26th June 2025

World of Quantum

Munich

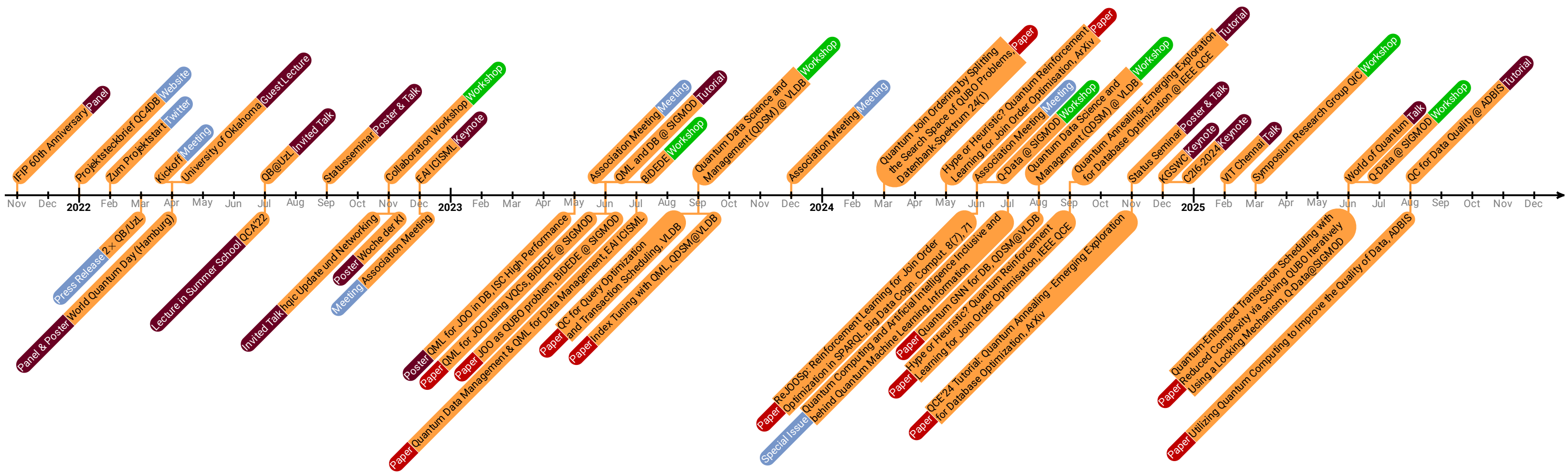
QC4DB: Accelerating Relational Database Management Systems via Quantum Computing

Professor Dr. rer. nat. habil. Sven Groppe
https://www.ifis.uni-luebeck.de/~groppe

QC4DB: Accelerating Relational Database Management Systems via Quantum Computing

Goal:	Accelerating Relational Database Management Systems via Quantum Computing	
Proj. Web:	Project Website@Quantentechnologien	
Funded by:	BMFTR (formerly BMBF) Funding Program "Anwendungsnetzwerk für das Quantencomputing"	
Duration:	3 years, 1.1.2022 - 30.6.2025 (extended)	
Volume:	1.8M Euros	
Topics:	Optimizing an open source relational database management system • Queries • Transaction Schedules	
Partners:	UNIVERSITÄT ZU LÜBECK INSTITUT FÜR INFORMATIONSSYSTEME (Coord.)	QUANTUM BRILLIANCE
Expertises:	Hardware-Acceleration of Databases	Room Temperature Diamond Quantum Accelerators/qbOS
Website:	https://www.ifis.uni-luebeck.de/~groppe/	https://quantumbrilliance.com/

Timeline of Activities



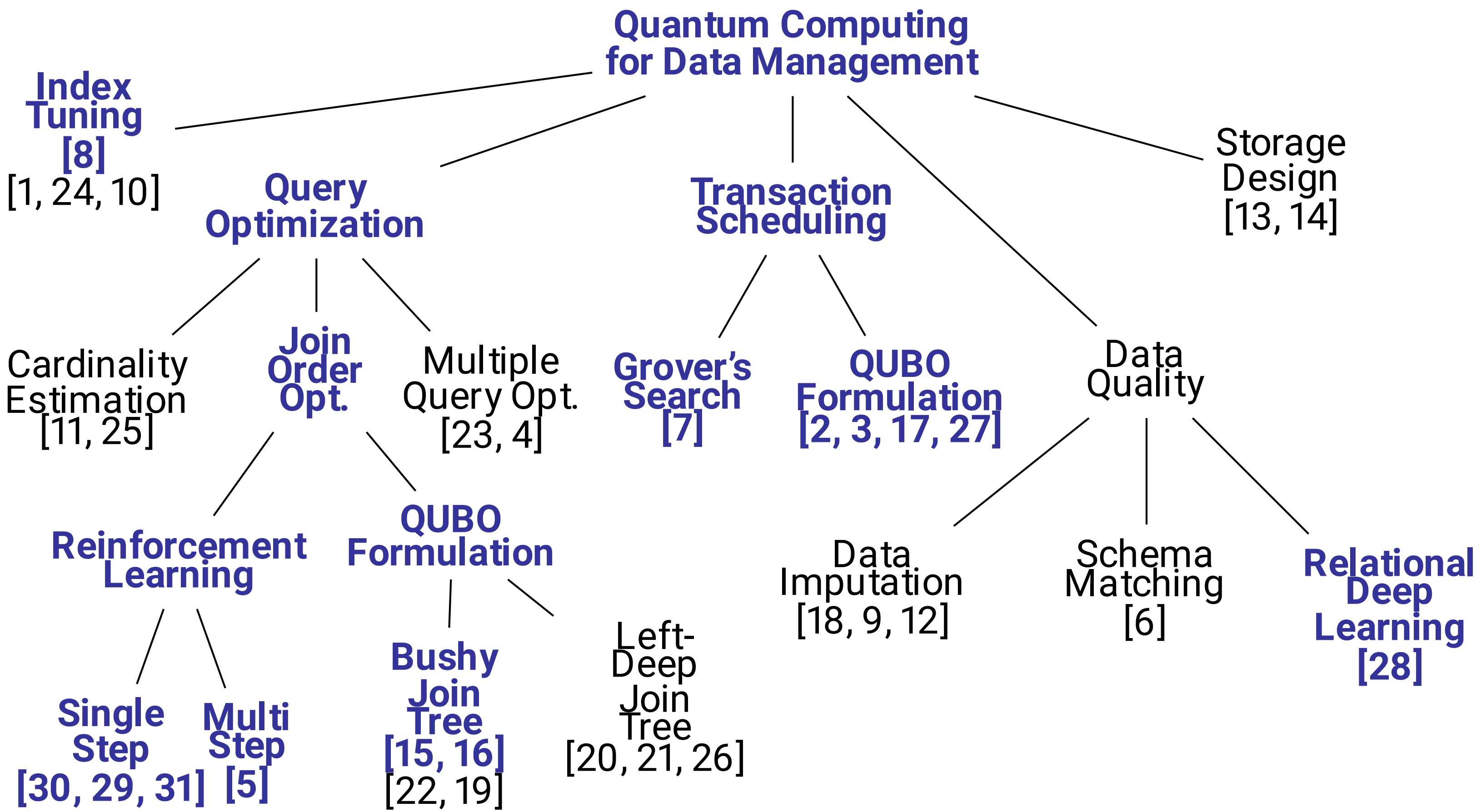
- 13 Papers
- 7 Workshops
- 3 Tutorials
- 5 Posters
- 2 Panels
- 3 Keynotes
- 7 Invited Talks
- 1 Special Issue in Journals

Number of Citations (27.5.2025)

#Citations	Publication
32	Quantum machine learning: Foundation, new techniques, and opportunities for database...
25	Constructing optimal bushy join trees by solving qubo problems on quantum hardware...
25	Opportunities for quantum acceleration of databases: opt. of queries and transaction schedules
18	Quantum machine learning for join order optimization using variational quantum circuits
18	Index Tuning with Machine Learning on Quantum Computers for Large-Scale Database...
6	Quantum data management and quantum machine learning for data management...
5	Hype or Heuristic? Quantum Reinforcement Learning for Join Order Optimisation
1	Quantum Join Ordering by Splitting the Search Space of QUBO Problems
1	ReJOOSp: Reinforcement Learning for Join Order Optimization in SPARQL
2	Supervised Learning on Relational Databases with Quantum Graph Neural Networks
0	QCE'24 Tutorial: Quantum Annealing - Emerging Exploration for Database Optimization
0	Quantum-Enhanced Transaction Scheduling with Reduced Complexity...
0	Utilizing Quantum Computing to Improve the Quality of Data
24	Optimizing Transaction Schedules ... Grover's Search Algorithm (Preliminary Work)
31	Avoiding Blocking by Scheduling Transactions Using Quantum Annealing (Preliminary Work)
22	... Optimization of Transaction Schedules via Quantum Annealing... (Preliminary Work)
Σ: 210	in total

according to Google Scholar

Taxonomy of Scientific Contributions

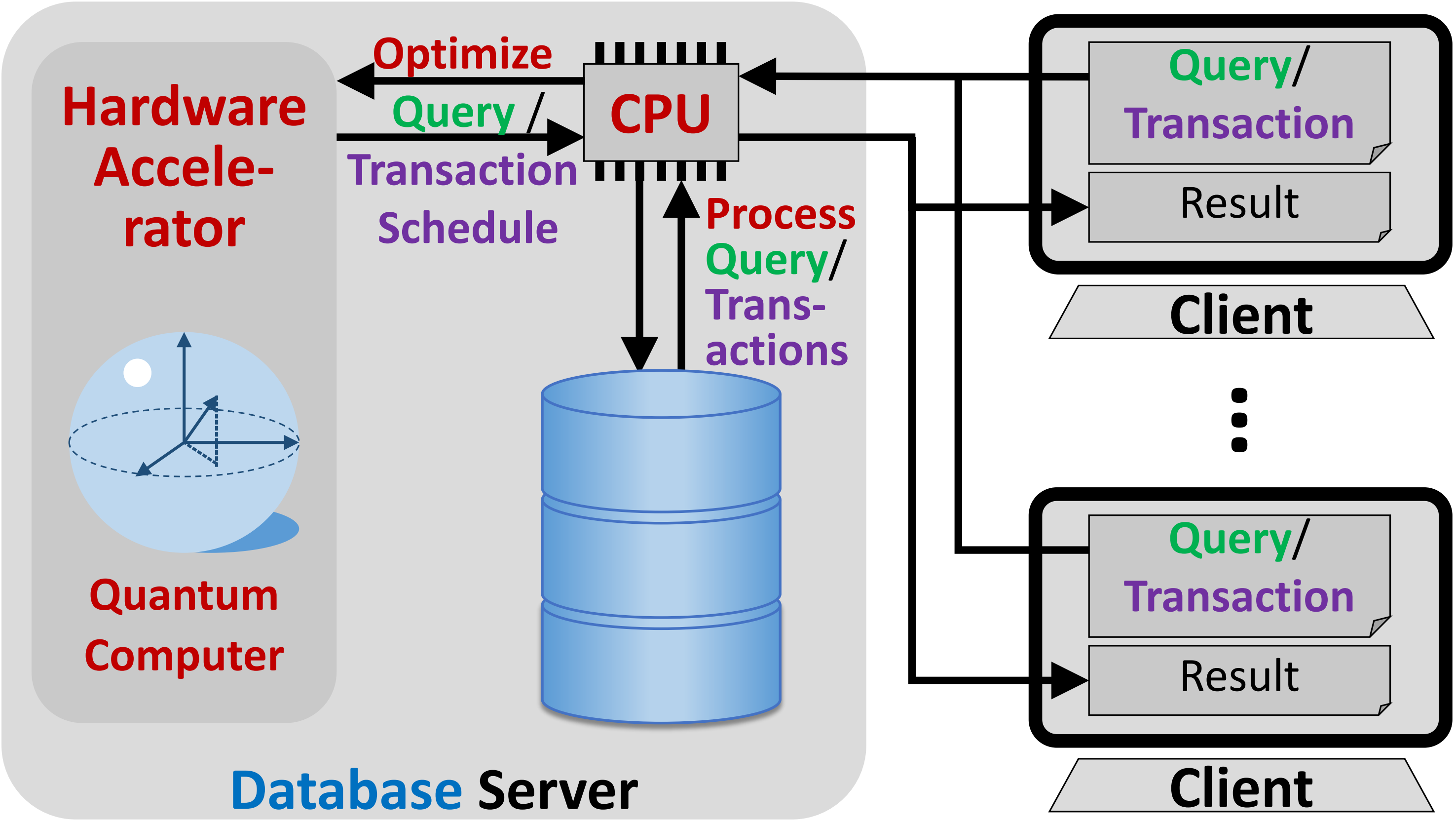


Topic related to QC4DB/QC4DB-Publication

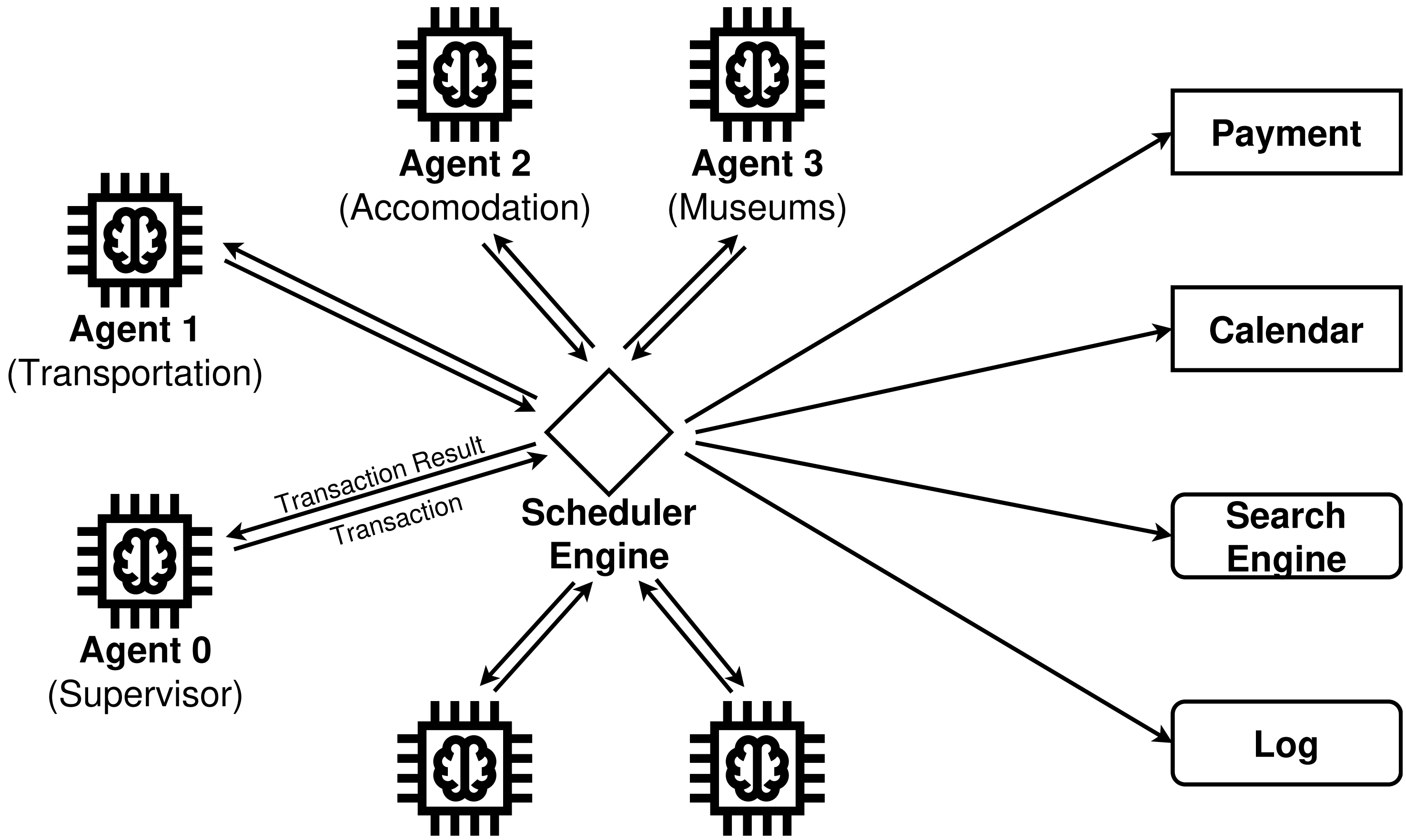
Importance of Collaboration

- Collaboration Workshop in Nov. 2022, Participants: Groups of
  1. Prof. Jiaheng Lu (University of Helsinki, Finland)
  2. Prof. Wolfgang Mauerer (OTH Regensburg, Germany)
  3. Prof. Le Gruenwald (University of Oklahoma, USA)
  4. Dr. Florian Preis (Quantum Brilliance, Germany)
  5. Prof. S. Groppe (University of Lübeck, Germany)
- Collaboration Activities ("result" of the collaboration workshop)
  - 5 Workshops: QDSM@VLDB '23/'24 (Org.: 1., 2., 3., 5.), BiDEDE@SIGMOD'23 (Org.: 3., 5.), QData@SIGMOD'24 (Org.: 4., Steering Committee: 1., 2., 5.), QData@SIGMOD'25 (Steering Committee: 1., 2., 5.)
  - 3 Tutorials: SIGMOD'23 (1., 2., 5.), IEEE QCE'24 (1., 2., 5.), ADBIS'25 (1., 5.)
  - 7 Papers: ADBIS'25 (1., 5.), IEEE QCE'24 (2., 5.), SIGMOD'23 (1., 2., 5.), QDSM@VLDB'23 (3., 5.), BiDEDE@SIGMOD'23 (3., 5.), VLDB'23 (3., 4., 5.), EAI ICISML'22 (3., 5.)
- Other Collaborations:
  - 2 Papers: QDSM@VLDB'24 (5., Martin Vogrin, University of Maribor, Slovenia), BDCC 8(7) (5., Shridevi Krishnakumar, VIT Chennai, India)

Using Hardware Accelerator for optimizing Queries / Transaction Schedules



Importance of Transaction Scheduling for Agentic AI - Example: Trip Planning



Classical Approaches

Query Optimization:

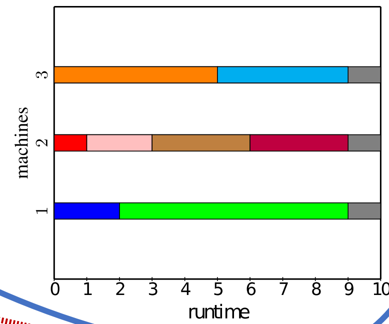
$(R_1 \bowtie R_2) \cdots \bowtie R_n$

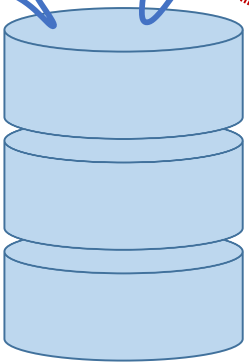
$\bowtie_{i=1}^{n} R_i$? $\vdots$

$(R_1 \bowtie R_n) \bowtie (\cdots)$

Transaction Schedule Optimization:

$\{T_1, \ldots, T_m\}$?





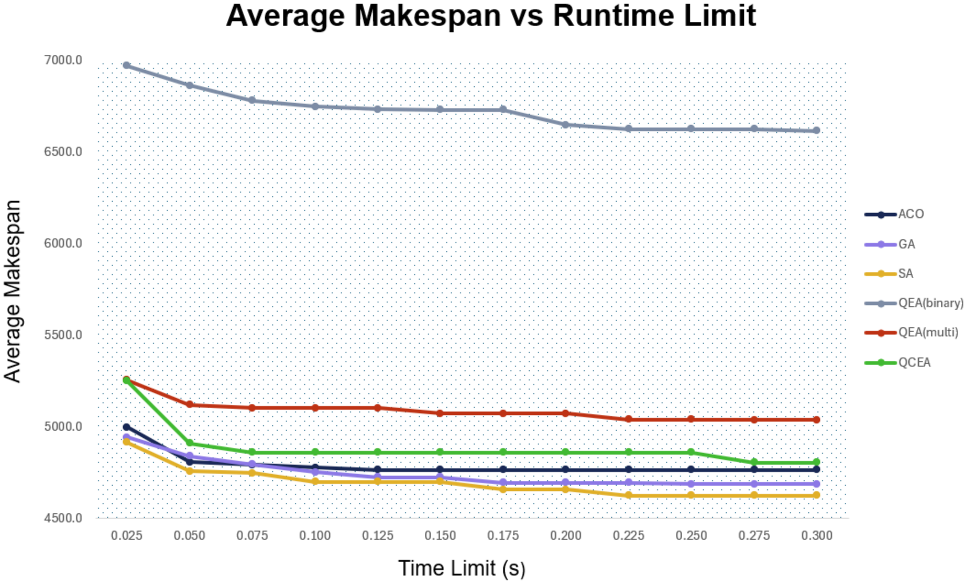
Open Source Relational Database Management System (RDBMS),

e.g. PostgreSQL, MySQL

Dynamic Programming
Random Walk
Linear Program-ming
Machine Learning
...
Simulated Annealing
Genetic Algorithm

Transaction Scheduling

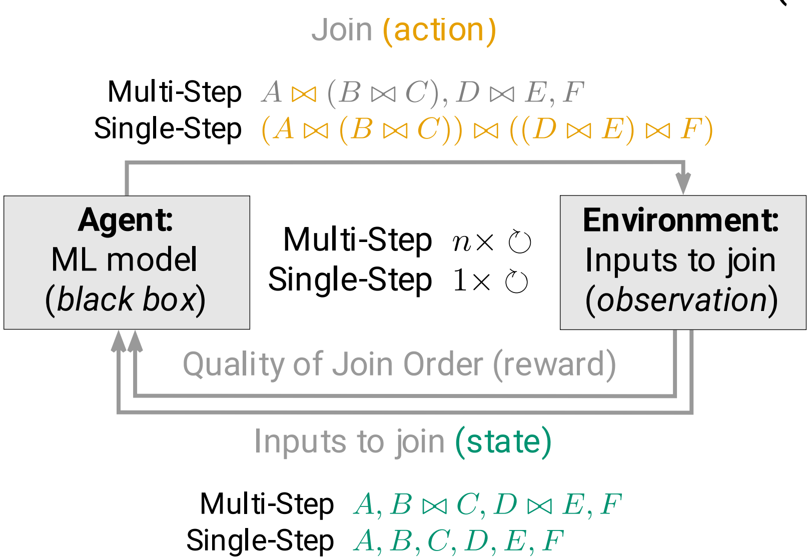
- Design choice: Fast quantum exact methods and good heuristics for scalable optimization times
- Classical
  - Dynamic Programming | Random Search | Simulated Annealing (SA) | Genetic Algorithm (GA) | Ant Colony Optimization (ACO)
- Quantum
  - Maximum Independent Set | Quantum Evolutionary Algorithms (QEA) (several variants: Binary | (Cultural (QCEA)) Multi-State) | QUBO | Grover

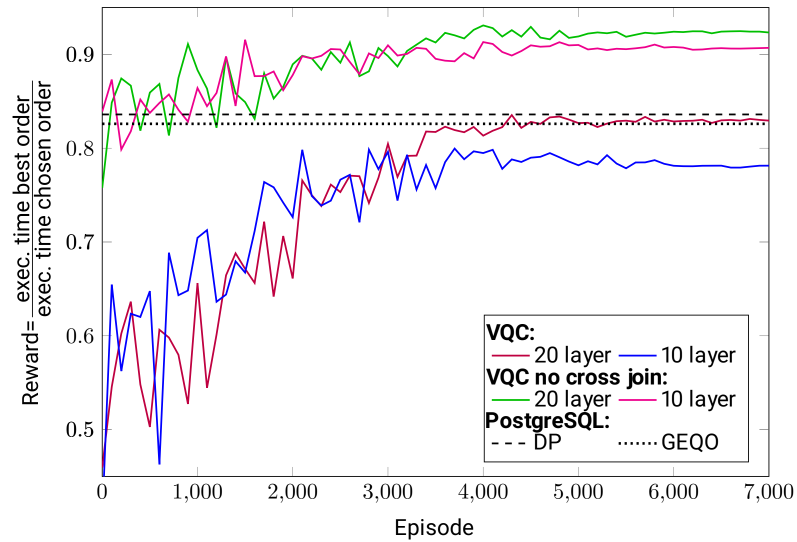


Average values for 100 problem instances with 30 transactions, 4 cores and 0.5 conflict probability

QML for Join Ordering

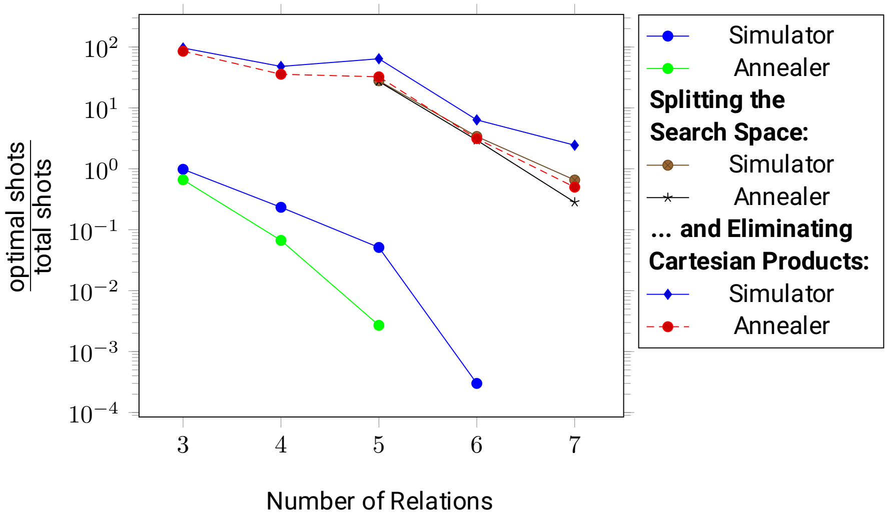
- Design choice: Predict best join order based on real execution times in contrast to estimated costs (EC)
  - can beat exact methods like dynamic programming (DP) based on EC
- Single-Step: Real-world queries (ErgastF1 Benchmark/PostgreSQL)
  - join orders with faster execution than DP (2.8%) and GEQO (11.2%)
  - close to classical ML like RTOS (6%) / best join orders (16.8%)

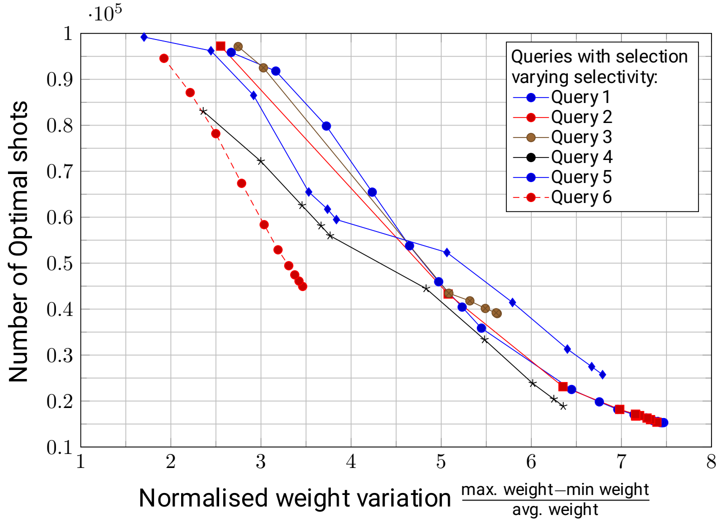




Join Ordering as QUBO Problem

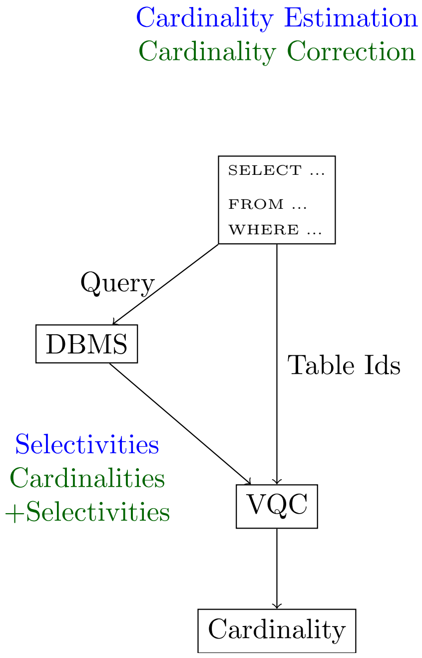
- Design choice: Direct Join Costs in contrast to calculated costs
  - Estimated costs for **each** join $\Rightarrow$ better join order
  - Runtime complexity $O(2^m - m)$ with m relations to join optimal for join ordering based on direct costs
    - Classical runtime: $O(3^m - 2^{m+1})$ using dynamic programming, best exact: $O(2^m \cdot m^3)$, $O(2^{3m/2}/\sqrt{\epsilon})$ with $(1+\epsilon)$-approx. algo.[SK24]
- Real-world queries (ErgastF1 Benchmark/PostgreSQL)

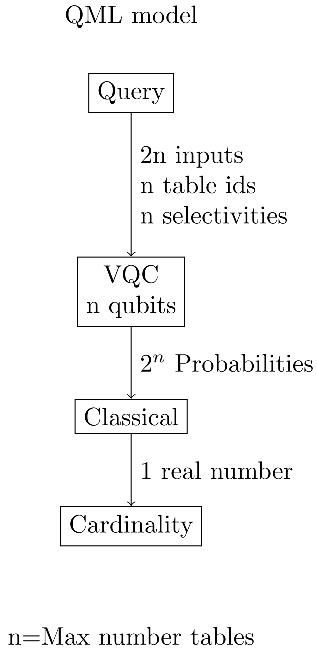


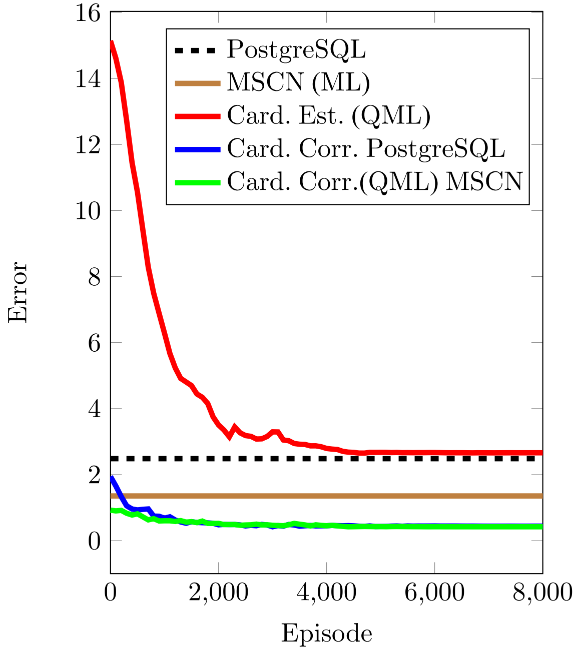


QML for Cardinality Estimation

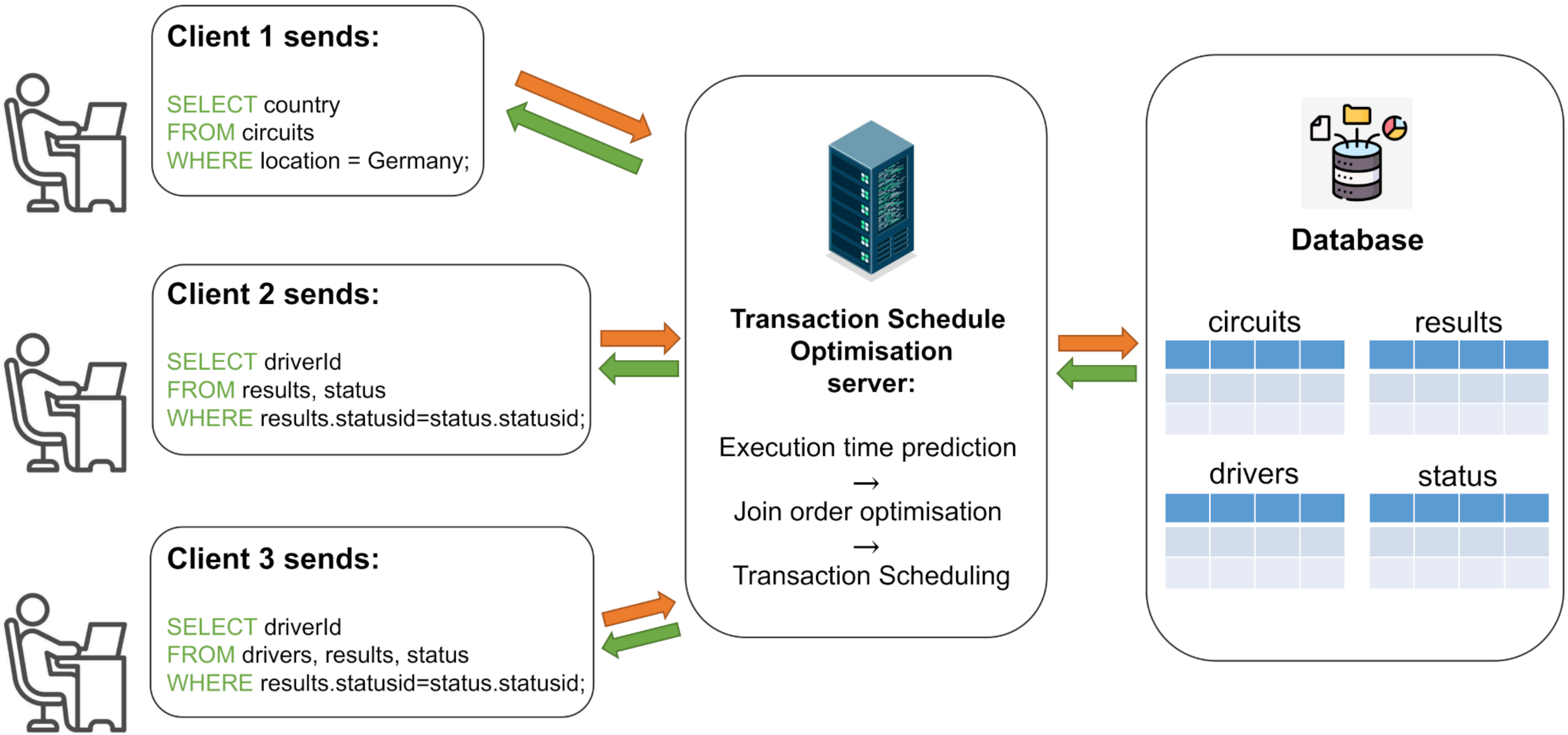
- Design choice: Predict correction factor of a Cardinality Estimator
  - Cardinality Predictor:PostgreSQL|MSCN|Hybrid Quantum Classical Network
  - Cardinality Correction: Hybrid Quantum Classical Network
- Queries of JOB-light Benchmark







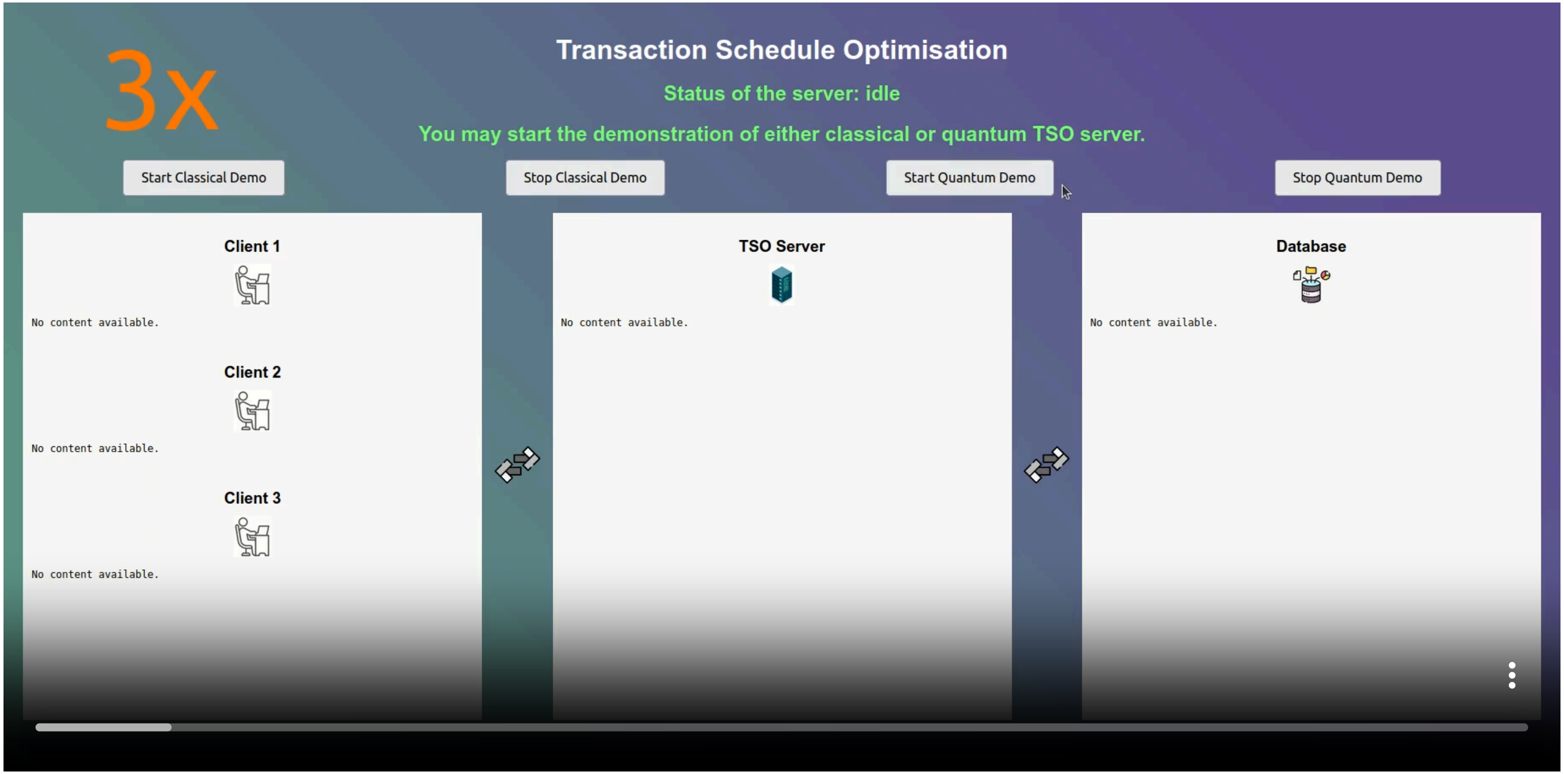
Transaction Scheduling Optimisation Server



- Demonstrator
  - fully quantum **versus** fully classical

Demonstrator

- is publicly available at the Quantum Brilliance web-page...



QC4DB Team

Partner:	University of Lübeck	Quantum Brilliance GmbH
Project Leaders:	Prof. Dr. rer. nat. habil. Sven Groppe (Coordinator)	Dr. Florian Preis Dr. Stefan Prestel Dr. Farida Shagieva
Project Employees:	Tobias Winker Umut Çalıkyılmaz Nitin Nayak Benjamin Warnke	Daanish Arya Dr. John Helm Dr. Johannes Kuhlmann Dr. Jeremy Rodriguez

References for Taxonomy of Contributions

[1] D. Barbosa, L. Gruenwald, L. D'Orazio, and J. Bernardino. Qrlit: Quantum reinforcement learning for database index tuning. *Future Internet*, 16(12):439, Nov. 2024. ISSN 1999-5903. doi: 10.3390/fi16120439. URL `http://dx.doi.org/10.3390/fi16120439`.

[2] T. Bittner and S. Groppe. Avoiding blocking by scheduling transactions using quantum annealing. In *IDEAS, Seoul, Republic of Korea (virtual due to Covid-19 pandemic)*, 2020. URL `https://doi.org/10.1145/3410566.3410593`.

[3] T. Bittner and S. Groppe. Hardware accelerating the optimization of transaction schedules via quantum annealing by avoiding blocking. *OJCC*, 7(1):1–21, 2020. URL `http://nbn-resolving.de/urn:nbn:de:101:1-2020112218332015343957`.

[4] T. Fankhauser, M. E. Solèr, R. M. Füchslin, and K. Stockinger. Multiple query optimization using a gate-based quantum computer. *IEEE Access*, 11: 114031–114043, 2023. ISSN 2169-3536. doi: 10.1109/access.2023.3324253. URL `http://dx.doi.org/10.1109/ACCESS.2023.3324253`.

[5] M. Franz, T. Winker, S. Groppe, and W. Mauerer. Hype or heuristic? quantum reinforcement learning for join order optimisation. In *IEEE International Conference on Quantum Computing and Engineering (QCE)*, 2024. URL `https://doi.org/10.1109/QCE60285.2024.00055`.

[6] K. Fritsch and S. Scherzinger. Solving hard variants of database schema matching on quantum computers. *VLDB*, 16(12):3990–3993, Aug. 2023. ISSN 2150-8097. doi: 10.14778/3611540.3611603. URL `http://dx.doi.org/10.14778/3611540.3611603`.

[7] S. Groppe and J. Groppe. Optimizing transaction schedules on universal quantum computers via code generation for grover's search algorithm. In *IDEAS, Montreal, QC, Canada*, 2021. URL `https://doi.org/10.1145/3472163.3472164`.

[8] L. Gruenwald, T. Winker, U. Çalıkyılmaz, J. Groppe, and S. Groppe. Index tuning with machine learning on quantum computers for large-scale database applications. In *QDSM@VLDB, Vancouver, Canada*, 2023. URL `https://ceur-ws.org/Vol-3462/QDSM5.pdf`.

[9] S. Kazdaghli, I. Kerenidis, J. Kieckbusch, and P. Teare. Improved clinical data imputation via classical and quantum determinantal point processes. *eLife*, 12, May 2024. ISSN 2050-084X. doi: 10.7554/elife.89947. URL `http://dx.doi.org/10.7554/eLife.89947`.

[10] M. Kesarwani and J. R. Haritsa. Index advisors on quantum platforms. *VLDB*, 17(11):3615–3628, July 2024. ISSN 2150-8097. doi: 10.14778/3681954.3682025. URL `http://dx.doi.org/10.14778/3681954.3682025`.

[11] F. Kittelmann, P. Sulimov, and K. Stockinger. Qardest: Using quantum machine learning for cardinality estimation of join queries. In *Q-Data*, SIGMOD/PODS '24, page 2–13. ACM, June 2024. doi: 10.1145/3665225.3665444. URL `http://dx.doi.org/10.1145/3665225.3665444`.

[12] D. Kochan, Z. Zhang, and X. Yang. A quantum-inspired hamiltonian monte carlo method for missing data imputation. In B. Dong, Q. Li, L. Wang, and Z.-Q. J. Xu, editors, *Proceedings of Mathematical and Scientific Machine Learning*, volume 190 of *Proceedings of Machine Learning Research*, pages 17–32. PMLR, 15–17 Aug 2022. URL `https://proceedings.mlr.press/v190/kochan22a.html`.

[13] T. Li, G. Yuan, C. Yao, M. Shi, Z. Wang, L. Qian, and J. Lu. Quantum storage design for tables in rdbms. In *QDSM@VLDB, Guangzhou, China*, 2024. URL `https://vldb.org/workshops/2024/proceedings/QDSM/QDSM.4.pdf`.

[14] T. Littau, Z. Li, and R. Hai. Quantum data structures for enhanced database performance. In *QDSM@VLDB, Guangzhou, China*, 2024. URL `https://vldb.org/workshops/2024/proceedings/QDSM/QDSM.6.pdf`.

[15] N. Nayak, J. Rehfeld, T. Winker, B. Warnke, U. Çalıkyılmaz, and S. Groppe. Constructing optimal bushy join trees by solving qubo problems on quantum hardware and simulators. In *BiDEDE, Seattle, WA, USA*, 2023. URL `https://doi.org/10.1145/3579142.3594298`.

[16] N. Nayak, T. Winker, U. Çalıkyılmaz, S. Groppe, and J. Groppe. Quantum join ordering by splitting the search space of qubo problems. *Datenbank-Spektrum*, 24(1):21–32, 2024. URL `https://doi.org/10.1007/s13222-024-00468-3`.

[17] N. Nayak, A. Prisacaru, U. Çalıkyılmaz, J. Groppe, and S. Groppe. Quantum-enhanced transaction scheduling with reduced complexity via solving qubo iteratively using a locking mechanism. In *2nd International Workshop on Quantum Computing and Quantum-Inspired Technology for Data-Intensive Systems and Applications (Q-Data), Berlin, Germany*, 2025. URL `https://doi.org/10.1145/3736393.3736701`.

[18] C. Sanavio, S. Tibaldi, E. Tignone, and E. Ercolessi. Quantum circuit for imputation of missing data. *IEEE Transactions on Quantum Engineering*, 5:1–12, 2024. ISSN 2689-1808. doi: 10.1109/tqe.2024.3447875. URL `http://dx.doi.org/10.1109/TQE.2024.3447875`.

[19] P. Saxena, I. Sabek, and F. Spedalieri. Constrained quadratic model for optimizing join orders. In *Q-Data*, SIGMOD/PODS '24, page 38–44. ACM, June 2024. doi: 10.1145/3665225.3665447. URL `http://dx.doi.org/10.1145/3665225.3665447`.

[20] M. Schönberger, S. Scherzinger, and W. Mauerer. Ready to leap (by co-design)? join order optimisation on quantum hardware. volume 1, New York, NY, USA, may 2023. Association for Computing Machinery.

[21] M. Schönberger, I. Trummer, and W. Mauerer. Quantum-inspired digital annealing for join ordering. In *VLDB*, volume 16, 10 2023.

[22] M. Schönberger, I. Trummer, and W. Mauerer. Quantum optimisation of general join trees. In *VLDBW'23*, 08 2023.

[23] I. Trummer and C. Koch. Multiple query optimization on the d-wave 2x adiabatic quantum computer. *VLDB*, 9(9):648–659, May 2016. ISSN 2150-8097. doi: 10.14778/2947618.2947621. URL `http://dx.doi.org/10.14778/2947618.2947621`.

[24] I. Trummer and D. Venturelli. Leveraging quantum computing for database index selection. In *Q-Data*, SIGMOD/PODS '24, page 14–26. ACM, June 2024. doi: 10.1145/3665225.3665445. URL `http://dx.doi.org/10.1145/3665225.3665445`.

[25] V. Uotila. Sql2circuits: Estimating metrics for sql queries with a quantum natural language processing method, 2024. URL `https://arxiv.org/abs/2306.08529`.

[26] V. Uotila. Left-deep join order selection with higher-order unconstrained binary optimization on quantum computers, 2025. URL `https://arxiv.org/abs/2502.00362`.

[27] V. Uotila and J. Lu. Quantum annealing method for dynamic virtual machine and task allocation in cloud infrastructures from sustainability perspective. In *2023 IEEE 39th International Conference on Data Engineering Workshops (ICDEW)*, pages 105–110, 2023. doi: 10.1109/ICDEW58674.2023.00023.

[28] M. Vogrin, R. Vogrin, S. Groppe, and J. Groppe. Supervised learning on relational databases with quantum graph neural networks. In *QDSM@VLDB, Guangzhou, China*, 2024. URL `https://vldb.org/workshops/2024/proceedings/QDSM/QDSM.5.pdf`.

[29] T. Winker, S. Groppe, V. Uotila, Z. Yan, J. Lu, M. Franz, and W. Mauerer. Quantum machine learning: Foundation, new techniques, and opportunities for database research. In *SIGMOD*, 2023. URL `https://doi.org/10.1145/3555041.3589404`.

[30] T. Winker, U. Çalıkyılmaz, L. Gruenwald, and S. Groppe. Quantum machine learning for join order optimization using variational quantum circuits. In *BiDEDE, Seattle, WA, USA*, 2023. URL `https://doi.org/10.1145/3579142.3594299`.

[31] U. Çalıkyılmaz, S. Groppe, J. Groppe, T. Winker, S. Prestel, F. Shagieva, D. Arya, F. Preis, and L. Gruenwald. Opportunities for quantum acceleration of databases: Optimization of queries and transaction schedules. *VLDB*, 16(9):2344–2353, 2023. URL `https://doi.org/10.14778/3598581.3598603`.