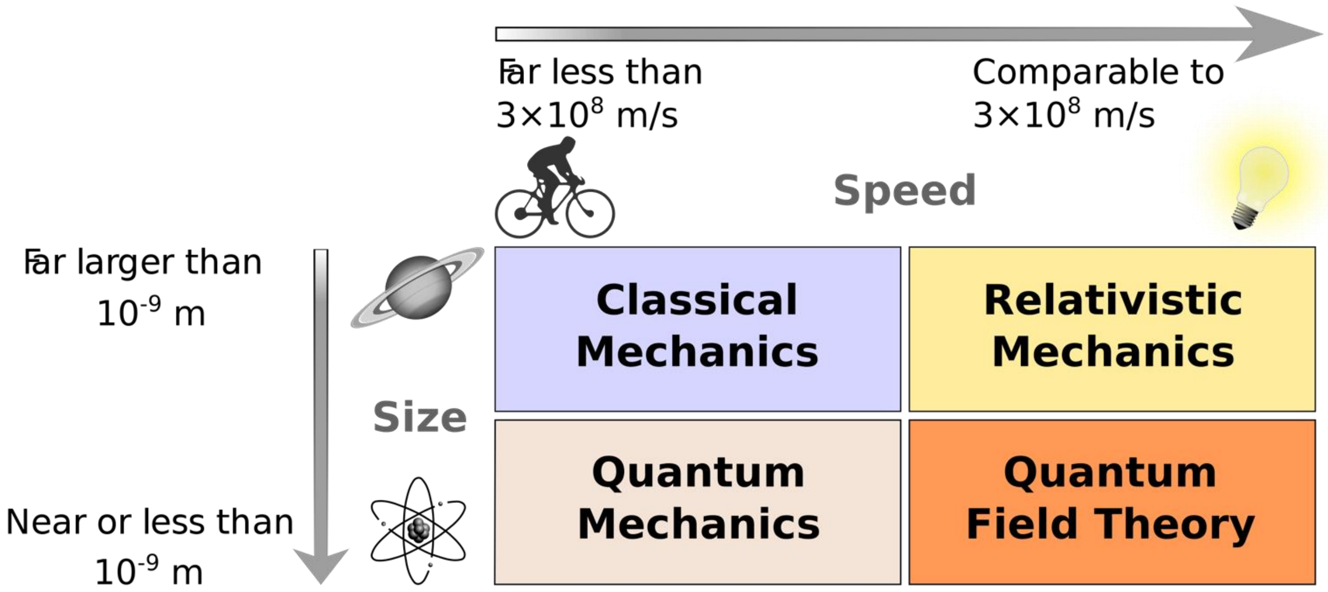
Quantum algorithm design for many-body simulation

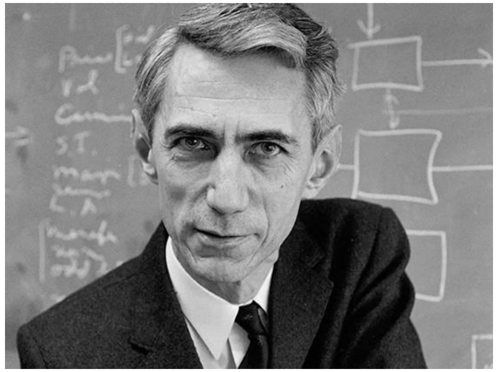
Prof. Dr. Mario Berta

LMU Munich April 30th, 2025

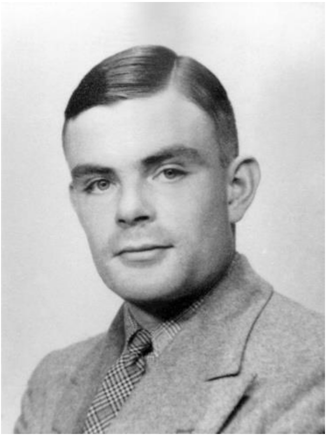
Information science

- Theory of information processing: Mathematical foundations in 1940s
- Abstract theory independent of implementation





Claude Shannon



Alan Turing

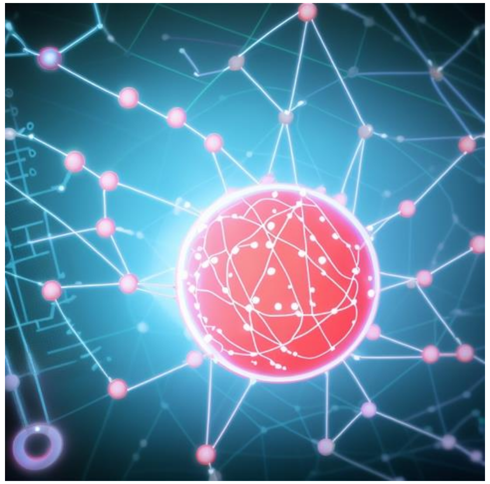
- Question: Also independent of underlying physics?

Quantum information science

- Notion of information for microscopical systems described by quantum mechanics? Quantum information $\neq$ classical information

- Bell's theorem (1964): Quantum mechanics is incompatible with local hidden-variable theories

John Stewart Bell



- New research area based on quantum technologies: Computing, communication, cryptography, sensing, …

Research group

JARA INSTITUTE QUANTUM INFORMATION

AN INITIATIVE OF

RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

- Institute for Quantum Information (IQI)
- Theory of quantum information science
- Members:

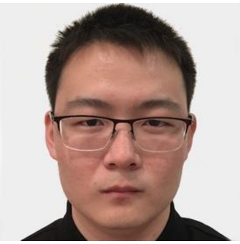
Mario Berta
Professor of Physics

Sreejith Sreekumar
Postdoc

Aditya Nema
Postdoc

Aadil Oufkir
Postdoc

Yongsheng Yao
Postdoc



Michael X. Cao
Postdoc

+ open PhD and postdoc positions, get in contact!

Tobias Rippchen
PhD student

Julius Zeiss
PhD student

Gereon Koßmann
PhD student

Nikolaos Louloudis
PhD student

Richard Meister
Postdoc (Imperial)

+ 5x Master students
RWTH Physics /
Computer Science

Theory of quantum information science

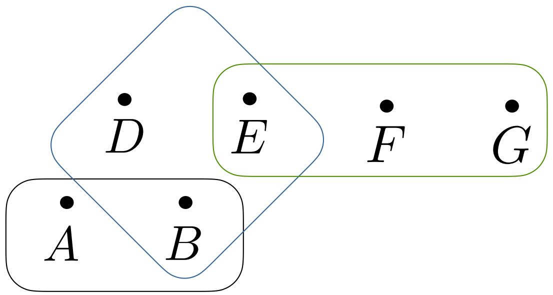
- Our focus areas:
  A. Mathematical foundations of quantum information
  B. Quantum algorithm development
- Cluster of Excellence: Matter and Light for Quantum Computing (ML4Q)
- Visiting Reader at Department of Computing Imperial College London
- Industry ties, e.g., with Amazon Web Services Center for Quantum Computing

A. Mathematics of quantum information

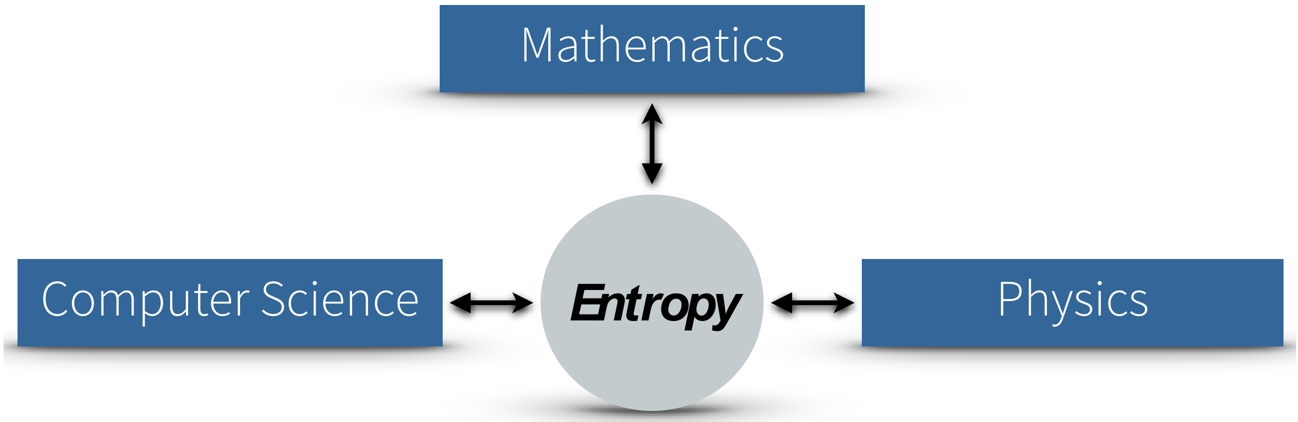
Mathematics of quantum information

European Research Council

- QENTROPY: Entropy inequalities for quantum states reveal their structure



- Entropy for multipartite quantum systems: Entanglement leads to non-commutativity
- Methods from matrix analysis and operator algebras: Symbiosis of quantum information with rigorous tools from mathematical physics



- Applications in quantum
  - statistics
  - Shannon theory
  - cryptography
  - error correction
  - algorithms

Example: Tools for non-commutativity

- Matrix trace inequalities for H_1, H_2 Hermitian

$$\exp\left(H_1 + H_2 + \frac{1}{2}[H_1, H_2] + \cdots\right) = \exp(H_1)\exp(H_2)$$

$$\mathrm{Tr}[\exp(H_1 + H_2)] \leq \mathrm{Tr}[\exp(H_1)\exp(H_2)]$$

→ for $\{H_k\}_{k=1}^{n}$ Hermitian and $\beta_0(t) := \frac{\pi}{2}(\cosh(\pi t)+1)^{-1}$ multivariate extension

$$\left\|\exp\left(\sum_{k=1}^{n} H_k\right)\right\|_{\mathrm{Tr}} \leq \int_{-\infty}^{\infty} \beta_0(t) \cdot \left\|\prod_{k=1}^{n} \exp\left((1+it)H_k\right)\right\|_{\mathrm{Tr}}$$

[Sutter, **B.**, Tomamichel, Comm. Math. Phys. (2017)] [**B.**, Fawzi, Tomamichel, Lett. Math. Phys. (2017)]

- Legendre dual of quantum entropy: $\mathrm{H} \mapsto -\log \mathrm{Tr}[\exp(H)]$

→ leads to novel entanglement monogamy inequalities!

- [**B.**, Brandão, Hirche, Comm. Math. Phys. (2021)]
- [**B.** & Tomamichel, Comm. Math. Phys. (2024)]
- [**B.**, Sutter, Walter, Comm. Math. Phys. (2023)]
- [**B.**, Cheng, Gao, Comm. Math. Phys. (2025)]

More on quantum entropy inequalities

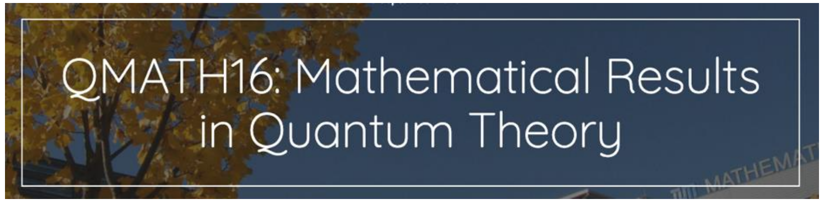
- Preprint: Asymptotic quantification of entanglement with a single copy

  arXiv:2408.07067 (2024) with Lami & Regula
  Quantum Information Processing (QIP) 2025 plenary talk

- 13th workshop on Beyond IID in Information Theory:
  14-18 July 2025 at Technical University of Munich

- QMATH16 Mathematical Results in Quantum Theory:
  1-5 September 2025 at Technical University of Munich

  → invited plenary speaker



- Mathematics of Quantum Information:
  10-12 July 2025 at RWTH Aachen University

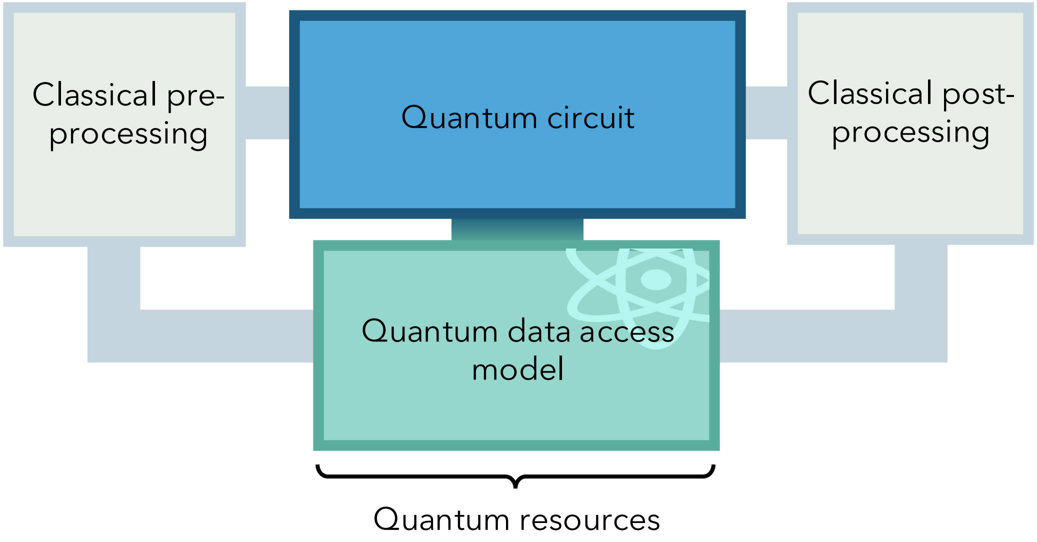
B. Quantum algorithm development

Classical versus quantum technologies

- *Do algorithms based on quantum components, including*
  - *quantum processing units (QPU)*
  - *quantum random access memory (QRAM)*

provide computational advantages compared to classical components?

- Goal is to identify use cases / areas of applications with
  - large (super-quadratic) quantum speed-up
  - minimal quantum footprint, i.e., use classical routines whenever possible
  - no galactic algorithms



Regimes for quantum algorithm design

- Nascent state of quantum technologies gives noisy and intermediate scale quantum (NISQ) computing, i.e.,
  - Quantum annealers
  - Analogue simulators, not universal, not fully programmable
  - NISQ digital quantum circuits, inbuilt noise resilience, error mitigation, severe scaling limitations, etc.
- Versus what one really wants long-term:

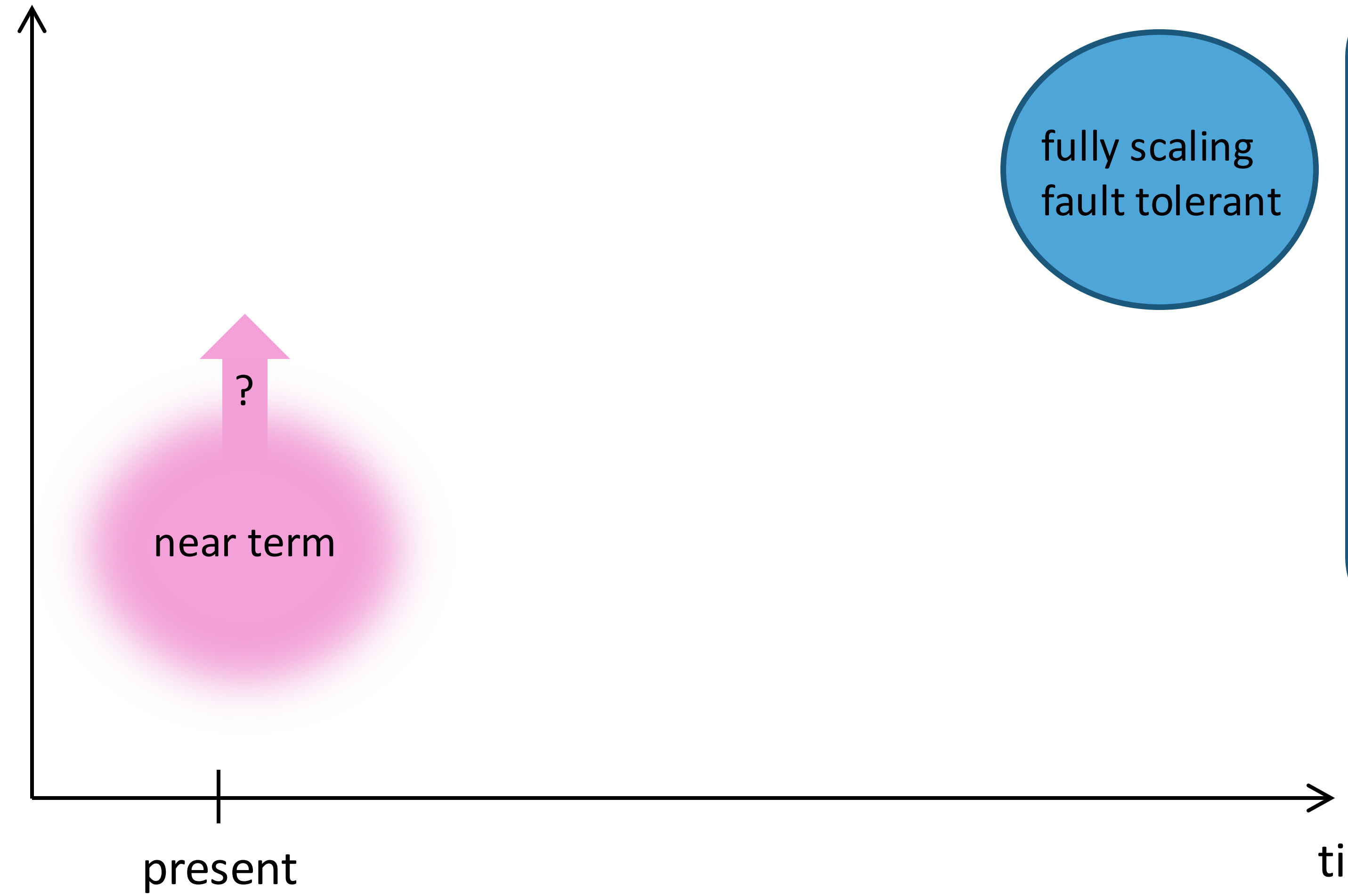
Quantum error-corrected and scaling quantum computer

(roughly two orders of magnitude away)

- What regime is of interest?

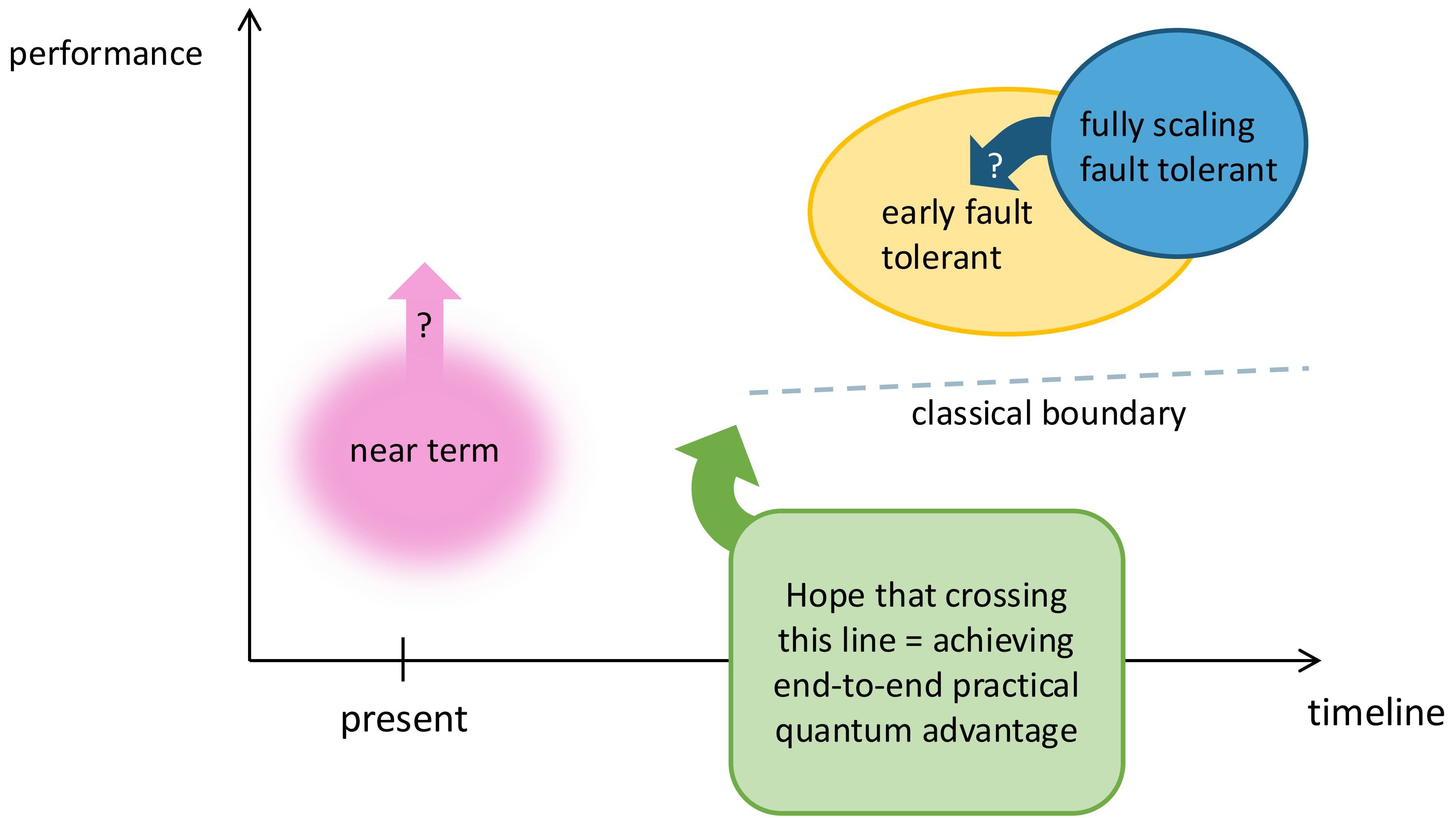
Early fault-tolerant regime

- Run many small circuits
- Leverage some classical power
- Usually no runtime/success guarantees



- Large hardware requirements
- Specified in terms of query complexity
- Runtime guarantees
- Caveats can cloud convincing practical advantage

Early fault-tolerant regime

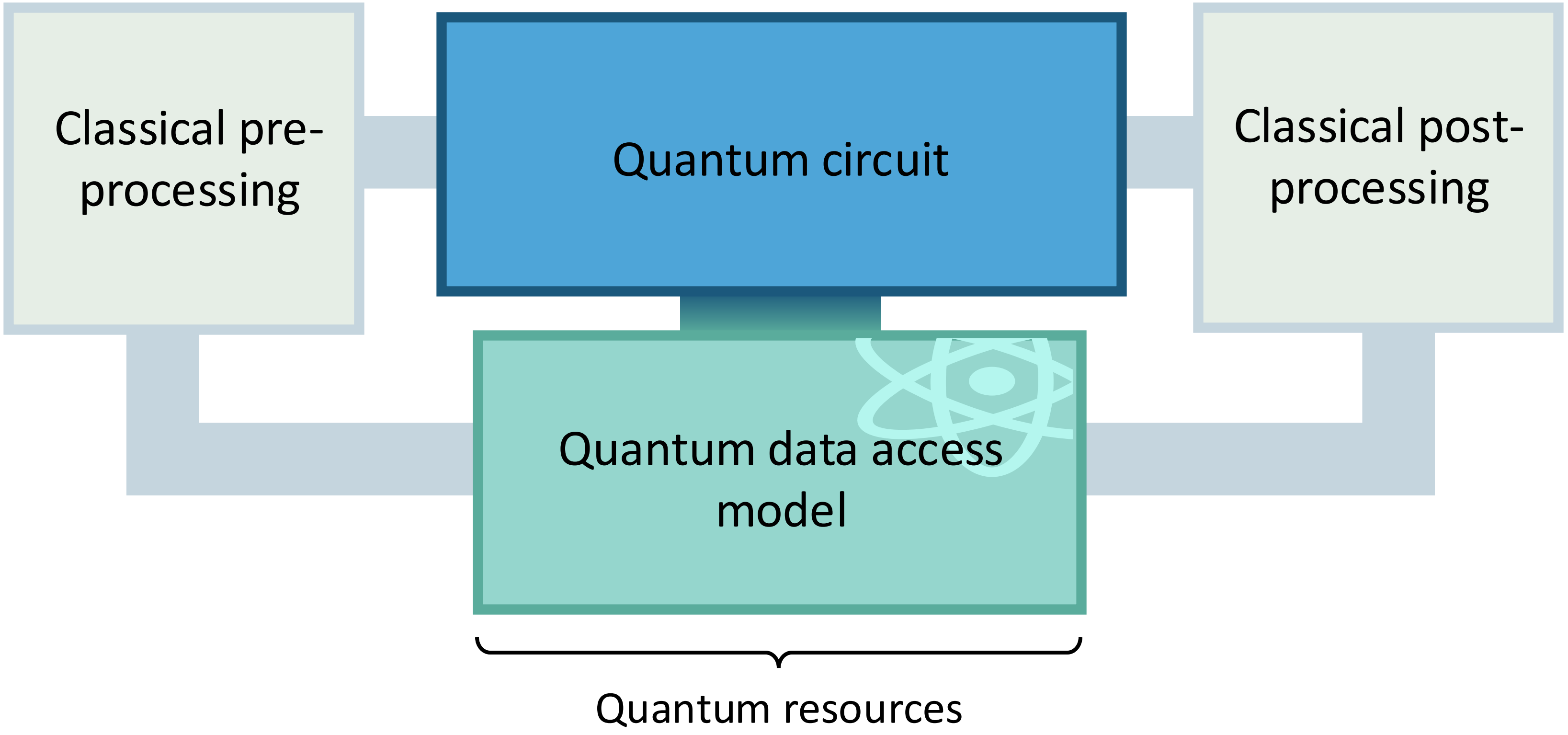


Early fault-tolerance characteristics

- Limited number of logical qubits, with limited quantum clock speed from error correction overhead
- Price of resources from most expensive to cheap (very debatable):
  1. Number of qubits
  2. Depth of quantum circuits
  3. Sample complexity
  4. Classical pre- and post-processing
- Goal is flexible trade-off between different resources
- Understand rigorous worst-case guarantees AND strong heuristics about performance for specific cases of interest

Quantum algorithms design

- Hybrid classical-quantum schemes with end-to-end complexity analysis



- Complexity estimates for comparison with state-of-the-art classical methods

Quantum algorithms:

A survey of applications and end-to-end complexities

Alexander M. Dalzell*[1], Sam McArdle*[1], Mario Berta[1,2,3], Przemyslaw Bienias[1], Chi-Fang Chen[1,4], András Gilyén[5], Connor T. Hann[1], Michael J. Kastoryano[1,6], Emil T. Khabiboulline[1,7], Aleksander Kubica[1], Grant Salton[1,4,8], Samson Wang[1,3] and Fernando G. S. L. Brandão[1,4]

[1] *AWS Center for Quantum Computing, Pasadena, CA, USA*
[2] *Institute for Quantum Information, RWTH Aachen University, Aachen, Germany*
[3] *Imperial College London, London, UK*
[4] *Institute for Quantum Information and Matter, Caltech, Pasadena, CA, USA*
[5] *Alfréd Rényi Institute of Mathematics, Budapest, Hungary*
[6] *IT University of Copenhagen, Copenhagen, Denmark*
[7] *Department of Physics, Harvard University, Cambridge, MA, USA*
[8] *Amazon Quantum Solutions Lab, Seattle, WA, USA*

Quantum Algorithms Wiki

Cambridge University Press (2025)

[open access & available at arXiv:2310.03011]

Quantum Algorithms Wiki

Quantum simulation

Example I: Ground states

Randomized quantum algorithm for statistical phase estimation

Phys. Rev. Lett. (2022) with Campbell & Wan

Quantum Information Processing (QIP) 2022

Qubit-efficient randomized quantum algorithms for linear algebra

PRX Quantum (2024) with McArdle & Wang

Quantum Computing Theory in Practice (QCTiP) 2023

Theory of Quantum Computation, Communication and Cryptography (TQC) 2023

Question: Ground state energy estimation

- Given n-qubit Hamiltonian

$$\mathrm{H} \coloneqq \sum_{l=1}^{L} \alpha_l P_l \text{ with } P_l \text{ } n\text{-qubit Paulis}$$

  and one-norm $\lambda \coloneqq \sum_{l=1}^{L} |\alpha_l|$, together with efficiently preparable n-qubit ansatz state $|\psi\rangle$ with overlap

$$|\langle \phi_0 | \psi \rangle|^2 \geq \eta > 0$$

  for ground state $|\phi_0\rangle$ with energy E_0

- Goal: Compute estimate $\tilde{E}_0$ of ground state energy with precision $\left|\tilde{E}_0 - E_0\right| \leq \delta$

- Approach: Randomized quantum algorithm with classical pre- and post-processing

Theorem: Ground state energy estimation

- Output $\tilde{E}_0$ with $\left|\tilde{E}_0 - E_0\right| \leq \delta$ with probability $1-\xi$ by employing

$$C_{\mathrm{sample}} = \tilde{O}(\eta^{-2}) \quad \left[= O\left(\eta^{-2}\log^2(\lambda\delta^{-1}\log(\eta^{-1}))\log(\xi^{-1}\log(\lambda\delta^{-1}))\right)\right]$$

quantum circuits on $n+1$ qubits, each using one copy of $|\psi\rangle$ and

$$C_{\mathrm{gate}} = \tilde{O}(\lambda^2\delta^{-2}) \quad \left[= O(\lambda^2\delta^{-2}\log^2(\eta^{-1}))\right]$$

- Comparison with qubitization [Lee *et al.*, PRX Quantum (2021)]

gate complexity $\tilde{O}\left(\sqrt{L}\lambda\delta^{-1}\right)$ on $\tilde{O}\left(\sqrt{L}\right)$ qubits → total $\tilde{O}(L\lambda\delta^{-1})$

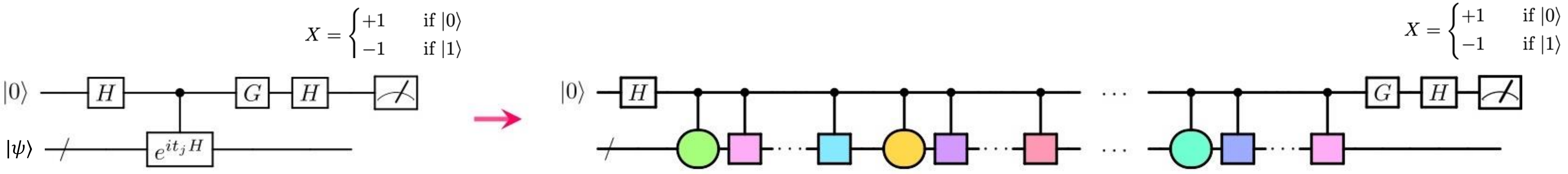
Main novel tool: Random compiler lemma

- **Hamiltonian simulation**: For $\mathrm{H} = \sum_{l=1}^{L} \alpha_l P_l$ we decompose time evolution $e^{itH} = \sum_k b_k U_k$ into U_k unitaries, $b_k > 0$, and r such that: (i) $\mathrm{C_{gate}}(U_k) = r \; \forall k$ (ii) $\sum_k b_k \leq \exp(t^2 r^{-1}) \cong C_{\mathrm{sample}}$

- **Trade-off**: Gate complexity $\mathrm{C_{gate}} = r$ vs sample complexity $C_{\mathrm{sample}} = \exp(t^2 r^{-1})$ independent of L!

  → e.g., $r = 2t^2$ gives Hamiltonian simulation for $\mathrm{C_{gate}} = 2t^2$ with constant $\mathrm{C_{sample}} = \sqrt{e}$

- **Approach**: Ground state energy estimation via Hadamard test + randomized Hamiltonian simulation as



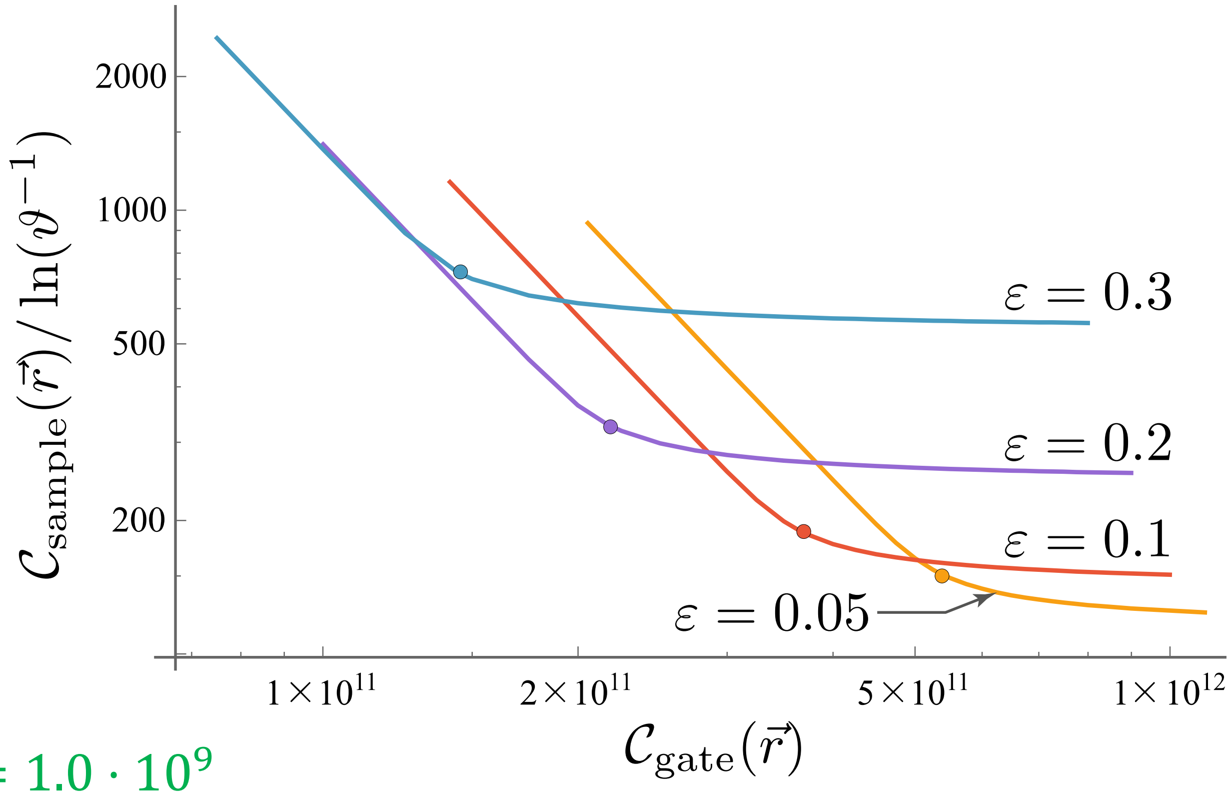
[Lin & Tong, PRX Quantum (2022)]

- Conceptually different from LCU [Berry *et al.*, Phys. Rev. Lett. (2015)] / qDRIFT [Campbell, Phys. Rev. Lett. (2019)]

Benchmark: FeMoco – resource trade-offs

- Li *et al.* FeMoco Hamiltonian 152 spin orbitals: $152 + 1 =$ 153 qubits
- Chemical accuracy $\delta = 0.0016$ Hartree, one-norm $\lambda = 1511$
- Qubitization [Lee *et al.*, PRX Quantum (2021)]

  2196 qubits: $C_{\text{gate}} = 3.2 \cdot 10^{10}$



- Latest development:
  - [Low *et al.*, arXiv (2025)] 1459 qubits: $C_{\text{gate}} = 1.0 \cdot 10^{9}$
  - [Günther *et al.*, arXiv (2025)] improved $\lambda = 568$ (!) → our scheme 153 qubits: $C_{\text{gate}} = 7.9 \cdot 10^{9}$
- Reminder: Ansatz state η-overlap bottleneck + classical methods scale polynomial!

Extensions and further work

- Quantum state preparation bottleneck can be avoided:
  - **Sparse random Hamiltonians are quantumly easy** Phys. Rev. X (2024) with Chen *et al.*
  - **Calculating response functions of coupled oscillators using quantum phase estimation** arXiv:2405.08694 (2024) with Danz *et al.*
- **Benchmark**: Hydrogen chain with $C_{\text{gate}} = \tilde{O}(N^{2.68}\delta^{-2})$
- Extension: Assumption on gap $\Delta(H) > 0$ gives $C_{\text{gate}} = \tilde{O}(\lambda^2\Delta^{-2})$ complexity
- Extension: Compute Green's function via inbuilt quantum linear system solver

from our work: novel framework randomized quantum linear algebra

- General Pauli input model complexities:

Quantum computational complexity of matrix functions arXiv:2410.13937 (2024) with Cifuentes *et al.*

Theory of Quantum Computation, Communication and Cryptography (TQC) 2025 - upcoming

Example II: Thermal states

Polynomial time quantum Gibbs sampling for Fermi-Hubbard model at any temperature

arXiv:2501.01412 (2025) with Šmíd, Meister, and Bondesan

Quantum Computing Theory in Practice (QCTiP) 2025

Theory of Quantum Computation, Communication and Cryptography (TQC) 2025 - upcoming

Question: Gibbs state preparation

- Goal: Given n-qubit Hamiltonian H and inverse temperature $\beta = T^{-1} > 0$, prepare the quantum Gibbs states $\sigma_\beta = \frac{\exp(-\beta H)}{Z}$ with $Z = \mathrm{Tr}[\exp(-\beta H)]$ the partition function
- More precisely: Prepare up to precision $\epsilon \in [0,1]$ in trace distance $\|\cdot\|_{\mathrm{Tr}}$ the purified Gibbs state

$$\left|\sqrt{\sigma_\beta}\right\rangle := Z^{-1/2} \sum_i \exp\left(-\frac{\beta E_i}{2}\right) |E_i\rangle \otimes |\bar{E}_i\rangle$$

- End-to-end extension: Compute the partition function Z up to relative error $\epsilon \in [0,1]$
- Physical quantity: Estimate Helmholtz free energy $F = -\beta^{-1}\log(Z)$ for different $\beta > 0$
- Intuition: Classically exponentially difficult, polynomial heuristics can suffer, e.g., from the sign problem

Fermi-Hubbard model

- Hamiltonian on D-dimensional lattice given by

$$H_{FH} \coloneqq -t \sum_{<i,j>} \sum_{\sigma \in \{\uparrow,\downarrow\}} (a_{i,\sigma}^{\dagger} a_{j,\sigma} + a_{j,\sigma}^{\dagger} a_{i,\sigma}) + U \sum_{i} a_{i,\uparrow}^{\dagger} a_{i,\uparrow} a_{i,\downarrow}^{\dagger} a_{i,\downarrow}$$

- Applications, e.g., for Mott metal-insulator transition or high temperature superconductivity
- Can be hard for classical methods (for $D \geq 2$) with unknown parts in phase diagram, e.g., the strange metal phase
- Standard computational benchmark
- Amenable to quantum methods in contrast to glassy spin systems? [Anschuetz *et al.*, QIP (2025)]

Quantum approach(es)

- More quantum versions of Markov chain Monte Carlo [Temme *et al.*, Nature (2011)]

  → delicate, partially missing rigorous guarantees, missing mixing time bounds

- Quantum singular value transformation [Gilyén *et al.*, STOC (2019)] → a priori exponentially expensive

- Lindbladian thermalization as fully quantum version of Markov chain Monte Carlo:
  - Exact quantum detailed balance AND step wise algorithmic efficiency [Chen *et al.*, QIP (2024)]
  - Quantum Glauber and Metropolis dynamics [Ding *et al.*, arXiv (2024)] [Gilyén *et al.*, arXiv (2024)]

- Need bound on mixing time t_{mix} ≅ number of steps:

$\mathrm{polylog}(n)$	$\mathrm{poly}(n)$	$\exp(\mathrm{poly}(n))$
ultra rapid	fast	slow

Chi-Fang (Anthony) Chen

Simulated Lindbladian thermalization

- From ρ_0 simulate dynamics $\rho(t) = \exp\left(t\mathcal{L}^\dagger\right)[\rho_0]$ via Linbladian [Ding *et al.*, arXiv (2024)]

$$\mathcal{L}^\dagger[\rho] \coloneqq -i[G,\rho] + \sum_{a\in\mathcal{A}} \left(L_a \rho L_a^\dagger - \frac{1}{2}\{L_a^\dagger L_a, \rho\} \right)$$

via the set $\mathcal{A}$ of jump operators A^a and filter functions $f^a(t)$ with

$$L_a \coloneqq \int_{-\infty}^{\infty} f^a(t) \cdot \exp(itH) A^a \exp(-itH) \mathrm{d}t$$

$$G \coloneqq \sum_{a\in\mathcal{A}} \int_{-\infty}^{\infty} g(t) \cdot \exp(itH)\left(L_a^\dagger L_a\right) \exp(-iHt) \mathrm{d}t \text{ for specific } g(t)$$

- Exact quantum detailed balance $\mathcal{L}^\dagger\left[\sigma_\beta\right] = 0$ AND step wise algorithmic efficiency – via modern Hamiltonian simulation + coherent function preparation [McArdle, Gilyén, **B.**, arXiv (2022)]

Task: Bound mixing time

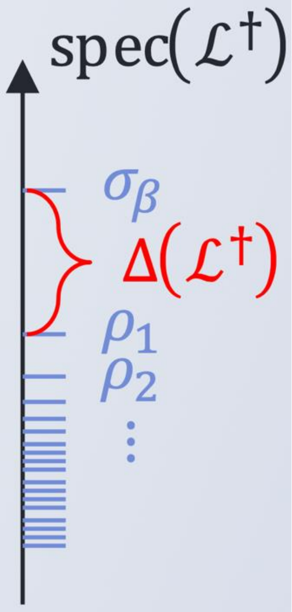
$\mathrm{polylog}(n)$ $\mathrm{poly}(n)$ $\exp(\mathrm{poly}(n))$

ultra rapid fast slow

- Mixing time $t_{\mathrm{mix}}(\epsilon) \coloneqq \inf\left\{t \geq 0 : \left\|\exp\left(t\mathcal{L}^\dagger\right)[\rho_0] - \sigma_\beta\right\|_{\mathrm{Tr}} \leq \epsilon \;\forall \rho_0\right\}$

- Hölder gives spectral gap bound

$$t_{\mathrm{mix}}(\epsilon) \leq \Delta\left(\mathcal{L}^\dagger\right)^{-1} \cdot \log\left(2\epsilon^{-1}\left\|\sigma_\beta^{-1/2}\right\|\right) = \Delta\left(\mathcal{L}^\dagger\right)^{-1} \cdot O\left(n + \log(\epsilon^{-1})\right)$$



- Lindbladian is non-Hermitian, vectorization on doubled Hilbert space gives parent Hamiltonian via similarity transform

$$\mathcal{H}[\cdot] \coloneqq \sigma_\beta^{-1/4}\mathcal{L}^\dagger\left[\sigma_\beta^{1/4}(\cdot)\sigma_\beta^{1/4}\right]\sigma_\beta^{-1/4} \Rightarrow t_{\mathrm{mix}}(\epsilon) \leq \Delta(\mathcal{H})^{-1} \cdot O\left(n + \log(\epsilon^{-1})\right)$$

- Understood, e.g., for high temperatures [Rouzé *et al.*, QIP (2024)]

Theorem: Gibbs state preparation

- **Main result**: For any quasi-local fermionic Hamiltonian $H = H_0 + \lambda \cdot V$ at any inverse temperature $\beta > 0$, there exists positive constants $\lambda_{\max}, d$ such that for any $|\lambda| \leq \lambda_{\max}$ the corresponding Lindbladian has spectral gap $\Delta \geq \Delta_0 - d|\lambda|$.

- **Corollary**: For λ small enough, prepare purified Gibbs state in quantum complexity $\tilde{O}\left(n^3 \cdot \mathrm{polylog}(\epsilon^{-1})\right)$ and compute the partition function in quantum complexity $\tilde{O}(n^5 \cdot \epsilon^{-2})$ using $\tilde{O}(n)$ qubits.

→ rigorous polynomial end-to-end complexity (versus, e.g., quantum phase estimation), no (rigorous) classical analogue!

Proof: Free fermions

- Quadratic Hamiltonian $H_0 = \sum_{i,j} \omega_i h_{ij} \omega_j = \boldsymbol{\omega}^{\boldsymbol{T}} \cdot h \cdot \boldsymbol{\omega}$ with ω_i Majorana fermion: $\omega_i^\dagger = \omega_i$ and $\{\omega_i, \omega_j\} = 2\delta_{ij}$ → exactly solvable Lindbladian $\mathcal{L}_0$

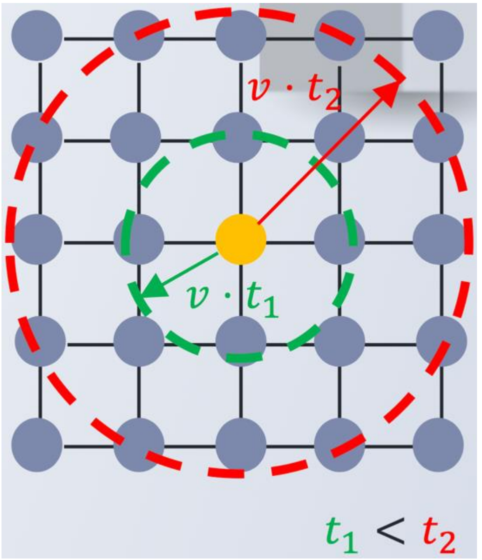
- Design choice: $A^a = \omega_a$ Majorana jumps and $\hat{f}^a = \hat{f}\ \forall a$ Gaussian for $\mathcal{L}_0 \Rightarrow$ coherent term $G = 0$

- Third quantization for vectorizing fermionic Lindbladians [Prosen, NJP (2008)]: Parent Hamiltonian $\mathcal{H}_0 \cong -\boldsymbol{c}^\dagger \cdot S \cdot \boldsymbol{c} + \boldsymbol{c} \cdot S \cdot \boldsymbol{c}^\dagger + \boldsymbol{c}^\dagger \cdot A \cdot \boldsymbol{c}^\dagger + \boldsymbol{c} \cdot A \cdot \boldsymbol{c}$ for $\{c_i^\dagger, c_i\}_{i=1}^{2n}$ and S, A simple functions of h

- System size independent gap $\Delta(\mathcal{H}_0) \equiv \Delta_0 = 2 \cdot \exp(-4\beta^2 ||h||)\cosh(2\beta||h||)$

- NB: Free fermions have ultra rapid mixing $t_{\mathrm{mix}}^{[0]}(\epsilon) \leq \frac{1}{2\Delta_0} \log\left(\frac{\tanh(2\beta||h||)}{2} \cdot \frac{n}{\epsilon}\right) = O(\mathrm{polylog}(n))$

Proof: Stability theorem

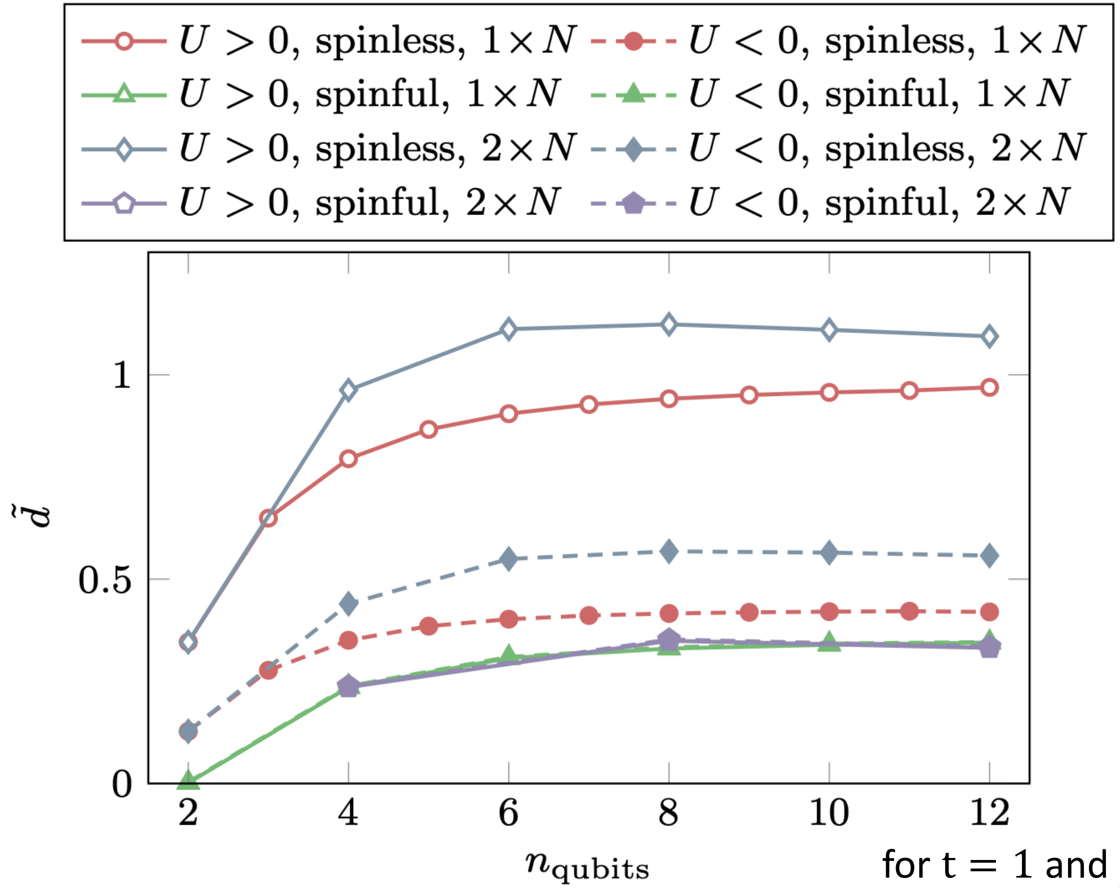


- **Tool**: Stability of spectral gap of free fermionic Hamiltonians under perturbation [Hastings, J. Math. Phys. (2019)] $\Rightarrow$ gap closes at most linearly in perturbation
- **Task**: Lift properties from fermionic Hamiltonian $H = H_0 + \lambda \cdot V$ to parent Hamiltonian $\mathcal{H} := \mathcal{H}_0 + \mathcal{V}$ of Lindbladian $\Rightarrow$ study perturbation $\mathcal{V}$
- **Proof steps**: (1) quasi-locality of perturbation $\mathcal{V}$ (2) bounded strength of perturbation $\mathcal{V}$ in λ
- (1) Lieb-Robinson bounds [Haah *et al.*, FOCS (2018)] on $\tilde{L}_a := \exp(\beta H/4) L_a \exp(-\beta H/4)$ to estimate $\left\|\tilde{L}_a - \tilde{L}_a^{(r)}\right\| \leq c \cdot \exp(-\mu r)$ (and G_a terms in coherent part G)

  (2) Duhamel's formula as $\exp\big((A+B)t\big) = \exp(A) + \int_0^t \exp\big((A+B)(t-s)\big) \cdot B \cdot \exp(As)\mathrm{d}s$ to estimate $\left\|\tilde{L}_a - \tilde{L}_a^0\right\| \leq c \cdot |\lambda|$ (and G_a terms in coherent part G)

Benchmark: Fermi-Hubbard weak coupling

- U/t small with Majorana jump operators and Gaussian filter functions (analytical results)



for $t = 1$ and $\beta = 1$

- Slope of gap closing:

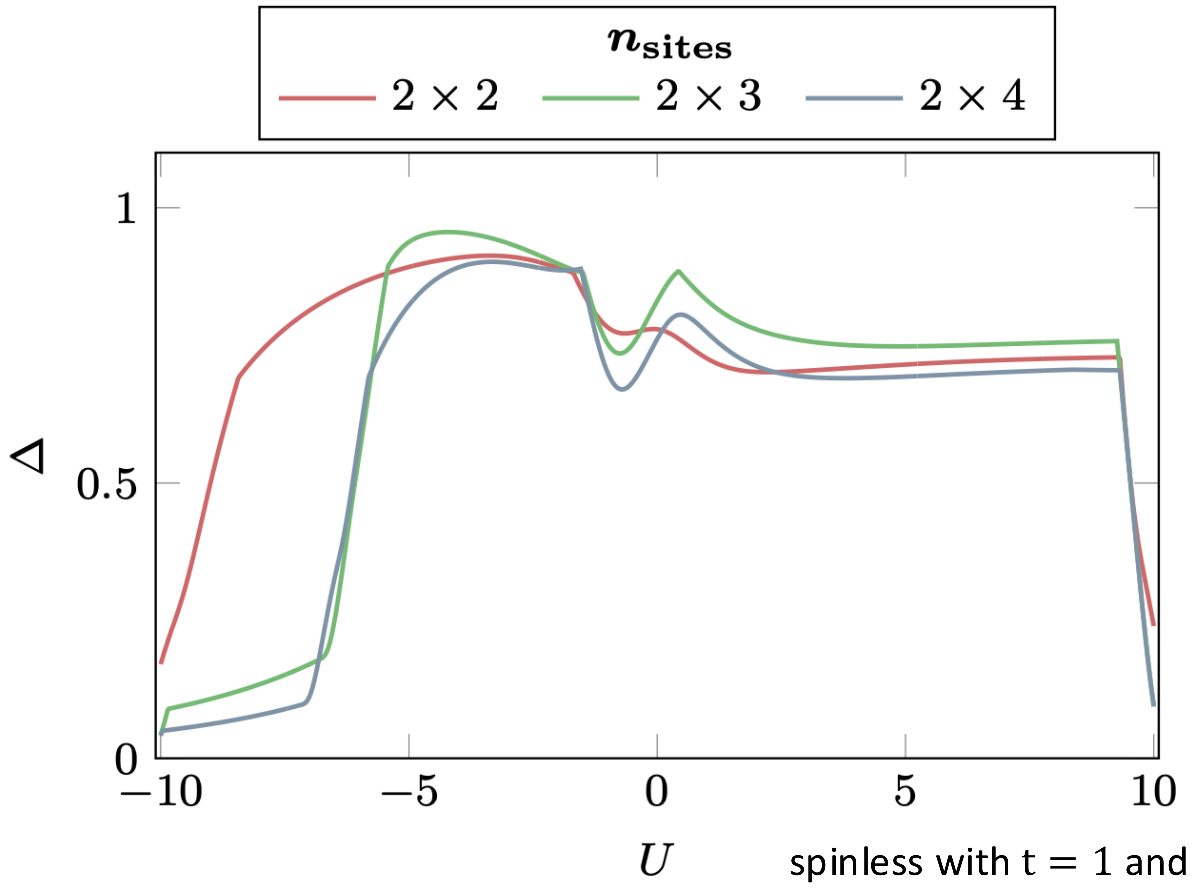
$$\tilde{d}^{\pm} := \mp \frac{\partial \Delta(\mathcal{L}^{\dagger})}{\partial U}\Big|_{U=0^{\pm}}$$

$\Rightarrow$ uniform upper bound in n

- NB: Dependence $\Delta_0 \sim \exp(-\beta^2)$ beyond analytics much improved with
  - single site Pauli jump operators
  - Metropolis style filter functions

Benchmark: Fermi-Hubbard medium coupling

- Intermediate $2 \lesssim U/t \lesssim 6$ for $D = 2$ with single site Pauli jump operators and Metropolis filter functions:
- NB: Again, favorable $\beta \gg 1$ dependence with this design choice
- No analytics, need larger system sizes, e.g., for interplay of coupling strength and support of filter functions?



spinless with $t = 1$ and $\beta = 1$

Extensions and next steps

- **Extension**: Starting from $t = 0$ atomic limit, similar results for spinful $U/t \gg 1$ strong coupling

  $\Rightarrow$ other systems via gap techniques, e.g., Bose-Hubbard model

- Improved mixing time for specific (local) information, e.g., via quantum Wasserstein distance?

- Faster (heuristic) algorithms all the way down to (quasi-) linear $\widetilde{\mathrm{O}}\big(n \cdot \mathrm{polylog}(\epsilon^{-1})\big)$, via ultra rapid mixing and adaptive jump operators?

- Larger scale numerical simulations – leading classical heuristics – analogue quantum simulators?

- Many more, e.g., how to (heuristically) verify convergence of quantum Gibbs samplers without a priori guarantees? Noise tolerance? Optimization applications, etc.

Conclusion

SCHWERPUNKT

QUANTENCOMPUTING

Algorithmen für neue Hardware

Quantenalgorithmen lösen nur bestimmte Rechenprobleme signifikant effizienter als klassische Algorithmen.

Mario Berta

- Guiding questions:
  - What quantum algorithms do we eventually want to run?
  - For what applications is the quantum footprint the smallest to become competitive with classical methods?
- 50-100 error corrected qubits could allow for meaningful tests

Theory of quantum information science

- Our focus areas:
  A. Mathematical foundations of quantum information
  B. Quantum algorithm development
- Symbiosis of quantum information with rigorous tools from mathematical physics

Mathematics

- Matrix Analysis
- Operator Algebras
- Quantum Statistics

Physics

- Quantum Simulation
- Quantum Entropy Inequalities
- Thermodynamics & Physics of Information

Computer Science

- Quantum Algorithms
- Quantum Communication & Cryptography
- Quantum Error Correction

- That’s it, thank you!

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