Quarterly Highlights 2024

Kipu Quantum provides application- and hardware-specific algorithms for early industrial usefulness within the next 12 to 24 months

Kipu Quantum – We stand at the forefront of quantum computing algorithms

We are specializing in application- and hardware-specific quantum software solutions that drastically reduce the requirements for solving industry use cases.

These solutions enable even the currently small and noisy quantum processors to yield significantly improved results, while approaching industrial usefulness.

Commercial Quantum Advantage Era – With Kipu!

Tackling major industry challenges with quantum computers requires algorithms that use over 70 qubits. Despite having processors with over 100 noisy qubits, this remains out of reach. Current qubit specifications and gates are inadequate for greedy quantum algorithms.

However, we anticipate overcoming this limitation in the next 12-24 months with advancements in quantum computing paradigms and hardware. This is particularly promising for optimization problems.

Kipu's Tech Edge – Our algorithmic compression achieves a massive reduction in the required circuit depth

We outperform competing state-of-the-art quantum algorithms through our digital, analog and digital-analog compression techniques, dramatically reducing the necessary circuit depth by orders of magnitude.

Our technology seamlessly integrates with leading hardware concepts such as superconducting circuits, ion traps, and neutral atoms.

Presenting our Quarterly Highlights!

Kipu Quantum constantly moves the needle on our path to making quantum computers useful. In the third quarter of 2024, we realized several breakthroughs, which we briefly discuss in this document.

Please reach out if you would like to learn more!

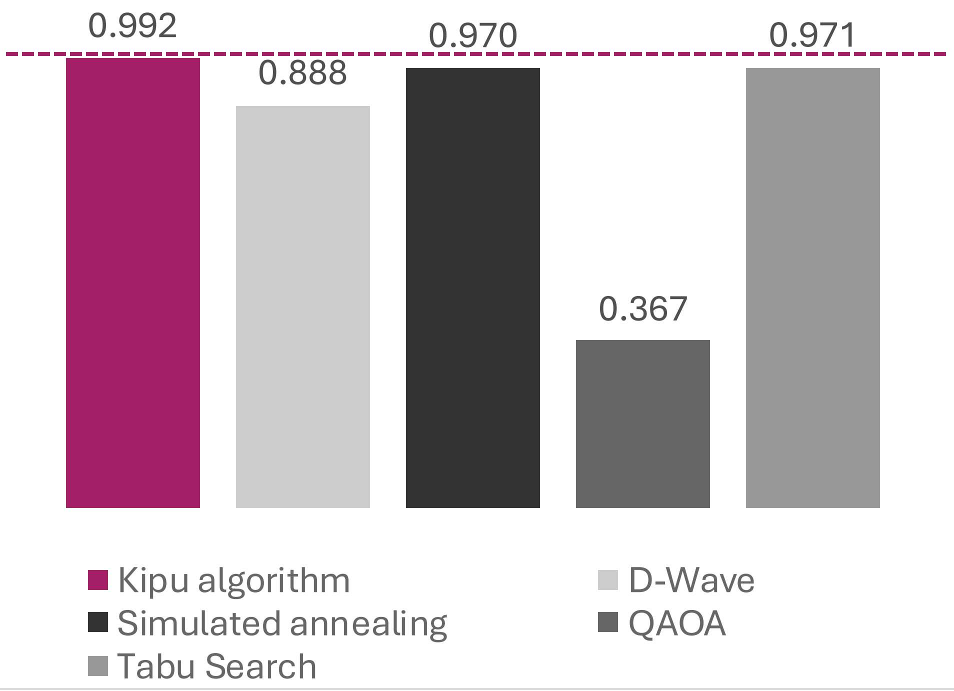
Overview

- Presented largest MIS optimization ever solved on a gate based quantum computer.
- IonQ leap-froged Quantinuum's superior fidelity processor, thanks to Kipu algorithms.
- New record in portfolio optimization achieved using non-hybrid methods.
- Slashed required parameters to train ML models for image processing by 1,000x.
- Improved digital algorithm makes large-scale optimization beyond 100 qubits possible on IBM hardware.
- A new hardware-specific quantum algorithm for neutral atoms solves MIS problems beyond 100 qubits, 200 x faster.
- Up to 1,000 x faster time-to-solution for BASF's logistic problems was achieved on IBM and IonQ hardware.
- Reduction of circuit depth by 50 x allows accurate chemical modeling to be done on small & noisy quantum hardware.

- We solved the largest optimization problem on IBM, using all 156 qubits.
- Our algorithms are now accessible as a service on our platform.
- We enhance AI by boosting the performance of feature selection.
- We boost neural networks to improve performance at ~1,000 fewer data inputs.
- Towards quantum advantage for feature extraction: 1,000x fewer training parameters using Kipu's new algorithm on D-Wave hardware
- Improved chem-informatics based on molecular screening – on the PLANQK platform
- We proved that our digital-analog encoding enables a radical reduction of algorithm runtime at improved quality for HUBO optimization problems
- Ultra-fast quantum simulation on 156 IBM qubits on IBM pave the way for advancements in materials science

Kipu Quantum starts the commercial quantum advantage era, by solving relevant optimization problems on IBM's 156-qubit quantum processors

Closeness to the solution (1 = 100%)



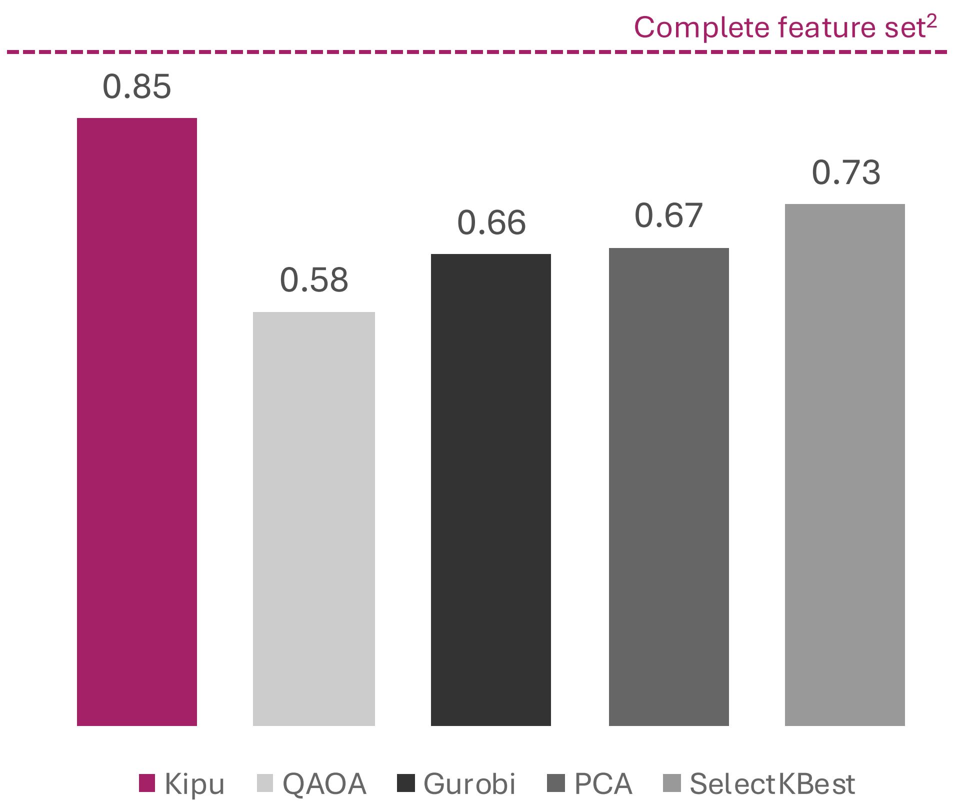
arXiv [Click here for the paper!]

- Kipu has successfully tackled **the largest and most complex HUBO problem**, by utilizing all 156 qubits of IBM's quantum processor, marking the **largest optimization experiment** to date
- We solved optimization problems with **higher-order interaction variables** directly[1]
- Our method can also be adapted for larger processors, e.g. 433 qubits
- In contrast to the QAOA algorithm[2], we maximizes the capabilities of current commercial quantum hardware by
  - Improving the quality of the solution by **more than 90%**
  - Saving computation resources by reducing the circuit depths **by 7 times** and required iterations on hardware **by 720 times**
- Our solution uses **HUBO mapping**, which fits to a wide range of industry use cases, **complex mixed-integer optimization, protein folding, portfolio optimization, network design, and decision-making processes**

1) Without mapping to quadratic unconstrained binary optimization formulation (QUBO)
2) Requires classical optimization and multiple hardware iterations; may get stuck in local minima or suboptimal solutions

Our quantum solution enhances AI by outperforming traditional feature selection algorithms by 47%

Churned customer prediction performance of F1-score[1]



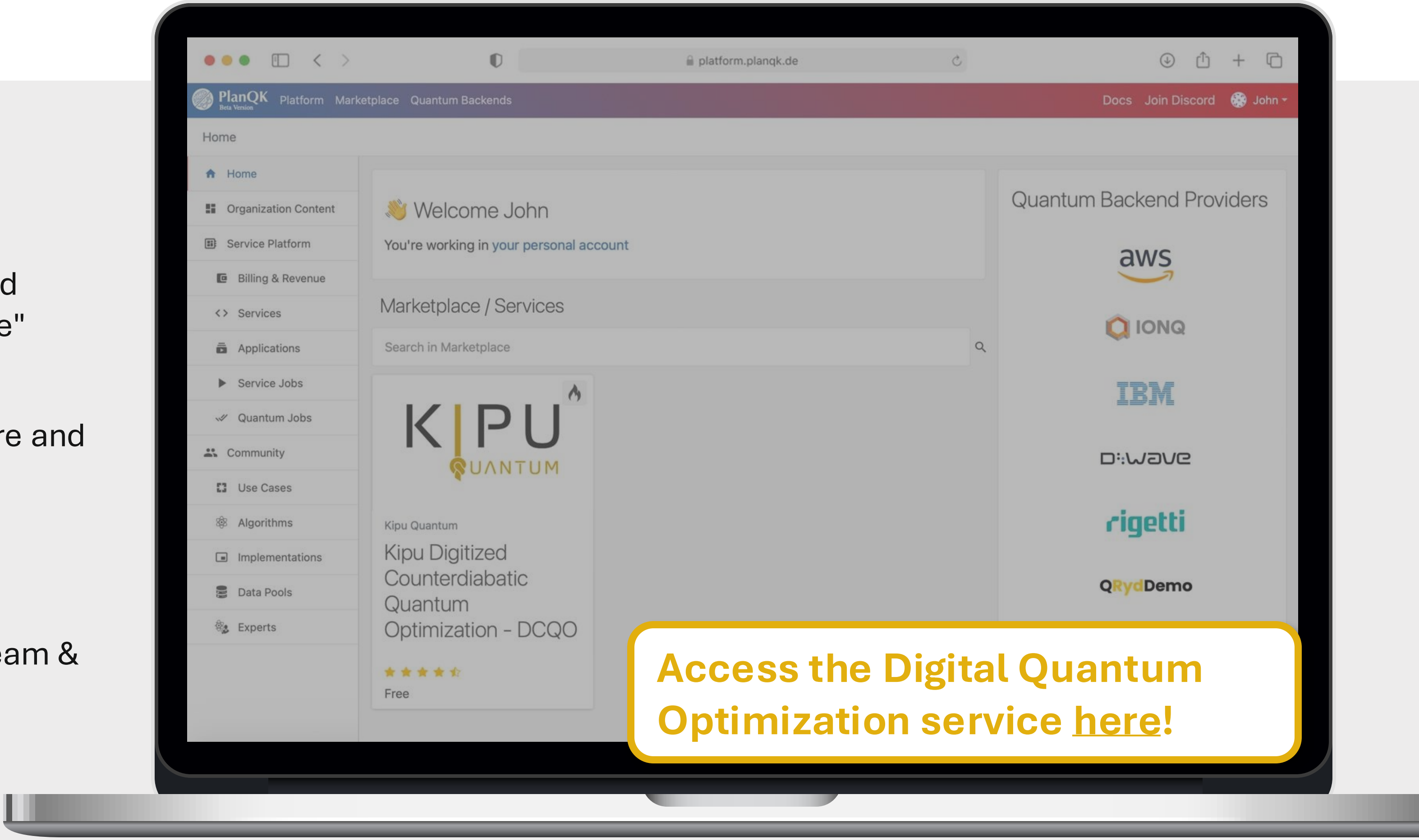
- **Feature selection is essential in AI**, for model efficiency, accuracy, and decision-making, reducing unnecessary computational overhead, especially for large data set. Mastering it improves model accuracy, reduces complexity, and enhances interpretability, all while lowering cost and preventing overfitting
- **But: Traditional tools struggle with complex datasets**, necessitating a faster and more precise solution. High-dimensional data, such as that used for predicting churned customers, poses significant challenges
- By selecting only 63% of the features, **Kipu's solution surpasses benchmarked algorithms by up to 47%**
- This enables **simultaneous exploration of vast feature spaces**, leading to faster and more accurate identification of key predictive features suitable for **classification problems, for instance in finance**

1) F1-score is the harmonic mean of precision and recall. It is a metric suitable in scenarios where the data is imbalanced. We validated the tool on 11 qubits using IBM Torino noisy simulator (11 variables).
2) Complete feature set: analysis of the complete classical dataset without selecting any features

The benefits from Kipu algorithms can now be reaped easily as services on our platform – a free version was launched for testing

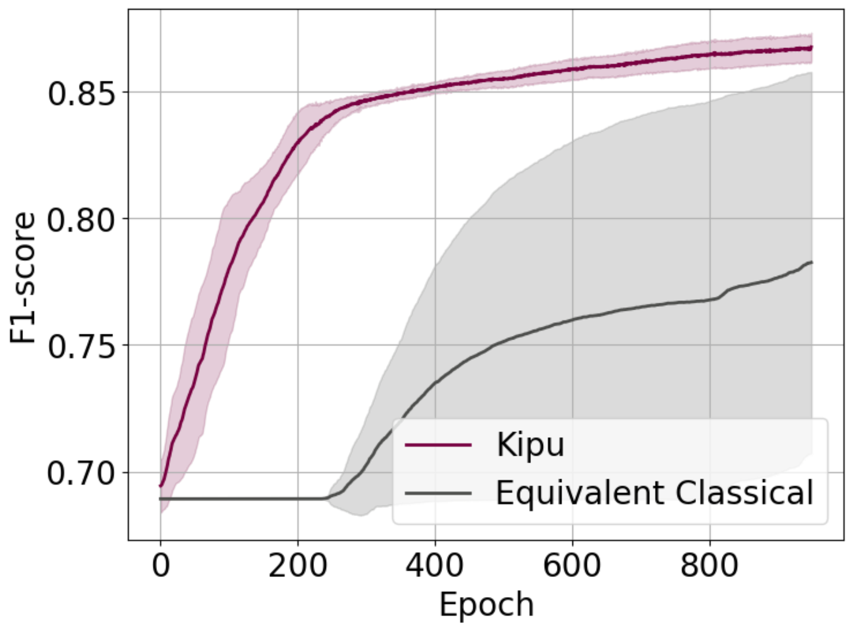
PlanQK platform users can now access Kipu‘s digital quantum optimization service based on our powerful DCQO[1] algorithm and benefit from:

- ”As a service" consumption through frictionless and automated execution - ”pay-as-you-go" or ”flat-rate" pricing model
- Access to different quantum and classical hardware and simulators
- Easy integration into existing processes and tools through API access
- Customization with Kipu's algorithm engineering team & possibility to build custom showcases for the management and / or marketing purposes



1) Digitized Counterdiabatic Quantum Optimization – see https://arxiv.org/abs/2201.00790

Coupling neural networks with quantum offers better performance at less input for tabular data sets – for instance in loan default predictions

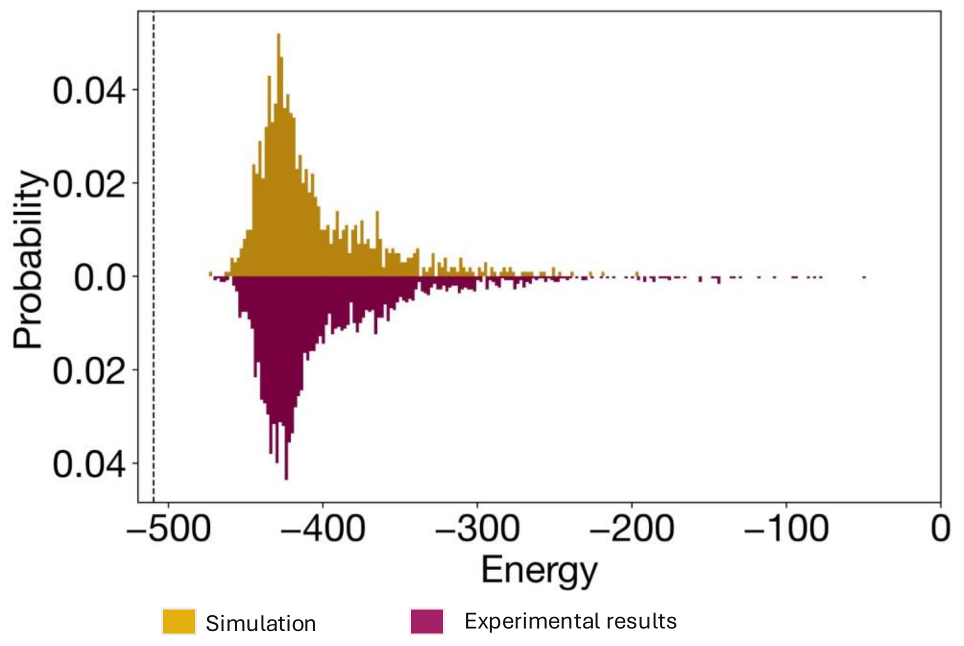


- **Accurate loan default prediction is critical for financial institutions**. As default rates climb to 5.5 – 6%[1], improving these predictions can reduce financial losses and strengthen institutional stability
- **Conventional ML struggles** to balance high-risk loans with missed opportunities, **requiring large amounts of training data**. Predicting loan defaults is particularly challenging due to the limitations of conventional models and data constraints
- Leveraging IBM Quantum, Kipu's algorithm **improves loan default prediction accuracy by 8%[2] using around 1,000 fewer training data**
- **Our quantum-enhanced preprocessing outperforms classical competitors today[3]** and can be applied to other financial classification problems, such as churn prediction and fraud detection
- This capability is based on **coupling neural networks with quantum** and can be extended to other **use cases based on tabular data**, for instance in health care

1) "Defaults expected to rise towards 5.5% in Europe and reach 6% in the US", ING Article and "Default Rates to Rise in U.S. and Europe as Weaker Growth Offsets Rate Cuts", Fitch Ratings Commentary.
2) The used Credit Risk Dataset: https://www.kaggle.com/datasets/laotse/credit-risk-dataset
3) F1-score is the harmonic mean of precision and recall. It is a metric suitable in scenarios where the data is imbalanced. We validated the tool on 11 qubits using IBM Torino noisy simulator (11 variables).

We present the largest MWIS optimization ever tackled on gate-based quantum hardware, using all 36 qubits of IonQ Forte

Experimental results for 36 qubit Maximum Weighted Independent Set on IonQ Forte with Kipu

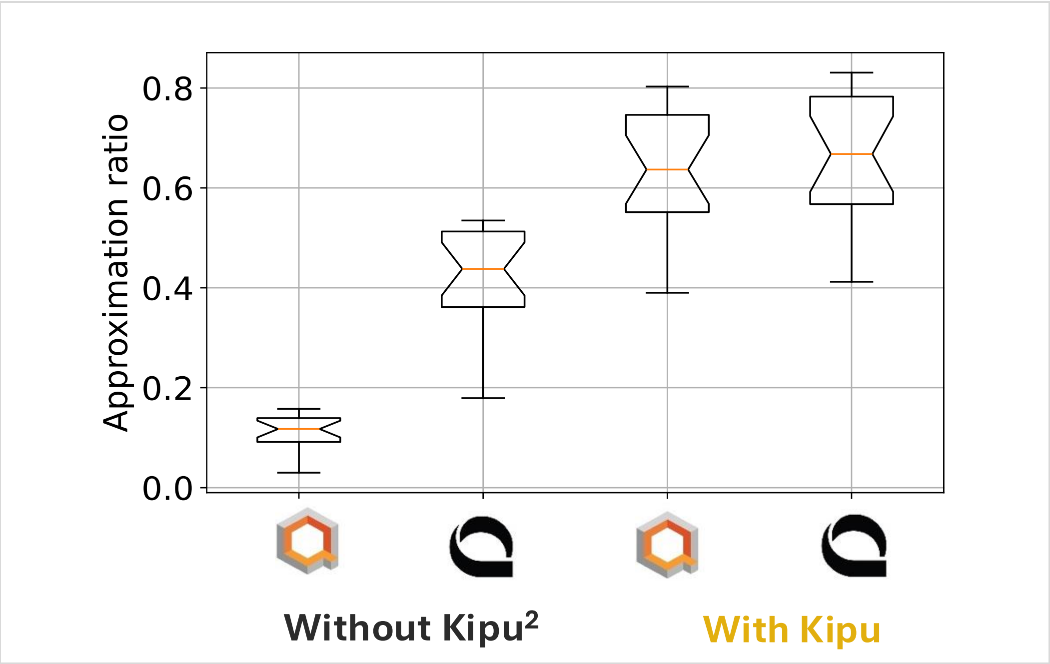


- Using many physical qubits in algorithms is challenging, because of the accumulation of noise. However, Kipu‘s algorithms are more robust against noise, because they require orders of magnitude fewer steps.
- This allowed us to use all 36 qubits of IonQ Forte, obtaining the largest maximal (weighted) independent set (MWIS) optimization tackled on a gate-based quantum computer.[2] MWIS can be applied to job shop scheduling, network optimization in energy and telco applications, as well as target interaction in drug discovery.
- While this problem size is no „quantum advantage“ yet, we consider this an important milestone, because the algorithm will also allow to solve intractable problems on larger ion traps, i.e. beyond ~60 qubits[3].

1 We show the energy distribution of simulated vs experimental results. We consider a randomly generated weighted MIS problem with 36 qubits and experimentally showed how our circuits suit current quantum hardware, such that the results agree with the expected outcome. We achieved an approximation ratio of 0.92 with merely two Trotter steps.
2 Due to our compression, we only required 64 2-qubit gates without hybrid workflows like QAOA, using every single available qubit of IonQ Forte.
3 Further improvement expected by adding error mitigation & hybrid workflows.

Hardware performance is a key factor to getting good results with quantum, but Kipu’s compression leads to decisive leaps

A-B test showing the impact of applying Kipu’s digital compression on IonQ vs Quantinuum[1]

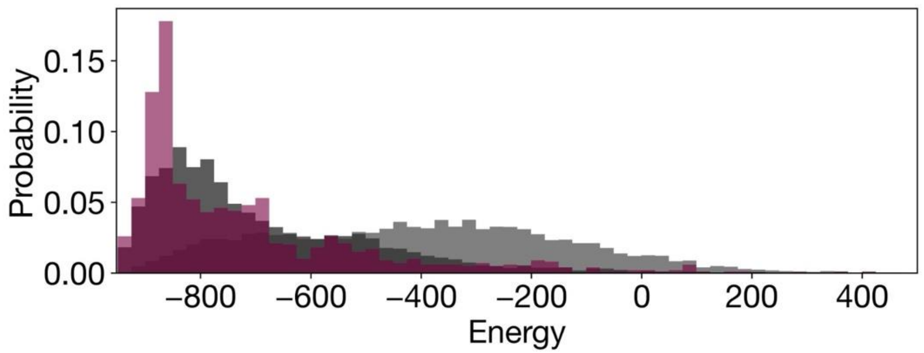


- IonQ and Quantinuum are the leading players in ion-trap hardware, in terms of qubit quality, Quantinuum has the superior machine, which typically translates into better results in direct benchmarks
- However, when combining Kipu’s digital compression technology with IonQ’s fidelities (99.26%, 36 qubits), IonQs hardware yields a ~6x increased approximation ratio from 0.10 to 0.65, outperforming what Quantinuum’s higher fidelities (99.8%, 32 qubits) without Kipu compression can deliver with AR = 0.45.[3]
- Due to our compression, we need about 10x less gates and simultaneously improve the solution quality, allowing IonQ hardware to catch up with Quantinuum.

1 1 We built a simple noisy trapped ion emulator (all-to-all connectivity) using the specified average one- and two-qubit gate fidelities of IonQ Forte and Quantinuum H2. This model is not intended to fully model hardware. However it allows a fair comparison of running algorithms with different gate fidelities. We ran 20 different portfolio instances with 13 assets/qubits each.
2 Reference was digitized quantum annealing (DQA).
3 As measured using the approximation ratio, i.e. how close the solution is to the global optimium (1 = 100% as a target).

Kipu technologies can also be applied to portfolio optimization - we set a new record and beat QAOA by 100x in time-to-solution

Experimental results using non-hybrid Kipu algorithm vs. simulated results with a hybrid QAOA[1]



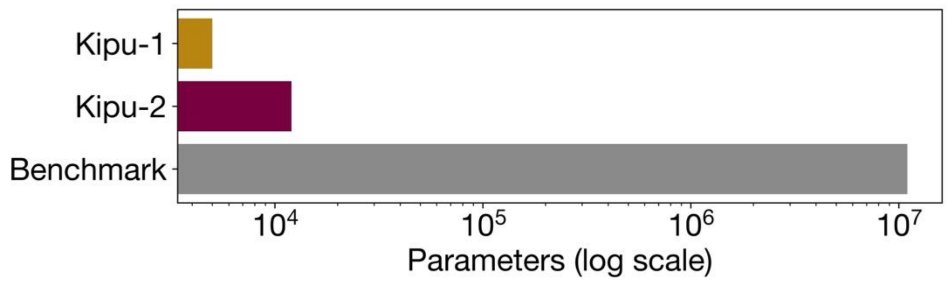
- **Kipu algorithm –** On hardware requires 122 2-qubit gates, approximation ratio (AR) of 0.75.
- **Simulated QAOA with one layer –** Requires 190 2-qubit gates for AR of 0.42.
- **Simulated QAOA with 5 layers –** Requires 950 2-qubit gates for AR of 0.72 – *cannot be implemented though because of the large number of gates*

- To reduce the impact of hardware noise, hybrid instead of pure quantum algorithms are often used. This comes at a price – Iterating between classical and quantum takes long and is expensive, and the scalability beyond 20+ qubits is a concern. Often, they are also too greedy and cannot be implemented.
- A pure quantum algorithms by Kipu outperforms hybrids like QAOA – We find a better solutions, about 100x faster and are compressed enough to allow implementation on noisy hardware
- This is one of the largest and highest quality demonstrations of portfolio optimization done on a quantum computer[2], and to our knowledge the largest pure quantum implementation for this problem[3]

1 We show the energy distribution of experimental results of Kipu's pure quantum algorithm done on IonQ Forte, vs. simulated results for hybrid methods QAOA with 1 and 5 layers, respectively.
2 We tested 20 asset portfolio optimization instance from real data.
3 For the largest hybrid (QAOA) implementation refer to this work by J.P. Morgans quantum team: https://www.nature.com/articles/s41534-023-00787-5

Digital-analog quantum compression improves ML models for image classification, better prediction with 1000x fewer parameters

Quantum-based machine learning models vs. larger classical CNNs for identification of breast cancer



Kipu-1 – CNN using 5,000 parameters, with 4 qubits

Kipu-2 – CNN using 12,000 parameters, with 9 qubits

Benchmark – CNN using 11 million parameters, no quantum[1]

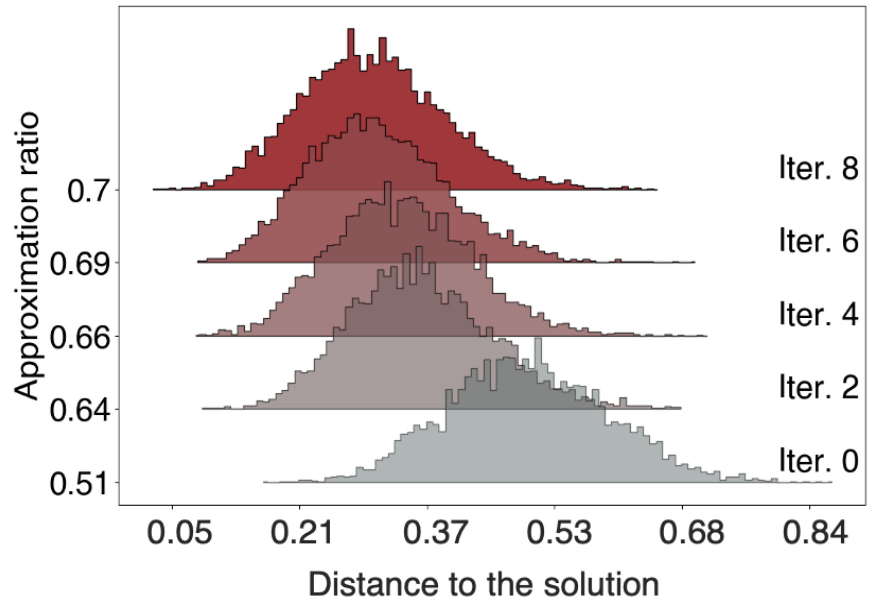
Click here for the paper!

- A critical pain point in AI/ML, especially in convolutional neural networks (CNNs) is the need for a large number of (expensive) parameters to train models, e.g., in image classification.
- Bringing quantum computing based on digital-analog compression into the workflow reduces the number of parameter by 1,000x at an improved performance.
- The resulting CNNs outperforms classical CNN on 4 and 9 qubits – the performance KPIs AUC2 of 91.8 and 92.6% respectively exceeds the 90.1 and 91.9% obtained with ResNEt-18 and Google AutoML. The same trend is found for the accuracy ACC with 87.2% and 89.1% vs 86.3% and 86.1% respectively.
- Even higher quality images can be achieved and require ~150 qubits on neutral atoms.[3]

1 1 Tested against ResNet-18 & Google AutoML.
2 AUC = area under the receiver operating characteristic curve; ACC = Accuracy. Test case was breast cancer; method also applicable for other diseases such as pneumonia, as well as image based data sets in finance (fraud detection), digital farming, object identification in AGVs.
3 Validation on 4-9 noiseless qubits was done using simulated neutral atom devices.

Improved digital algorithm makes large-scale optimization beyond 100 qubits possible on IBM hardware

We proved that Kipu can solve combinatorial optimization beyond 100 qubits on IBM



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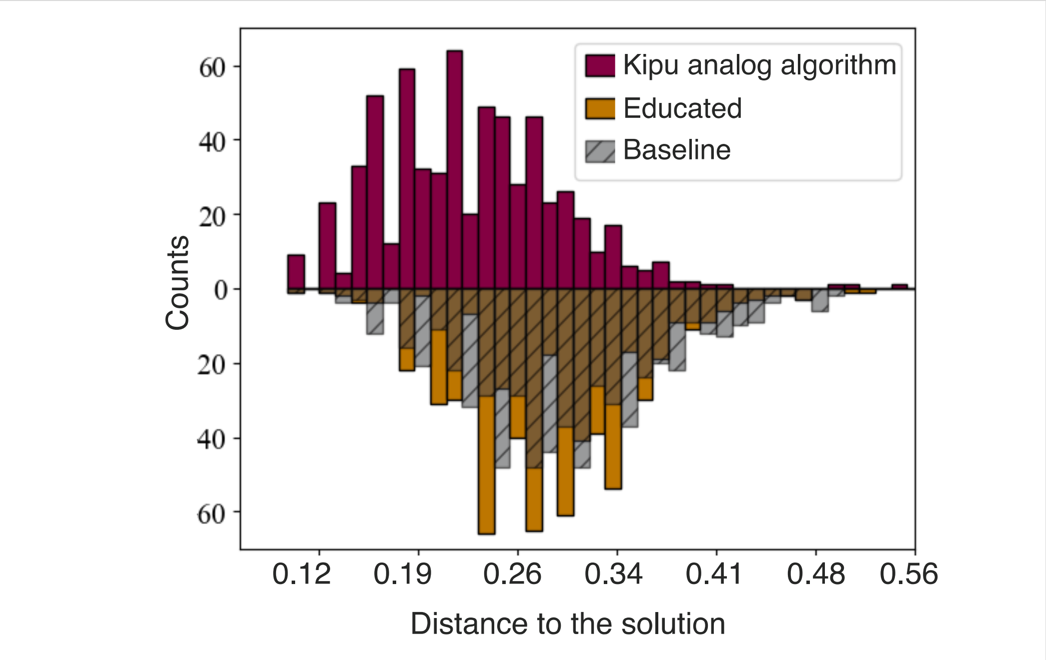
- Our quantum algorithms outperform non-scalable ones like QAOA. We achieve 200 x higher success rate, better answers and scaling to larger problems.[1]
- We used 100 qubits of IBM Brisbane to solve a spin glass problem, which maps to industry problems like scheduling. This is relevant for logistics and manufacturing.
- This is a key milestone on our path to quantum advantage – solving 100+ qubit problems is a prerequisite. Based on IBMs roadmaps for 2024 and 2025, we expect to solve an intractable problem soon, by boosting classical heuristics and hybrid solvers!

1 Apples-for-apples comparison done on 20 qubits; approximation ratio or AR as a metric for how close we are to a global optimum is improved by 30%

Brand-new analog algorithm opens a path to near-term usefulness on neutral atom hardware for graph problems

Fast, high quality, large scale optimization on neutral atoms is possible with Kipu



arXiv [Click here for the paper](#).

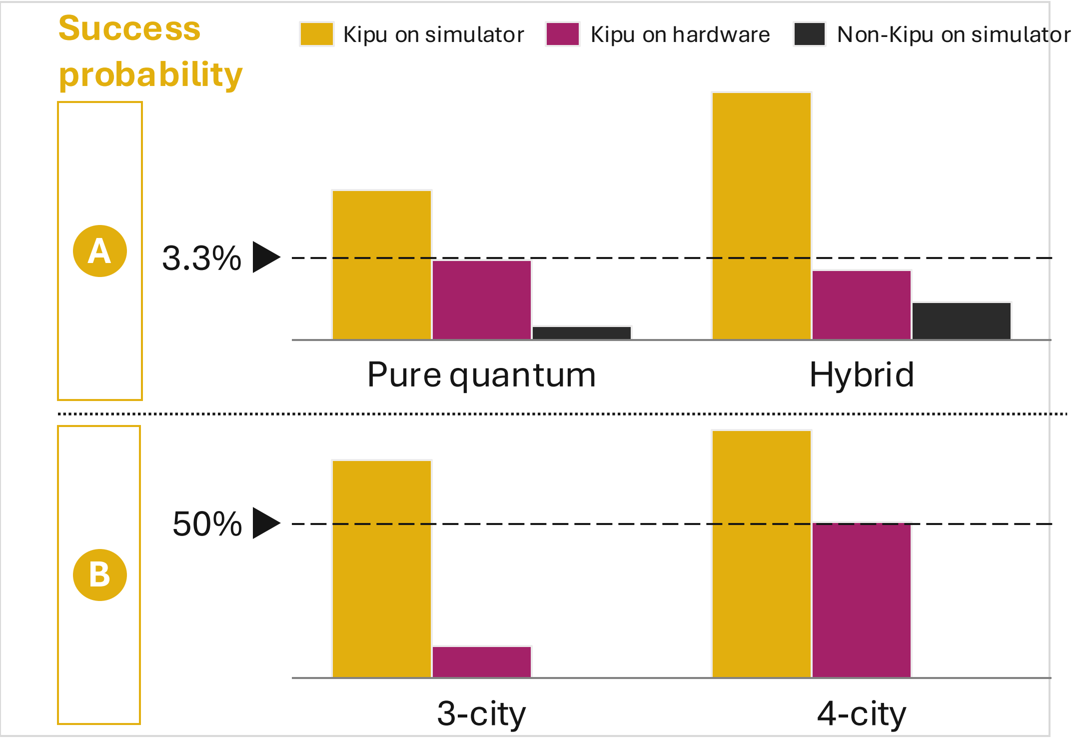
[Click here for a practical example with customer MásOrange](#)

- Neutral atom hardware can solve use cases that can be mapped against a MIS2, such as network optimization.
- On a 100+ qubit problem, we proved that our analog algorithm improves what neutral atoms can do:
  – Accelerate to 200 x time-to-solution – getting an answer fast is crucial for practical applications
  – Get 20 % better answer[3]
  – No classical optimization needed[4] – this assures a path to run 500+ qubits.
- Based on QuEra's and Pasqal's roadmaps beyond 2024, we expect to see neutral atom QPUs with hundreds of qubits, this will approach quantum advantage when combined with our algorithms!

1 Figure shows the energy distribution from experiments performed on QuEra's cloud accessed Aquila device solving MIS on a 100-qubit graph for T = 1µs; 2 MIS Maximum independent set; 3 measured in approximation ratio or AR, a metric for how close we are to a global optimum; 4 such as costly hybrid methods or Bayesian optimization protocols

With BASF, Kipu algorithms gave 1,000 x improvement & allowed solving non-implementable problems on real hardwarde

Drastic boost by combining Kipu algorithms vs. existing problem decomposition methods



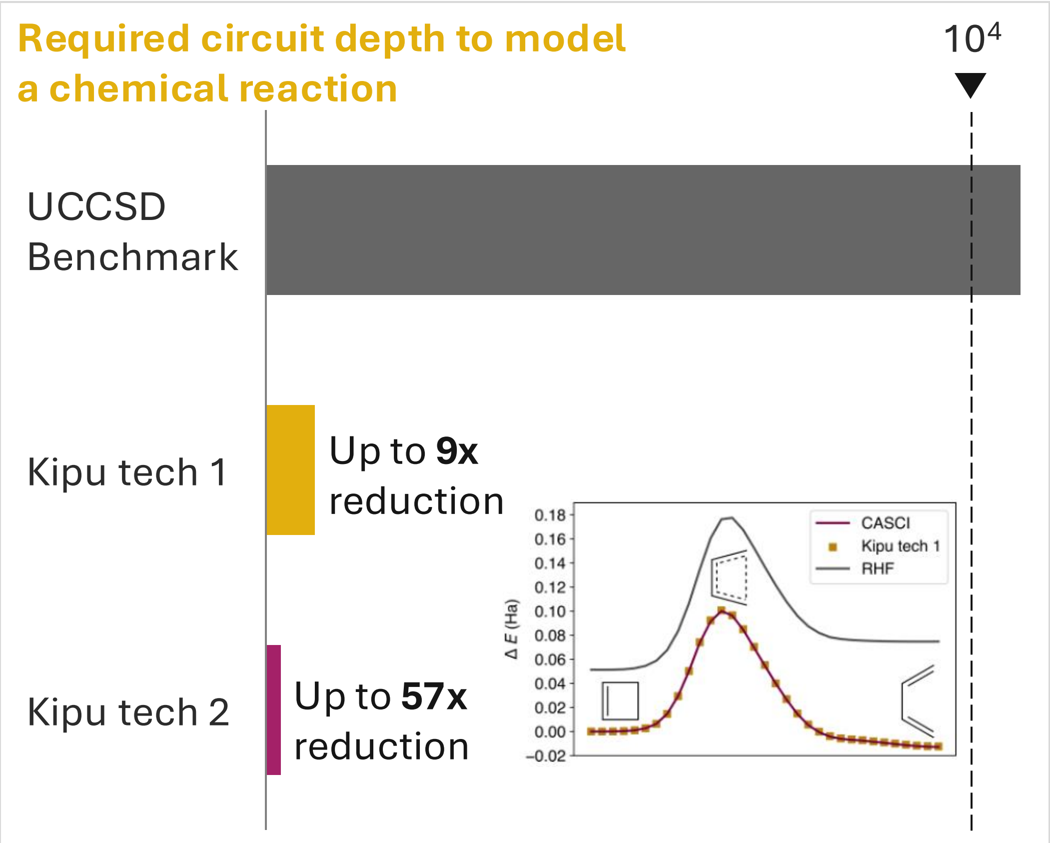
arXiv [Click here for the paper.](#)

- Many challenges in manufacturing and logistics companies can be mapped on traveling salesman problem (TSP) or job-shop scheduling problem (JSSP).
- At scale, these problems are hard, even for super computers. However, quantum often fail due to short coherence times of the QPUs or give suboptimal solutions.
- With our customer BASF, we recently demonstrated:
  - Up to 1,000 x higher success probability compared to standard algorithms such as QAOA.
  - We ran problems on real hardware that were previously not implementable within the limits of today's hardware.
- A near-term path to quantum advantage lies in quantum solutions that combine our algorithms & near-term hardware to boost classical heuristics and hybrid solvers.

(A) We solve a JSSP subproblem. We show that Kipu outperforms QAOA in terms of success probability; (B) 3-city TSP instances are solved on IBM and IonQ

Kipu brings chemical modeling on near-term quantum computers, by reducing required circuit depth & time by 50x

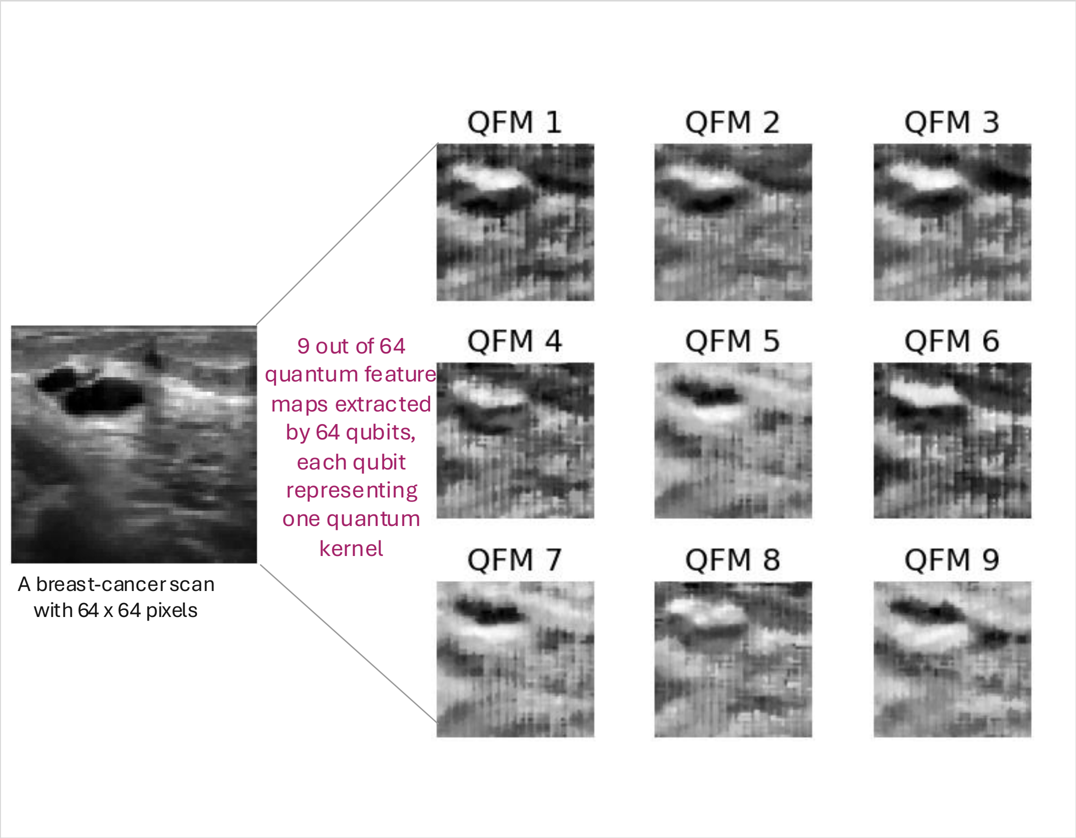
With Kipu, modelling chemical reactions may be realized on quantum computers by 2025



- Predicting the properties of molecules & chemical reactions[1] is considered a very hard application for quantum computers.
- Even on fault tolerant hardware, current algorithms will require huge circuit depths, and consequently would take weeks, i.e., too long for real-time applications.
- We show for a use case[2] that Kipu's algorithms require less quantum resources than UCCSD while achieving:
  - Chemical accuracy in comparison to exact methods
  - Up to a 50-fold reduction in the number of CX gates and up to 57-fold reduction in circuit depth
- Implications are significant – We reduce the required number of gates to an extent that NISQ hardware can deal with as soon as 2025, and provide a way to shorten the time-to-solution by a factor of 50 as well!

1 Underlying use case is atomistic modelling / electronic structure modelling; 2 Geometries as used in Nature Physics 19, 1787 (2023), link

Towards quantum advantage for feature extraction: 1,000x fewer training parameters using Kipu's new algorithm on D-Wave hardware

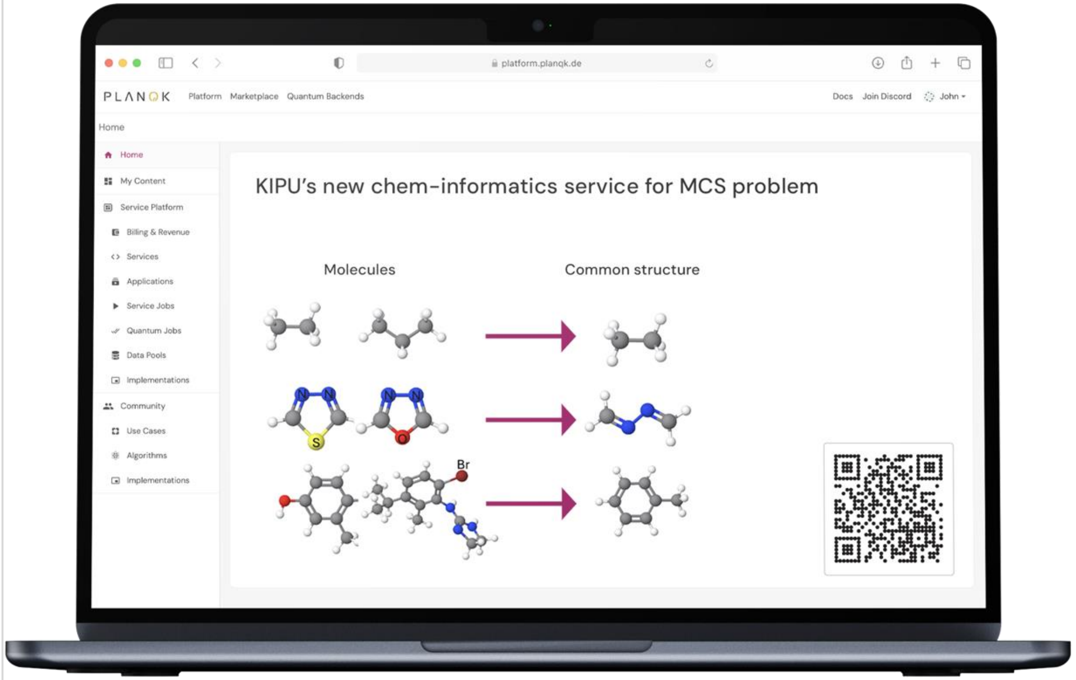


- Image classification is a relevant task in healthcare diagnostics, quality control in manufacturing. Yet, complex datasets challenge traditional methods like CNNs[1], make them **costly and ineffective**
- Kipu's analog algorithm[2] uses up to **1,000x fewer training parameters** vs. models like ResNet-18, enabling faster training
- We've demonstrated feature extraction **using D-Wave quantum processors[3]**, aiming for quantum-advantage in image classification

Quantum-boosted CNNs uncover features and relationships that classical methods can't reach – this leads to drastic performance improvements in quality at reduced resources!

1) CNNs: convolutional neural networks
2) AQCNN, analog Quantum Convolutional Neural Network (AQCNN).
3) Details: annealing time is 20 ns within coherence time; # of shots: 6,000, D-Wave Advantage 2 with 1,200 qubits

Improved chem-informatics based on molecular screening – now on the PLANQK platform

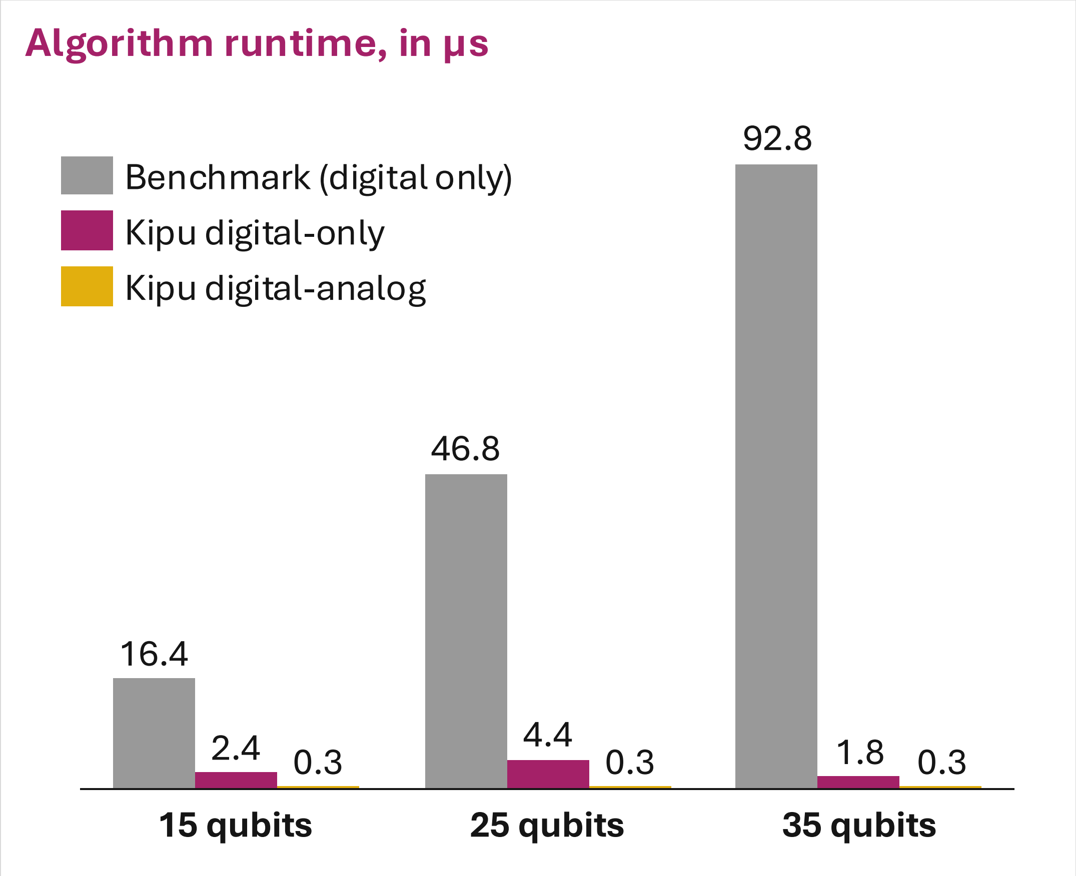


- **Molecular screening is highly relevant in pharma R&D.** Classical algorithms struggle with solving the underlying maximum common substructure problems **for more than two molecules**, making these computations impossible for large and complex molecules

- Kipu's quantum computing approach is making significant advancements in this area and is paying the way for further developments.

The early-version of the service is now available on PLANQK for selected customers.

We proved that our digital-analog encoding enables a radical reduction of algorithm runtime at improved quality for HUBO optimization problems



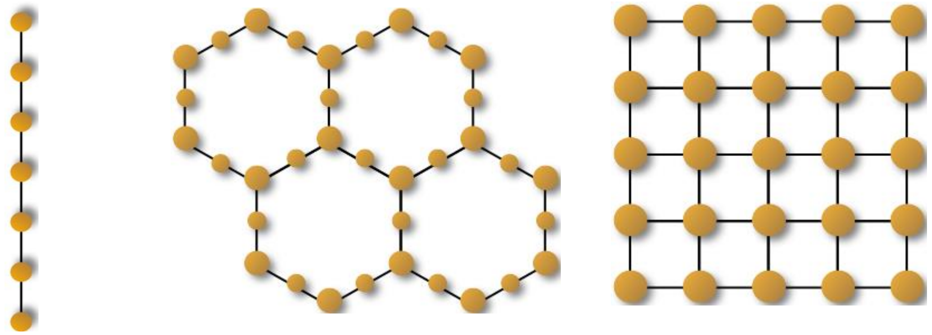
- HUBO[1] problems are vital for complex industrial challenges, such as LABS[2]. However, classical computers struggle with **over 66 variables.**[4]
- Kipu's digital-analog encoding and constant depth quantum algorithms ensure runtime doesn't grow with system size for HUBO and QUBO[3] problems.
- On top of slashing down the algorithmic runtime, our digital and analog techniques improved solution quality by 2.5 times.

This tech can solve HUBO problems at the quantum-advantage level – providing a speed advantage.

1) HUBO: Higher-Ordinary Unconstrained Binary Optimization; 2) LABS: Low Autocorrelation Binary Sequence problem, its mathematicalformulation has 4-order interactions between variables; 3) QUBO: Quadratic Unconstrained Binary Optimization 4) https://arxiv.org/pdf/2106.03377: Classical computers using exhaustive search techniques can solve LABS problem for sequence sizes up 66 in practical time frames

Beyond optimization: Ultra-fast quantum simulation on 156 qubits on IBM paves the way for advancements in materials science

Reduced defect density by up to 48% of the benchmark value



We studied different geometries of the dynamic systems: 1D chain, heavy-hexagonal lattice, and 2D square lattice – defects were reduced by 48%.

arXiv [Click here for the paper!]

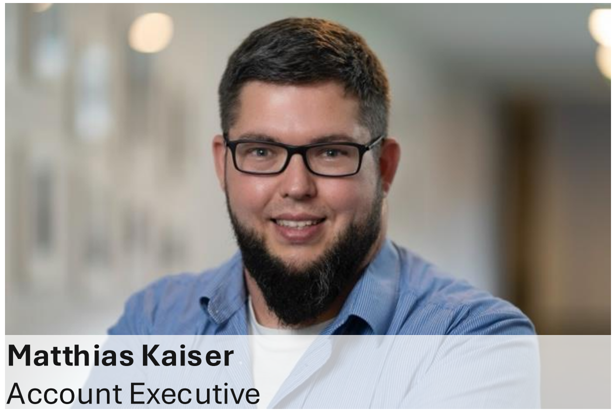
- Quantum simulations provide insights into complex phenomena that **classical computers struggle to study**
- Kipu's algorithm **runs large-scale simulations** on IBM's Heron chip, achieving up to 156 qubits
- Our algorithm reduces defect density by **up to 48%**, leading to more reliable simulations
- This technology enables accurate quantum state preparation, advancing materials science and quantum chemistry

For the first time, Kipu pushes large-scale quantum simulation beyond 156 qubits which would otherwise take weeks.

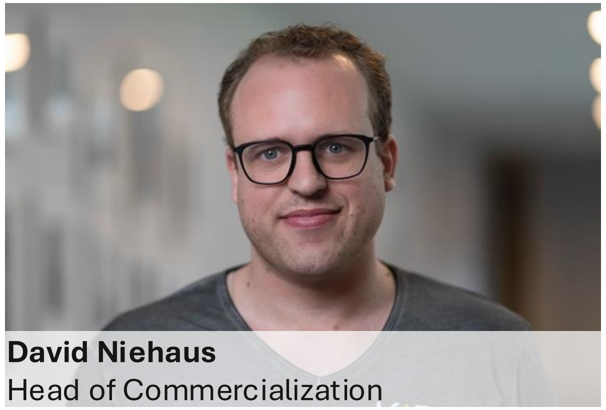
Contact our customer team and start a quantum journey with us

Ways to engage with us:

- Enter the discussion regarding your use cases, value, and strategy
- Test our quantum solutions on PLAQNK platform
- Transform ideas into actionable pilots and bring real-world results to your business
- Embark on a 12 – 18 months journey to demonstrate first usefulness



Matthias Kaiser
Account Executive



David Niehaus
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