Universal quantum computation and quantum error correction with ultracold atomic mixtures

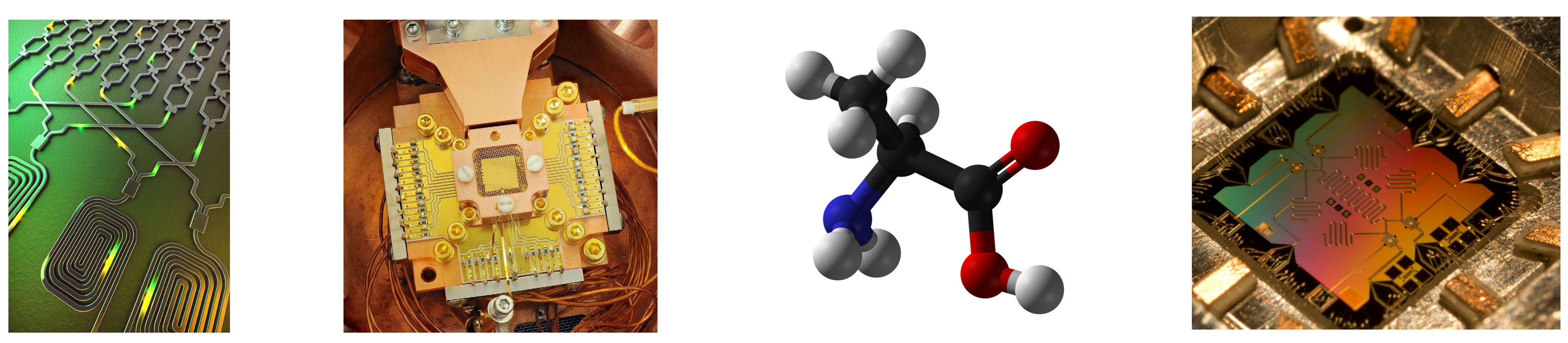
Valentin Kasper[1], Daniel González-Cuadra[1], Apoorva Hegde[2], Andy Xia[2], Alexandre Dauphin[1], Felix Huber[1], Eberhard Tiemann[3], Maciej Lewenstein[1,4], Fred Jendrzejewski[2], Philipp Hauke[5]

[1]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology,Av. Carl Friedrich Gauss 3, 08860 Barcelona, Spain
[2]Universität Heidelberg, Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany
[3]Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany
[4]ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain
[5]INO-CNR BEC Center and Department of Physics,University of Trento, Via Sommarive 14, I-38123 Trento, Italy

arXiv:2010.15923

Motivation

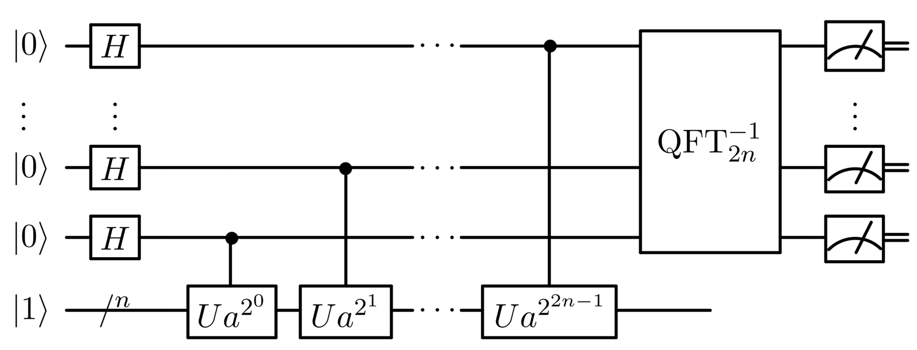
Platforms for quantum computation



photonics, ion, NMR, superconducting qubits, ultracold atoms, …

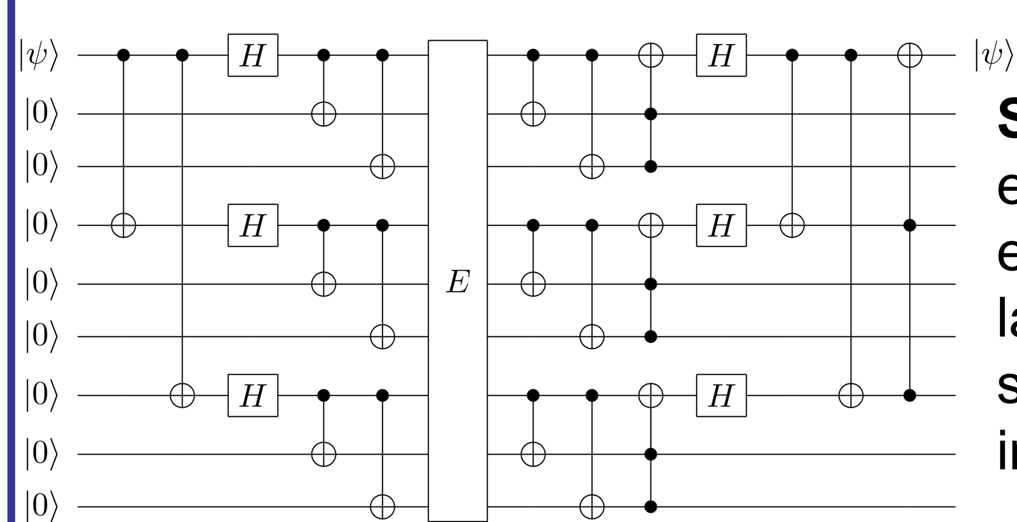
Challenges

Connectivity



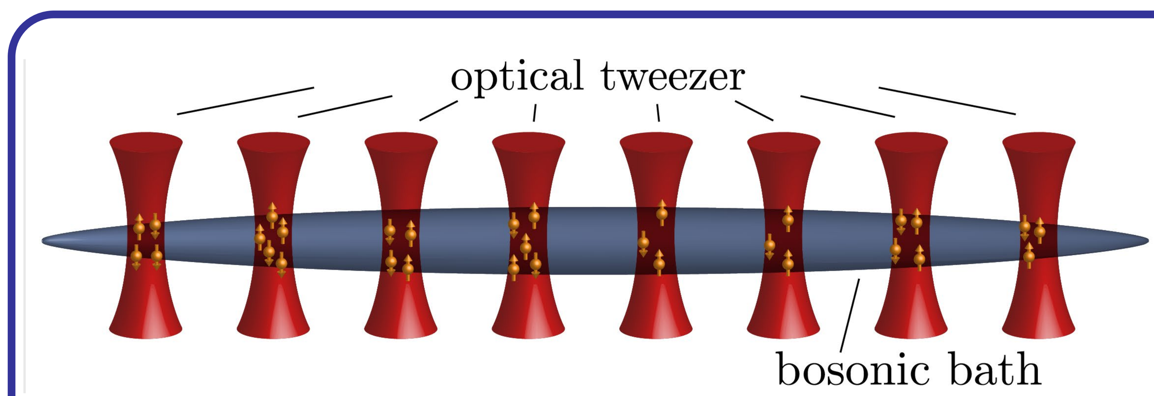
Shor's algorithm has as basic ingredient the QFT (quantum Fourier transform), which is a multi-qubit gate

Error correction



Shor's 9-qubit code employs the idea to encode a single qubit in a larger dimensional Hilbert space to protect the information against error

Experimental setup

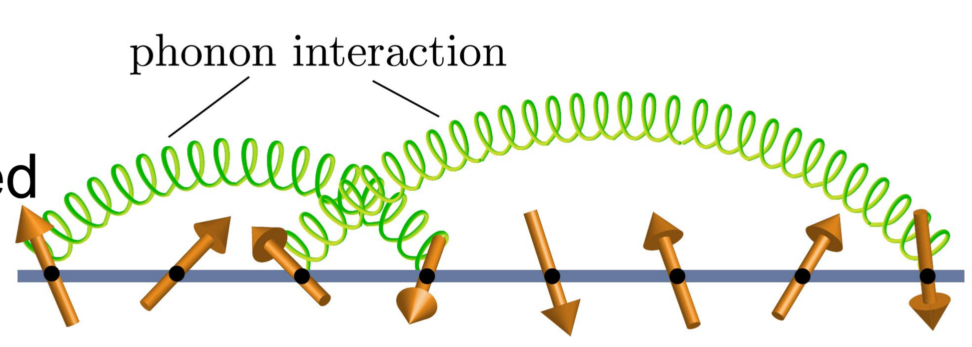


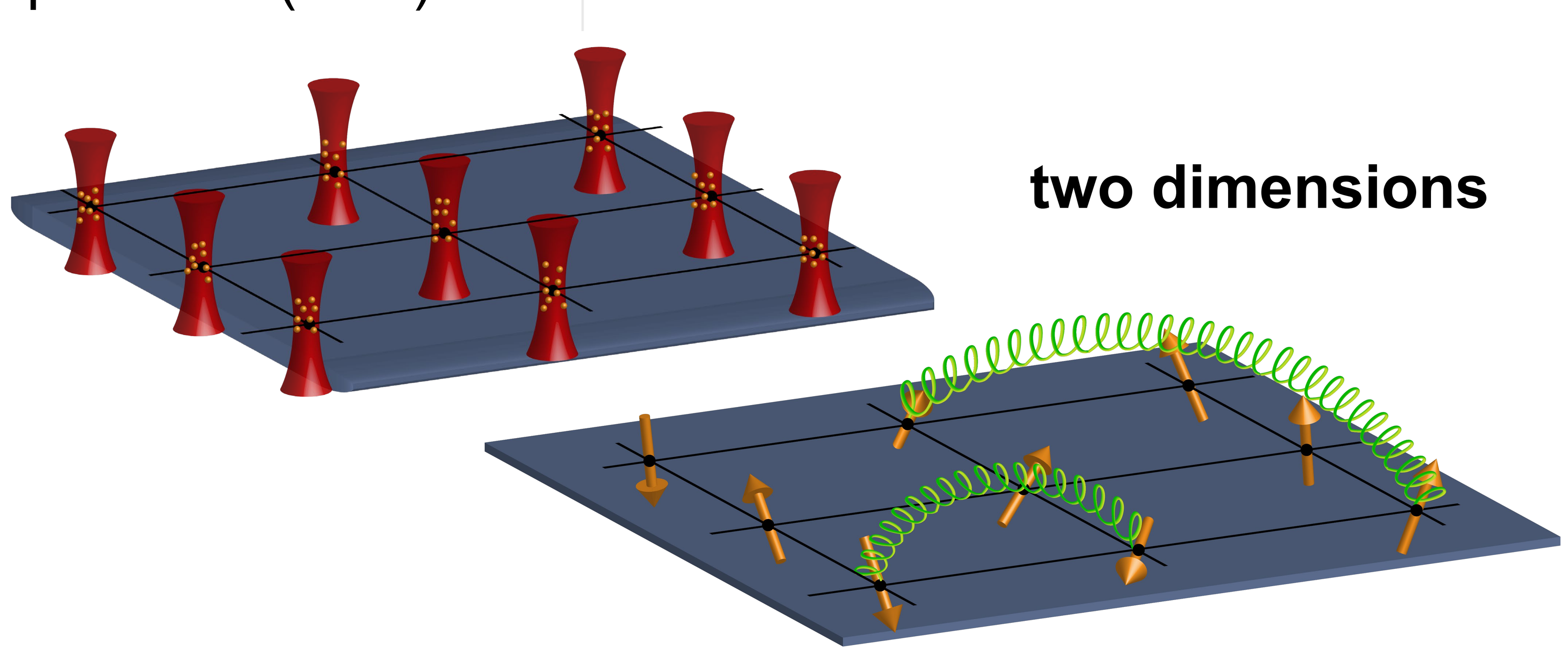
one dimension

two bosonic species

species A (yellow) trapped in tweezer

species B (blue)





two dimensions

Effective spin phonon model

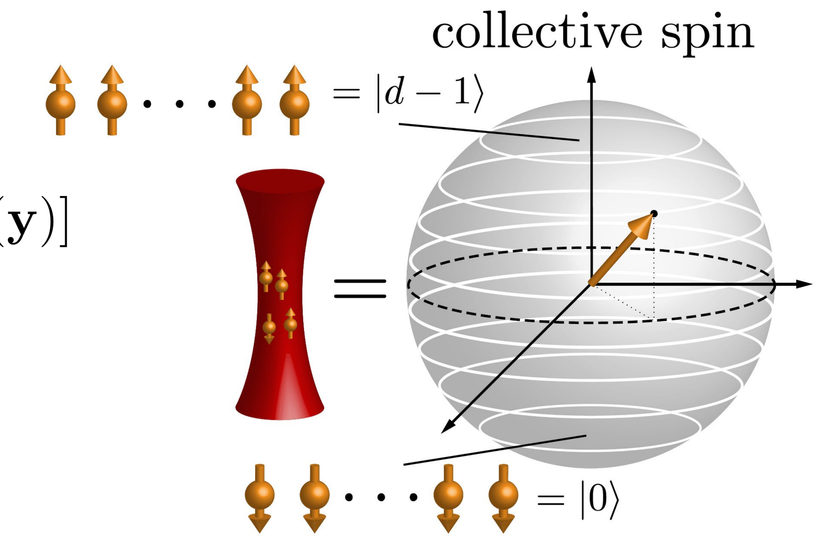
Collective spin

Schwinger representation

$$L_z(\mathbf{y}) = \frac{1}{2}[a_1^\dagger(\mathbf{y})a_1(\mathbf{y}) - a_0^\dagger(\mathbf{y})a_0(\mathbf{y})]$$

$$L_+(\mathbf{y}) = a_1^\dagger(\mathbf{y})a_0(\mathbf{y})$$

$$L_-(\mathbf{y}) = a_0^\dagger(\mathbf{y})a_1(\mathbf{y})$$

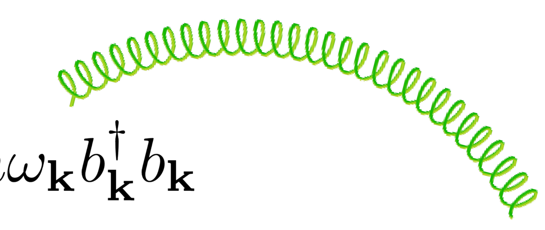


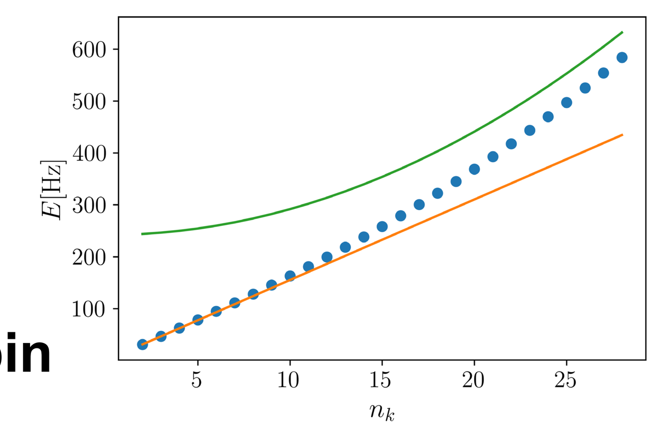
Hamiltonian

$$H_A = \sum_{\mathbf{y}} [\chi(\mathbf{y})L_z^2(\mathbf{y}) + \Delta(\mathbf{y})L_z(\mathbf{y}) + \Omega(\mathbf{y})L_x(\mathbf{y})]$$

Phonons

$$H_B = \sum_{\mathbf{k}} \hbar\omega_{\mathbf{k}} b_{\mathbf{k}}^\dagger b_{\mathbf{k}}$$

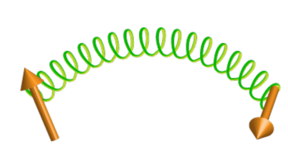




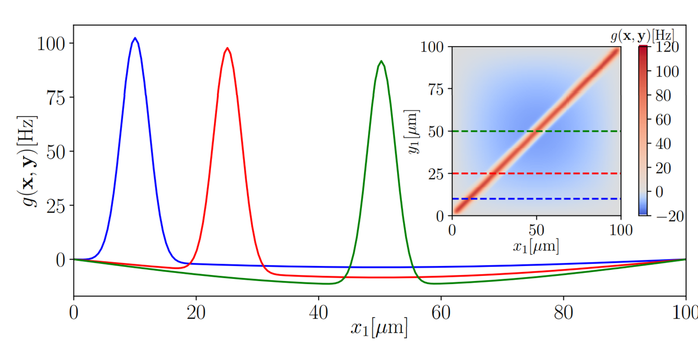
Interaction between phonons and spin

$$H_{AB} = \sum_{\mathbf{y},\mathbf{k}} [\bar{g}_{\mathbf{k}}(\mathbf{y})L(\mathbf{y}) + \delta g_{\mathbf{k}}(\mathbf{y})L_z(\mathbf{y})]\,(b_{\mathbf{k}} + h.c.)$$

Integrating out phonons

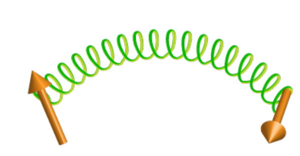


$$H_{AB} = \sum_{\mathbf{x},\mathbf{y}} g(\mathbf{x},\mathbf{y})L_z(\mathbf{x})L_z(\mathbf{y})$$



Universal QC and error correction

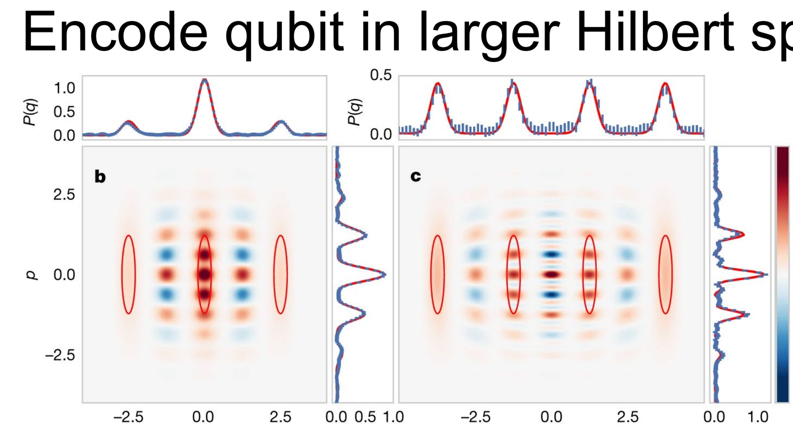
Entangling of two spin $H_{AB} = \sum_{\mathbf{x},\mathbf{y}} g(\mathbf{x},\mathbf{y})L_z(\mathbf{x})L_z(\mathbf{y})$



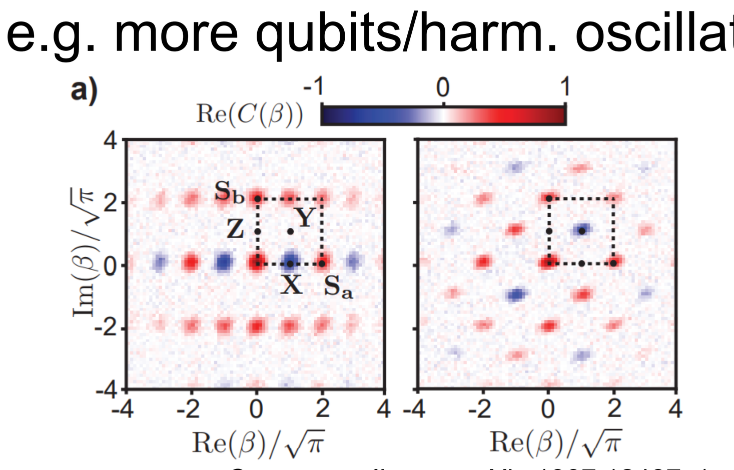
Controlled Z gate $CZ_{i,j} = \sum_{k,l=0}^{D} \omega^{kl}\, |k\rangle\langle k|_i \otimes |l\rangle\langle l|_j$

Quantum error correction

Encode qubit in larger Hilbert space e.g. more qubits/harm. oscillator



Flühmann et al. Nature 566, (2019)



Campagne-Ibarcq, arXiv:1907.12487v1

Finite GKP codes (d=16)

Generalized Pauli operators

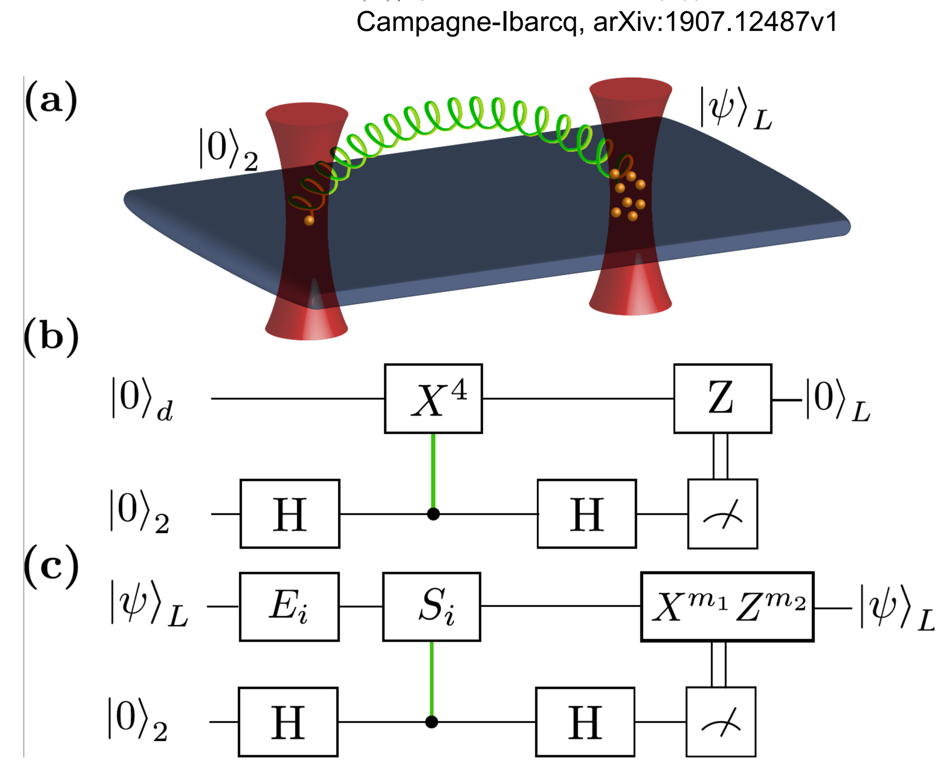
$$Z\,|k\rangle = \omega^k\,|k\rangle$$

$$X\,|k\rangle = |(k+1) \bmod d\rangle$$

Code states (eigenstates of X^6)

$$|\bar{0}\rangle = \frac{1}{\sqrt{3}}(|0\rangle + |6\rangle + |12\rangle)$$

$$|\bar{1}\rangle = \frac{1}{\sqrt{3}}(|3\rangle + |9\rangle + |15\rangle)$$



Generalitat de Catalunya · Universitat Politècnica de Catalunya BarcelonaTech · Fundació Privada CELLEX · Fundació Privada MIR-PUIG · Excelencia Severo Ochoa 2016-2019 · Gobierno de España, Ministerio de Economía y Competitividad · Unió Europea · ICREA · BIST Barcelona Institute of Science and Technology