# SHORTCUTS TO QUANTUM ADVANTAGE

With superconducting circuits

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18.6.24 I FRANK WILHELM-MAUCH, INSTITUTE FOR QUANTUM COMPUTER ANALYTICS



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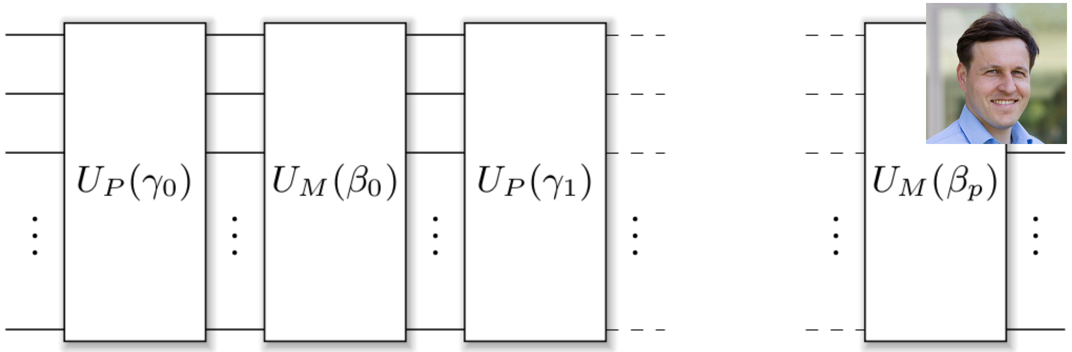
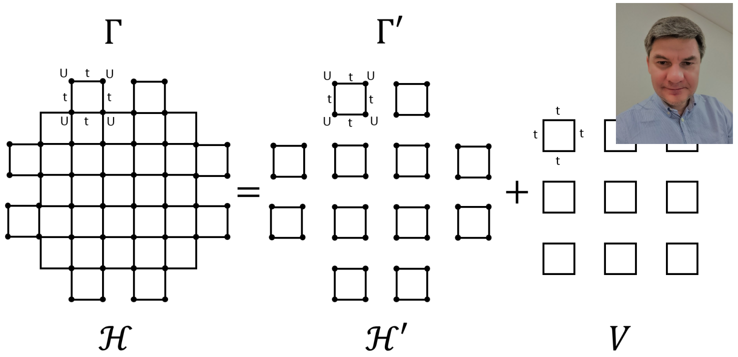
# Institute portrait

# Institute for Quantum Computing Analytics - Groups




Quantum Algorithms Group

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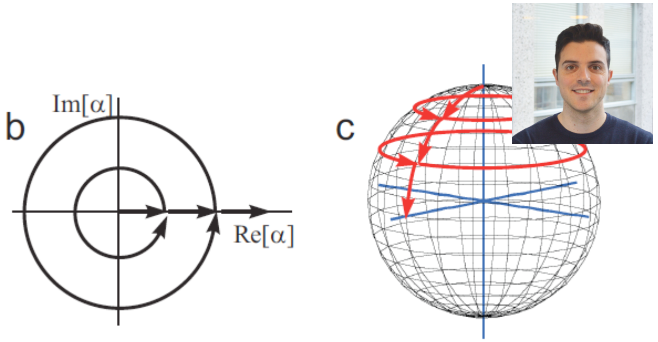


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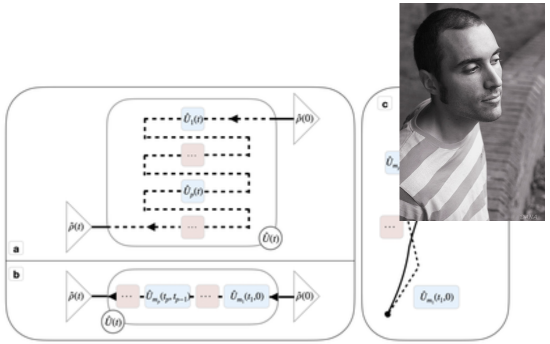

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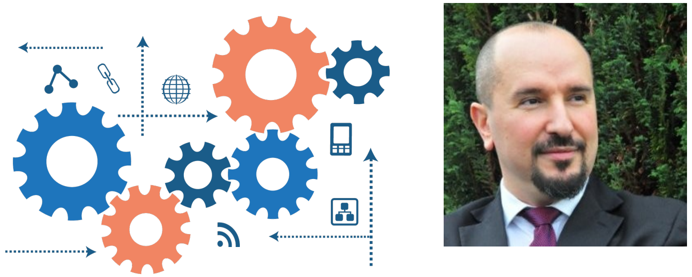


Systems Integration & Analysis Group

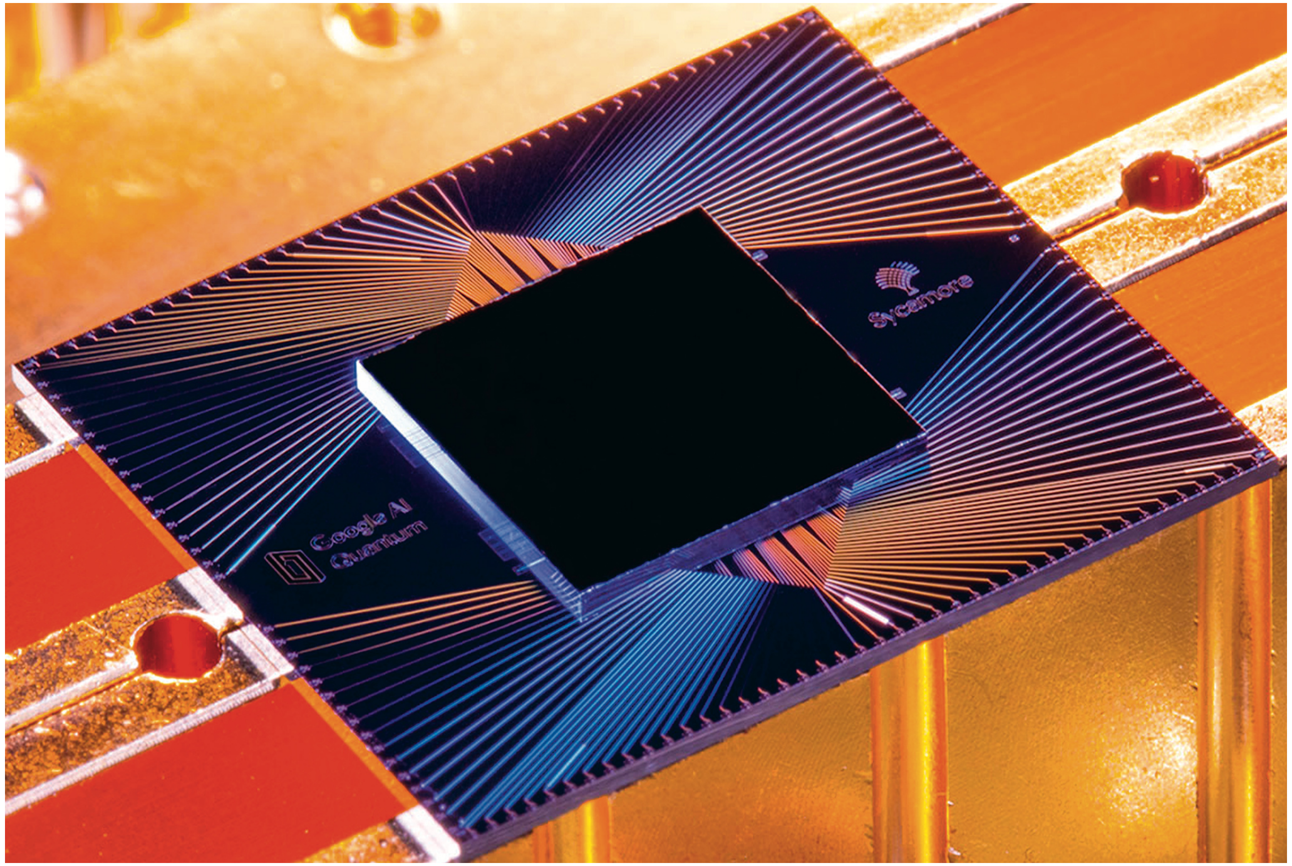
# CONTENTS

# WHAT IS NISQ AND WHY DO WE CARE?

# BASIS OF QUANTUM SUPREMACY

- saving a 50 qubit quantum states requires $2^{50}$=1.126E15 complex numbers
- need to accomplish a sufficiently general task (otherwise it is not a computer)
- need to be coherent enough / low enough errors (otherwise it is classical)
- needs to be certified without simulation
- Shown in 2019 with a synthetic benchmarks

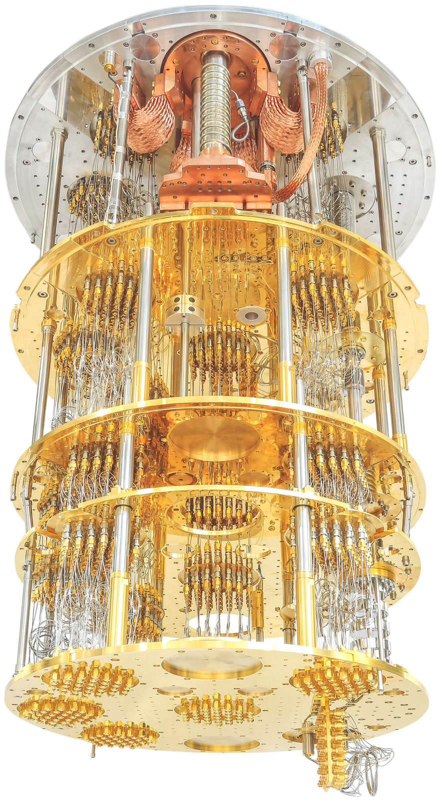
$$|\psi\rangle = \frac{1}{2^{n/2}} \sum_{s=0}^{2^n-1} c_s |s\rangle$$

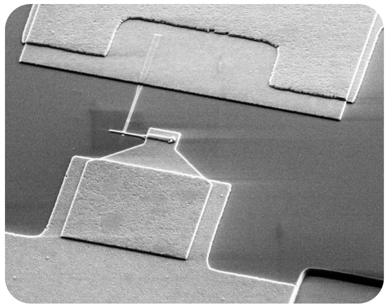


# STATUS OF HARDWARE

## Error rate, not qubits

- Quantum computers are intrinsically highly **sensitive to errors** (more mature hardware will reduce but not eliminate that!)
- Current error rate: 0.1% per hard operation - 1000 steps
- **Applied** benchmarks use **10ish** qubits within large chips
- Next goal: Use more than 50 qubits for real-world applications
- Roadmaps for 1000 qubits need an error roadmap
- (Making 1000 Josephson junctions is routine)
- Key ingredient: Improvement of materials





# THE ERA OF EARLY QUANTUM SUPREMACY

## Meaning of the Google 2019 and later results

| Up to 50 qubits | Beyond 50 qubits | NISQ-Era | Beyond 1MQubits |
|---|---|---|---|
| Basic research in physics | Quantum advantage In synthetic benchmarks | Applied quantum advantage possible? | Provable quantum advantager |

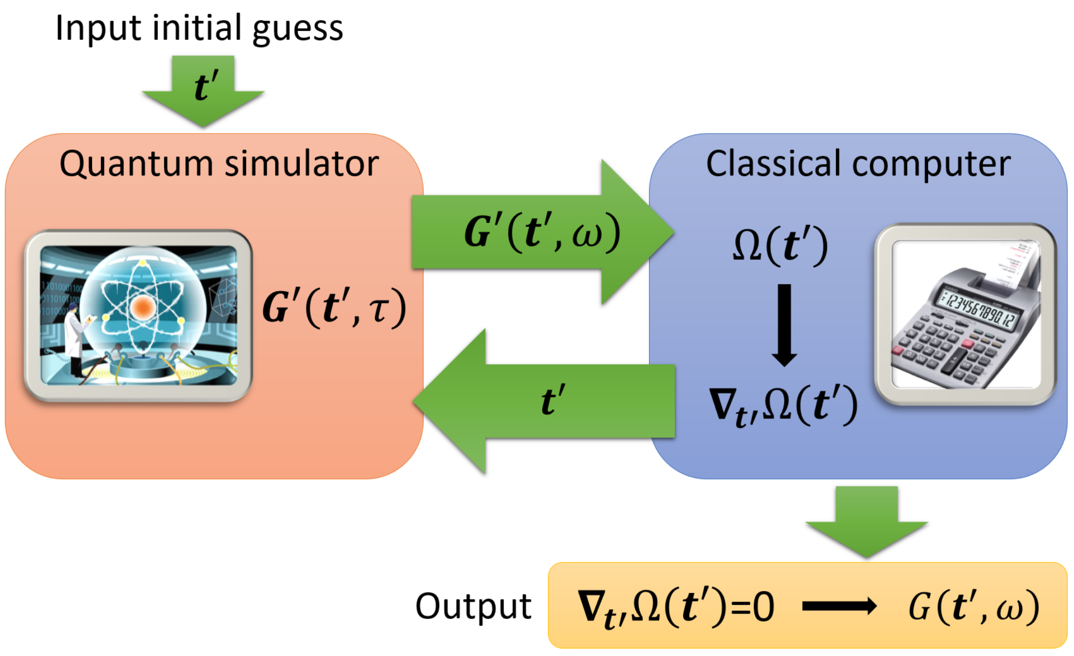
- Quantum advantage based on exponential need for memory: **Most likely irreversible**
- N qubits correspond to $2^N$ floating point numbers - beyond large HPC at N>50
- Current goal: Better machines and more efficient algorithms: NISQ Era (NISQ: Noisy intermediate-scale quantum technologies)
- NISQ-Macines are **R&D infrastructure**

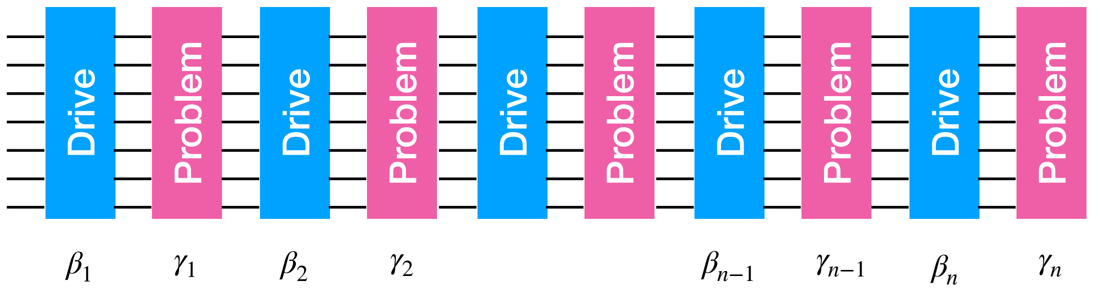
# NISQ: QUANTUM COPROCESSOR

## Classical algorithm calls a shallow and fat routine

- Inside: Parameterized quantum circuit = Algorithm that depends on classical numbers
- Outside: Classical optimizer improving that numbers
- Uses fast quantum sampling of space
- Example: Quantum Approximate Optimization Algorithm (QAOA)
- Speedup conjectured
- Shallow circuit + reset during classical optimization: NISQ friendly

Needs: Reasonable qubits, fast I-O and low-latency Reprogramming



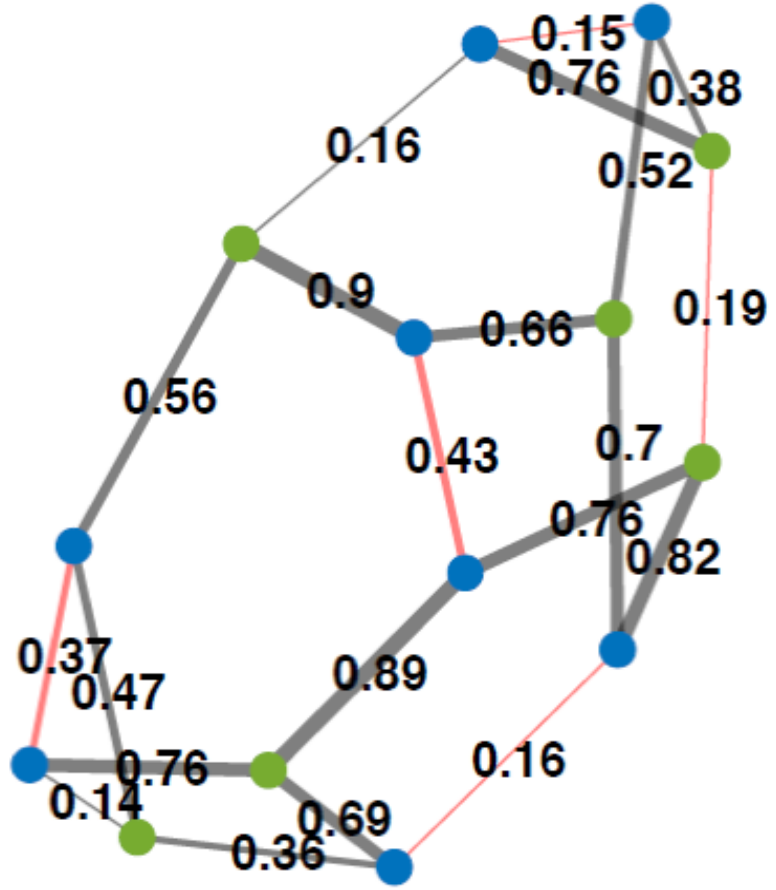
# OPTIMIZING ON QUANTUM COMPUTERS AND QAOA

# (Random) Optimization problems

- Many NP-hard or/and complete probelms afford *classical* Ising formulation:

$$H_P = -\sum_{i<j}^{N} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)} - \sum_{j=1}^{N} h_j\sigma_z^{(j)}$$

- Optimal string corresponds to the ground state !
- For random couplings/graphs Ising Hamiltonian defines the spin glass
- Examples:
  - Number partitioning problem
  - Graph coloring
  - Hopfield neural network




See A. Lucas “Ising formulations of many NP problems“, 2014

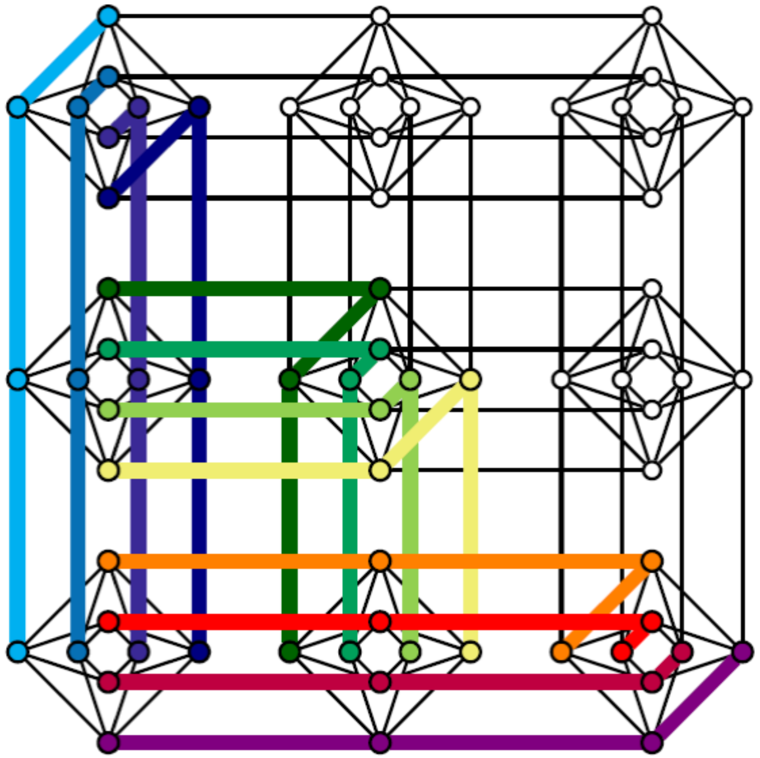
# Quantum annealing

- Use of adiabatic theorem to find the ground state

$$H(s) = s\,H_P + (1-s)H_D, \qquad H_D = -\sum_{j=1}^{N} \sigma_x^{(j)}$$

- D-wave system:
  - 5000+ flux qubits with tunable couplings

D-wave
The Quantum Computing Company™



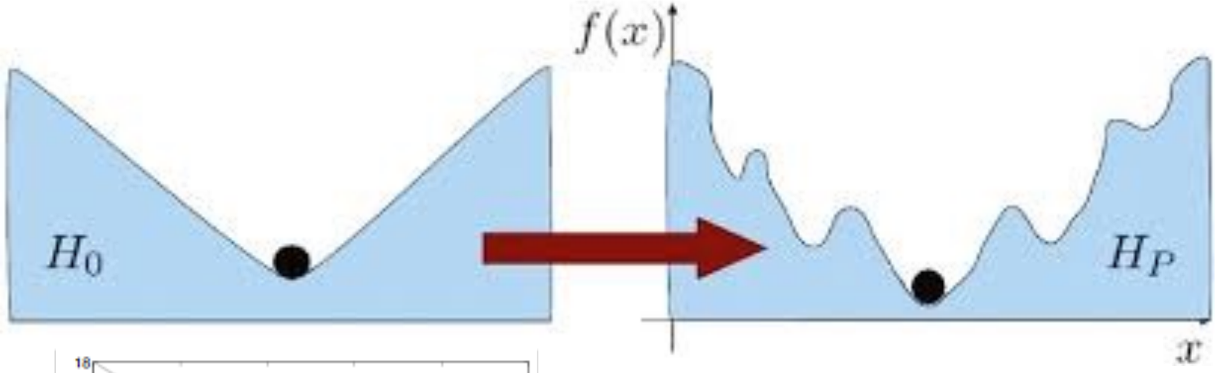
Imbedding of a problem graph into *Chimera* one of D-wave

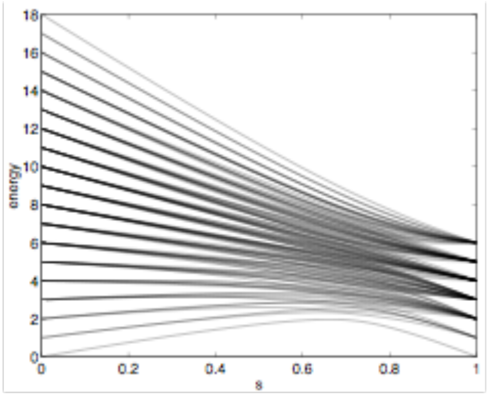
# SOLVING BY PHYSICS

## Adiabatic algorithms

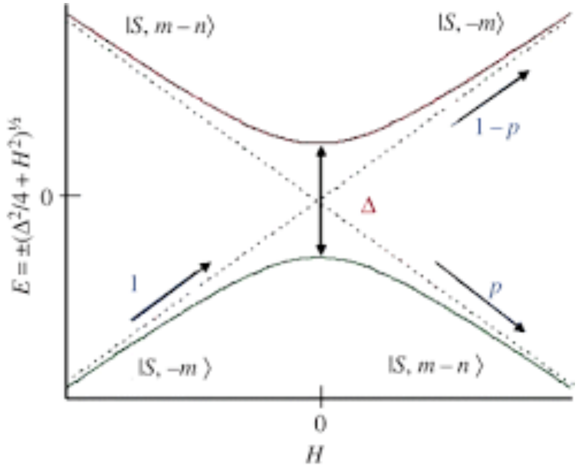
- Transform a simple into a hard optimization problem
- Stay in the ground state
- Speed protected by energy gap, based on the superconducting tunnel effect
- Predicting the gap is NP-hard
- Has reached more than 2000 qubits already
- Discussion about inefficiencies
- Speedup debated

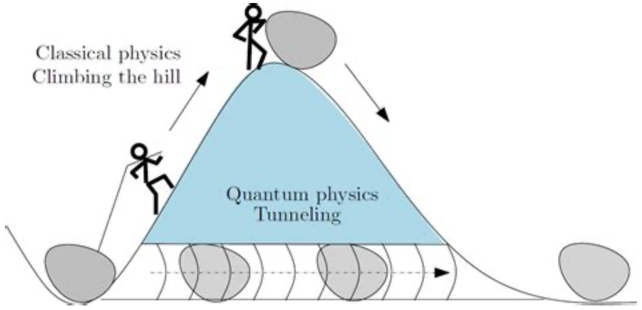
Needs: Many qubits, a pre-settable interaction, Global adiabatic control




Speed: $(\text{Gap})^{-1}$




Tunnel effect

# Quantum Approximate Optimization Algorithm (QAOA)

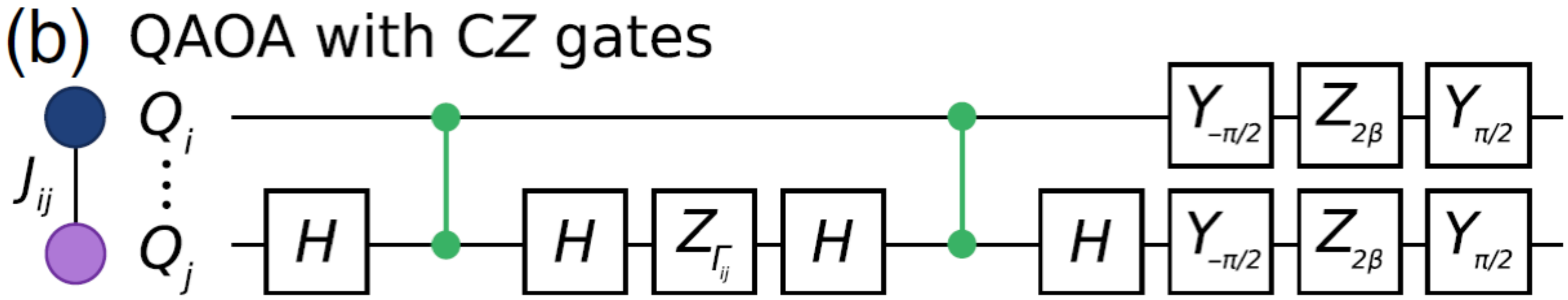
E.Farhi, J.Goldstone, S. Gutmann‘ 2014

- Evolution: variational ansatz for the ground state ~ Trotterization of adiabatic protocol

$$|\beta,\gamma\rangle = \prod_{j=1}^{p} e^{-iH_D\beta_j} e^{-iH_P\gamma_j} \left( |+\rangle_X \right)^{\otimes N}$$

- Optimum: to be minimized over a set of $(\beta_j,\ \gamma_j)$

$$E_*(\beta,\gamma) = \langle \beta,\gamma | H_P | \beta,\gamma \rangle$$

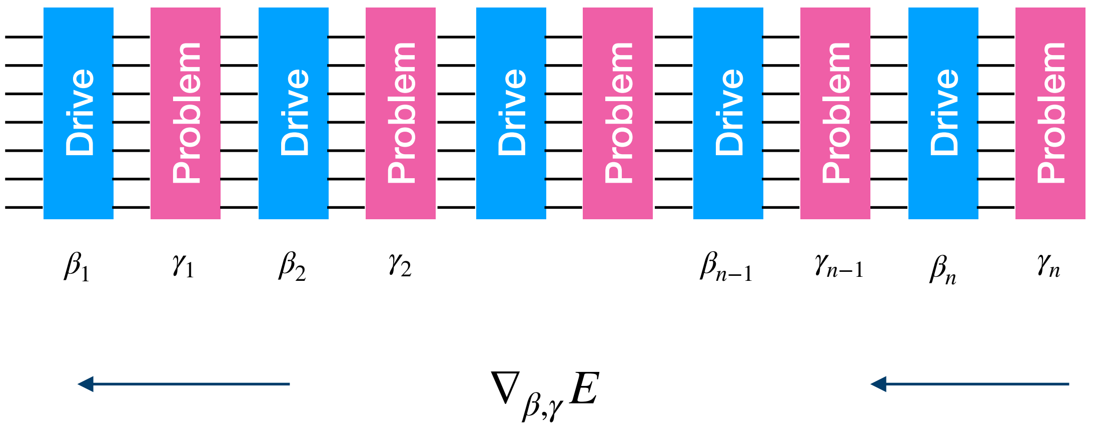



A. Wallraff et al., 2020

# NISQ: QAOA ALGORITHM

## Classical algorithm calls a shallow and fat routine

- Speedup conjectured
- Shallow circuit + reset during classical optimization: NISQ friendly
- Allows to implement higher-order / long range interactions by compilation (rather than hard-wire)
- Feedback loop allows to adjust to variable gap
- Speedup claimed for MAXCUT (Farhi) then quantum-inspired algorithm with same complexity appeared (Hastings)




Drive: $e^{-i\beta H_d}$ $\quad H_d = \sum_i X_i$

Problem - $e^{-i\gamma H_p}$ - with diagonal $H_p$

$$H_p = \sum_i h_i Z_i + \sum_{i<j} J_{ij} Z_i Z_j + \sum_{i<j<k} K_{ijk} Z_i Z_j Z_k + \ldots$$

Needs: Reasonable qubits, fast I-O and low-latency Reprogramming



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# WHERE CAN SPEEDUP (NOT) COME FROM?

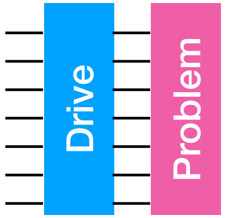
## A physical argument

- Exponential speedup on general NP-hard combinatorical optimization problems extremely unlikely (viz: Optimality of Grover)
- A lot of heuristics and empiricism
- Our goal: Get a good solution for cost fuctional with high probability - why should that work?
- Note: Other quantum algortihms (Shor, Grover) contain uncomputing of superpositions for that purpose
- So - under which conditions does the state converge onto a narrow distribution, centered at low values?
- Our statement is: Often this has to do with classical simulability

# QAOA AS A DISCRETE PATH INTEGRAL

Start: Hadamard State - all at once

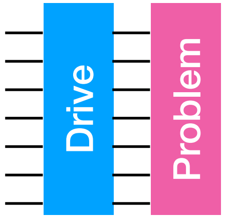
$$\frac{1}{2^{n/2}} \sum_{s=0}^{2^n-1} |s\rangle$$




Give all of them a phase factor

$$\frac{1}{2^{n/2}} \sum_{s=0}^{2^n-1} e^{-i\gamma E(s)} |s\rangle$$

Mix-Phase etc.



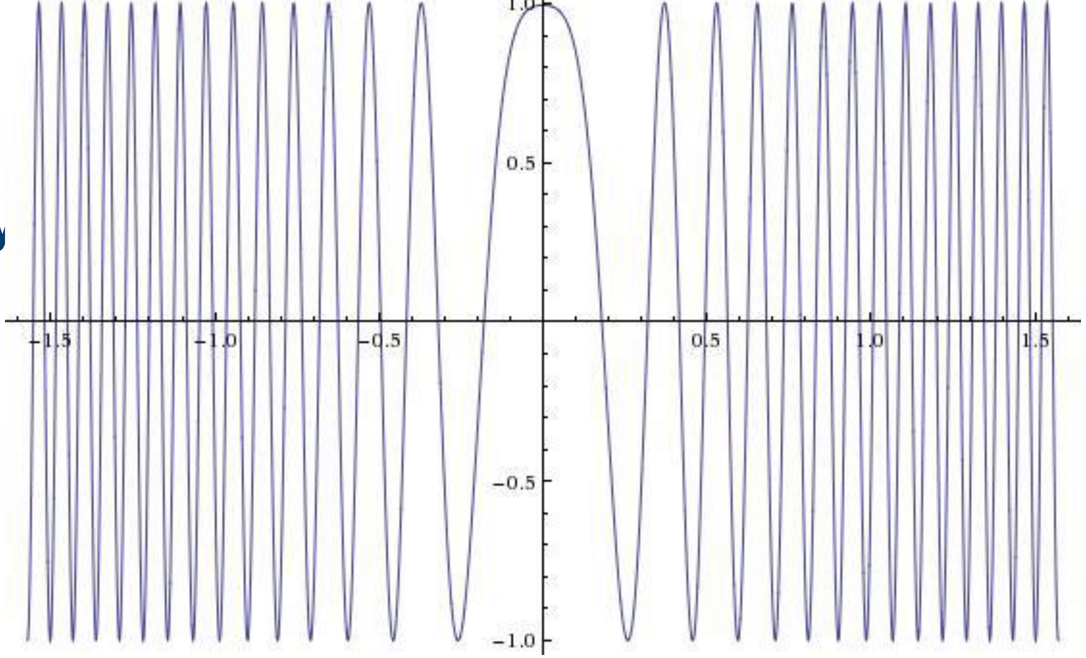

Continuous path integral: Compute time evolution in space

$$U(x_i, x_f) = \sum_{x_1} \lim_{\delta t \to 0} \left\langle x_i \left| e^{-i\delta t E_{\text{kin}}} | x_1 \rangle \langle x_1 | e^{-i\delta t E_{\text{pot}}} \cdots \right| x_f \right\rangle = \int_{x_i}^{x_f} \mathcal{D}x(t) e^{iS[x(t),\dot{x}(t)]}$$

Path integral = sum over all paths, each with their phase factor
Aha: Kinetic energy similar to driver / mixer - potential energy similar to problem Hamiltonian - can we access path integral methods?
Analogy even closer for AQC with arbitrary annealing schedule

# SEMICLASSICS

## Emergence of a particle-like theory from a wave-like theory




We can do a lot of optics without waves - a lot of mechanics without quanta - classical / particle limit

Those are driven by variational principles for wavepackets

Optics: Fermat principle - Light ray maximizes the total time $t = \int \frac{ds}{c}$

Mechanics: Newtons equation follow from the stationary action $\delta S = 0$

$$\int_{x_i}^{x_f} \mathscr{D}x(t) e^{iS[x(t),\dot{x}(t)]}$$

Dominated by $\delta S = 0$ - else oscillatory integrand

Semiclassics: Take $\delta^2 S$ into account

# WHAT CAN WE DO FOR QAOA / AQC

## Main ingredient: Qubits / spins instead of scalar waves

Mean field theory (in real time): $H_p = \sum_i h_i Z_i + \sum_{i<j} J_{ij} Z_i Z_j$ replaced by

$H_{MF} = \sum_i h_{i,\mathrm{mf}} Z_i$ with self-consistent field $h_{\mathrm{i,mf}} = h_i + \frac{1}{2} \sum_{j \neq i} J_{ij} \langle Z_j \rangle$

Know in equilibrium thermodynamics: Works well in high (graph) dimension

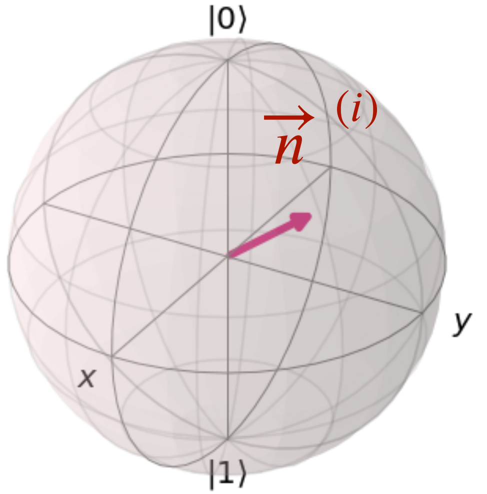
Keeps two real coordinates for qubit state, keeps some correlation, throws away entanglement

# Mean-field AOA

- Hamiltonian with the SU(2) Poisson bracket for classical spins

$$H(n) = -\gamma(t)\sum_{i<j}^{N} J_{ij} n_z^{(i)} n_z^{(j)} - \beta(t)\sum_{j=1}^{N} n_x^{(j)}, \quad \left\{ n_a^{(i)}, n_b^{(j)} \right\} = \delta^{ij}\varepsilon_{abc} n_c^{(i)}$$

Bloch sphere



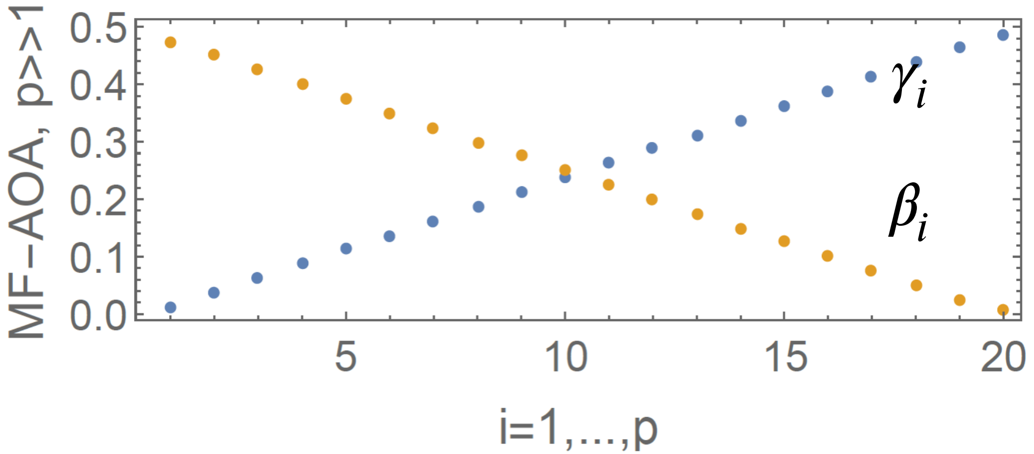

- Initial state:

$\vec{n}^{(i)} = (1, 0, 0)$ for all spins

- Classical (~mean-field) evolution,

$$\frac{d}{dt} n_a^{(k)}(t) = \left\{ n_a^{(k)}(t), H \right\}$$

can be solved *exactly* using Trotterization scheme



# Mean-field AOA

- The Bloch vectors evolve according to

$$\vec{n}^{(i)}(j) = \prod_{k=1}^{j} \hat{V}_D(k)\hat{V}_P(k)\hat{n}^{(i)}(0)$$

where

$$\hat{V}_D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(2\beta(k)) & \sin\left(2\beta(k)\right) \\ 0 & -\sin(2\beta(k)) & \cos(2\beta(k)) \end{pmatrix}$$

- driver matrix

$$\hat{V}_P = \begin{pmatrix} \cos(2\gamma(k)m_i(k)) & \sin(2\gamma(k)m_i(k)) & 0 \\ -\sin(2\gamma(k)m_i(k)) & \cos(2\gamma(k)m_i(k)) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- problem matrix

$$m_i(k) = \sum_j J_{ij} n_3^{(j)}(k) + h_i$$

- mean-field at discrete time k

Note: only the problem matrix depends on the mean-field m(k)

- Total time scales as ~ $pN^2, \quad p \gg 1$

# Sherrington-Kirkpatrick model

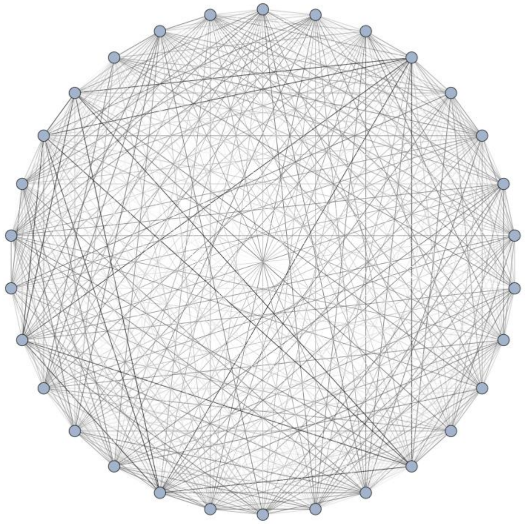
$$H_P = -\sum_{i<j}^{N} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)}, \quad \left\langle J_{ij}^2 \right\rangle = 1/N$$

i.i.d. random Gaussian

Parisi'79:

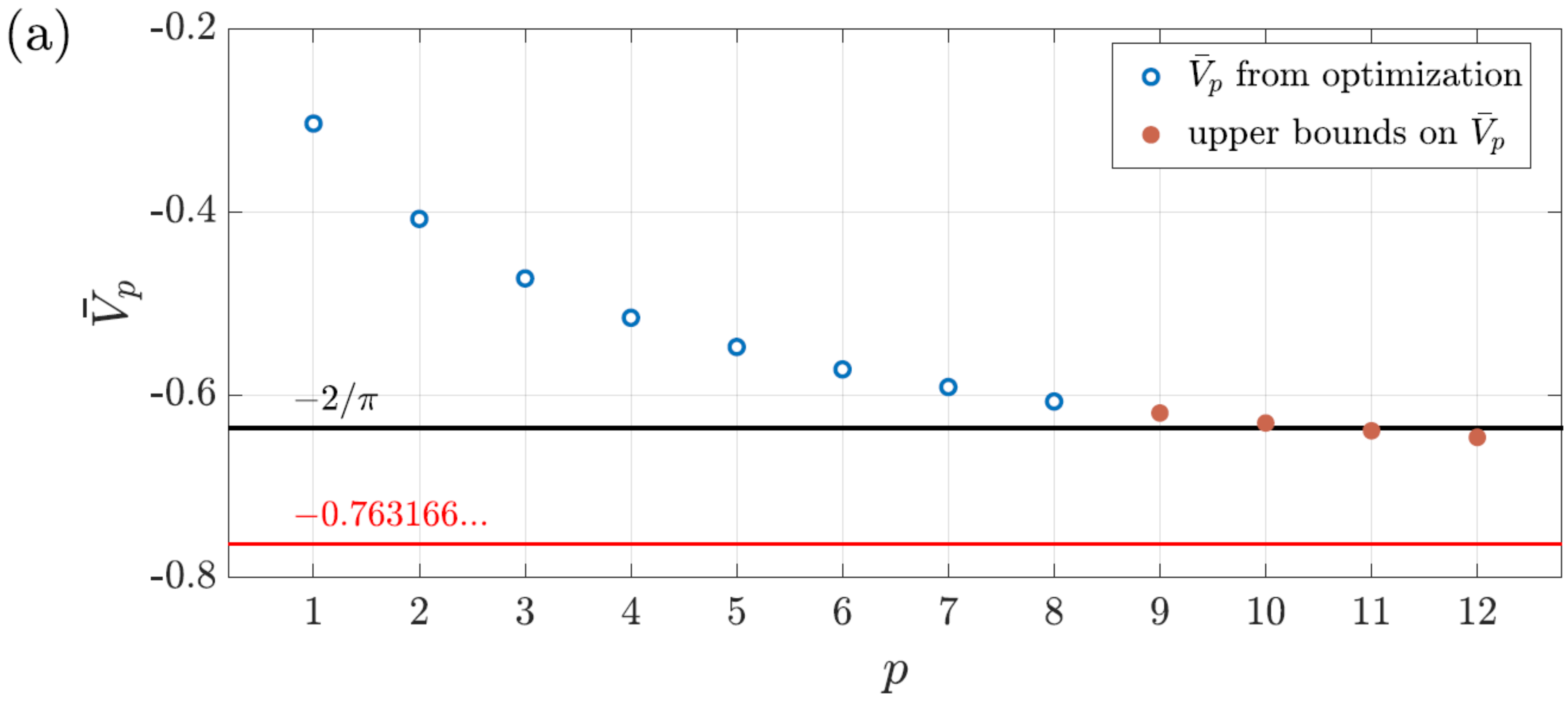
$$\lim_{N\to\infty} \left\langle E_0/N \right\rangle_J = -0.763166\ldots$$

- results from spin-glass replica symmetry breaking theory



# Bencmarking of QAOA for SK-model

Farhi et al. ‘2019:

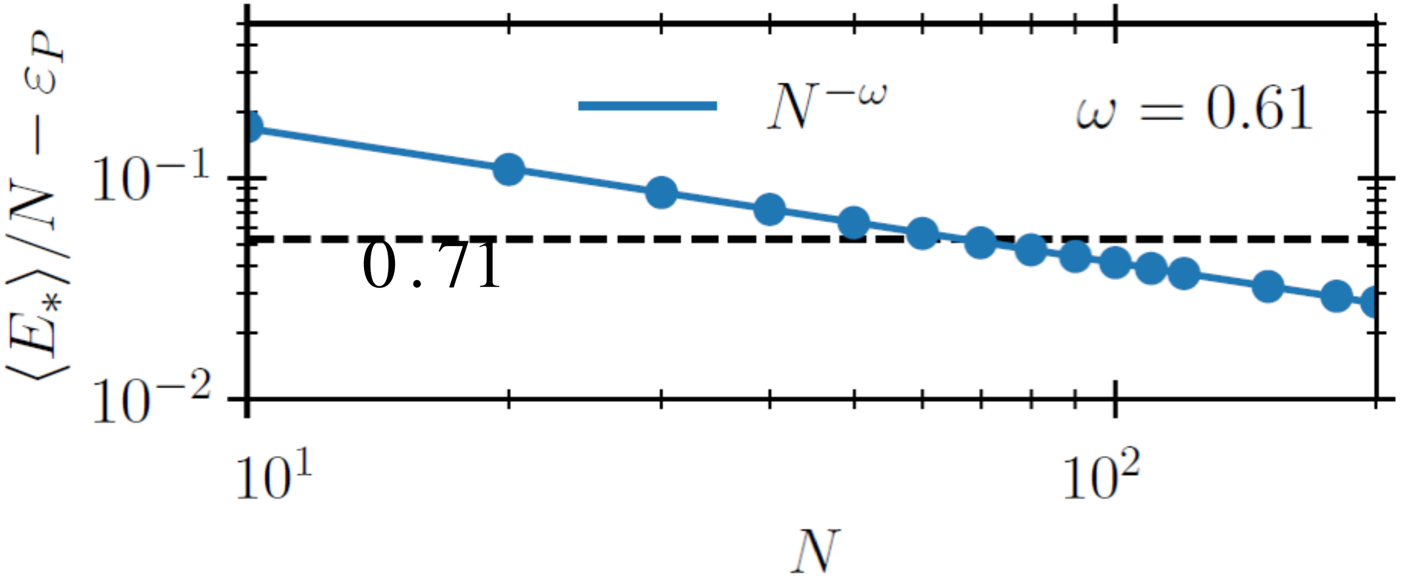


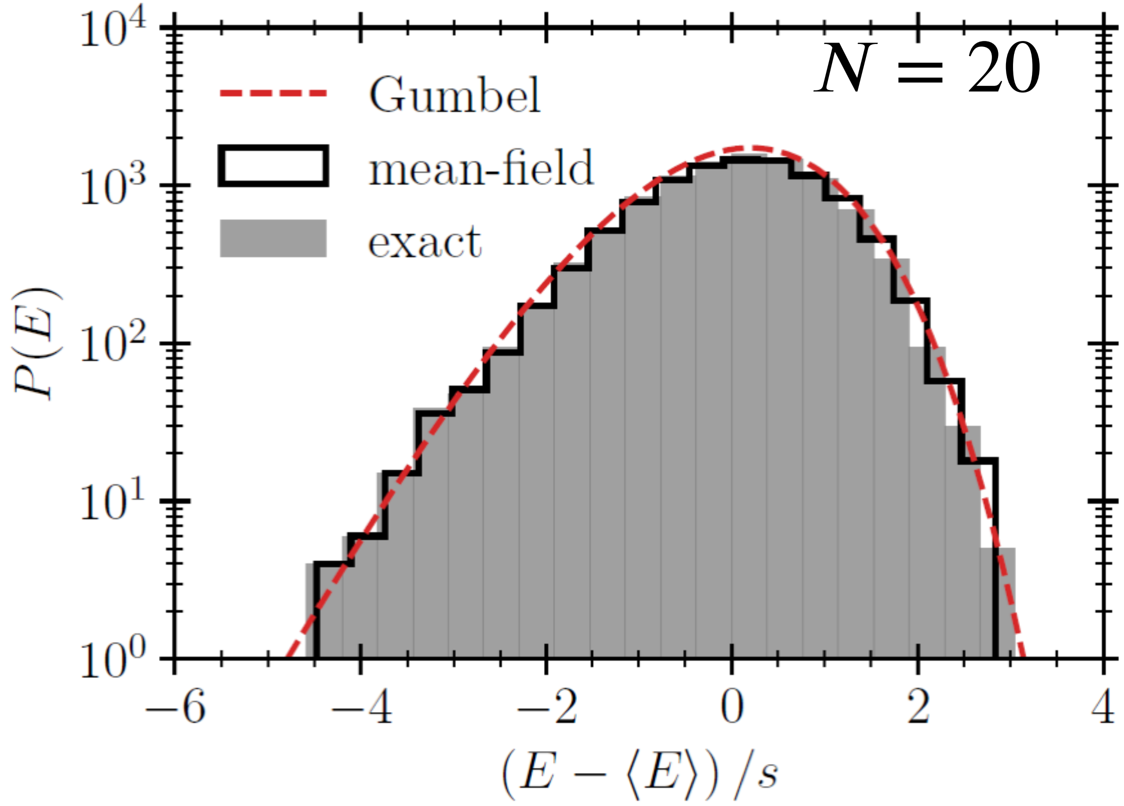

- Semidefinite programming algorithm: $\langle E_*/N \rangle_J = -2/\pi$
- QAOA is not able to achieve Parisi‘s result at finite p

# Large-N scaling

- Parisi „constant“: $\varepsilon_P = 0.763166\ldots$

$10^4$ samples



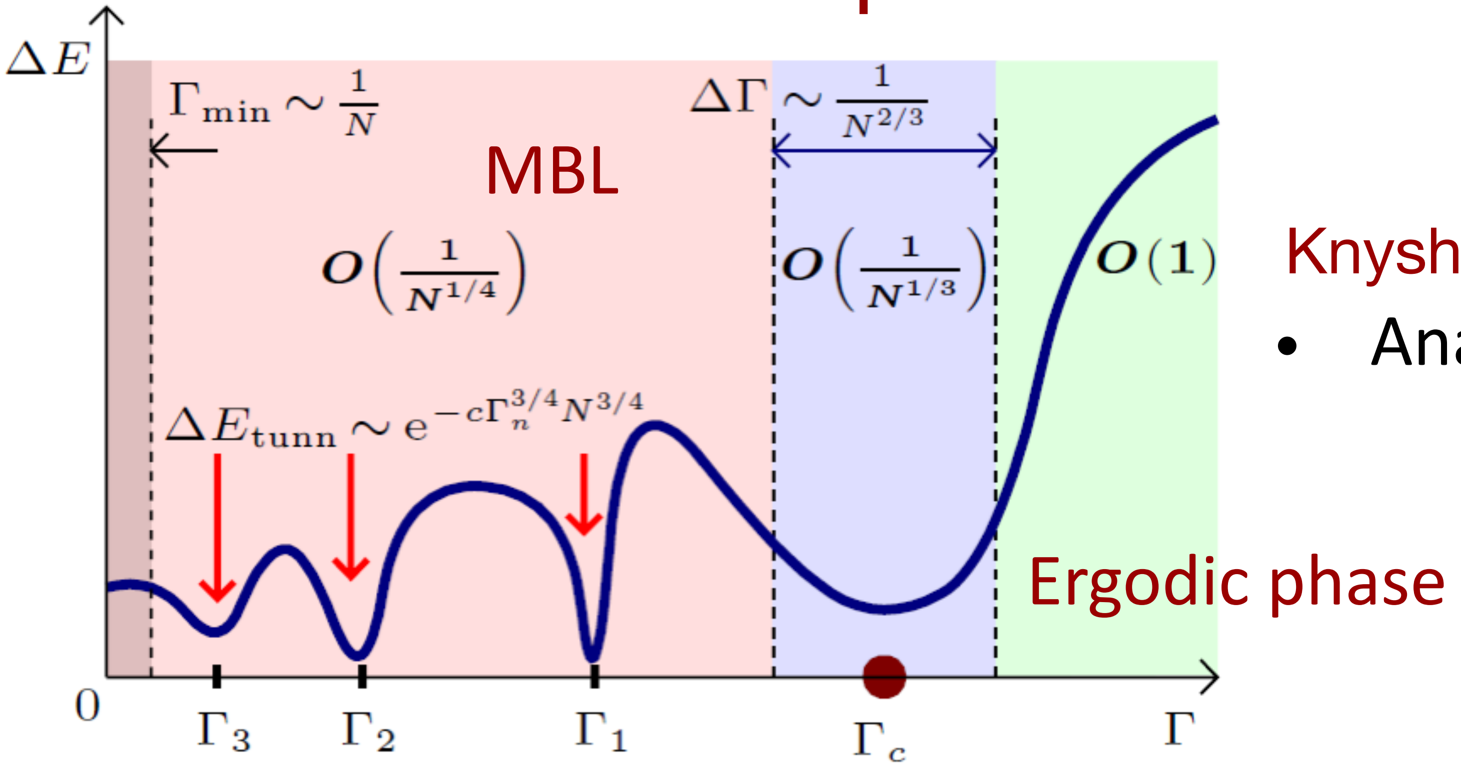




M. Palassini‘ 2003, $\omega \cong 2/3 = 0.666\ldots$

Fluctuations of $E_0$ (MF-AOA vs. exact)

- Hybrid of genetic algorithm (GA) & local optimization
- Mean-field AOA outperforms QAOA on average at large N

# NP hardness in quantum annealing




Knysh'2015:

- Analyis of Hopfield model

$$H = -\sum_{i<j}^{N} J_{ij}\sigma_z^{(i)}\sigma_z^{(j)} - \mathrm{G}(t)\sum_{j=1}^{N}\sigma_x^{(j)}$$

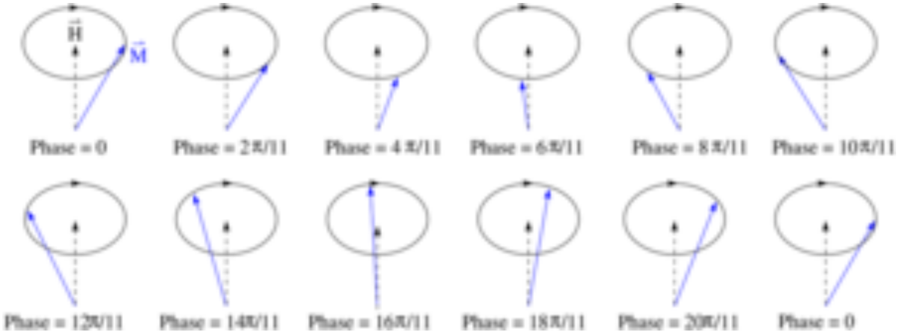
- Exponentially small gaps are due to MBL physics (~ NP hardness)
- The 1st gap at $\Gamma_c$ is polynomial in N

# ANALYZING FLUCTUATIONS

## Judging the quality of MF-AOA

- MF-AOA=stationary action path
- Leading correction is of second order $\delta^2 S$ - Gaussian path integral

$$\int_{x_i}^{x_f} \mathscr{D}x(t) e^{iS[x(t),\dot{x}(t)]} \simeq e^{iS_{cl}} \int \mathscr{D}\delta x(t) e^{-\delta x K \delta x} \qquad \delta x = x - x_{cl}$$




- Here coded via spins - quadratic correction to the action

$$\mathcal{S}[\eta, \bar{\eta}] = \frac{i}{2} \int_0^t (\bar{\eta}, \eta) \begin{bmatrix} -i\partial_t + \hat{A} & \hat{B} \\ \hat{B}^\dagger & i\partial_t + \hat{A}^* \end{bmatrix} \begin{pmatrix} \eta \\ \bar{\eta} \end{pmatrix}$$

- Eigenmode analysis of this Dirac-type equation - steep or flat landscape / encoded as Lyapunov exponents
- Fluctuations = paramagnons

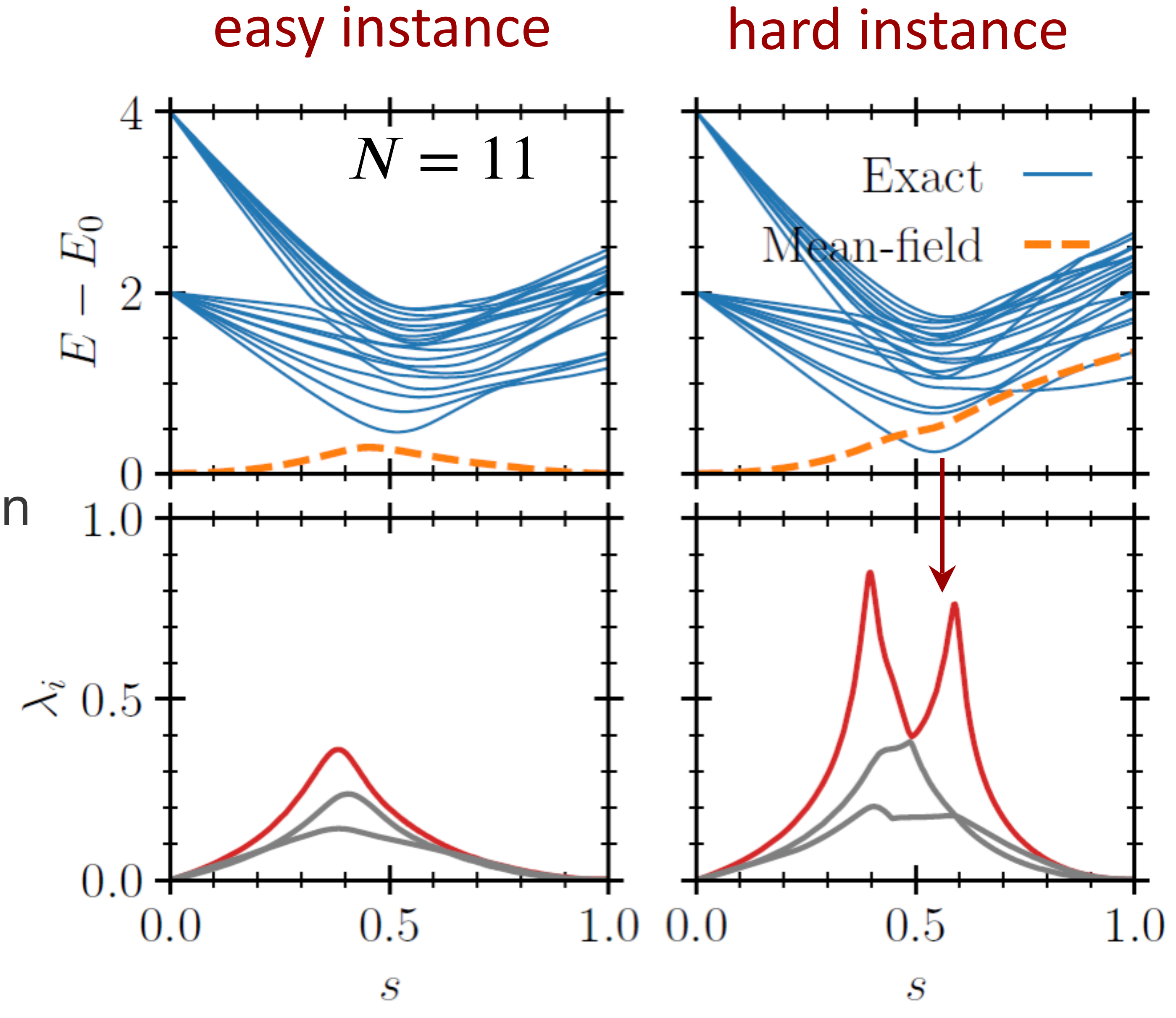
# Spectrum of Lyapunov exponents

- Fluctuations:

$$\langle |\eta_i(t)|^2 \rangle \sim \frac{1}{N} e^{2\lambda_0(t)}$$

maximal exponent

- 2nd peak: ergodic-to-MBL transition



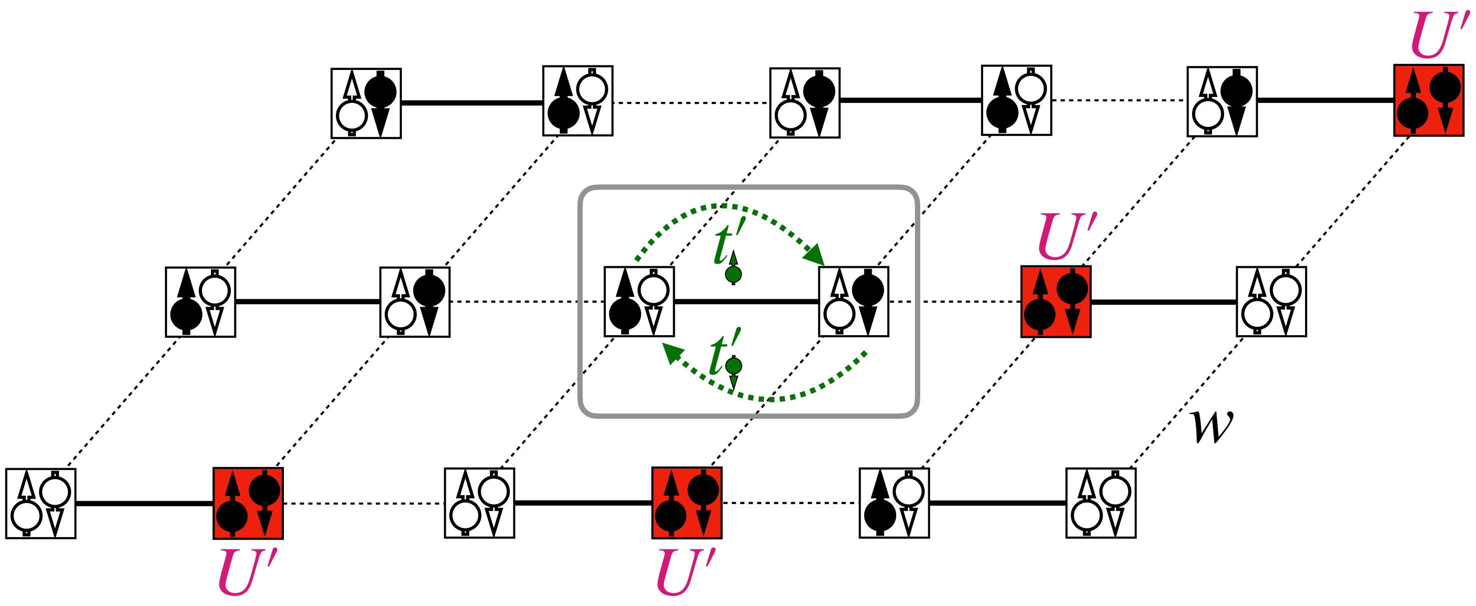
# SIMULATING STRONGLY CORRELATED ELECTRONS

# 1. Motivation (i)

## Electronic correlation is captured in the Fermi-Hubbard model

Fermi-Hubbard model

$$\hat{H}_{FH} = -t \sum_{\langle i,j \rangle,\sigma} (\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + \hat{c}^{\dagger}_{j,\sigma}\hat{c}_{i,\sigma}) + U \sum_{i} \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

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|---|---|
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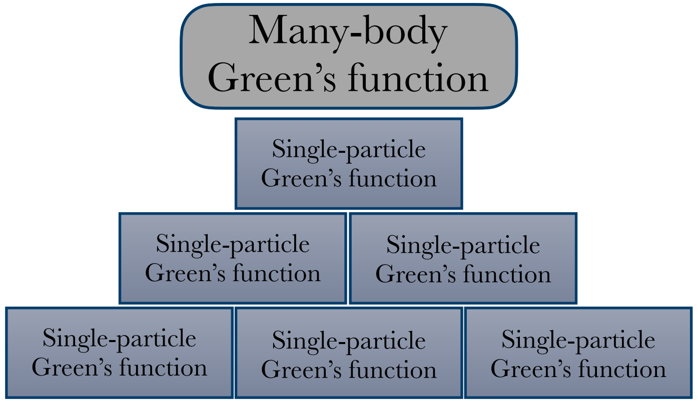
| 4 | 256B |
| 8 | 4MB |
| 36 | 1TB |
| 49 | 9PB |

# 1. Motivation (iii)

## Green's function gives access to phase space

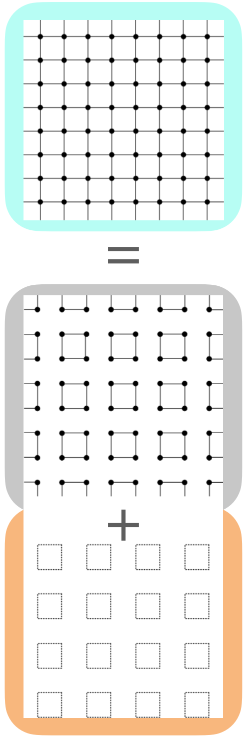



### Selection of observables

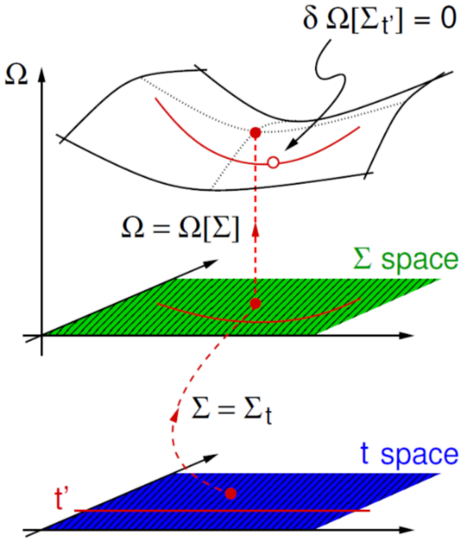
- Average particle density $\langle n_{i,\sigma} \rangle$
- Superconducting gap $\Delta$
- Density of states $N(\omega)$
- Cooper pair coherence length $\xi$

Requires exact Green's function, e. g. via Variational Cluster Approach (VCA)

### Variational Cluster Approach




$$\Omega_t[\Sigma] = \Omega' - \mathrm{Tr}\ln(\mathbb{I} - VG')$$





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# 1. Motivation (ii)

## Introducing the single-particle (retarded) Green's function

Retarded single-particle Green's function

$$G^R_{ij} = \theta(\tau)[G^<_{ij}(\tau) - G^>_{ij}(\tau)]$$

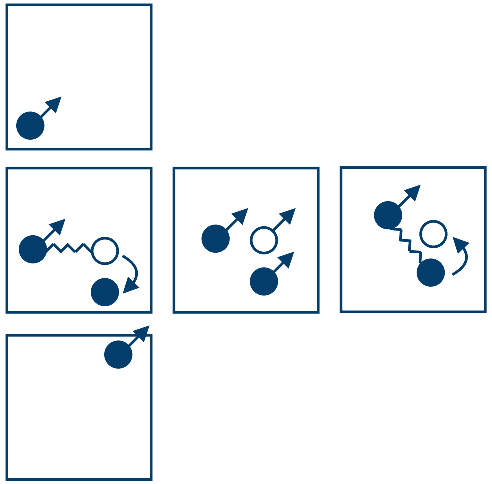
$$G^<_{ij}(\tau) = -i\langle\Psi|e^{iH\tau}c_i e^{-iH\tau}c_j^\dagger|\Psi\rangle$$

$$G^>_{ij}(\tau) = i\langle\Psi|c_j^\dagger e^{iH\tau}c_i e^{-iH\tau}|\Psi\rangle$$

$t = 0$

$t < \tau$

$t = \tau$



Linear response Green's function

$$\chi_{ij}(\tau,\tau') = -i\theta(\tau-\tau')\langle[A_i(\tau), A_j(\tau')]\rangle$$

$$\hat{H}(t) = \hat{H}' + \hat{V}(\tau)$$

$$\hat{V}(t) = \sum_i \Phi_i(\tau)\hat{A}_i(\tau)$$

$\Phi_i(\tau)$ → perturbation sources

$\hat{A}_i(\tau)$ → some operator, e. g. hopping operator

$$\delta\langle\hat{A}_i(\tau)\rangle = \sum_i \chi_{ij}(\tau,\tau')\Phi_j$$

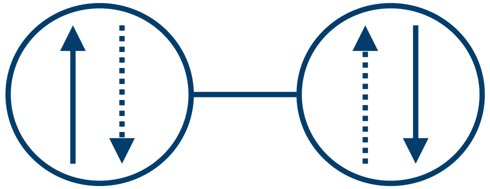
$\chi_{ij}(\tau,\tau')$ → Response function

Kubo's formula

# 3. Toy model: Two-site dimer (i)

## Course of action

*Hubbard site* *Bath site*

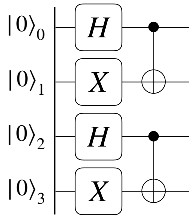


$$H' = H_0 + H_U = -t\sum_{\sigma}(c_{\sigma}^{\dagger}b_{\sigma} + b_{\sigma}^{\dagger}c_{\sigma}) + \frac{U}{2}(n_c^2 - 2n_c)$$

Initialization stage → Time evolution → Measurement

### Ground state preparation

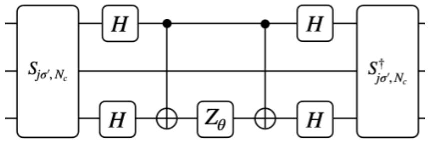
Guess state




Variational Hamiltonian Ansatz

$$U(\theta) = \prod_{k=1}^{n}\prod_{j=1}^{p} e^{-i\theta_{j,k}H_j}$$

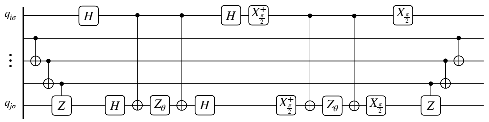
Perturbation



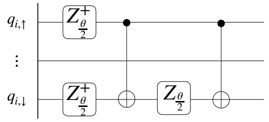

### Trotterization

Application of elementary circuits

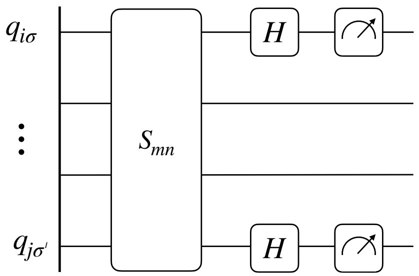
- Hopping



- Repulsion



### $\langle Z_{i\sigma}Z_{j\sigma'}\rangle$



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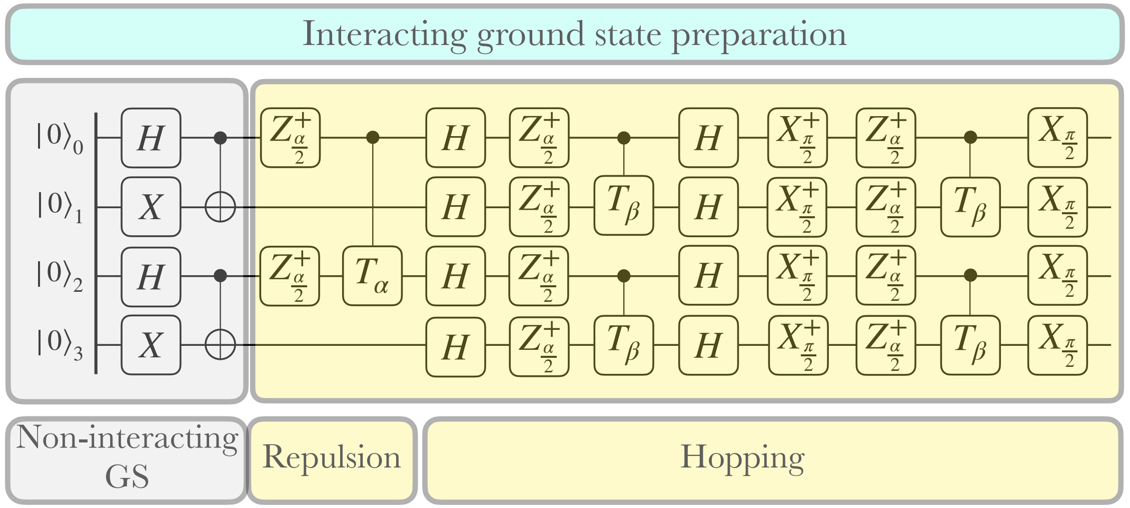
# 3. Two-site dimer (ii)

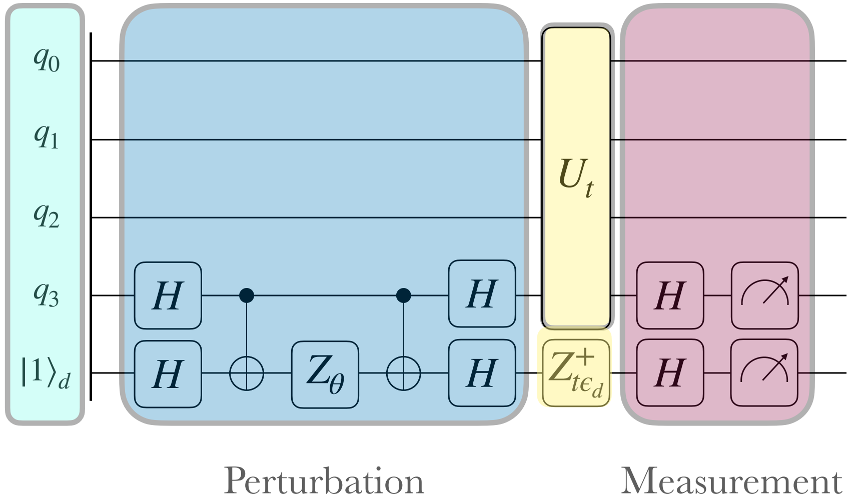
## Ground state preparation via Variational Hamiltonian Ansatz

1. Prepare ground state
2. Bring it out of equilibrium
3. Let it evolve
4. Measure $\langle ZZ \rangle$ expectation value

$$\langle \{ x_{i\sigma}(\tau) y_{j\sigma'} \} \rangle = \frac{\langle i x_{i\sigma} x_d \rangle_{\Phi_{j\sigma'}}(\tau, \epsilon_d) - \langle i x_{i\sigma} x_d \rangle_{\Phi_{j\sigma'}}(\tau, -\epsilon_d)}{2\Phi_{j\sigma'} \sin(\epsilon_d \tau)}$$




$\langle \{ x_3(\tau) x_3(0) \} \rangle$





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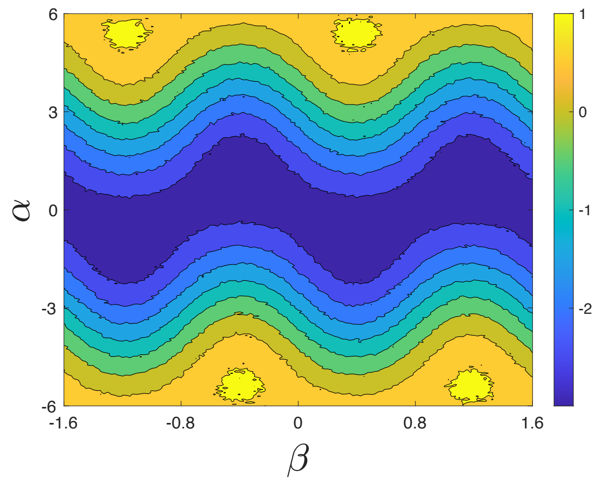
# 4. Results

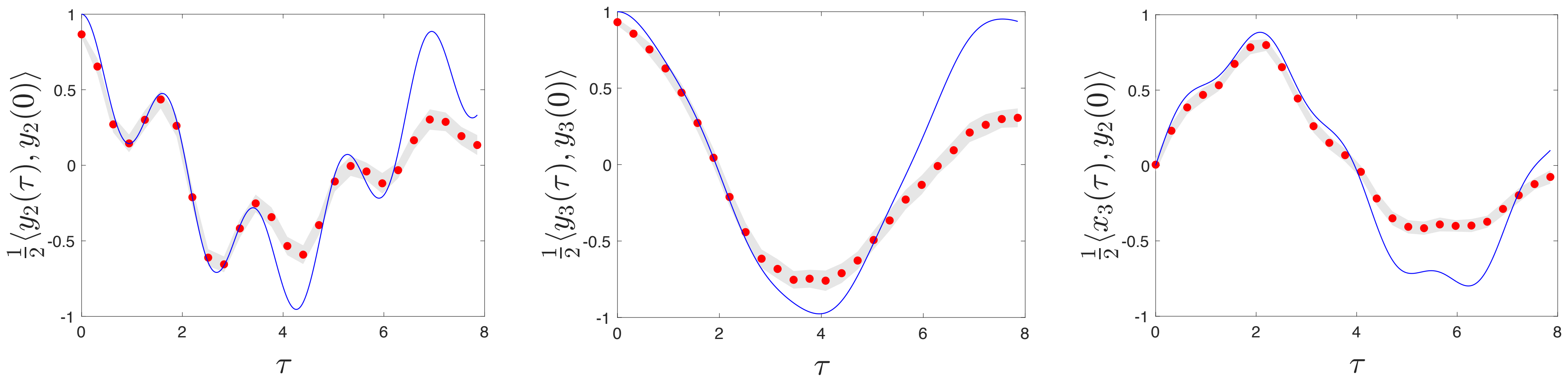



Energy landscape on *ibmq_kolkata* noisy simulator

Correlators on *ibmq_kolkata* noisy simulator

Error mitigation

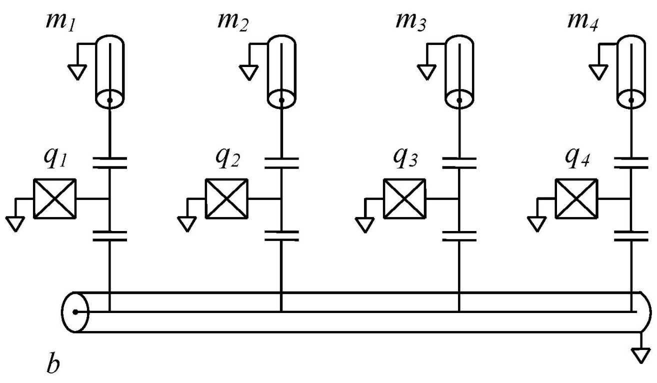
- Readout error mitigation
- Pauli twirling
- Dynamical decoupling
- Zero noise extrapolation



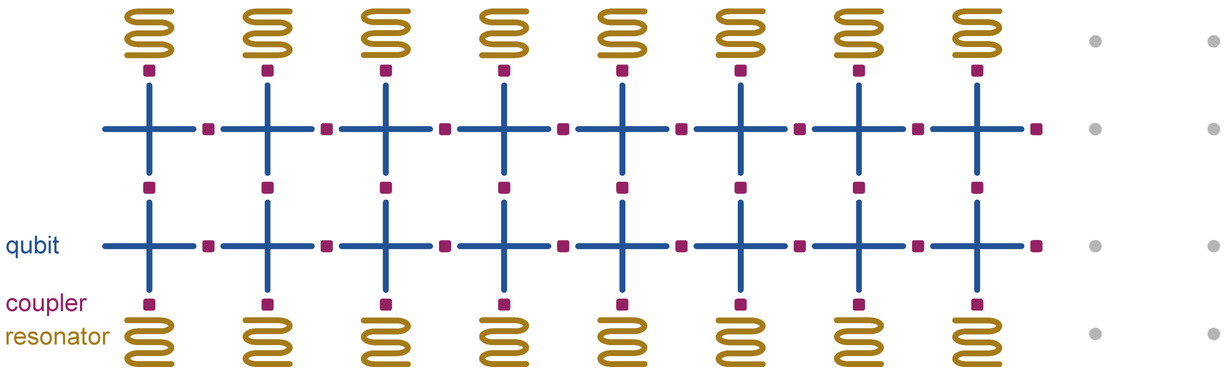
# USING ALL DEGREES OF FREEDOM

## Resonators are easy to add to superconducting procesors

Add extra resonators … coherent, easy to make, high-dimensional:
What can they do?

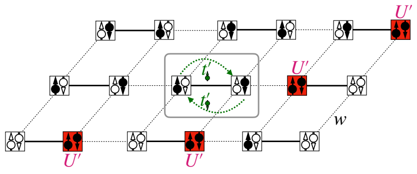



Martinis Group 2012 (!)

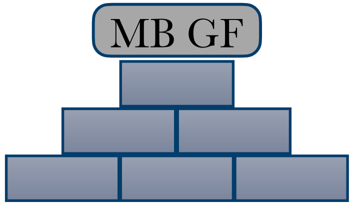



Current plan at FZJ

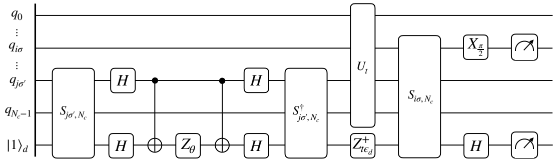
# 5. Summary



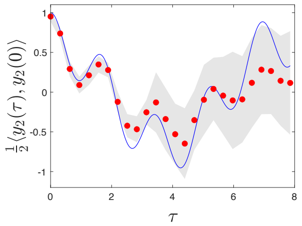
Electronic correlation captured in Fermi-Hubbard model



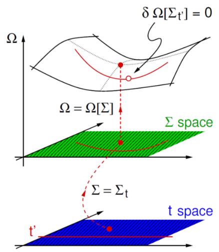

Solve FH by means of many-body Green's function, build from single-particle Green's function



Directly measure the correlators within the Green's function



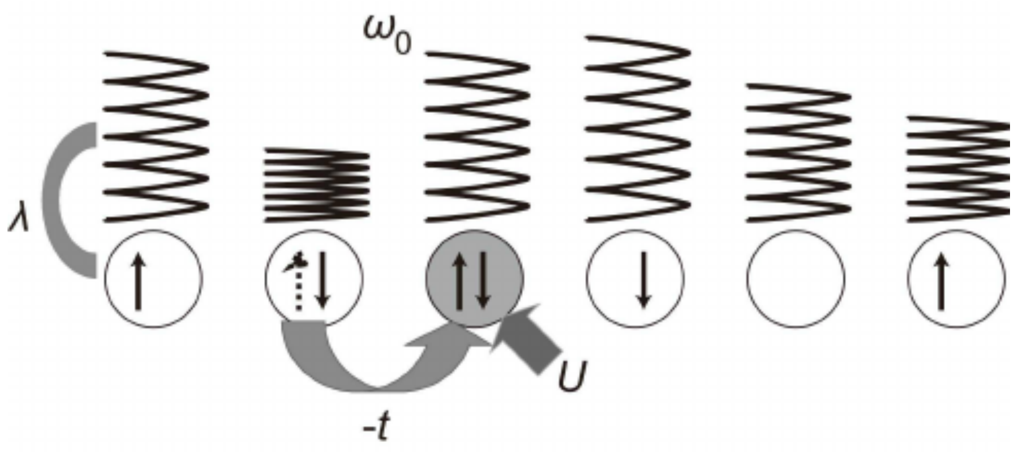
Apply error mitigation to results




Extrapolate to larger system sizes via VCA

# PHONONIC MODELS

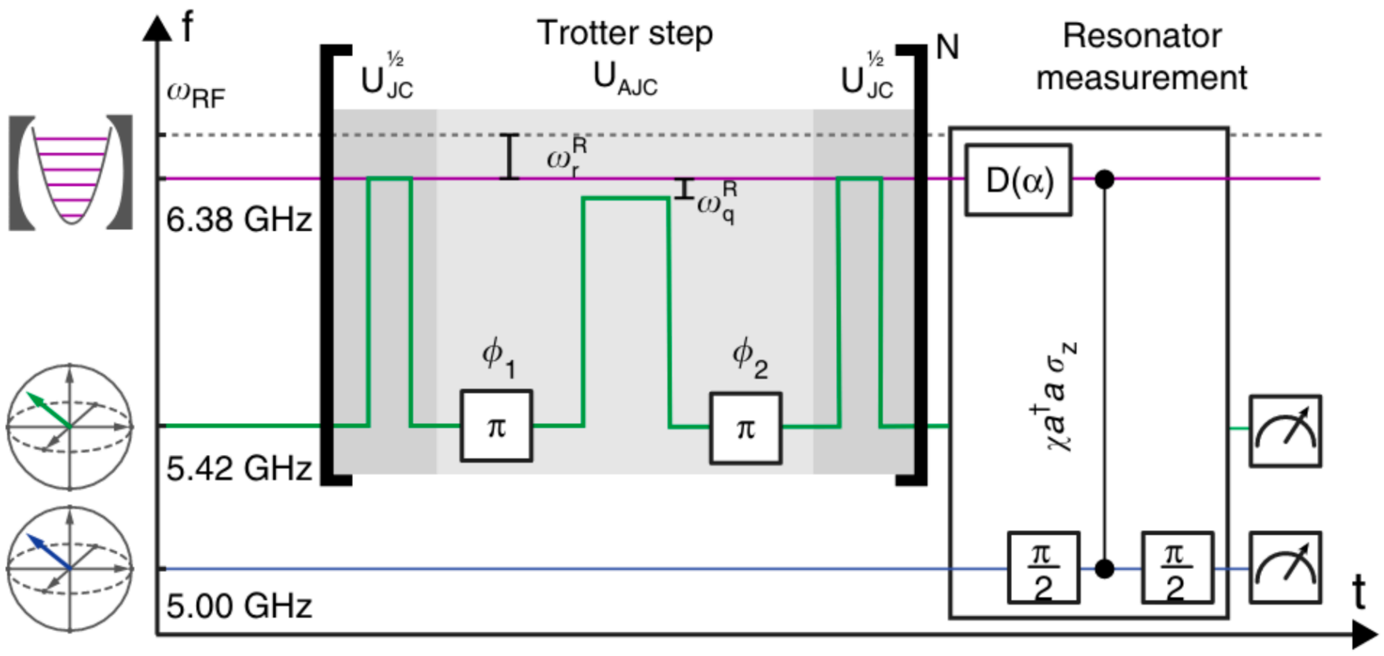
## Hubbard Holstein and friends




Qubit encodings

| | Unary | Binary |
|---|---|---|
| Complexity for N levels | N qubits | Log N qubits |
| Number of qubits required | High | Low |
| CNOT overhead | Low | High |

# A GATE ON THE MODE



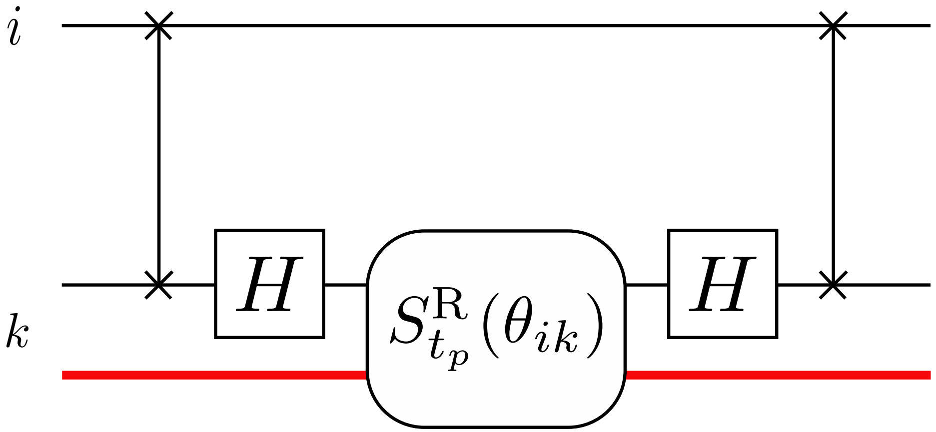

Jaynes-Cummings Hamiltonian:

$$\hat{H}_{\mathrm{JC}} = \omega_r \hat{a}^\dagger \hat{a} - \frac{1}{2}\omega_q \hat{\sigma}^z + g\left(\hat{\sigma}^+ \hat{a} + \hat{\sigma}^- \hat{a}^\dagger\right) \xrightarrow{\omega_q = \omega_r} S_{\mathrm{JC}}(\theta) = e^{-i\theta\left(\hat{\sigma}^+ \hat{a} + \hat{\sigma}^- \hat{a}^\dagger\right)}$$

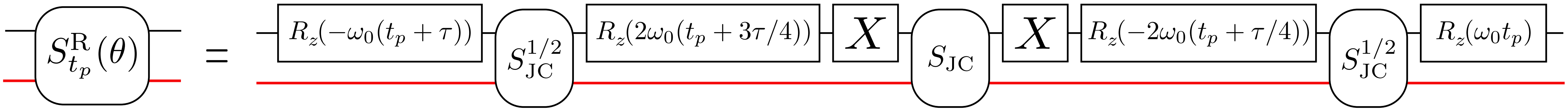
# Coupling Terms: Hubbard Holstein

$$\hat{H}_{\mathrm{HH}} = \sum_{i,\sigma} g \left( \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{i,\sigma} \right) \left( \hat{a}^{\dagger} + \hat{a} \right)$$

$$e^{-i\hat{H}_{\mathrm{HH}}\tau}$$



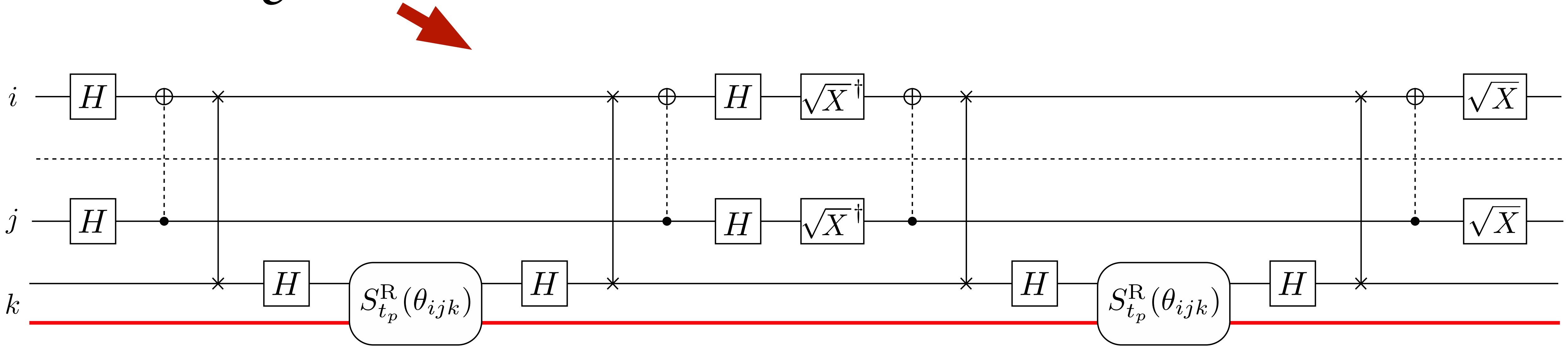

$$S_{\mathrm{JC}}(\theta) = e^{-i\theta\left(\hat{\sigma}^{+}\hat{a} + \hat{\sigma}^{-}\hat{a}^{\dagger}\right)}$$



# Coupling Terms (2): generalised hopping

$$\hat{H}_{\mathrm{XY}} = g \sum_{i \neq j, \sigma} \left( \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} \right) \left( \hat{a}^{\dagger} + \hat{a} \right)$$

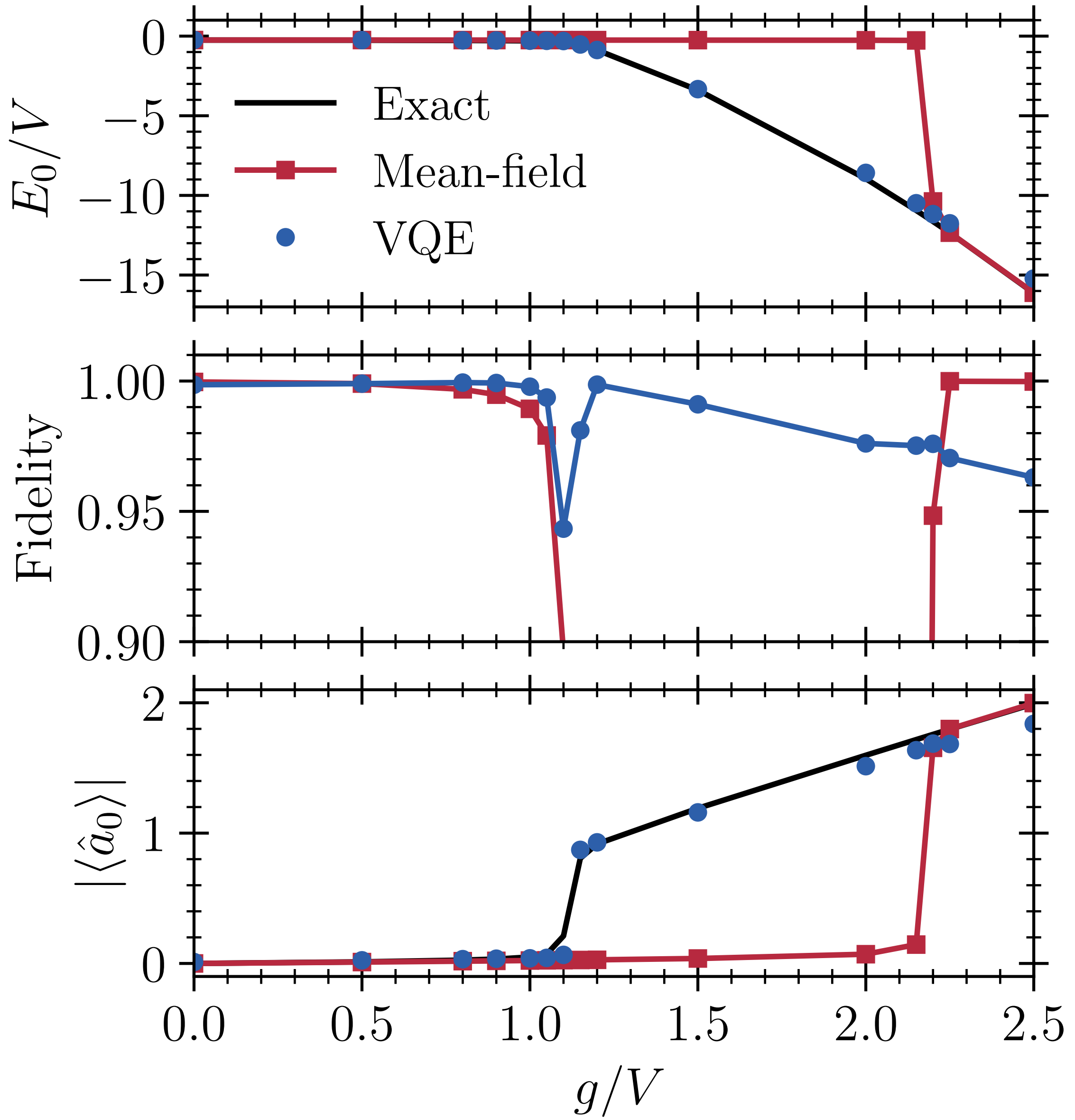
$$e^{-i\hat{H}_{\mathrm{XY}}\tau}$$



# The Variational Hamiltonian Ansatz

$$\mathsf{A}(\boldsymbol{\theta}) = \hat{D}\left(\phi\right)\prod_{i,\sigma}^{N-1} \mathsf{YY}_{i,\sigma}(v_{i,\sigma})\mathsf{XX}_{i,\sigma}(v_{i,\sigma})\hat{U}_{\Theta}^{i,\sigma;i+1,\sigma}(\gamma_{i,\sigma})$$

$$\times \prod_{i=1}^{N} \mathsf{ZZ}_i(u_i)\prod_{\sigma}\hat{U}_{\Theta}^{i,\sigma}(\zeta_{i,\sigma})R_z(2\epsilon_{i,\sigma})$$



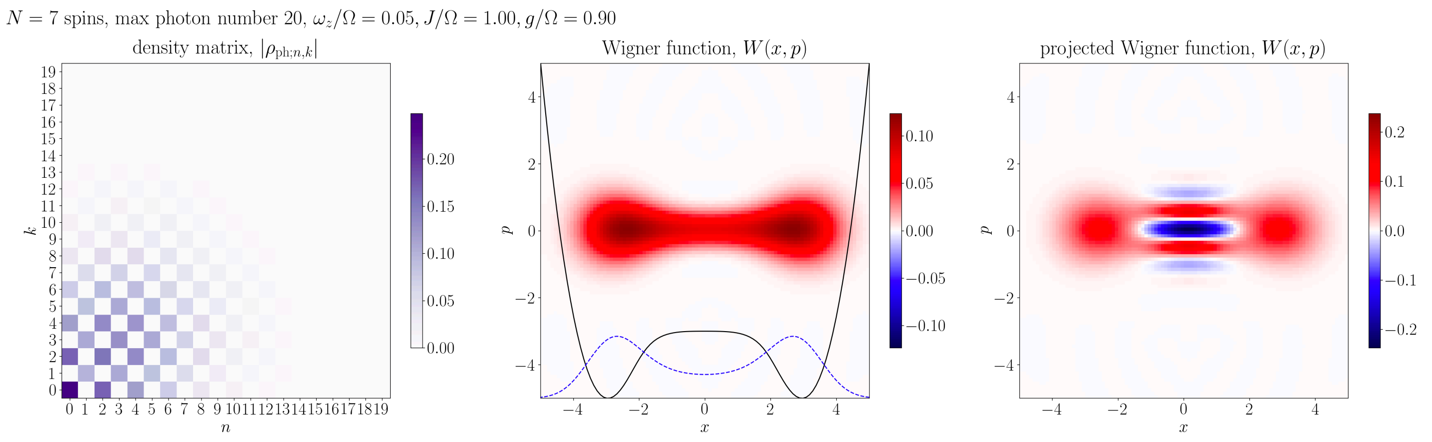

Displacement operator

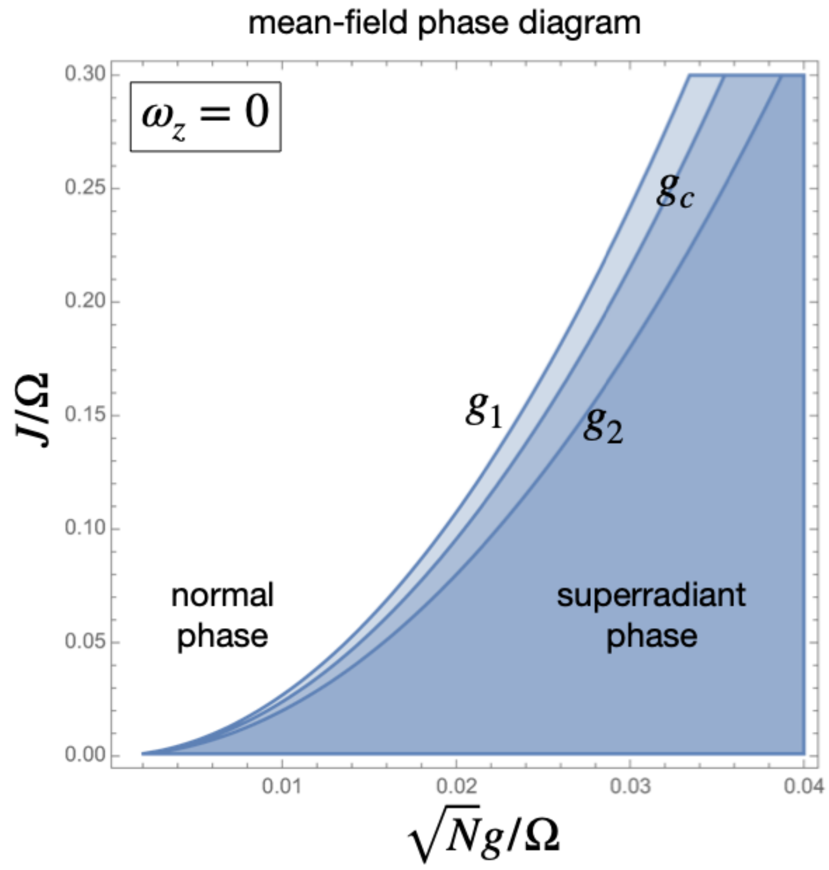
$$\hat{D}(\alpha) = e^{\alpha\hat{a}^\dagger - \alpha^*\hat{a}}$$

# SUPERRADIANCE WITH INTERACTIONS

## Ising Dicke model

$$\hat{H}_{\mathrm{ID}} = -J\sum_{i=1}^{N}\sigma_i^z\sigma_{i+1}^z - \omega_z\sum_{i=1}^{N}\sigma_i^z + g(\hat{a}+\hat{a}^\dagger)\sum_{i=1}^{N}\sigma_i^x + \Omega\hat{a}^\dagger\hat{a}$$



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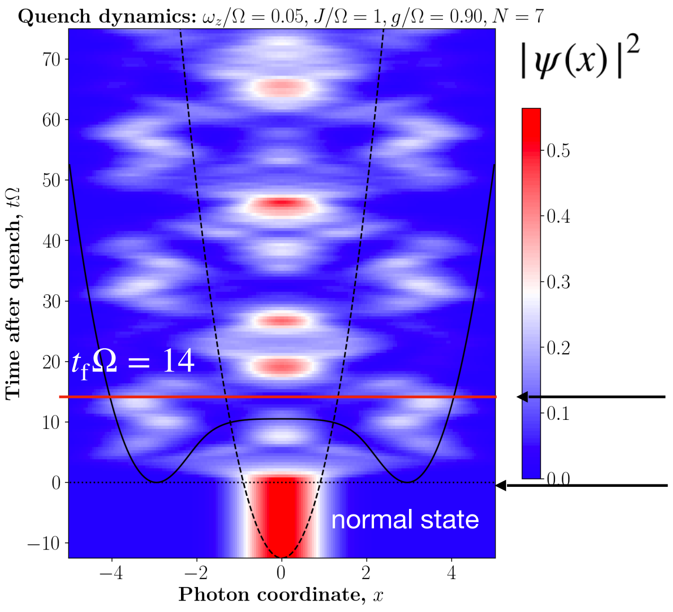
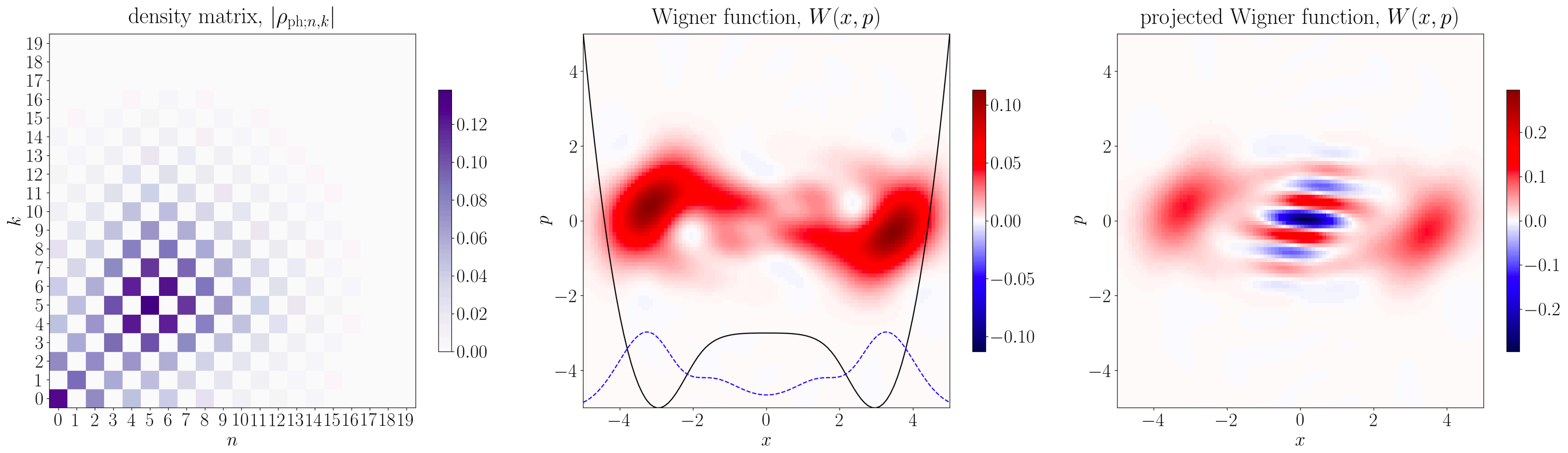
# Approximation of the superradiant state via quench




measurement $\rho_f = \hat{U}_f |\psi_0\rangle\langle\psi_0| \hat{U}_f^\dagger$ , $\hat{U}_f = \exp(-i\hat{H}_{ID} t_f)$

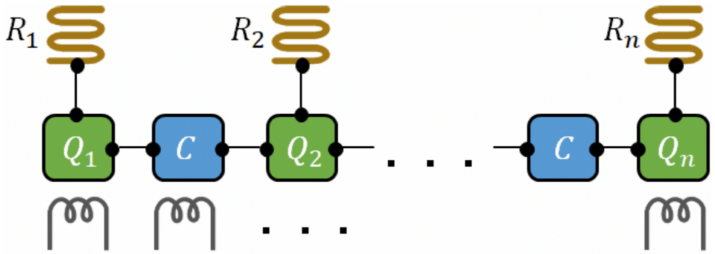
quench

## *Density matrix and Wigner functions after the quench*



# Quantum circuit

## *Qubit-boson architecture*




- flux-tunable transmons (Q) and couplers (C), capacitively coupled to resonators (R)

## *Simulation protocol for quench dynamics*

- evolution operator for Ising-Dicke Hamiltonian

$$\tilde{S}_{\mathrm{ID}}(t_p) = \prod_{k=0}^{p-1} e^{-i\tau H_Z} e^{-i\tau H_{ZZ}} \tilde{S}_D(t_k+\tau, t_k), \qquad t_k = k\tau$$

- Dicke Hamiltonian gate

$$\tilde{S}_D(t+\tau,t) = \mathrm{SWAP}^{(12)} \tilde{S}_R^{(1)}(t+\tau, t+\tau/2) \mathrm{SWAP}^{(12)} \tilde{S}_R^{(1)}(t+\tau/2, t)$$

- Rabi Hamiltonian gate

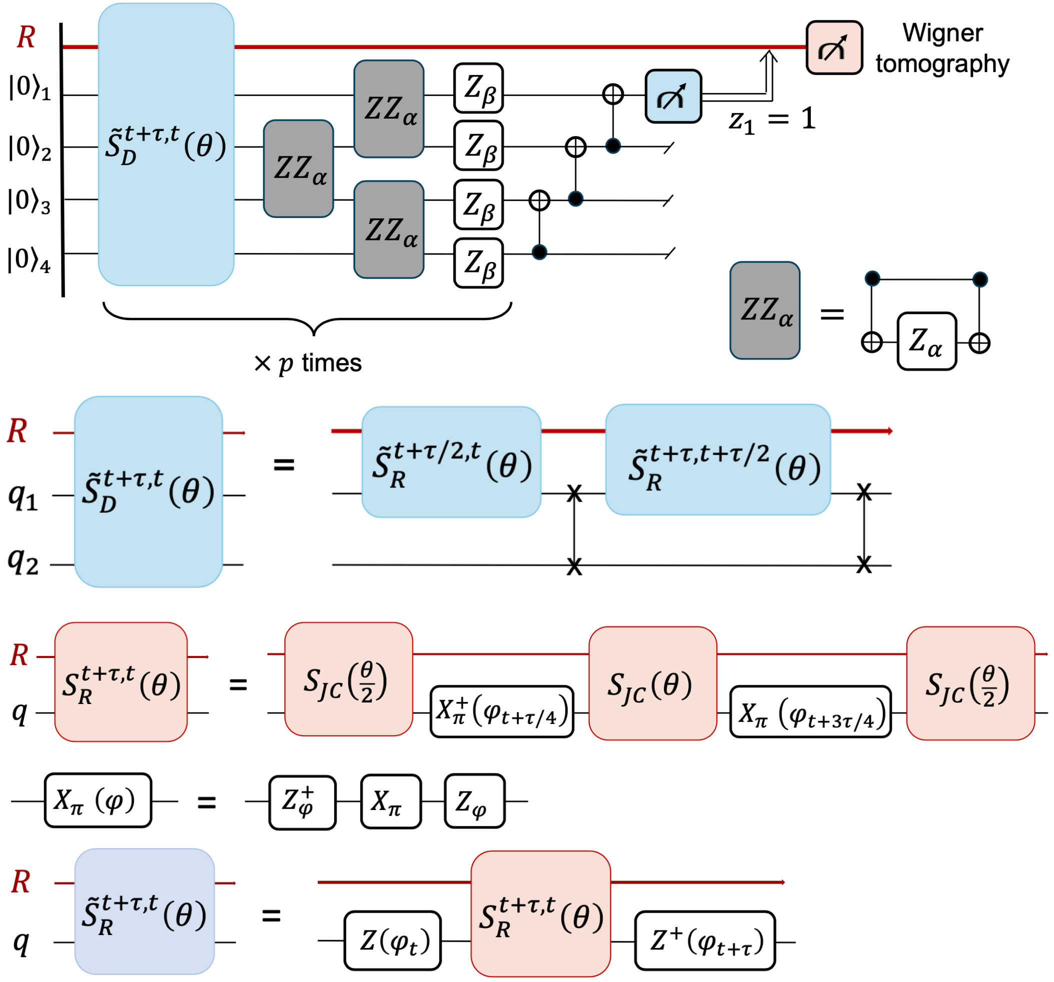
$$\tilde{S}_R(t+\tau,t) = \tilde{S}_{\mathrm{JC}}(\theta/2, t+\tau)\sigma_x \tilde{S}_{\mathrm{JC}}(\theta, t+\tau/2)\sigma_x \tilde{S}_{\mathrm{JC}}(\theta/2, t)$$

- Janes-Cummings gate

$$\tilde{S}_{\mathrm{JC}}(\theta,t) = e^{-i\hat{h}_z t} e^{-i\theta(\hat{\sigma}^+\hat{a} + \hat{\sigma}^-\hat{a}^\dagger)} e^{i\hat{h}_z t}, \theta = \tau g$$

# Quantum circuit

## *Quantum gates*



# CONCLUSIONS

- Mean Field AOA - often a good proxy for QAOA
- Green’s function measurement - physics inspired method to simulate manybody systems
- If your experimental colleague gives you resonators … simulate Bosons

Misra-Spieldenner et al., PRX Quantum 4, 030335
G. Bishop, D. Bagrets, FKW, arXiv:2310.10412