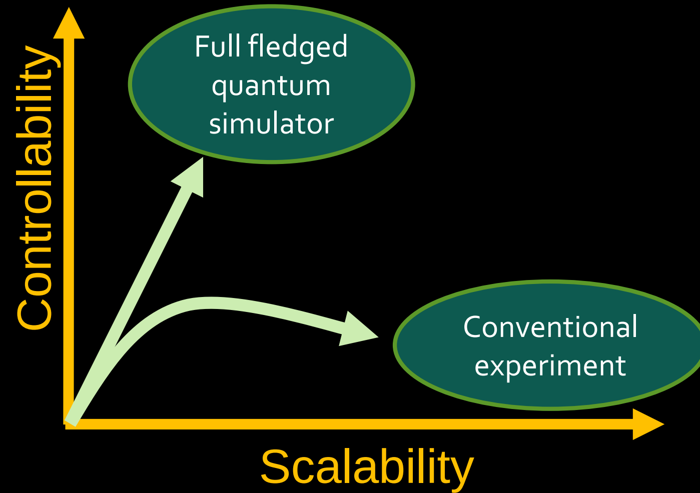
Spectral signatures of Many-body localization with interaction photons

Pedram Roushan
Google Inc.
Paris, Nov 2017

Simulating condensed matter systems

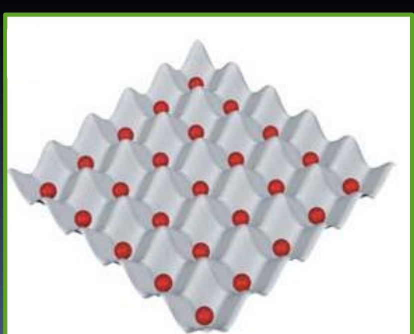
Let nature calculate for us !



+ measurability

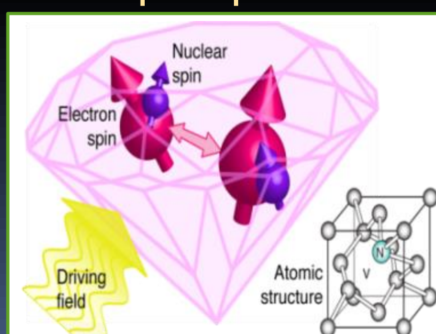
+ coherence

Ultra-cold atoms



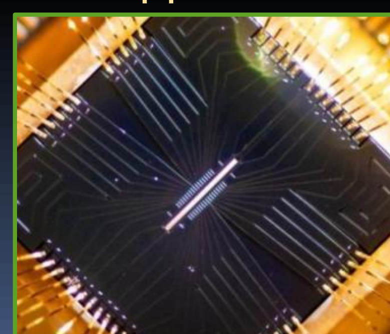
Bloch, Nature Physics (2005)

Spin qubits



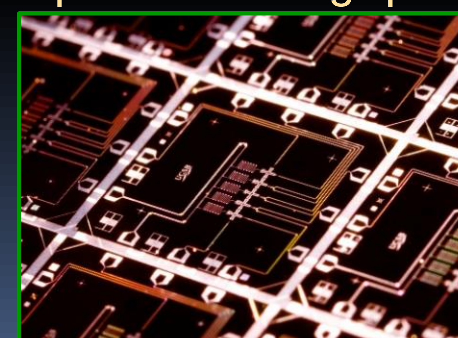
Toyli, *et al.*, Nano Lett. 2010

Trapped ions



Monroe, *et al.*, Science 2013

Superconducting qubits



E. Lucero, Google Inc. (2014)

What can be done with small number of qubits ?

David Huse, Princeton university

"…once you can go over 20 q-bits, you are exploring stuff that we have no other way of exploring now."

quantum stat. mech.
cond. matt. physics
(even) string theory

Chetan Nayak, Microsoft station-Q

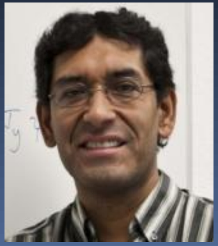
" …small quantum computers - on the order of 100 qubits - will be useful in the solution of scientific problems."

quantum chemistry
High-T_C

Anatoli Polkovnikov, Boston university

" If you go to 20 you reach the maximum one can do with exact diagonalization …, if you have more, you are beyond theory."

thermalization
many body localization
controlled disorder

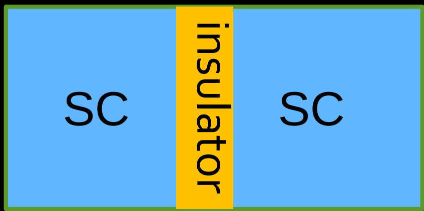


Enrique Solano, U. of the Basque Country

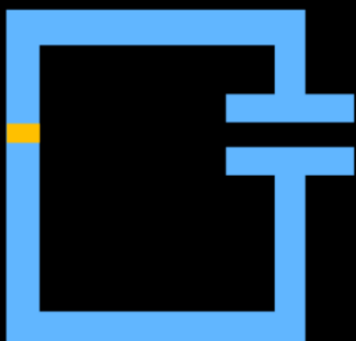
"…with something like 10-20 qubits coupled to 5-10 cavity modes, we will be able to produce nontrivial quantum simulations."

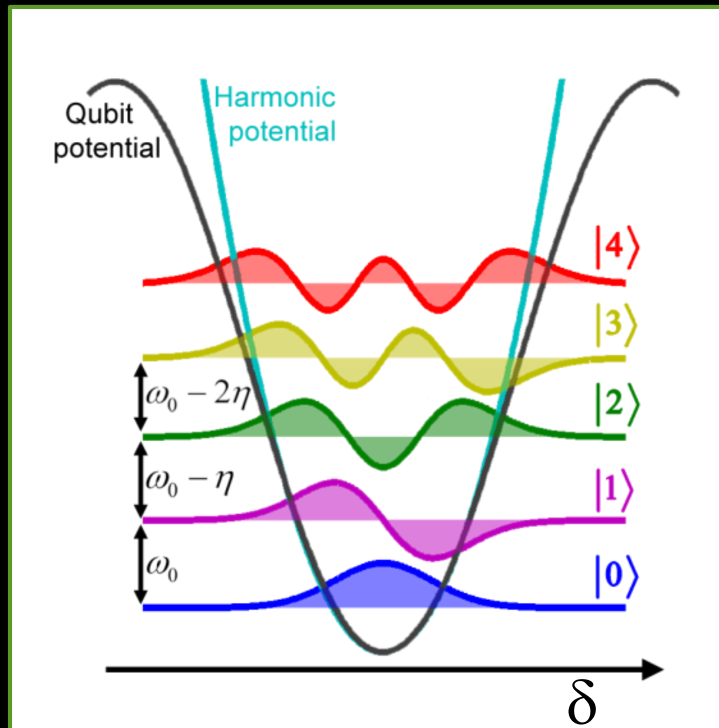
Unphysical operations
quantum field theories
fluid mechanics

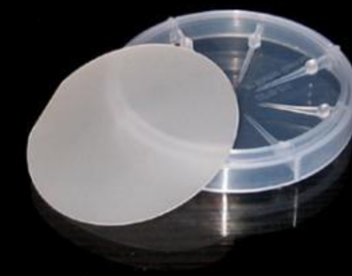
Superconducting Qubits: Weakly non-linear Harmonic oscillators

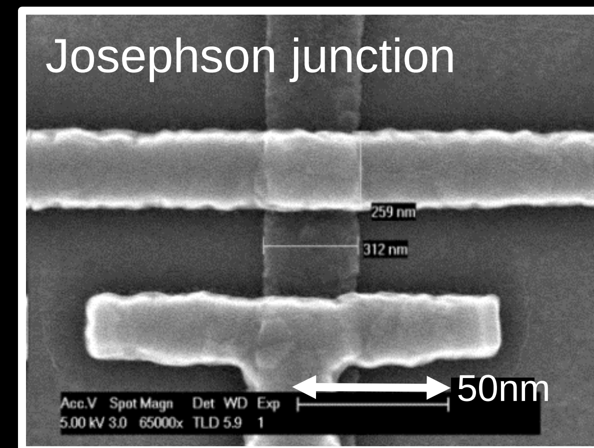


$$I = I_0 \sin(\delta)$$



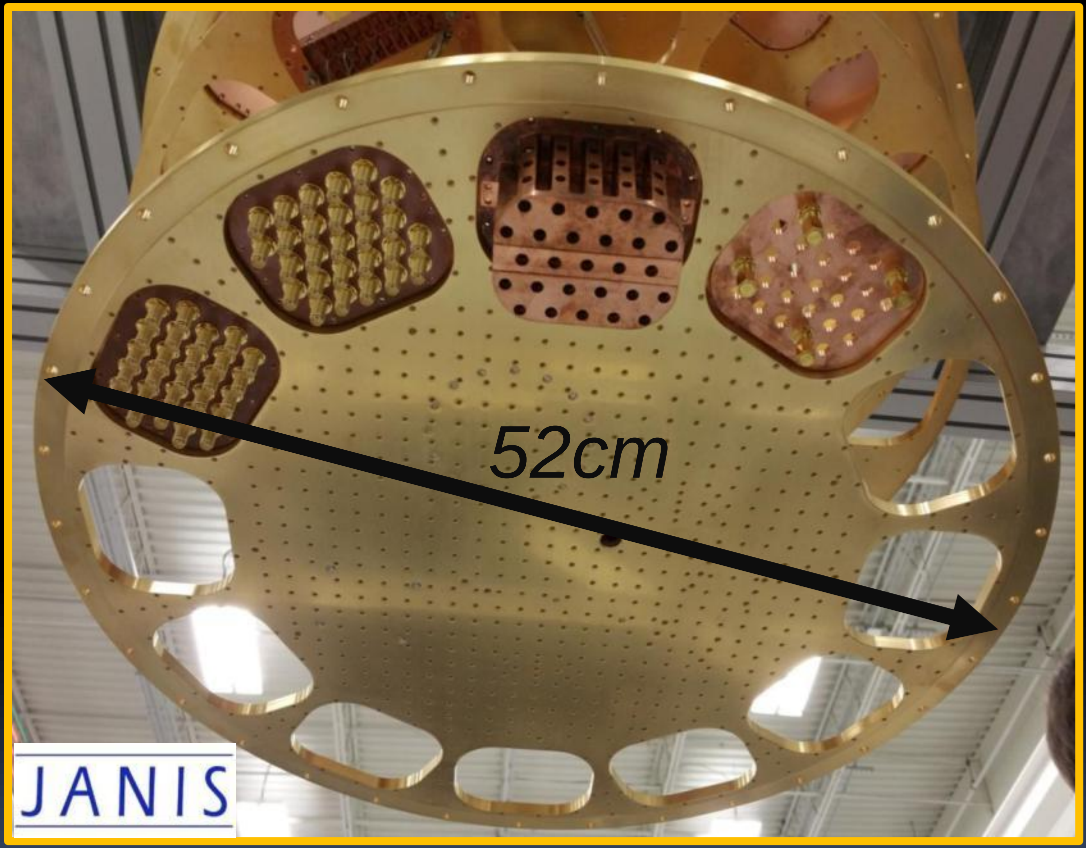






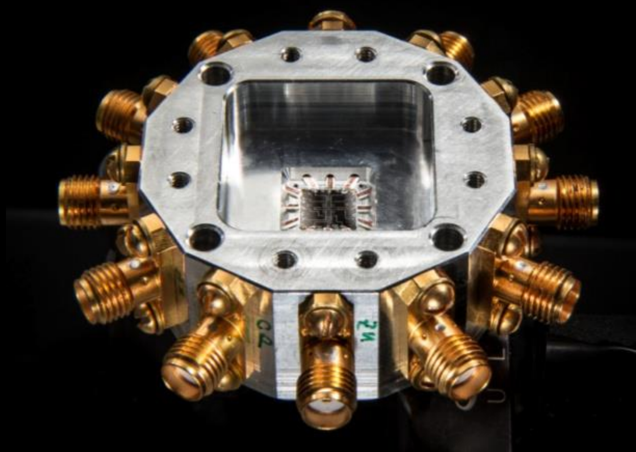
Experimental setup:
fridge and wiring

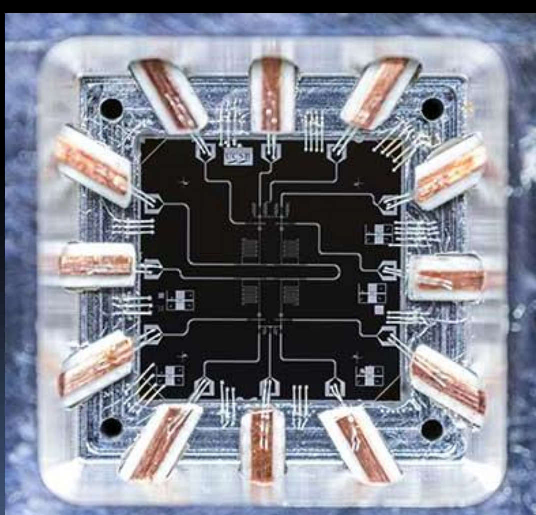
500μW at 100mK



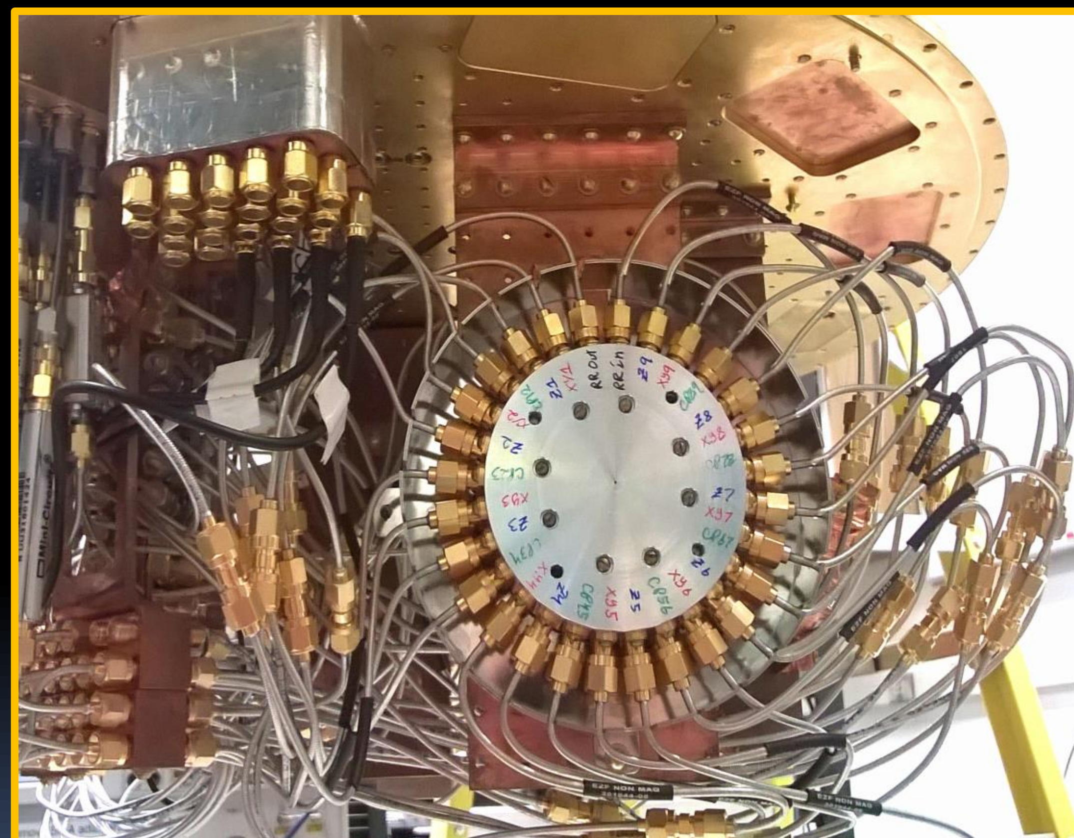
Base temperature ~10mK

Experimental setup:
fridge and wiring

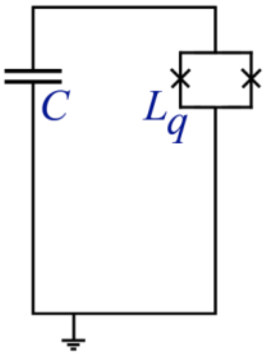




1cm



Base temperature ~10mK



$$H_{Qubit} = \frac{\hat{Q}^2}{2C} - \frac{(\Phi_0/2\pi)^2}{L_q}\cos(\hat{\varphi})$$

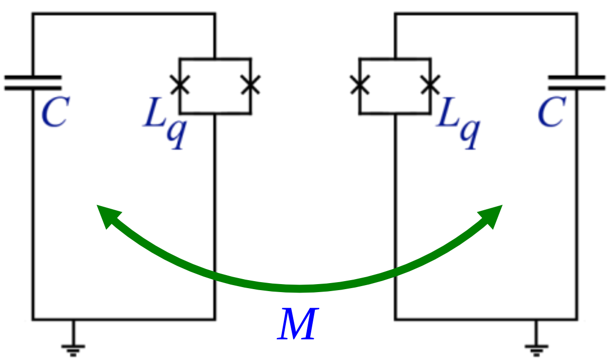
$$\hat{\varphi} \to a^+ + a$$
$$\hat{Q} \to i(a^+ - a)$$
$$\hat{n} = a^+ a$$

$$H_{Qubit} = \frac{\hat{Q}^2}{2C} - \frac{(\Phi_0/2\pi)^2}{L_q}\left(1 - \frac{\hat{\varphi}^2}{2!} + \frac{\hat{\varphi}^4}{4!} - \frac{\hat{\varphi}^6}{6!} + \ldots\right)$$

$H_{h.o.}$ H_{int}

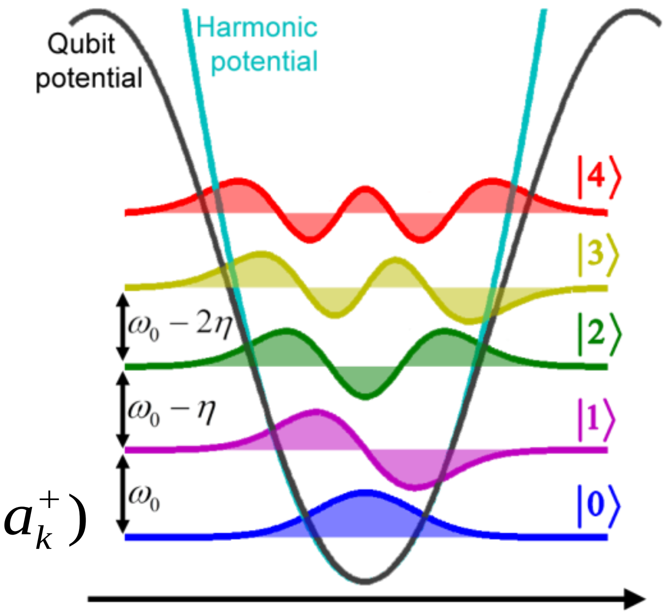
$$H_{h.o.} \underset{RWA}{\to} \hbar\frac{\Delta_0}{2}(\hat{n} + 1/2)$$

$$H_{int} \underset{RWA}{\to} -\frac{U_2}{2}\hat{n}(\hat{n}-1) + \frac{U_3}{6}\hat{n}(\hat{n}-1)(\hat{n}-2) + \ldots$$



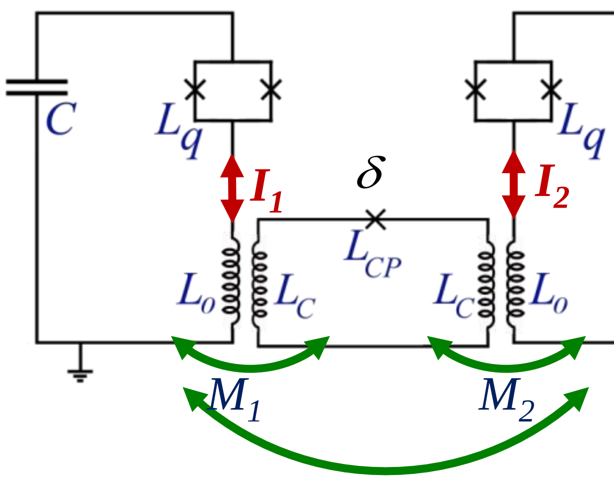
$$H_{hop} = \frac{M}{2L_q^2}\hat{\varphi}_1\hat{\varphi}_2$$

$$H_{hop} \underset{RWA}{\to} g(a_j^+ a_k + a_j a_k^+)$$



$$H_{BH} = \sum^{Qubits} \mu_n a_n^\dagger a_n + \frac{U}{2}\sum^{Qubits} a_n^\dagger a_n(a_n^\dagger a_n - 1) + J\sum^{Couplers} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$

The gmon (Jmon) architecture



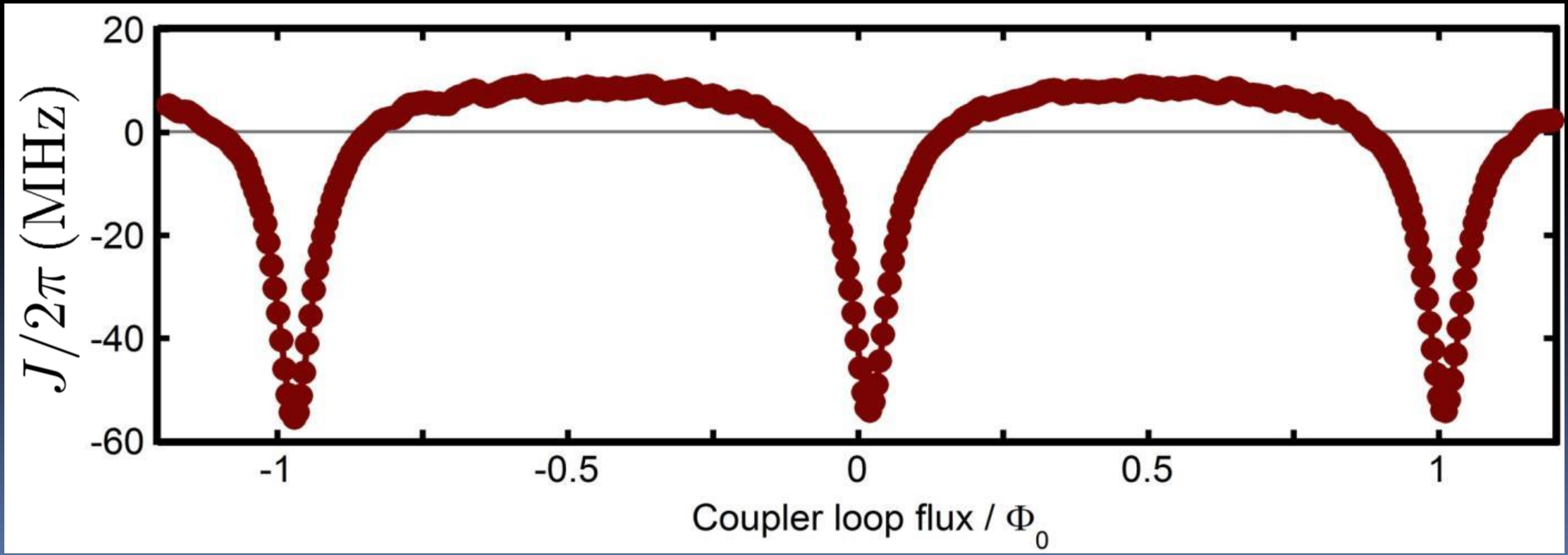
$$\omega_1 = \omega_0\left(1 - \frac{M}{2L_q}\right)$$

$$\omega_2 = \omega_0\left(1 + \frac{M}{2L_q}\right)$$

$$J \equiv \frac{\omega_2 - \omega_1}{2}$$

$$M = \frac{M_1 M_2}{L_{CP} + 2L_C}$$

$$J/\omega_0 = \frac{M_1 M_2}{2L_q} \frac{\cos(\delta)}{2L_0\cos(\delta) + L_C}$$

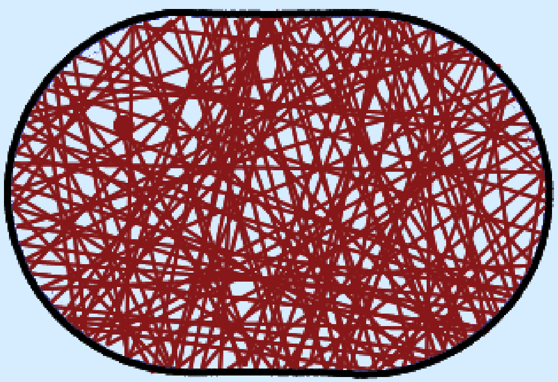


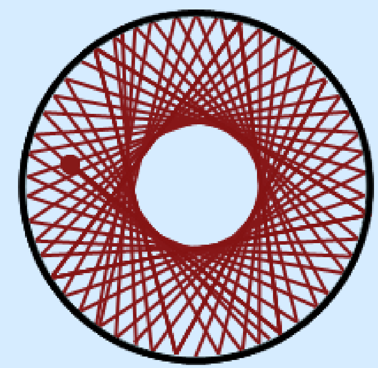
Absence of thermalization in interacting systems?

Fundamental assumption of statistical mechanics:
All micro-states associated with a given macro-states have equal probability.

Ergodic hypothesis:
System explores all accessible micro-states over time.

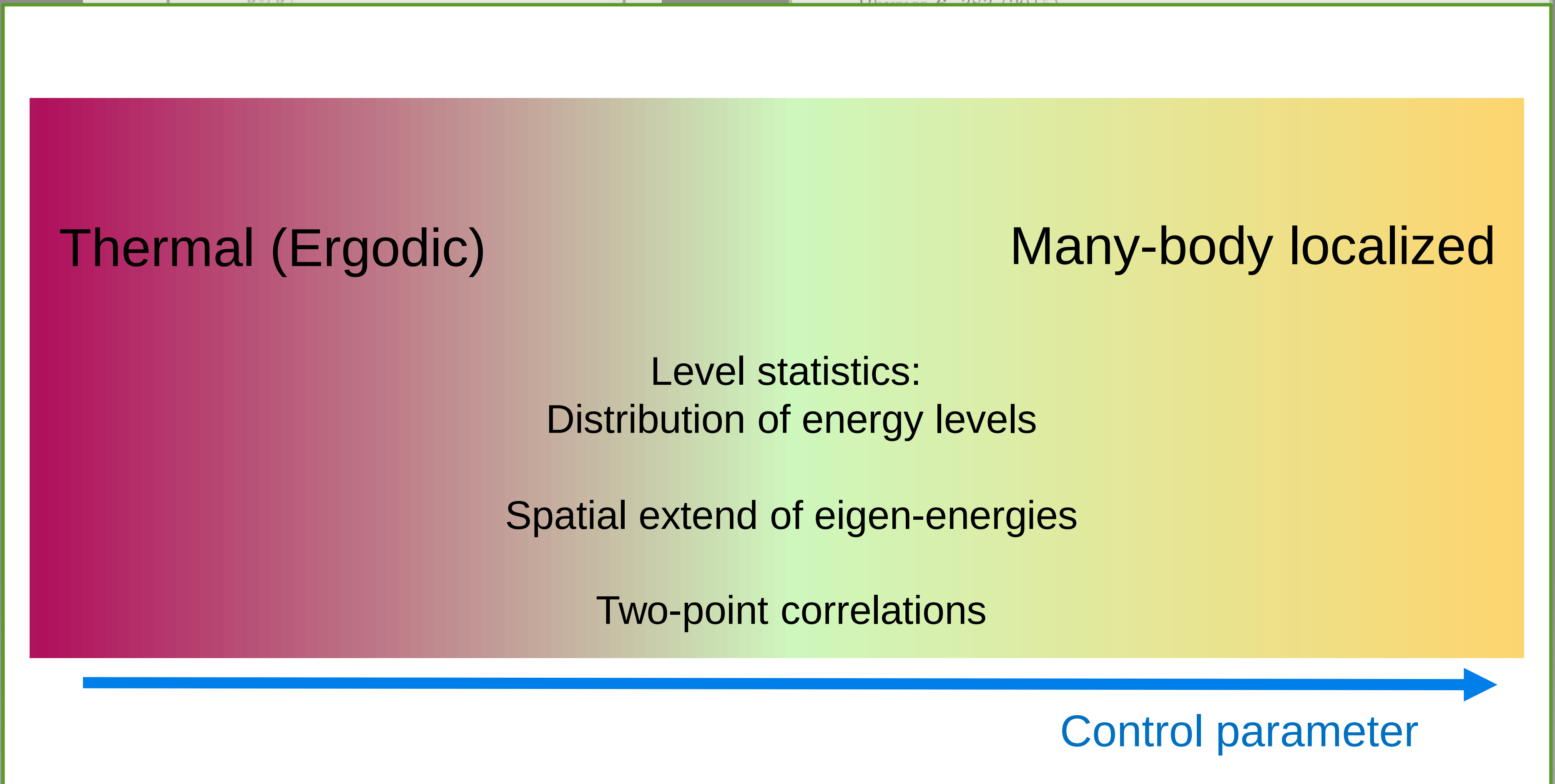
Chaotic → Ergodic → Thermal

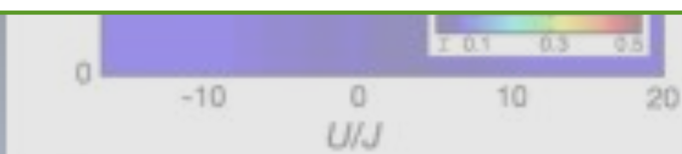




Break down of ergodicity

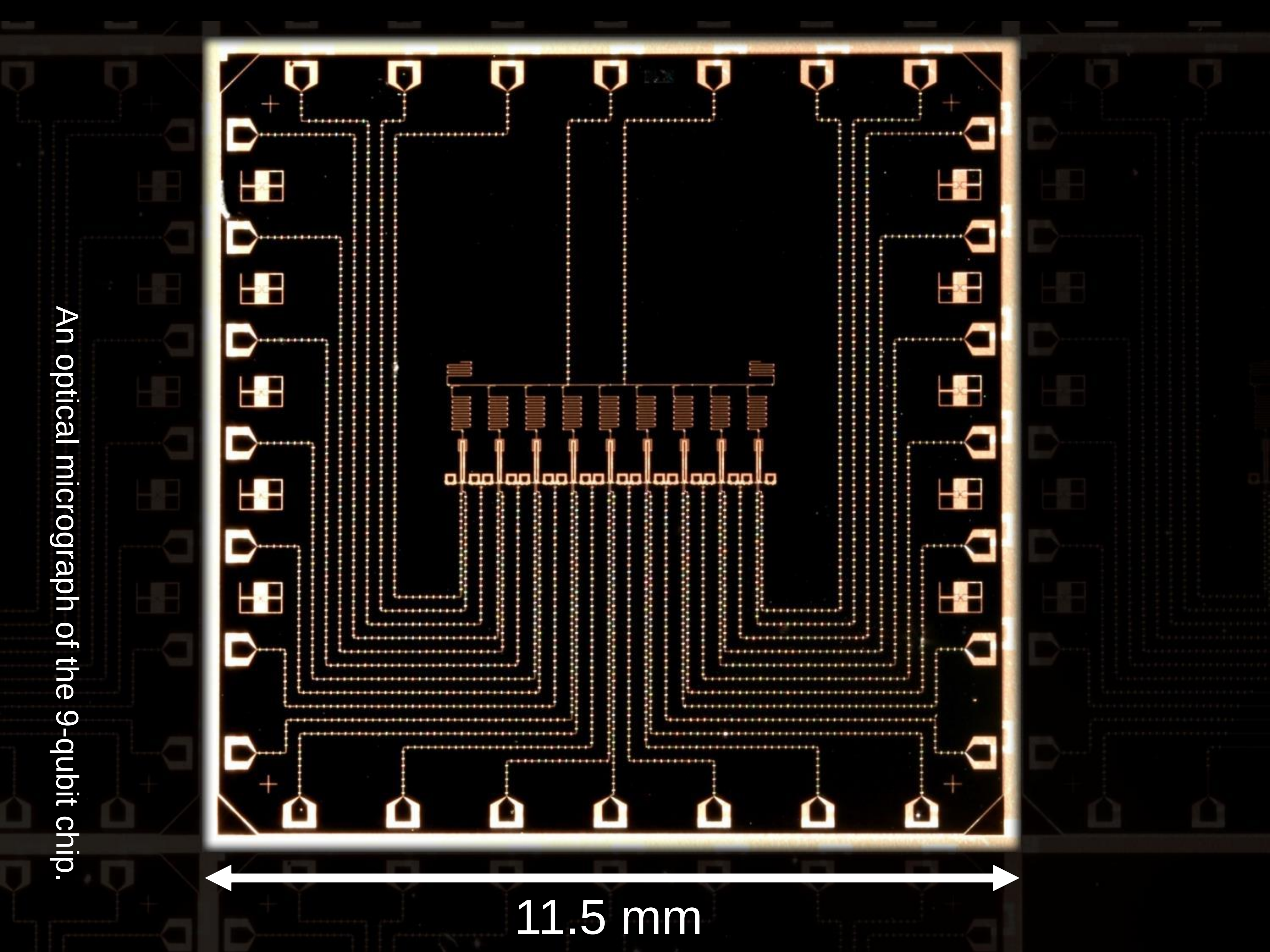
Recent studies of many-body localization





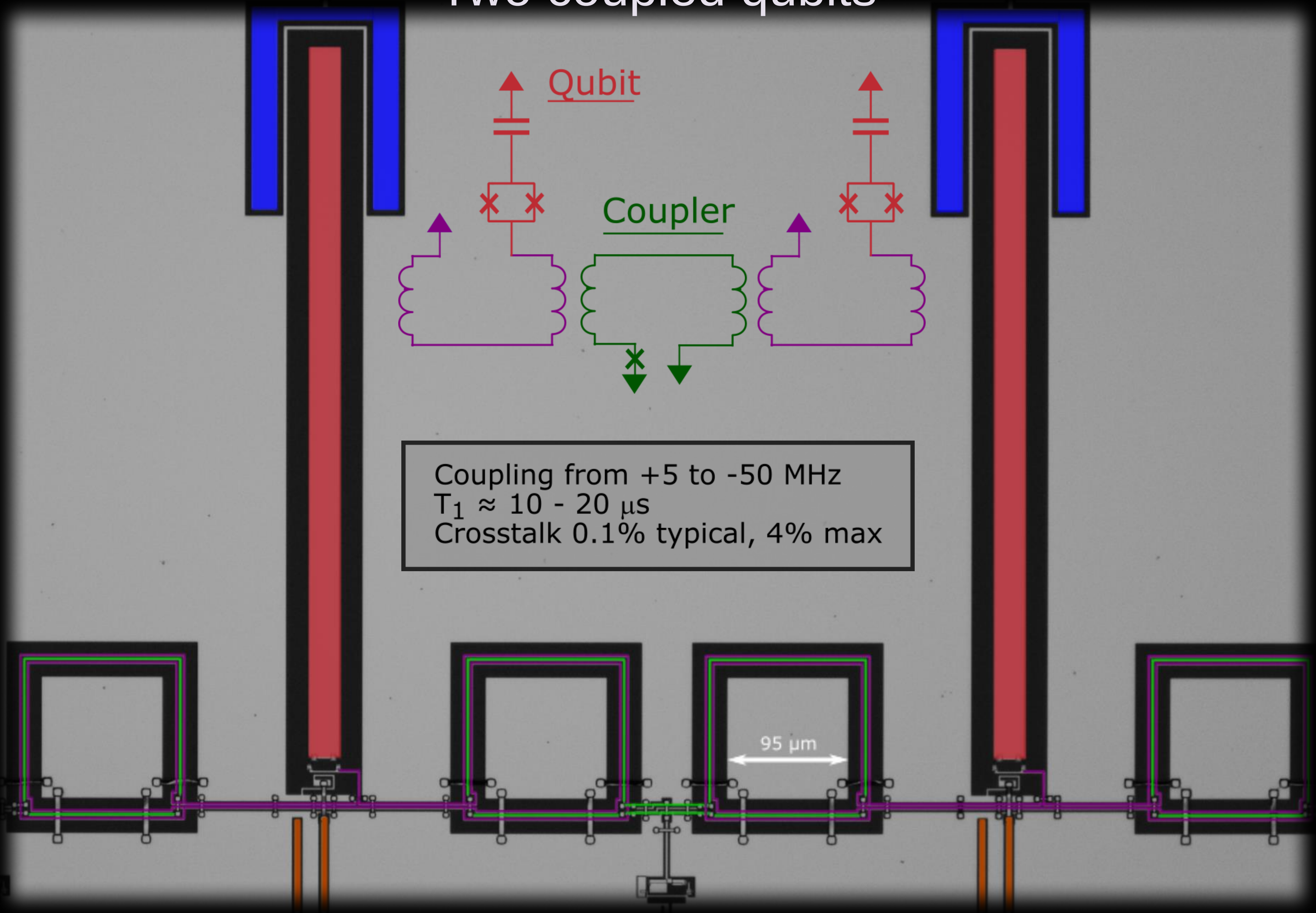
[1] D.M. Basko, I.L. Aleiner, and B.L. Altshuler, "Metal-insulator transition in a weakly interacting many-electron system with localized single-particle states," Annals of Physics **321**, 1126–1205 (2006).
[2] R. Nandkishore and D. A. Huse, "Many-body localization and thermalization in quantum statistical mechanics," Annual Review of Condensed Matter Physics **6**, 15–38 (2015).
[3] E. Altman and R. Vosk, "Universal dynamics and renormalization in many-body-localized systems," Annual Review of Condensed Matter Physics ...

Nature Communications **6**, 7341 (2015).
[15] John Z. Imbrie, "Diagonalization and many-body localization for a disordered quantum spin chain," Phys. Rev. Lett. **117**, 027201 (2016).
[16] F. Iemini, A. Russomanno, D. Rossini, A. Scardicchio, and R. Fazio, "Signatures of many-body localization in the dynamics of two-site entanglement," Phys. Rev. B **94**, 214206 (2016).



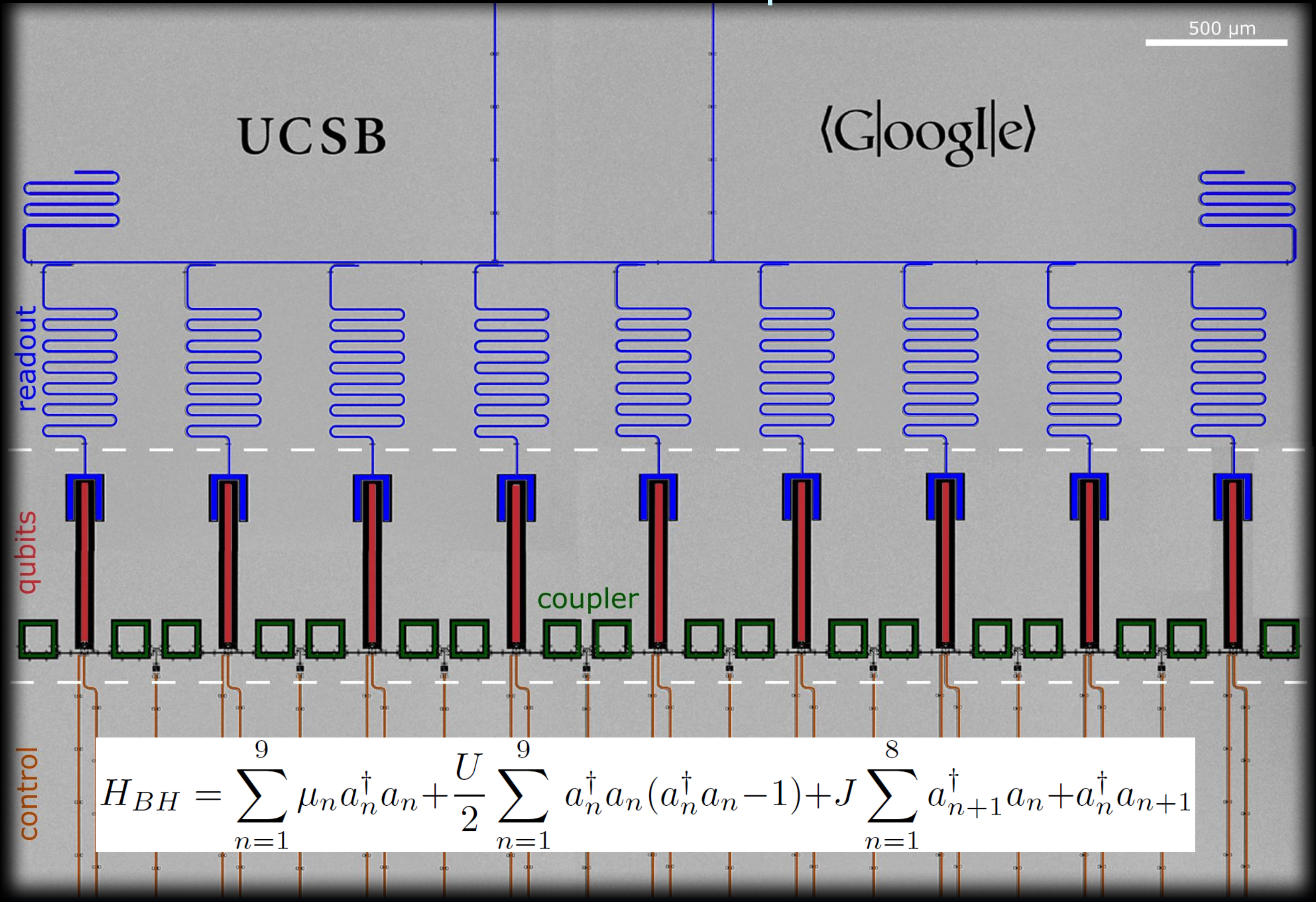
An optical micrograph of the 9-qubit chip.

Two coupled qubits



Coupling from +5 to -50 MHz
$T_1 \approx 10 - 20\ \mu s$
Crosstalk 0.1% typical, 4% max

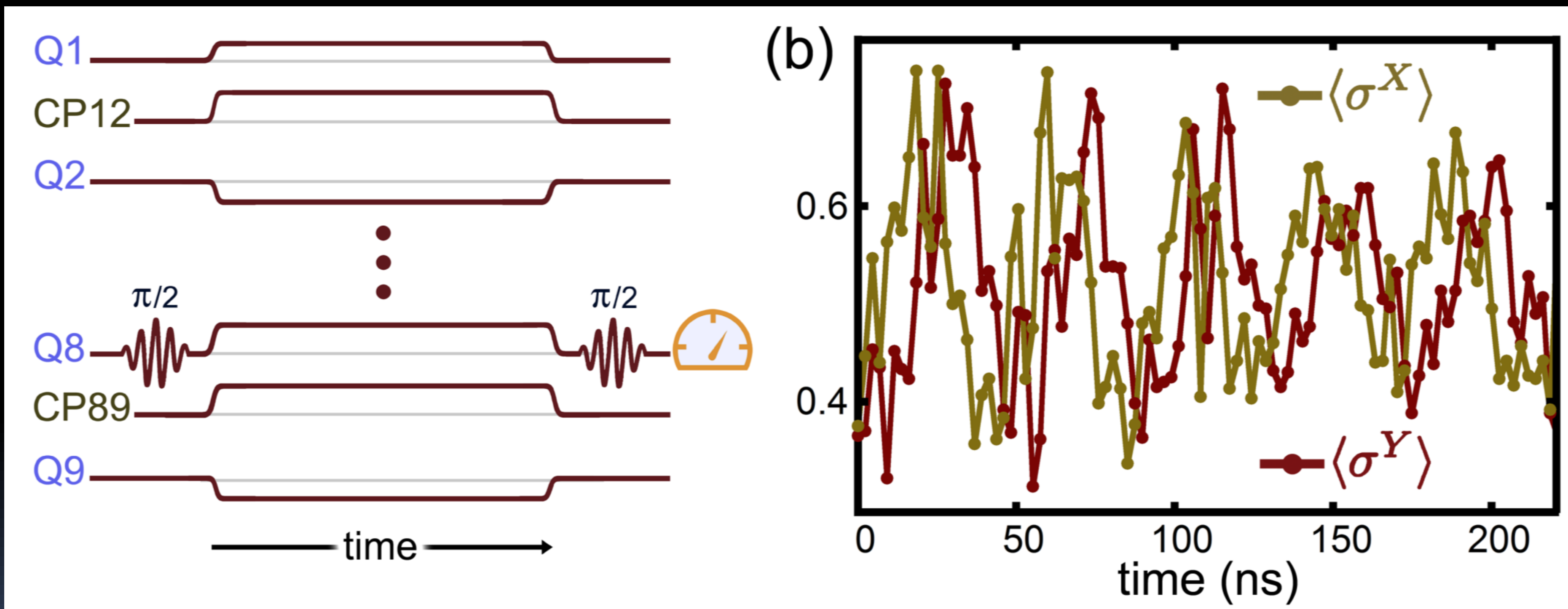
1D chain of 9 qubits



$$H_{BH} = \sum_{n=1}^{9} \mu_n a_n^\dagger a_n + \frac{U}{2} \sum_{n=1}^{9} a_n^\dagger a_n (a_n^\dagger a_n - 1) + J \sum_{n=1}^{8} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$

Time-domain spectroscopy-I

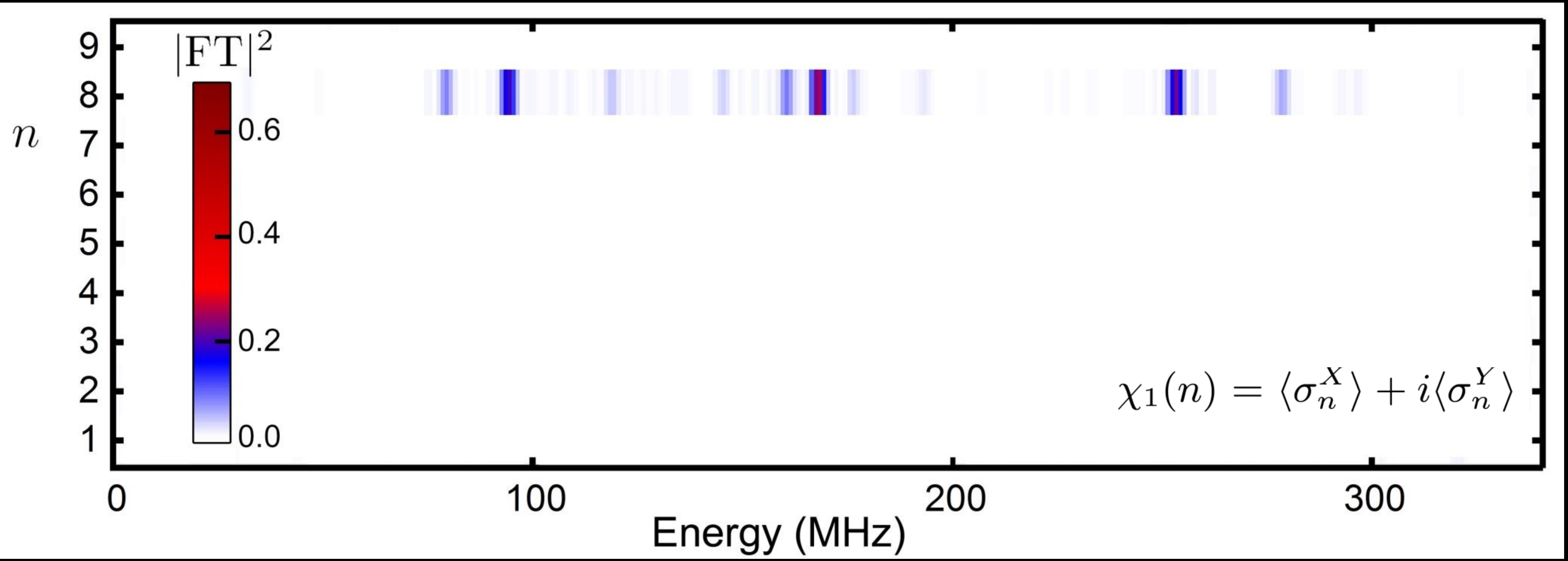
$$|\psi(t)\rangle = \sum_{\alpha} C_\alpha e^{-iE_\alpha t/\hbar} |\phi_\alpha\rangle$$, where $$\hat{H}|\phi_\alpha\rangle = E_\alpha |\phi_\alpha\rangle$$



$$H = \sum_{n=1}^{9} \mu_n a_n^\dagger a_n + J \sum_{n=1}^{8} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$

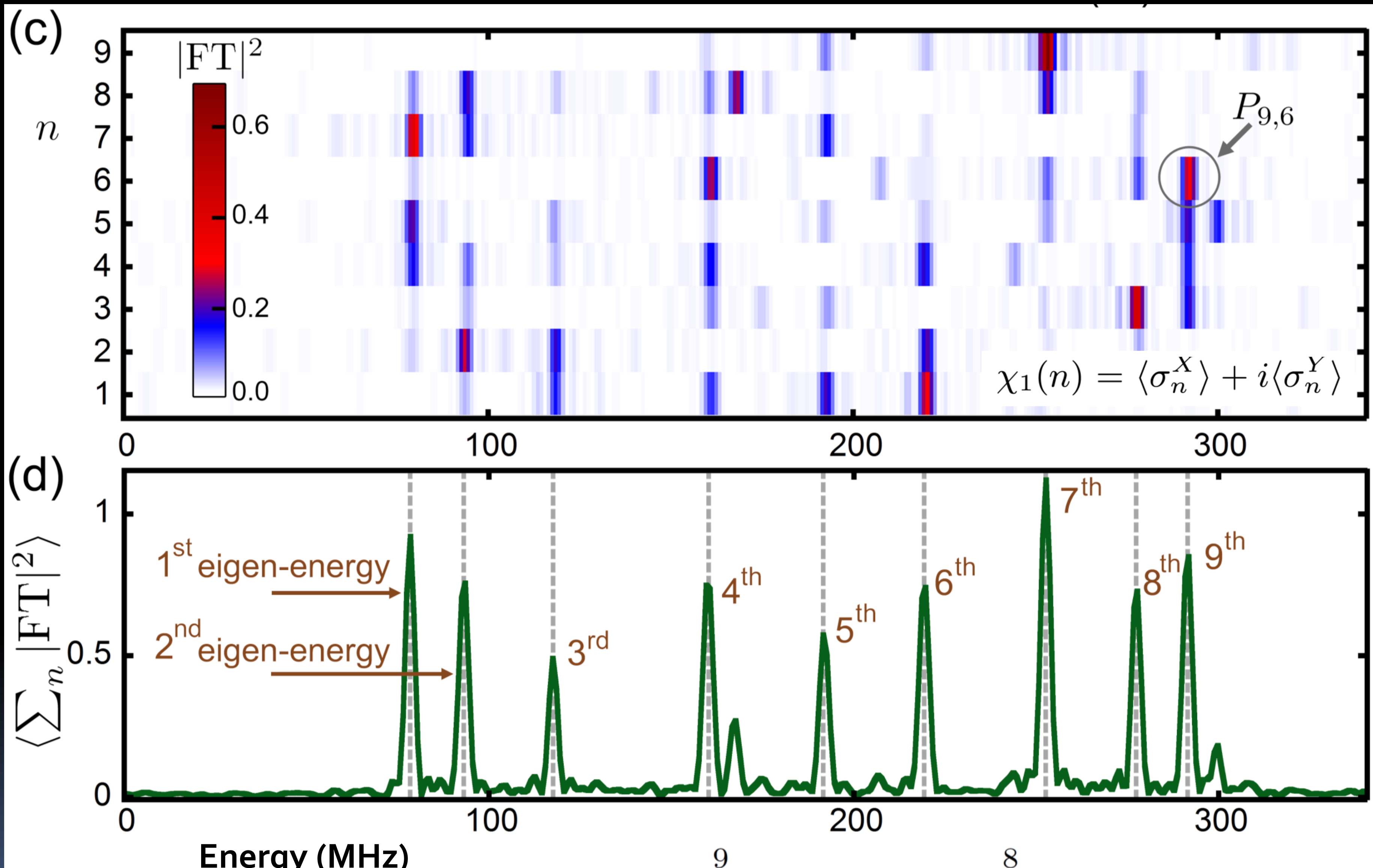
Roushan *et al.*, Science (2017)

Time-domain spectroscopy-II



Roushan *et al.*, Science (2017)

Time-domain spectroscopy-II



$$H = \sum_{n=1}^{9} \mu_n a_n^\dagger a_n + J \sum_{n=1}^{8} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$

Roushan *et al.*, Science (2017)

Time-domain spectroscopy-III

In our method:

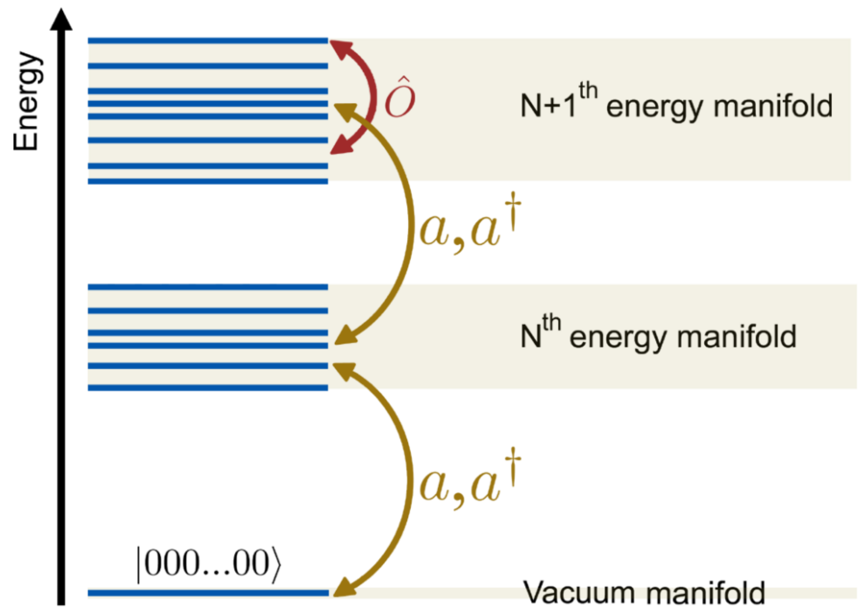
$$|\psi(t)\rangle = \sum_{\alpha} C_\alpha e^{-iE_\alpha t}|\phi_\alpha\rangle$$

We measure observables:

$$\hat{O} = \sum_{\alpha,\alpha'} O_{\alpha',\alpha}|\phi_{\alpha'}\rangle\langle\phi_\alpha|$$

, where

$$O_{\alpha',\alpha} = \langle\phi_{\alpha'}|\hat{O}|\phi_\alpha\rangle$$



Which becomes

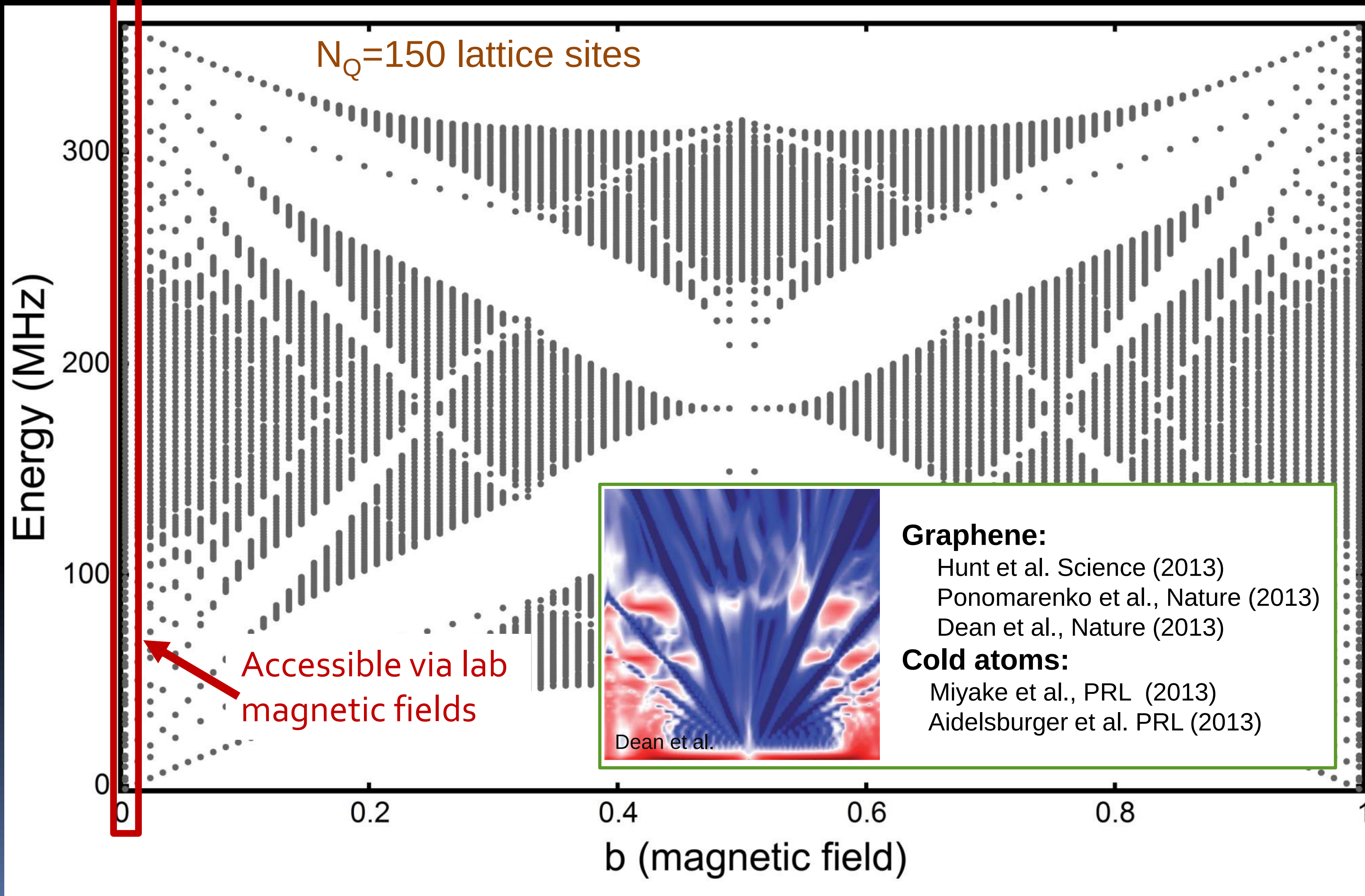
$$O(t) = \langle\psi(t)|\hat{O}|\psi(t)\rangle = \sum_{\alpha,\alpha'} O_{\alpha',\alpha} C_\alpha C^*_{\alpha'} e^{-i(E_\alpha - E_{\alpha'})t}$$

Initial states \ operators	$\langle a_1^\dagger a_1\rangle$	$\langle a_1\rangle$
$\lvert\psi_0\rangle = \lvert 10\rangle$	$\frac{1}{2}[1+\cos((E_+ - E_-)t)]$ ✗	0 ✗
$\lvert\psi_0\rangle = \frac{\lvert 00\rangle + \lvert 10\rangle}{\sqrt{2}}$	$\frac{1}{4}[3+\cos((E_+ - E_-)t)]$ ✗	$\frac{1}{4}\left(e^{-iE_+t} + e^{-iE_-t}\right)$ ✓

Hofstadter Butterfly

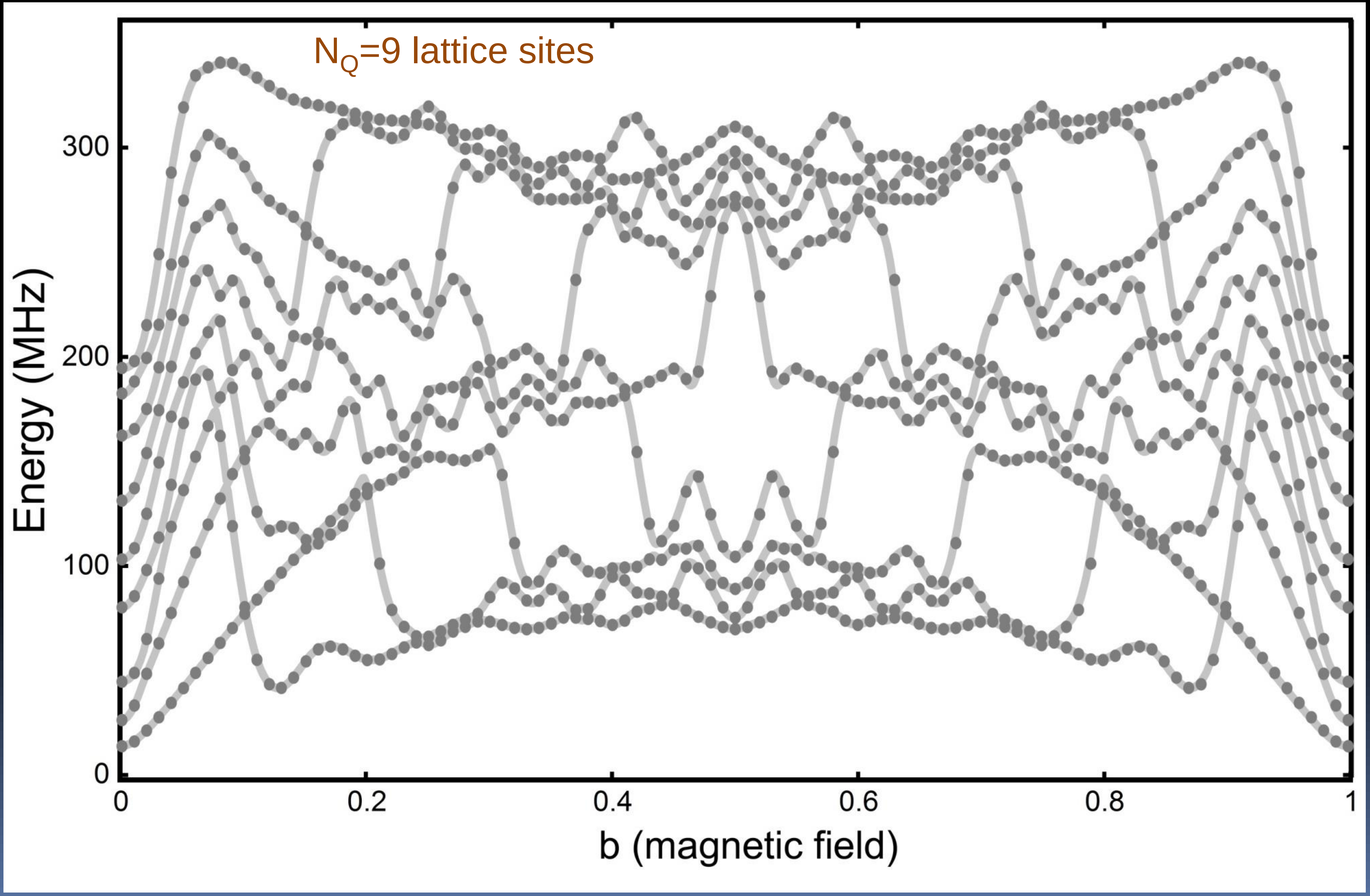
$$H_{\text{Harper}} = \Delta \sum_{n=1}^{150} \cos(2\pi n b) a_n^\dagger a_n + J \sum_{n=1}^{149} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$

$$l_B = \sqrt{\frac{\hbar}{eB}} \sim 10{,}000T$$

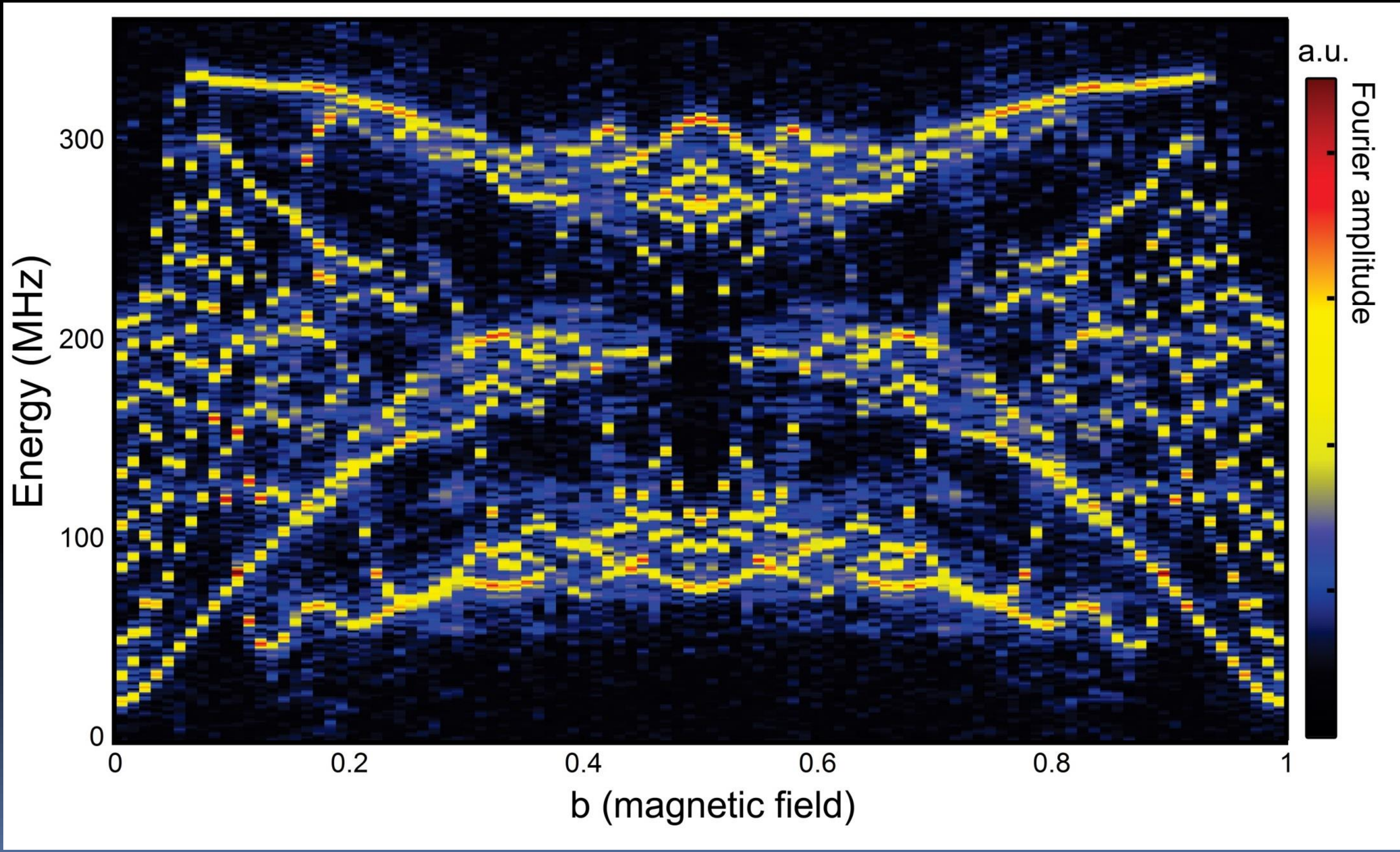


Hofstadter Butterfly

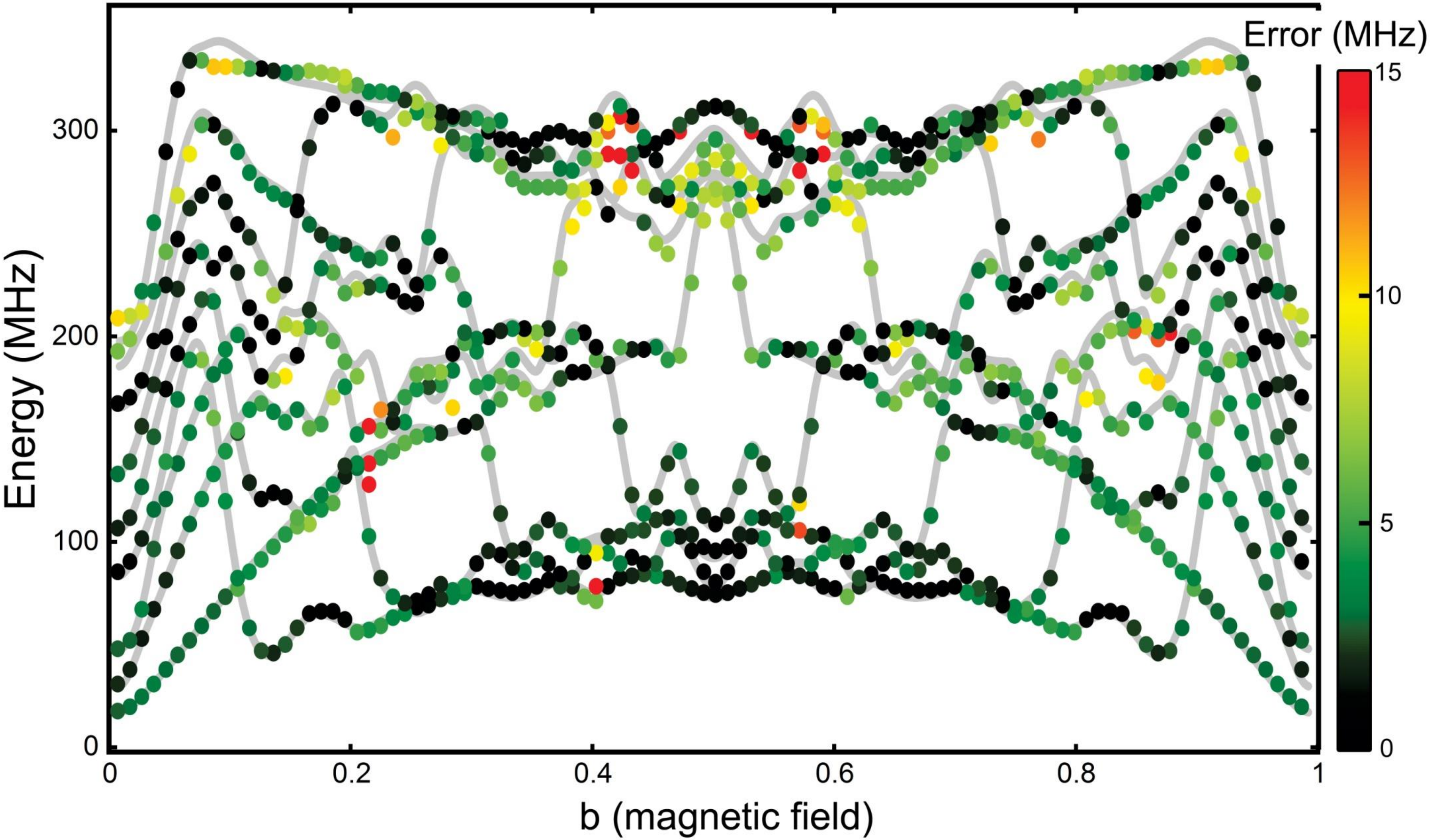
$$H_{\text{Harper}} = \Delta \sum_{n=1}^{9} \cos(2\pi n b) a_n^\dagger a_n + J \sum_{n=1}^{8} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$



9 qubit Hofstadter Butterfly

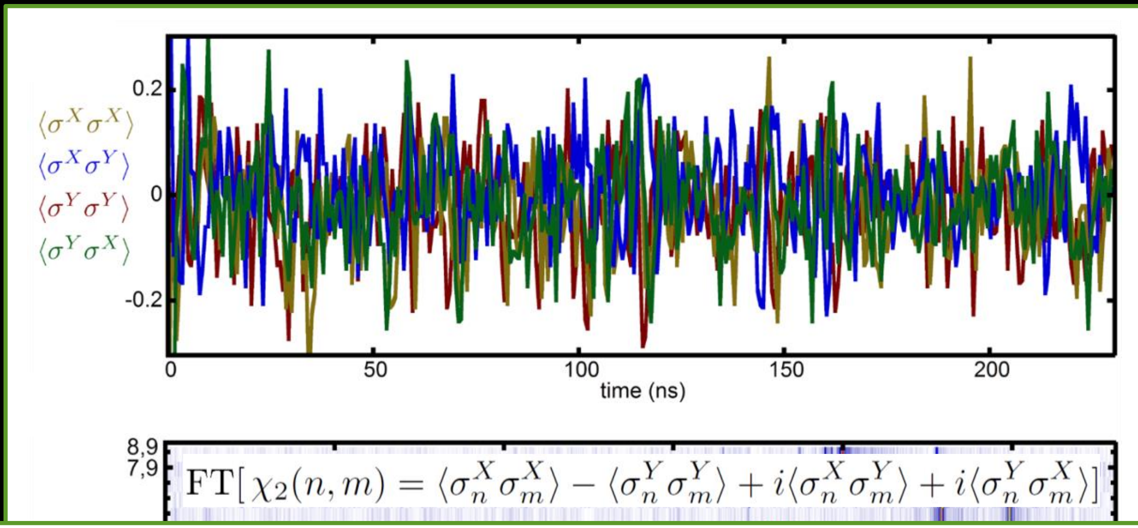


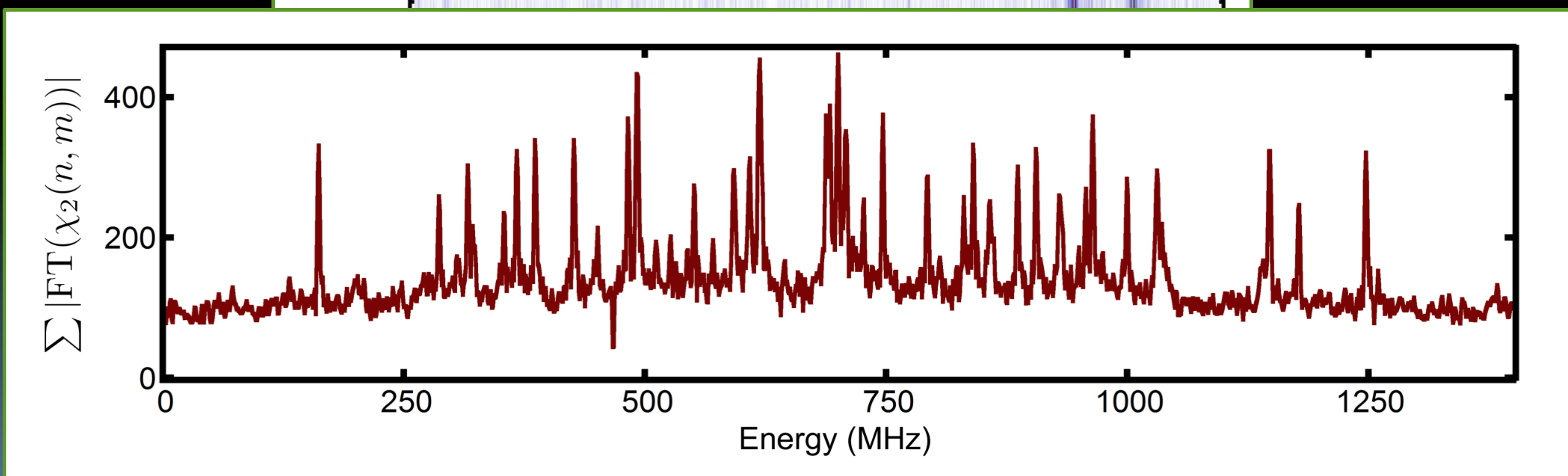
Systematic (calibration) error



Two photons: interacting systems

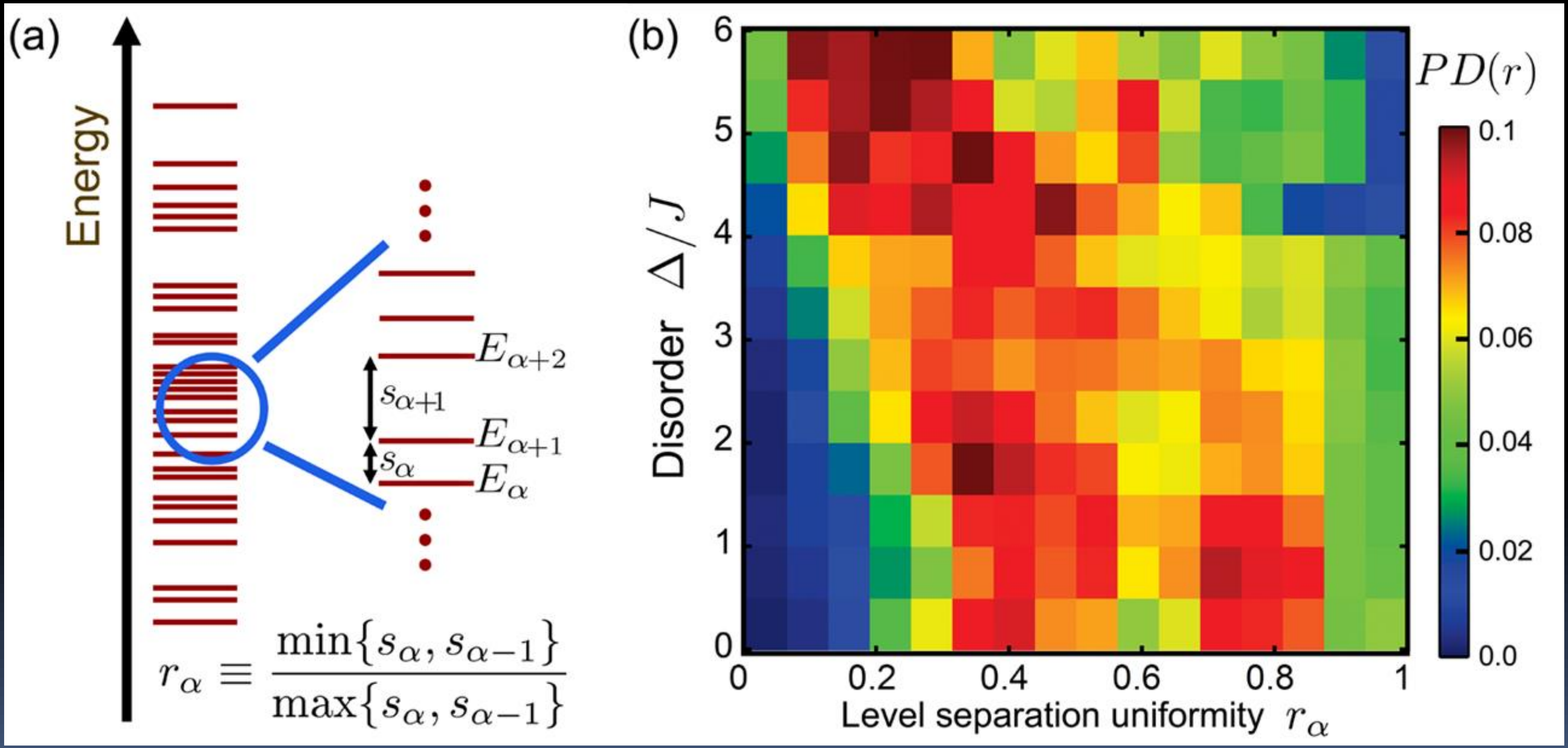
$$H_{BH} = \Delta \sum_{n=1}^{9} \cos(2\pi n b) a_n^\dagger a_n + \frac{U}{2} \sum_{n=1}^{9} a_n^\dagger a_n (a_n^\dagger a_n - 1) + J \sum_{n=1}^{8} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$





Energy level statistics

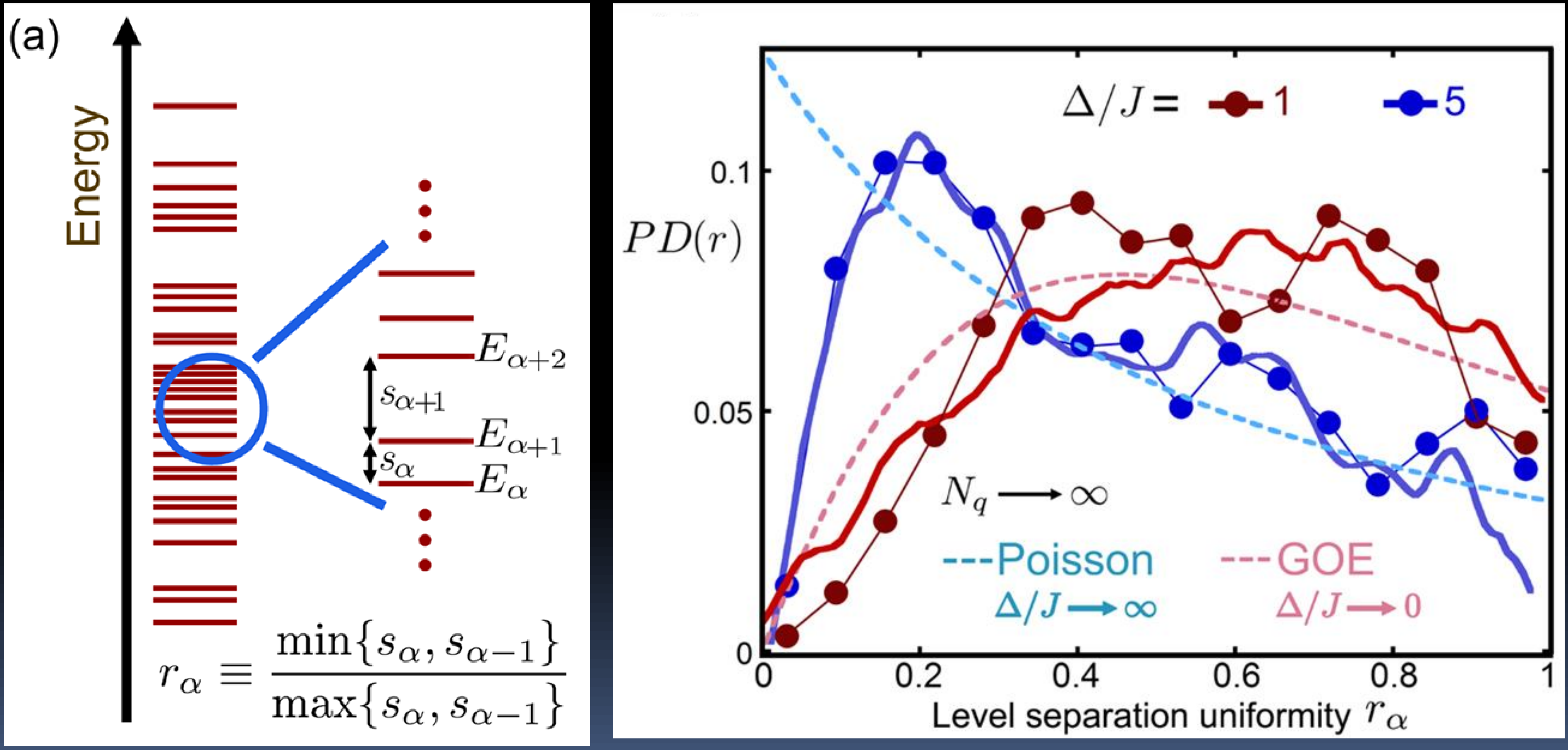
$$H_{BH} = \Delta \sum_{n=1}^{9} \cos(2\pi n b) a_n^\dagger a_n + \frac{U}{2} \sum_{n=1}^{9} a_n^\dagger a_n (a_n^\dagger a_n - 1) + J \sum_{n=1}^{8} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$



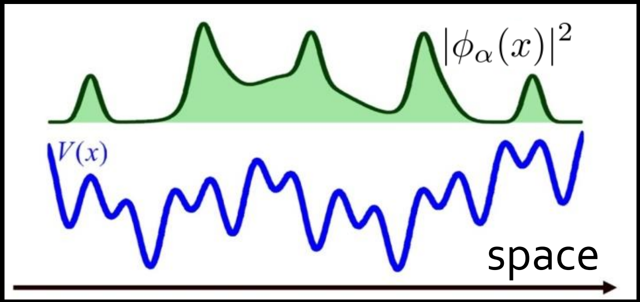
V. Oganesyan and D. Huse, PRB (2007)
Y.Y. Atas *et al.*, PRL (2013)
O. Bohigas *et al.*, PRL (1984)

Energy level statistics

$$PD_{\mathrm{GOE}}(r) = \frac{27}{4}\frac{r+r^2}{(1+r+r^2)^{5/2}} \qquad PD_{\mathrm{Poisson}}(r) = \frac{2}{(1+r)^2}$$



Participation ratio



We are interested in:

$$|\phi_\alpha\rangle = \sum_n C_{\alpha,n}|\mathbf{1}_n\rangle$$

Our method:

$$|\psi(t)\rangle = \sum_\alpha C_\alpha e^{-iE_\alpha t/\hbar}|\phi_\alpha\rangle$$

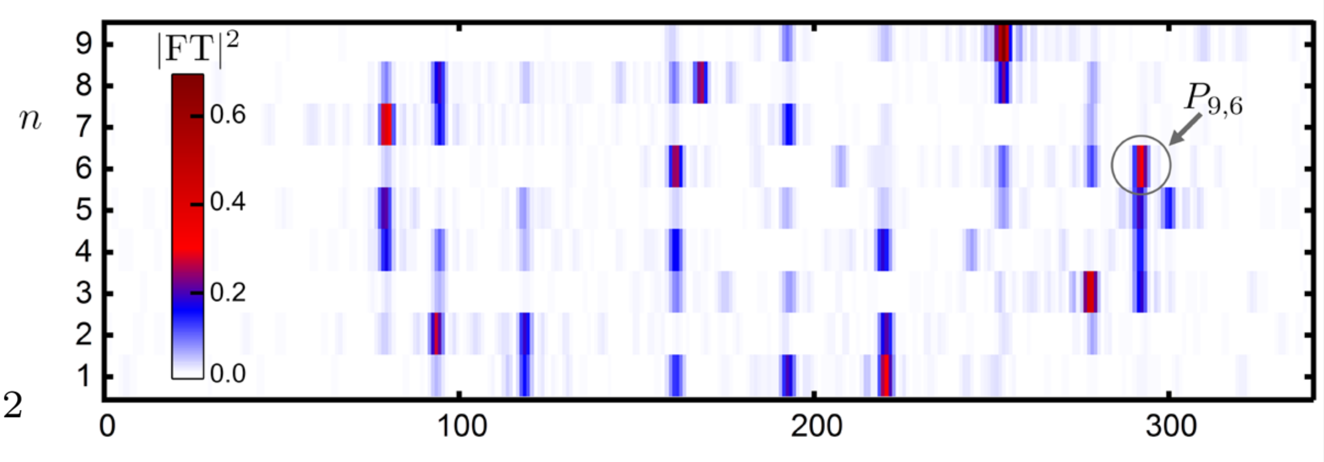
At time=0:

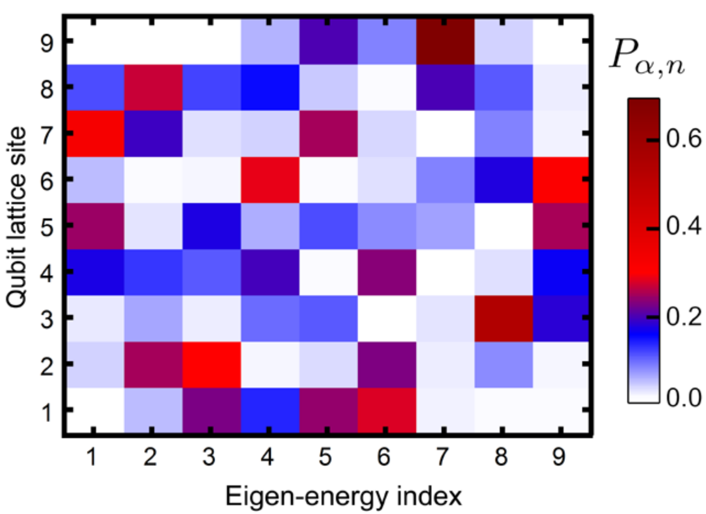
$$|\psi_0\rangle = \sum_\alpha C_\alpha|\phi_\alpha\rangle$$

Fock state as initial state:

$$|\mathbf{1}_n\rangle = \sum_\alpha C_{n,\alpha}|\phi_\alpha\rangle$$

$$P_{\alpha,n} = |C_{\alpha,n}|^2$$





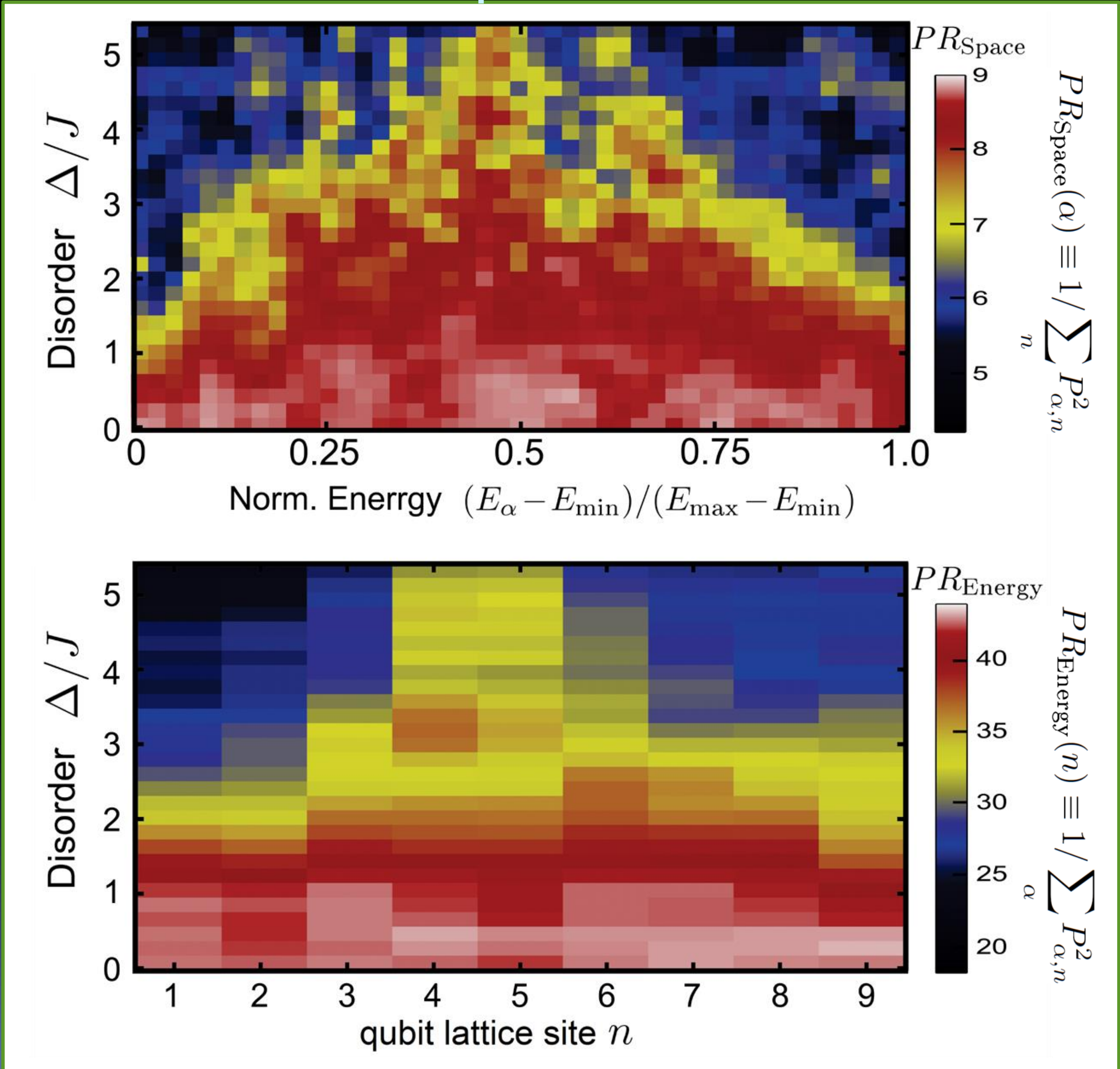
$$PR_{\mathrm{Space}}(\alpha) \equiv 1/\sum P_{\alpha,n}^2$$

Number of sites that an energy eigenstate is extended over.

$$PR_{\mathrm{Energy}}(n) \equiv 1/\sum P_{\alpha,n}^2$$

Number of energy eigenstates present in a lattice site.

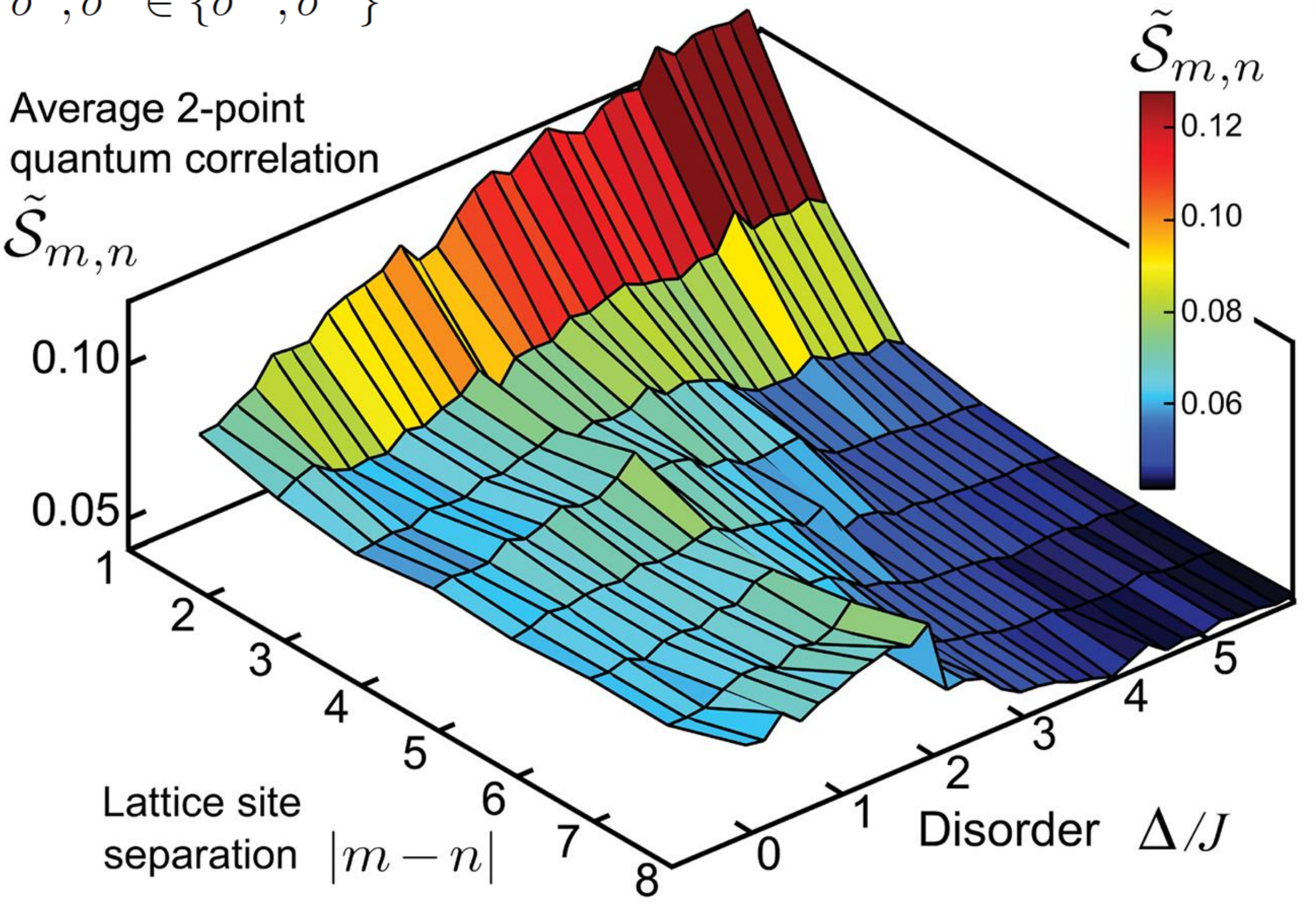
Participation ratio



Quantum correlations

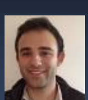
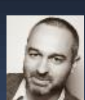
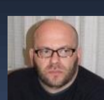
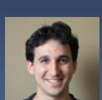
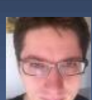
$$\mathcal{S}_{m,n} \equiv |\langle\sigma_m^1\sigma_n^2\rangle - \langle\sigma_m^1\rangle\langle\sigma_n^2\rangle|$$

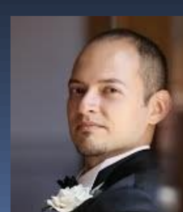
$$\sigma^1, \sigma^2 \in \{\sigma^X, \sigma^Y\}$$



Google quantum team

Los Angele theory team:



V. Bastidas


J. Tangpanitanon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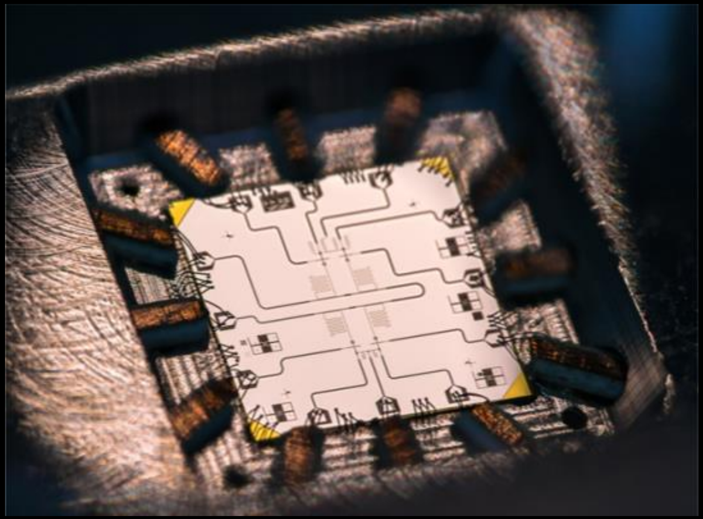
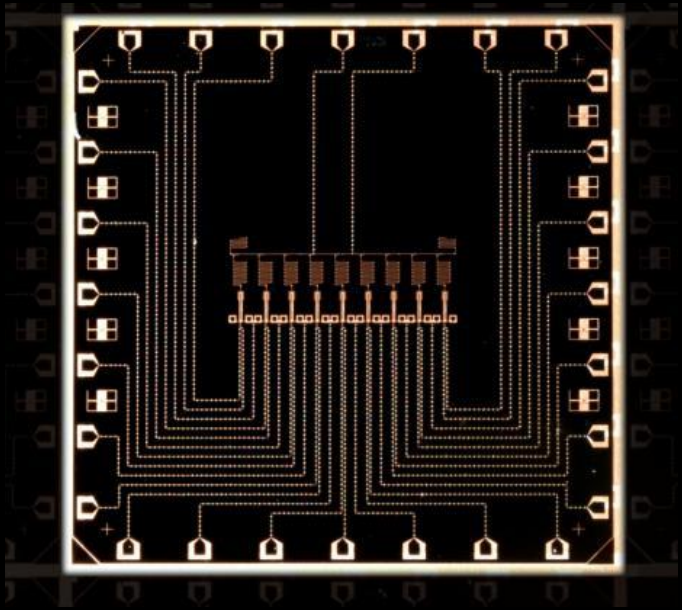
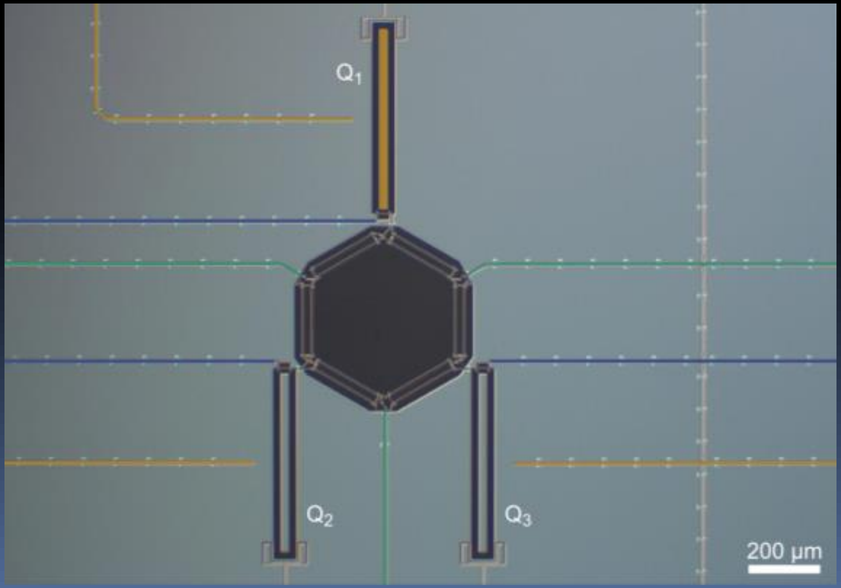
2-qubit gmon (2013-2014)



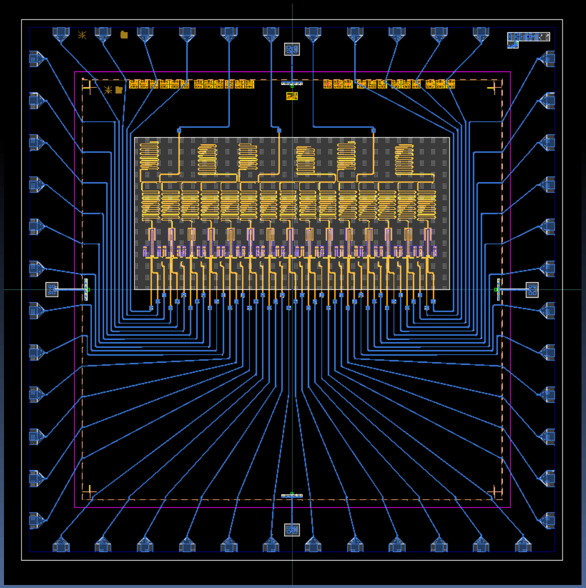
9-qubit gmon (2015-2016)



3-qubit gmon (2014-2015)

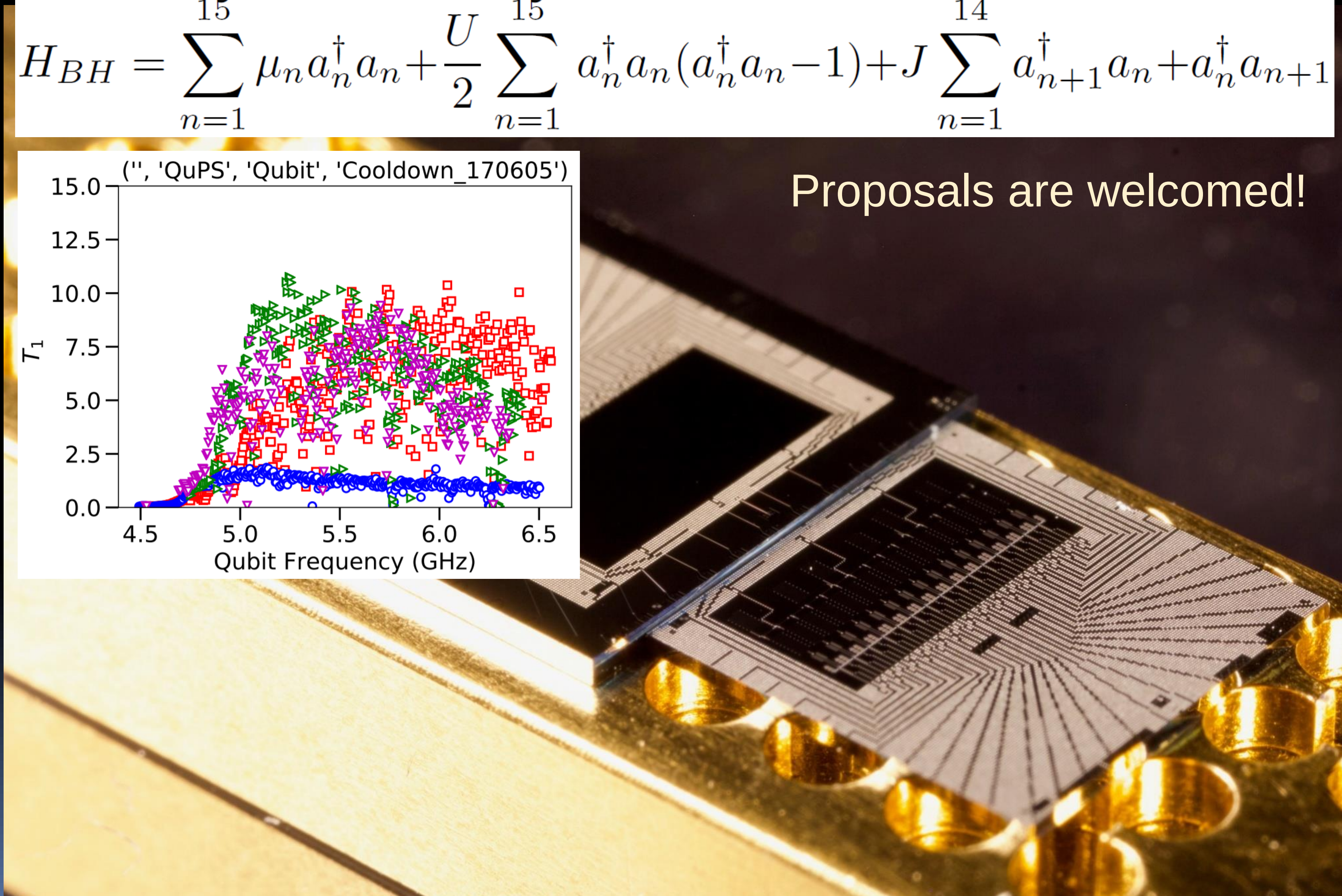


15-qubit gmon (2017)



1D chain of 15-qubits

$$H_{BH} = \sum_{n=1}^{15} \mu_n a_n^\dagger a_n + \frac{U}{2} \sum_{n=1}^{15} a_n^\dagger a_n (a_n^\dagger a_n - 1) + J \sum_{n=1}^{14} a_{n+1}^\dagger a_n + a_n^\dagger a_{n+1}$$



Proposals are welcomed!

Research Engagement

1) Support external grants
2) Focus Awards (research grants)
3) Quantum computing access
4) Faculty Awards
5) Visiting Faculty
6) Interns
7) Residency
8) PhD Fellowships
9) Consultants, visiting academic