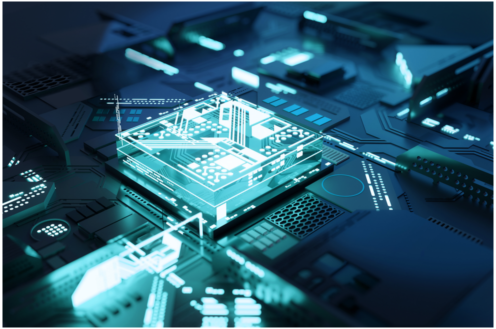
Quantum Computing: a future perspective for scientific computing

Quantum Computing

Karl Jansen

CQTA, DESY Zeuthen , 16.1.2025

Overview



- Introduction
- Heisenberg model
- Optimal Flight Gate Assignment
- Quantum Electrodynamics
  1+1 and 2+1-dimensions
- Quantum painting and music
- Center for Quantum Technology and Applications
- Conclusion

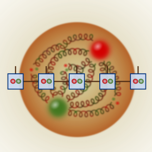
Why quantum computing

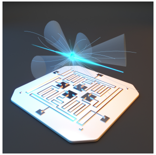
- **Quantum Biotechnology**, N. Mauranyapin, et.al, arXiv:2111.02021
- *Emerging quantum computing algorithms for* **quantum chemistry**, M. Motta, et.al., arXiv:2109.02873
- **Quantum Theory Methods** *as a Possible Alternative for the Double-Blind Gold Standard of* **Evidence-Based Medicine***: Outlining a New Research Program*, D.k Aerts, et.al., arXiv:1810.13342
- **Quantum Battery** *with Ultracold Atoms: Bosons vs. Fermions*, Tanoy Kanti Konar, et.al., arXiv:2109.06816
- *Hybrid Quantum-Classical Algorithms for* **Loan Collection Optimization** *with Loan Loss Provisions*, J. Tangpanitanon, et.al, arXiv:2110.15870
- *A Quantum Natural Language Processing Approach to* **Musical Intelligence** E. Miranda, et.al., arXiv:2111.06741

Why quantum computing

- **Quantum Biotechnology**, N. Mauranyapin, et.al, arXiv:2111.02021
- *Emerging quantum computing algorithms for* **quantum chemistry**, M. Motta, et.al., arXiv:2109.02873
- **Quantum Theory Methods** *as a Possible Alternative for the Double-Blind Gold Standard of* **Evidence-Based Medicine***: Outlining a New Research Program*, D.k Aerts, et.al., arXiv:1810.13342
- **Quantum Battery** *with Ultracold Atoms: Bosons vs. Fermions*, Tanoy Kanti Konar, et.al., arXiv:2109.06816
- *Hybrid Quantum-Classical Algorithms for* **Loan Collection Optimization** *with Loan Loss Provisions*, J. Tangpanitanon, et.al, arXiv:2110.15870
- *Developing a Framework for* **Sonifying** *Variational Quantum Algorithms: Implications for* **Music Composition**, Paulo Vitor Itaboraí, Peter Thomas, Arianna Crippa, Karl Jansen, Tim Schwägerl, María Aguado Yáñez, arXiv: 2409.07104

Why a quantum computer

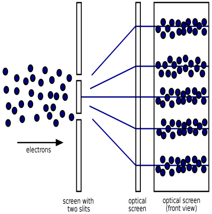


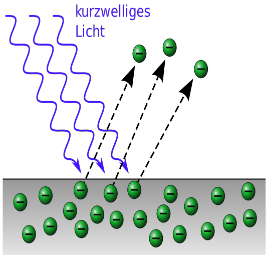


- systems in e.g.
  - high energy physics
  - chemistry
  - biology
  - material science
  - condensed matter physics
- are **quantum systems**
  ”*Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem because it doesn’t look so easy.*”, R. Feynman, around 1980, see https://arxiv.org/pdf/2106.10522.pdf
- potential to solve problems very hard or inaccessible for classical computers
  $\rightarrow$ models with sign problem (topological models, non-zero baryon density, ...)

Bit versus Qubit

> quantum world: particle–wave duality



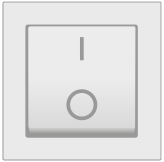


electrons behave as waves

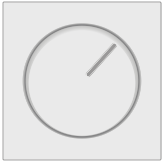
light behaves as particles

Bit versus Qubit

- bit: only 2 states 0 or 1 possible
- qubit: 2-level *quantum system* with state $|0\rangle$, or $|1\rangle$
  $\rightarrow$ superposition
  $|\text{qubit}\rangle = \alpha|0\rangle + \beta|1\rangle$, $\alpha^2 + \beta^2 = 1$
- realization of qubit: 2-level atom, Josephson junction, polarized photons, ...



bit: switch on/off



qubit: dimmer continuous

Quantum advantage I: superposition

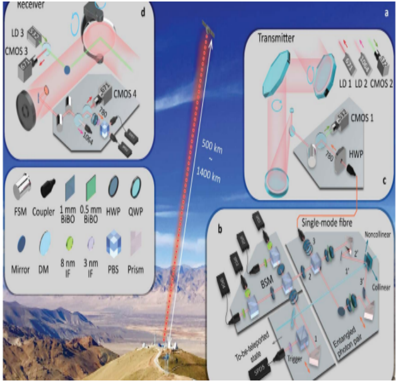
> qubit = behaves as wave: superposition

> sound wave

- superposition allows
  - to store much more information
  - to explore a much larger space

Quantum advantage II: entanglement

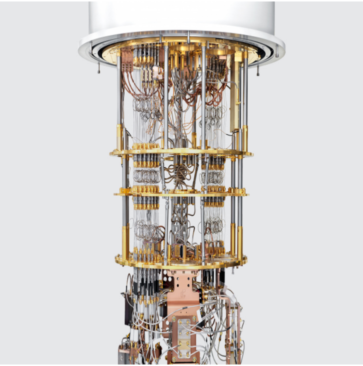
- 2 qubits (Q_1, Q_2) can be entangled $\rightarrow$ acting on Q_1 influences Q_2
  - without connection (e.g. no wire)
  - over (in principle) arbitrary distances



- 2 photon experiment
- claim proof of entanglement over $O(1000)$ kilometer
  (J. Yin et.al., Nature volume 582, 501 (2020))
- entanglement:
- no classical analogue
- opens completely new possibilities

Quantum computer: from the outside

Quantum computer: from the inside



- Shielded to 50,000 times less than Earth's magnetic field
- In a high vacuum: pressure is 10 billion times lower than atmospheric pressure
- Cooled 180 times colder than interstellar space (0.015 Kelvin) → prevent quantum noise

- IBMQ: 433 qubits 2022, >1000 qubits 2023, >4000 qubits 2024

→ 10K to 100K error corrected, parallelized

- Google promise: 1.000.000 qubits 2030, 1000 qubits error corrected

How to quantum compute

- python programming language
  → company provides quantum libraries
- very convenient setup
  → simulator runs on your local machine
  → hardware usable through quantum cloud service
  → build on reservation system
- documentation, tutorials and examples availabe on website, e.g. IBM's textbook: https://qiskit.org/textbook/preface.html

Qiskit

→ you can start now!

Quantum computing the Heisenberg model

- 1-dimensional Heisenberg model
  Heisenberg, W. *Zur Theorie des Ferromagnetismus.* Z. Physik 49, 619–636 (1928)

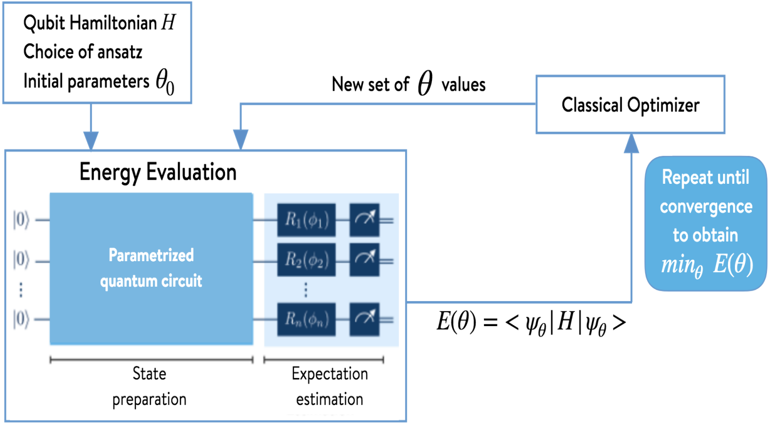
$$H = \sum_{i=1}^{N} \beta \left[\sigma_x(i) \otimes \sigma_x(i+1) + \sigma_y(i) \otimes \sigma_y(i+1) + \sigma_z(i) \otimes \sigma_z(i+1)\right] + J\sigma_z(i)$$

- microscopic description of magnetism
- phase transition from un-magnetized to magnetized phase
- mathematical structure typical for models in **Lattice Gauge Theories** (LGT)
- very flexible: can use $N = 2$ or $N = 1000$ lattice sites

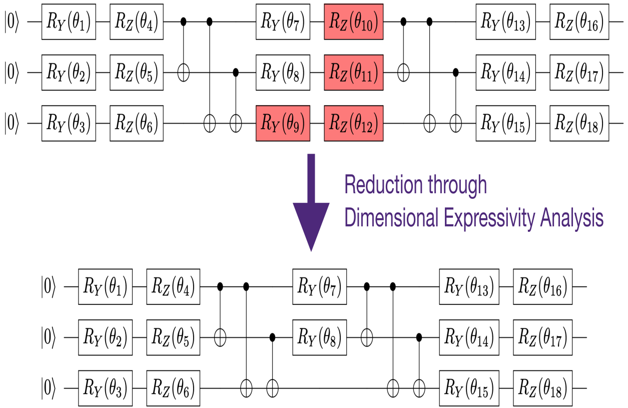
  $\rightarrow$ can be studied **already now** on quantum computers

Variational Quantum Eigensolver (VQE)

> a hybrid quantum/classical variational approach



Example for a quantum circuit

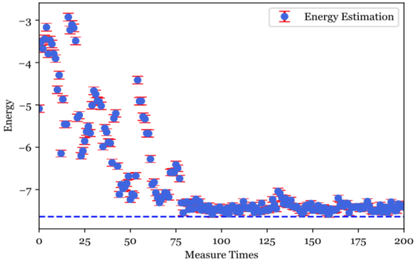


Quantum computing the heisenberg model

> Quantum computing the lowest physical energy using 3 qubits

> Using the exact simulation on laptop

> dashed line exact result

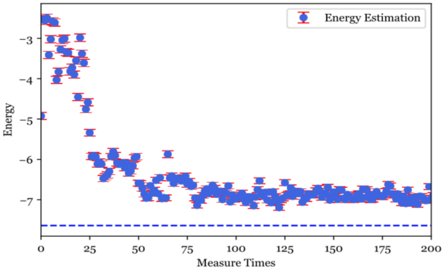


- exact simulation
- find correct result

Quantum computing the Heisenberg model

> Quantum computing the lowest physical energy using 3 qubits

> On quantum computer: exist **quantum noise**
> $\Rightarrow$ add noise model

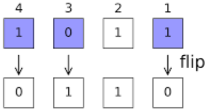


- noisy simulation
- fail to find correct result

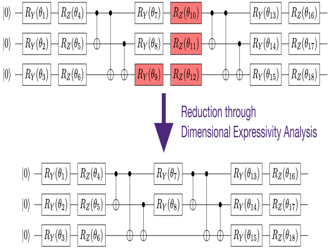
Error mitigation and expressivity of quantum circuits

- Quantum computers are noisy: bit-flips in readout process

- analytically correct for readout errors
  (L. Funcke, T. Hartung, S. Kühn, P. Stornati,
  X. Wang, K.J., arxiv:2007.03663, to appear in PRA)



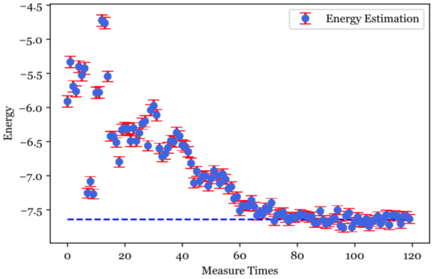
- dimensional expressivity analysis of quantum circuits
  (L. Funcke, T. Hartung, S. Kühn, P. Stornati,
  K.J, Quantum 5 (2021) 422)
  $\rightarrow$ remove superfluous gates
- both methods scale polynomially
  $\Rightarrow$ they are efficient



- methods are developed from applications in **fundamental research**

Quantum computing the Heisenberg model

> Mitigate quantum noise through analytical method on minimal, but maximally expressive circuit

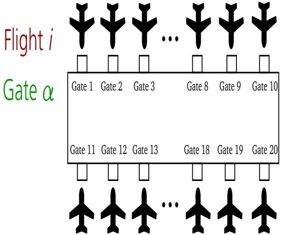


- error mitigated noisy simulation
- find correct result

> develop new methods from basic research (LGT)

Quantum computing the flight gate assignment problem

- A classical optimization problem: flight gate assignment
  (Y. Chai, L. Funcke, T. Hartung, S. Kühn, T. Stollenwerk, P. Stornati, K. Jansen, arXiv:2302.11595)
- Find shortest path between connecting flights
- Different incoming and outgoing flights need to be assigned to gates
  $\rightarrow$ find optimal assignment
- Classical optimization problem
  $\rightarrow$ quantum advantage?



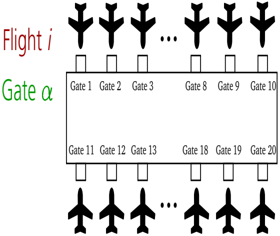
Quantum computing the flight gate assignment problem

> binary variables encoding gates and flights

$$x_{i\alpha} = \begin{cases} 1, & \text{if flight } i \in F \text{ is assigned to gate } \alpha \in G \\ 0, & \text{otherwise} \end{cases}$$

$x \in \{0,1\}^{F \otimes G} \rightarrow x$ binary variable $\rightarrow x \in \{-1, 1\}$

eigenstate of third Pauli matrix σ_z



> leads to mathematical description of Hamiltonian

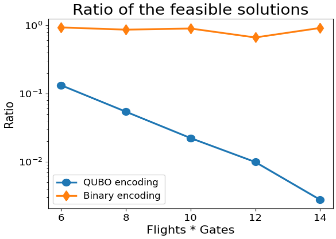
$$H = \sum_{j=1}^{n} Q_{jj}\sigma_j^z + \sum_{\substack{j,k=1 \\ j<k}}^{n} Q_{jk}\sigma_j^z \otimes \sigma_k^z$$

> Task: find lowest energy $\Leftrightarrow$ shortest path

> Same mathematical description for problems in **traffic, logistics, particle tracking, ...**

Quantum computing the flight gate assignment problem

- Started with QUBO implementation
- Implementation of various improvements
  - using binary encoding
  - reformulation of Hamiltonian through projectors
  - Using Conditional Value at Risk (CVaR)

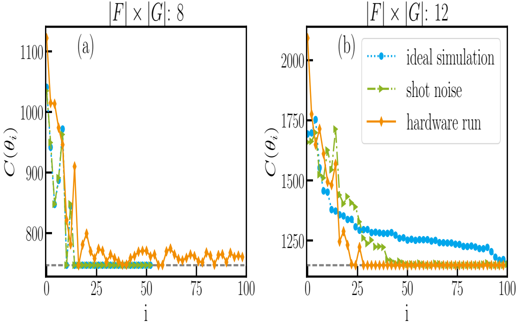


Feasible ratio

Quantum hardware runs of flight gate assignment problem

(Y. Chai, E. Epifanovsky, K. Jansen, A. Kaushik, S. Kühn, arxiv:2309.09686)

- hardware runs on IonQ's Aria trapped ion quantum computer
- circuit: efficientSU2
- real VQE and inference runs



Convergence

The Schwinger model

(Schwinger 1962)

Quantization via Feynman path integral

$$\mathcal{Z} = \int \mathcal{D}A_\mu \mathcal{D}\Psi \mathcal{D}\bar{\Psi} e^{-S_{\text{gauge}} - S_{\text{ferm}}}$$

Fermion action

$$S_{\text{ferm}} = \int d^2x \bar{\Psi}(x) \left[D_\mu + m \right] \Psi(x)$$

gauge covriant derivative

$$D_\mu \Psi(x) \equiv (\partial_\mu - i g_0 A_\mu(x)) \Psi(x)$$

with A_μ gauge potential, g_0 bare coupling

$$S_{\text{gauge}} = \int d^2x F_{\mu\nu} F_{\mu\nu} \;,\; F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x)$$

Schwinger Model

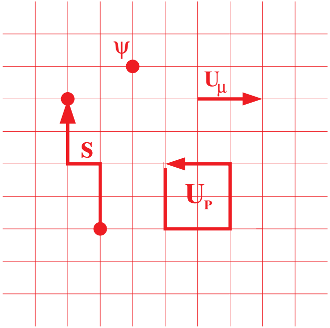
(Schwinger 1962)

- existence of bound states (mass gap)
- asymptotic free ($g_0 \to 0$ for distance between charges going to zero)
- exactly solvable for zero fermion mass (Coleman)
- super-renormalizable
- with topological term: interesting CP-violating phase transition

$\Rightarrow$ valuable test laboratory for QCD

The Schwinger model: QED in 1+1 dimensions

> introduce a 2-dimensional lattice with lattice spacing a



> fermion fields $\Psi(x)$, $\bar{\Psi}(x)$ on the lattice sites
  $x = (t, \mathbf{x})$ integers

> discretized fermion action

$$S \rightarrow a^2 \sum_x \bar{\Psi} \left[\gamma_\mu \partial_\mu - r \underbrace{\partial_\mu^2}_{\nabla_\mu^* \nabla_\mu} + m\right] \Psi(x)$$

> discrete derivatives

$$\partial_\mu = \frac{1}{2}\left[\nabla_\mu^* + \nabla_\mu\right]$$

$$\nabla_\mu \Psi(x) = \frac{1}{a}\left[\Psi(x + a\hat{\mu}) - \Psi(x)\right] \;, \quad \nabla_\mu^* \Psi(x) = \frac{1}{a}\left[\Psi(x) - \Psi(x - a\hat{\mu})\right]$$

> second order derivative $\rightarrow$ remove doubler $\leftarrow$ break chiral symmetry

The Schwinger model: implementing gauge invariance

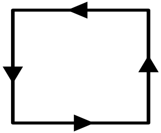
- Wilson's fundamental observation: introduce parallel transporter connecting the points x and $y = x + a\hat{\mu}$:

$$U(x,\mu) = e^{iaA_\mu(x)} \in U(1)$$

- lattice derivative: $\nabla_\mu \Psi(x) = \frac{1}{a}\left[U(x,\mu)\Psi(x+\mu) - \Psi(x)\right]$
- plaquette action

$$U_p = U(x,\mu)U(x+\mu,\nu)U^\dagger(x+\nu,\mu)U^\dagger(x,\nu)$$

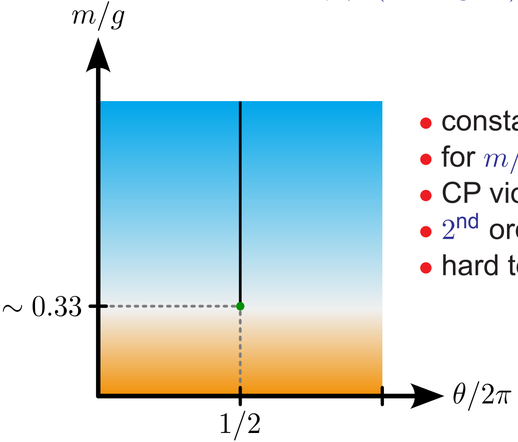
$$\rightarrow F_{\mu\nu}F^{\mu\nu}(x) \quad \text{for} \quad a \rightarrow 0$$



$$S = a^2 \sum_x \left\{ \beta(= \tfrac{1}{g_0^2}) \left[1 - \text{Re}(U_{(x,p)})\right] + \bar{\Psi}(x) \left[m + \tfrac{1}{2}\{\gamma_\mu(\nabla_\mu + \nabla_\mu^\star) - a\nabla_\mu^\star \nabla_\mu\}\right] \Psi \right\}$$

Schwinger model in the continuum and phase diagram

$$\mathcal{H} = -i\bar{\psi}\gamma^1 \left(\partial_1 - igA_1\right)\psi + m\bar{\psi}\psi + \frac{1}{2}\left(\dot{A}_1 + \frac{g\theta}{2\pi}\right)^2$$



- constant external electric field: θ
- for $m/g > 0.33$, 1^{st} order phase transition
- CP violating
- 2^{nd} order endpoint at $m/g = 0.33$
- hard to explore with Monte Carlo methods

Schwinger model on the lattice: Wilson fermions

(Takis Angelides, Arianna Crippa, Lena Funcke, Karl Jansen,
Stefan Kühn, Pranay Naredi, Ivano Tavernelli, Derek Wang, arxiv:2312.12831)

- Wilson Hamiltonian

$$H_W = \sum_{n=0}^{N-2} \left(\bar{\phi}_n \left(\frac{1 + i\gamma^1}{2a} \right) U_n \phi_{n+1} + \text{ h.c. } \right)$$
$$+ \sum_{n=0}^{N-1} \left(m_{\text{lat}} + \frac{1}{a} \right) \bar{\phi}_n \phi_n + \sum_{n=0}^{N-2} \frac{ag^2}{2} \left(L_n + l_0 \right)^2 .$$

- mass m_{lat}; coupling g; lattice spacing a; electric field $l_0 = \frac{\theta}{2\pi}$

- Link operator $U_\mu = e^{igA_\mu}$, A_μ gauge potential

Pauli representation through Jordan-Wigner transformation

- Jordan-Wigner transformation

$$\phi_{n,\alpha} \to \chi_{2n-\lfloor \frac{\alpha}{2} \rfloor+1}$$

$$\chi_n = \prod_{k<n} (iZ_k)\sigma_n^-$$

- (dimensionless) Wilson Hamiltonian, $x = 1/(ag)^2$
  $\to$ open boundary conditions: eliminate gauge fields

$$W_W = x \sum_{n=0}^{N-2} (X_{2n+2}X_{2n+3} + Y_{2n+2}Y_{2n+3}) + \left(\frac{m_{\text{lat}}}{g}\sqrt{x} + x\right) \sum_{n=0}^{N-1} (X_{2n+1}X_{2n+2} + Y_{2n+1}Y_{2n+2}) + \sum_{n=0}^{N-2} (l_0 + \sum_{k=0}^{n} Q_k)^2$$

Pauli representation through Jordan-Wigner transformation

- electric field density operator

$$L_W = \sum_{k=0}^{N-1} Q_k = \sum_{k=0-1}^{N} \phi_n^\dagger \phi_n$$

$\rightarrow$ JW-transformation: $$L_W = l_0 + \frac{1}{2} \sum_{k=0}^{\lceil N/2 \rceil -1} (Z_{2k} + Z_{2k+1})$$

- particle number operator

$$P_W = N + \tfrac{1}{2} \sum_{n=0}^{N-1} \phi\phi$$

$\rightarrow$ JW-transformation: $$P_W = N + \tfrac{1}{2} \sum_{n=0}^{N-1} (X_{2n+1} X_{2n+2} + Y_{2n+1} Y_{2n+2})$$

Pauli representation through Jordan-Wigner transformation

- (dimensionless) Wilson Hamiltonian, $x = 1/(ag)^2$
  $\rightarrow$ open boundary conditions: eliminate gauge fields

$$W_W = x \sum_{n=0}^{N-2} \left(X_{2n+2} X_{2n+3} + Y_{2n+2} Y_{2n+3}\right) + \left(\frac{m_{\text{lat}}}{g}\sqrt{x} + x\right) \sum_{n=0}^{N-1} \left(X_{2n+1} X_{2n+2} + Y_{2n+1} Y_{2n+2}\right) + \sum_{n=0}^{N-2} \left(l_0 + \sum_{k=0}^{n} Q_k\right)^2$$

- electric field density operator

$$L_W = l_0 + \sum_{k=0}^{\lceil N/2 \rceil - 1} Q_k = l_0 + \frac{1}{2} \sum_{k=0}^{\lceil N/2 \rceil - 1} \left(Z_{2k} + Z_{2k+1}\right)$$

- particle number operator

$$P_W = N + \frac{1}{2} \sum_{n=0}^{N-1} \left(X_{2n+1} X_{2n+2} + Y_{2n+1} Y_{2n+2}\right)$$

Schwinger model on the lattice: staggered fermions

> staggered Hamiltonian

$$H_S = -\frac{i}{2a}\sum_{n=0}^{N-2}\left(\phi_n^\dagger U_n \phi_{n+1} - \text{h.c.}\right) + m_{\text{lat}} \sum_{n=0}^{N-1}(-1)^n \phi_n^\dagger \phi_n + \frac{ag^2}{2}\sum_{n=0}^{N-2} L_n^2$$

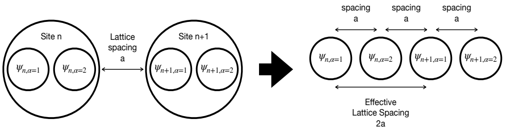
> mass shift

$$\frac{m_r}{g} = \frac{m_{\text{lat}}}{g} + \frac{1}{8/\sqrt{x}}$$

> Pauli representation

$$W_S = \frac{x}{2}\sum_{n=0}^{N-2}\left(X_n X_{n+1} + Y_n Y_{n+1}\right)$$

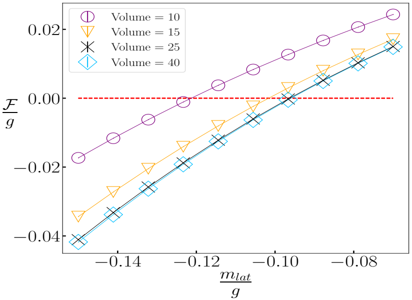
$$+ \frac{m_{\text{lat}}}{g}\sqrt{x}\sum_{n=0}^{N-1}(-1)^n Z_n + \sum_{n=0}^{N-2}\left(l_0 + \sum_{k=0}^{n} Q_k\right)^2$$



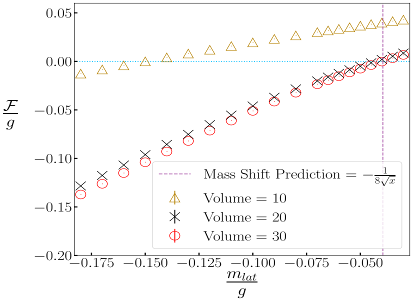
Determining the mass shift: a MPS calculation

> electric field density (EFD) in mass perturbation theory

$\frac{\mathcal{F}}{g} = \frac{e^{\gamma}}{\sqrt{\pi}} \left(\frac{m}{g}\right) \sin\theta - 8.9139 \frac{e^{2\gamma}}{4\pi} \left(\frac{m}{g}\right)^2 \sin(2\theta) \Rightarrow$ for $m = 0$ EFD vanishes

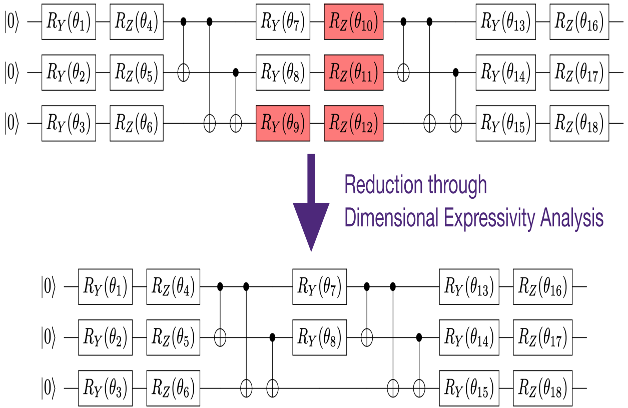


Wilson

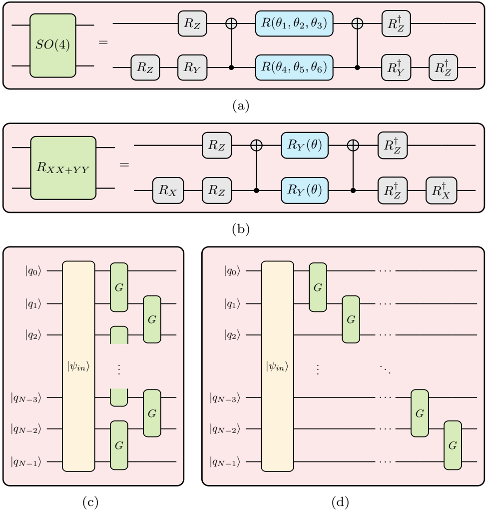


staggered

Example for a quantum circuit



The Ansatz



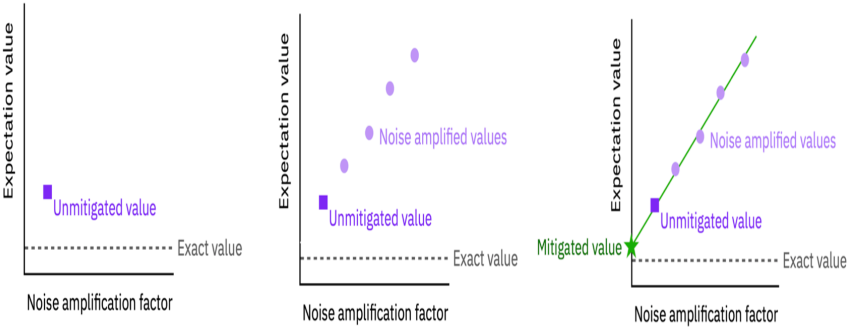
- decomposition of $SO(4)$ and R_{XX+YY} gates
- brick and ladder ansatz

Mitigating quantum computing results

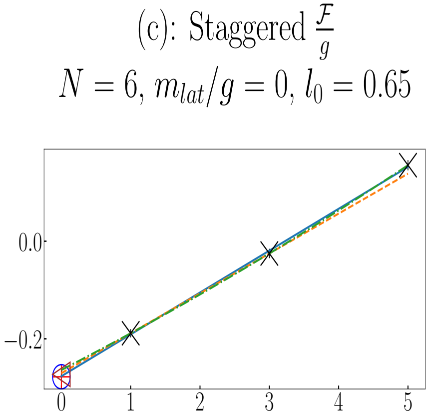
> zero noise extrapolation (ZNE) in theory

$$< \psi|O|\psi\rangle =< 0\left|U^{\dagger}OU\right|0 >$$

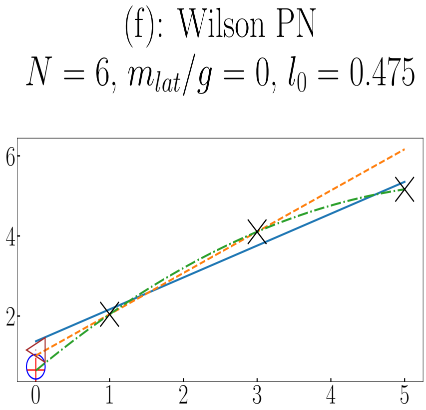
$$|\psi >= U|0 >= UU^{\dagger}U\left|0 >= UU^{\dagger}UU^{\dagger}U\right|0 >$$



ZNE in practise



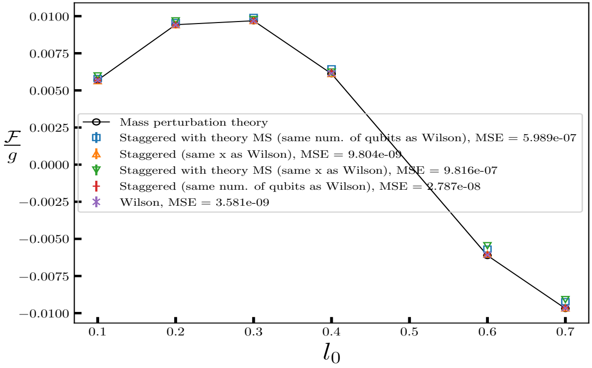
when it works

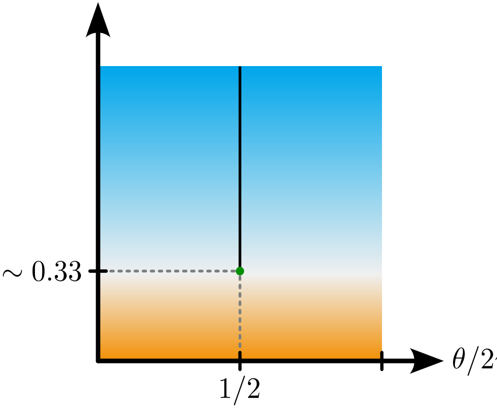


when not

Results: small mass

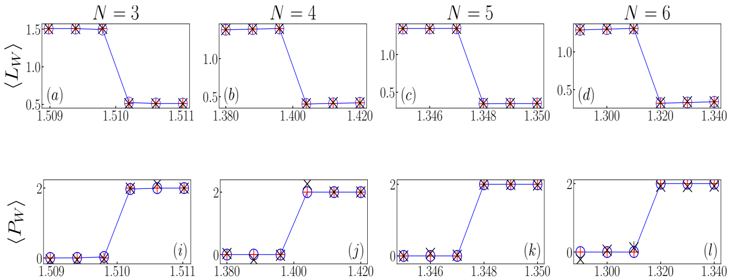
> results for $m_r/g = 0.01$ (remember: $x = 1/(ag)^2$)

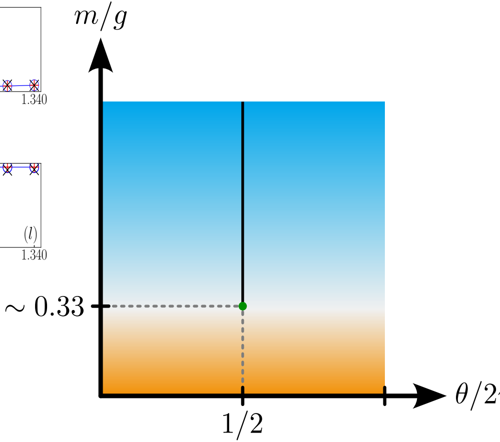




- blue circles: exact diagonalization, red pluses: exact simulations, black crosses: quantum hardware

Results: large mass $m_r/g = 10$



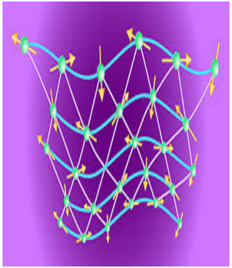


- including hardware results

‘

2+1 dimensional Quantum Electrodynamics

- shows confinement and asymptotic freedom
  $\rightarrow$ resemblence with Quantum Chromodynamics
- microscopic model for condensed matter physics
- Hamiltonian approach:
  - add topological Chern-Simons term
  - supply with non-zero matter density
  - real time evolution
- Here: Quantum Computing

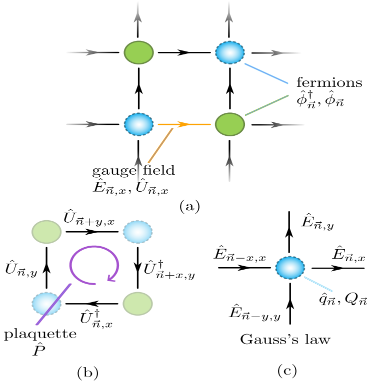


The Hamiltonian of 2+1 dimensional QED $\hat{H}_{\text{QED}}$

- Electric field operator: $\frac{g^2}{2}\sum_{\vec{n}}\left(\hat{E}^2_{\vec{n},x}+\hat{E}^2_{\vec{n},y}\right)$
- Plaquette operator: $-\frac{1}{2a^2g^2}\sum_{\vec{n}}\left(\hat{P}_{\vec{n}}+\hat{P}^\dagger_{\vec{n}}\right)$
- mass term $+m\sum_{\vec{n}}(-1)^{n_x+n_y}\hat{\phi}^\dagger_{\vec{n}}\hat{\phi}_{\vec{n}}$
- kinetic term $\hat{U}_{\vec{n},x}=e^{iag\hat{A}_{\vec{n},x}}$

$$\frac{i}{2a}\sum_{\vec{n}}\left(\hat{\phi}^\dagger_{\vec{n}}\hat{U}^\dagger_{\vec{n},x}\hat{\phi}_{\vec{n}+x}-\text{ h.c. }\right)$$

$$-\frac{(-1)^{n_x+n_y}}{2a}\sum_{\vec{n}}\left(\hat{\phi}^\dagger_{\vec{n}}\hat{U}^\dagger_{\vec{n},y}\hat{\phi}_{\vec{n}+y}+\text{ h.c. }\right)$$



- Gauss law

$$\left[\sum_{\mu=x,y}\left(\hat{E}_{\vec{n}-\mu,\mu}-\hat{E}_{\vec{n},\mu}\right)-\hat{q}_{\vec{n}}-Q_{\vec{n}}\right]|\Phi\rangle=0\iff|\Phi\rangle\in\mathcal{H}_{\text{ph}}$$

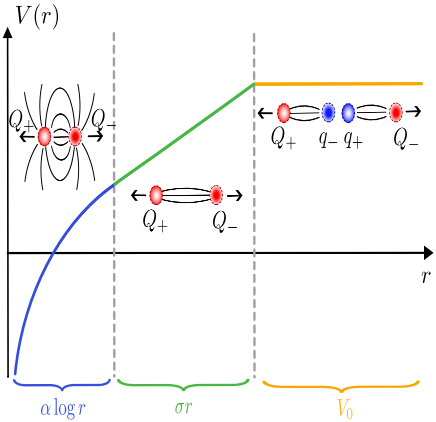
Static potential

(Arianna Crippa, Karl Jansen, Enrico Rinaldi, arXiv:2411.05628)

- potential between static charges at distance r

$$V(r) = V_0 + \alpha \log r + \sigma r$$

- α coupling from Coulomb part
- σ string tension from linear part
- large distance $\rightarrow$ string breaking
- V_0 constant



Numerical implementation

- action of electric field and link operators

$$\hat{E}_{\vec{n},\mu} \left| e_{\vec{n},\mu} \right\rangle = e_{\vec{n},\mu} \left| e_{\vec{n},\mu} \right\rangle , \quad \text{with } \; e_{\vec{n},\mu} \in [-l, l] ,$$

$$\hat{U}_{\vec{n},\mu} \left| e_{\vec{n},\mu} \right\rangle = \left| e_{\vec{n},\mu} + 1 \right\rangle , \quad \hat{U}^{\dagger}_{\vec{n},\mu} \left| e_{\vec{n},\mu} \right\rangle = \left| e_{\vec{n},\mu} - 1 \right\rangle .$$

- encoding of gauge fields

$$|-1\rangle_{\text{ph}} \mapsto |00\rangle \, , , \quad |0\rangle_{\text{ph}} \mapsto |01\rangle \, , , \quad |1\rangle_{\text{ph}} \mapsto |11\rangle \, .$$

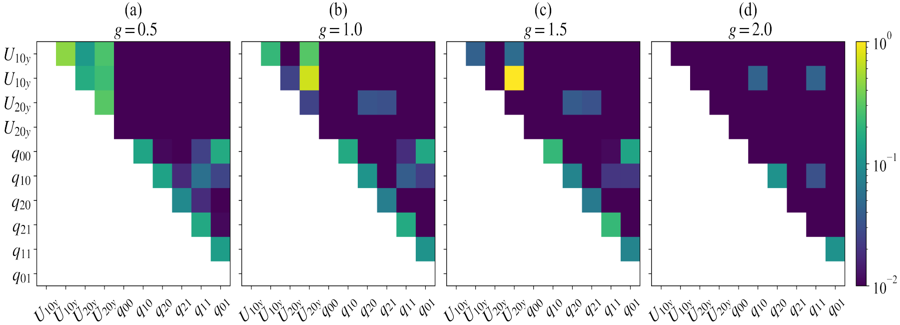
- encoding of fermionic operator through Jordan Wigner transformation

$$\hat{\phi}_{\vec{n}} = \left[\prod_{\vec{k}<\vec{n}} (-i\sigma^{z}_{\vec{k}}) \right] \sigma^{+}_{\vec{n}} , , \quad \hat{\phi}^{\dagger}_{\vec{n}} = \left[\prod_{\vec{k}<\vec{n}} (i\sigma^{z}_{\vec{k}}) \right] \sigma^{-}_{\vec{n}}$$

- discretization: $U(1) \to \mathbb{Z}(2l+1)$

Mutual information

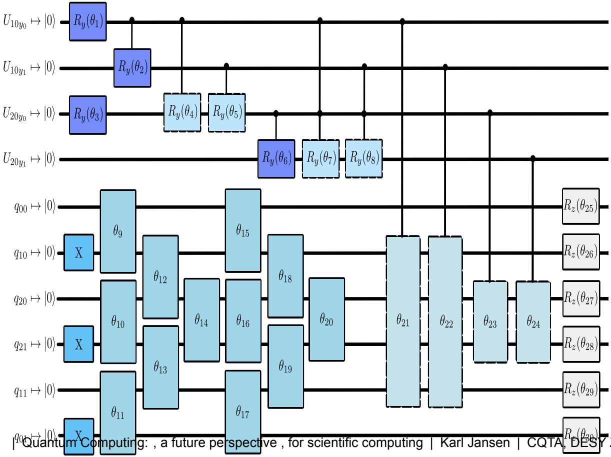
- definition of mutual informatioan, $S(.)$ von Neumann entropy
  $I(X;Y) = S(X) + S(Y) - S(X,Y)$
- use mutual information to construct quantum circuits

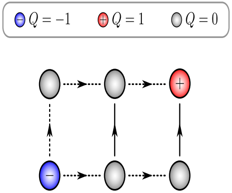


g = 0.5, 1.0, 1.5, 2.0, panel (a), (b), (c), (d)

3x2 lattice

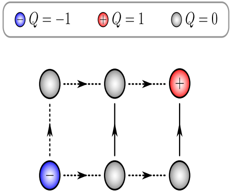
- 3x2 lattice system
- quantum circuit





Lattice and resources

> start with 3x2 lattice
> resource estimation



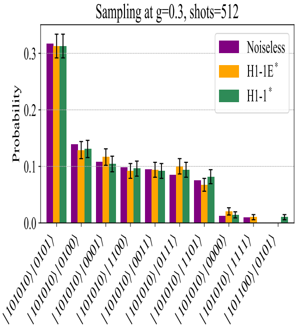
Resource Estimation 3×2 OBC system				
l	# Qubits	# CNOTs	CNOT Depth	# Parameters
1	10	152	60	30
3	12	200	88	41
7	14	252	122	54

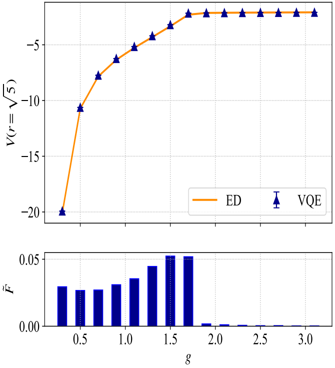
Quantinuum hardware

- used Quantinuum H- series System Model H1-1
- based on Ytterbium-171 ions along a linear trap
- work-flow through Quantinuum Nexus cloud plat
- Emulator runs on H1-1E
- used various noise mitigation techniques
- performed also mid-circuit measurements

Sampling and VQE results inCoulomb regime

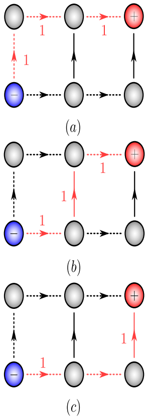
- VQE expectation values, ED and VQE
- infidelity $\tilde{F} \equiv 1 - F = 1 - |\langle\psi_{\mathrm{VQE}}|\,|\psi_{\mathrm{ED}}\rangle|^2$
- sampling states
- ground state probabilities

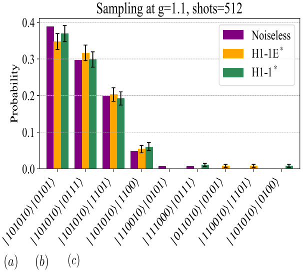




Confinement regime

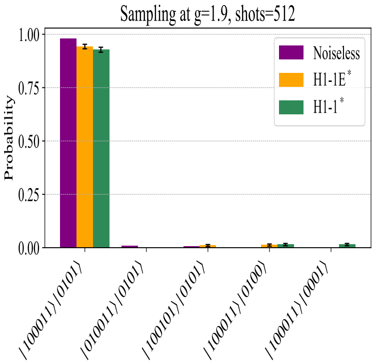
- ground state probabilities in the Confinement regime
- flux configurations



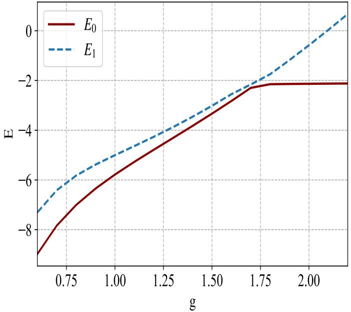


String breaking regime

- probabilities and avoided level crossing



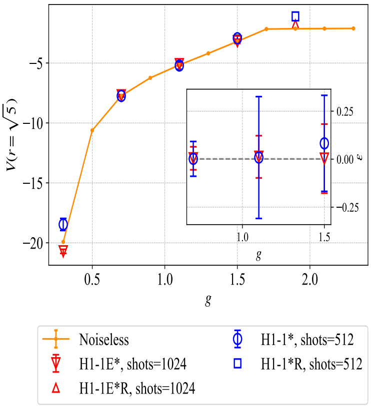
probabilities



avoided level crossing

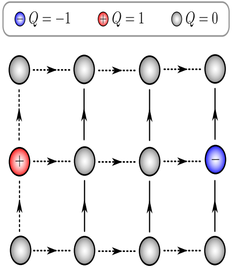
Hardware results

- using H1-1 system of Quantinuum
- performing inference runs



4×3 lattice

> 4×3 lattice system

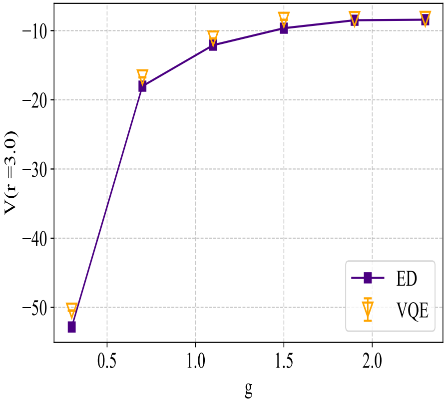


> resource estimate

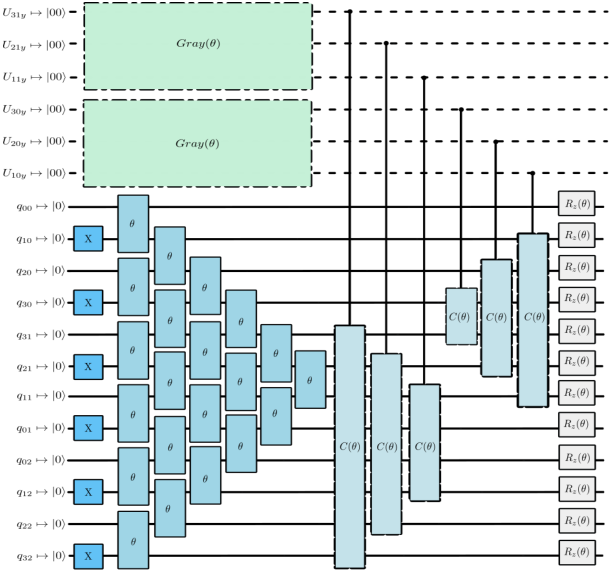
Resource Estimation 4×3 OBC system				
l	# Qubits	# CNOTs	CNOT Depth	# Parameters
1	24	450	136	81
3	30	582	186	123
7	36	738	238	177

VQE results for the 4×3 lattice

- static potential, ED and VQE

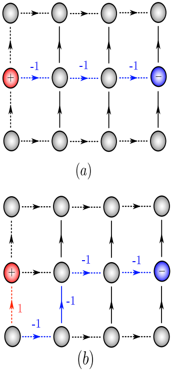


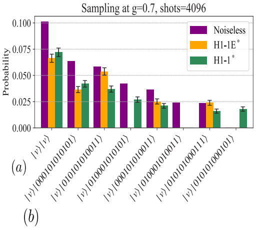
Quantum circuit



Coulomb regime for 4×3 lattice

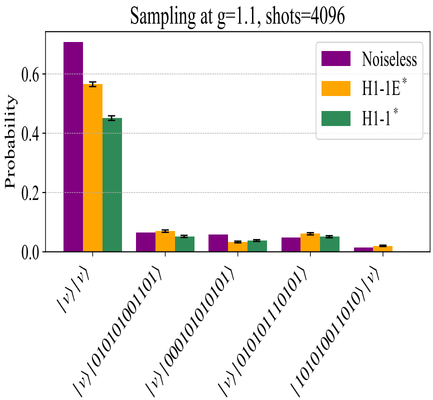
- flux configurations
- state probabilities





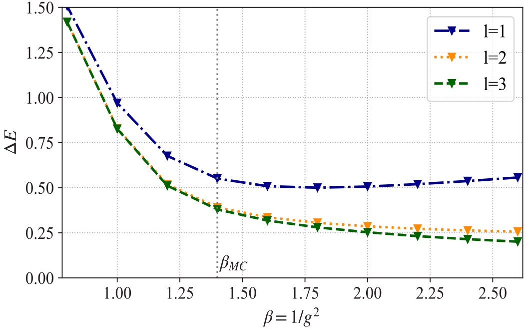
Confinement regime for 4×3 lattice

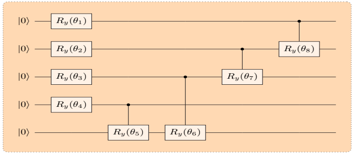
- state probabilities
- single flux string connecting static charges



Quantum computing particle masses

- quantum circuit preserving zero charge sector
- Energygap $E_1 - E_0$
  $\rightarrow$ physical particle mass

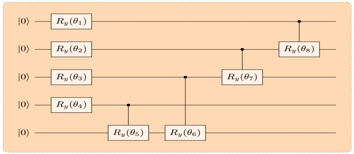


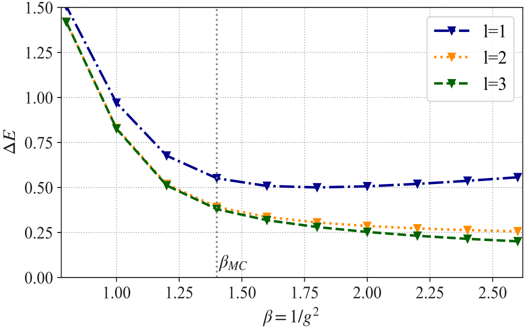


Quantum computing particle masses

> quantum circuit preserving zero charge sector

> Energygap $E_1 - E_0$
> $\rightarrow$ physical particle mass





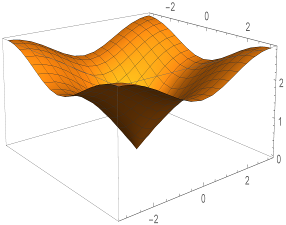
- chemical potential
- Chern-Simons term
- Λ-parameter
- real time phenomena

Chern-Simons term in 2+1 dimensional QED

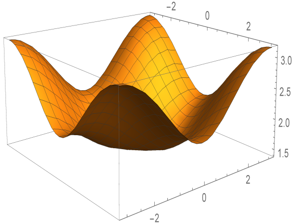
(C. Peng, C. Diamantini, L. Funcke, A. Hassan, K. Jansen, Stefan Kühn, D. Luo, P. Naredi, arxiv:2407.20225)

$$\hat{H} = \sum_{x \in \text{ sites}} \frac{e^2}{2a^2} \left[\left(\hat{p}_{x;1} - \frac{ka^2}{4\pi} \hat{A}_{x-\hat{2};2} \right)^2 + \left(\hat{p}_{x;2} + \frac{ka^2}{4\pi} \hat{A}_{x-\hat{1};1} \right)^2 \right] + \frac{1}{2e^2} \left(\Box \hat{A}_{x;1,2} \right)^2$$

- energy bands



pure Maxwell theory
massless photon

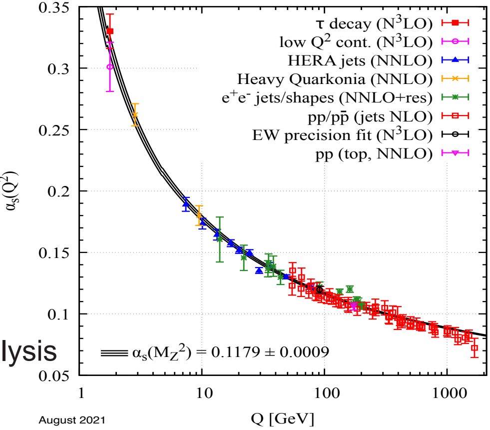


adding Chern-Simons term
topological mass generation

- opens door to investigate e.g. fermion/boson dualities, fractional quantum Hall effect,

1-loop QCD β-function

- running coupling in QCD in 1-loop order
  $\alpha_{\text{strong}}(\mu) = 1/\left(\beta_0 \log(\mu^2/\Lambda^2_{\text{QCD}})\right)$
- β_0 known constant
- Λ_{QCD} QCD Λ-parameter
  $\rightarrow$ provides scale when perturbation theory breaks down
  $\rightarrow$ scale when confinement sets in
- very important quantity
  $\rightarrow$ used in basically all experimental analysis



1-loop QED β-function

- β-function in 2+1-dimensional QED in 1-loop order

  $$\beta(\alpha(\mu)) = -g^2 + N_f b_1 g^4$$

  - g^2 bare coupling in Hamiltonian
  - b_1 known constant
  - N_f number of “flavours” (fermion degrees of freedom)
  - β-function starts negative, ala QCD
    $\Rightarrow$ confinement!

Towards the Λ-parameter

- β-function recast

  $\frac{d\mu}{\mu} = dg(\mu)/\beta(g(\mu))$

- integrated form with integration constant Λ

  $\int_{\Lambda}^{\mu} 1/\mu' d\mu' = \ln(\mu/\Lambda) = \int_{g}^{g(\mu)} dg'/\beta(g')$

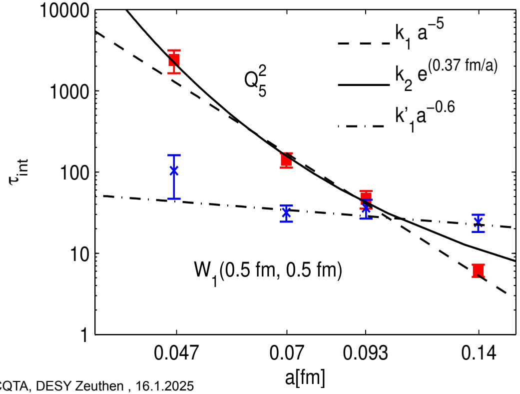
- computing the runnng coupling
  $\rightarrow$ obtain μ/Λ

- use inverse lattice as scale $\mu = 1/a$

- need to convert to physical units
  $\rightarrow$ need the value of the lattice spacing
  $\rightarrow$ need, in particular small values of the lattice spacing

Autocorrelations at small lattice spacing a

- Markov Chain Monte Carlo algorithms (MCMC)
  $\rightarrow$ intrinsic problem of autocorrelations
- prevents reaching small lattice spacing
  $\rightarrow$ only $a > 0.05$ feasible
- quantum computing
  avoids autocorrelations
- also advantage over tensor networks?



Encoding and quantum circuit

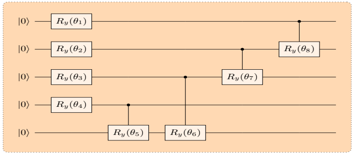
- discretizing group $U(1) \to Z(2L+1)$
- encoding of states, example L=1

$$|-1\rangle_{\text{ph}} \mapsto |00\rangle$$
$$|0\rangle_{\text{ph}} \mapsto |01\rangle$$
$$|1\rangle_{\text{ph}} \mapsto |11\rangle$$

- electric field and link operators

$$\hat{E} \mapsto -|00\rangle\langle 00| + |11\rangle\langle 11|,$$
$$\hat{U} \mapsto |01\rangle\langle 00| + |11\rangle\langle 01|,$$
$$\hat{U}^\dagger \mapsto |00\rangle\langle 01| + |01\rangle\langle 11|$$

- quantum circuit preserving zero charge sector

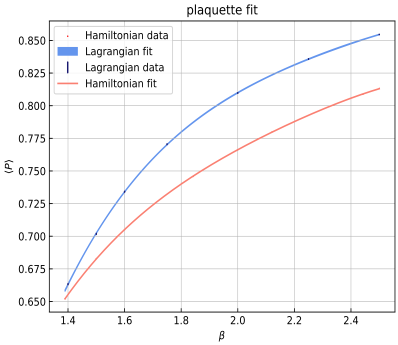


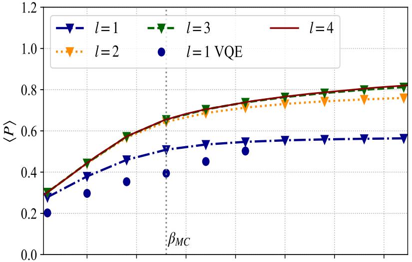
Matching Langrangian and Hamiltonian

(Christiane Gross, Lena Funcke, Karl Jansen, Stefan Kühn, Simone Romiti, Carsten Urbach)

- matching suitable quantities
  - plaquette expectation value
  - "mass gap"
- matching through different procedures
  - taking time direction towards infinity
    $\rightarrow$ remaining time lattice spacing a_t effects
  - taking also limit $a_t \rightarrow 0$
    $\rightarrow$ demanding procedures
- action on lattice woith space L and time T extend: $S = \beta_s \sum_{xx} \Box_{xx} + \beta_t \sum_{xt} \Box_{xt}$
- $\Box_{xx}$ space-like plaquettes, β_s coupling in space
- $\Box_{xt}$ spacetime-like plaquettes , β_t coupling in space time
  $\beta_t \rightarrow \infty : a_t \rightarrow 0$

Matching Monte Carlo and quanrum computing



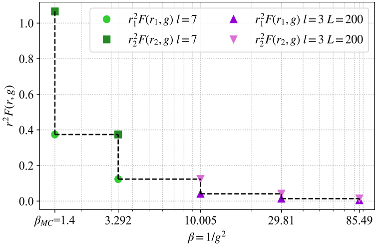


matching plaquette

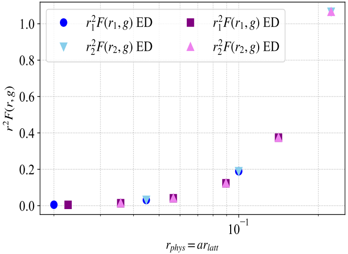
ED and VQE results for different L

Running coupling (demonstration for pure gauge theory)

- physical distance $r_{\text{phys}} = a r_{\text{latt}}$
  $\rightarrow$ lattice spacing a from large volume Monte Carlo simulations
  (here using an artificial value)
- physical distance r_{phys} implicitly given through bare coupling g
- coupling from static force $\alpha(r = 1/\mu) = r^2 F(r, g)$



running coupling as function of g



as function of physical distance

Scattering on a quantum computer

(Yahui Chai, Arianna Crippa, Karl Jansen, Stefan Kühn, Ivano Tavernelli, Francesco Tacchino, arxiv:2312.02272)

- Continuum Lagrangian of Thirring model

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial_\mu \psi - m\overline{\psi}(x)\psi(x) - \frac{\lambda}{2}(\overline{\psi}\gamma_\mu\psi)(\overline{\psi}\gamma^\mu\psi)$$

- Hamiltonian lattice version

$$H = \sum_{n=0}^{N-1} \left\{ \frac{i}{2a} \left(\xi_{n+1}^\dagger \xi_n - \xi_n^\dagger \xi_{n+1} \right) + (-1)^n m \, \xi_n^\dagger \xi_n \right\} + \sum_{n=0}^{N-1} \frac{g(\lambda)}{a} \xi_n^\dagger \xi_n \xi_{n+1}^\dagger \xi_{n+1}$$

- Spin representation $\rightarrow$ Jordan Wigner

Spin representation

> Jordan-Wigner transformation

$$\xi_n^\dagger = \prod_{l<n} \sigma_l^z \sigma_n^- , \quad \xi_n = \prod_{l<n} \sigma_l^z \sigma_n^+$$

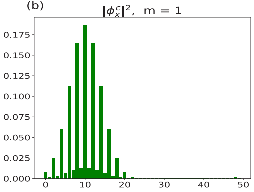
$$\sigma_l^\pm = \left(\sigma_l^x \pm i\sigma_l^y\right)/2$$

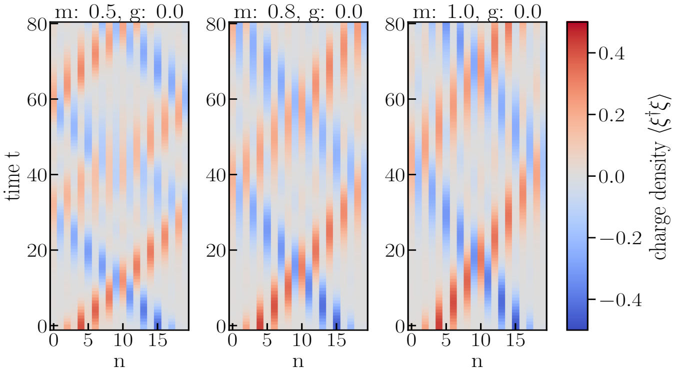
> Hamiltonian

$$\begin{aligned} H = & \frac{i}{2a} \sum_{n=0}^{N-2} \left(\sigma_{n+1}^- \sigma_n^+ - \sigma_n^- \sigma_{n+1}^+\right) \\ & + \frac{i}{2a} \left(\sigma_0^- \sigma_1^z \ldots \sigma_{N-2}^z \sigma_{N-1}^+ - \sigma_{N-1}^- \sigma_{N-2}^z \cdots \sigma_1^z \sigma_0^+\right) \\ & + \frac{m}{2} \sum_{n=0}^{N-1} (-1)^n \left(\mathbb{1} - \sigma_n^z\right) + \frac{g}{4a} \sum_{n=0}^{N-1} \left(\mathbb{1} - \sigma_n^z\right) \left(\mathbb{1} - \sigma_{n+1}^z\right) \end{aligned}$$

Gaussian wave packets

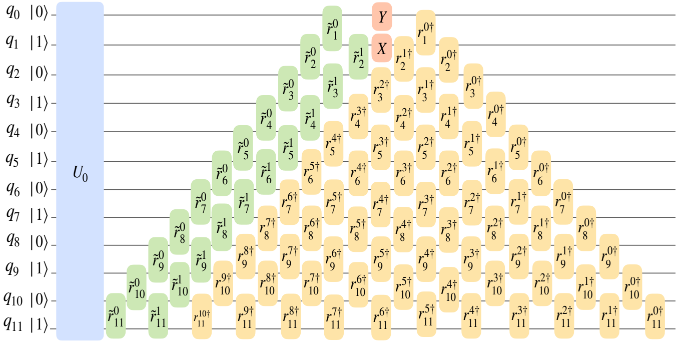
- Gaussian wave packets $\phi_k^{c(d)} = \frac{1}{\mathcal{N}_k^{c(d)}} e^{-ik\mu_n^{c(d)}} e^{-(k-\mu_k^{c(d)})^2/4\sigma_k^2}$
- time evolution: Givens rotation
- time evolution for free fermions: charge distribution



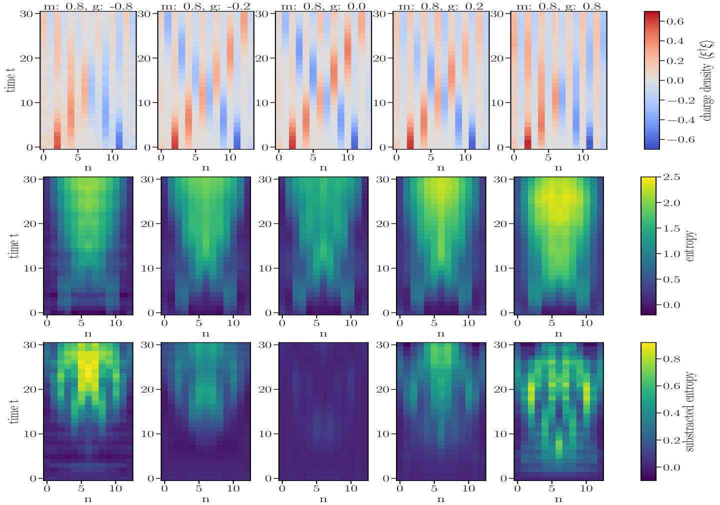


Quantum circuit

- blue box: vacuum preparation
- green and yellow boxes: wave packet preparation and time evolution

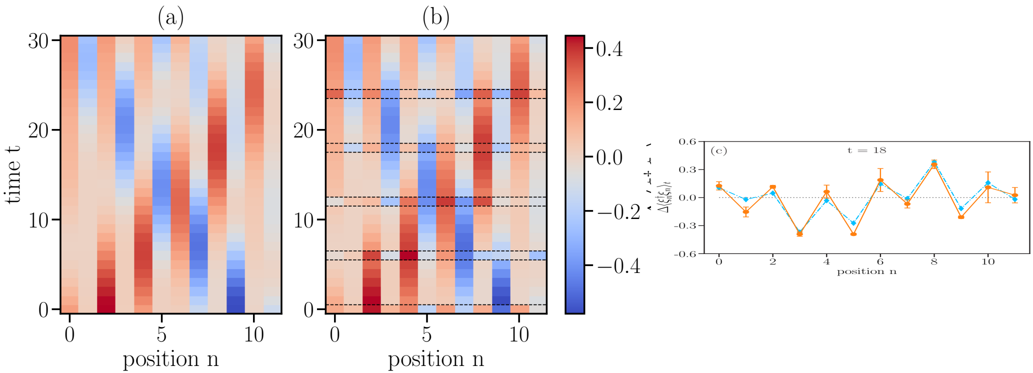


Interacting case



Hardware runs

> Ideal versus hardware



Quantum computing inspired paintings: reinterpreting classical masterpieces

(Arianna Crippa, Yahui Chai, Omar Costa Hamido, Paulo Itaborai, Karl Jansen, arXiv:2411.09549)

> a journey from classical art to abstraction

Caravaggio: “Narciso”

→

Magritte: “Le fils de l’homme”

→

Richter: “192 Fraben”

Numerical methods

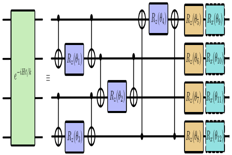
- physical system: ising model

$$H = \sum_{n=0}^{N-1} J_n Z_n Z_{n+1} + \sum_{n=0}^{N-1} h_{z,n} Z_n + \sum_{n=0}^{N-1} h_{x,n} X_n$$

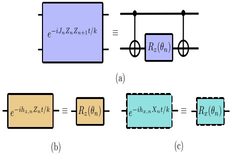
- Trotterization

$$|\psi(t)\rangle = U(t)\,|\psi(0)\rangle \equiv e^{-iHt}\,|\psi(0)\rangle\,,\; U(t) \approx \prod^{k} \prod_{n=0}^{N-1} e^{-iH_n t/k}$$

- quantum circuit



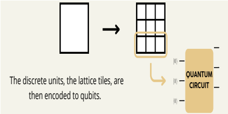
quantum circuit



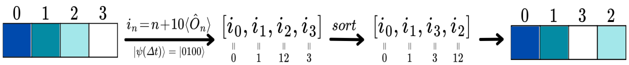
Trotter step

Principle of quantum art transformation

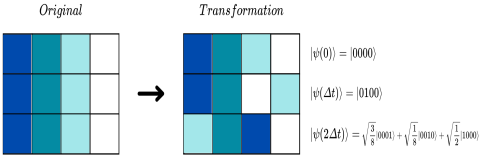
> tiling the painting



> re-ordering



> transformation



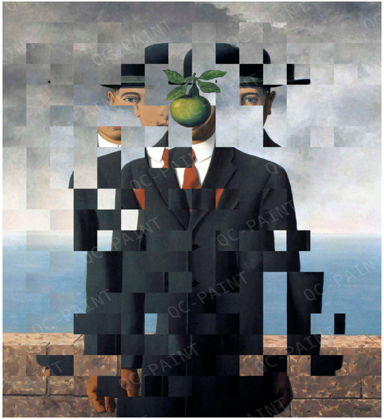
Caravaggio

> Transformation I: Caravaggio

"Quantum Transformation I: Caravaggio" (oil on wooden panel): This photograph of the oil painting illustrates how the reflection (lower part) has been modified by translating the results from quantum computation. Panel size: 70 × 84 cm.

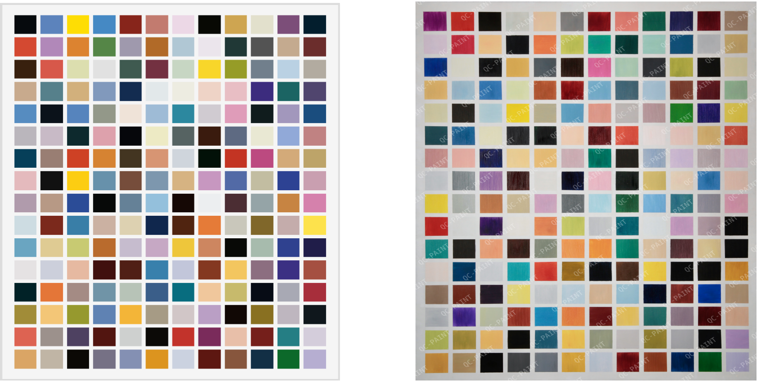
magritte

> Transformation II: Magritte



The painting "Quantum Transformation II: Magritte" (digital image): The entire picture is modified by the quantum time evolution. The only element that remains untouched is the green apple.

Transformation III: Richter

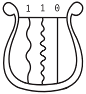


The painting "Quantum Transformation III: Richter": (panel (a)) The original version titled "192 Farben" (digital reconstruction): The image has been produced digitally based on the original painting. (panel (b)) The revisited version (oil on wooden panel, foto). Panel size: 75 × 100 cm.

The Variational Quantum Harmonizer

(Paulo Itaborai, Peter Thomas, Arianna Crippa, Karl Jansen, Tim Schwägerl, Maria Aguado)

- encoding a harp



- encoding a chord

1	0	0	0	1	0	0	1	0	0	0	0
C	$C\#$	D	$D\#$	E	F	$F\#$	G	$G\#$	A	$A\#$	B

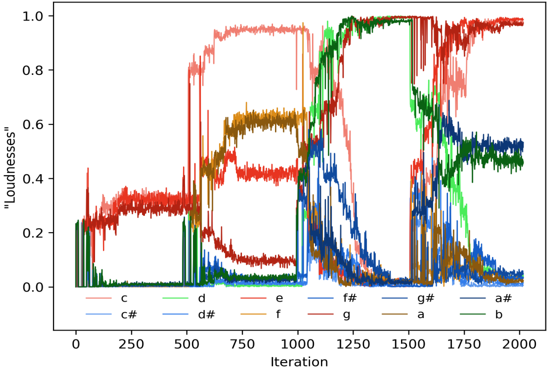
- Hamiltonian (0,1) $\rightarrow$ (-1,1)

$$H(Z) = \sum_i^N a_i^{VQE} Z_i + \sum_i^N \sum_{j<i}^N b_{ij}^{VQE} Z_i Z_j$$

$\rightarrow$ same as for flight gate assignment

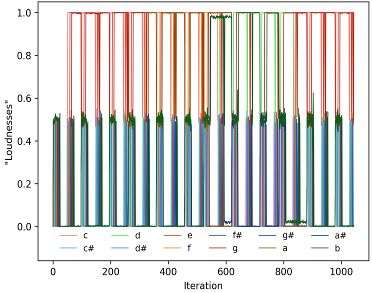
Chord progression

- A I-IV-V-I chord progression
- using Cobyla optimizer

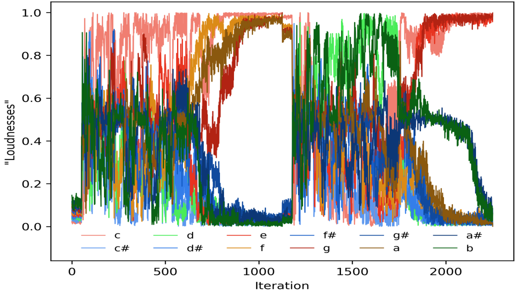


Optimizers

> How optimizers sound



NFT

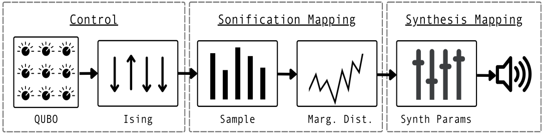


SPSA

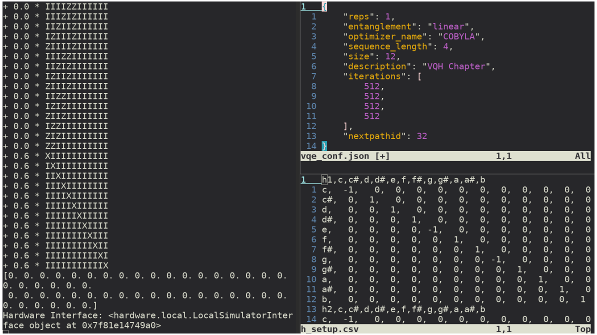
> hopefully a link to listen

VQH live as musical intrument

> VQH instrument



> how it looks
> in live performance



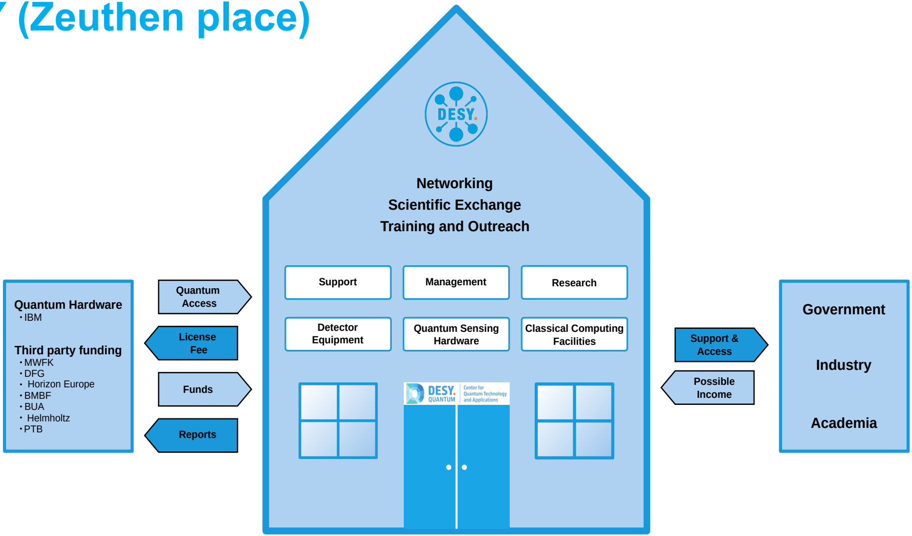
Quantum music

> International conference on quantum music in Berlin, 5th/6th of October

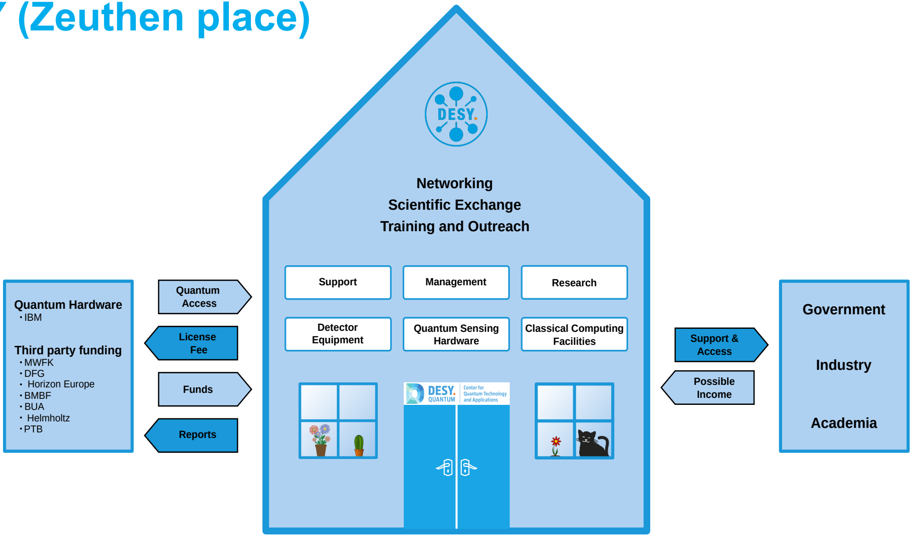
Examples of quantum music

- CTM Festival, January 2024
  CTM event
- Rasgar, Saber (2022-23) - by Paulo Itaborai
  Rasgar, Saber
- ReVeR (2023) - by Paulo Itaborai and Dino Vicente
  ReVeR
- Hexagonal Chambers (2023-24) - by Cephas Teom and Paulo Itaborai
  Hexagonal Chambers
- Premiere of ”Dependent Origination” at IKLECTIK, London:
  Dependent Origination
- Performance of ”Dependent Origination” at the ICFO Quantum Sounds Symposium
  Dependent Origination

Center for Quantum Technology and Applications at DESY (Zeuthen place)



Center for Quantum Technology and Applications at DESY (Zeuthen place)



The CQTA group

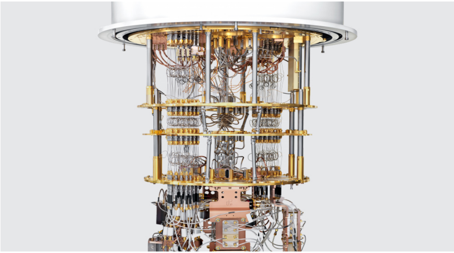
> The group in Zeuthen in September 2021

The CQTA group

- The present group in Zeuthen (missing 3 female members)

The pillars of CQTA

- **Quantum Field Theoretical models from condensed matter and high energy physics** $\rightarrow$ sign problem, real time phenomena
- **Optimization/classification**
  - Particle track reconstruction/jet classification
  - Flight gate assignment
  - Gene/exon classification
- **Quantum art**
  - Quantum music, Quantum painting
- **Others**
  - factoring, Feynman diagrams, matrix models, ...
- **training**
- **Algorithm development**
  - Expressivity
  - controllability
  - warm starts



Phase 1: visibility → Brandenburg Roadmap

Federführend:
Dr. Karl Jansen
Dr. Anne Techen
Übergabe: 24.9.204

Auf dem Weg zu einer gemeinsamen Quantentechnologie Hauptstadtregion: Quantentechnologie Roadmap Brandenburg

Inhaltsverzeichnis

Vorwort

Quanteneffekte bilden die Grundlage für moderne Techniken wie z.B. Mikrochips, Laser oder Satellitennavigation. Quantentechnologien (Sensorik, Kommunikation, Computing, Materialien) der zweiten Generation werden unser Leben durch neue Erkenntnisse, Produkte und Dienstleistungen zukünftig nachhaltig und revolutionär verändern. Sie sind Impulsgeber und öffnen die Türen für Innovationen in der Grundlagenforschung sowie in einer Vielzahl von Anwenderbranchen wie u.a. in der Gesundheitswirtschaft, Mobilität, Logistik, Batterieforschung oder im Finanzwesen. Ihr Potenzial wird von Experten und Expertinnen als disruptiv und einschneidend für die Gesellschaft, bestehende Märkte, der Wissenschaft und die Wirtschaft bewertet.

Sichere Kommunikation, eine schnellere Datenverarbeitung, disruptives Computing oder auch neue Sensoren sind nur einige Beispiele für die enorme Leistungsfähigkeit dieser Schlüsseltechnologie.

Phase 1: visibility → Brandenburg connections

- Brief von Herrn Saule, WFBB, an Staatssekretär Dünow
  - mögliche Förderwege für die zweite Phase des „Zentrums für Quantentechnologie und Anwendungen (CQTA) – Zeuthen“ identifizieren und schaffen
  - die Verankerung der Quantentechnologie in der brandenburgischen Forschungslandschaft vorantreiben und sicherstellen (z.B. neue Professuren, Anreize für hochschulübergreifenden Kooperationen, etc.)
  - Bereitschaft zeigen, Quantencomputer-Hardware in Brandenburg aufzustellen und zu betreiben
  - eine Brücke zu den Berliner Quantentechnologie Aktivitäten bauen und unterstützen (evtl. Chance auf neue, gemeinsame Förderprogramme)
  - Unterstützung und Sichtbarmachung der Brandenburger Quantentechnologieaktivitäten auf Bundesebene
- Kooperation mit TH Wildau, IHP Frankfurt, Einstein Research Unit Berlin, ...
- Austausch mit Rössler (Photonic Cluster), Paluszynski (MWFK), Dünow (MWFK), ...

ERA Chair QUEST (QUantum computing for Excellence in Science and Technology)

- European Research Executive Agency funding (2.5 million Euro)
- focus activities
  - Building up a quantum computing group at the CyI
  - develop applications of uses case for industry, governmental agencies and academia
  - Act as hub for Eastern Mediterranean region
  - closely connected to Center for Quantum Technology and Applications (CQTA) at DESY

The CQTA group

- The present group at the CyI under the ERA Chair
- Assistant professor to be recruited beginning of 2025

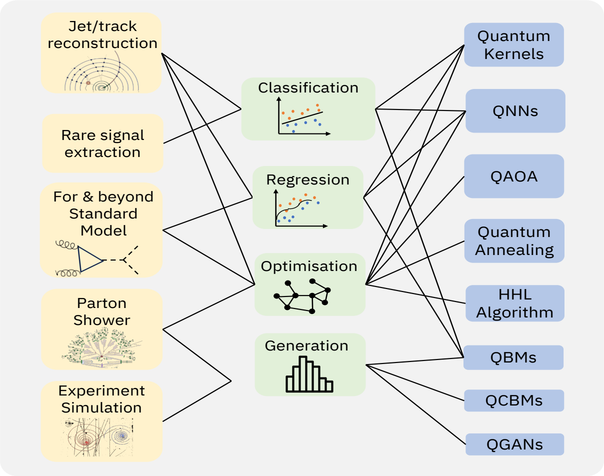
QC4HEP whitepaper, arXiv:2307.03236

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[5,3] Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[10,1] Arianna Crippa,[2,11] Vincent Croft,[12] Roland de Putter,[6] Andrea Delgado,[13] Vedran Dunjko,[12] Daniel J. Egger,[4] Elias Fernández-Combarro,[14] Elina Fuchs,[1,15,16] Lena Funcke,[17] Daniel González-Cuadra,[18,19] Michele Grossi,[1] Jad C. Halimeh,[20,21] Zoë Holmes,[22] Stefan Kühn,[2] Denis Lacroix,[23] Randy Lewis,[24] Donatella Lucchesi,[25,26,1] Miriam Lucio Martinez,[27,28] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[25,26] Lento Nagano,[29] Voica Radescu,[30] Enrique Rico Ortega,[31,32,33,34] Alessandro Roggero,[35,36] Julian Schuhmacher,[4] Joao Seixas,[37,38,39] Pietro Silvi,[25,26] Panagiotis Spentzouris,[40] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[29] Jordi Tura,[12,41] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[42] Shinjae Yoo,[43] and Jinglei Zhang[44,45]

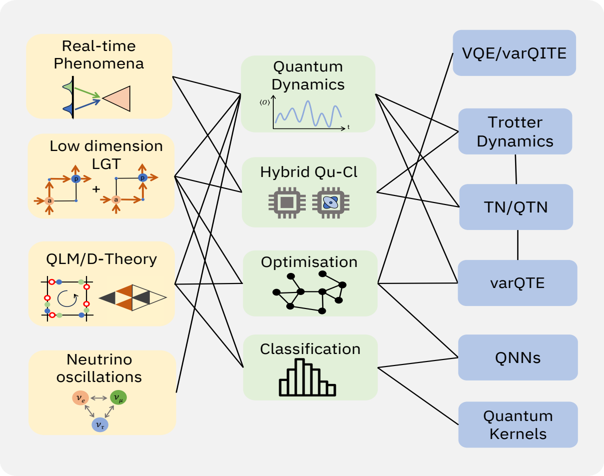
Abstract

Quantum computers offer an intriguing path for a paradigmatic change of computing in the natural sciences and beyond, with the potential for achieving a so-called quantum advantage, namely a significant (in some cases exponential) speed-up of numerical simulations. In particular, the high-energy physics community plays a pivotal role in accessing the power of quantum computing, since the field is a driving source for challenging computational problems. ...

QC4HEP: Experiment summary

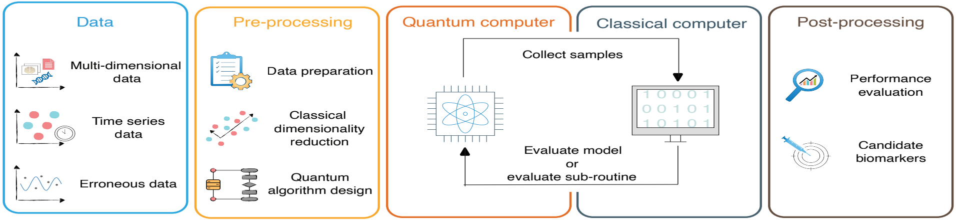


QC4HEP: Theory summary



Quantum computing enhances biomarker discovery

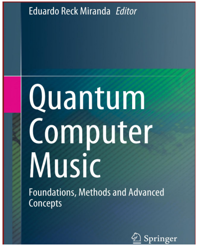
(Frederik Flöther, Daniel Blankenberg, Maria Demidik, Karl Jansen, Raga Krishnakumar, Rajiv Krishnakumar, Numan Laanait, Laxmi Parida, Carl Saab, Filippo Utro, arXiv:2411.10511)



Modality	Pre-processing	Quantum algorithms	Classical algorithms	Use case application
Electronic health records	Definition of relevant cohorts, data quality analysis, imputation	QML, QRNNs, QReservoir , QNLP, linear equation solving with quantum algorithms	Deep learning, ML and statistical learning Small/missing data, undetermined system, data quality, multi-modality, generalizability	Clinical note processing, population stratification, drug/patient response
Omics	Noise removal (intra- and inter-omics variability), size reduction, normalization, imputation	QML, QK-means, QBMs, QVAE, Quantum least squares, QGNNs, VQE, QAOA, linear equation solving with quantum algorithms	Deep learning, ML and statistical learning Small/missing data, multi-modality, exponential scaling of resources, undetermined system	GWAS, population stratification, gene regulatory network, drug/patient response, disease subtyping and progression
Medical images	Background removal, denoising, resampling, registration, intensity normalization	QML, QGAN, QVAE, QTDA	Deep learning, ML Data volume, labelling, processing power	Identification of region of interest, disease subtyping and progression

Summary and outlook

- It took 40 years to start realizing Feynman's vision of using quantum computers
- **Now:** first computations in high energy physics with $O(10)$ qubits on NISQ devices
  - experiment: particle tracking, Boltzmann machines, quantum neural networks, ...
  - theory: low-dimensional, abelian and non-abelian models in 1+1 and 2+1 dimensions, scattering, ...
- **soon:** demonstrations, $O(100)$ qubits and circuit depth of $O(100)$
  - identify and evaluate applications for quantum computers
  - develop further quantum algorithms and methods
  - evaluate scaling with the number of qubits
    $\rightarrow$ quantum advantage? for what? when?
- **future:** fault tolerant quantum computing



Thank you!

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Karl Jansen
0000-0002-1574-7591
Center for Quantum Technologies and Applications
karl.jansen@desy.de
+49–33762–77286