Quantum Computing for NuMeriQS

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with the help of Emil Rosanowski (thanks!)

CRC Retreat, Kloster Steinfeld, 17.09.2025

Quantum computing: where do we stand?

Quantum hardware

Achievements

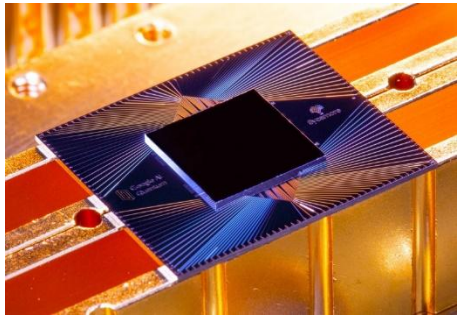
Quantum advantage: outperformed classical computers [1]

Exponential speedup of *specific* classical computations

Challenges

$\mathcal{O}(10 - 1000)$ qubits with $V_Q \leq 2^{21}$ → increase size

Noise → need quantum error mitigation / correction



Arute et al. (2019)

Zhong et al. (2020)

[1] Morvan et al. (2024), earlier claims by e.g. Arute et al. (2019), Zhong et al. (2020), Madsen et al. (2022) refuted by e.g. Liu et al. (2021), Oh et al. (2024)

Quantum algorithms

Potential future applications

Particle / condensed matter physics, quantum chemistry, …

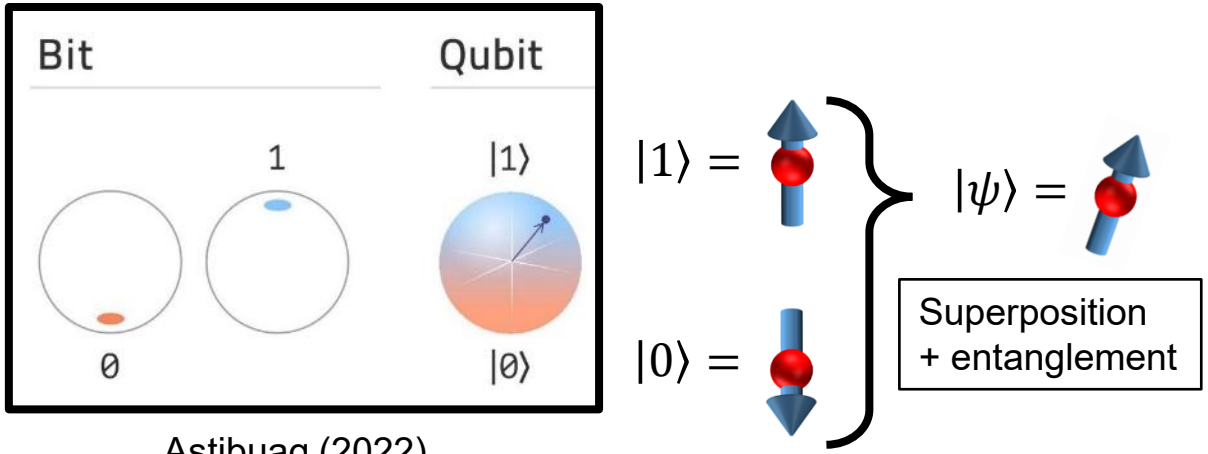
Challenges

New technology → need fundamentally new algorithms

(see projects A04, C01, C03)

Competition → classical algorithms quickly advance

(see David Luitz' talk on tensor networks)

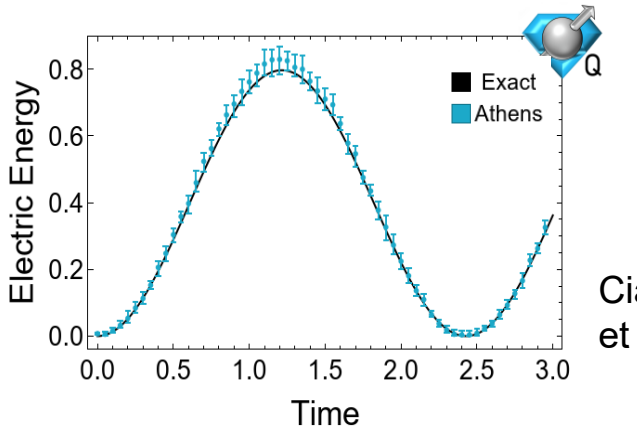


Astibuag (2022)

Which quantum systems have already been simulated?

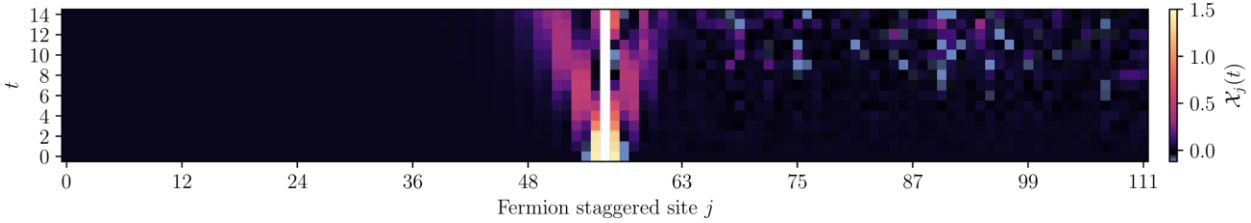
Real-time evolution

1+1D quantum electrodynamics (QED),[1] SU(2),[2] SU(3),[3] ...



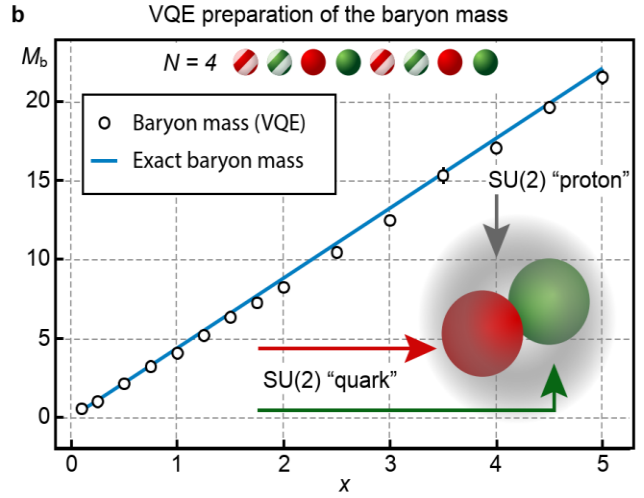
Ciavarella et al. (2019)

1+1D QED with 1 fermion, on > 100 qubits [4]

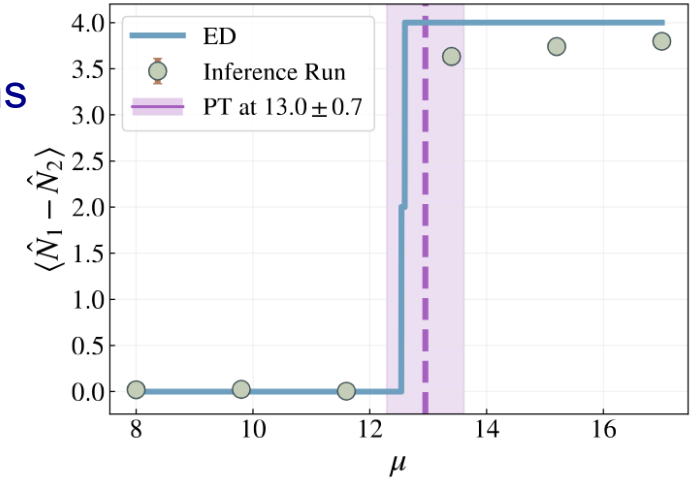


Ground-state preparation

1+1D "baryon" masses [5]



2+1D QED with 2 fermions at finite density [6]



[1] Klco et al. (2018), de Jong et al. (2021), [2] Klco et al. (2019), [3] Ciavarella et al. (2019), [4] Farrell et al. (2024), [5] Atas et al. (2021), …, [6] Rosanowski et al., manuscript in preparation, part of project C01

Survey: using quantum algorithms (QA) in NuMeriQS?

Current situation

Are QA applied in your project?

- So far, only in C01 and C03
- A04 studies time evolution algorithms, applicable in principle to classical and quantum computers

Could your QA be useful to other NuMeriQS projects?

- QA exchange between C01 and C03
- A04 results could help in future projects?

Outlook

Could your project benefit from incorporating QA?

- Yes for C01 and C03, potentially yes for A02
- Others: No clear benefits at this stage / unclear

Would you benefit from learning more about QA?

- Many wrote: eager to learn more
- Suggestion: join our new seminar series?

Seminar “Quantum Computing (QC) for Natural Sciences”

Overview

Why?

- Bring together CRC researchers interested in QC
- Teach students the prospects and limitations of QC

When?

- WiSe 25/26, Fridays 10:15-11:45am @ HISKP SR I

How many students?

- $\leq$ 5 from MSc Chemistry and $\leq$ 15 from MSc Physics

Content

What?

- 20 seminar talks by students about research papers, 30mins talk + 15mins questions
- Topics: foundations of QC, potential future applications in physics & chemistry, comparison to classical methods

Lecturers?

- Chemistry: Kirchner, Hansen
- Physics: Funcke, Kroha, Luu, Ostmeyer, Stollenwerk, Urbach

Interested in joining? Let me know!

Workshops, lectures, …

Workshops

Lectures

“Introduction to Quantum Computing”

- WiSe 25/26, Tuesdays 10-12 @ HS HISKP

“Lattice Field Theory – Hamiltonian and Lagrangian Methods” (tentative title…)

- SoSe 26, together with Simran Singh (Z02)

Sign 2027 Workshop @ Bonn?

Seminars, journal clubs, …

NuMeriQS seminars

Starting from WiSe 25/26

- Weekly theory seminars, Tuesday 3pm @ HS HISKP
- ~ 50% NuMeriQS-related talks by students & postdocs
- Talks about QC, tensor networks, machine learning, …

Want to give a talk?

- Simran Singh will send around Google sheet soon

New mailing list …

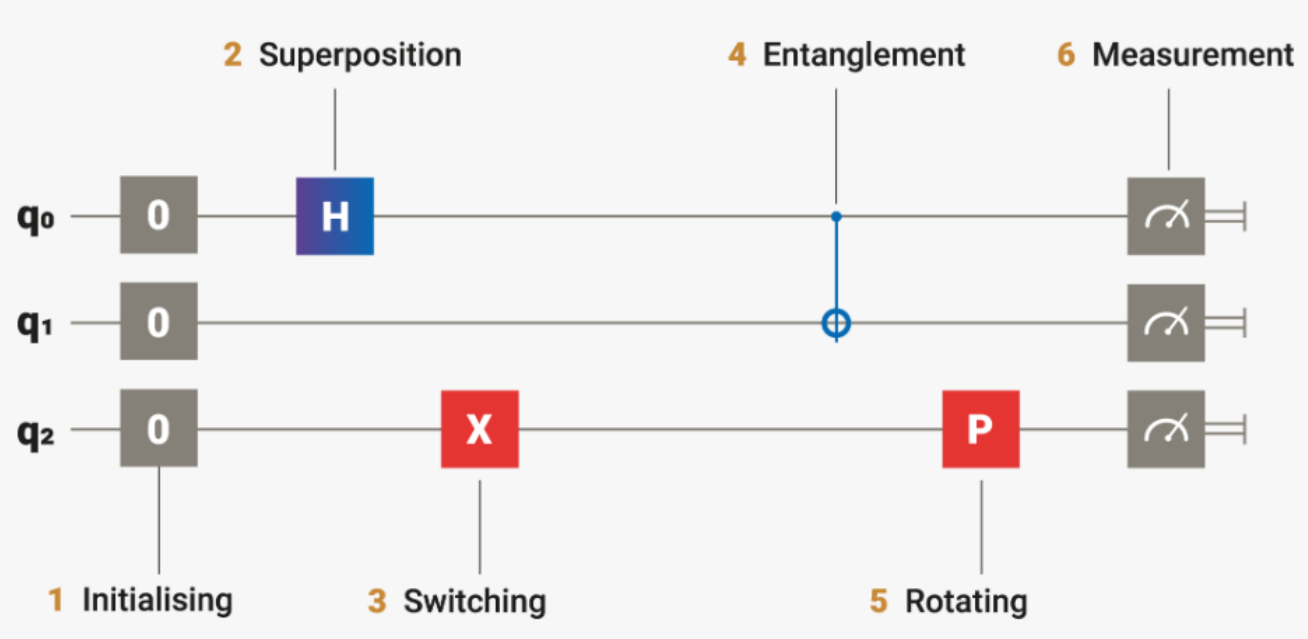
… for theoretical physics @ Uni Bonn

- Announcement of theory seminars, journal clubs, PhD and Master colloquia, discussion sessions, etc.
- Default members: HISKP Theory & PI Theory
- If you want to be added to the mailing list:

Backup: Content of “Seminar on Quantum Computing for Natural Sciences”

Learning the foundations of quantum computing

- Qubits, gates, superposition, entanglement, measurement, quantum noise, …



$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$R_x(\theta_0) = \exp(-i\frac{\theta_0}{2}\sigma_x)$$

$$\langle\psi(\vec{\theta})|H|\psi(\vec{\theta})\rangle$$

Understanding the potential future applications (& limitations) of quantum computing for natural sciences

- Physics: real-time evolution, out-of-equilibrium dynamics, comparison to (classical) HMC & TN methods, …
- Chemistry: FCI problem, NMR problem, comparison to (classical) CC or DFT methods, …