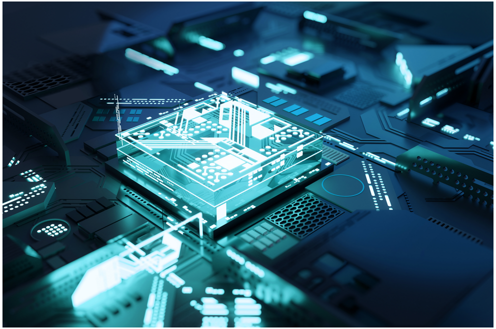
Quantum Computing: a future perspective for scientific computing

CQTA

Karl Jansen
University of Padova, 10.4.2025

Overview



- > Introduction
- > Quantum Electrodynamics in 1+1 dimensions
- > Real time scattering experiment
- > Optimal Flight Gate Assignment
- > CQTA
- > 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

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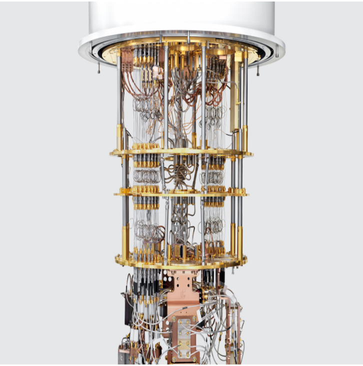
- *Developing a Framework for* **Sonifying** *Variational Quantum Algorithms: Implications for* **Music Composition**, Paulo Vitor Itaboraí, Peter Thomas, Arianna Crippa, Karl Jansen, Tim Schwägerl, María Aguado Yáñez, arXiv: 2409.07104

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

→ you can start now!

Schwinger model: 2-dimensional Quantum Electrodynamics

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

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

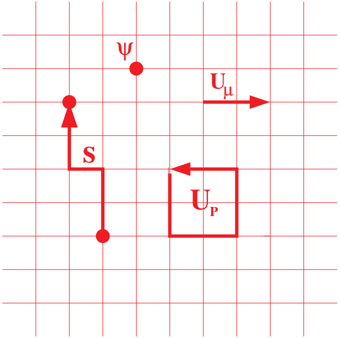
with A_μ gauge potential, g_0 bare coupling

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

Lattice Schwinger model

introduce a 2-dimensional lattice with lattice spacing a

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



discretized fermion action

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

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

discrete derivatives

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

second order derivative $\to$ remove doubler $\leftarrow$ break chiral symmetry

Implementing gauge invariance

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

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

$\Rightarrow$ lattice derivatives

$$\begin{aligned}
\nabla_\mu \Psi(x) &= \frac{1}{a}\left[U(x,\mu)\Psi(x+\mu) - \Psi(x)\right] \\
\nabla^*_\mu \Psi(x) &= \frac{1}{a}\left[\Psi(x) - U^{-1}(x-\mu,\mu)\Psi(x-\mu)\right]
\end{aligned}$$

action gauge invariant under

$$\begin{aligned}
&\Psi(x) \rightarrow g(x)\Psi(x),\ \ \bar{\Psi}(x) \rightarrow \bar{\Psi}(x)g^*(x), \\
&U(x,\mu) \rightarrow g(x)U(x,\mu)g^*(x+\mu)
\end{aligned}$$

The Schwinger model: the action

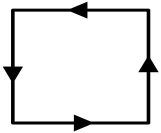
- Wilson's fundamental observation: introduce parallel transporter connecting the points x and $y = x + a\hat{\mu}$:

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

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

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

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



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

Physical observables

expectation value of physical observables $\mathcal{O}$

$$\underbrace{\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int_{\text{fields}} \mathcal{O} e^{-S}}$$

$\downarrow$

lattice discretization

$\downarrow$

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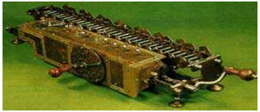
$\downarrow$



Going to Quantum Chromodynamics

change	factor
2-d $(40 \times 40) \rightarrow$ 4-d (40^4)	1600
gauge field $U(x,\mu) \in U(1) \rightarrow U(x,\mu) \in SU(3)$	8
Pauli matrices $\sigma_\mu \rightarrow$ Gell-Mann-matrices γ_μ	4
spinors become 12-component complex vectors	24

- total factor: 1228800
- theory needs renormalization

Present day Lattice Gauge Theory calculations

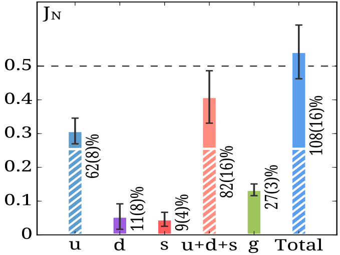
- Large activity of theoretical lattice simulations of the standard model of particle interaction
  $\rightarrow$ see FLAG review, Y. Aoki et.al, Eur.Phys.J.C 82 (2022) 10, 869
- discretize space and time
- use euclidean metric
- Feynman path integral $\rightarrow$ statistical mechanical system
- Lattice simulations of QCD, Higgs-Yukawa sector, Supersymmetry via **Markov Chain Monte Carlo Methods**

A Towards resolving the spin puzzle of the nucleon

(C. Alexandrou, M. Constantinou, K. Hadjiyiannakou,
C. Kallidonis, G. Koutsou, A. Vaquero Avilés-Casco, C. Wiese, K. Jansen)

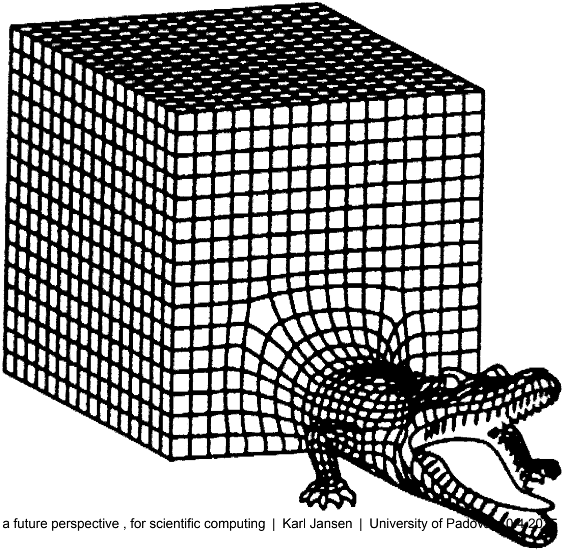
> old puzzle: quarks provide only surprisingly small contribution to spin
  $\rightarrow$ remained unsolved for decades

> lattice gauge theory advances
  – very demanding, dedicated effort
  – including four lightest quarks **and gluon** $\rightarrow$ obtain full spin decomposition



- stripped segments: valence quarks
- solid segments: sea quarks and gluons
- find large gluon contribution

There are dangerous lattice animals



Understanding the early universe

> Markov Chain Monte Carlo: only zero baryon density accessible

→ understanding of phase transitions?

- early universe
- heavy ion experiments
- exotic regions of PD

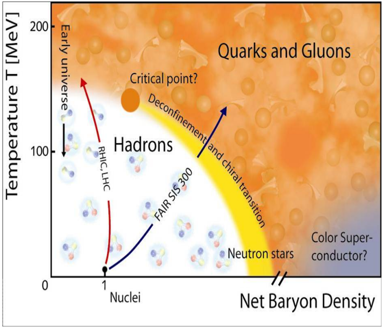
> do not understand origin of todays universe

> topological terms

> real time evolution

> large autocorrelations towards continuum limit

→ solution: Hamiltonian formulation



A problem with Hamiltonian approach

- determine wave function $|\Psi>$

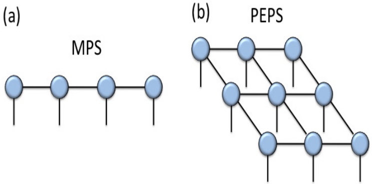
$$|\Psi>=\sum_{i_1,i_2,\cdots,i_N} C_{i_1,i_2,\cdots,i_N}|i_1 i_2 \cdots i_N>$$

$C_{i_1,i_2,\cdots,i_N}$ coefficient matrix with 2^N entries

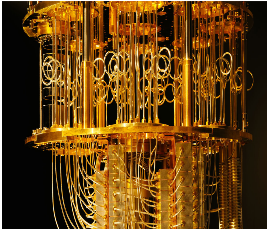
$\rightarrow$ problem scales exponentially

Two solutions for Hamiltonian approach

- Tensor Networks
  - gapped, local Hamiltonians
    $\rightarrow$ area law
    $\rightarrow$ very fast (exponential) convergence
  - costly: entanglement
    $\rightarrow$ phase transitions, (long) real time evolution



- Quantum Computing
  - conceptually clean path
  - noise, low number of qubits, ...



- **Here: focus on quantum computing Quantum Field Theories**

Schwinger Model

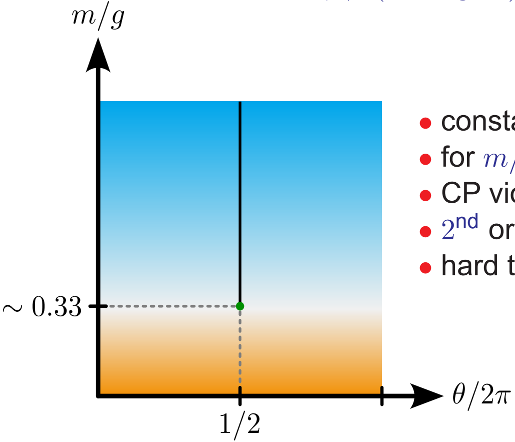
(Schwinger 1962)

- 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

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

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

- 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

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

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

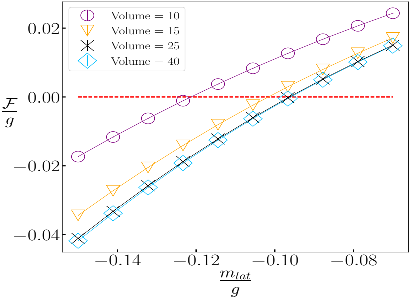
- particle number operator

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

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

Determining the mass shift: a MPS calculation

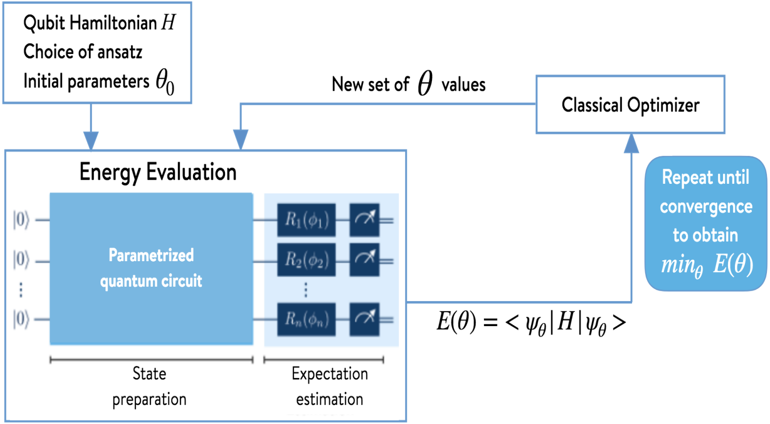
> electric field density (EFD) in mass perturbation theory
$\frac{\mathcal{F}}{g} = \frac{e^\gamma}{\sqrt{\pi}} \left(\frac{m}{g}\right) \sin\theta - 8.9139 \frac{e^{2\gamma}}{4\pi} \left(\frac{m}{g}\right)^2 \sin(2\theta) \Rightarrow$ for $m = 0$ EFD vanishes



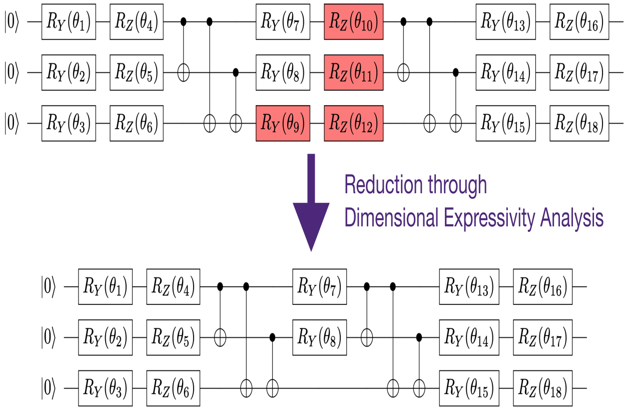
Wilson

Variational Quantum Eigensolver (VQE)

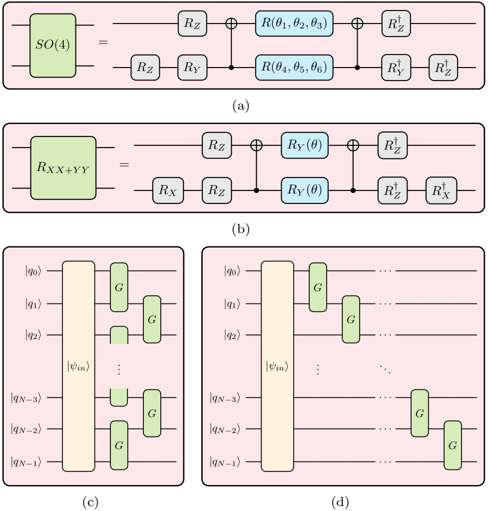
> a hybrid quantum/classical variational approach



Example for a quantum circuit



The Ansatz



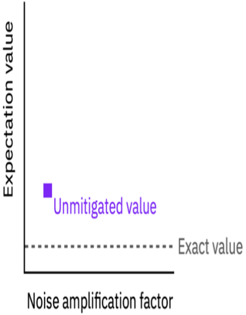
- decomposition of $SO(4)$ and R_{XX+YY} gates
- brick and ladder ansatz

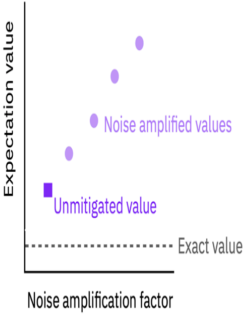
Mitigating quantum computing results

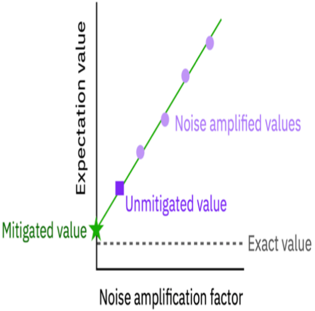
> zero noise extrapolation (ZNE) in theory

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

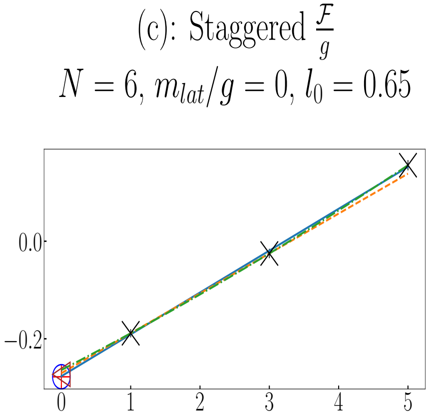
$$|\psi >= U|0 >= UU^\dagger U \left|0 >= UU^\dagger UU^\dagger U \right| 0 >$$



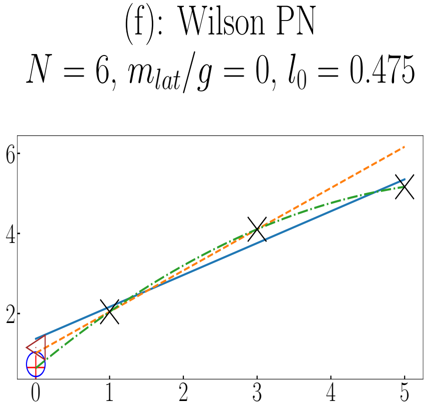




ZNE in practise



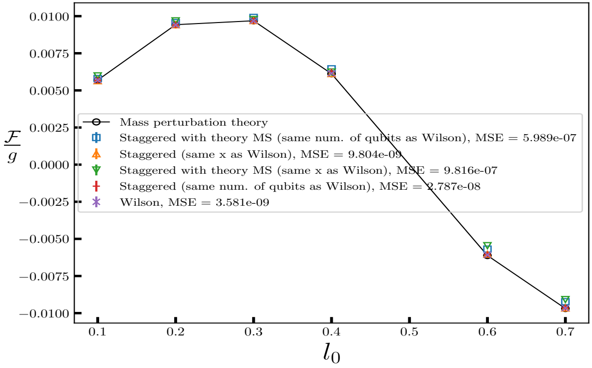
when it works

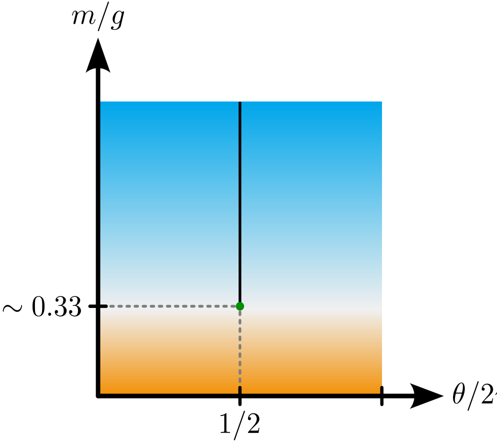


when not

Results: small mass

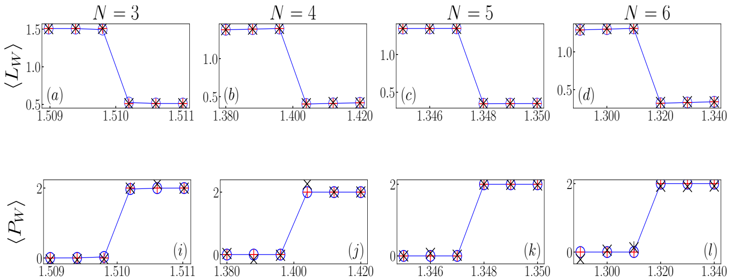
> results for $m_r/g = 0.01$ (remember: $x = 1/(ag)^2$)

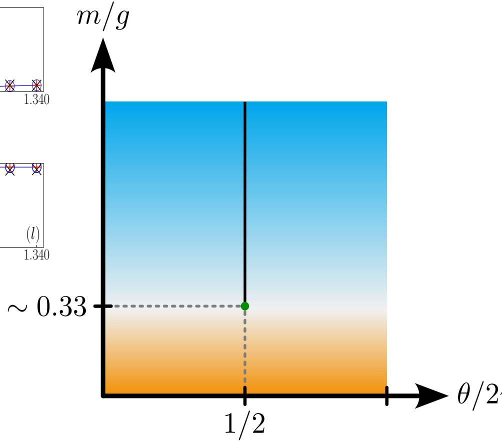




- blue circles: exact diagonalization, red pluses: exact simulations, black crosses: quantum hardware

Results: large mass $m_r/g = 10$





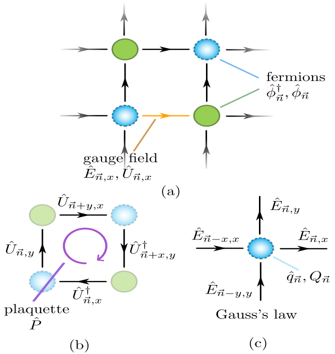
- including hardware results

‘

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 $\hat{U}_{\vec{n},x}=e^{iag\hat{A}_{\vec{n},x}}$

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



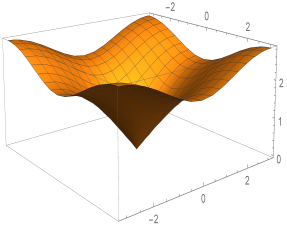
- investigated the running coupling with matching to Markov Chain Monte Carlo
- looked at electric flux configurations for Coulomb, confinement and string breaking regimes of static potential
- developed lattice Chern-Simons Hamiltonian

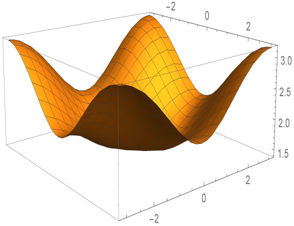
Chern-Simons term in 2+1 dimensional QED

(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





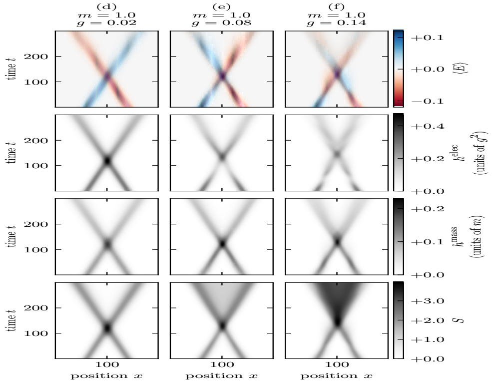
pure Maxwell theory
massless photon

adding Chern-Simons term
topological mass generation

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

Scattering from MPS: real mesons 1+1 dimensional Schwinger model

Marco Rigobello, Simone Notarnicola, Giuseppe Magnifico, Simone Montangero,
Phys. Rev. D 104, 114501



- meson wave packets
- generate entanglement
- strong dependence on coupling
- rich phenomenology after collision

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

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

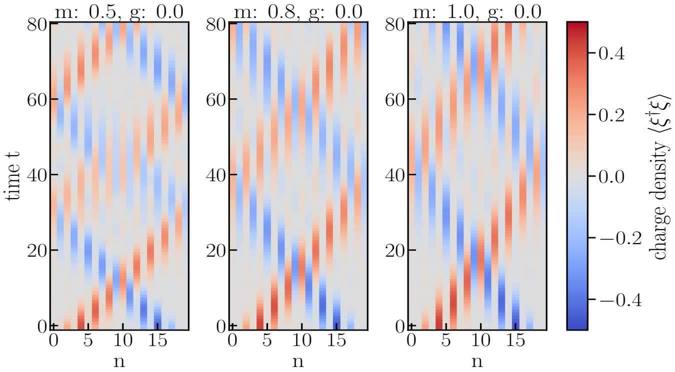
$$\sigma_l^\pm = \left(\sigma_l^x \pm i\sigma_l^y\right)/2$$

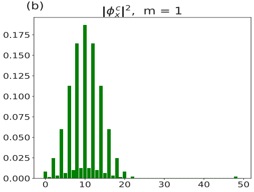
- Hamiltonian

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

Gaussian wave packets

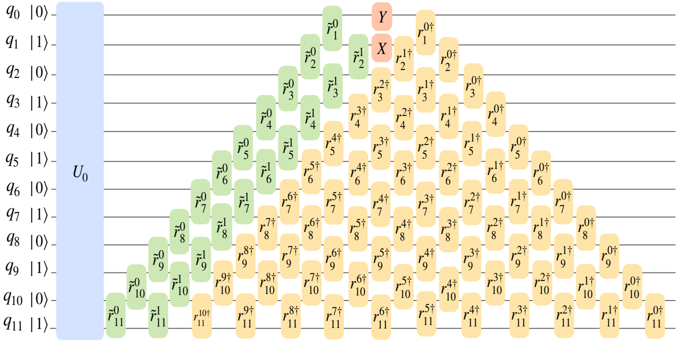
- Gaussian wave packets $\phi_k^{c(d)} = \frac{1}{\mathcal{N}_k^{c(d)}} e^{-ik\mu_n^{c(d)}} e^{-(k-\mu_k^{c(d)})^2/4\sigma_k^2}$
- time evolution: Givens rotation
- time evolution for free fermions: charge distribution



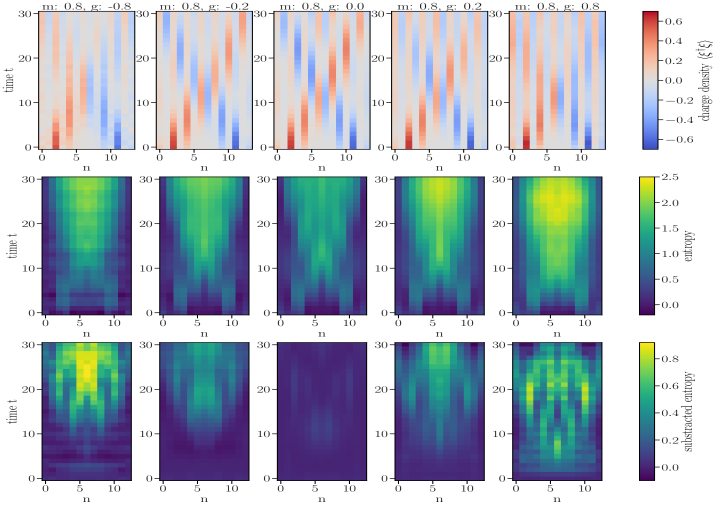


Quantum circuit

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

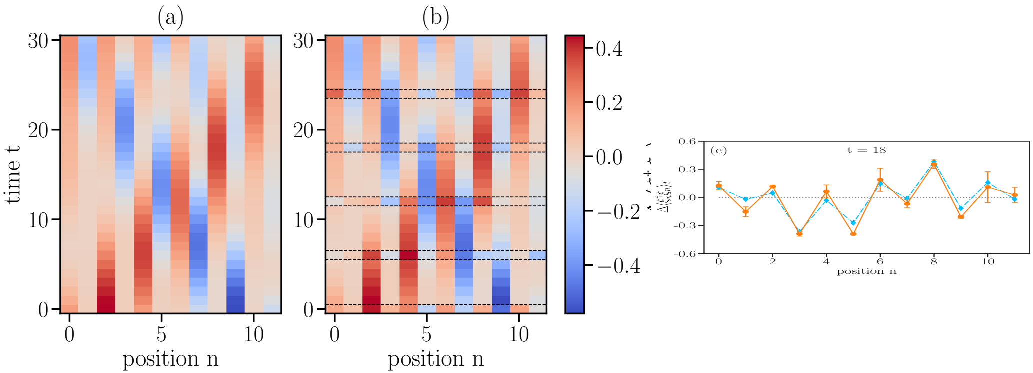


Interacting case



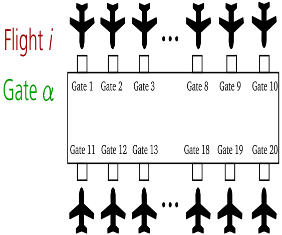
Hardware runs

> Ideal versus hardware



Quantum computing 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
  → find optimal assignment
- Classical optimization problem
  → quantum advantage?



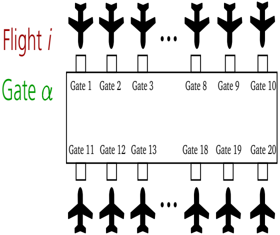
Quantum computing the flight gate assignment problem

- binary variables encoding gates and flights

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

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

eigenstate of third Pauli matrix σ_z



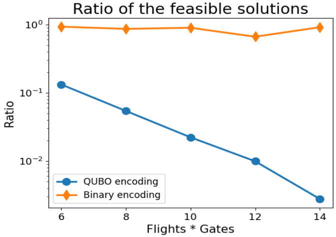
- leads to mathematical description of Hamiltonian

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

- 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)

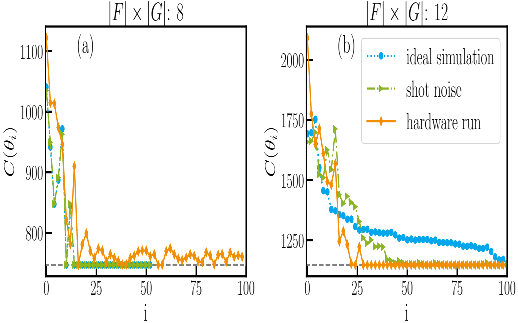


Feasible ratio

Quantum hardware runs of flight gate assignment problem

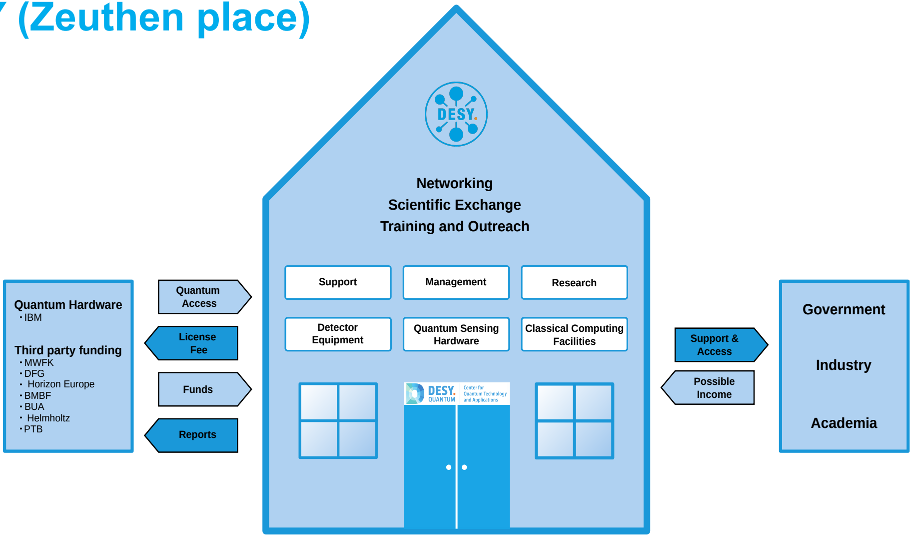
(Y. Chai, E. Epifanovsky, K. Jansen, A. Kaushik, S. Kühn, arxiv:2309.09686)

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

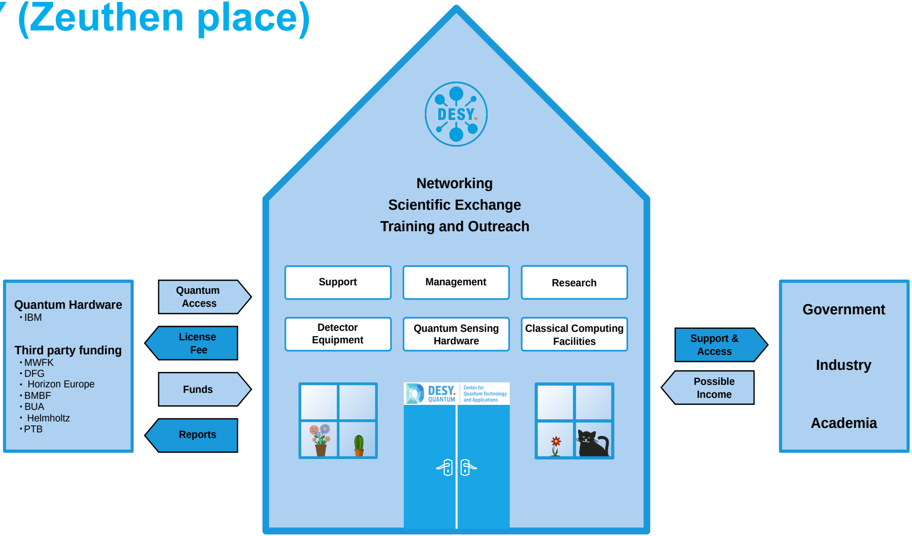


Convergence

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



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



The CQTA group

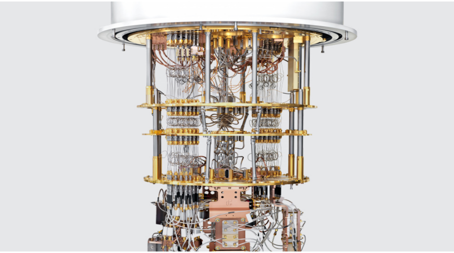
> The group in Zeuthen in September 2021

The CQTA group

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

Center for Quantum Technology and Applications

- **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, WS 9.7.-11.7.
- **Others**
  - factoring, Feynman diagrams, matrix models, ...
- **training**
- **Algorithm development**
  - Expressivity
  - controllability
  - warm starts



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

QC4HEP whitepaper, arXiv:2307.03236

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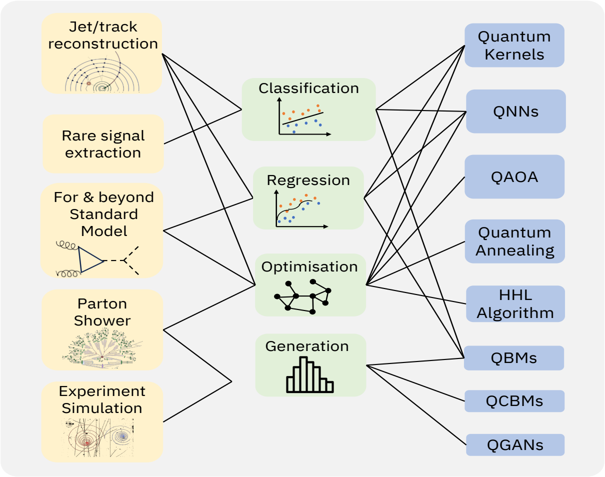
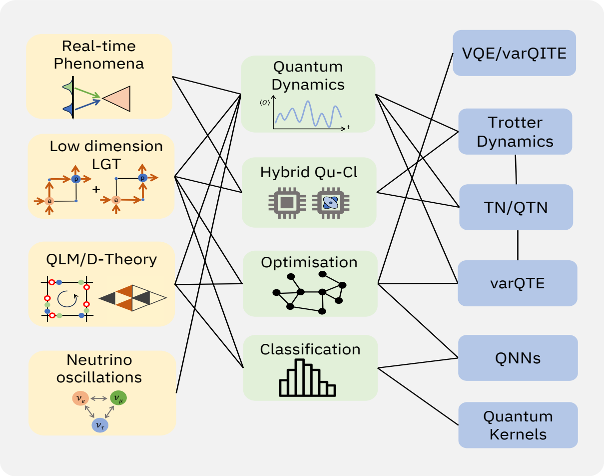
Abstract

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

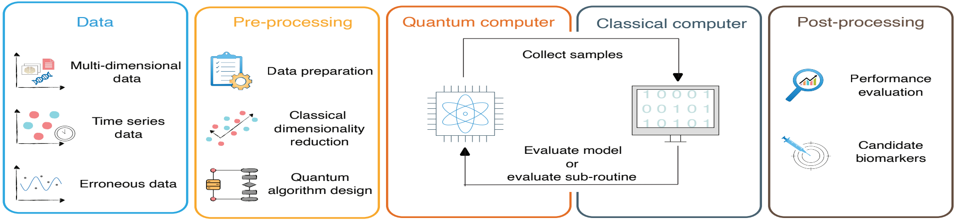


QC4HEP: Theory summary



Quantum computing enhances biomarker discovery

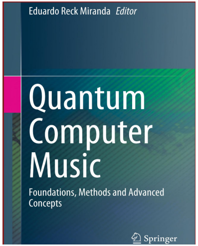
(Frederik Flöther, Daniel Blankenberg, Maria Demidik, Karl Jansen, Raga Krishnakumar, Rajiv Krishnakumar, Numan Laanait, Laxmi Parida, Carl Saab, Filippo Utro, arXiv:2411.10511)



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!

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