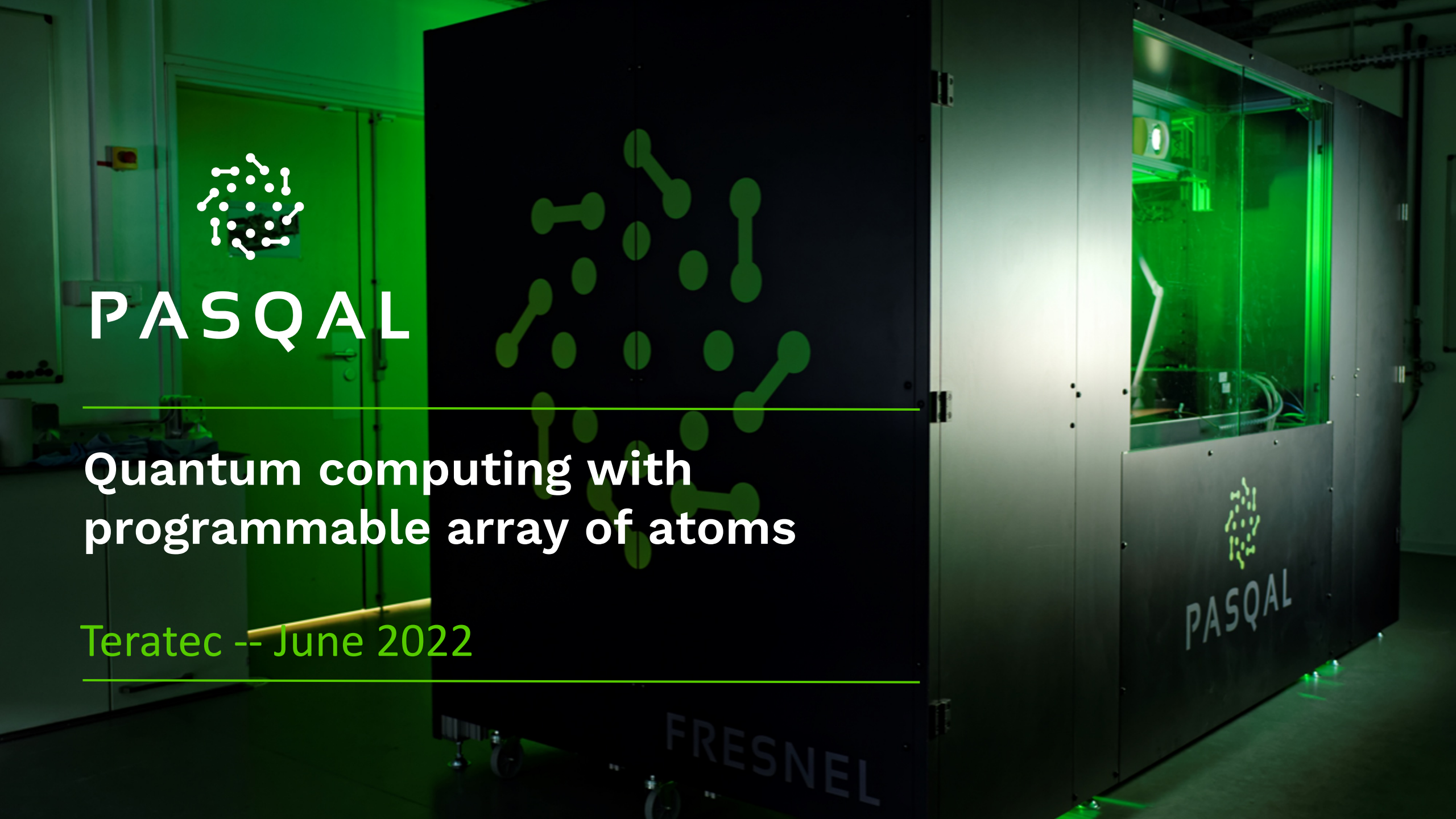
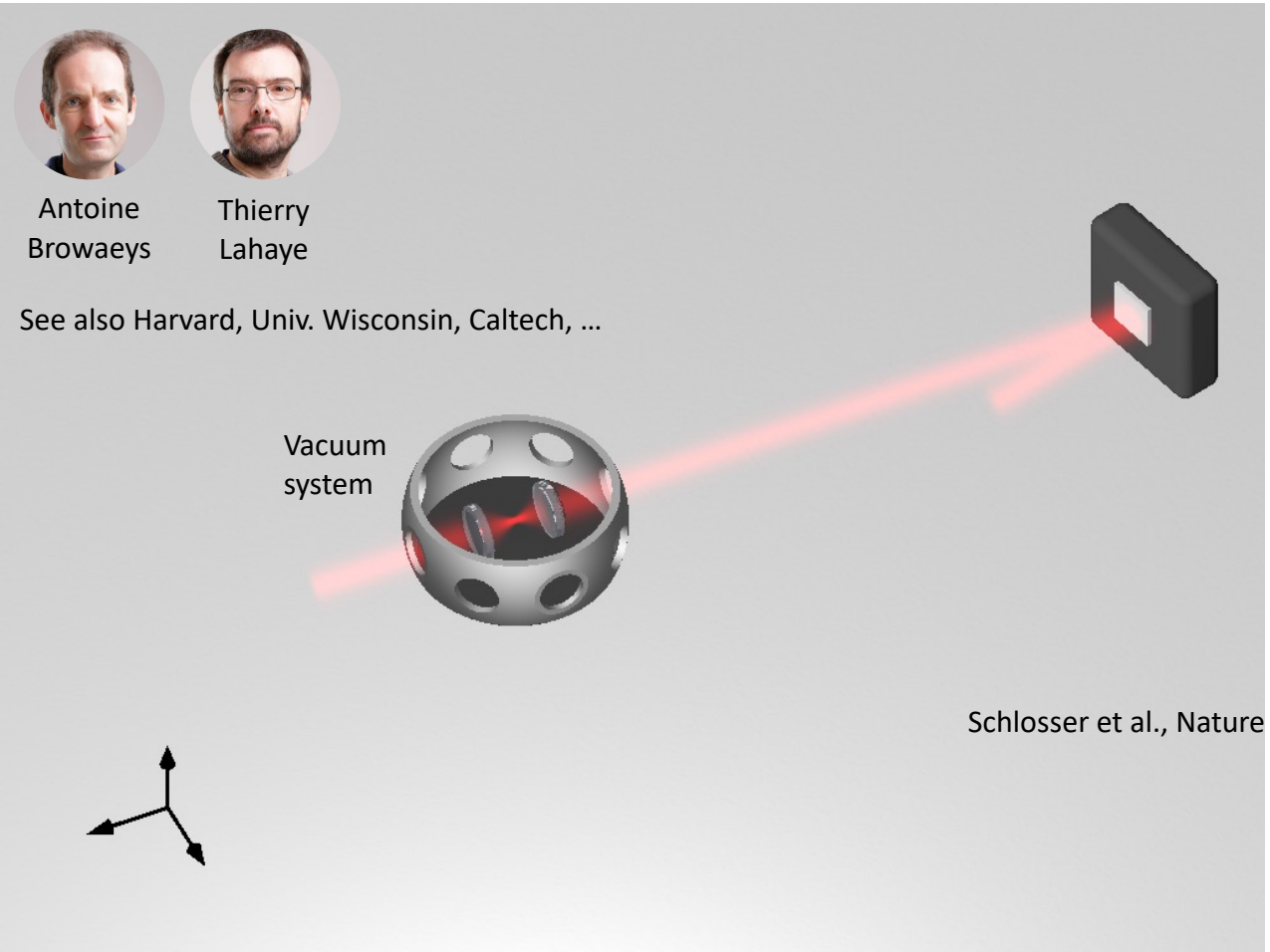


Quantum computing with programmable array of atoms

Teratec -- June 2022

Neutral atom quantum processors

A technology pioneered at IOGS:
Trapped Rb atoms in an array of optical tweezers[1]



[1] Quantum computing with neutral atoms, Quantum 4, 327 (2020)

Neutral atom quantum processors

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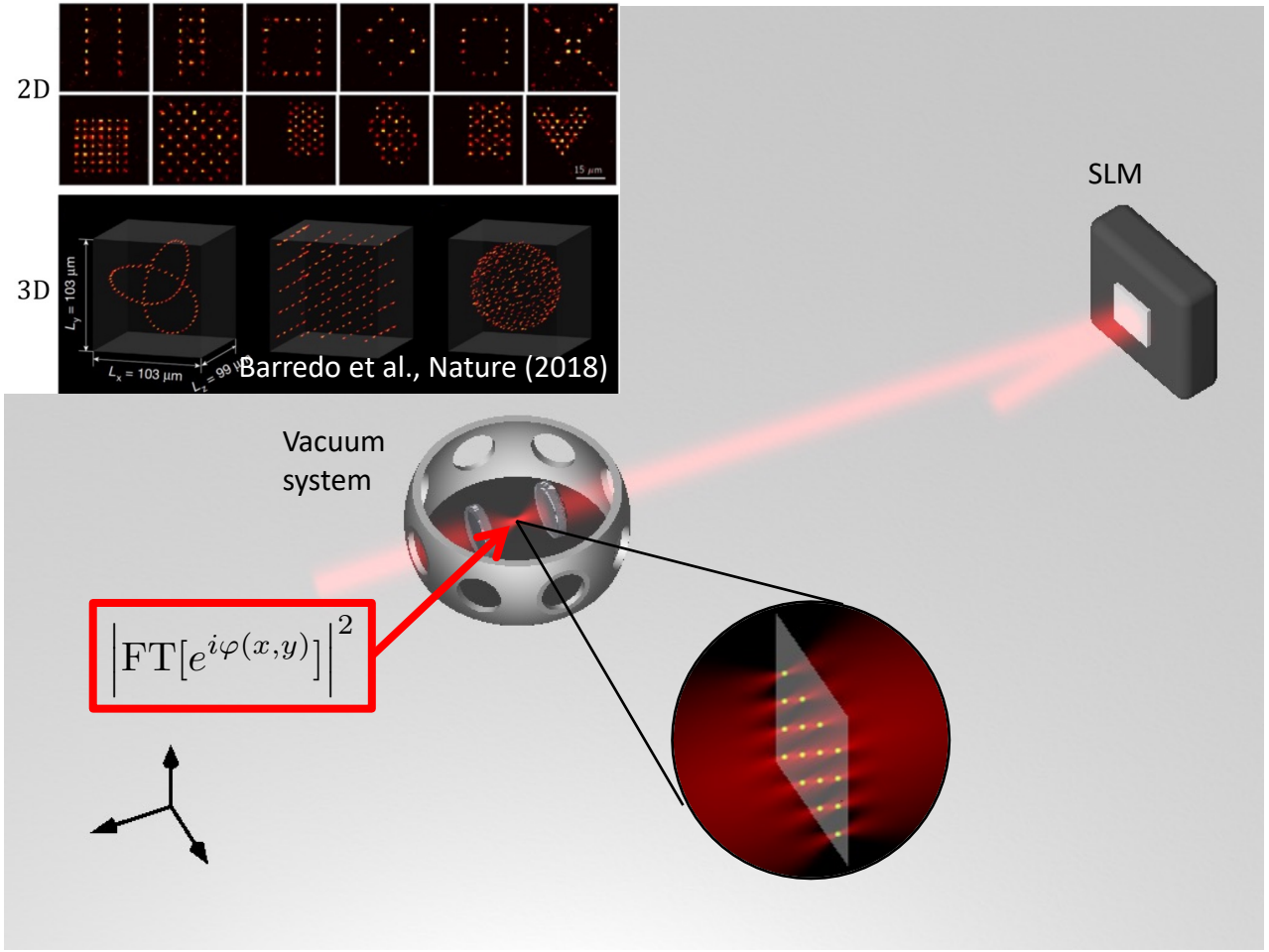
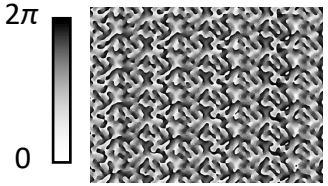
Using a SLM, one can reconfigure the geometry of the qubit register



phase pattern



Nogrette et al., PRX (2014)

[1] Quantum computing with neutral atoms, Quantum 4, 327 (2020)

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Neutral atom quantum processors

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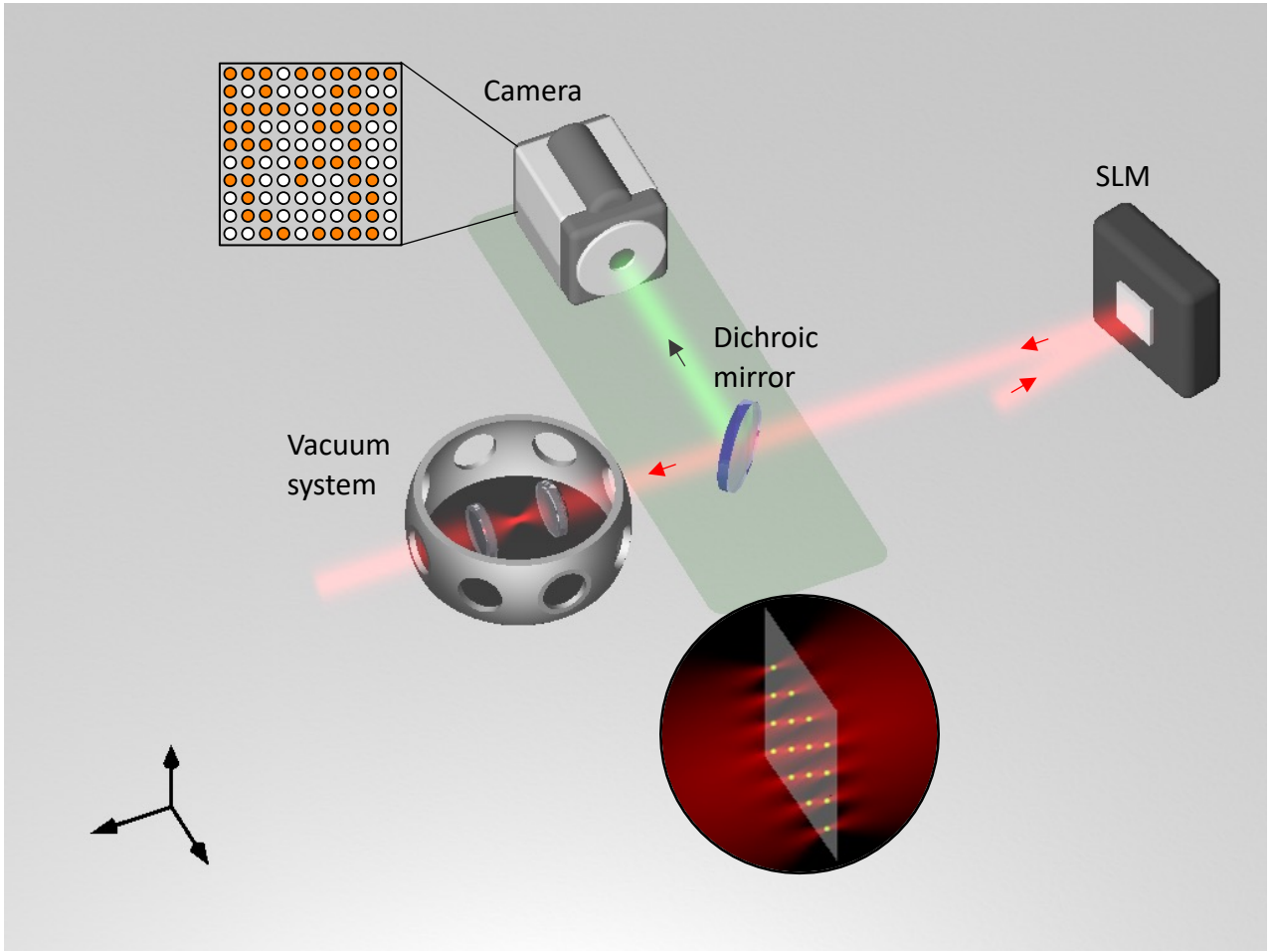
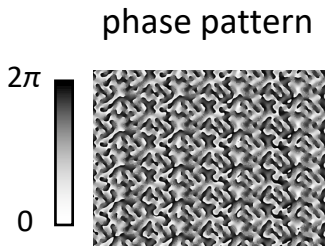
Atoms are imaged using a camera with single-site resolution





Nogrette et al., PRX (2014)

[1] Quantum computing with neutral atoms, Quantum 4, 327 (2020)

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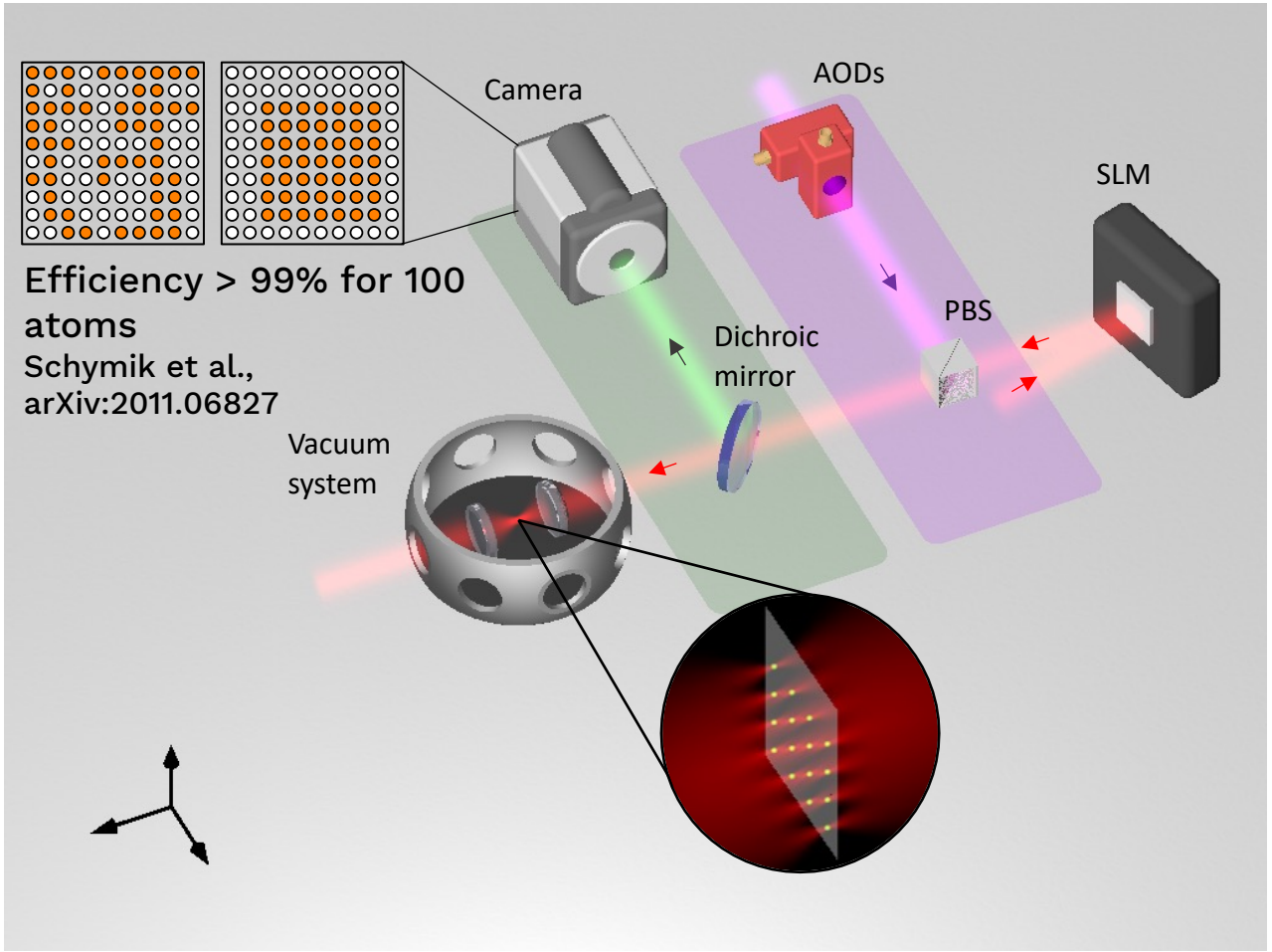
PASQAL's processor is designed to offer scalability for a wide range of algorithms

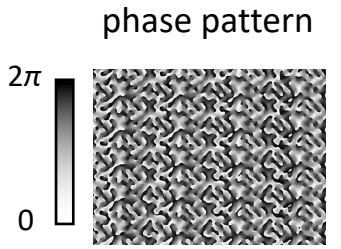
A technology pioneered at IOGS: Trapped Rb atoms in an array of optical tweezers[1]

Using a SLM, one can reconfigure the geometry of the qubit register

Atoms are imaged using a camera with single-site resolution

With an additional optical tweezer, one can re-arrange the geometry of the registers, atom by atom.





Nogrette et al., PRX (2014)

[1] Quantum computing with neutral atoms, Quantum 4, 327 (2020)

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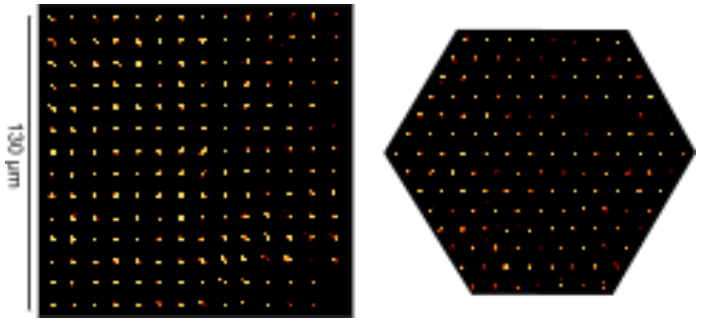
Neutral Atoms : a unique approach to quantum computing

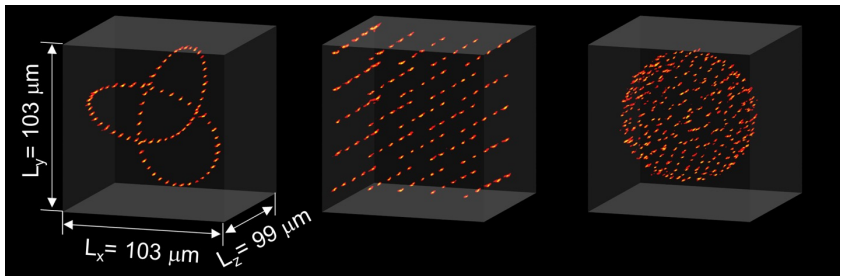
A unique scalability potential:
Our QPUs offer quantum registers with 100+ qubits as of today, and we have a clear blueprint for a **1000-qubit processor by 2023**

High flexibility level:
Our QPUs can be configurated in different geometries: **1D, 2D & 3D**, paving the way towards a Universal Quantum processor

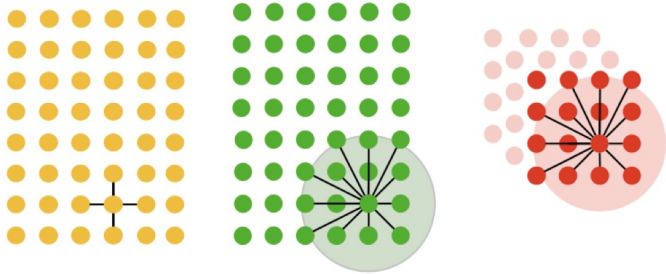
High connectivity:
One-to-many. We can design the connectivity between qubits by adjusting the distance between atoms and the geometry of the quantum register



Experimental realisation of quantum registers with 196 qubits[1]. Each dot is the captured fluorescence from an individual atom.



Experimental realisation of quantum registers in different geometries.



[1] P. Scholl et al. Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms, Nature 595, 233-238 (2021)

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Controls of a neutral-atom QPU

Our efforts towards industrialized QPUs

Application

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Controls of a neutral-atom QPU

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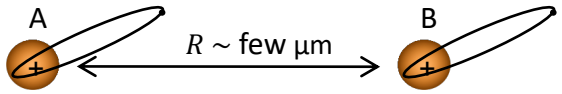
Processing quantum information

Rydberg interaction as entanglement resource

$$H_{ising} = \frac{\hbar\Omega}{2}\sum_{i=1}^{N}\sigma_i^x - \hbar\delta\sum_{i=1}^{N}\sigma_i^z + \sum_{j<i}\frac{C_6}{r_{ij}^6}n_i n_j, \quad n_i = \frac{\sigma_i^z + 1}{2}$$



Jaksch et al., PRA (2000)
Saffman, RMP (2010)
Browaeys & Lahaye, Nat. Phys. (2020)

$$H_{XY} = \frac{\hbar\Omega}{2}\sum_{i=1}^{N}\sigma_i^x - \frac{\hbar\delta}{2}\sum_{i=1}^{N}\sigma_i^z + 2\sum_{j<i}\frac{C_3}{r_{ij}^3}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+)$$

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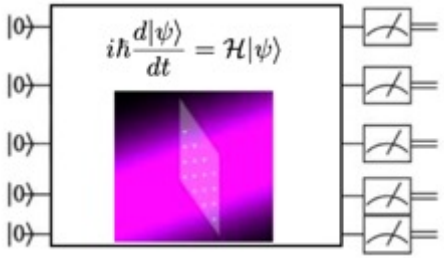
Two controls modes supporting versatility

Quantum resources can be used in two different modes:

ANALOG CONTROL
programming a Hamiltonian sequence

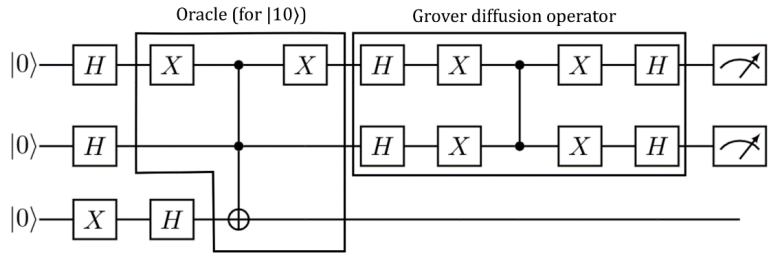


$$H = \sum_j [\hbar\delta(t)\,\sigma_j^z + \hbar\Omega(t)\,\sigma_j^x] + \sum_{i,j} U_{i,j}\,\sigma_i^z\sigma_j^z$$

The Hamiltonian faithfully describes the dynamics of a physical system or the constraints of an operational case. Parameters can be tuned continuously.

This computation mode is not universal but offers better performances, allowing for the implementation of practical use cases as of today.

DIGITAL CONTROL
programming a quantum circuit with digital quantum gates



Elementary operations are discrete digital quantum gates, that can act either on individual qubits, or on several qubits at the same time.

This computation mode is universal. The reached performances with neutral atoms systems are comparable with performances of other platforms.

A numerical study realized by: M. Troyer (Microsoft), A. J. Daley (Strathclyde), I. Bloch (MPQ) and P. Zoller (Innsbruck), comparing the **requirements to simulate the same quantum dynamics** of a 10x10 2D Hubbard model system using an **analogue vs digital** modes: with typical error level of 1% of the analogue mode → 10^6 gate operations are required with F > 0.999999

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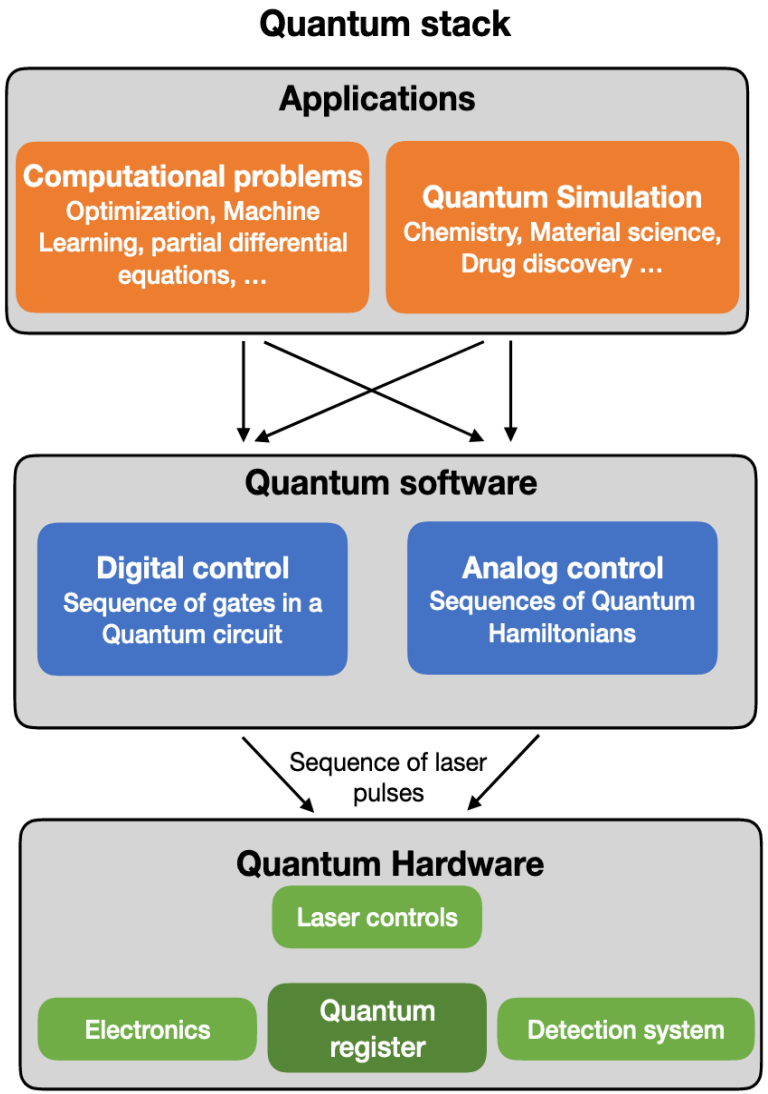
Quantum Stack of neutral atom Quantum Processors



Metrics

Quality, speed or reliability of the procedure in comparison with state-of-the art classical methods

Complexity of the procedure, and/or gate count

Number of atoms, gate fidelity $\mathcal{F}$ quality factor $\mathcal{Q}$, and repetition rate of the QPU

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Taking the technology out of the lab

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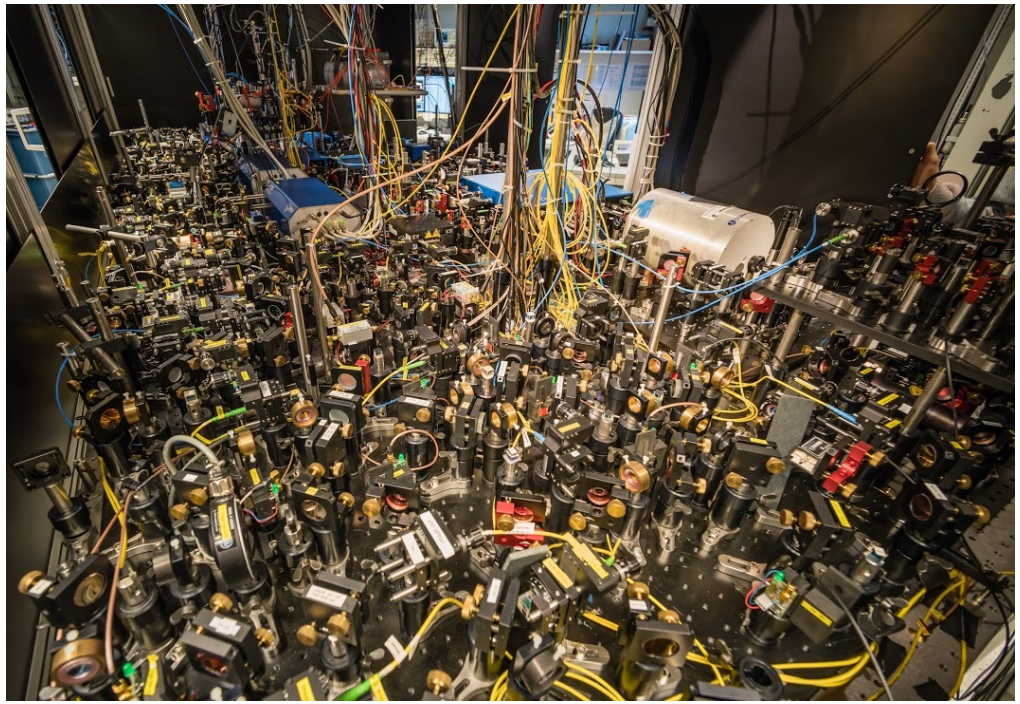
Pasqal : from an academic experiment to an industrial machine



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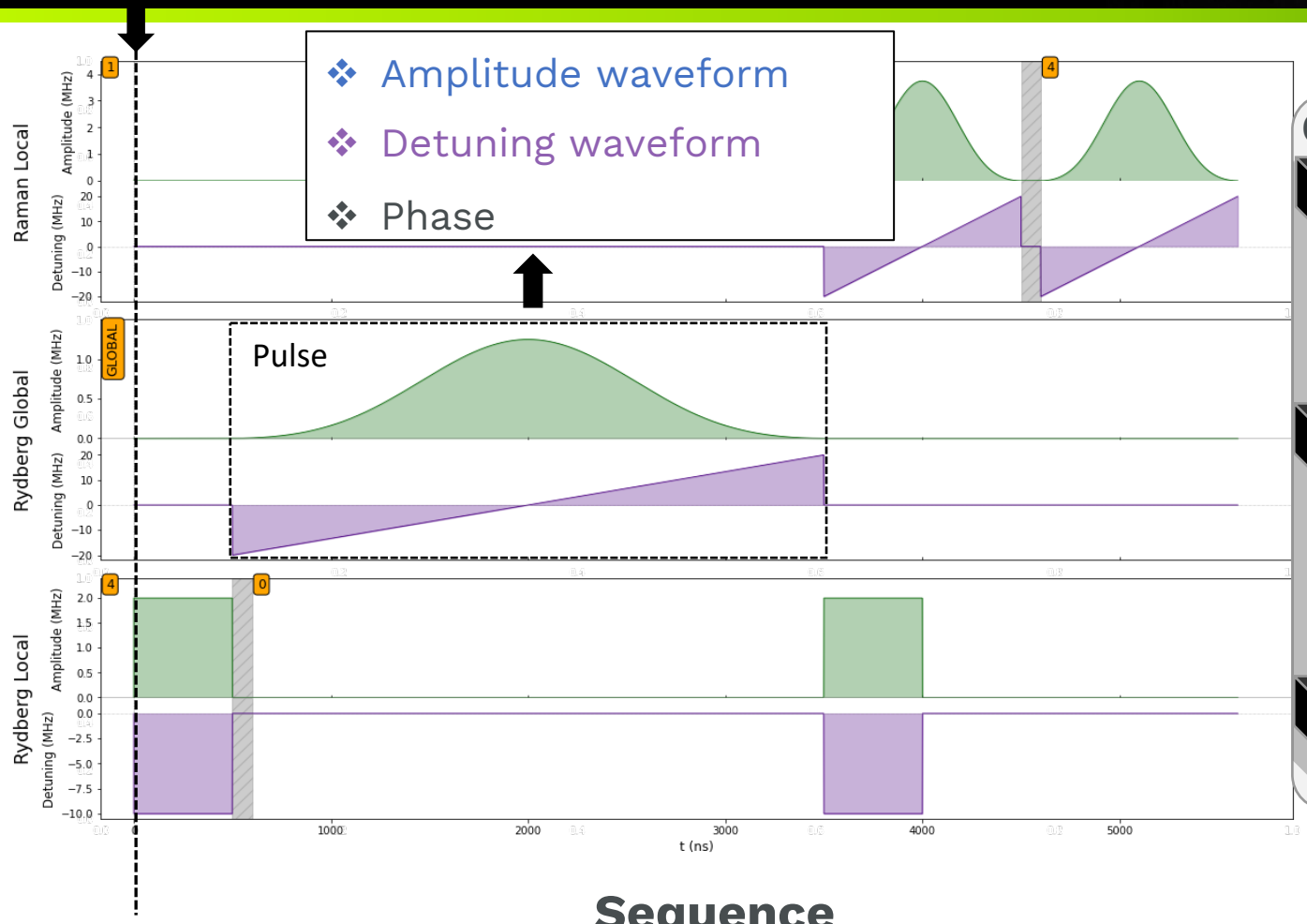
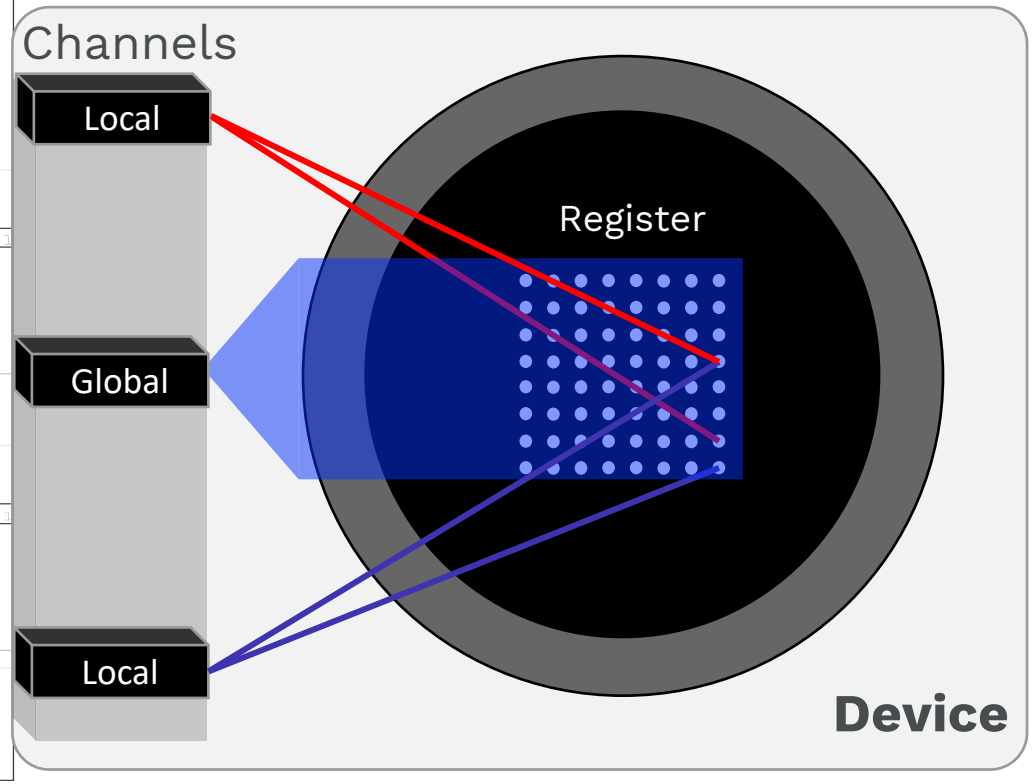
Anatomy of a Pulser Sequence



Sequence



GitHub Repository: https://github.com/pasqal-io/Pulser

Documentation: https://pulser.readthedocs.io/

Paper: *Silvério et al.*, Quantum 6, 629 (2022), https://arxiv.org/abs/2104.15044

A few applications

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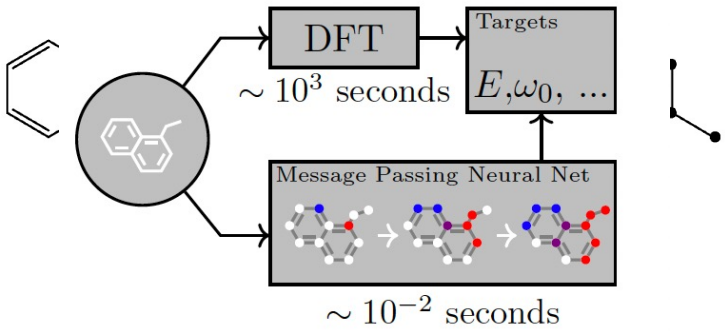
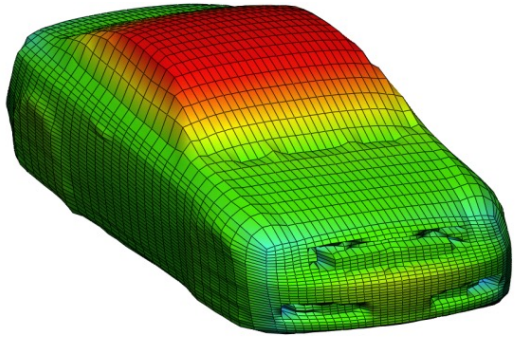
Quantum Machine Learning Phys Rev. A 2021 and experimental results upcoming

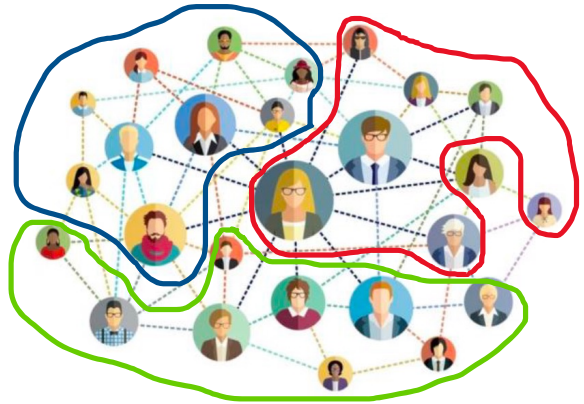


Molecules

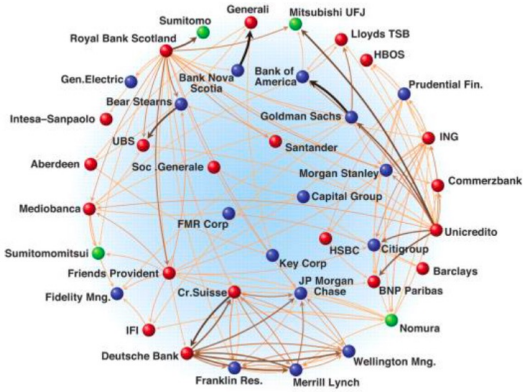
Gilmer et al. *Neural Message Passing for Quantum Chemistry*



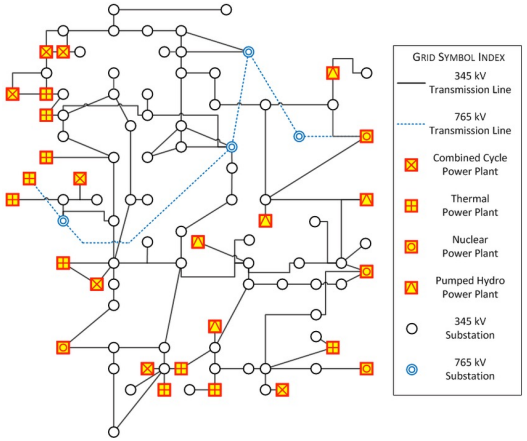
3D shapes



Social networks



Economic networks



Power networks

Image credits to be found at: Jure Leskovec, Stanford CS224W, http://web.stanford.edu/class/cs224w/slides/01-intro.pdf

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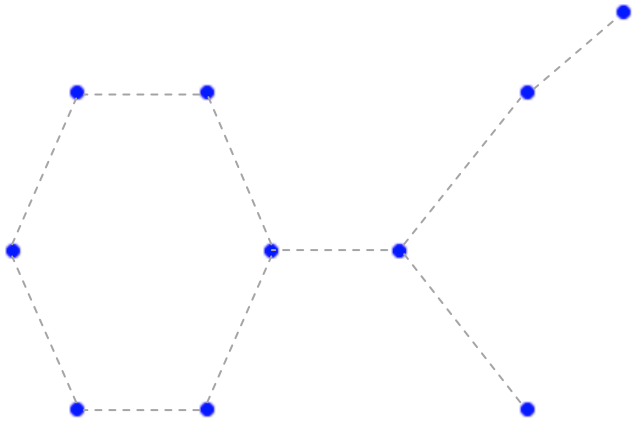
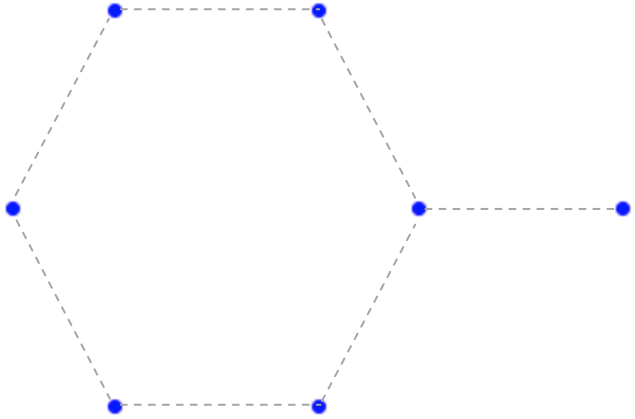
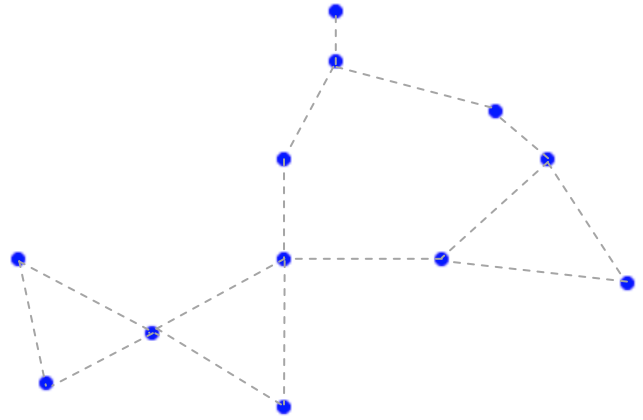
Examples of graphs







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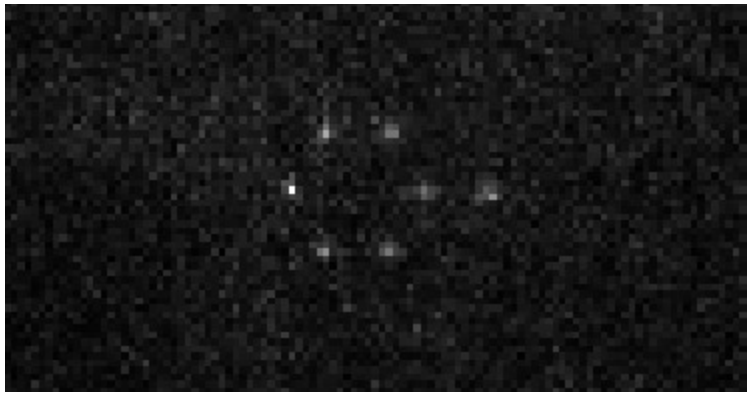
Atom registers

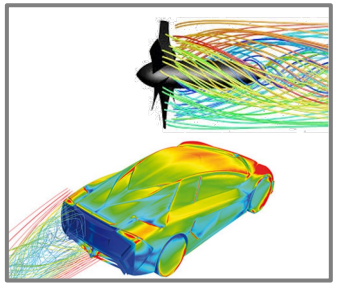


Multiphysics simulations

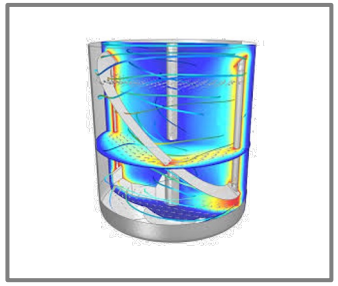
Computational Challenge:

Solving Differential Equations

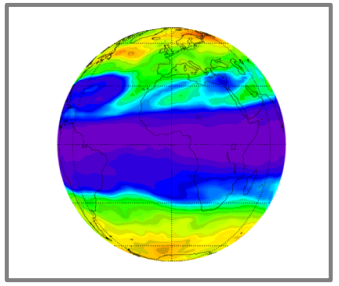
Mechanical Engineering



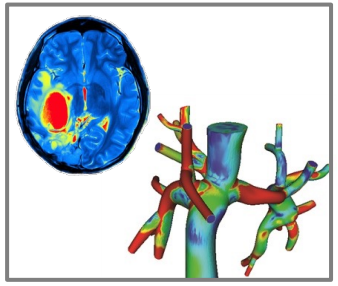
Chemical engineering



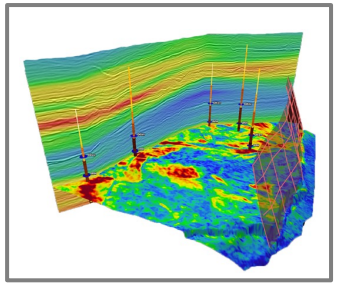
Metrology & Climate



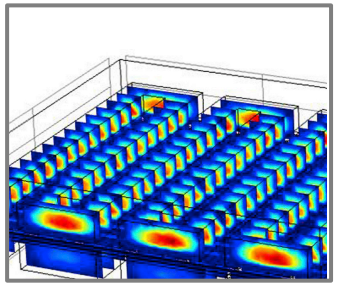
Biomedical



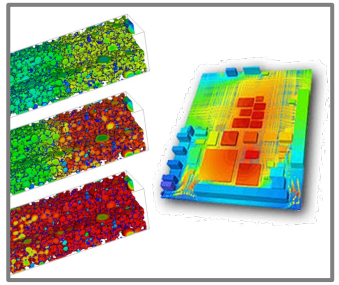
Oil & Gas



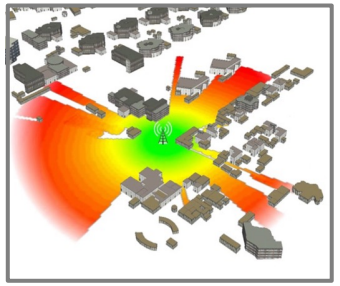
Fuel cell design



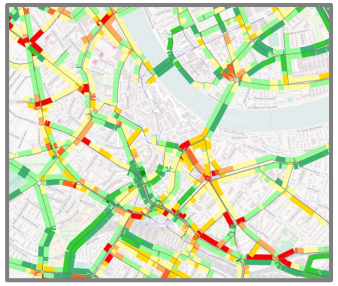
Batteries & Electronics



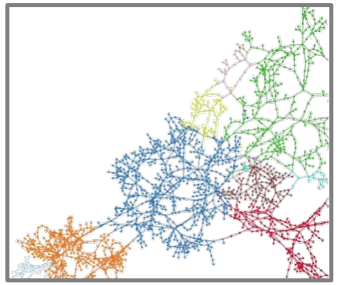
Wireless networks



Traffic & Logistics

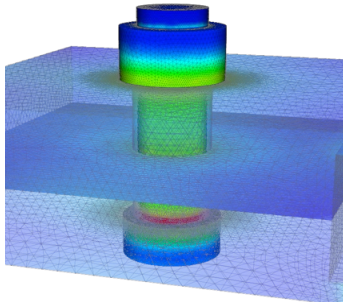


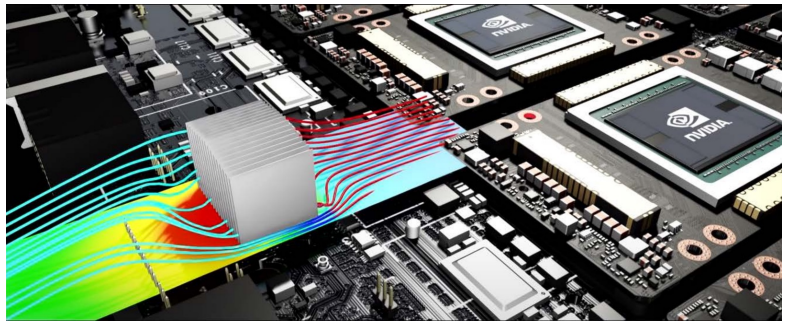
Powergrids



Traditional Methods: FEM

Latest State-of-the-Art: PINN





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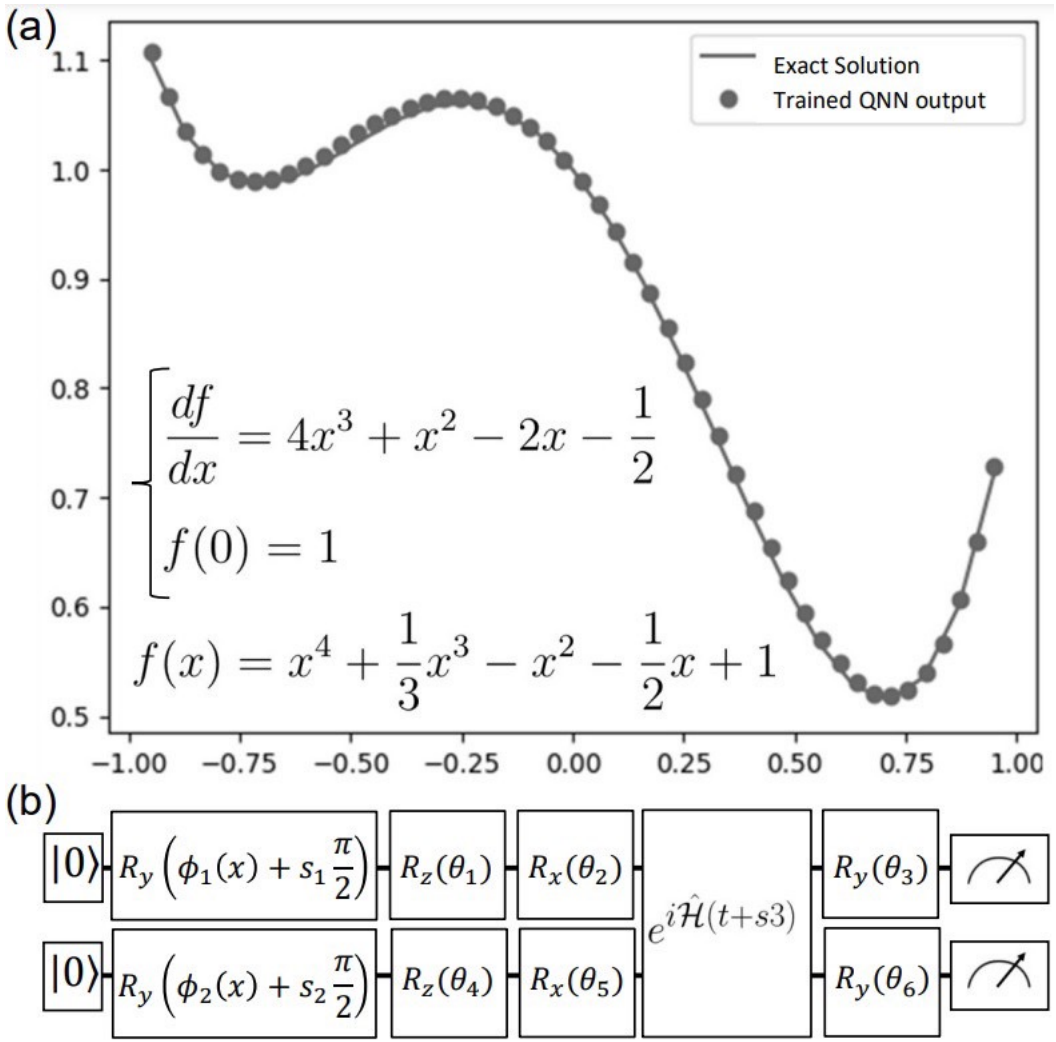
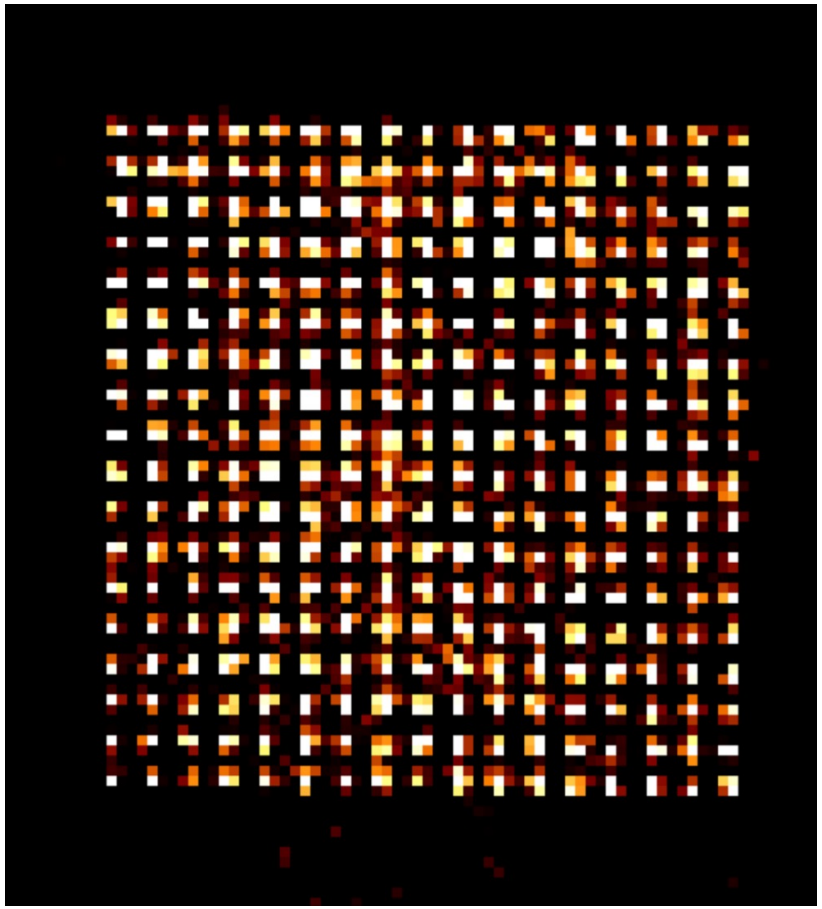
Digital-analog quantum algorithms for solving differential equations





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