UNIVERSITÄT DES SAARLANDES

Bundesamt für Sicherheit in der Informationstechnik

Quantum computers

State of play, prospects, and a European perspective

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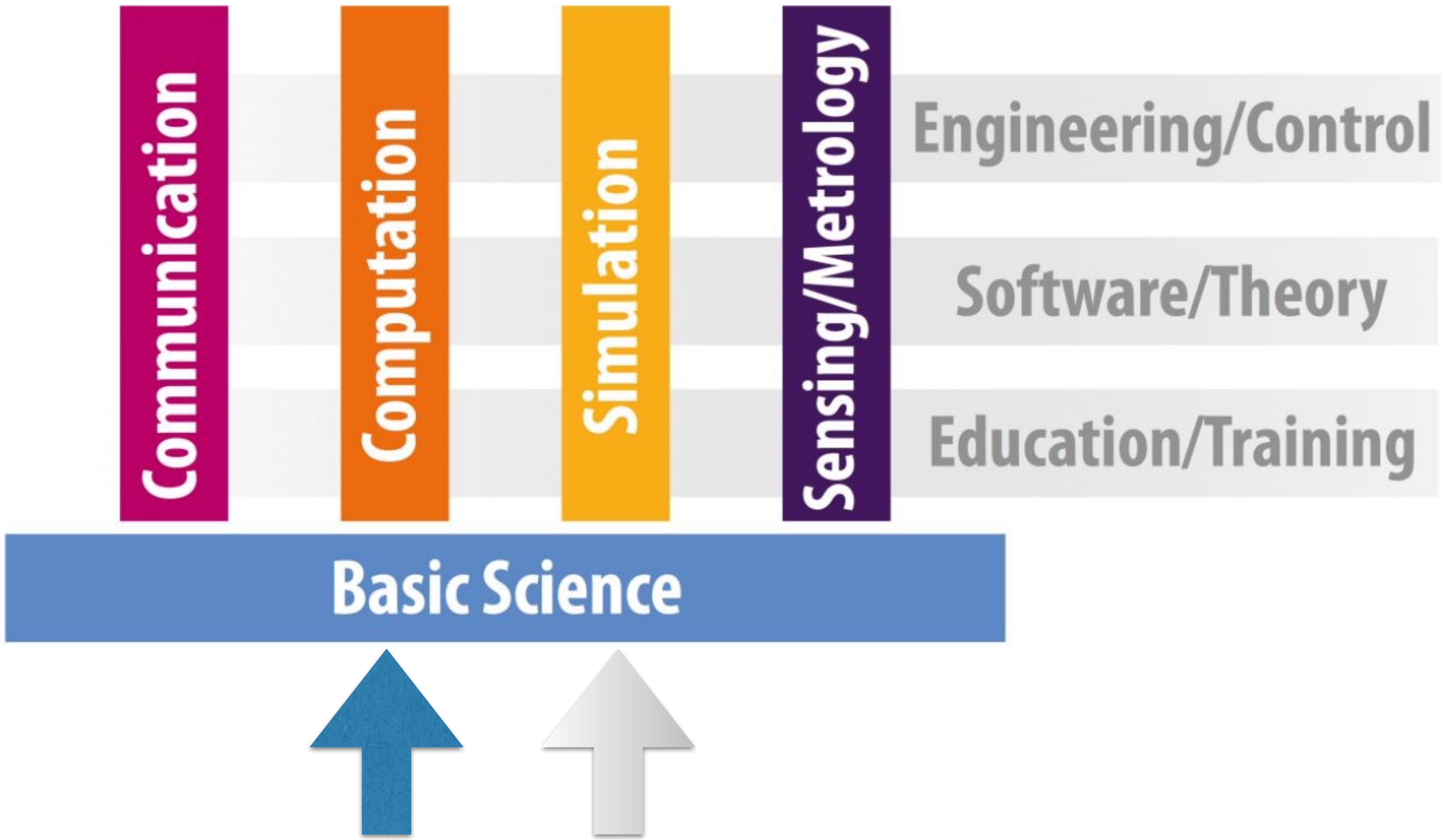
QUANTUM FLAGSHIP

OpenSuperQ

https://www.bsi.bund.de/DE/Publikationen/Studien/Quantencomputer/quantencomputer_node.html

Dimensions of quantum technology

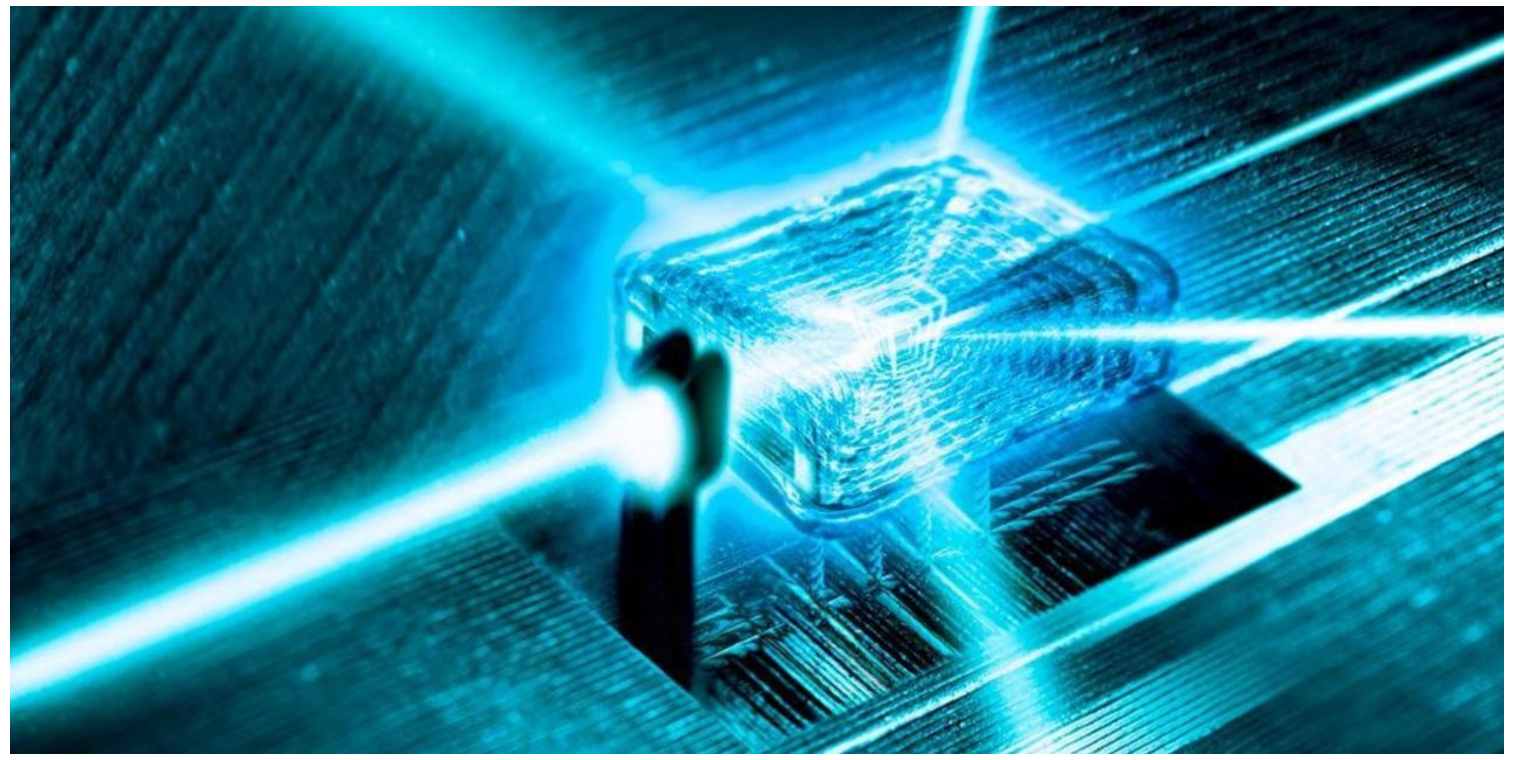


The power of quantum

Classical computer

- Binary information
- Registers with well-defined binary value
- Commands on registers one-by-one
- Parallel operations = parallelized hardware

Quantum computer



- Binary information
- Superpositions of registers

$$|\psi\rangle = \sum_{\{\sigma_i\}} c_{\{\sigma_i\}} |\{\sigma_i\}\rangle$$

- Operations on complete state space
- intrinsic parallelism

Harnessing quantum

Challenge:

- Undo parallelism before readout
- Make operations unitary

Operational:

- intermediate states are analog
- prevent output errors

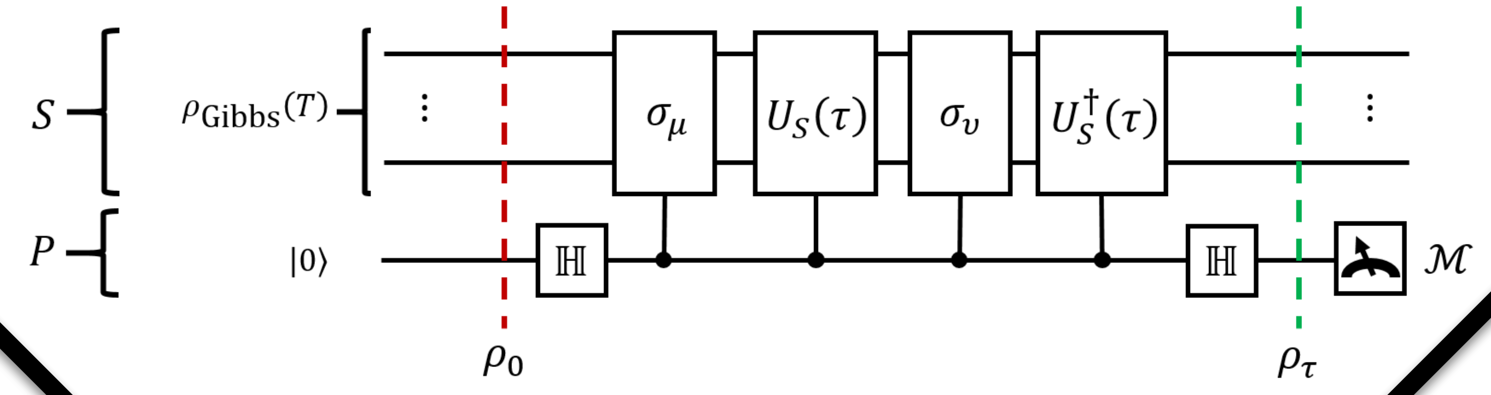
Binary input

Probability amplitudes

$$|\psi\rangle = \sum_{\{\sigma_i\}} c_{\{\sigma_i\}} |\{\sigma_i\}\rangle$$

Unitary operations in parallel

Binary output

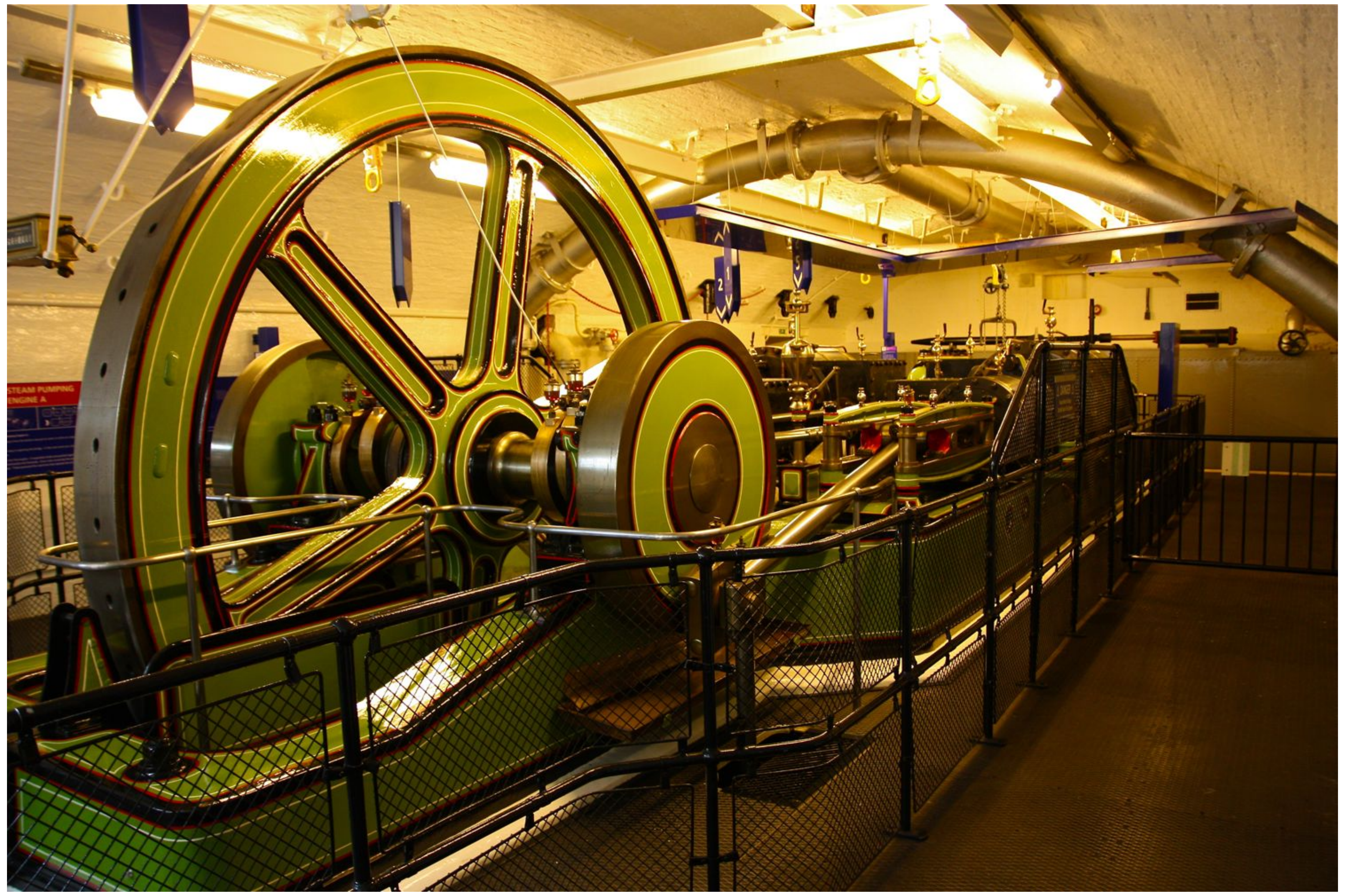


There are few known solutions to this

But those are important

Applications

- Theoretical chemistry and materials science
- Combinatorical optimization
- Machine learning
- Graph theory
- Signal processing
- Cryptanalysis



Fundamentel algorithms with borad application portfolio

Overview

- Three paths to quantum computing
- NISQ: Using your noisy hardware
- A European flagship project
- Extrapolation: What it takes to be fault-tolerant
- Quantum annealing
- Have we found the best way to program a quantum computer yet?

Three paths to quantum computing

Universal fault-tolerant quantum computer:

- massive overhead from error correction
- long-term goal
- powerful tool
- potentially large time savings

Non error-corrected co-designed processor

- 50 qubits reached
- outperform supercomputer (in simulating quantum computers)
- gate number limited by physical errors
- potential memory savings

Quantum annealer / adiabatic quantum computer

- accessible technology
- quantum speedup?
- need more powerful versions (non stoquastic / manybody coupler)

NISQ

Noisy Intermediate-scale quantum computer (NSQ)

Clive Sinclair

Simple, primitive, error-prone hardware: Coding needs to follow architecture

Quantum chip

- 9 Qubits
- NN coupling
- separate control and readout
- Unpublished: 72 Qubits

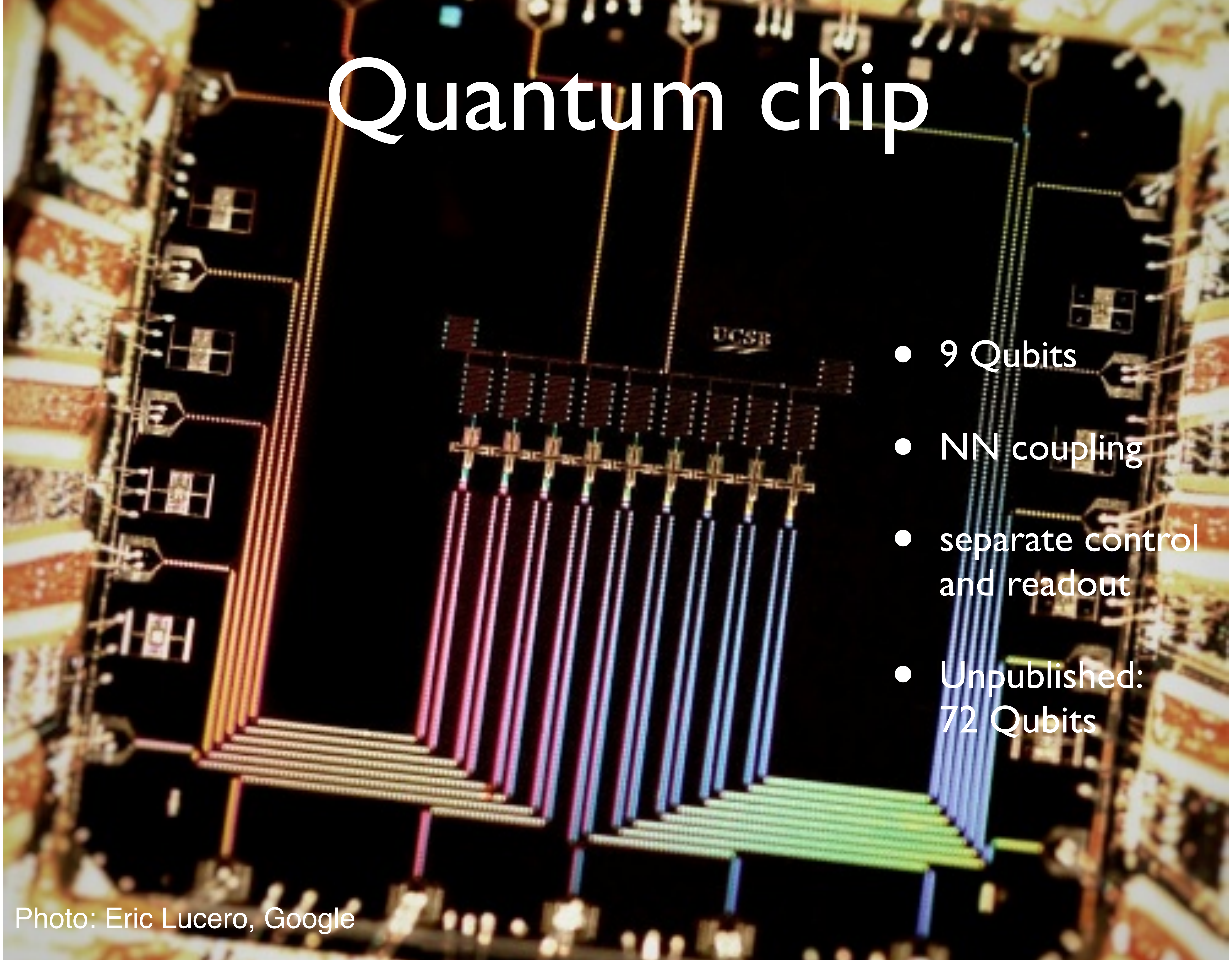


Photo: Eric Lucero, Google

Basis of quantum supremacy

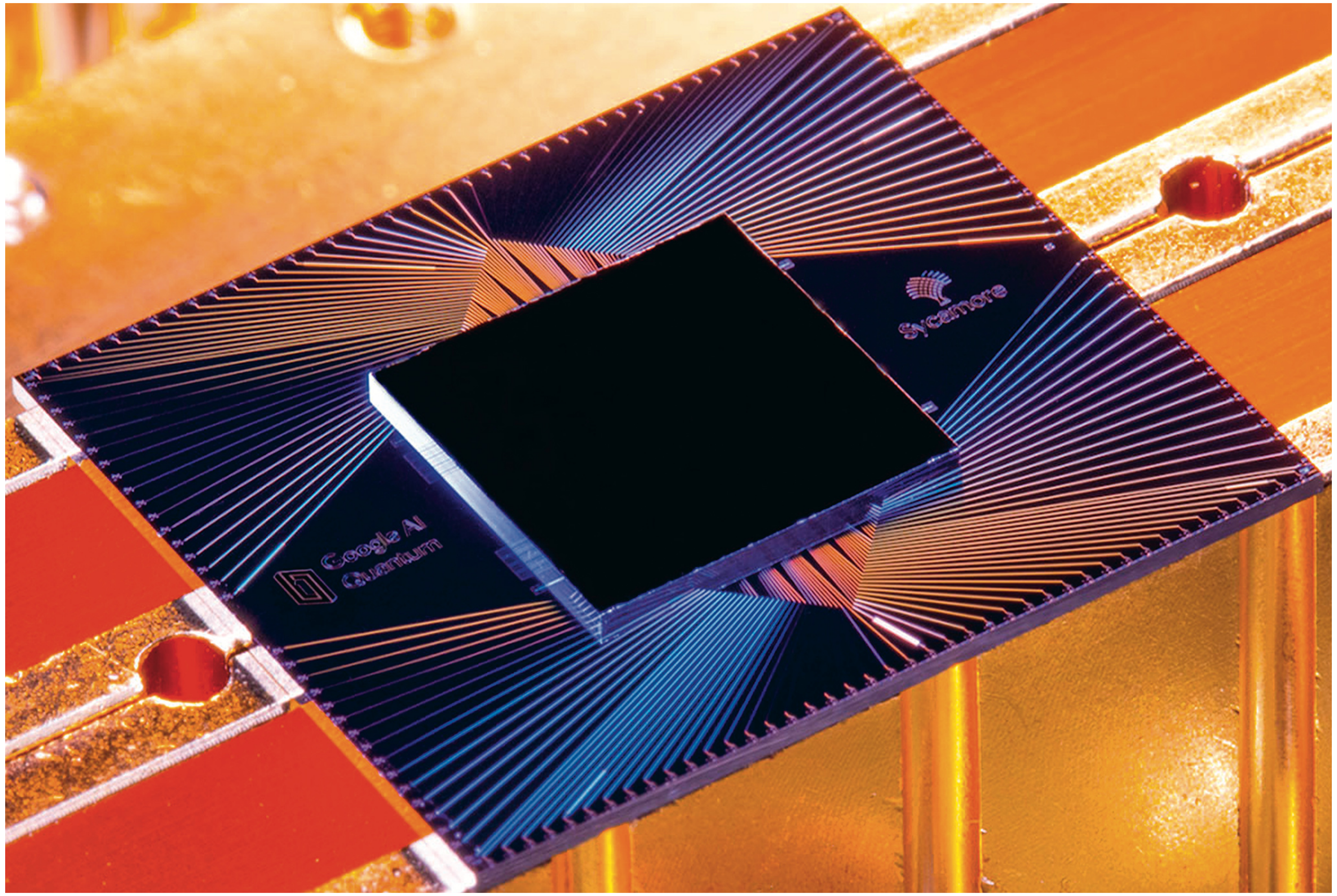
$$H^{\otimes n}|0\rangle^{\otimes n} = \frac{1}{2^{n/2}} \sum_{s=0}^{2^n-1} c_s |s\rangle$$

- 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)

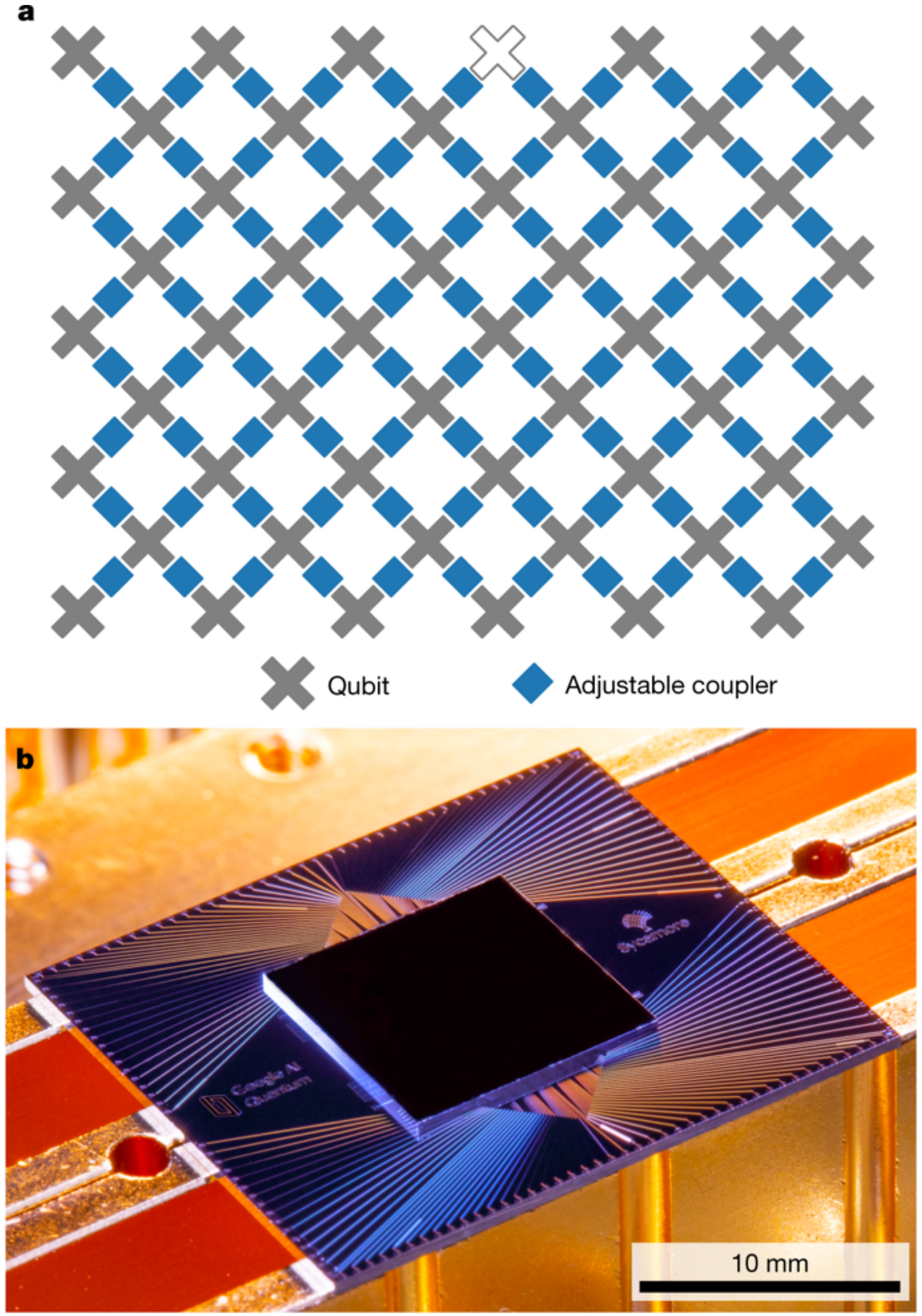
- need to be coherent enough / low enough errors (otherwise it is classical)

- needs to be certified without simulation



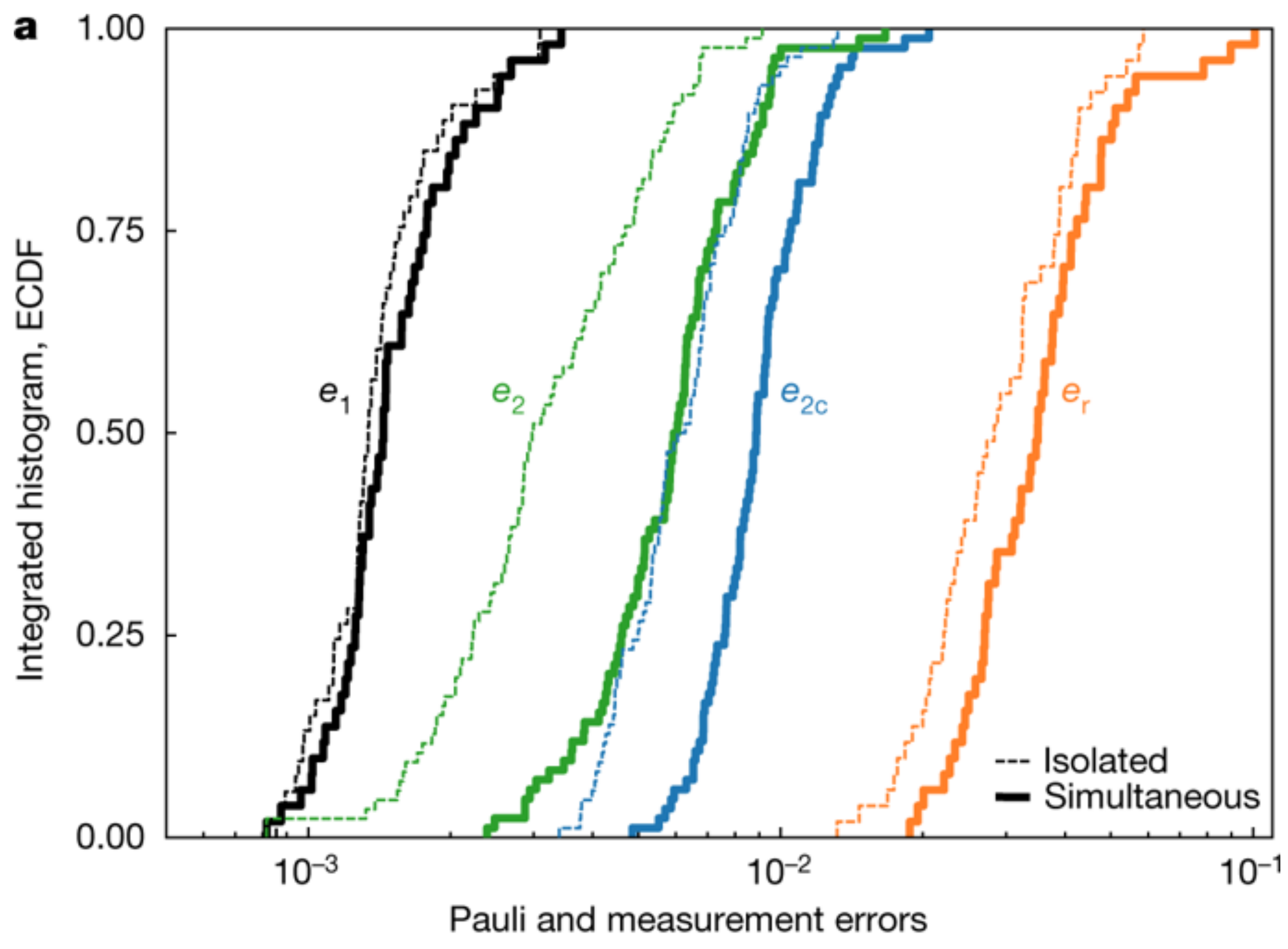
Technological platform

- Josephson platform
- Adjustable couplers (almost qubits)
- 9 x 6 grid
- One qubit defective
- Integrated measurement infastructure

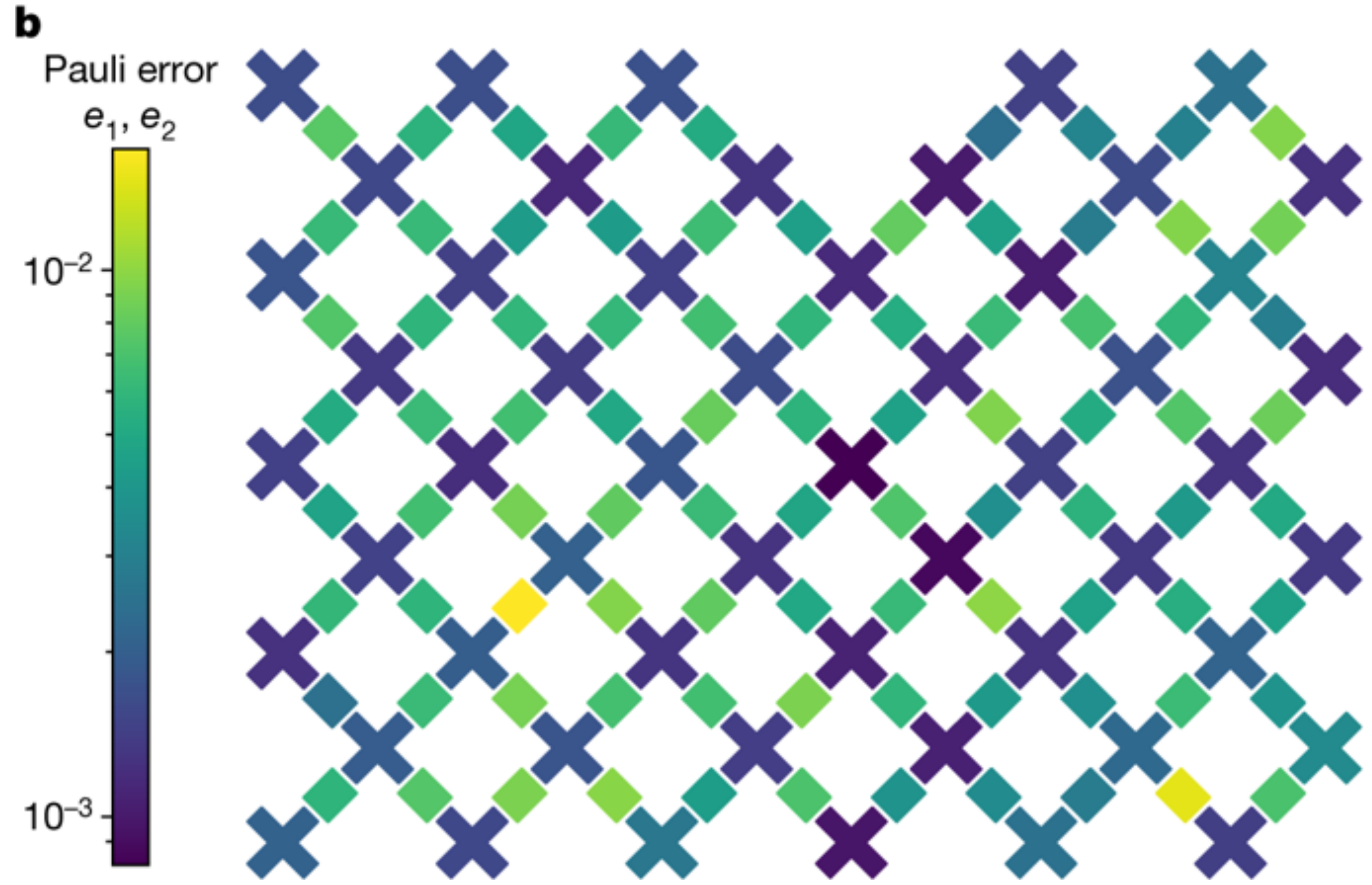


Consistently low errors

- previous best in superconducting qubits: 0.6%
- achievement: even the bad qubits are in that range
- very disciplined engineering

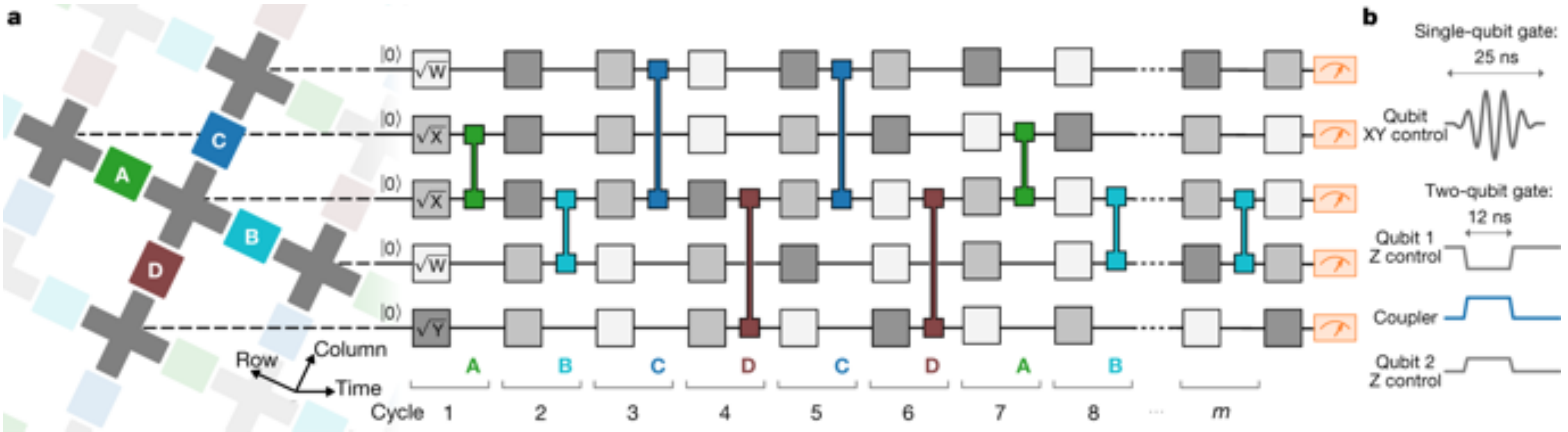


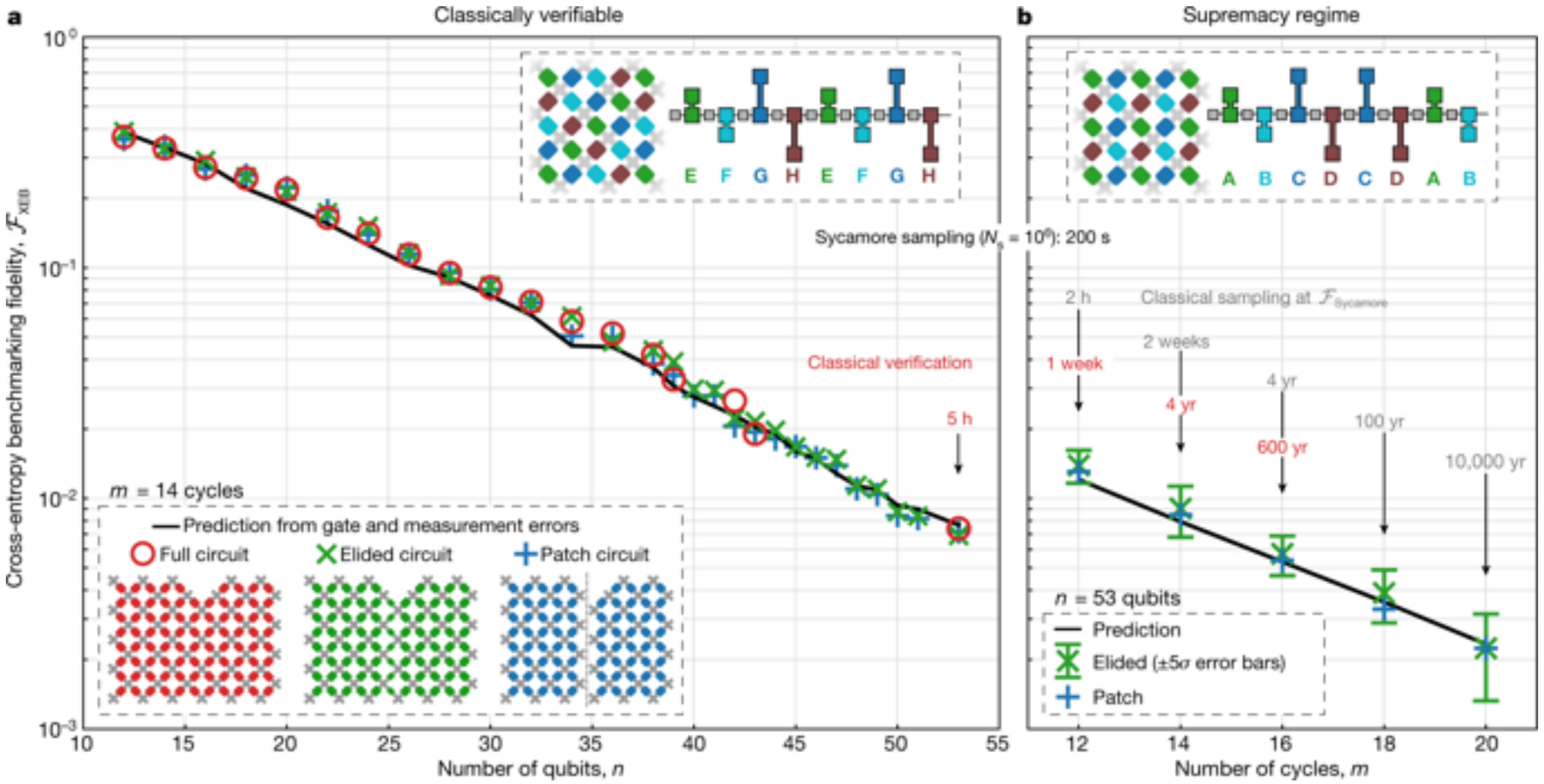
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



Algorithm

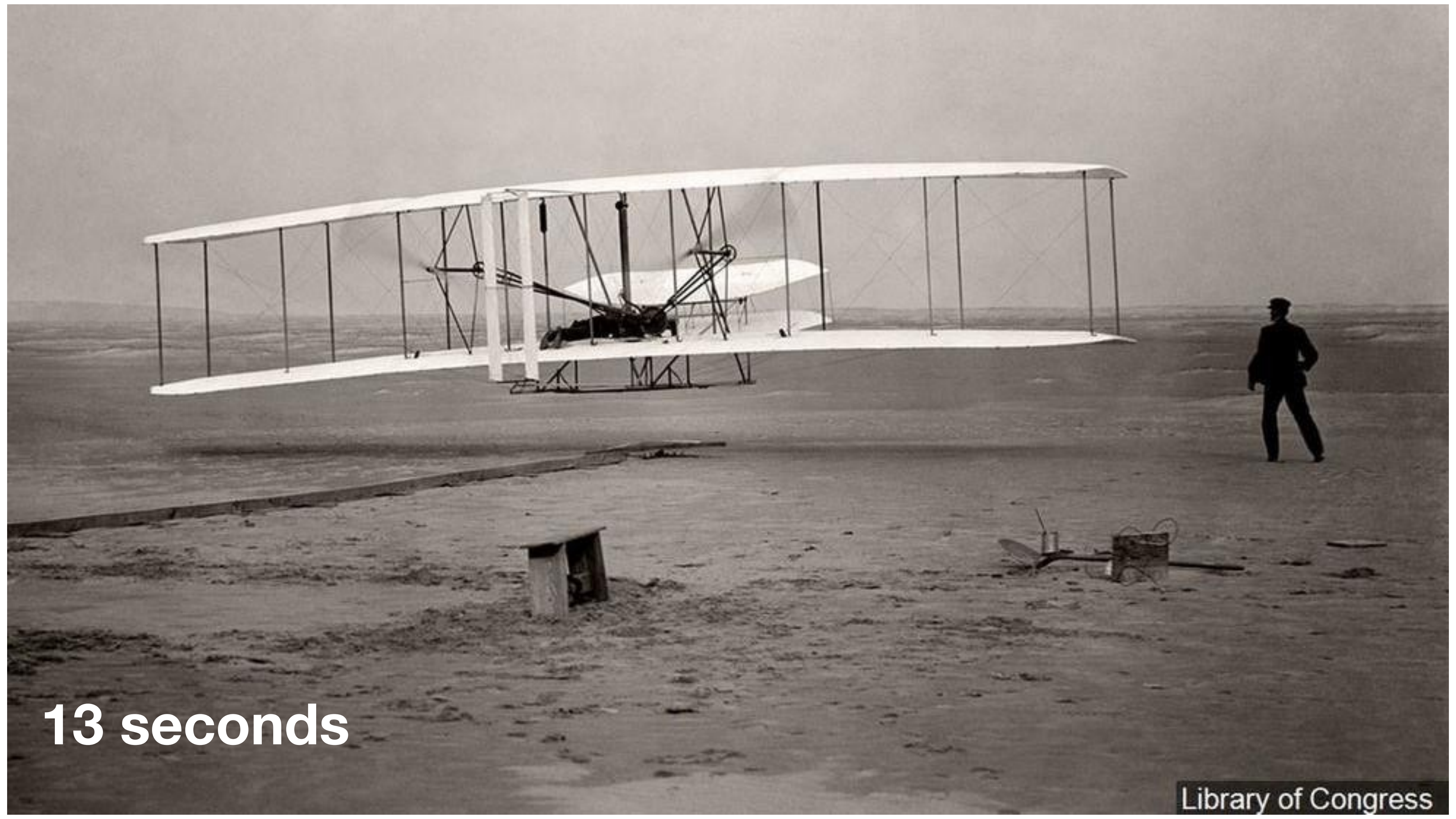
- Random compiled circuit
- simulates a distribution from quantum chaos
- sampling is classically hard
- verified by cross-entropy benchmarking

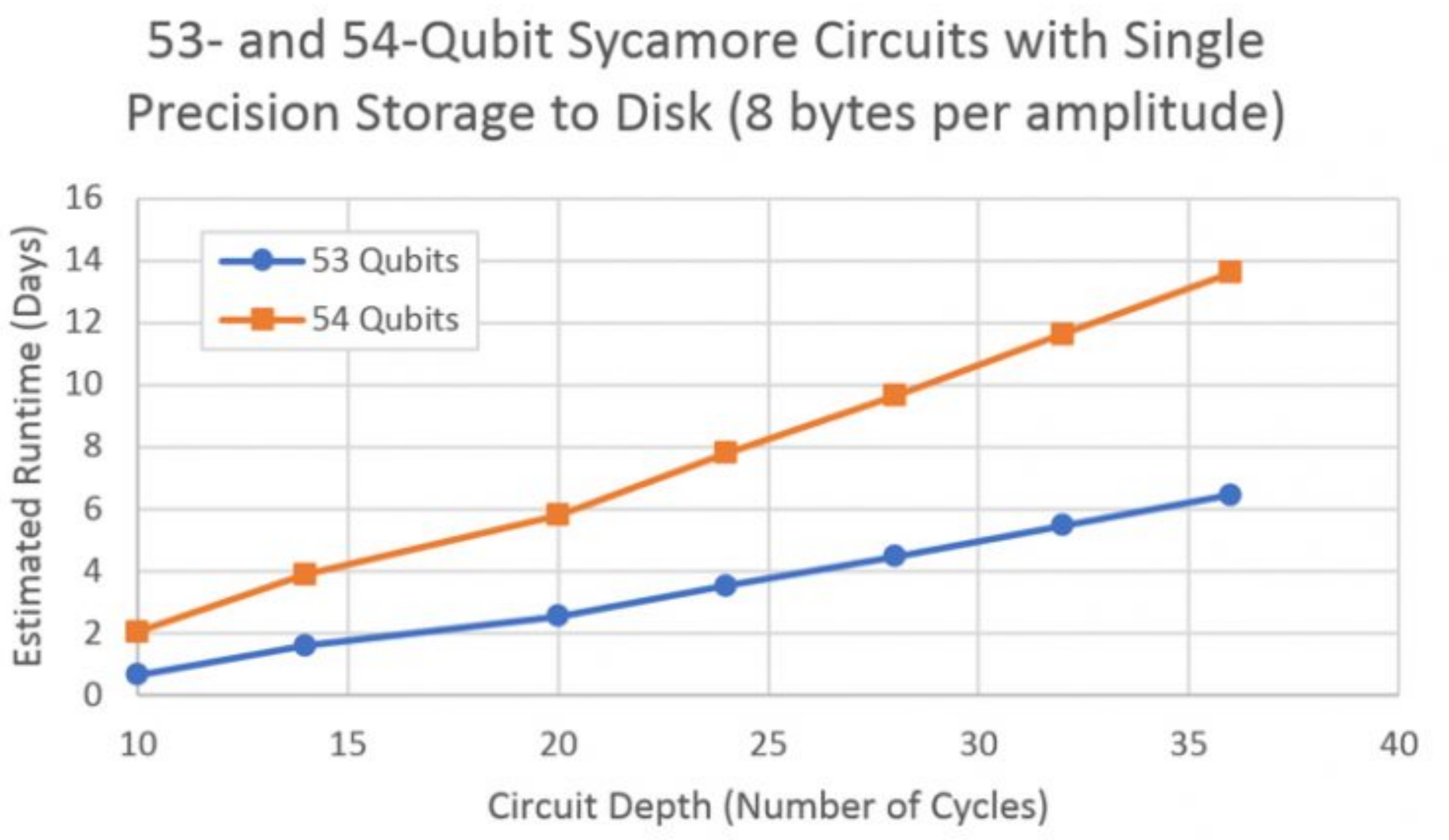


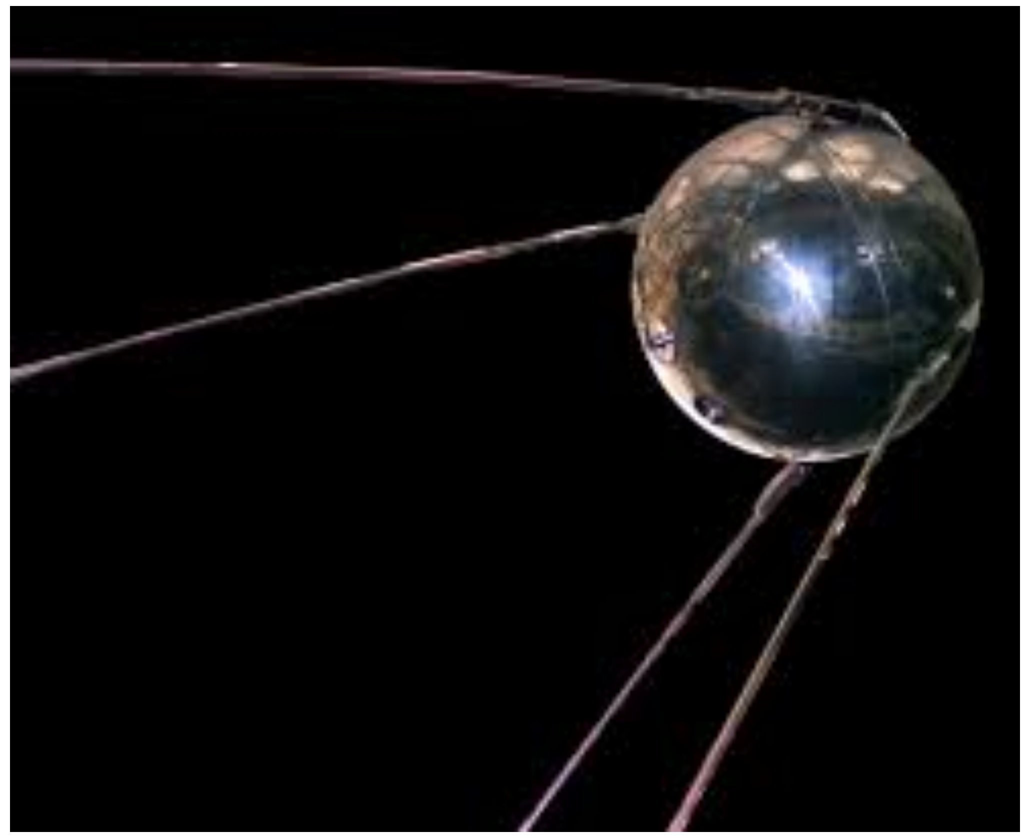


Meaning

- Amazing technology push in qubit number and fidelity
- fully programmable
- Wright Brothers flight / Sputnik moment







Impact

- Gold standard for the community
- Software will try to get away with minimal upgrades
- hardware development will be influenced
- Strong emphasis on calibration and XEB

Supplementary information for
"Quantum supremacy using a programmable superconducting processor"

Google AI Quantum and collaborators†
(Dated: October 25, 2019)

66 pages!

CONTENTS

From ~~useless~~ academic
to ~~useful~~ applied
supremacy

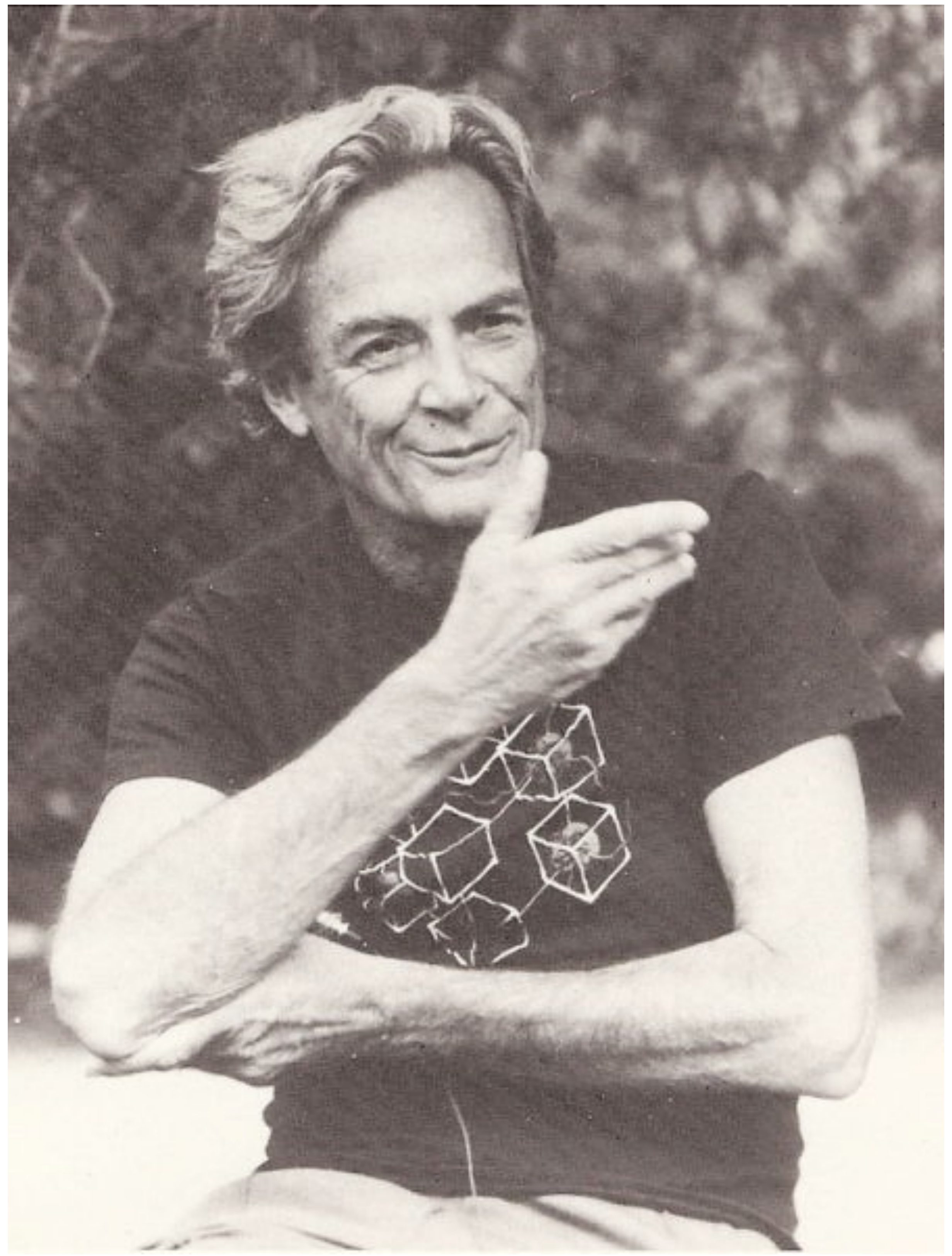
Quantum computing and simulation

“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”
Richard P. Feynman, „Simulating physics with computers“, 1981

- wave function of N two-state quantum system occupies 2^N real numbers

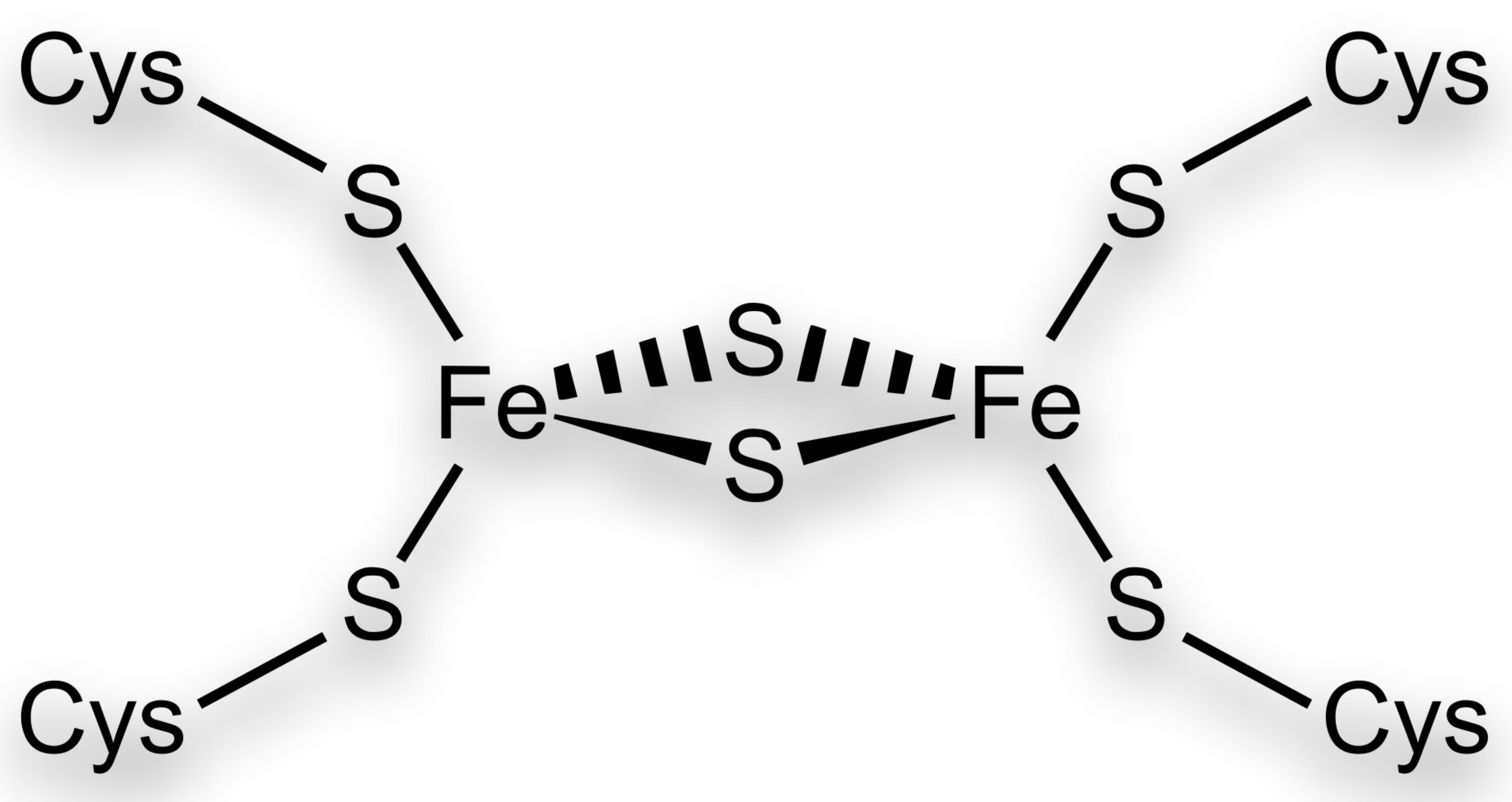
  - makes simulating quantum physics hard

  - accelerates computational problems if harnessed



Electronic structure calculation

- problem setting: Given position of nuclei in a molecule, find ground state energy
- gives bond lengths, energetics etc.
- important as a catalyst in biological nitrogen fixation
- understanding could hold the key to replace Haber-Bosch: CO_2 reduction



Ferredoxin: Fe_2S_2-cluster:
16 valence electrons, 84 total

Problem setting

Hamiltonian: Description of a quantum system based on its energetics, Hermitian matrix

Ground state: Eigenvector to lowest eigenvalue

Hamiltonian of a Molecule:

$$\hat{H}_{ESH} = -\sum_{i=1}^{N_e} \frac{1}{2}\nabla_i^2 - \sum_{i=1}^{N_e}\sum_{J=1}^{N_I} \frac{Z_J}{r_{iJ}} + \sum_{i=1}^{N_e}\sum_{j>i}^{N_e} \frac{1}{r_{ij}} + \hat{h}_{nuc}.$$

Broken down to orbitals:

$$\hat{H} = \sum_{PQ} h_{PQ}\hat{a}_P^\dagger \hat{a}_Q + \frac{1}{2}\sum_{PQRS} g_{PQRS}\hat{a}_P^\dagger \hat{a}_Q^\dagger \hat{a}_R \hat{a}_S + \hat{h}_{nuc}.$$

Hamiltonian of a quantum computer:

$$\hat{H} = \hat{H}_0 + \sum_i F_i(t)\hat{H}_i \qquad \hat{H} = \sum_i \hat{H}_i(t) + \sum_{i<j} \hat{H}_{ij}(t)$$

Drift:
Defines qubit

Control:
Used for programming

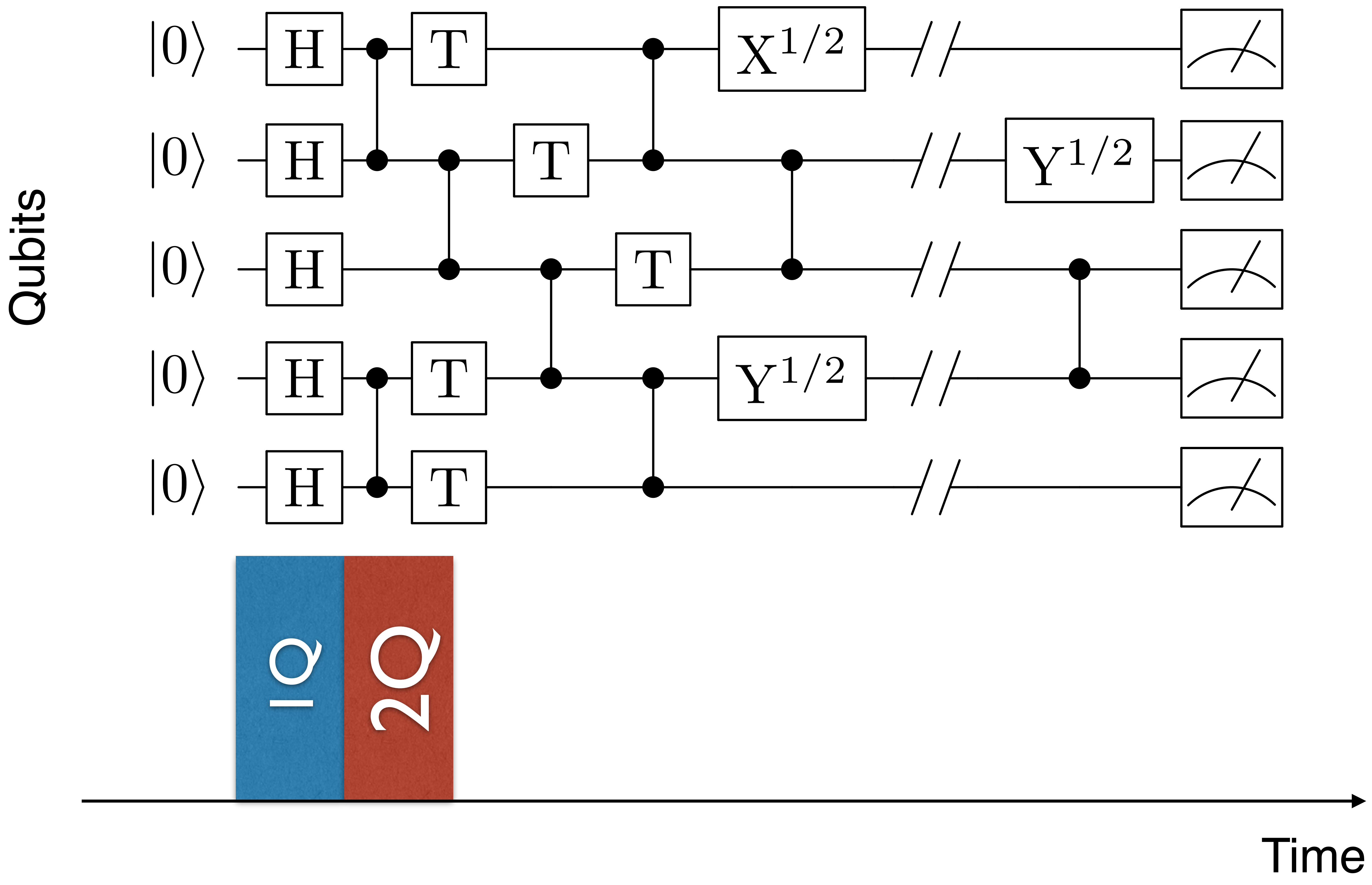
Single qubit

Interactions: Used
for two-qubit gates

Implementation of gates

$$\hat{H} = \hat{H}_0 + \sum_i F_i(t)\hat{H}_i$$

$$\hat{H} = \sum_i \hat{H}_i(t) + \sum_{i<j} \hat{H}_{ij}(t)$$



$$\hat{U}_{\text{gate}} = \exp(-i\hat{H}t_g)$$

Switch energies with precise timing to implement gates

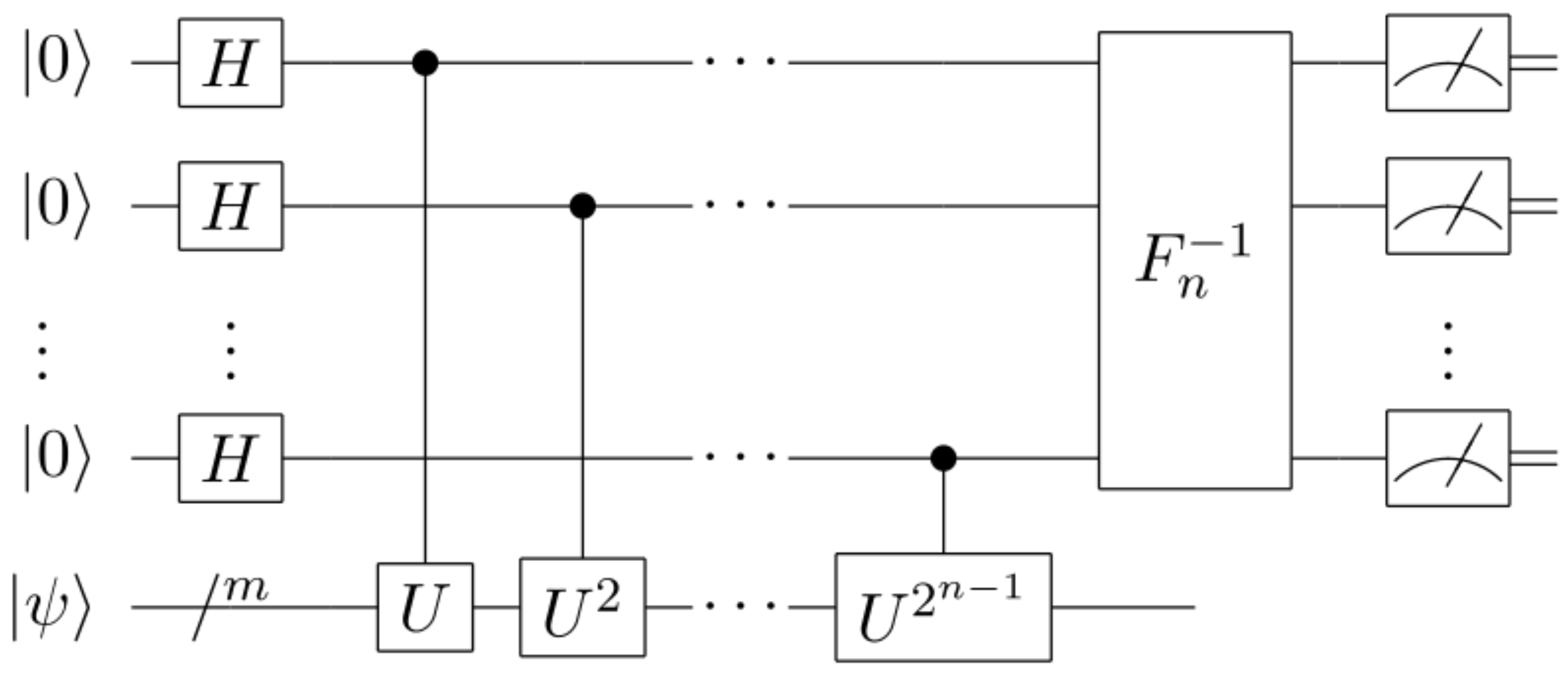
Trotter-based simulation

$$\hat{H} = \sum_{PQ} h_{PQ}\hat{a}^\dagger_P \hat{a}_Q + \frac{1}{2}\sum_{PQRS} g_{PQRS}\hat{a}^\dagger_P\hat{a}^\dagger_Q\hat{a}_R\hat{a}_S + \hat{h}_{nuc}.$$

Break down time evolution by Trotter decomposition

$$e^{i\hat{H}\tau} \approx \left[\prod_X e^{i\hat{h}_X \frac{\tau}{M}}\right]^M$$

Find a quantum algorithm for the Trotter step (multi-qubit!)



Slowest evolution: Ground state!

- quantum advantage: Natural Fourier transform
- quantum advantage: natural gate sequence for physical interactions
- but: leads to long algorithms

Takes a long time, gets the ground state

Reducing the size of the quantum operation

- let the (cheap) classical computer do what it is best at

- enhance its performance with the (expensive) quantum computer

Variational quantum eigensolver

Fiducial state

$|\Phi_0\rangle = |001111\rangle = |HF\rangle$

→ Create candidate state w/ quantum circuit

$|\psi\rangle = \hat{U}(\theta_1 \dots \theta_N)|\Phi_0\rangle$

→ Measure manybody observables

$E(\theta_1 \dots \theta_N) = \left\langle \psi \middle| \hat{H} \middle| \psi \right\rangle$

↓ Classical minimization algorithm

← Propose new $\theta'_1 \dots \theta'_N$

↑ (back to Create candidate state)

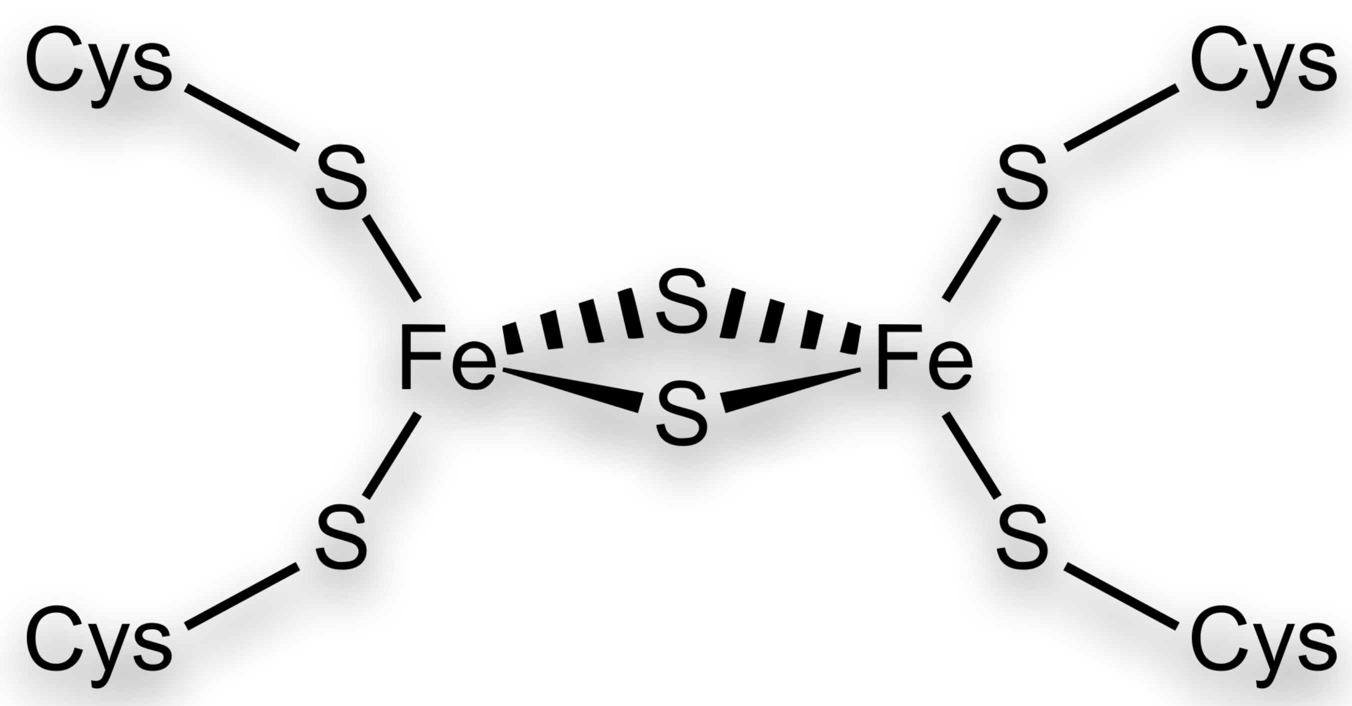
- relatively short quantum algorithm: NISQ-friendly
- quantum advantage in memory
- JW/BK complexity in measurement, not algorithm

Still: N orbitals in O(poly(N)) qubits

Can we build an effective VQE for the Hubbard model?

From molecules to materials!

Moonshot of quantum computer chemistry



YBCO

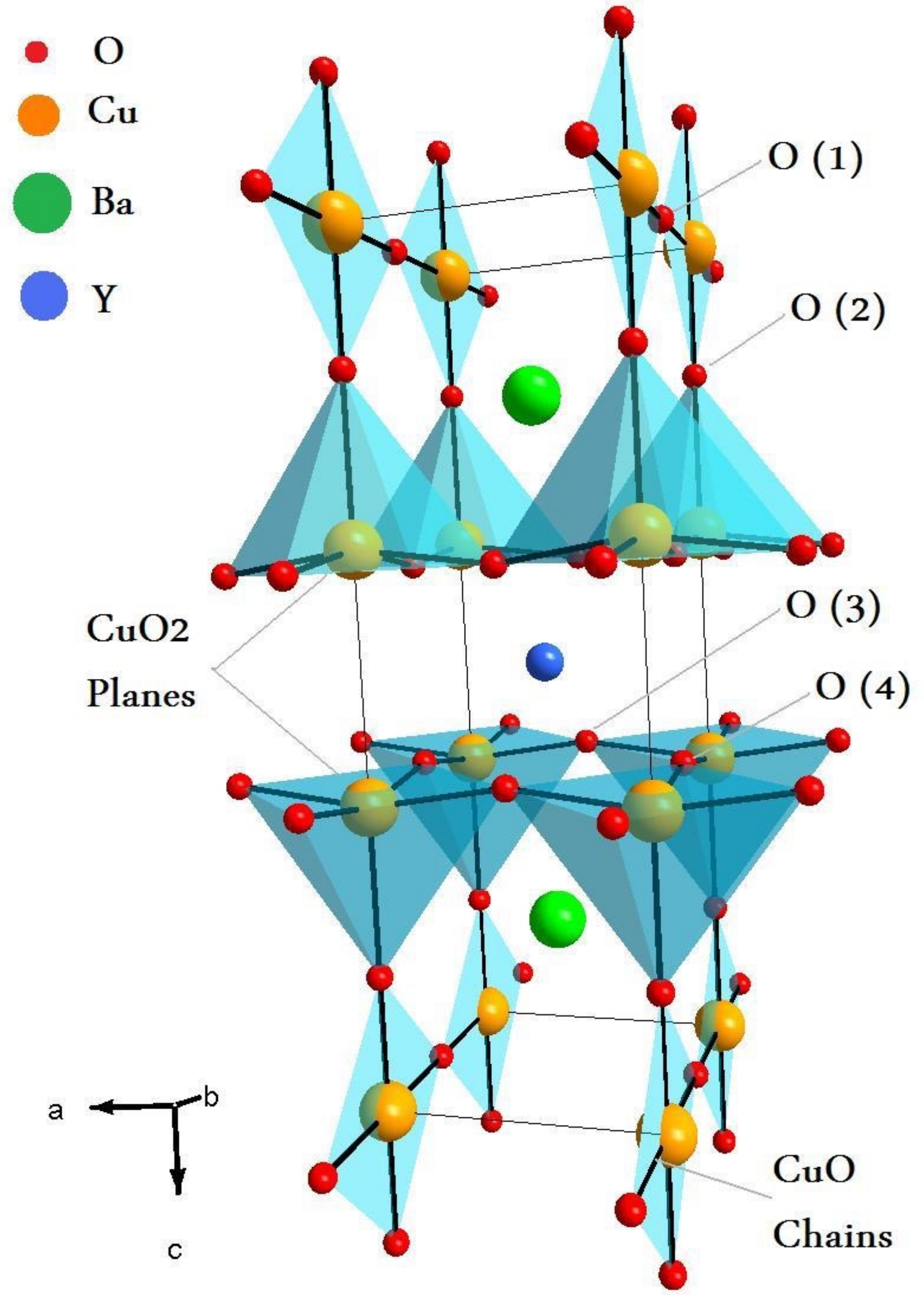
More is different

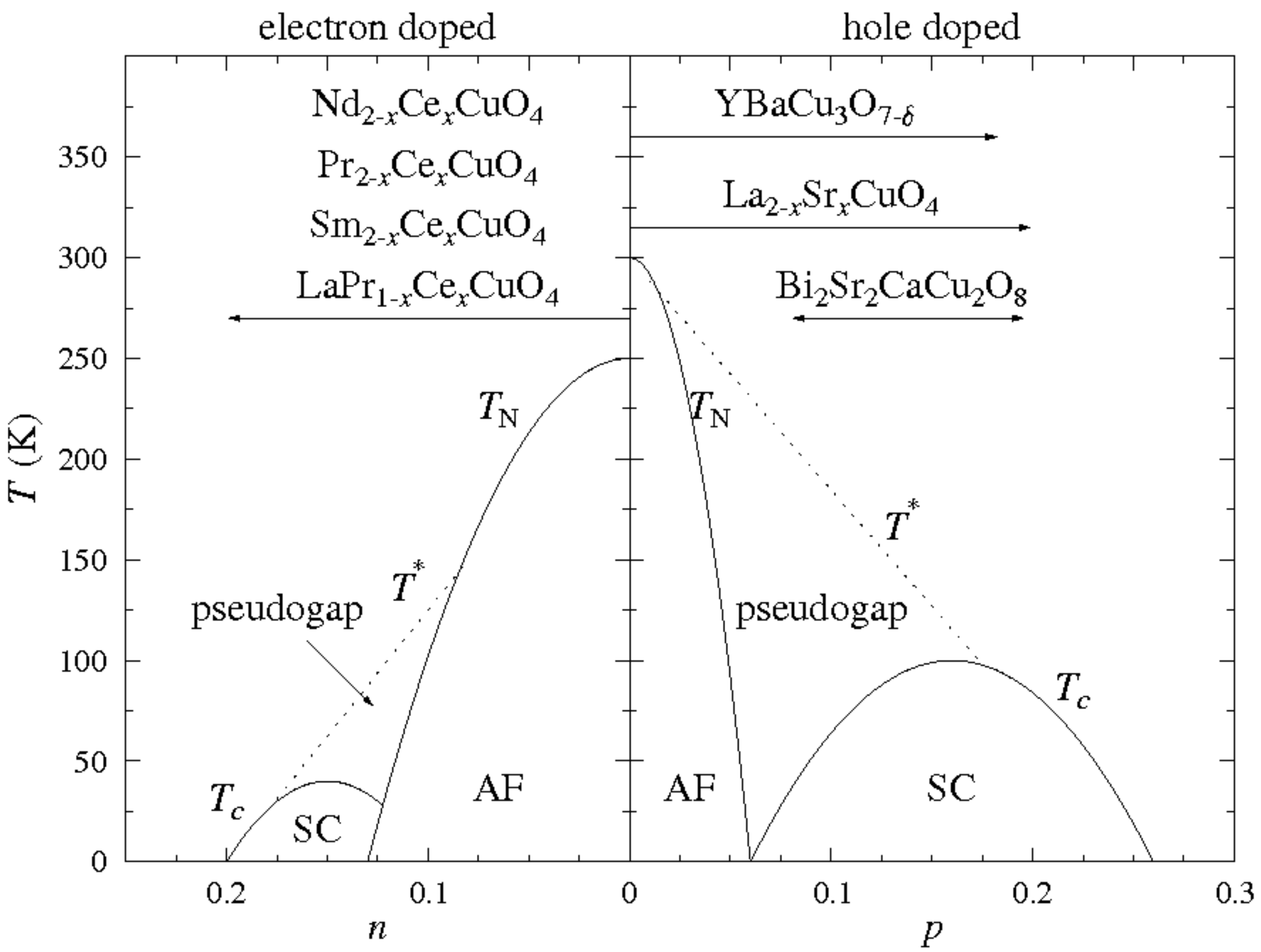
Do we need poly(N_A) qubits?

High-Tc and Hubbard model

Low (<1 eV) physics of electrons on lattices

$$H = -t \sum_{\langle i,j\rangle,\sigma} (c^\dagger_{i,\sigma} c_{j,\sigma} + c^\dagger_{j,\sigma} c_{i,\sigma}) + U \sum_{i=1}^{N} n_{i\uparrow} n_{i\downarrow},$$





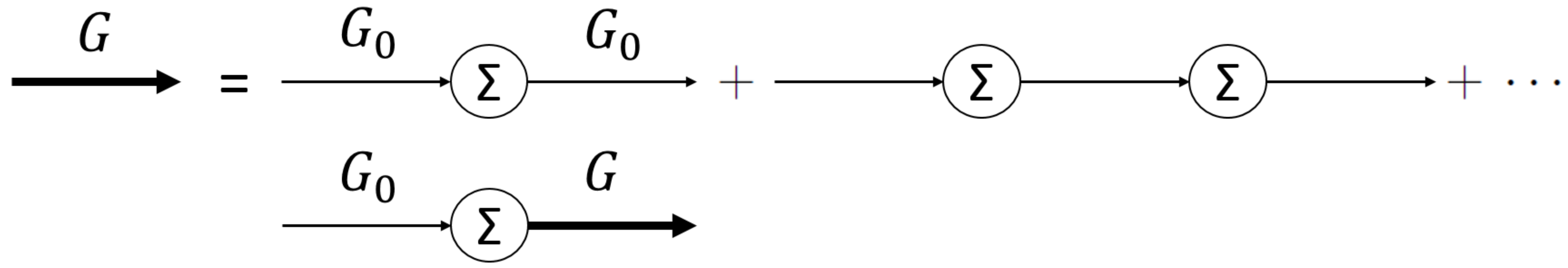
- non-integrable
- QMC: Fermionic sign problem
- reproduces d-wave superconductivity

Variational eigensolver for Hubbard

Describe physical properties through the time-ordered two-point Green's function

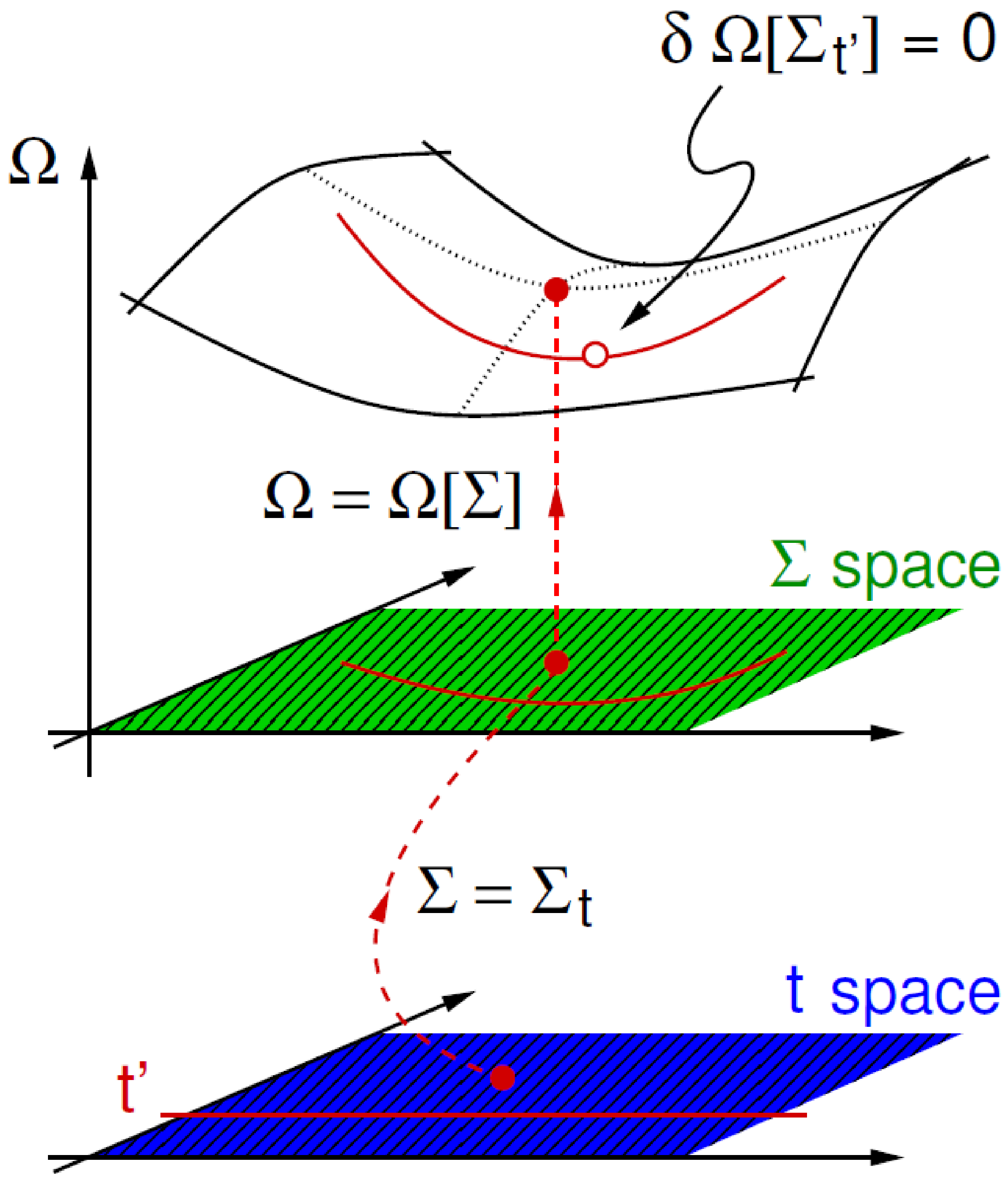
$$G^{(j)}\left(\vec{r},t|\vec{r}',t'\right) = -i\left\langle \mathbf{T}^{(j)}\Psi(\vec{r},t)\Psi^{\dagger}(\vec{r}',t')\right\rangle$$

Self-energy: Effect of the manybody system on the single propag
particle:
Dyson equation



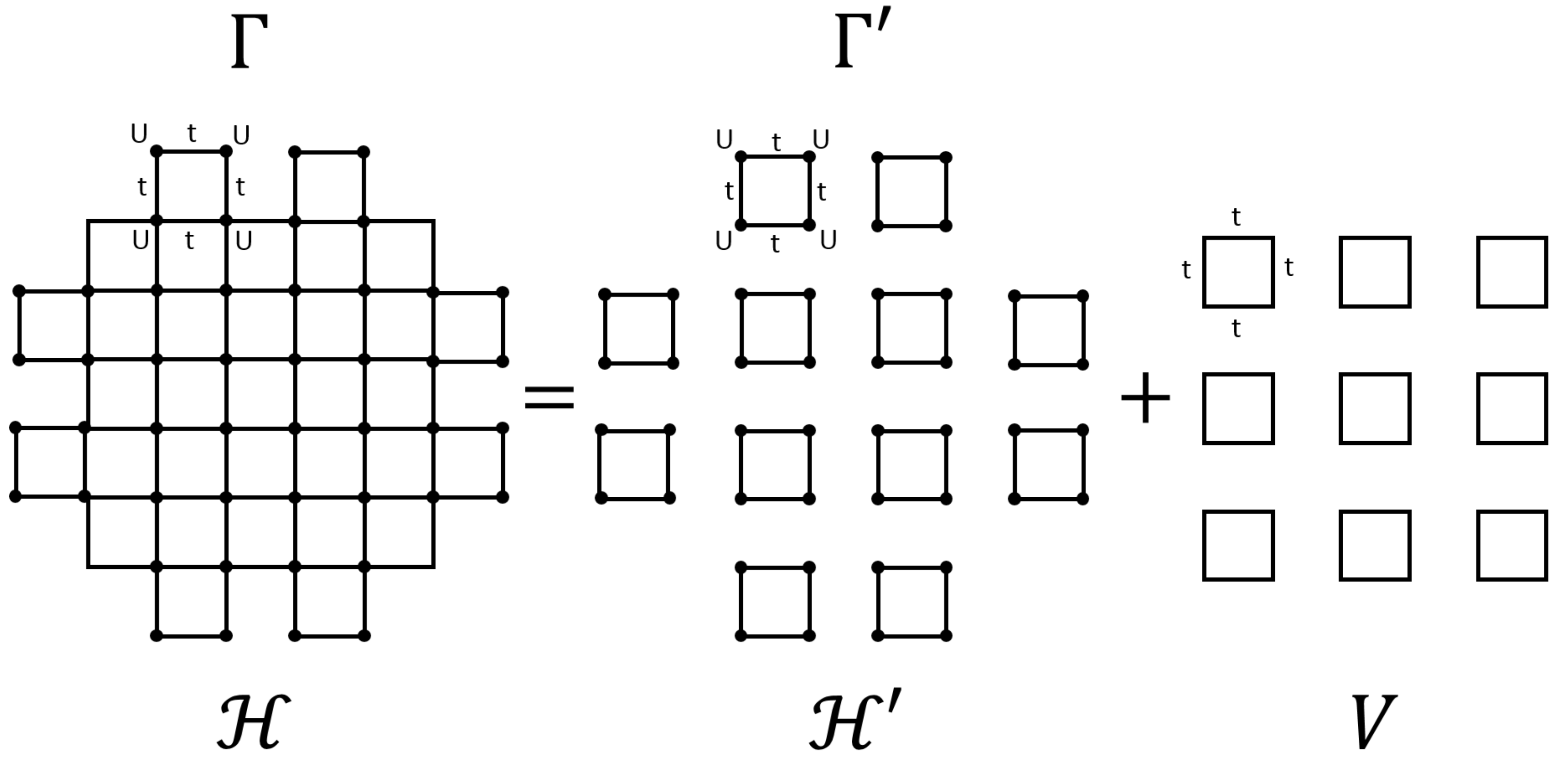
Variational principle

$$\frac{\delta\Omega_t\left[\mathbf{\Sigma}\right]}{\delta\Sigma} = \left(\mathbf{G}_{\mathbf{0t}}^{-1} - \Sigma\right)^{-1} - \mathbf{G} = 0.$$



Variational cluster

Exact cluster Green's function $\mathbf{G}'^{-1}(\omega) = \omega - \mathbf{t}' - \Sigma'(\omega)$



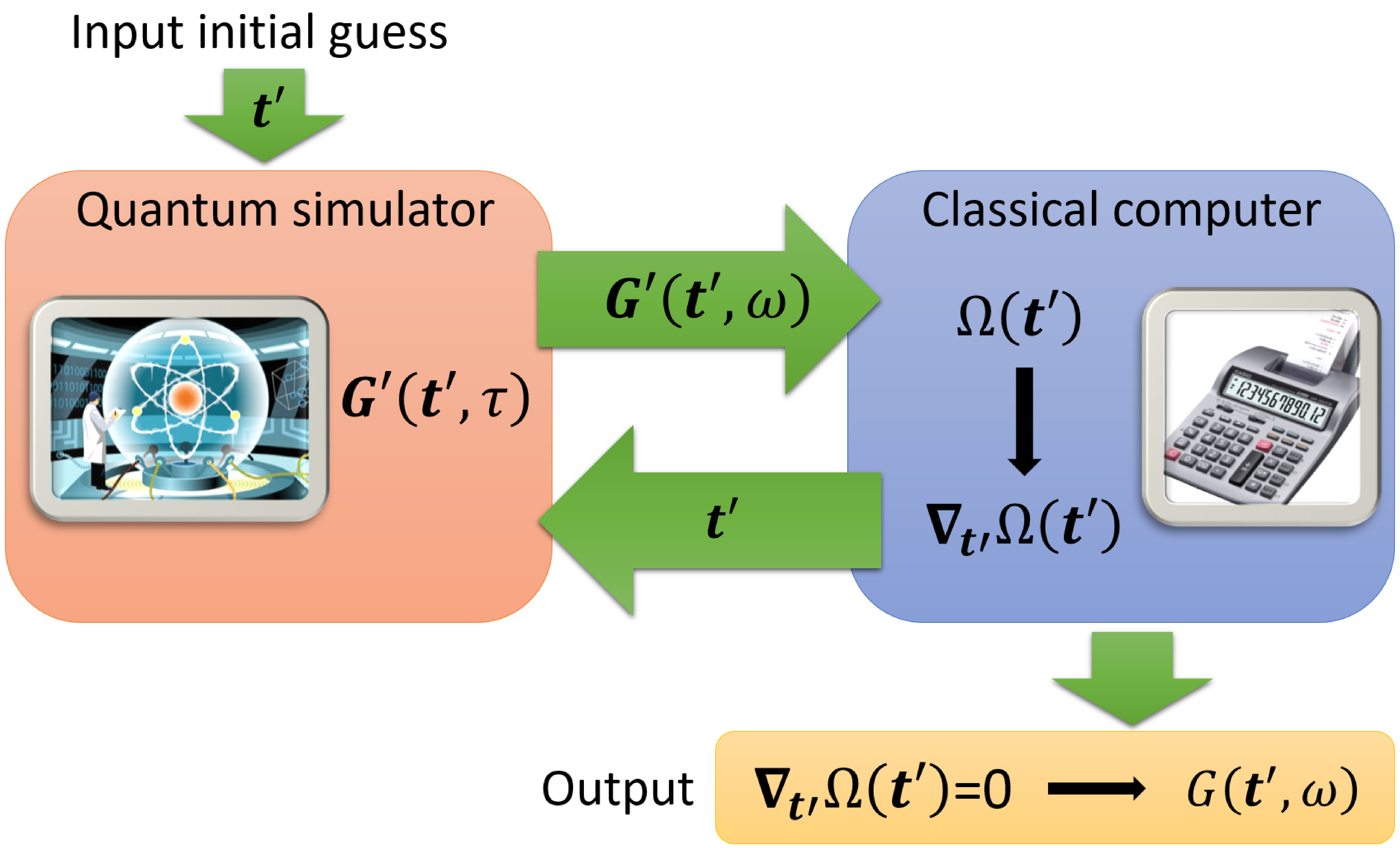
- split lattice into exact clusters
- couple clusters perturbatively: Closed form

$$\mathbf{G}[\mathbf{\Sigma}'] = \mathbf{G}_{\text{cpt}} = \left(\mathbf{G}'^{-1} - \mathbf{V}\right)^{-1}.$$

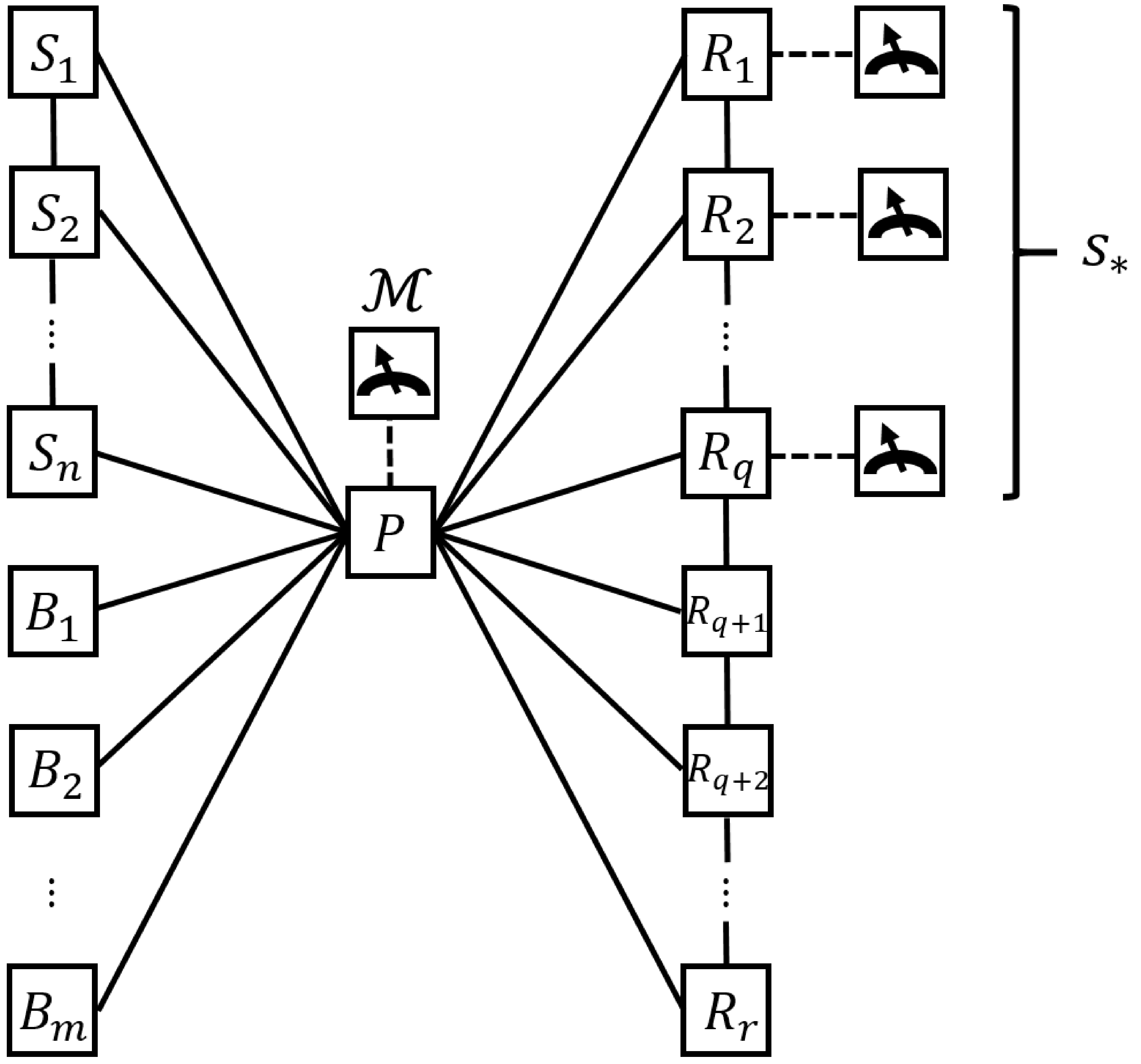
Classical variational calculus for $\Omega_t[\mathbf{\Sigma}'] = \Omega' - \operatorname{Tr}\ln[\mathbf{1} - \mathbf{V}\mathbf{G}'].$

Potthoff, Senechal …

Hybrid algorithm



Architecture and performance



Dimension(s)	Size	Orbitals (singlets) [n]	Dim. of Hilbert space [2^n]	Qubits required [$n+1$]	Measured correl. functions [$< 4n^2$]	$c-$SQGs to tune [$7n$]	$c-\pm$iSWAPs to tune [$2n-2$]	Gates / Trotter-Suzuki step (hopping terms)
1D	2	4	16	5	64	28	6	24
1D	3	6	64	7	144	42	10	48
1D	4	8	256	9	256	56	14	72
2D	2×2	8	256	9	256	56	14	96
2D	3×3	18	262,144	19	1,296	126	34	336
2D	4×4	32	4,294,967,296	33	4,096	224	62	768
3D	$2 \times 2 \times 2$	16	65,536	17	1,024	112	30	416
3D	$3 \times 3 \times 3$	54	1.8×10^{16}	55	11,664	378	106	2,736
3D	$4 \times 4 \times 4$	128	3.4×10^{38}	129	65,536	896	254	10,368

Quantum advantage

P.-L. Dallaire-Demers and FKW, PRA 2017

Limitations and classification

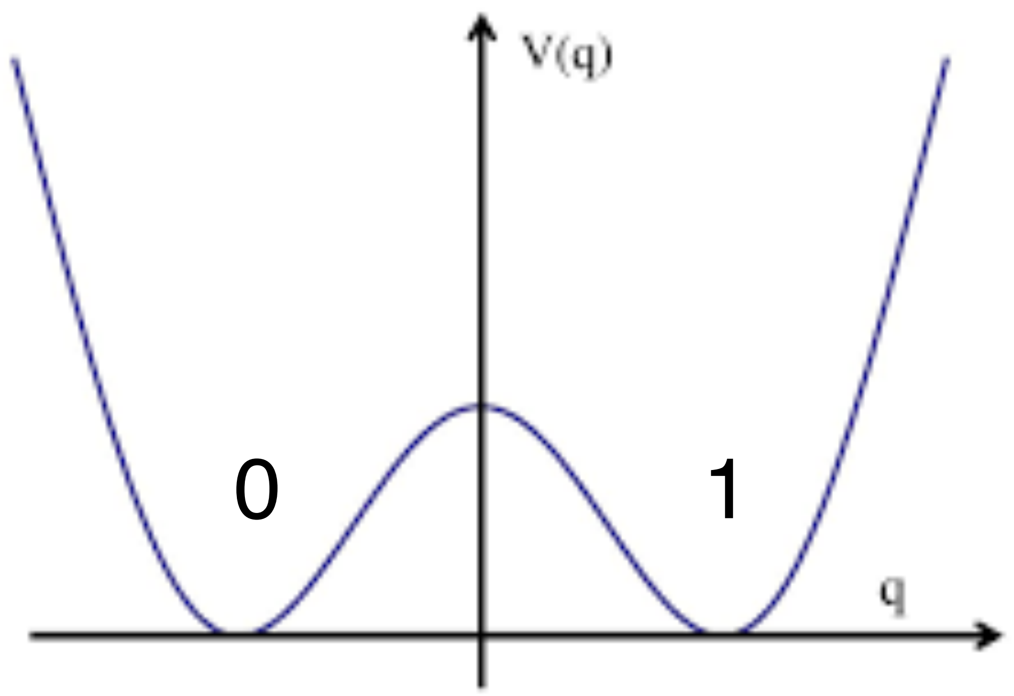
- Limited length of algorithms: $(\text{Error rate})^{-1}$
- Builds on algorithms that are classically limited by memory
- Probably restricted to simulation of quantum systems

How do we run longer, time-limited algorithms?

Fault-tolerant quantum computing

Classical vs. quantum errors

Classical stability

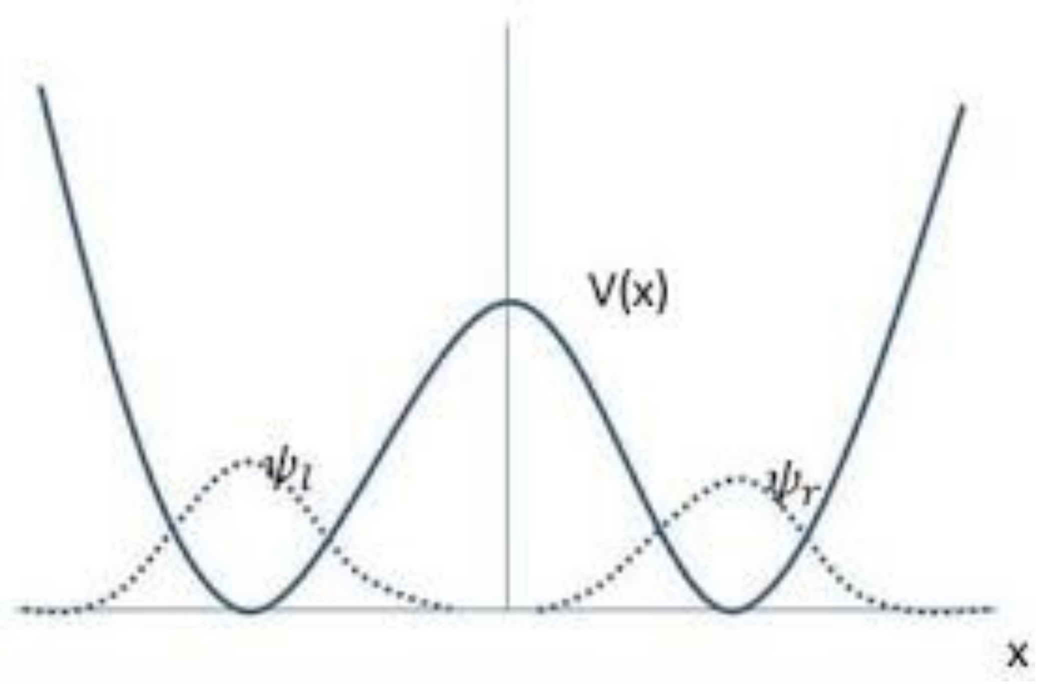


Energy barrier:

Error rate

$$\propto \exp - \frac{\Delta U}{k_B T}$$

Quantum:



$\cos\theta|0\rangle$ $\sin\theta e^{i\phi}|1\rangle$

Bit-flip+phase errors
amplitudes matter

How do we deal with analog errors?

Error correction: Classical and quantum

- similar to error correction in communication
- redundantly encode data
- compare bits to identify where error happened
- relies on errors being uncorrelated
- more redundancy = more protection

Quantum measurement

Measurement affects the quantum state

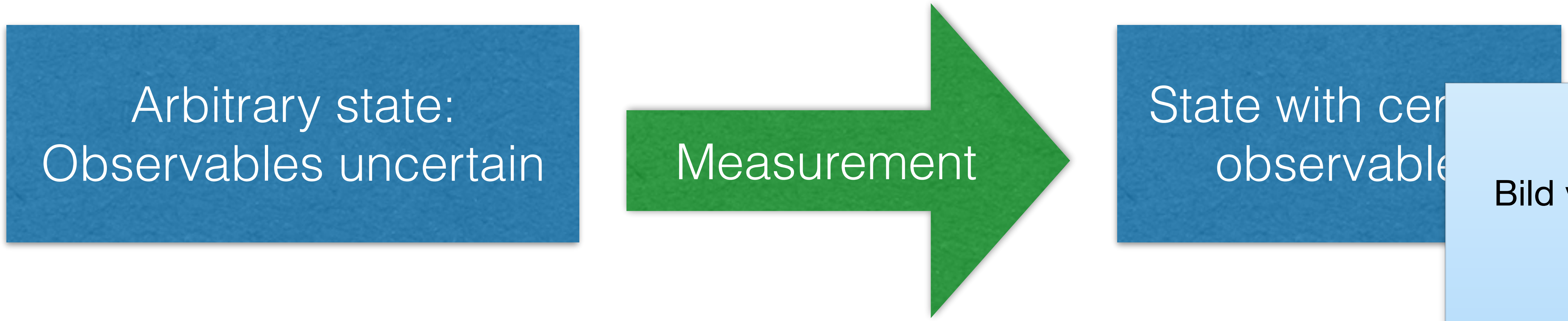


Bild von Stern-Gerlach

- Measuring data qubits destroys supe
quantum advantage: **don’t**
- Measurement of error syndrome realizes error probability: **do**

Digitization of errors

Projective quantum measurement: No error detected -> error eliminated

$\hat{U}_{\text{error}}|00\rangle$ Miscalibration of Q2 $|\psi\rangle = \cos\theta|00\rangle + \sin\theta|01\rangle$

Measure:

$$ZZ = +1 : \quad p_1 = \cos^2\theta, \quad |\psi\rangle_1 = |00\rangle$$

$$ZZ = -1 : \quad p_{-1} = \sin^2\theta \quad |\psi\rangle_{-1} = X_2|01\rangle$$

In practice:

- Syndrome measurement digitizes error
- Digital errors are tracked and matched but only corrected in the output
- Topological protection: Only errors that change the genus / connect surfaces remain uncorrected

Syndrome extraction

Basic idea: Redundant encoding + rare errors

Syndrome extraction:

Measure error without learning state

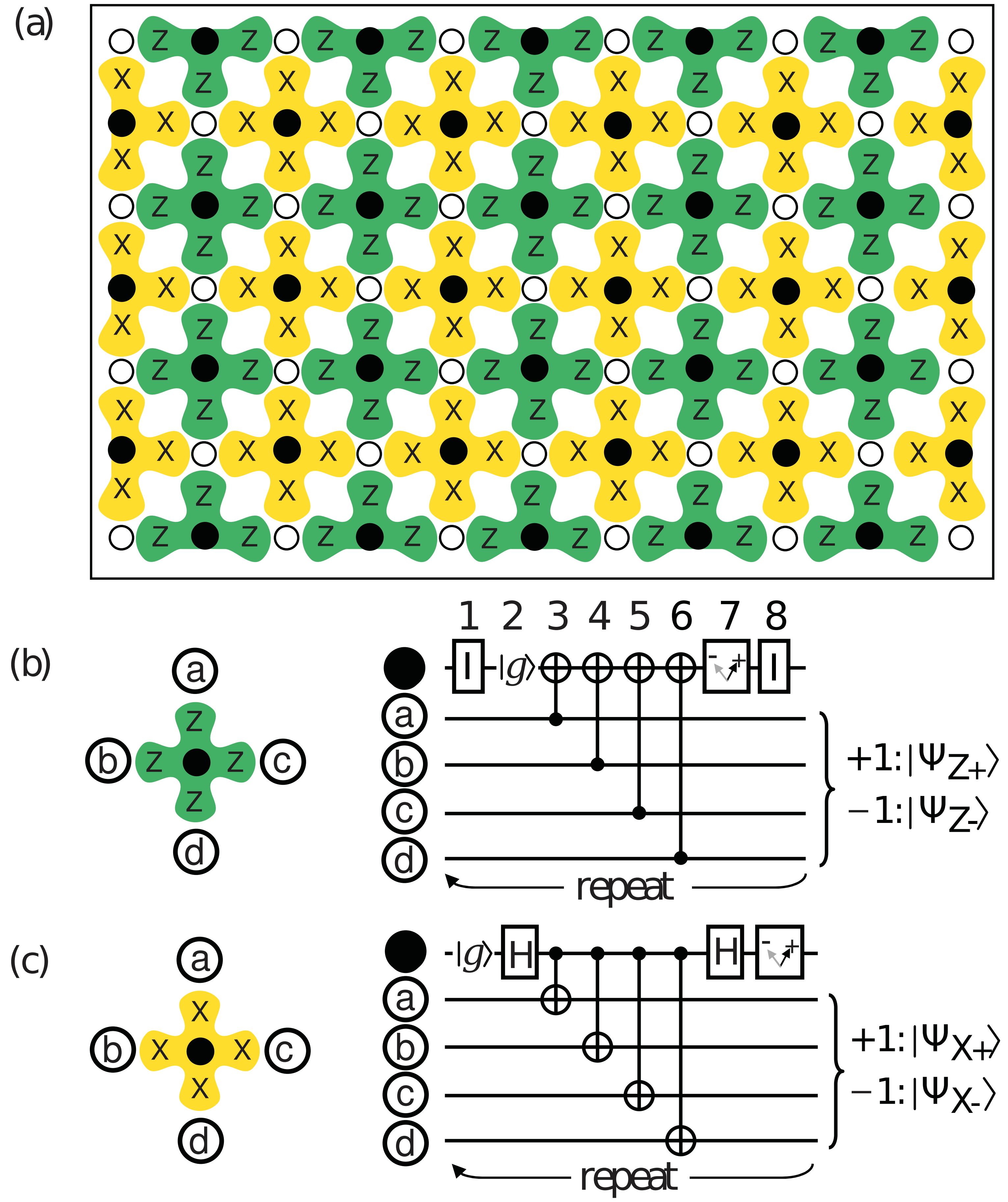
$$Z_1 \otimes Z_2 \otimes Z_3 \otimes Z_4$$

Two degenerate eigenvalues +/- 1
Reveals number of flips

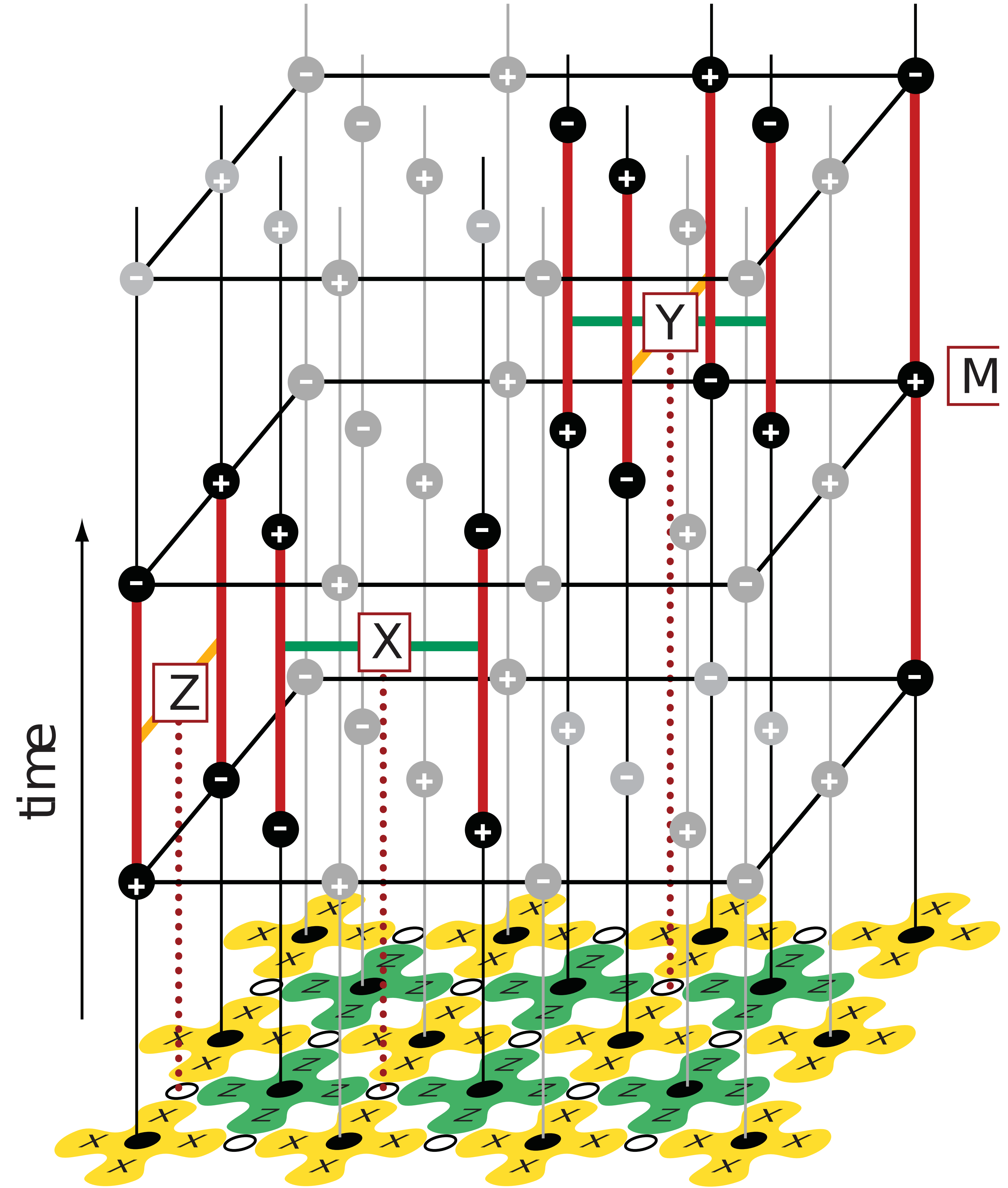
$$X_1 \otimes X_2 \otimes X_3 \otimes X_4$$

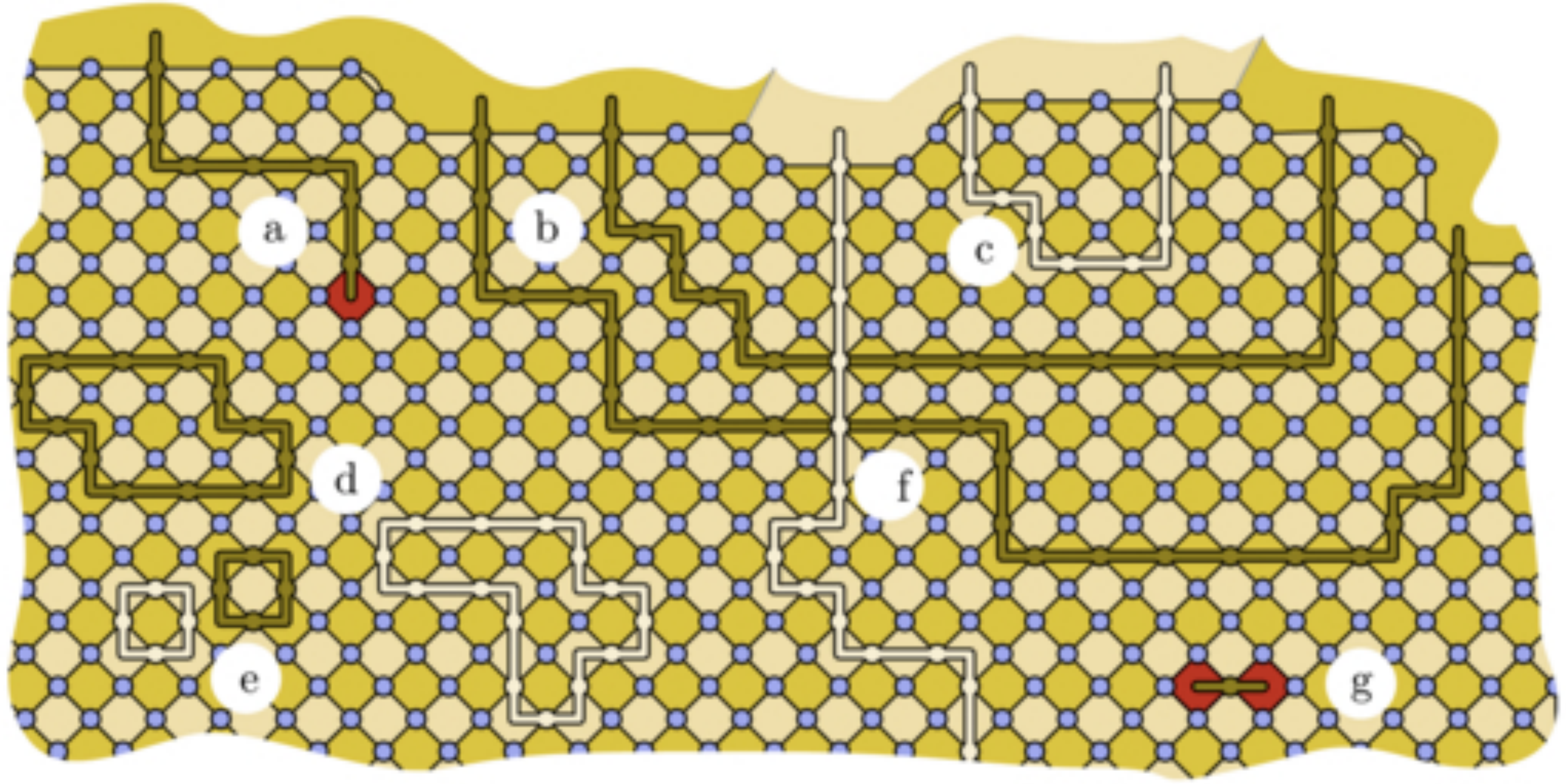
Commute, simultaneous measurement
Reveals number of phase flips

Surface Code: Raussendorf, Fowler …



Error tracking

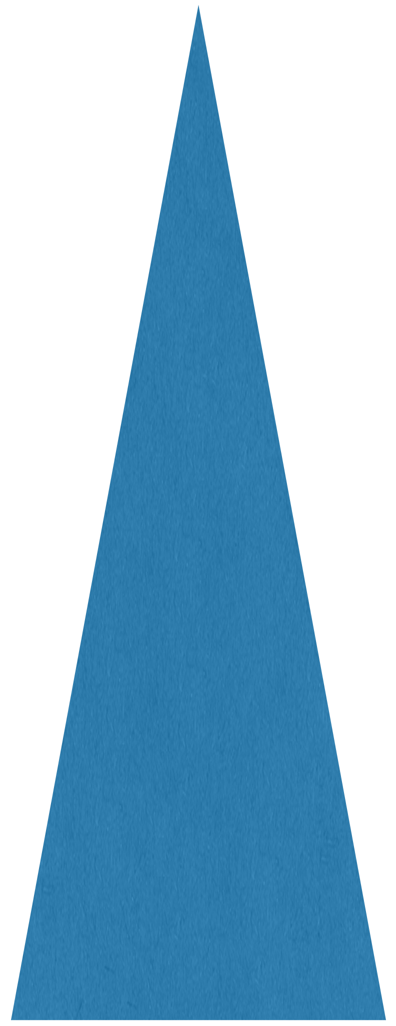


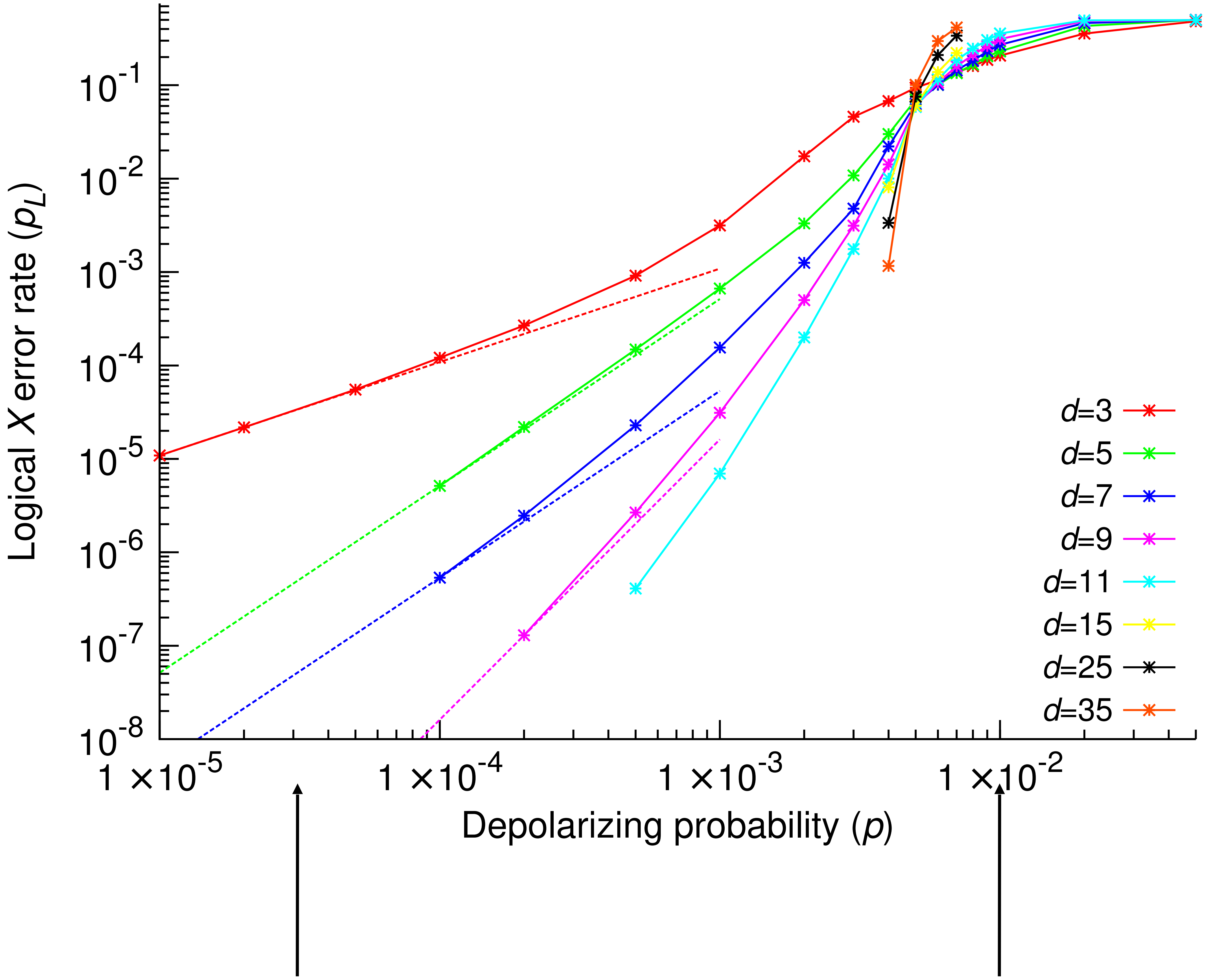


Long strings connecting boundaries go undetected:
Unlikely if errors are uncorrelated

Threshold-Theorem

More Qubit error
+ longer Algorithm
=more Overhead





Useful

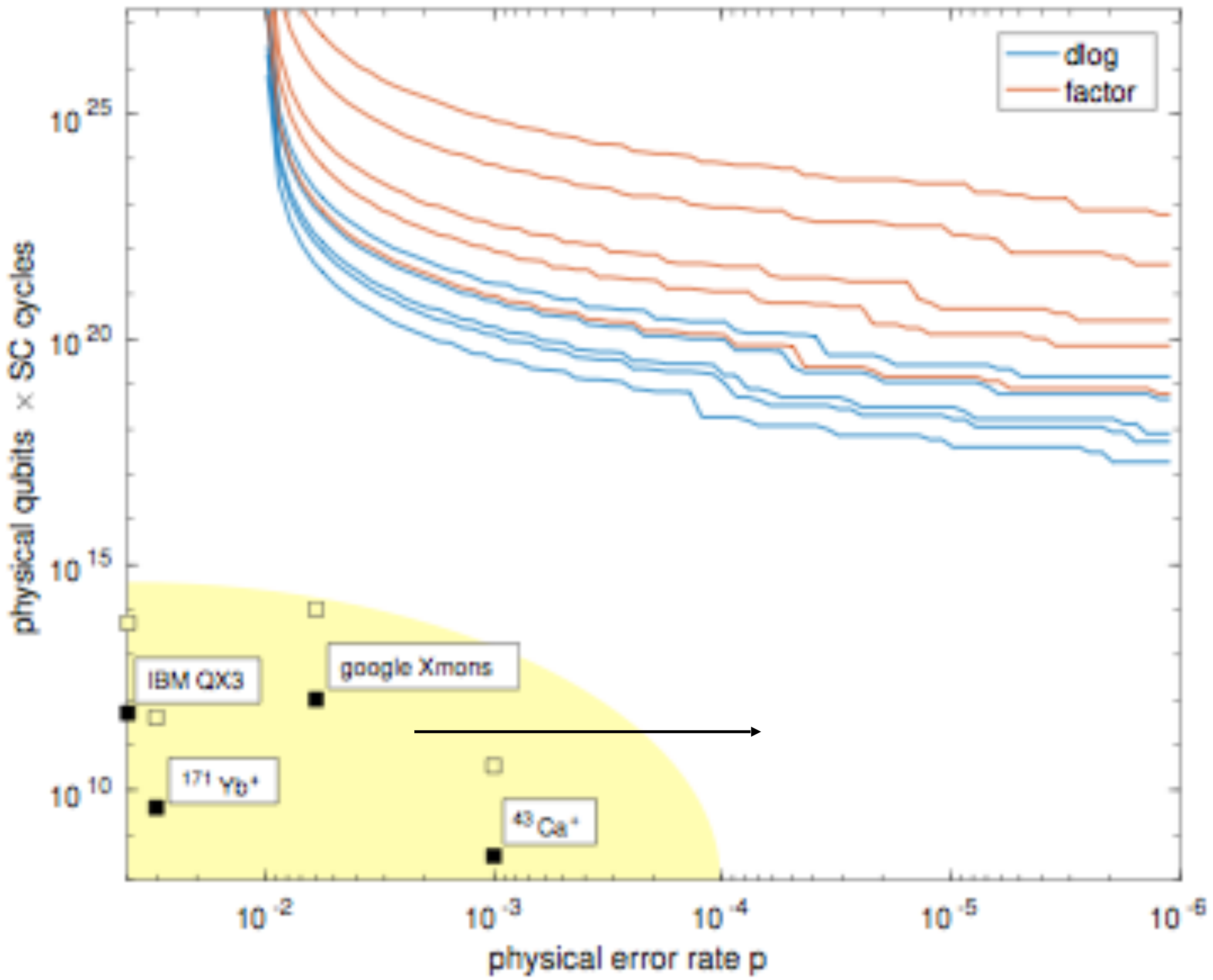
Harmful

Poly(n)*p^n

overhead

uncorrelated errors

You are here …



- Current goal: Consistently $p=10^{-4}$
- Technological challenge: Scale-up

N.B: Ion traps are cleaner than superconducting chips but have a slower clock
Filled: 1 day, Open: 100 days

Our main project

High level summary

- Reach a size scale of 50 - 100 qubits (i.e., outperform classical supercomputers)
- use Josephson junctions
- build a sustainable central quantum computing laboratory
- Reach fidelities that allow for meaningful molecular simulation
- Build a sustainable technological ecosystem in Europe
- Interact with stakeholders
- Interact with national initatives
- Engage in the flagship

OpenSuperQ

Beneficiaries

Universities

ETH zürich

CHALMERS UNIVERSITY OF TECHNOLOGY

UNIVERSITÄT DES SAARLANDES

University of the Basque Country

RTOs

JÜLICH Forschungszentrum

VTT

Companies

Zurich Instruments

LOW NOISE FACTORY www.lownoisefactory.com

BLUEFORS

EURICE EUROPEAN RESEARCH AND PROJECT OFFICE GMBH

Geography: Germany (3), Sweden, Finland, Switzerland (2), Spain (1)

Partner

UNIVERSITÄT DES SAARLANDES

Coordination and Management
Control, Benchmarking,
Firmware
Applications and theory

ETH zürich

Chip fabrication
Measurement
Cryogenics and wiring

CHALMERS UNIVERSITY OF TECHNOLOGY

Chip fabrication
Control and Modeling
Applications

University of the Basque Country

Applications

JÜLICH Forschungszentrum

Modeling
High-level software and simulation
Hosting

VTT

Readout and amplification
Packaging
3D-Integration

BLUEFORS

Cryogenics
Cryo wiring

Zurich Instruments

Electronics
Readout and control

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Microwave technoolgy

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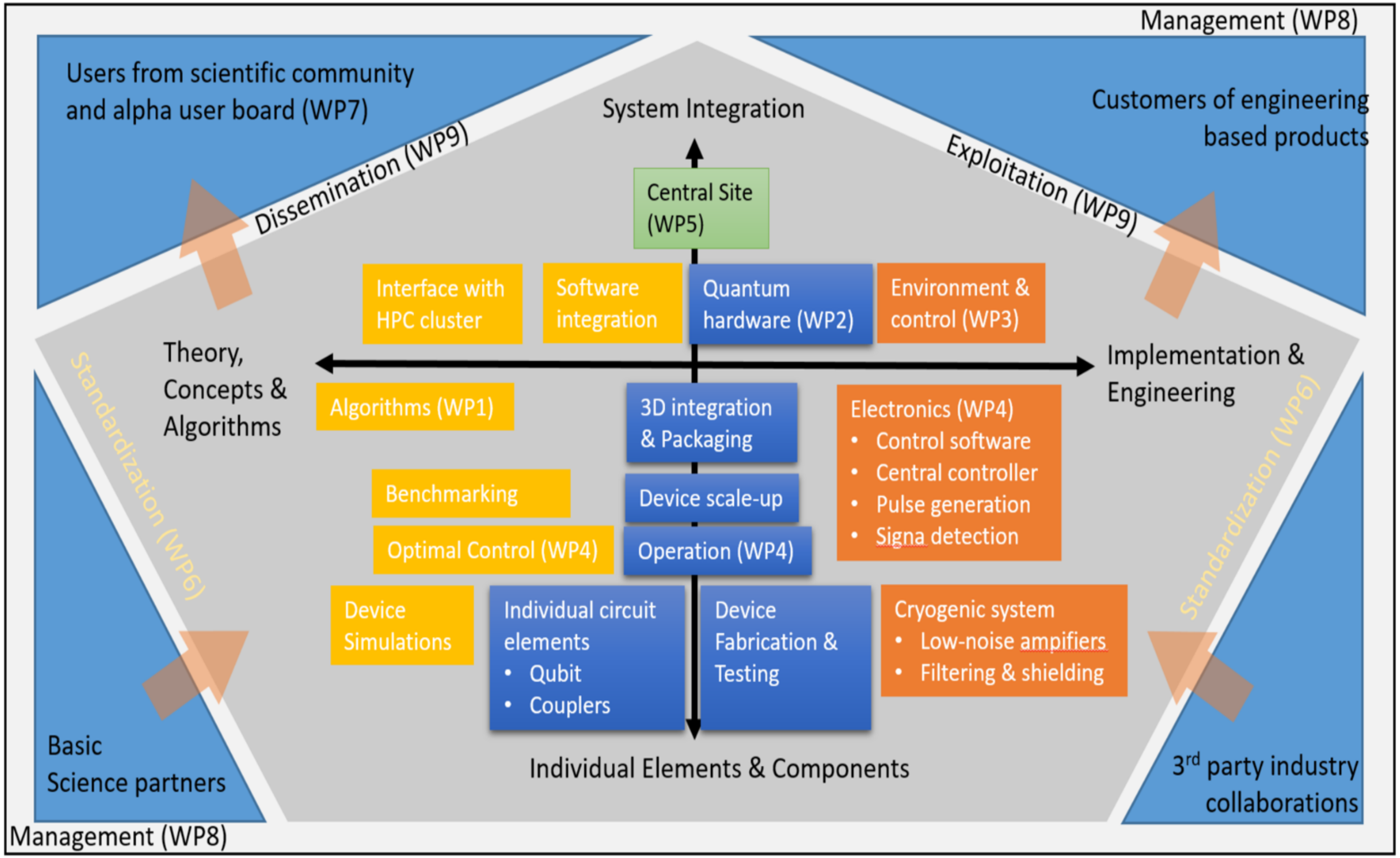
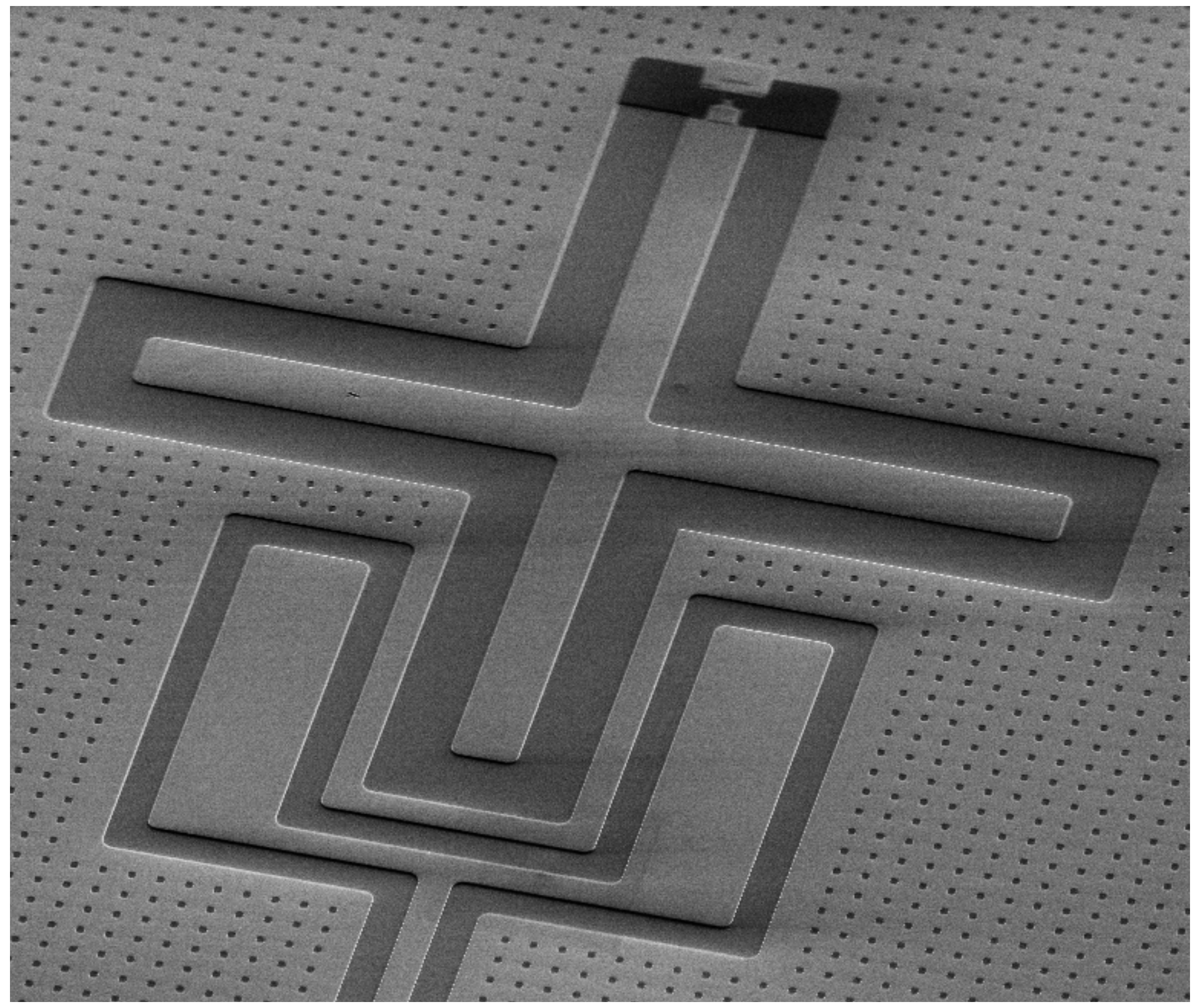
Project management

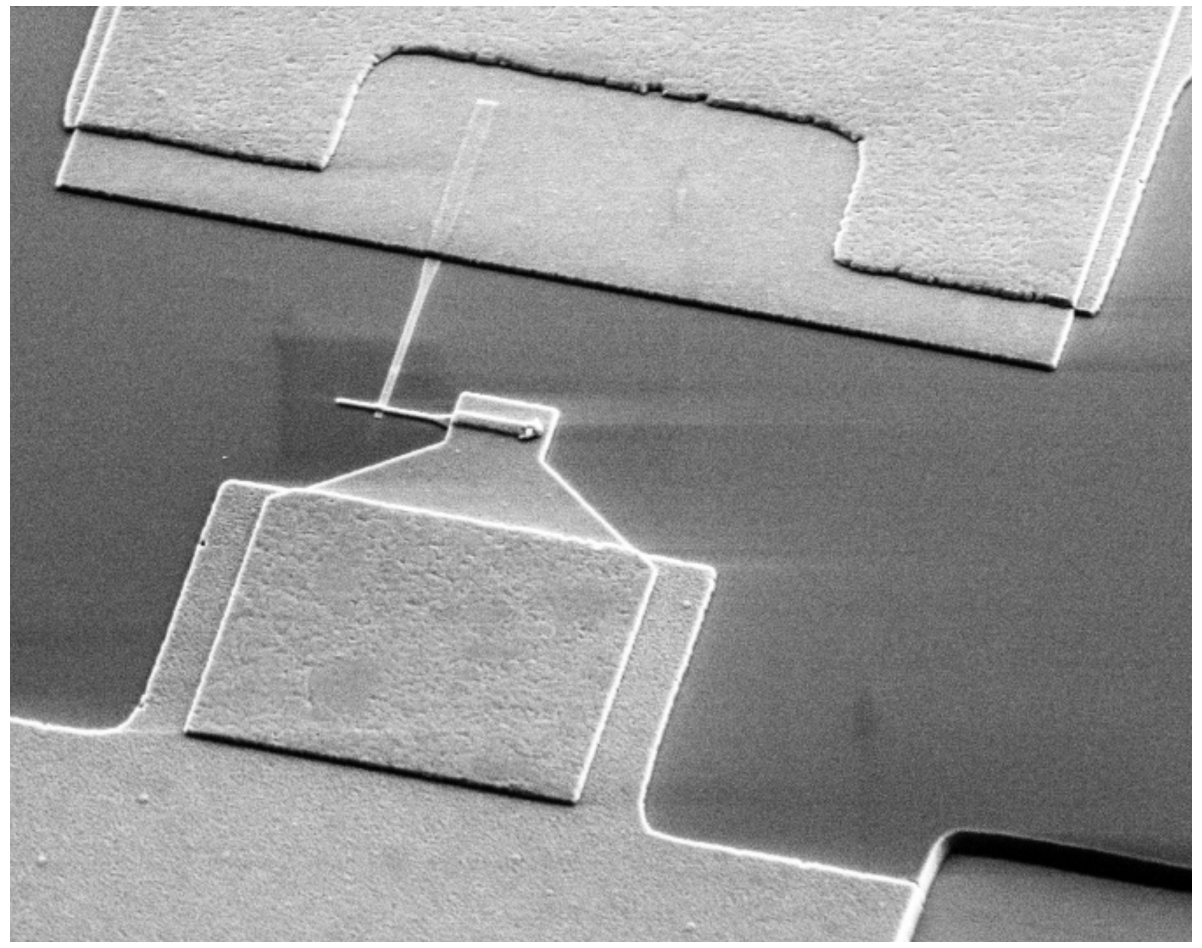
OpenSuperQ


Management (WP8)
Users from scientific community and alpha user board (WP7)
System Integration
Customers of engineering based products
Dissemination (WP9)
Exploitation (WP9)
Central Site (WP5)
Interface with HPC cluster
Software integration
Quantum hardware (WP2)
Environment & control (WP3)
Theory, Concepts & Algorithms
Implementation & Engineering
Algorithms (WP1)
3D integration & Packaging
Electronics (WP4)
• Control software
• Central controller
• Pulse generation
• Signa detection
Standardization (WP6)
Benchmarking
Device scale-up
Optimal Control (WP4)
Operation (WP4)
Device Simulations
Individual circuit elements
• Qubit
• Couplers
Device Fabrication & Testing
Cryogenic system
• Low-noise ampifiers
• Filtering & shielding
Standardization (WP6)
Basic Science partners
Individual Elements & Components
3rd party industry collaborations
Management (WP8)

Transferable tools and engineering

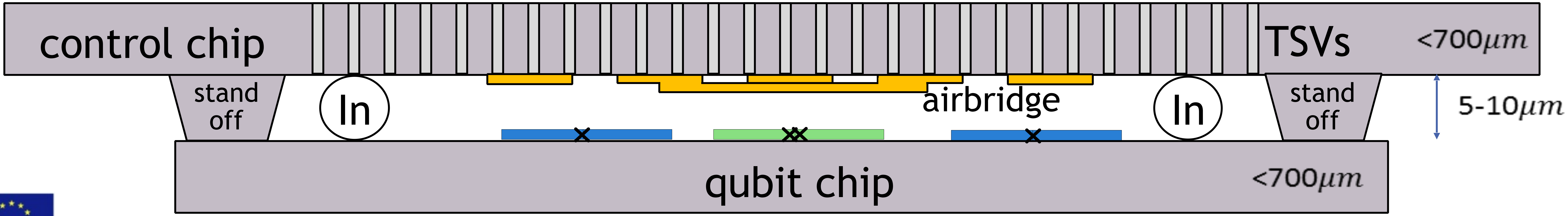
Superconducting circuit Fabrication





+ TWPAs from Chalmers and VTT

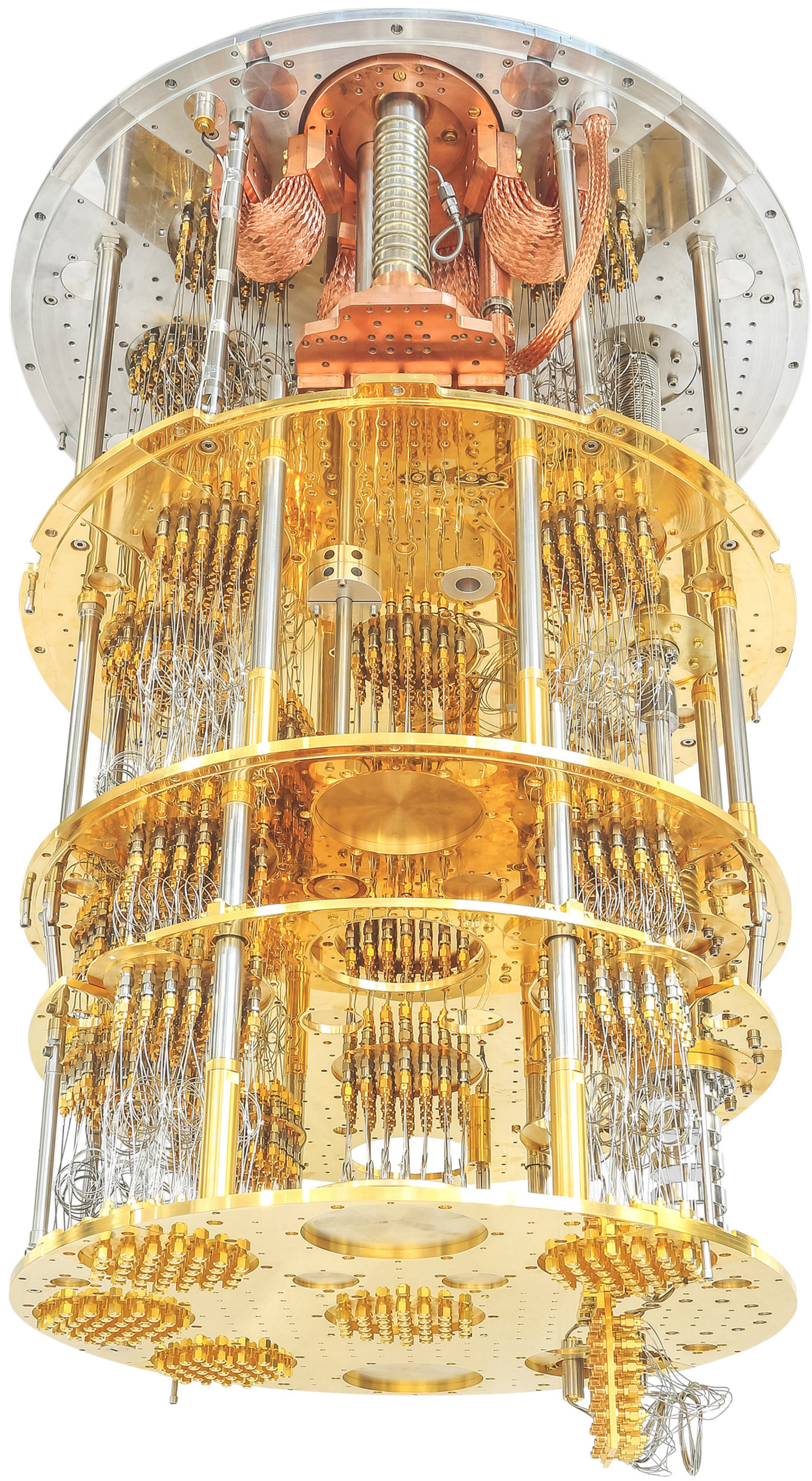
Three-dimensional integration



OpenSuperQ

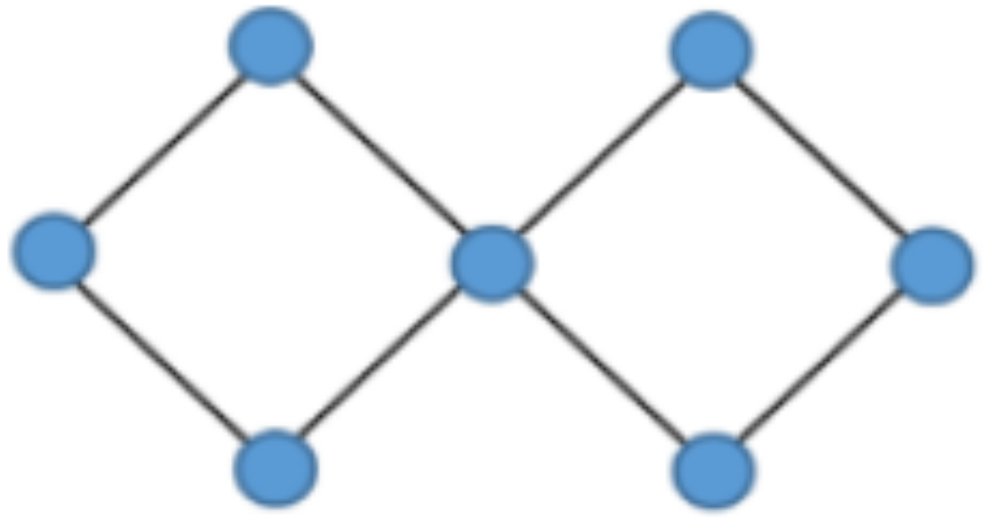
Classical infrastructure

- Custom cryogenic setup
- Custom electronics
- Equipment developers are integrated: Strong customization and early commercialization



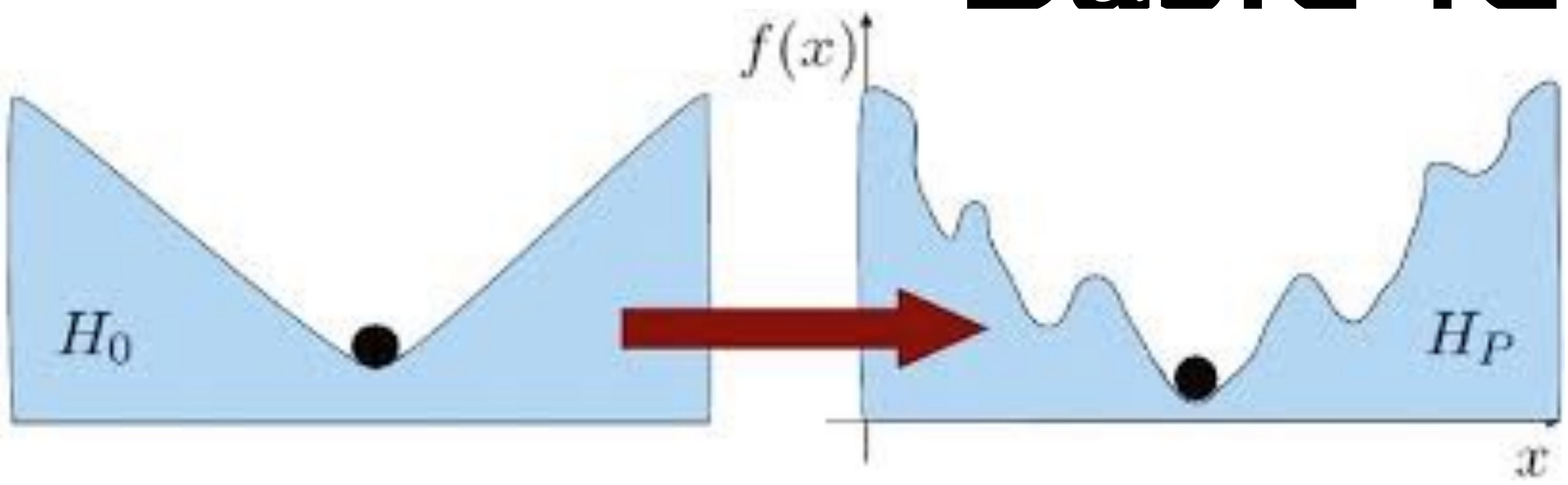
Why a European project

- Expanding technological ecosystem
- Complementary, Airbus-style approach to collaboration
- Result under European legislation
- Research and training infrastructure with deep access



Universal adiabatic quantum computing

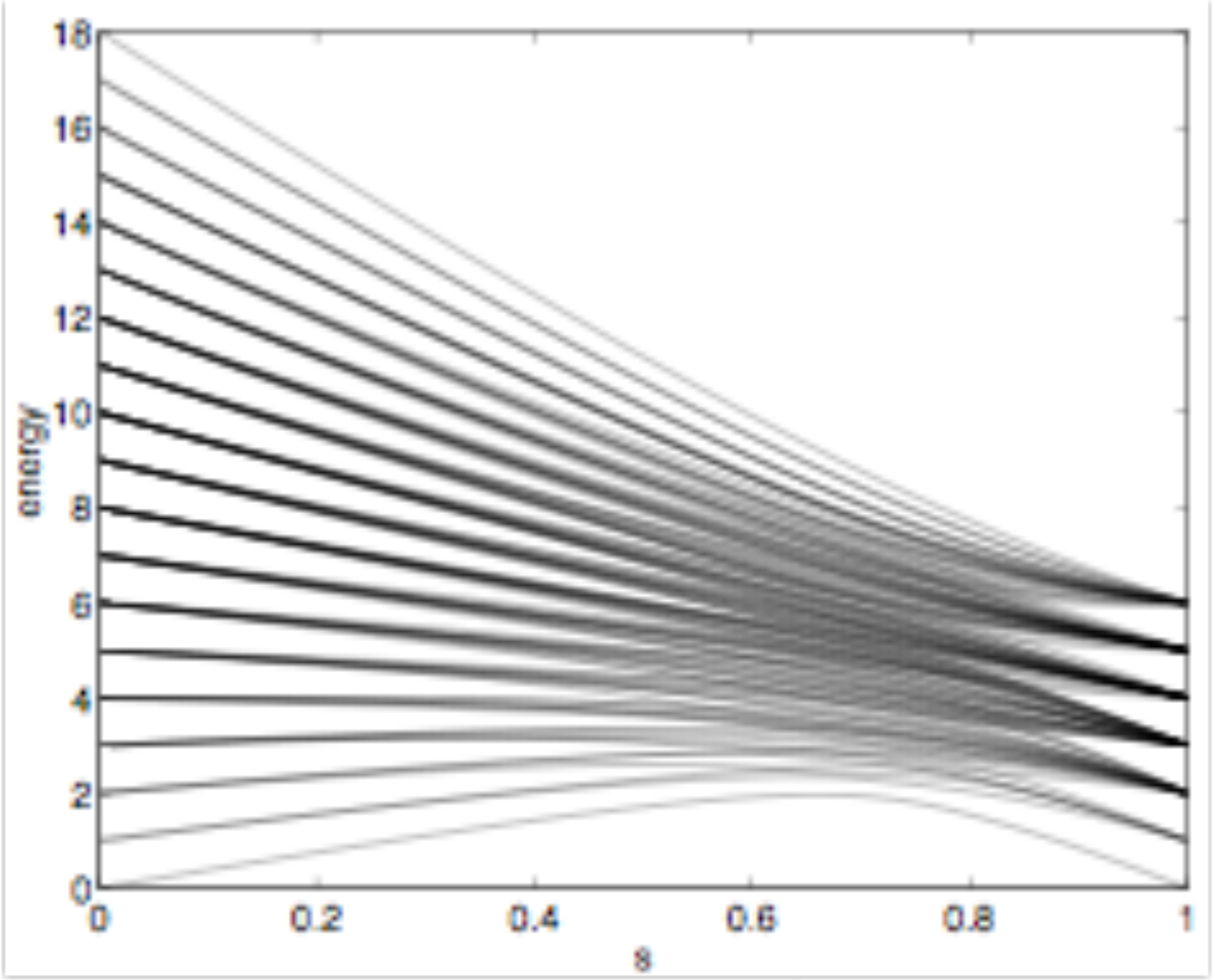
Basic idea



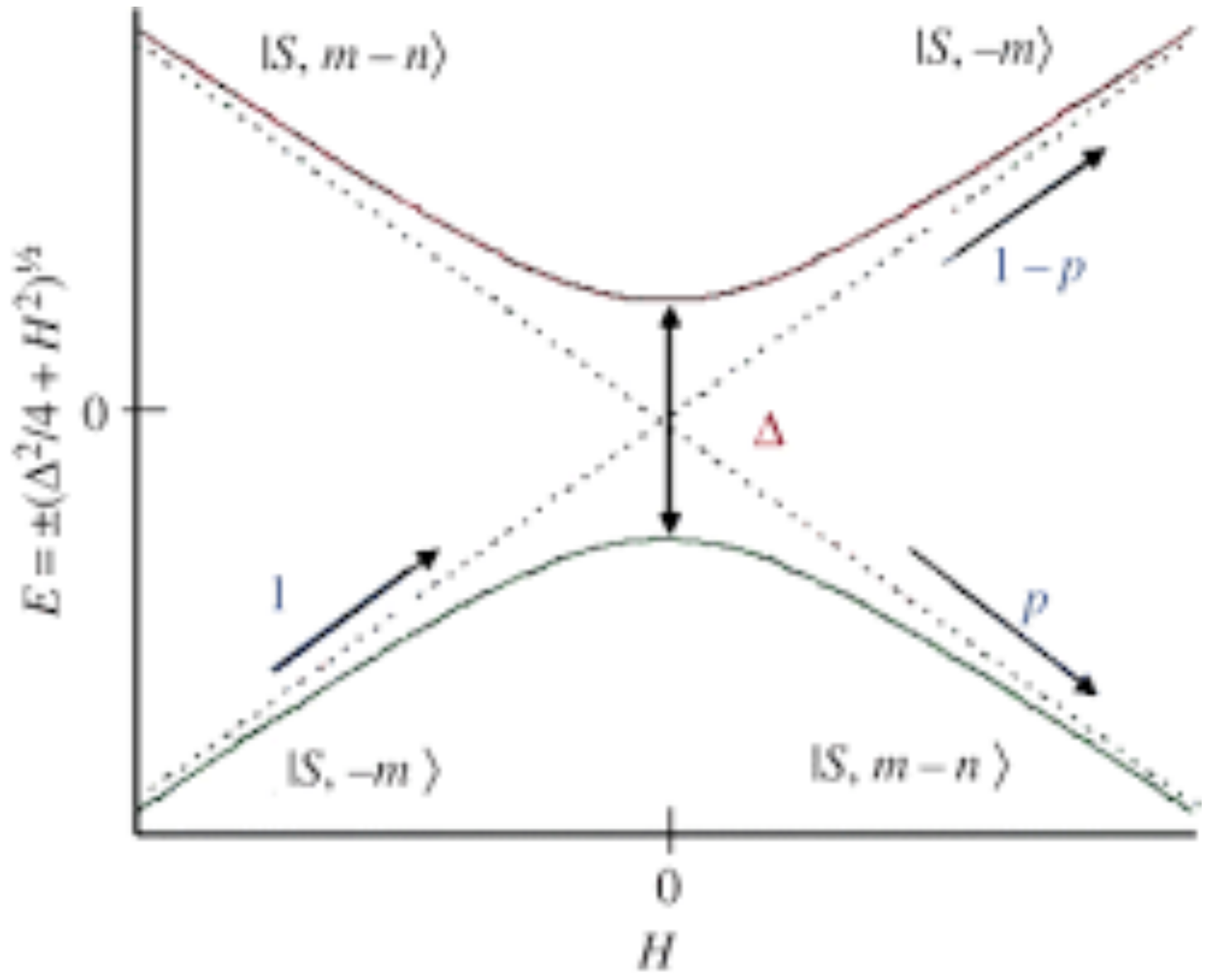
$$H(s) = (1 - A(s))H_d + A(s)H_p$$

Driver: $H_d = -D\sum_i \hat{X}_i$

Find solution of hard constrained optimization problem by adiabatic sweep



$$1 - p = \exp\left(-\frac{\Delta^2}{hv}\right)$$



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

Problem Hamiltonian:

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

Annealing schedule:

$$A\left(\frac{t}{T}\right) \quad A(0) = 0 \quad A(1) = 1$$

Proven result

Adiabatic Quantum Computation is Equivalent to Standard Quantum Computation

Dorit Aharonov
School of Computer Science and Engineering,
Hebrew University, Jerusalem, Israel

Wim van Dam
Department of Computer Science,
UC Santa Barbara, CA

Julia Kempe
CNRS-LRI UMR 8623,
Université de Paris-Sud, Orsay, France

Zeph Landau
Department of Mathematics,
City College of New York, NY

Seth Lloyd
Department of Mechanical Engineering,
MIT, Cambridge, MA

Oded Regev
Computer Science Department,
Tel Aviv University, Israel

February 1, 2008

- Assumes 6-state „qubits“
- Assumes 3-body coupling $Z_1Z_2Z_3$
- Proves that gap shrinks proportional to number of gates

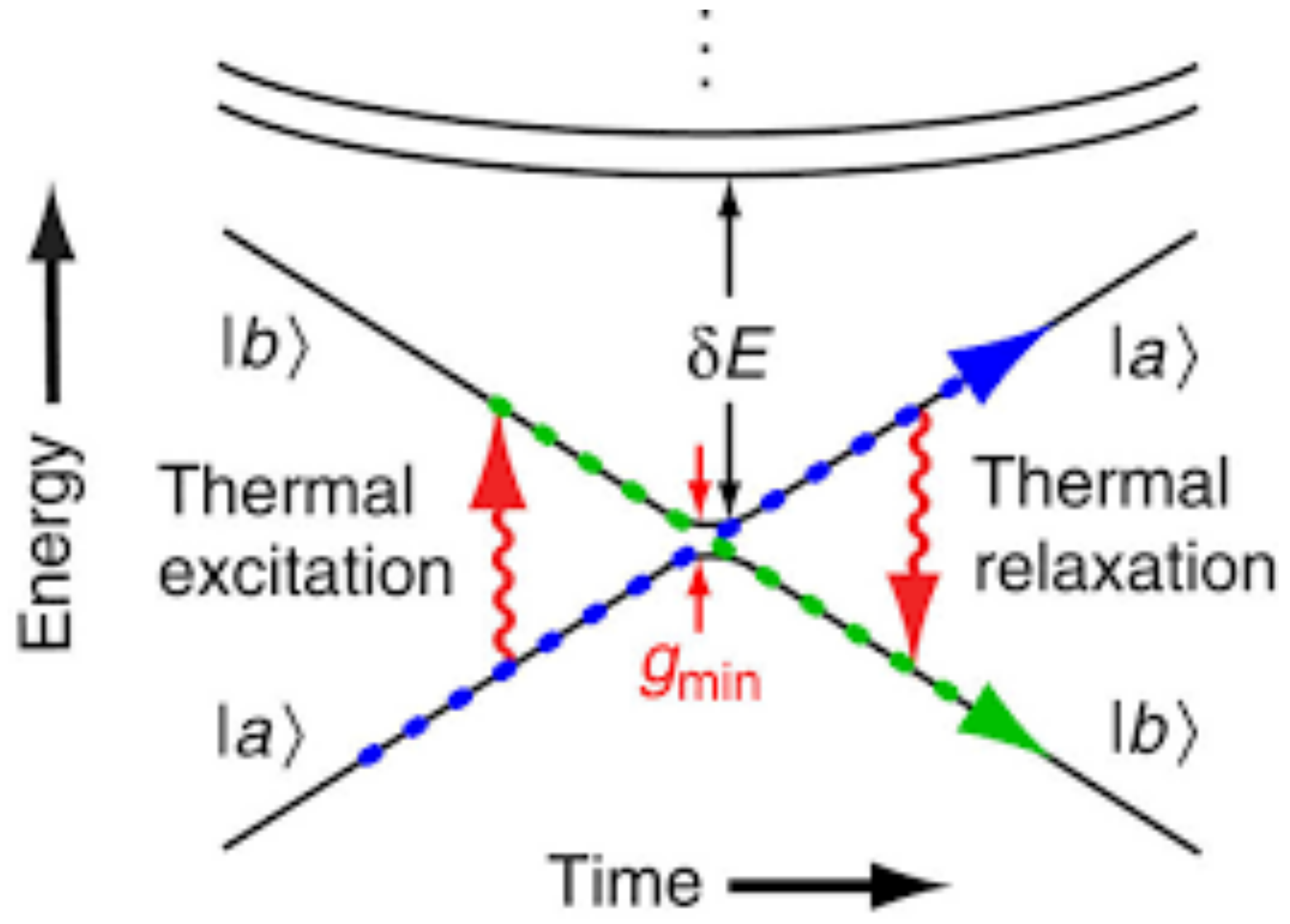
Any quantum gate circuit can be run on an adiabatic quantum computer

(if it is sufficiently general)

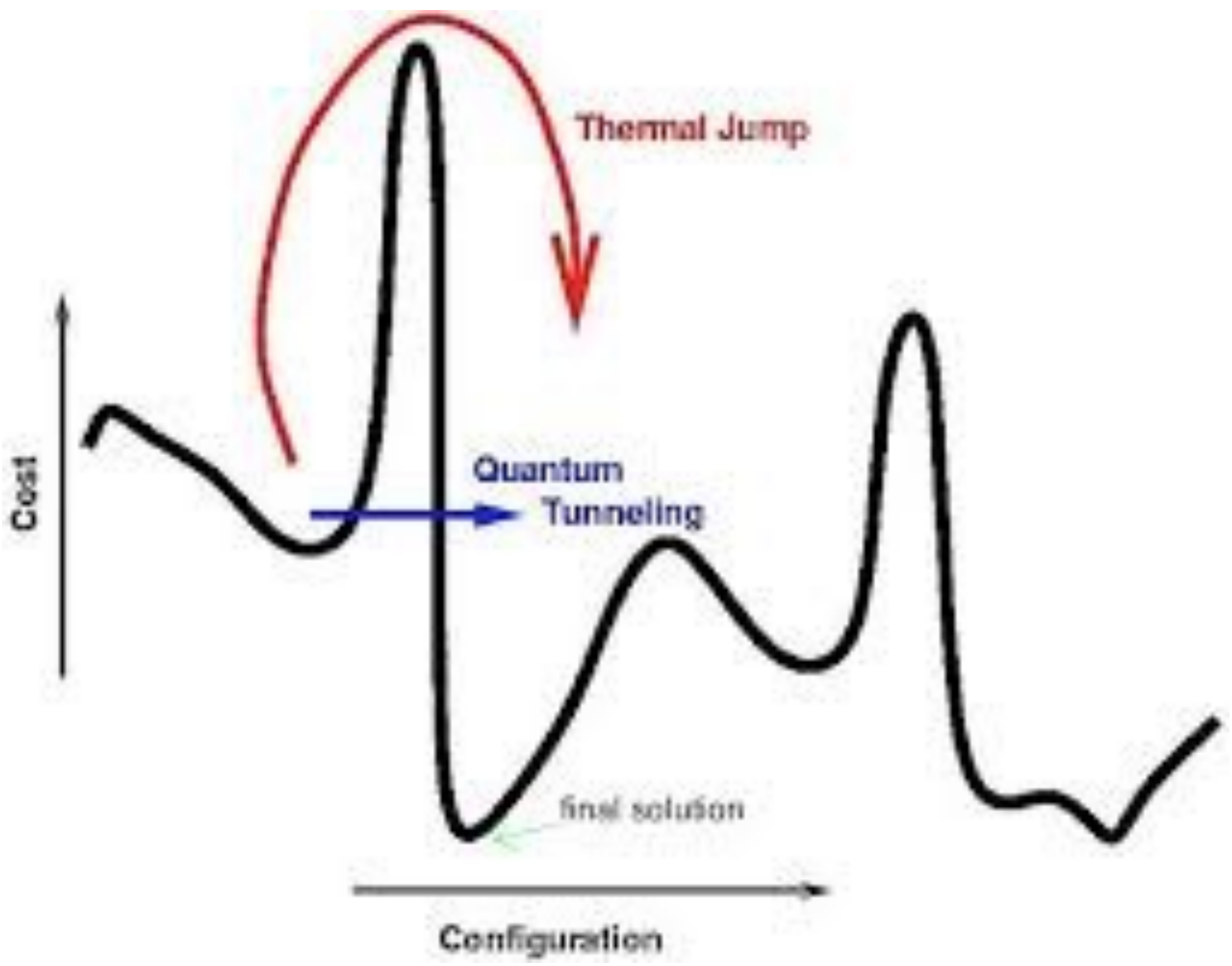
Does not currently apply to general combinatorical optimization problems (and is unlikely to)

Quantum annealing

Temperature and speed
lead to excitations



But tunneling gets us to the minimum faster
(heuristically)



Nishimori (spin systems), Amin (quantum computers)

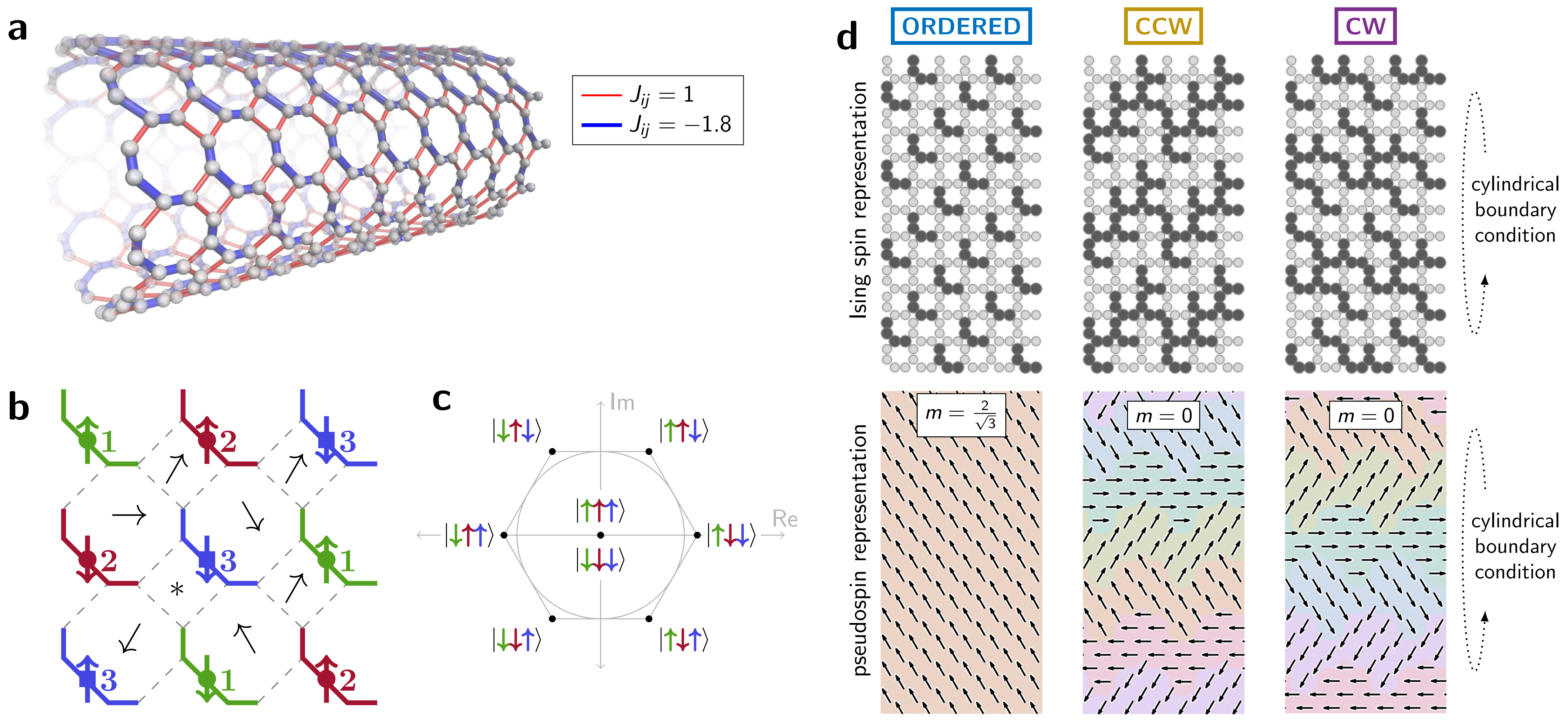
Combinatorical optimization

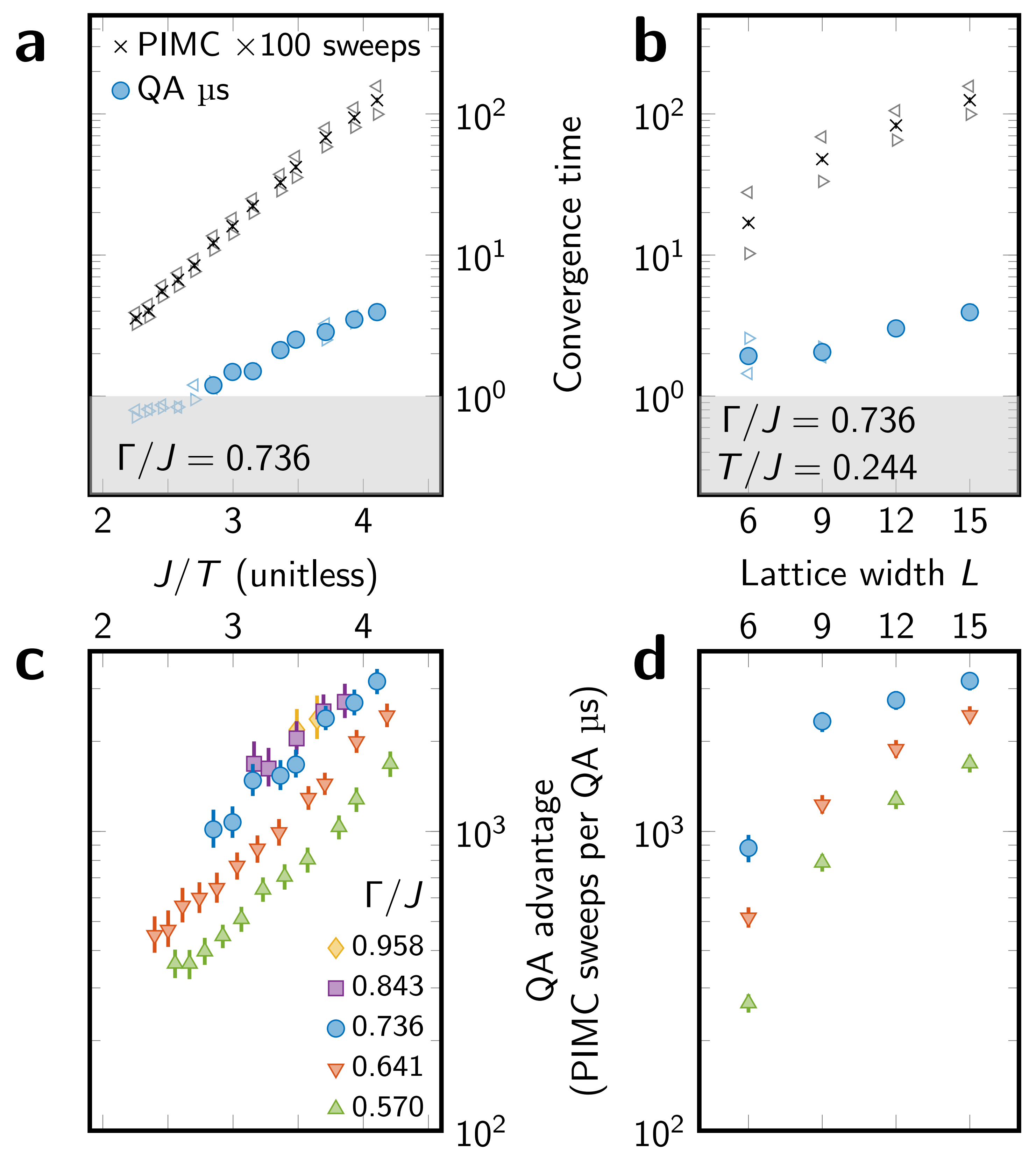
- Routing problems
- Machine learning
- Complex systems analysis
- Airport management
- Nurse schedules

Quantum simulation

Ising spin glass: Complex testbed of condensed matter and field theory

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

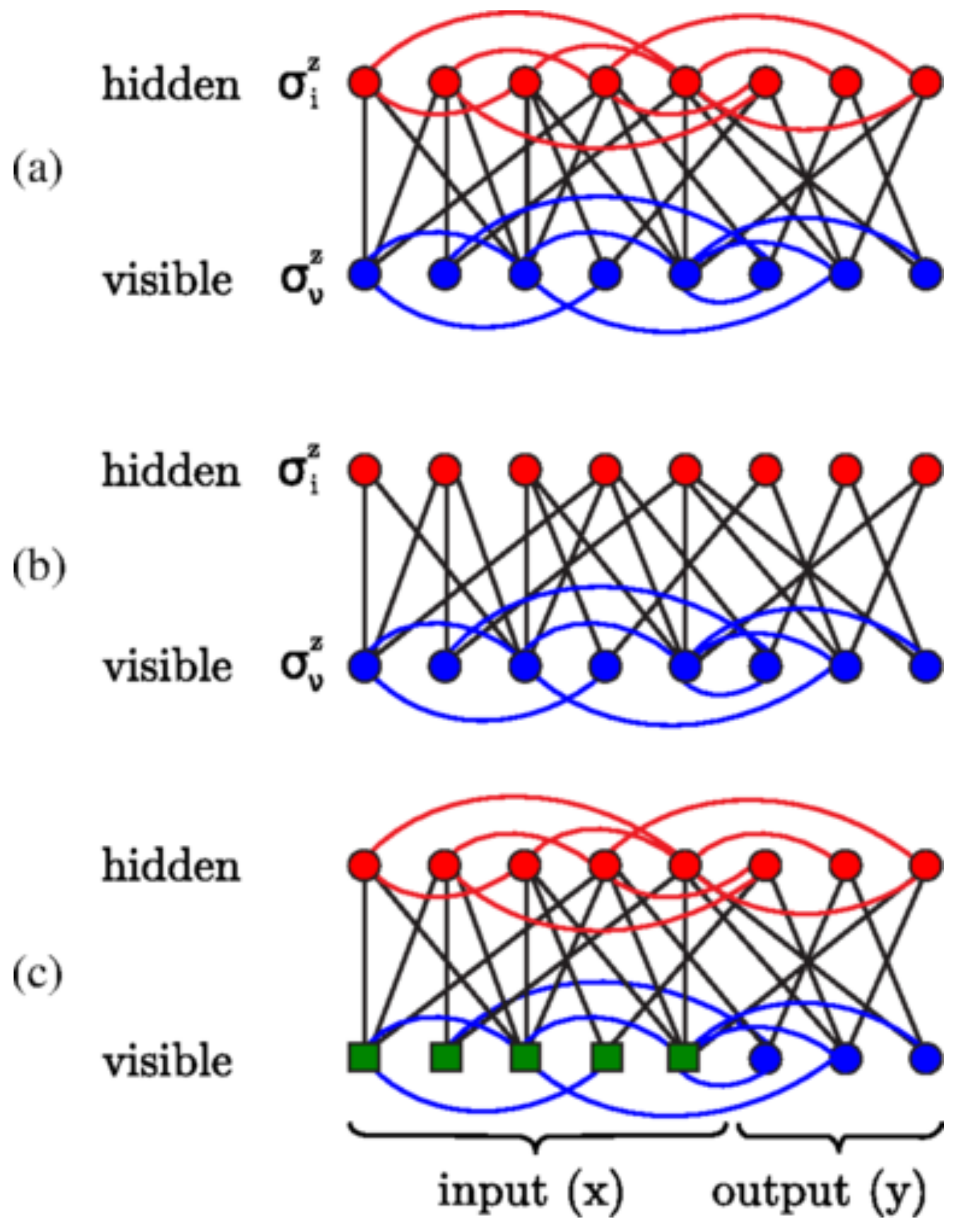




Sweet spot: Larger than gate based computers, but more versatile and programmable than optical lattices

Quantum adiabatic Boltzmann machine

- common approach in machine learning: sample from Boltzmann distribution
- preparing Boltzmann distribution for hard problem hard
- diabatic annealing: welcome thermal transitions
- need custom annealing schedules

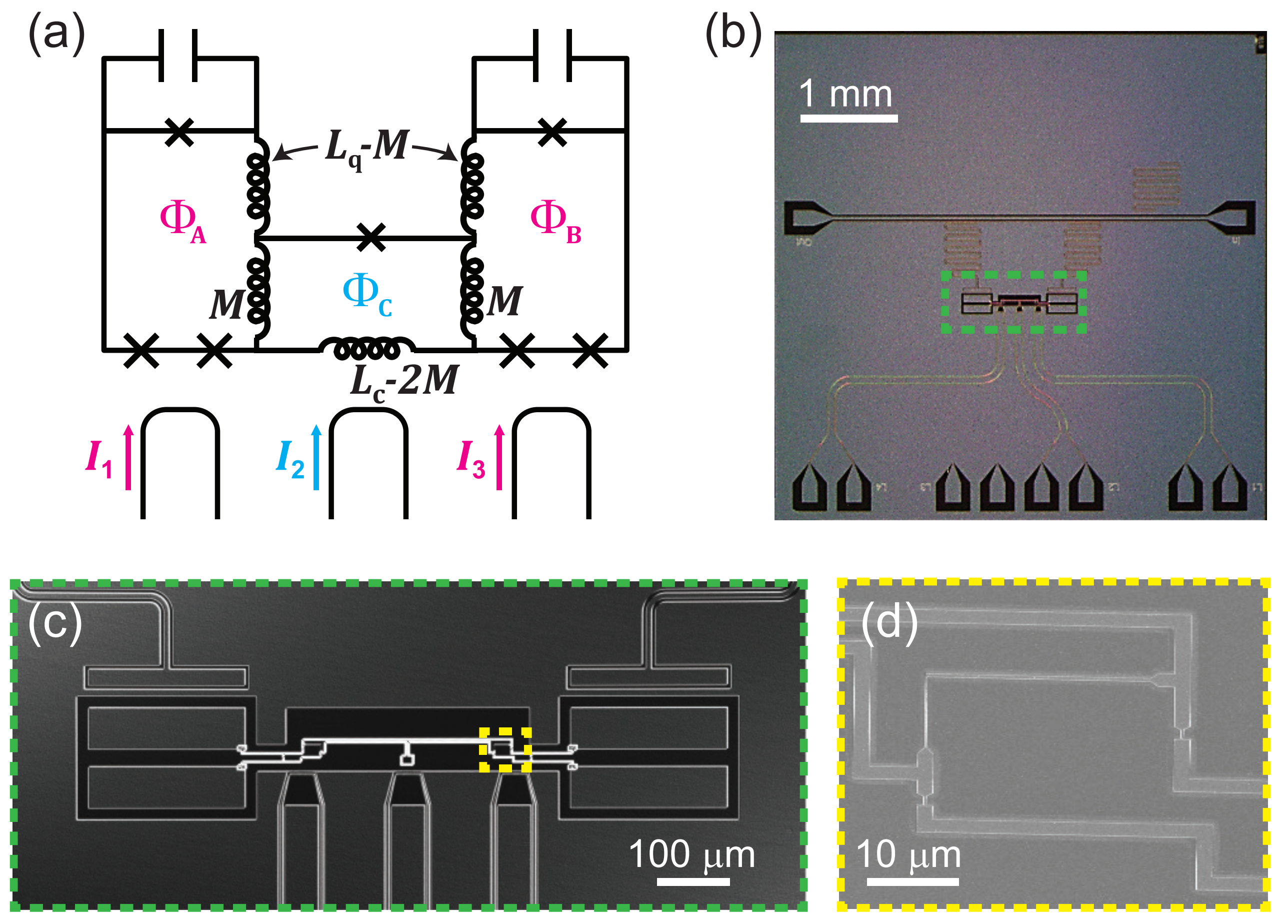


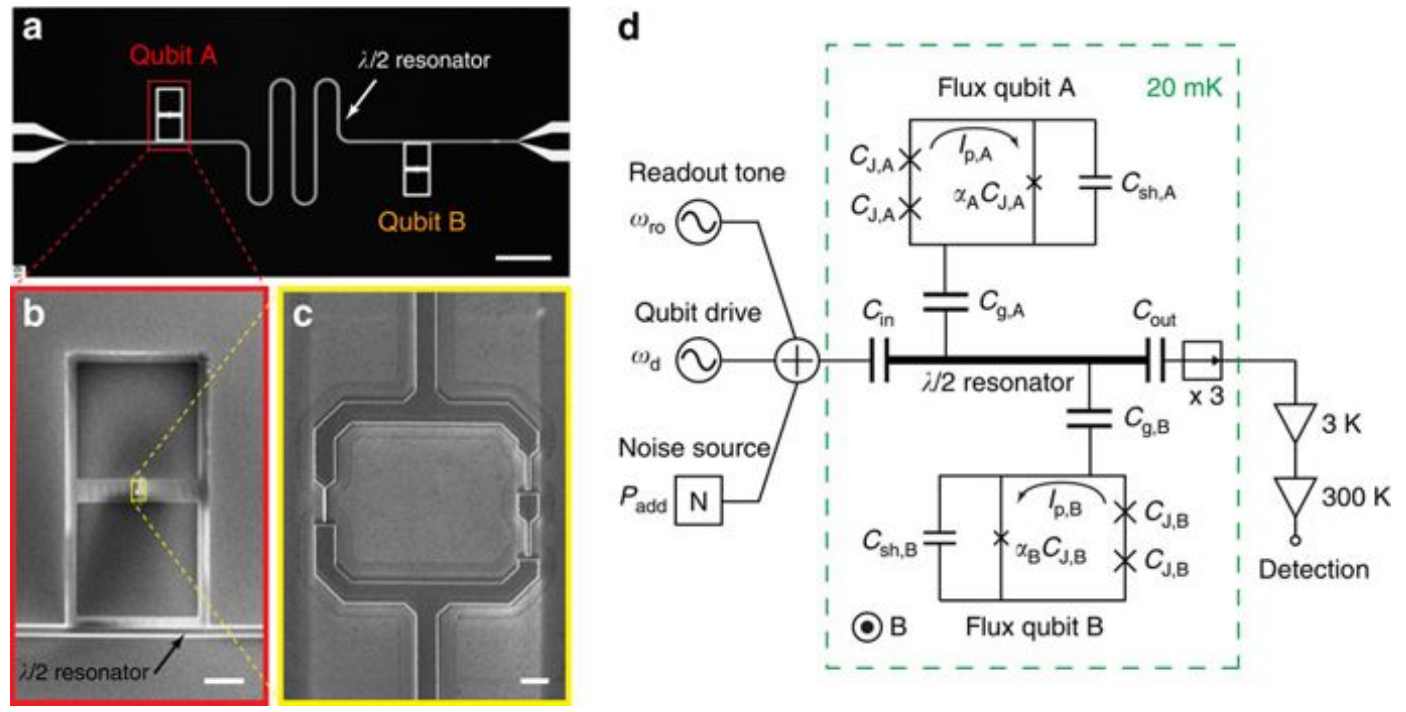
Famous caveats

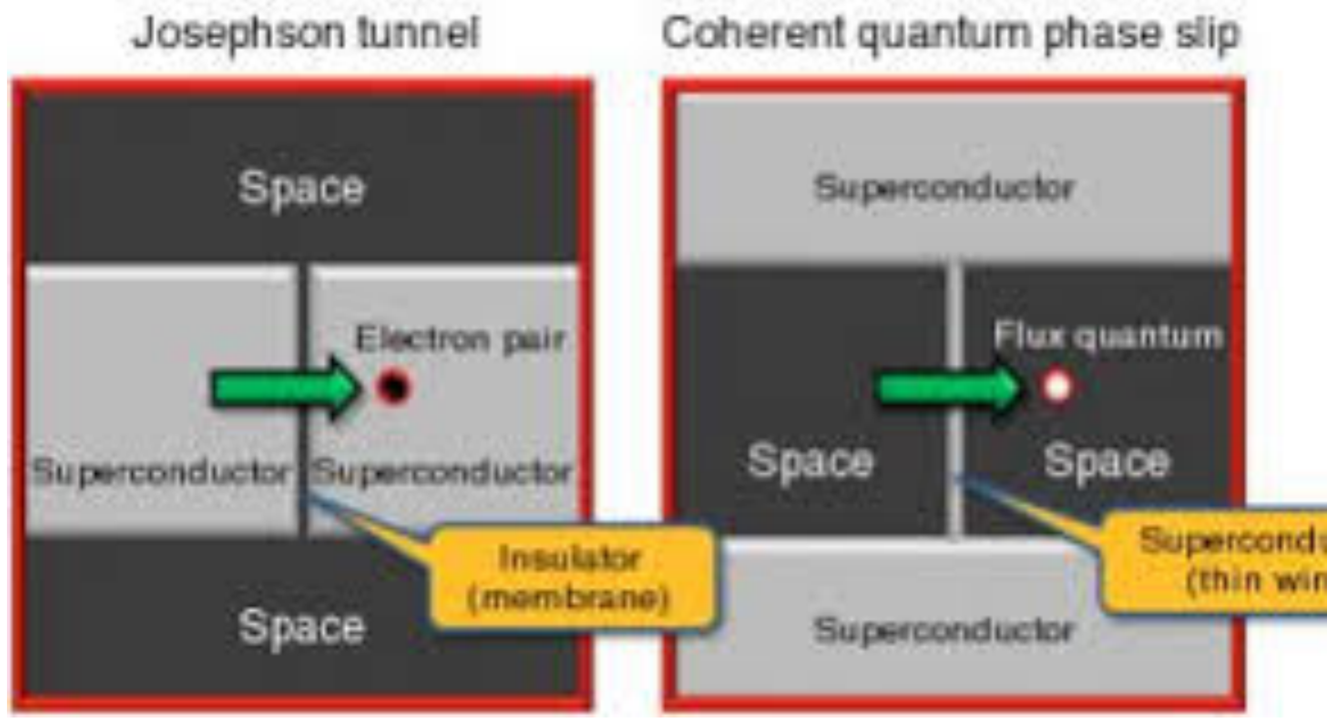
- Adiabatic quantum computing and the gate model can **efficiently** (= with polynomial overhead) simulate each other
- For arbitrary combinatorical optimization, there are no **proofs** of speedup in either model (AQC/QA is a *metaheuristic*)
- Quantum annealing **can** be error corrected against thermal excitation
- A universal quantum annealer needs more coherent and versatile hardware than d-Wave's current offerings (which can be simulated efficiently by spin vector Monte Carlo)

Hardware consequences

- Program by physics: Higher degree of coupling
- Control adiabatically rather than pulse: Simpler drive, fewer microwave issues
- Non-simulable coupling: Couple by conjugate variable







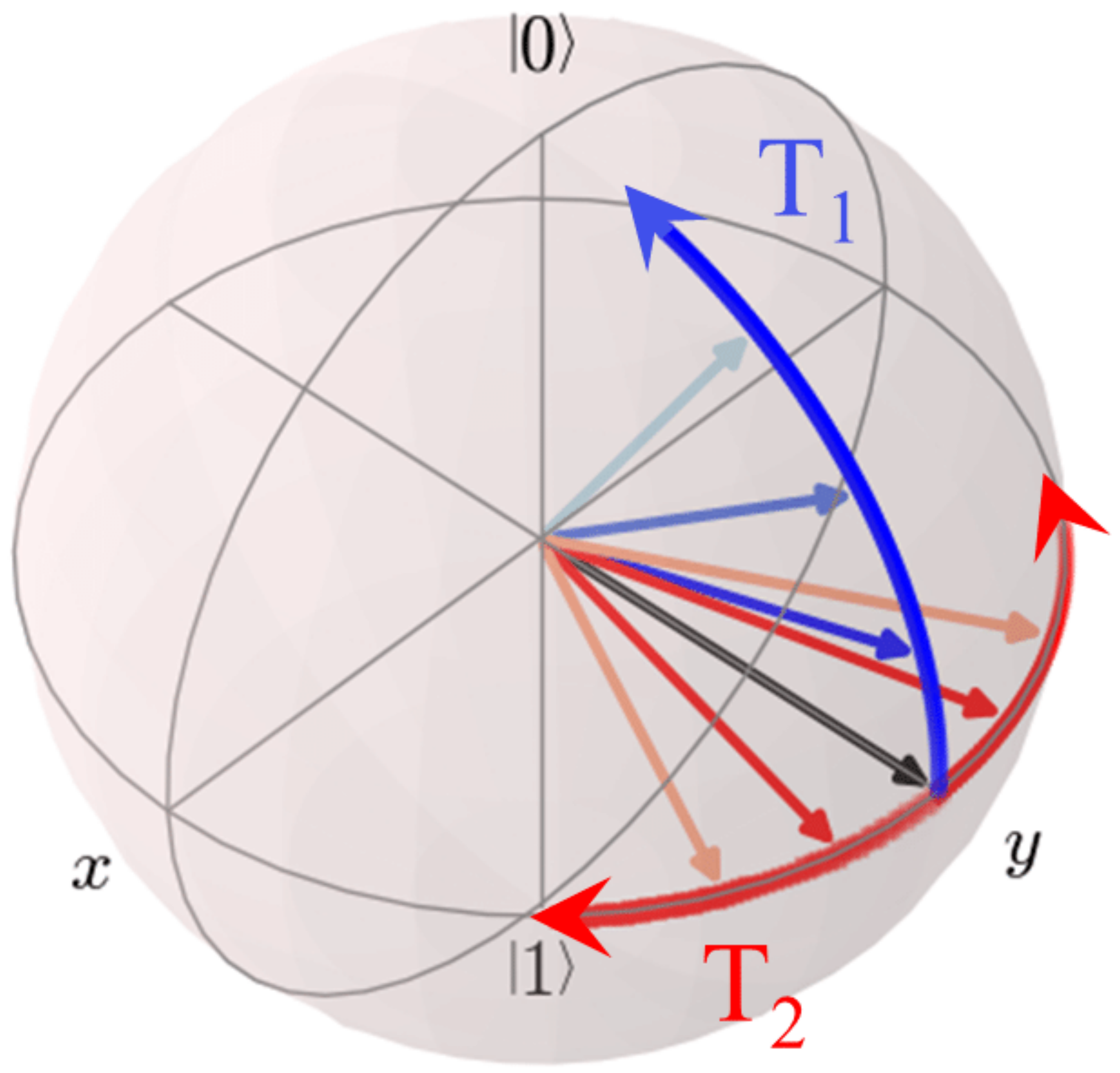
Decoherence in annealers

Three impacts of decoherence in the simplest picture

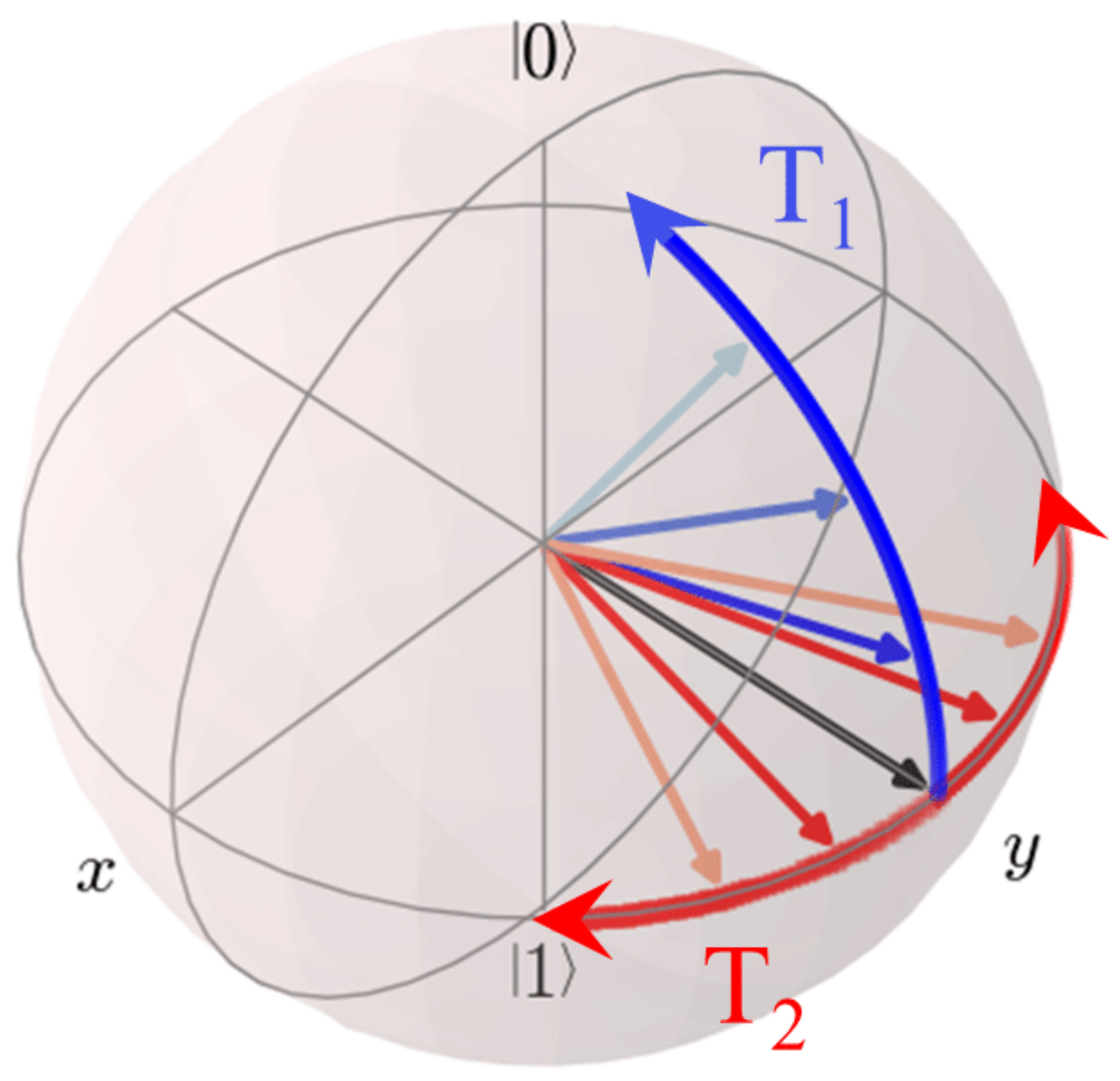
- Dephasing: Loss of superpositions between eigenstates (T_2)

- Relaxation / Excitation: Transitions between eigenstates leading to thermalization (T_1)

- Renormalization: Change of effective Hamiltonian (Lamb shift)

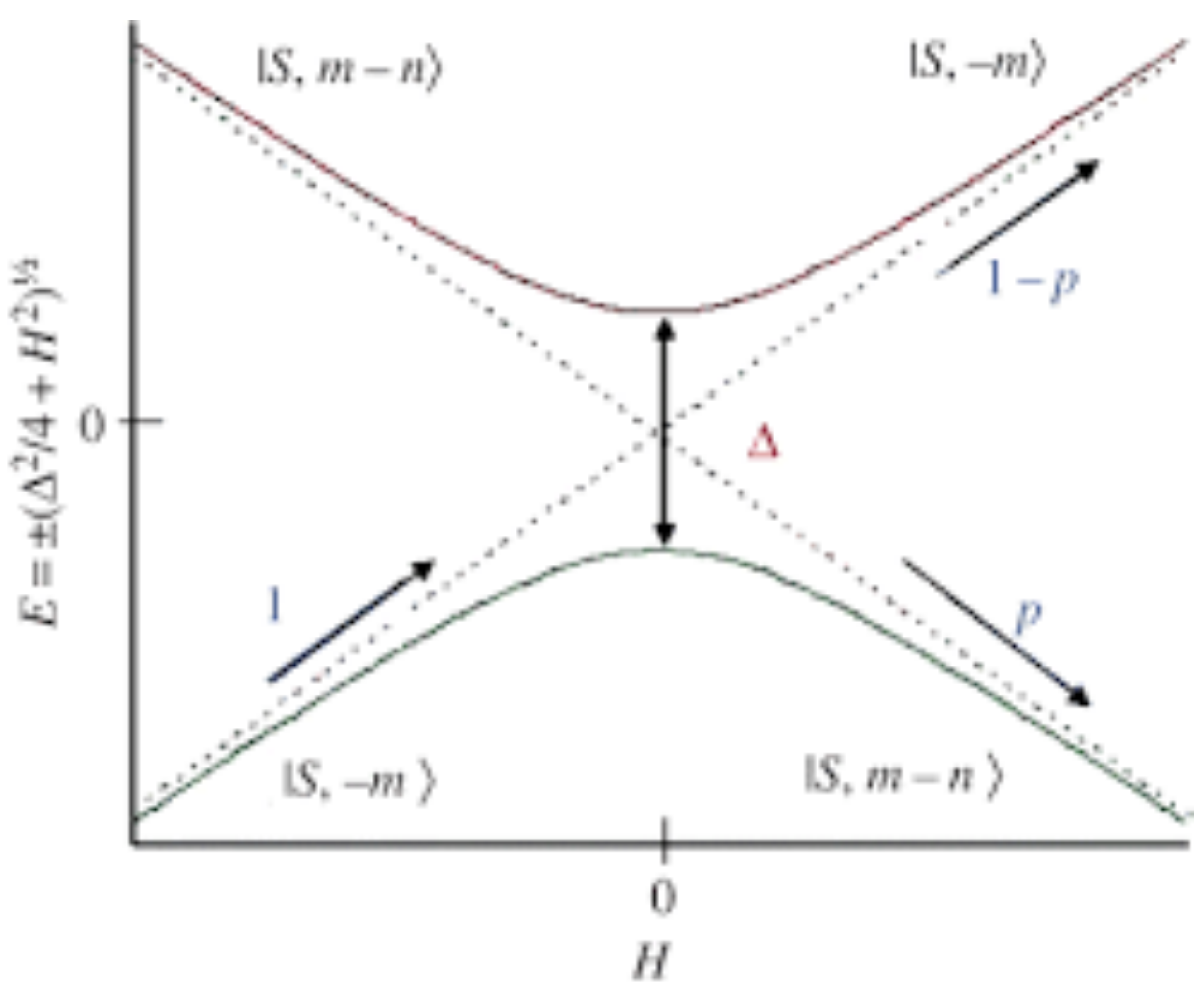


Pivotal role of the Energy eigenbasis



Basic questions

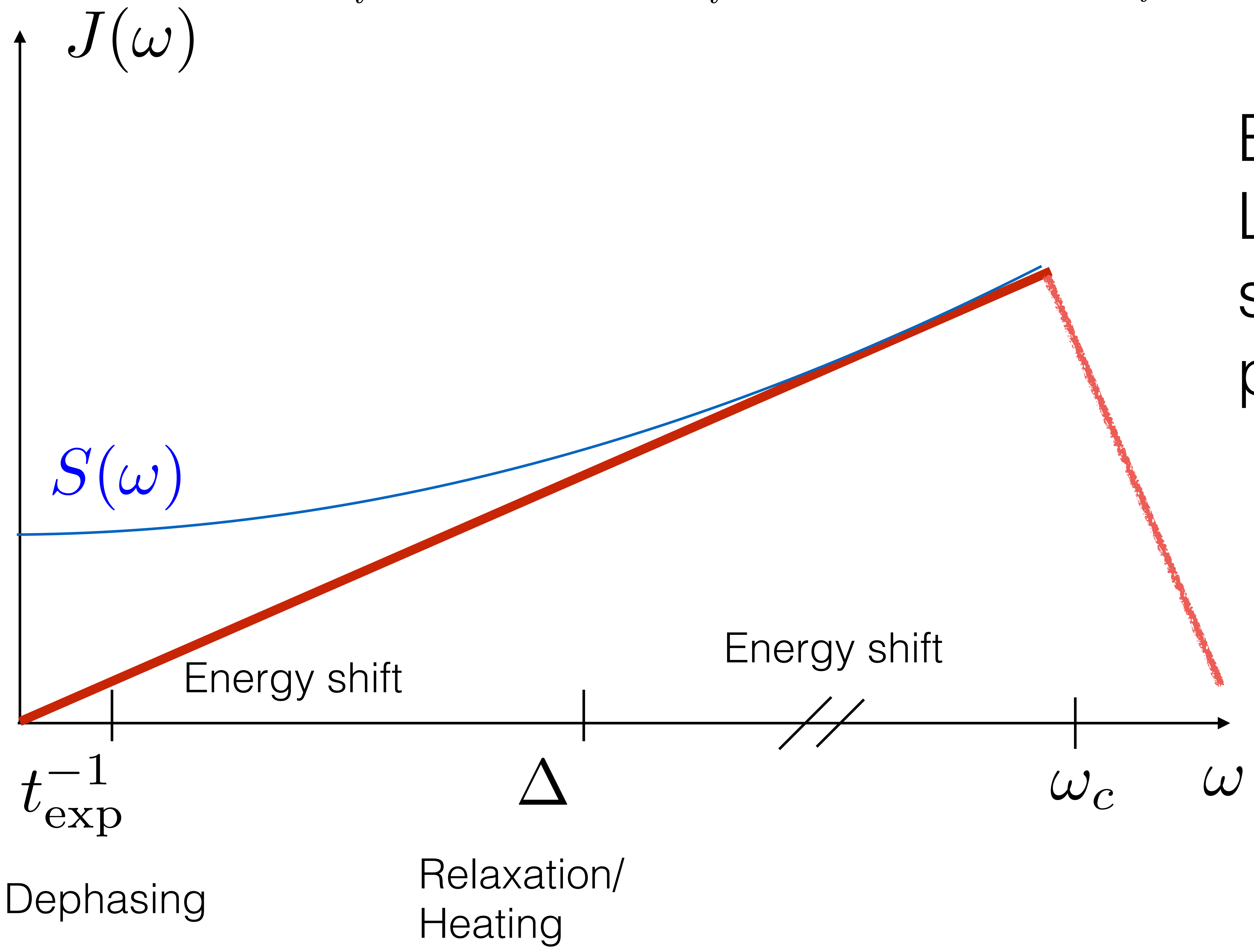
- Does keeping the ground state even need coherence?
- Is relaxation even hepful?
- „Can there be quantum speedup without quantum coherence?“ (J. Martinis, before 2014)
- „What is the role of the reorganization energy of the environment“ (A.J. Kerman, 2017)
- „Isn’t quantum annealing cheating“ (many in the circuit-model community)



The dissipative phase transition

The Ohmic Spin-Boson model

$$\hat{H} = \frac{\Delta_0}{2}\hat{\sigma}_z + \frac{\hat{\sigma}_z}{2}\sum_i \lambda_i(\hat{a}_i + \hat{a}_i^\dagger) + \sum_i \hbar\omega_i \hat{a}_i^\dagger \hat{a}_i \quad J(\omega) = \sum_i \lambda_i^2 \delta(\omega - \omega_i) = \alpha\omega f_{\text{cut}}\left(\frac{\omega}{\omega_c}\right)$$

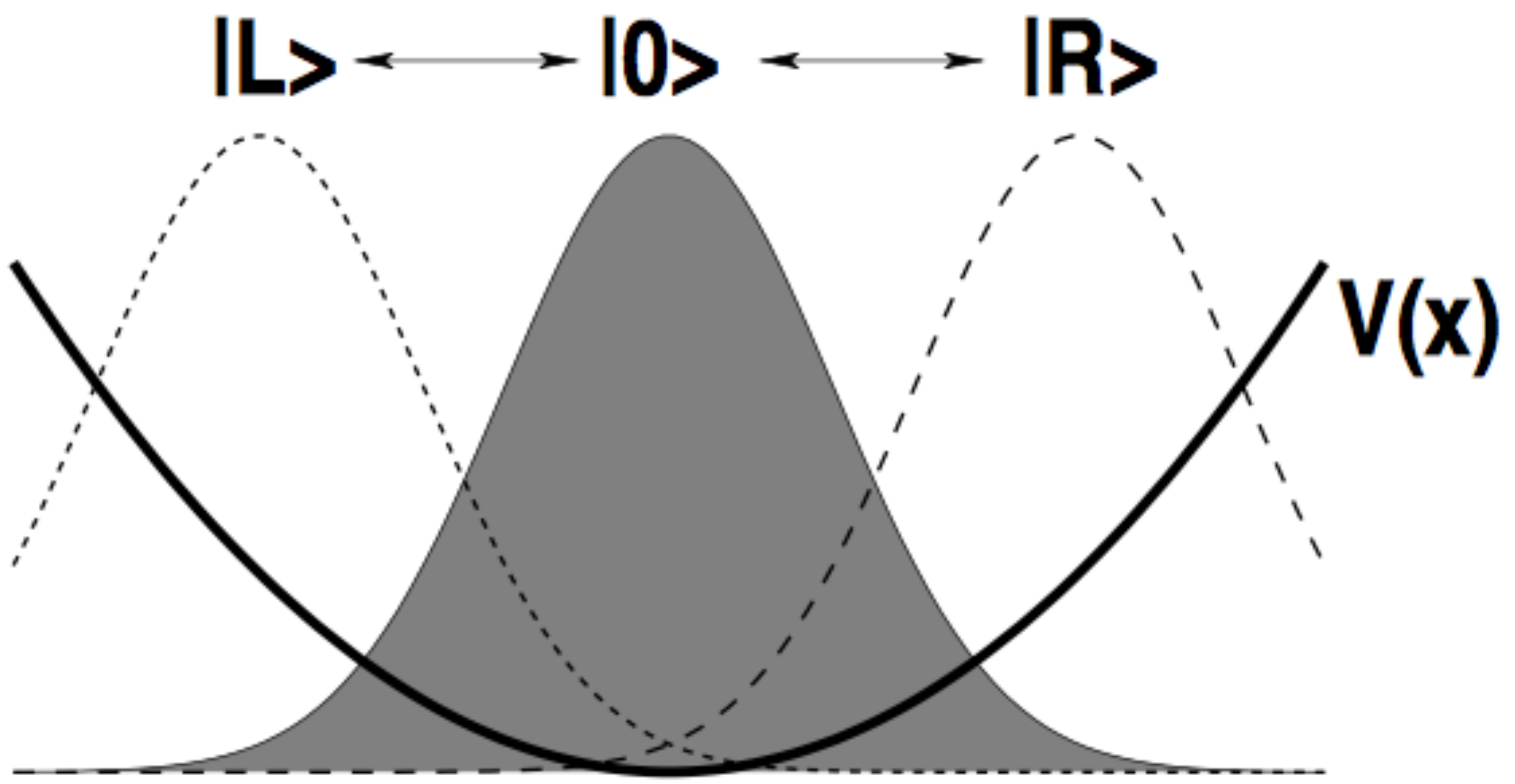


Energy shift:
Level repulsion /
second order
pert. th.

Adiabatically dressed states

$$\hat{H} = \frac{\Delta_0}{2}\hat{\sigma}_z + \frac{\hat{\sigma}_z}{2}\sum_i \lambda_i(\hat{a}_i + \hat{a}_i^\dagger) + \sum_i \hbar\omega_i \hat{a}_i^\dagger \hat{a}_i$$

High-frequency part - treat qubit as perturbation



Dressed states:

Displaced vacua

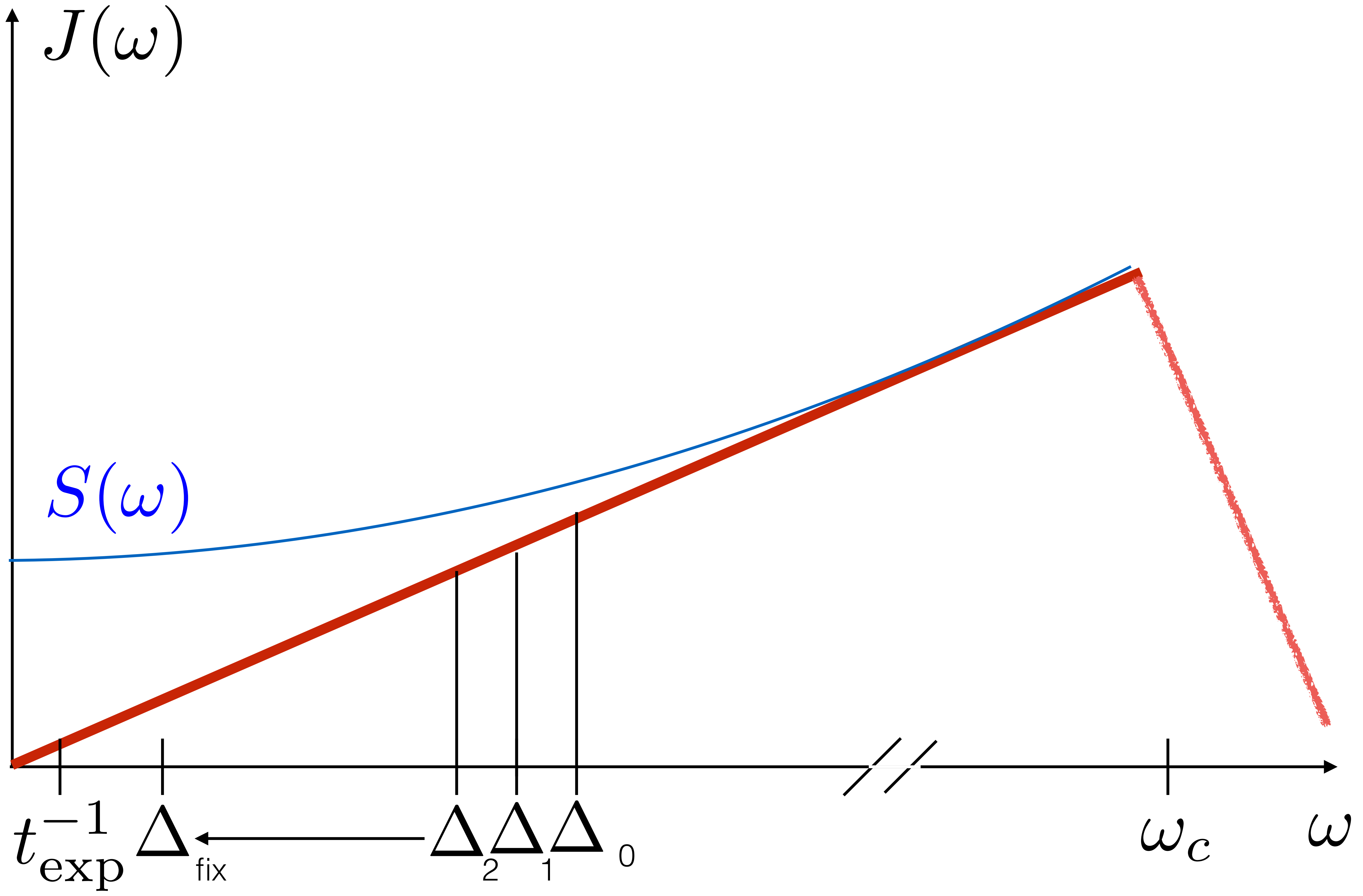
$$|0/1\rangle_{\text{eff}} = |0/1\rangle \bigotimes_{\omega_i > \Delta} \left| \pm \frac{\lambda_i}{2\omega_i} \right\rangle$$

= 1 Cat per mode

Effect on qubit: Dressed tunneling

$$H_{Q,\text{eff}} = _{\text{eff}}\langle 0 | H_Q | 1 \rangle_{\text{eff}}$$

Running tunneling element



Reduction of Tunneling element widens bandwidth of dressing cloud

$$\Delta_{\text{eff}} = \Delta_0 \exp\left(-\int_{\Delta_{\text{eff}}}^{\omega_c} \frac{J(\omega)}{\omega^2}\right)$$

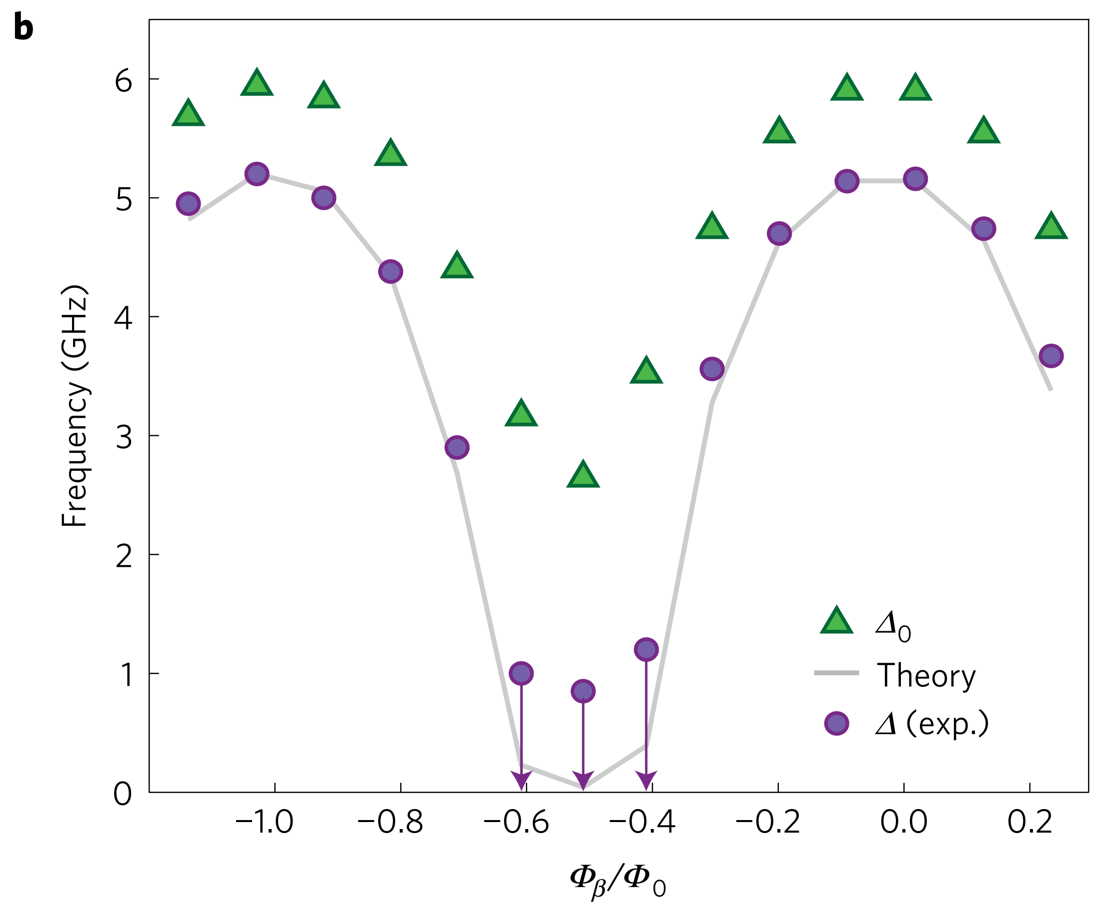
Phase diagram and fixed point

Delocalized:
Quantum phase

Localized:
Classical phase

0 1 α

$$\Delta_{\text{eff}} = \Delta_0 \left(\frac{\Delta_0}{\omega_c}\right)^{\frac{\alpha}{1-\alpha}}$$



A.J. Leggett et al., RMP 1988

Dissipative PT: Why the flux qubit was invented before quantum computing

Macroscopic quantum coherence

Macroscopic Quantum Systems and the Quantum Theory of Measurement

A. J. Leggett

School of Mathematical and Physical Sciences
University of Sussex, Brighton BN1 9QH

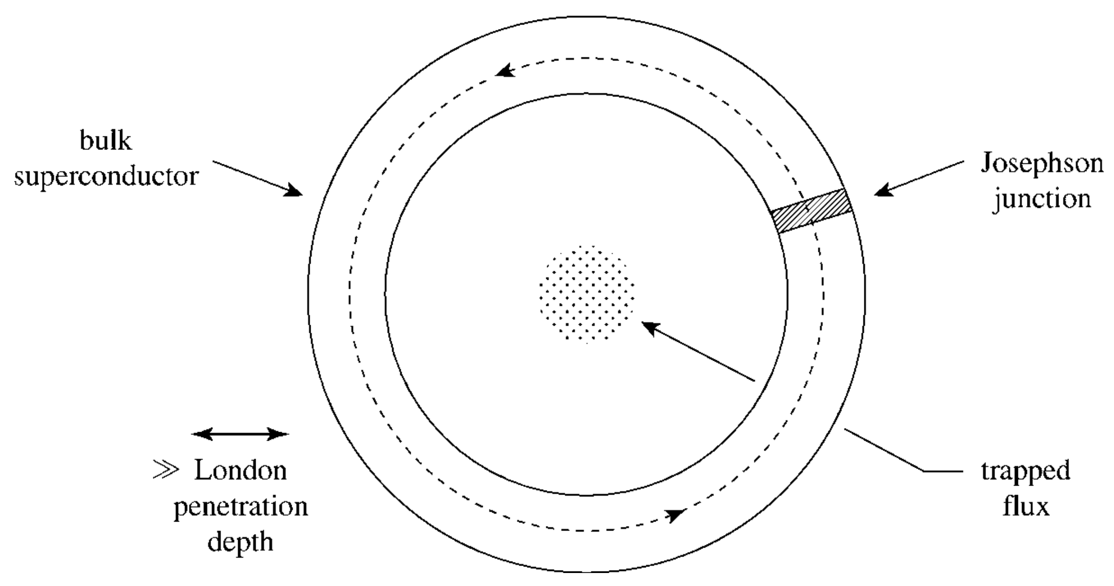


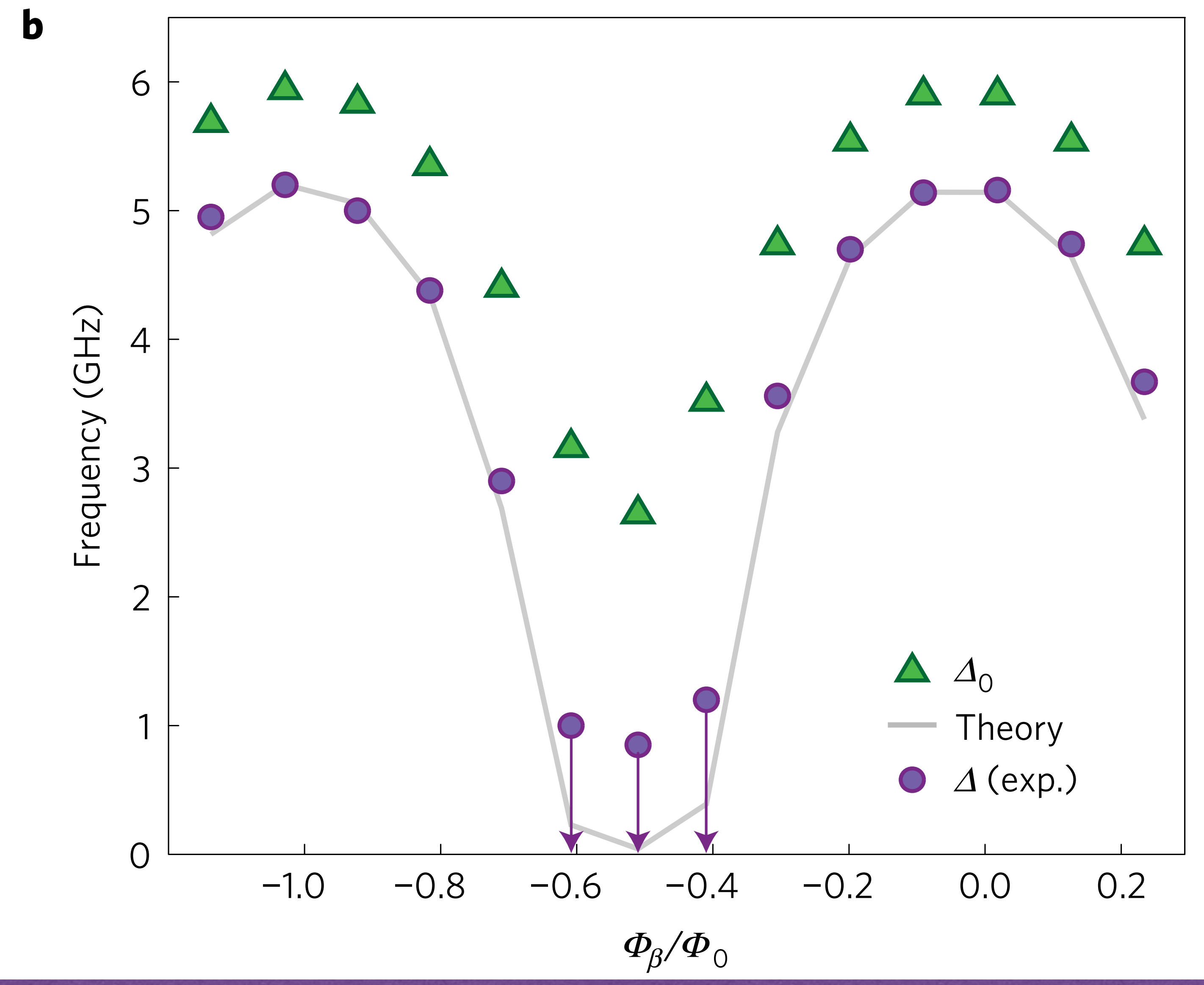
Figure 1. A single rf (or single-junction) SQUID ring.

A.J. Leggett,
Prog. Th. Phys. 1980

nature physics | LETTERS
PUBLISHED ONLINE: 10 OCTOBER 2016 | DOI: 10.1038/NPHYS3905

Ultrastrong coupling of a single artificial atom to an electromagnetic continuum in the nonperturbative regime

P. Forn-Díaz[1,2,3]*, J. J. García-Ripoll[4], B. Peropadre[5], J.-L. Orgiazzi[1,3,6], M. A. Yurtalan[1,3,6], R. Belyansky[1,6], C. M. Wilson[1,6*†] and A. Lupascu[1,2,3*†]



Tuning sytem-bath interactions kills tunneling

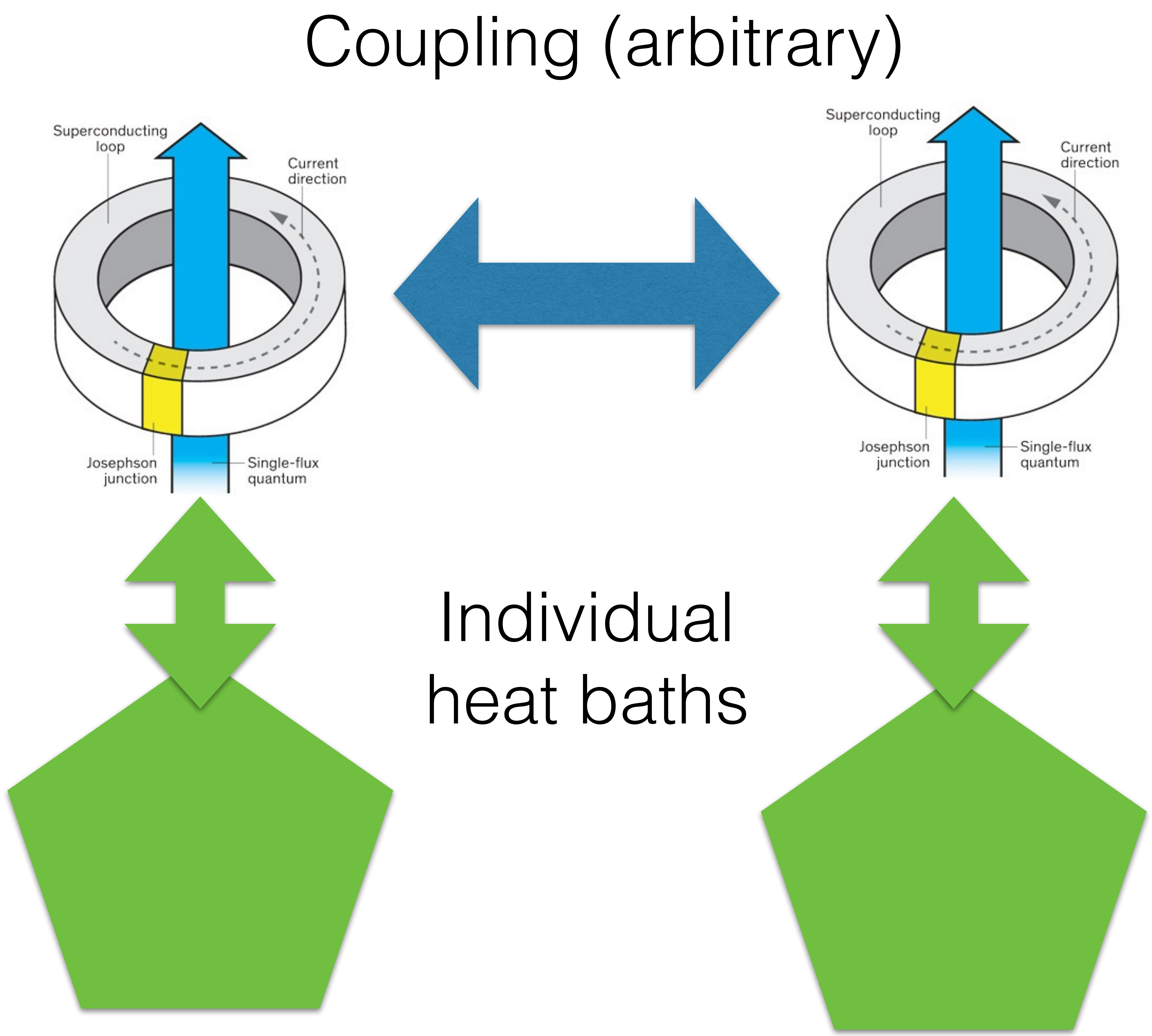
A technical note

- Adiabatic renormalization visualizes lowest-order *perturbative renormalization group* („Poor man's scaling")

- Higher order calculations typically done with flow equations (Wegner / Kehrein; Glaczek / Wilson)

Dissipative phase transition for many qubits

Setting


Coupling (arbitrary)
Superconducting loop
Current direction
Josephson junction
Single-flux quantum
Superconducting loop
Current direction
Josephson junction
Single-flux quantum
Individual heat baths

From two to many

Disappearance of fixed-point matrix Hamiltonian elements

Recall: Single qubit dressing $H_{Q,\text{eff}} =_{\text{eff}} \langle 0 \,| H_Q |\, 1 \rangle_{\text{eff}}$

Renormalization ratio at cutoff $C =_{\text{eff}} \langle 0 | \hat{\sigma}_x | 1 \rangle_{\text{eff}} = \left(\frac{\Delta_{\text{fix}}}{\omega_c} \right)^{\alpha} < 1$

Matrix element renormalization: Count OD-Elements

$$_{\text{eff}} \left\langle \{\sigma_i\} \left| \hat{H} \right| \{\sigma_i'\} \right\rangle_{\text{eff}} = \left\langle \{\sigma_i\} \left| \hat{H} \right| \{\sigma_i'\} \right\rangle C^{\sum_i |\sigma_i - \sigma_i'|}$$

Energetics of Hamiltonian

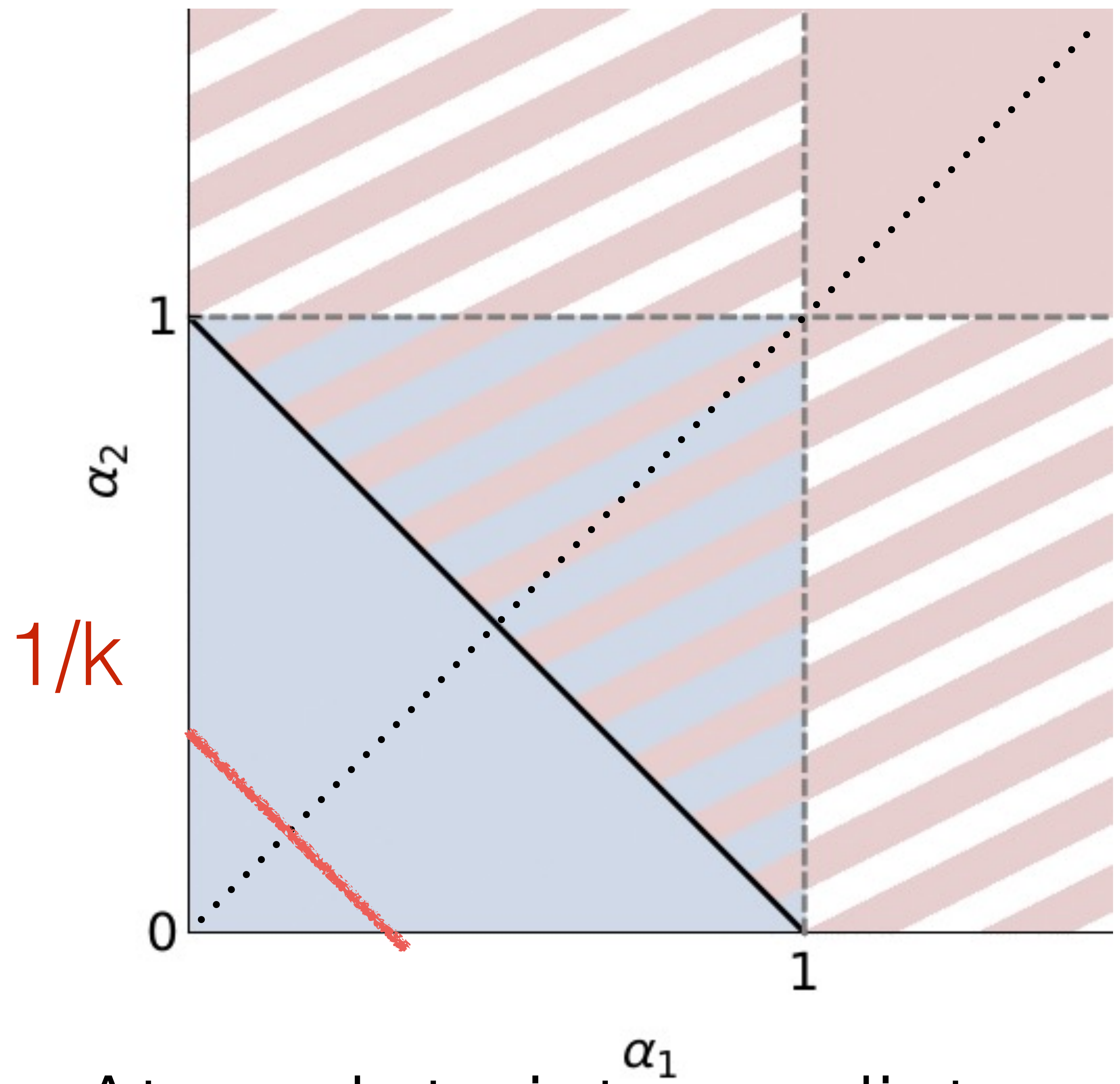
- More lines in the phase diagram

- for a k-local-Hamiltonian: Lines at

$$\alpha = \frac{1}{k}$$

- In coherent phase: weak shift

$$\frac{J_k}{J_0} \simeq 1 - k\alpha \log \frac{\omega_c}{J_0}$$



At weak-to-intermediate coupling, the energetics are safe

Structure of the ground state

In **spin systems**, short-range interactions create long-range order

In **quantum annealers**, k-local interactions can create N>k weight entanglement

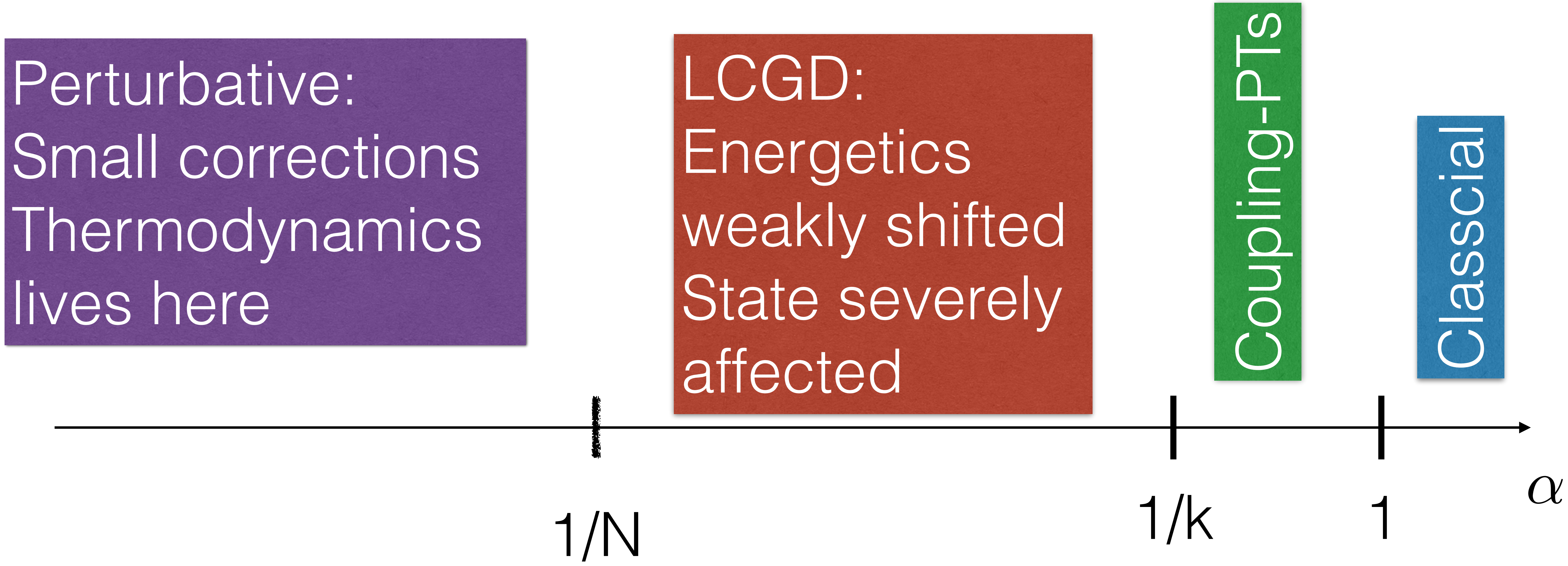
Reduced density matrix of the ground state

$$\langle\{\sigma_i\}|\hat{\rho}_R|\{\sigma_i'\}\rangle = \langle\{\sigma_i\}|\hat{\rho}|\{\sigma_i'\}\rangle\, C^{\sum_i |\sigma_i - \sigma_i'|}$$

State overlap reduction for system-only obversables

$$\hat{O}_S \equiv \hat{O}_S \otimes \mathbf{1}_B \qquad \left\langle \hat{O}_S \right\rangle = \mathrm{Tr}\left(\hat{O}_S \hat{\rho}_R\right)$$

Regimes and clarifications



N-qubits, k-Local Hamiltonian, k<<N

Locally coherent globally dephased (LCGD) regime

Eigenstate thermalization in perturbative regime!

Working in the LCGD regime

Relevance:
At N=1000 and k=2 (or 4), this is where most current annealers are / could be

Compute ground-state DM with local dephasing channels

One qubit $D_1 : \rho_1 \mapsto C\rho_1 + (1-C)\sigma_z\rho\sigma_z$

Quantum annealer $D^{\otimes N}$

Related to GHZ-state dephasing

$|0\rangle^{\otimes N} + |1\rangle^{\otimes N}$ Survives with probability C^N

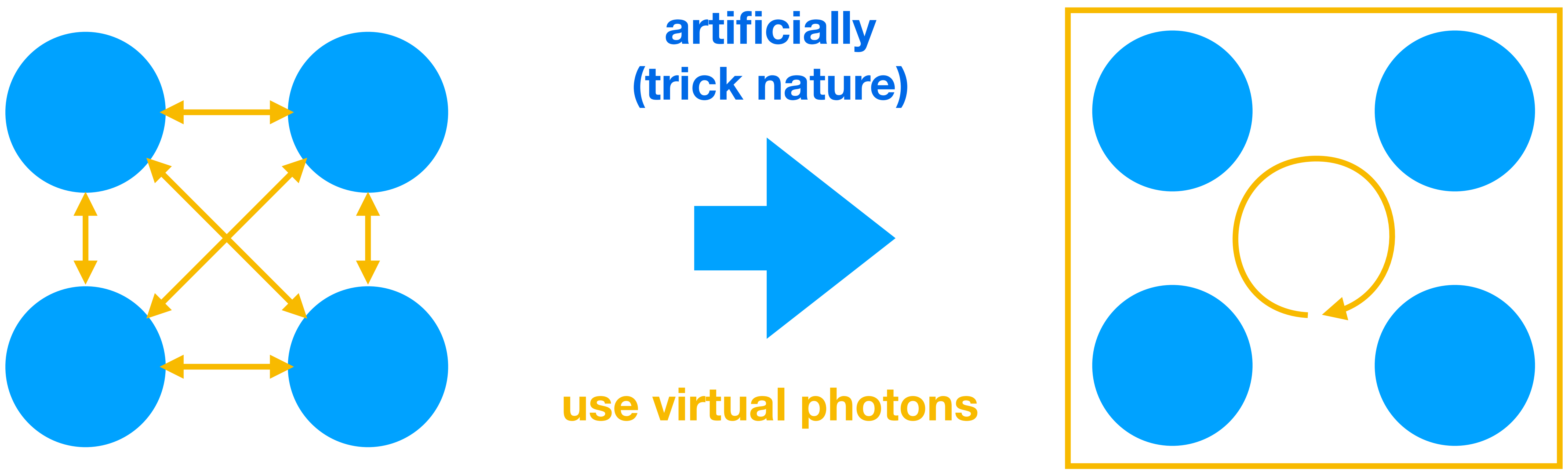
Error sensitivity of QA

- ultimately also hit by decoherence - no cheating
- much more subtle
- huge advantage in short time (1/N vs. 0.001/N)
- more forgiving of control inaccuracies
- simple error supression goes far
- expect disruption before error correction
- community is working on speedup manifesto

Nonpairwise interactions

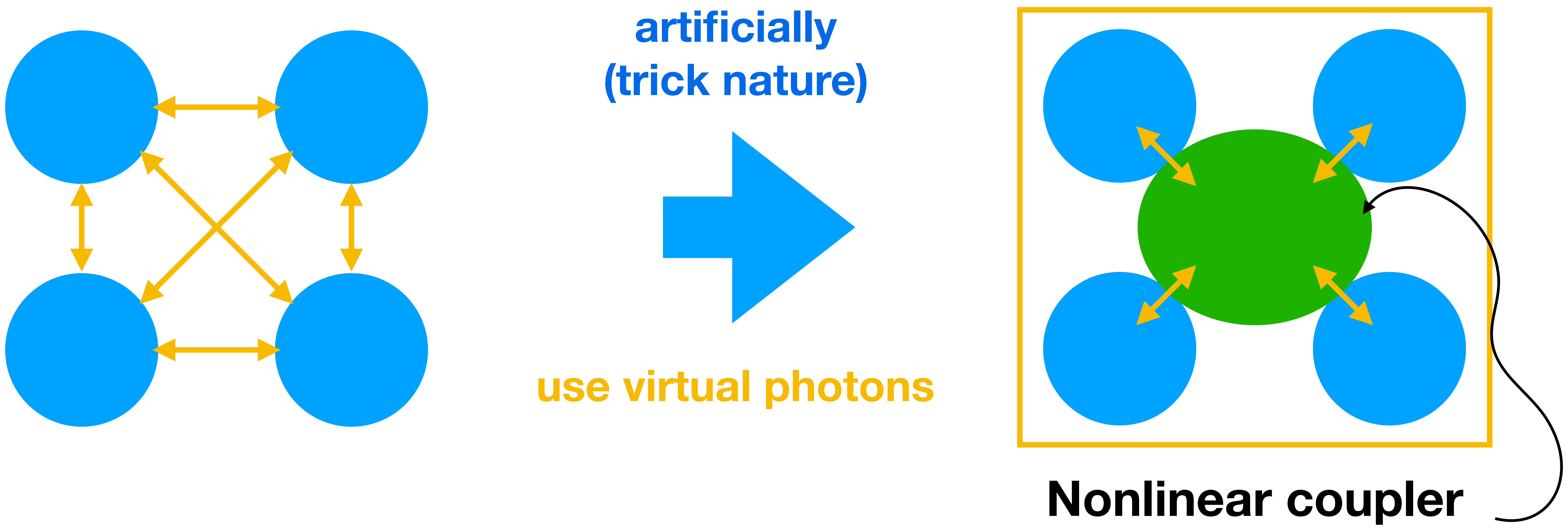
Motivation

- In electrical circuit nature only provides pairwise interactions



Idea+Motivation

- In electrical circuit nature only provides pairwise interactions



- **Virtual photons lead to higher order correlations**
- **purely quartic coupler**

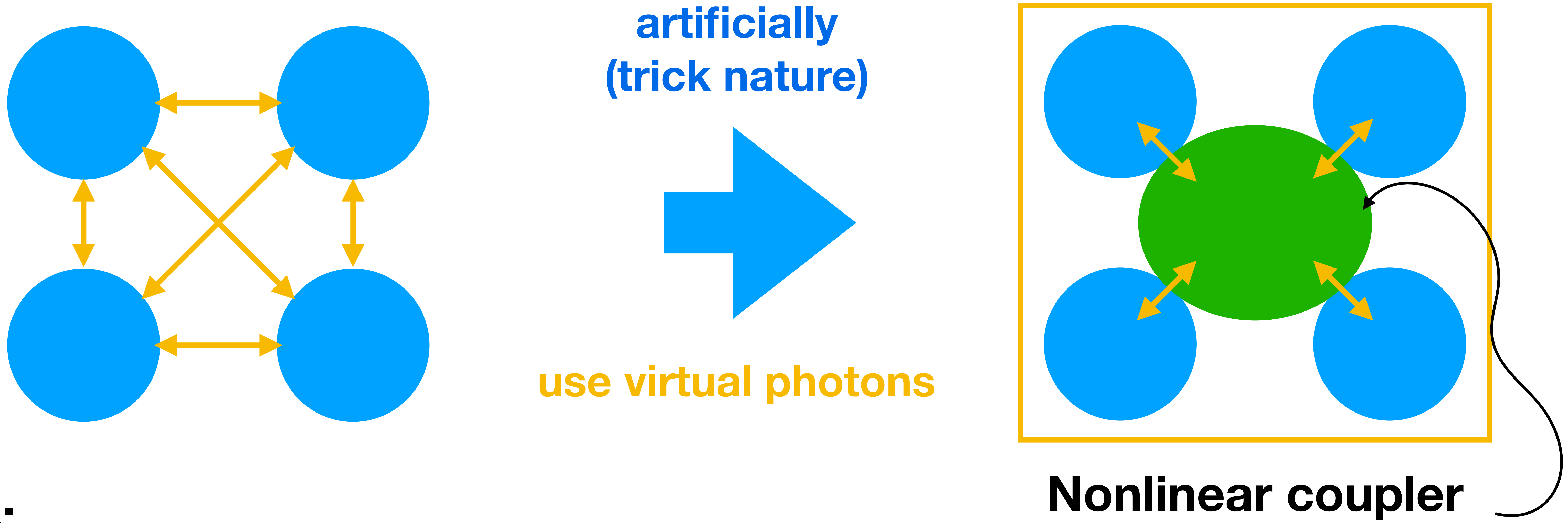
$$\Rightarrow \hat{H}_{\text{int}} \propto \hat{\sigma}_{z,1}\hat{\sigma}_{z,2}\hat{\sigma}_{z,3}\hat{\sigma}_{z,4}$$

Four local

Idea+Motivation

UNIVERSITÄT DES SAARLANDES

- In electrical circuit nature only provides pairwise interactions



Applications:

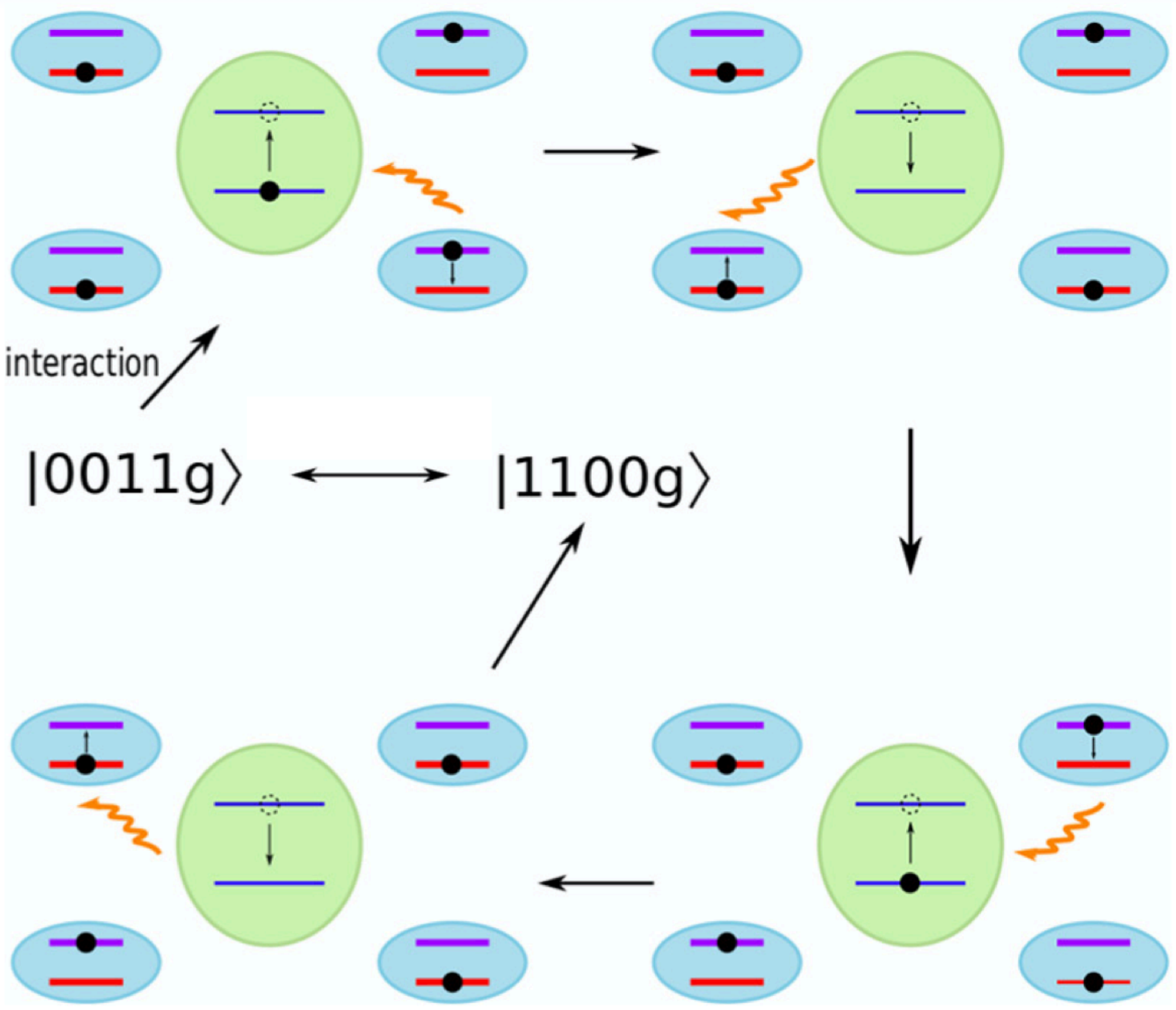
- **Universal AQC**
- **Error correction for AQC**
- **Reduce embedding overhead**
- **Fundamentally interesting**

- **Virtual photons lead to higher order correlations**
- **purely quartic int. potential**

$$\Rightarrow \hat{H}_{\mathrm{int}} \propto \hat{\sigma}_{z,1}\hat{\sigma}_{z,2}\hat{\sigma}_{z,3}\hat{\sigma}_{z,4}$$

Four local

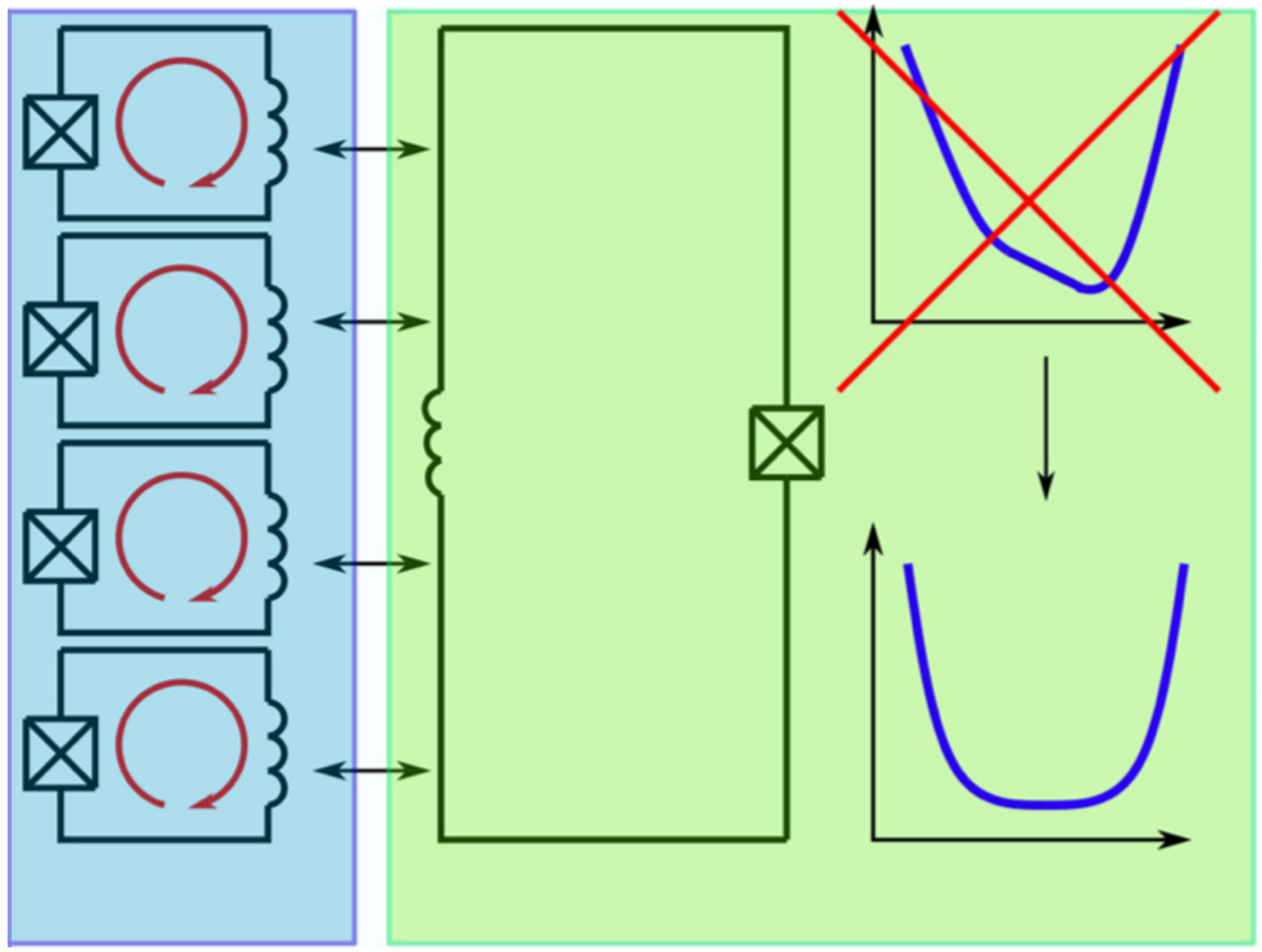
Virtual interactions



Schrieffer-Wolff: Higher order processes lead to nonpairwise interactions

[8] Schöndorf and Wilhelm, Phys. Rev. Appl. 20.012305 (2019)

Setup and Hamiltonian

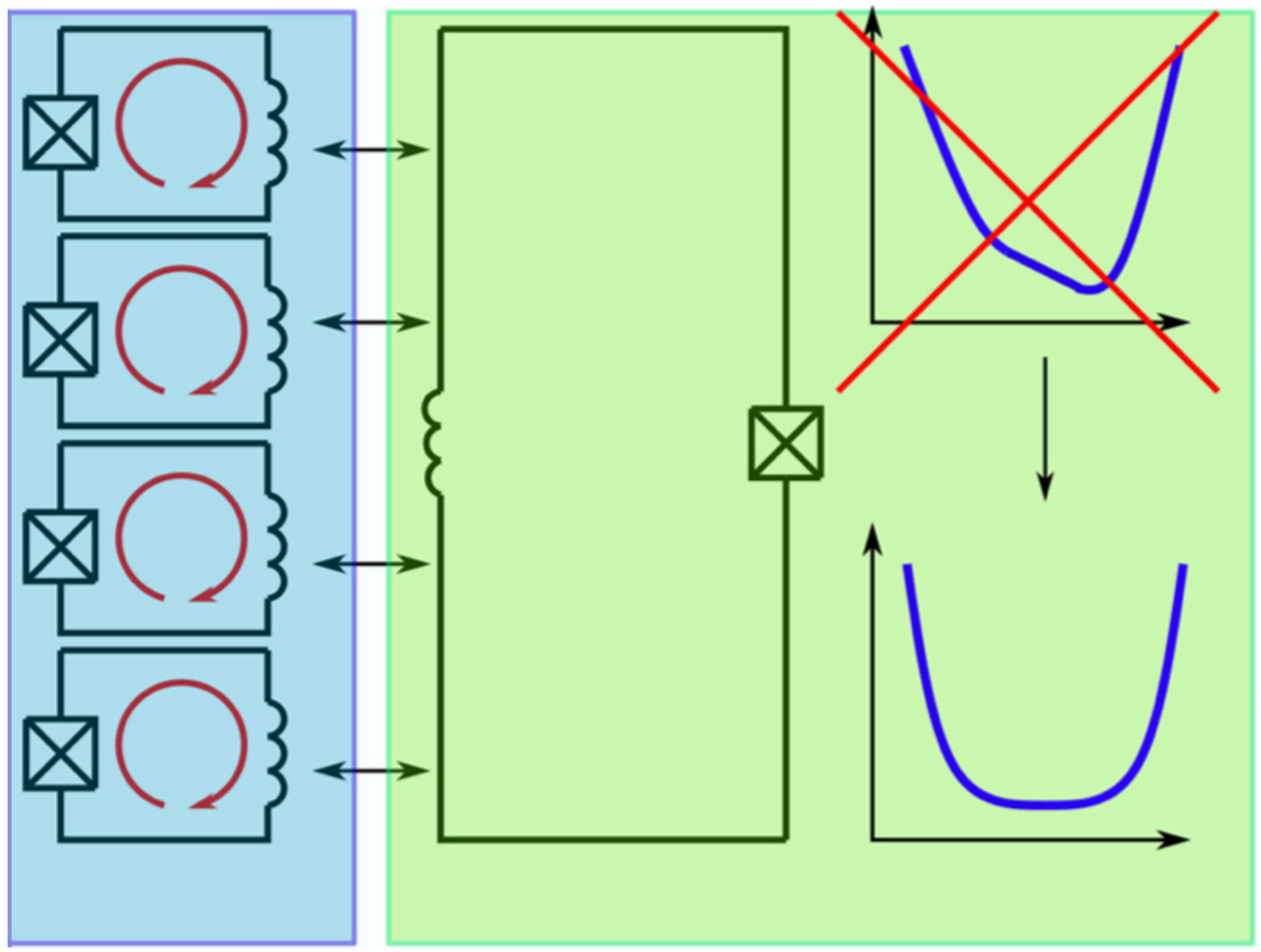


- Four flux quits coupled via large rf SQUID $\Rightarrow$ nonlinear coupler
- Inductively coupled
- $\omega_c \gg \omega_{\mathrm{QB}}$

In qubit basis:

$$\hat{H}_{\mathrm{int}} \propto \tilde{\alpha}^2 \sum_{i,j=1}^{4} \hat{\sigma}_{z,i}\hat{\sigma}_{z,j} + \tilde{\alpha} \sum_{i=1}^{4} \hat{\sigma}_{z,i}\hat{\varphi}_c$$

Setup and Hamiltonian



- Four flux quits coupled via large rf-SQUID ⇒ nonlinear coupler
- Inductively coupled
- $\omega_c \gg \omega_{\text{QB}}$

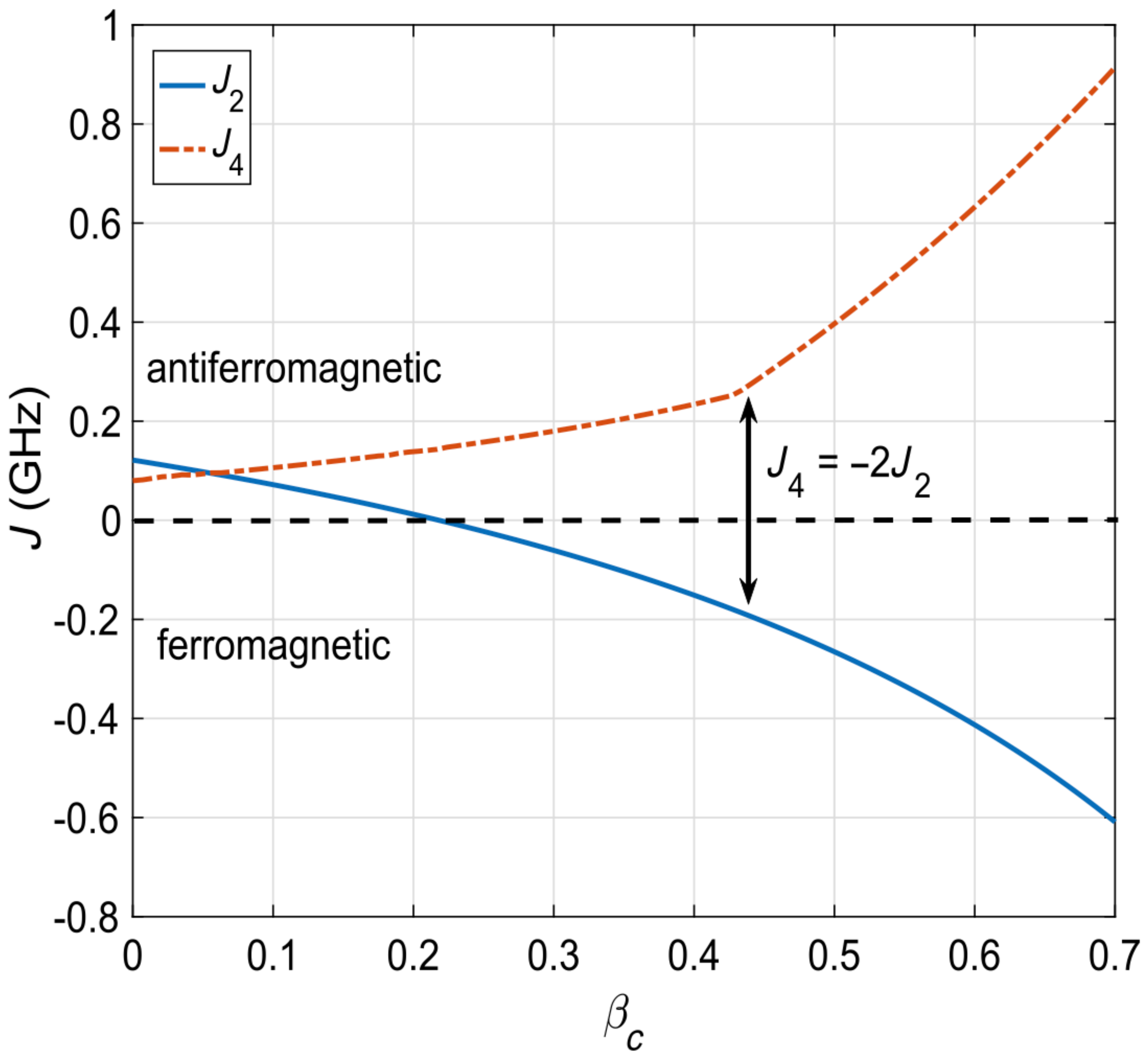
In qubit basis:

$$\hat{H}_{\text{int}} \propto \tilde{\alpha}^2 \sum_{i,j=1}^{4} \hat{\sigma}_{z,i}\hat{\sigma}_{z,j} + \tilde{\alpha} \sum_{i=1}^{4} \hat{\sigma}_{z,i}\hat{\varphi}_c$$

Direct qubit-qubit coupling

Indirect coupling

Results



- For the right parameters:
  $J_4 > J_2$
- Four body couplings in the strong coupling regime
- Suppress J_2 using external flux

[8] Schöndorf and Wilhelm, Phys. Rev. Appl. 20.012305 (2020)

Obervations on annealing

	Gate model	Annealing
Short term	**NISQ:** Memory-limited algorithms Competition with early starters about 50-100 qubits significant microwave engineering Short-range coupling - long range gate delegated into software (with overhead)	**d-Wave** Incoherent qubits Limited connectivity: can be simulated with spin-vector monte carlo > 2000 Devices simple high-speed engineering Long-range interactions embedded
Long term	**FTQC:** All algorithms Enormous qubit overhead (>1000 physical per logical) Currently on a very primitive level significant system integration (multi-cryostat) short-range coupling sufficient	**Universal annealing** All algorithms accessible Early start on coherence - simple error mitigation goes a long way Only IARPA projects - accessible? Complex controls (NISQ-level) Delegate interactions to physical level

European annealing readiness

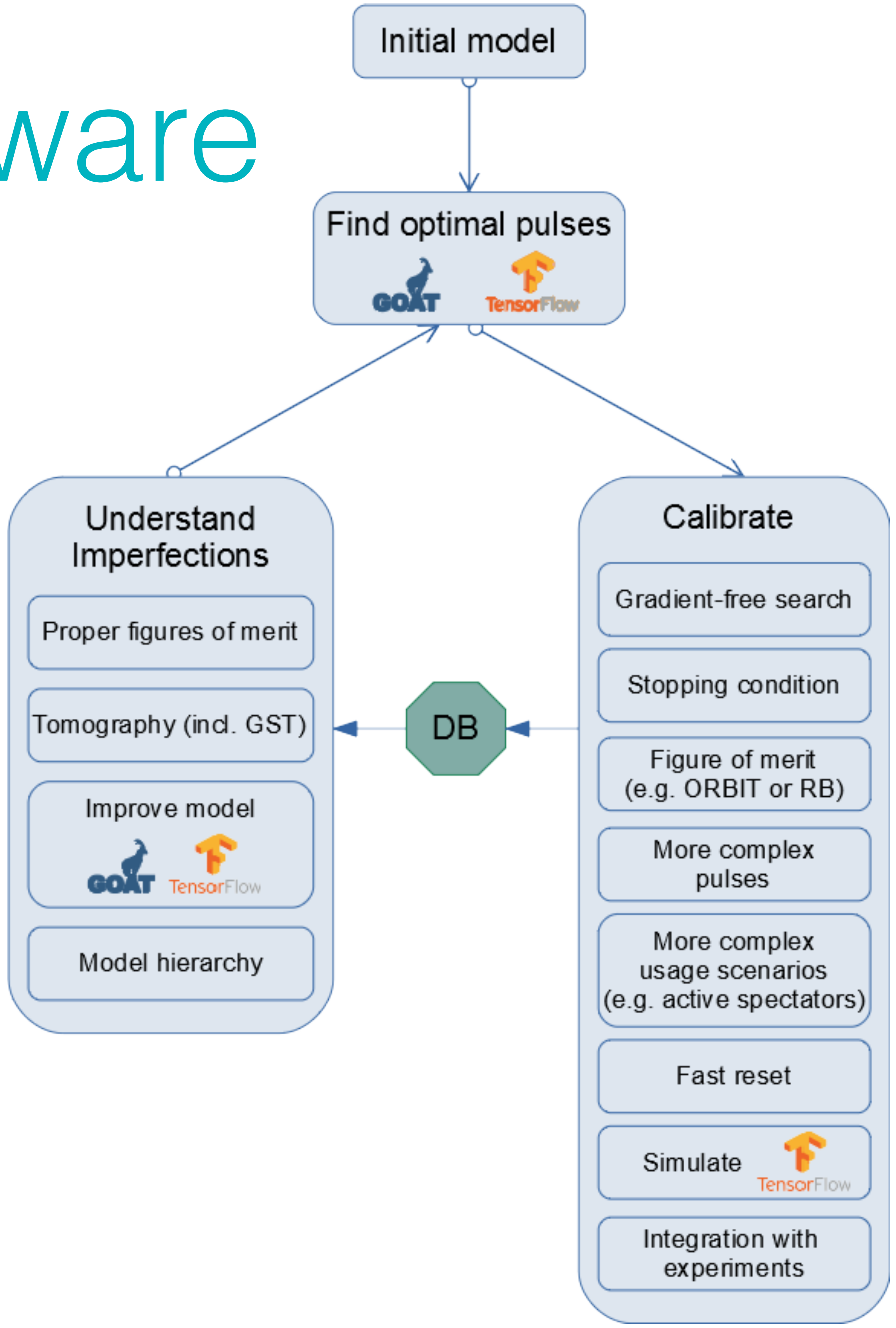
- European users (HPC, companies) interest in AQC/ Annealing
- So far only overseas partnerships
- disappointed by d-wave's performance
- Alternative would be highly welcome

- Europeans physicists set aback by d-Wave's PR
- coherent annealing mostly developed in US (closed) and Japan
- Needs NISQ-type fabrication and infrastructure: European leadership
- Limited competition with other open projects - niche

A possible future

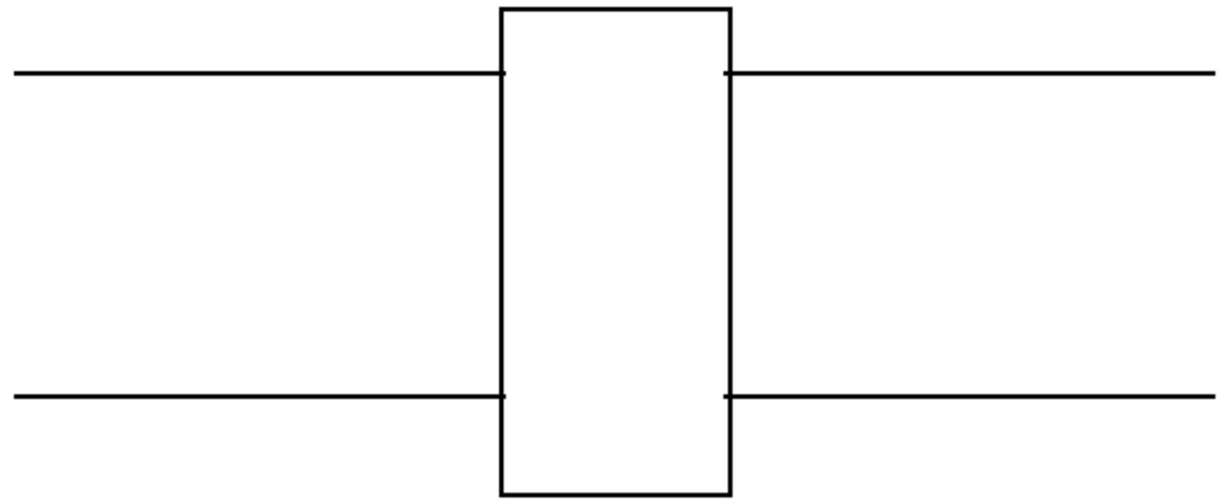
Applications and quantum firmware

- Control, benchmarking, calibration tools
- microarchitecture
- interoperable with openQASM / Qiskit
- platform-agnostic and open source
- Want to know more? Ask for our public deliverable on the software stack description



OpenSuperQ

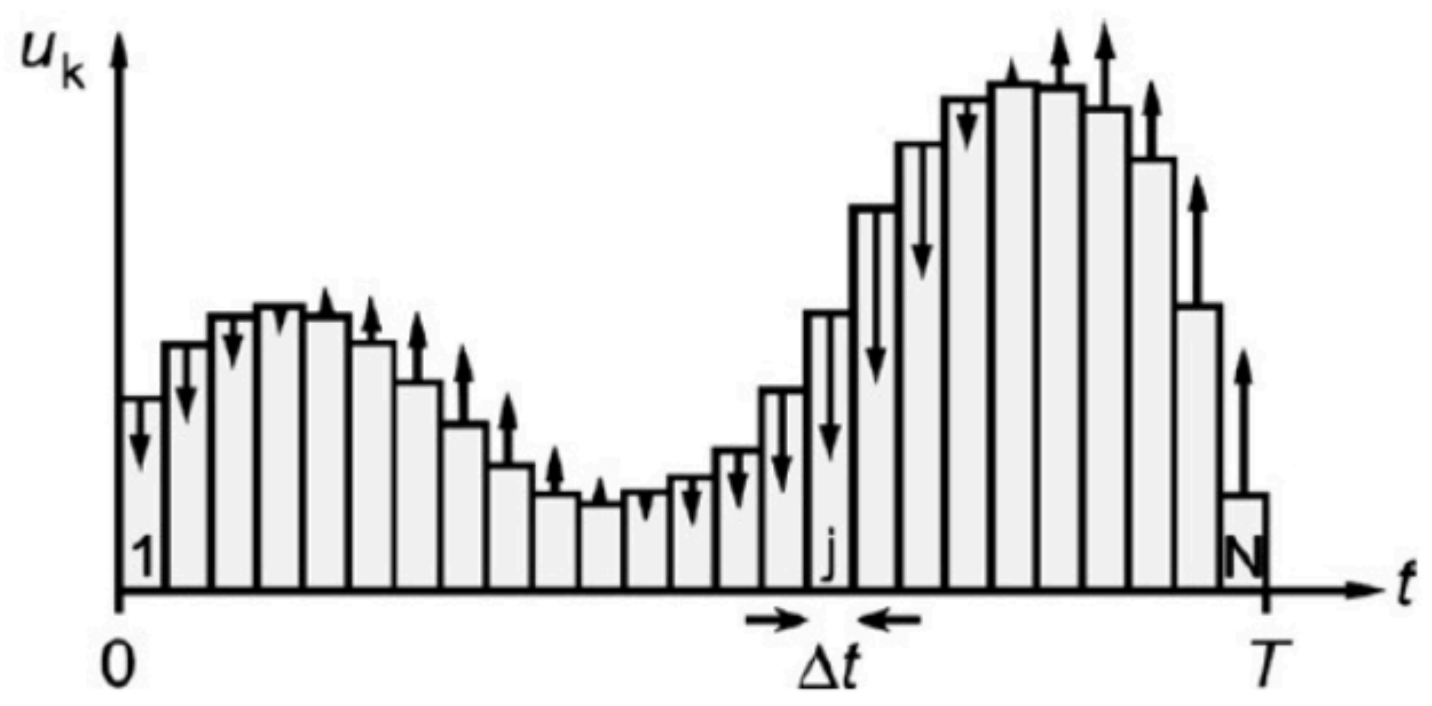
Analog gate design



$$\hat{U}_{\text{gate}}(t_{i+1}, t_i): \quad i\partial_t \hat{U}(t, t_i) = \hat{H}(t)\hat{U}(t, t_i)$$

$$\hat{H} = \hat{H}_0 + \sum_i u_i(t)\hat{H}_i$$

Find controls implementing U
fast and reliably:
Analog control problem



Practical wishlist:

Fast (limited coherence!)
Simple (easy to calibrate)
Robust (tolerate fluctuations)

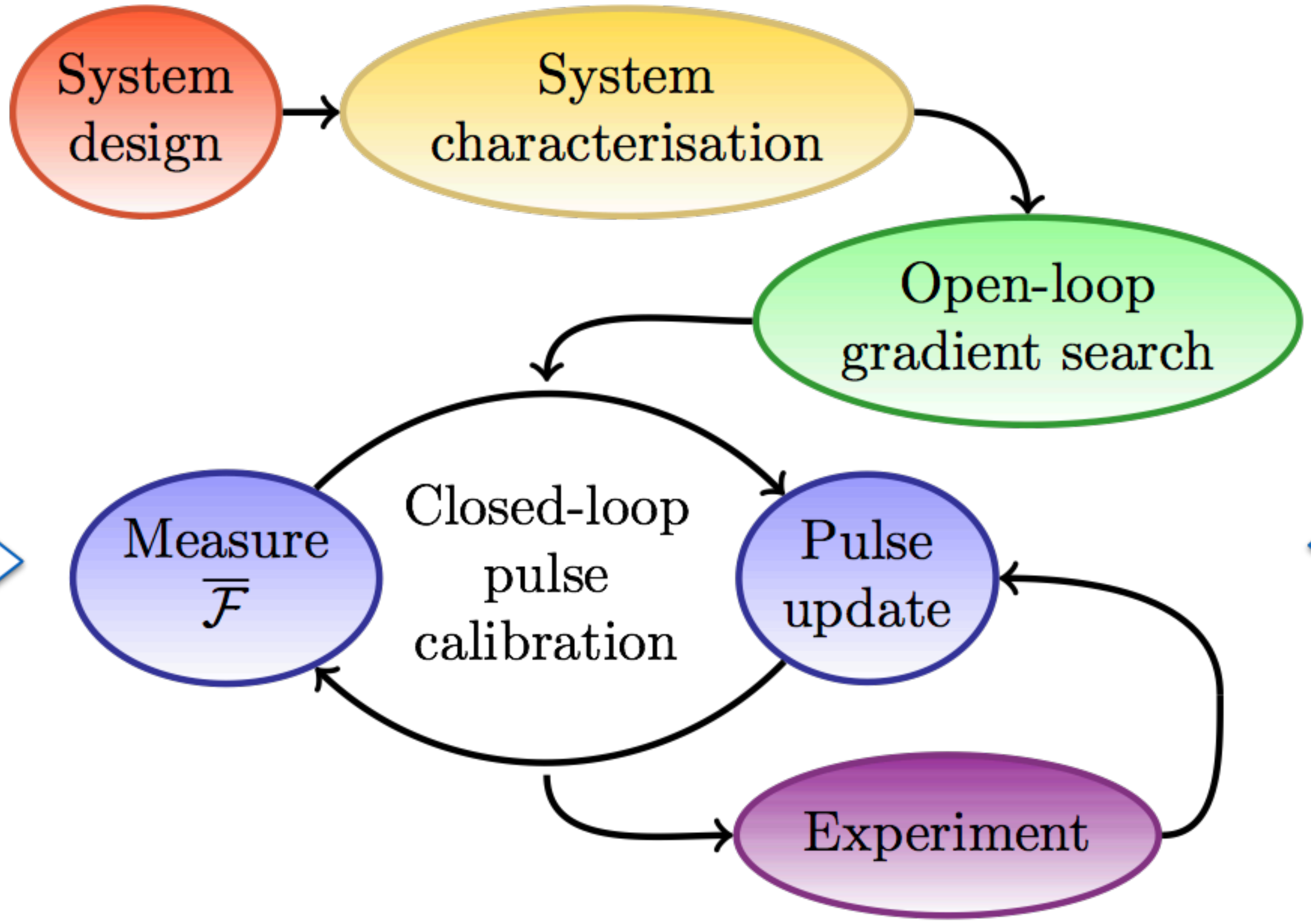
Find controls that maximize fidelity

S.J. Glaser et al., EPJ D 2015

OpenSuperQ

Adaptive Hybrid Optimal Control

Good benchmarking needed



Simple pulses needed

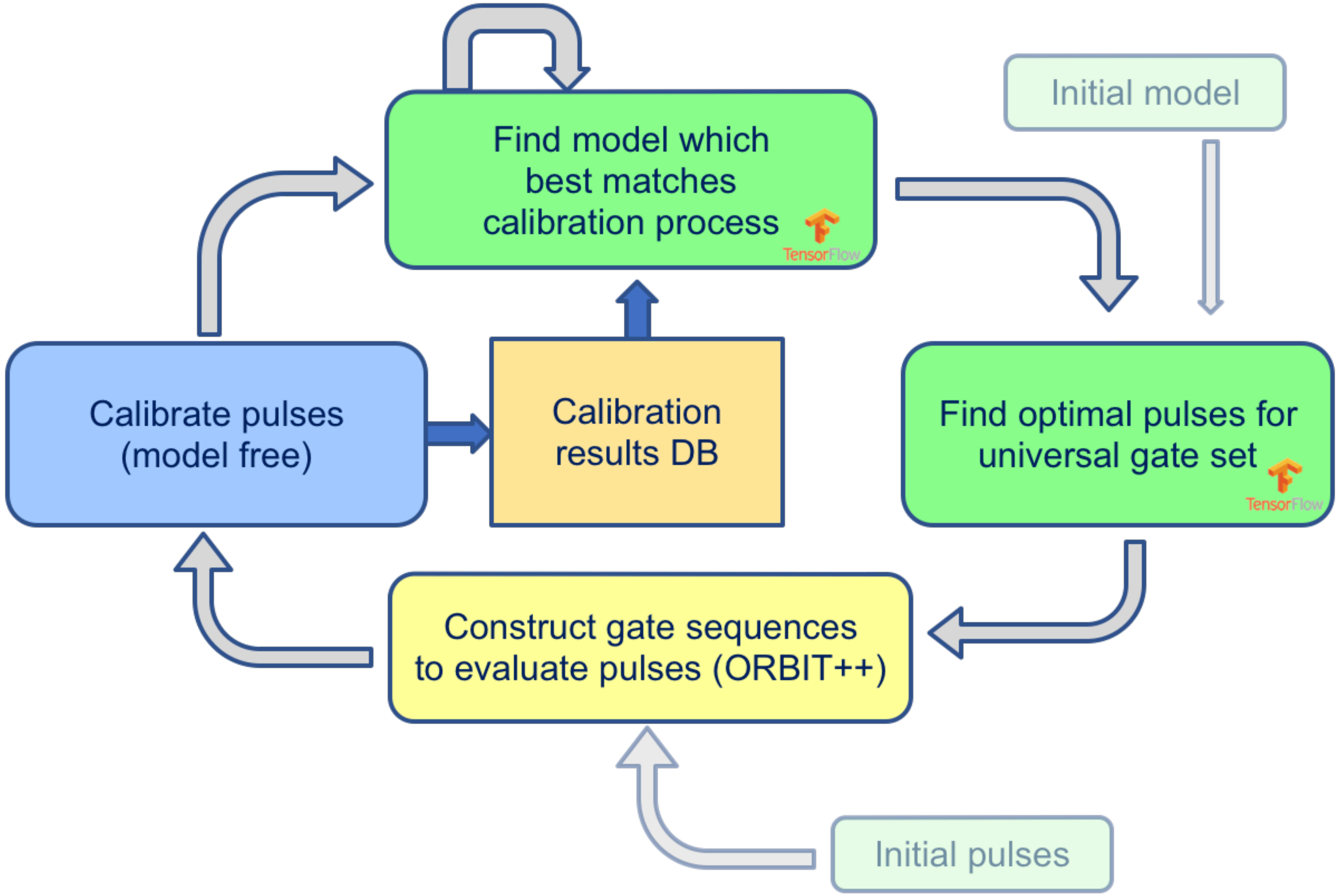
J. Kelly et al., PRL 2014

Note the analogy with VQE / QAOA

D.J. Egger and FKW, PRL 2014

OpenSuperQ

C³: Combined Calibration and Characterization



Open-source (permissive), Python

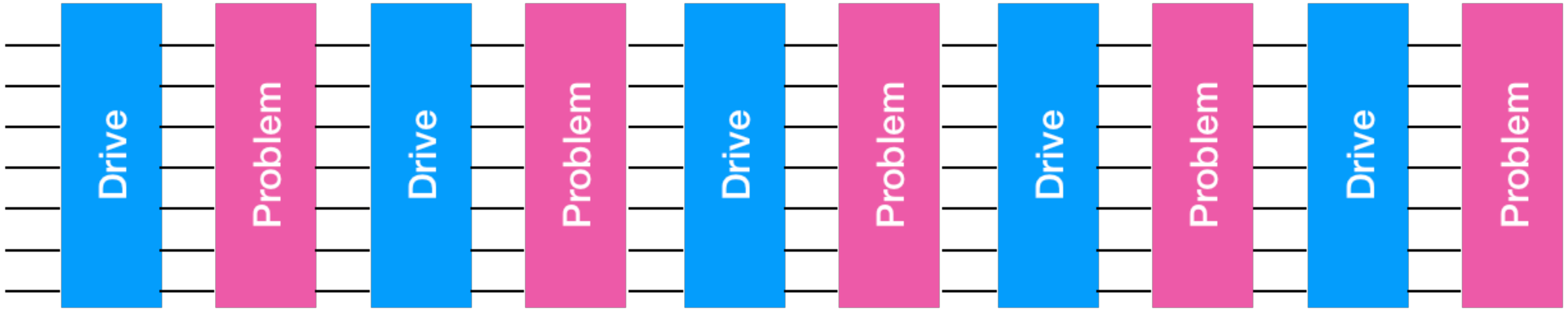
QAOA / Digitized AQC for combinatorical optimization

Problem Hamiltonian: Ising-type $H_p = \sum_i h_i Z_i + \sum_{i<j} J_{ij} Z_i Z_j + \ldots$ $\quad \exp\left(-i\beta_i H_p\right)$

Driver Hamiltonian: Tunneling $H_d = -\frac{\Delta}{2} \sum_i X_i$ $\quad \exp\left(-i\gamma_i H_d\right)$

$$\hat{H} = \hat{H}_0 + \sum_i F_i(t) \hat{H}_i$$

$$\hat{H} = \sum_i \hat{H}_i(t) + \sum_{i<j} \hat{H}_{ij}(t)$$



β_1 γ_1 β_2 γ_2 … β_{n-1} γ_{n-1} β_n γ_n

Measure: $\left\langle \beta, \gamma \middle| H_p \middle| \beta, \gamma \right\rangle$ **Classically minimize** $\beta = \{\beta_i\}$ $\gamma = \{\gamma_i\}$

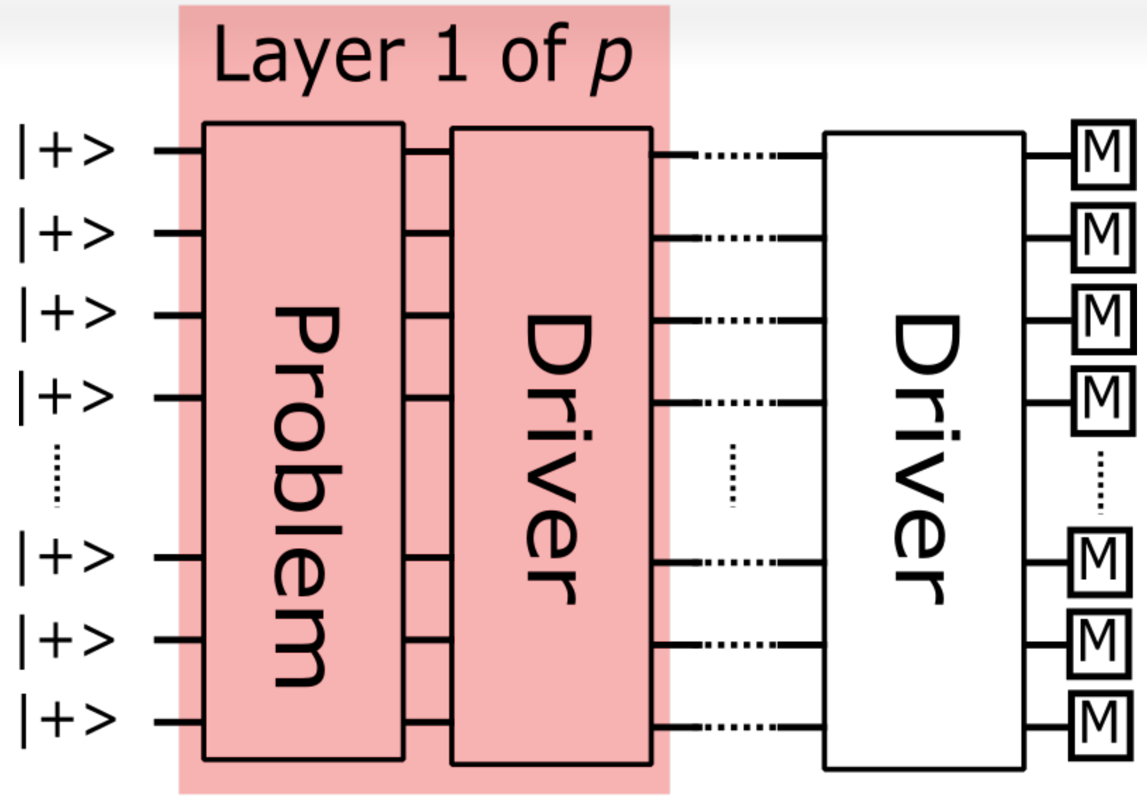
Digital Analogue QAOA

QAOA

- Alternate non-commuting parameterized operators

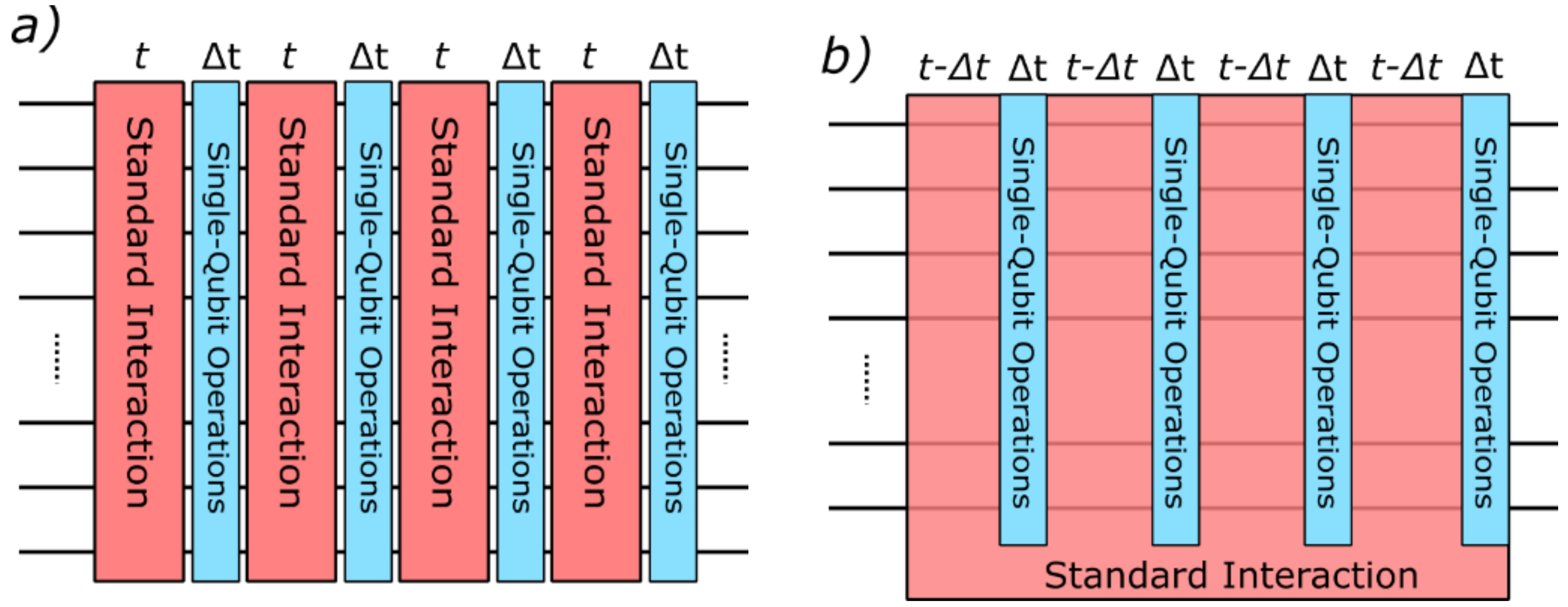
$$\left|\vec{\beta},\vec{\gamma}\right\rangle = \prod_{p'=0}^{p} e^{i\beta_{p'}H_{\mathrm{D}}} e^{i\gamma_{p'}H_{\mathrm{P}}} |+\rangle^{\otimes n}$$

- Classical optimiser maximises expectation value of a problem solution



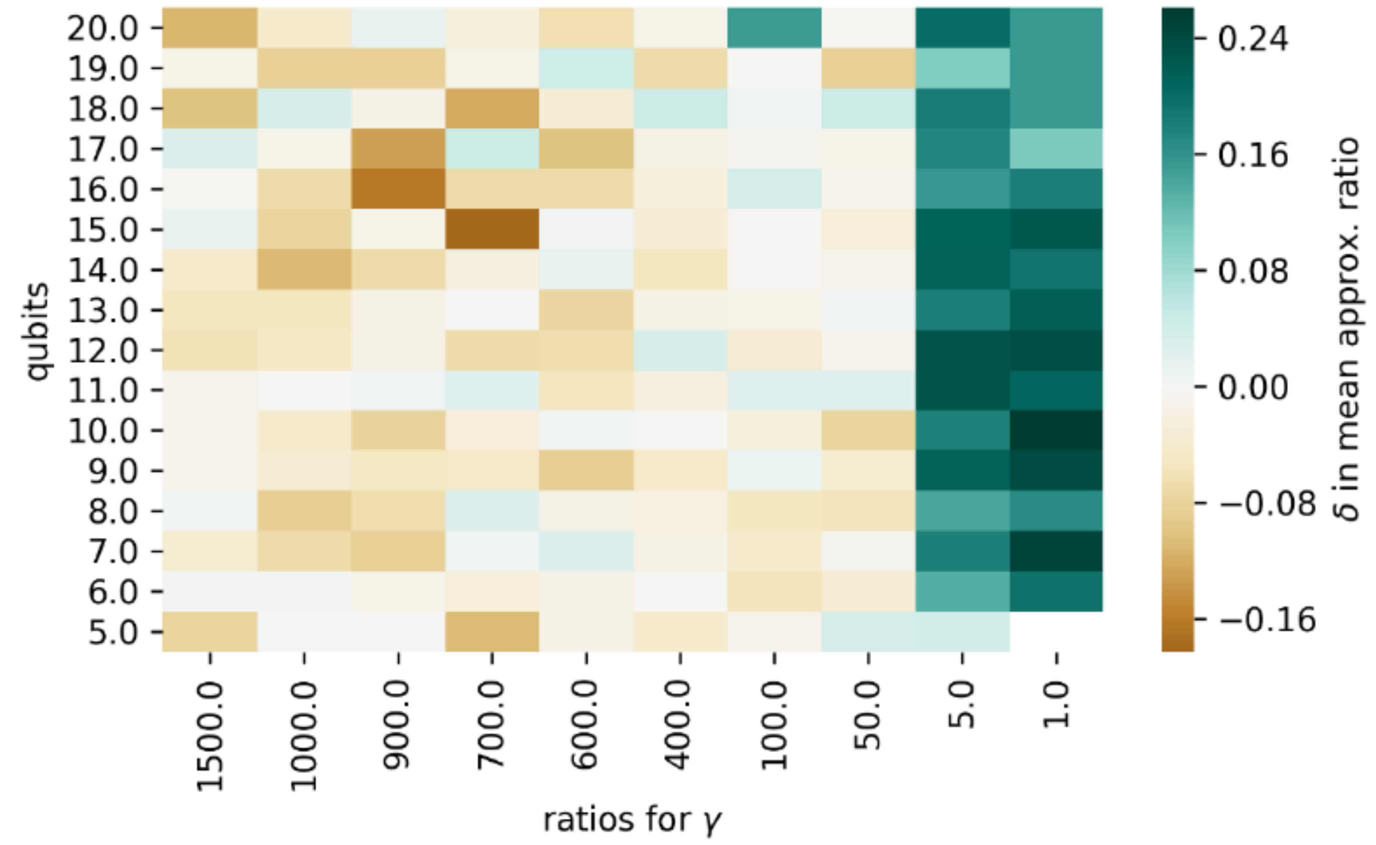
Digital Analogue Scheme

- Express all two-qubit operations in terms of an all-to-all resource
- Use single-qubit operations to 'steer' this resource Hamiltonian
- If resource always on simultaneity of resource and single qubit ops causes error

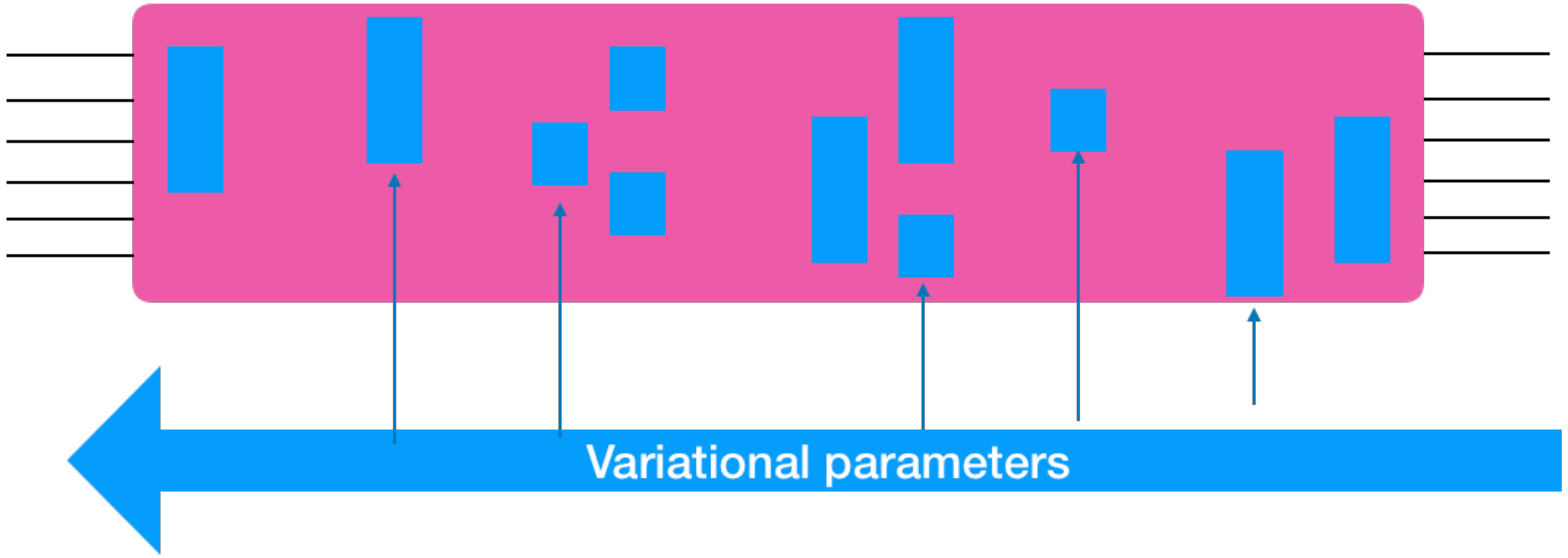


DA-QAOA

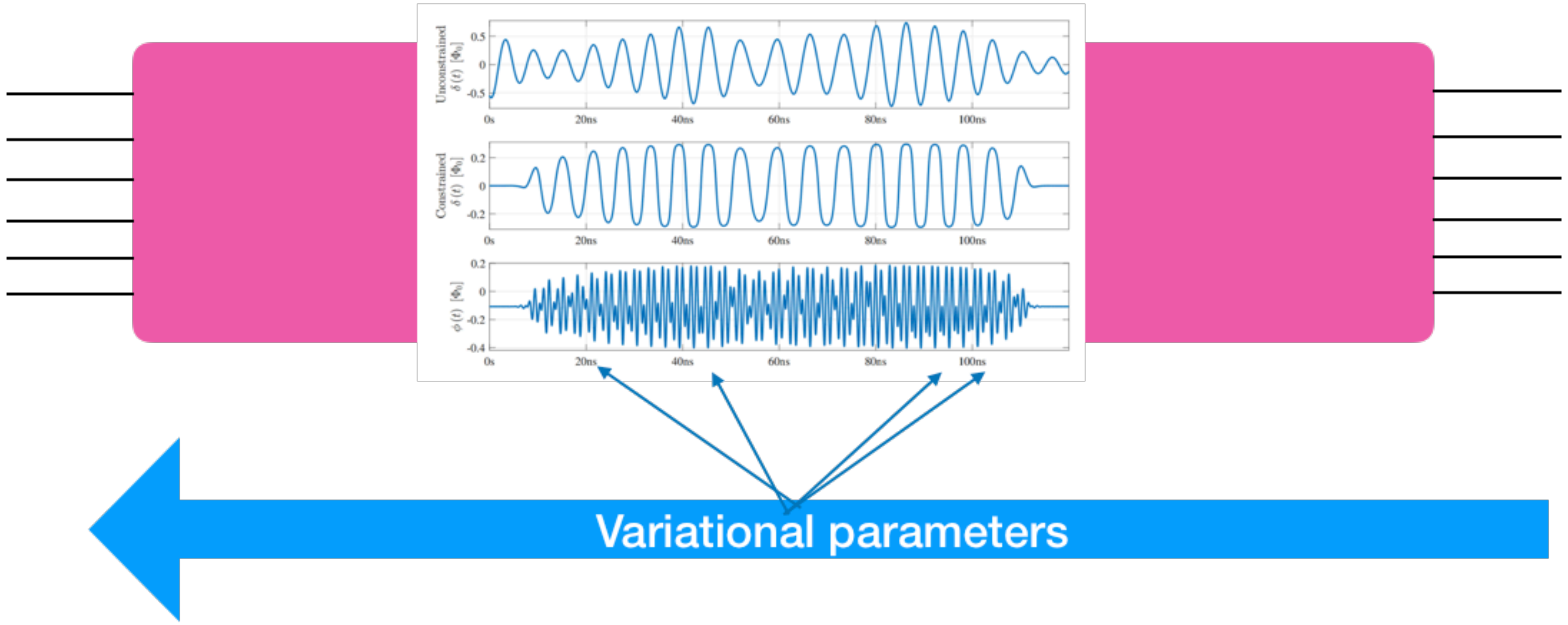
- QAOA problem Hamiltonians suit DA scheme, easy to express
- QAOA can use variational freedom to 'eat' coherent DA error
- Faster single-qubit operations improve performance



Many ways to write an algorithm



Gate-based algorithm
Universal gate set
Tuneup of gates



Optimal control
Controllability
Analogue programming

Conclusions

- 3 paths to quantum computing
- early stages with fast development
- multitude of platforms
- coherent annealing: the grey horse of quantum computing