QUANTUM TECHNOLOGIES FOR HIGH ENERGY PHYSICS

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DESY - Hamburg 26/11/19

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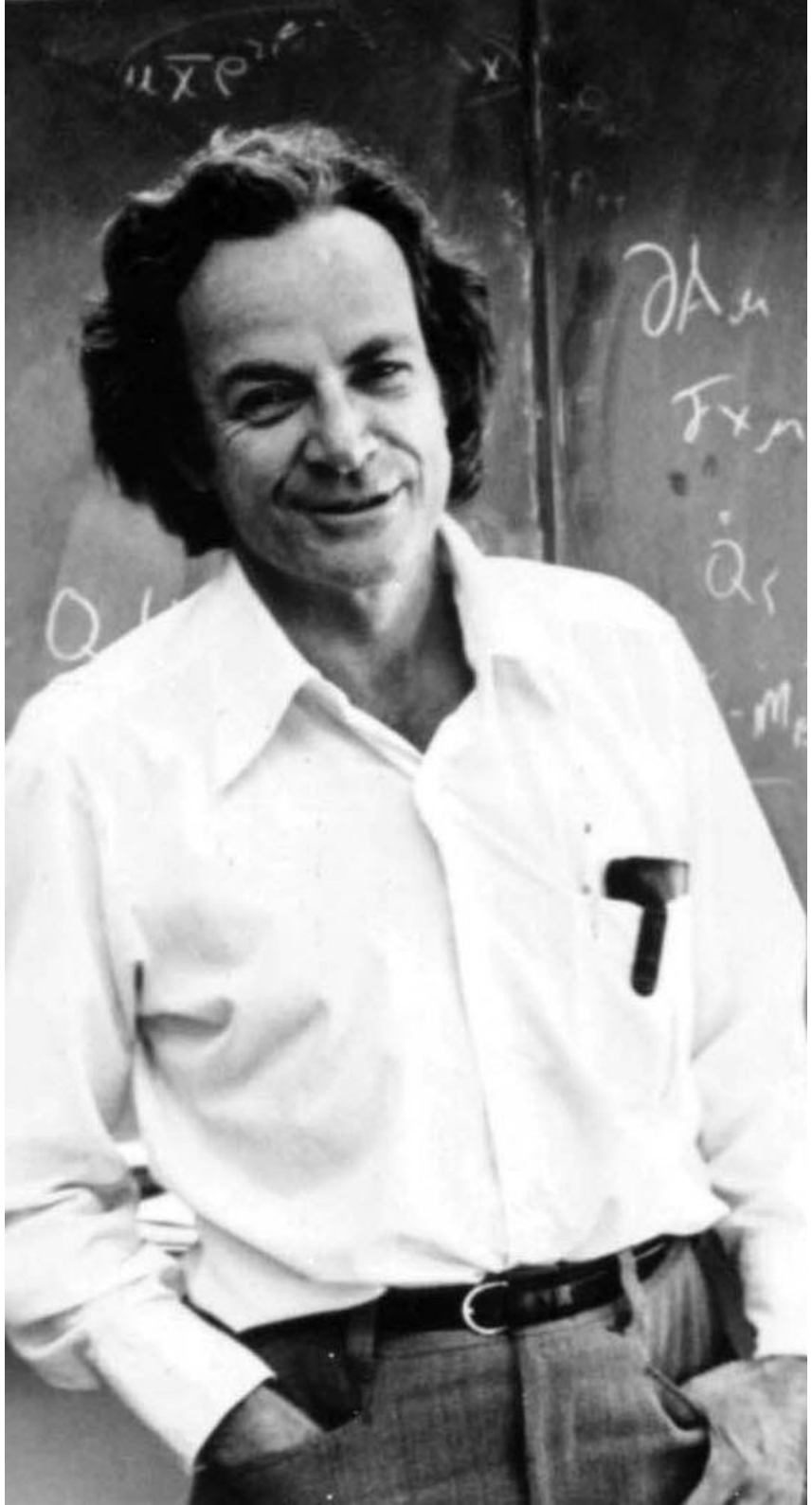
"Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."



RICHARD FEYNMAN (1982)

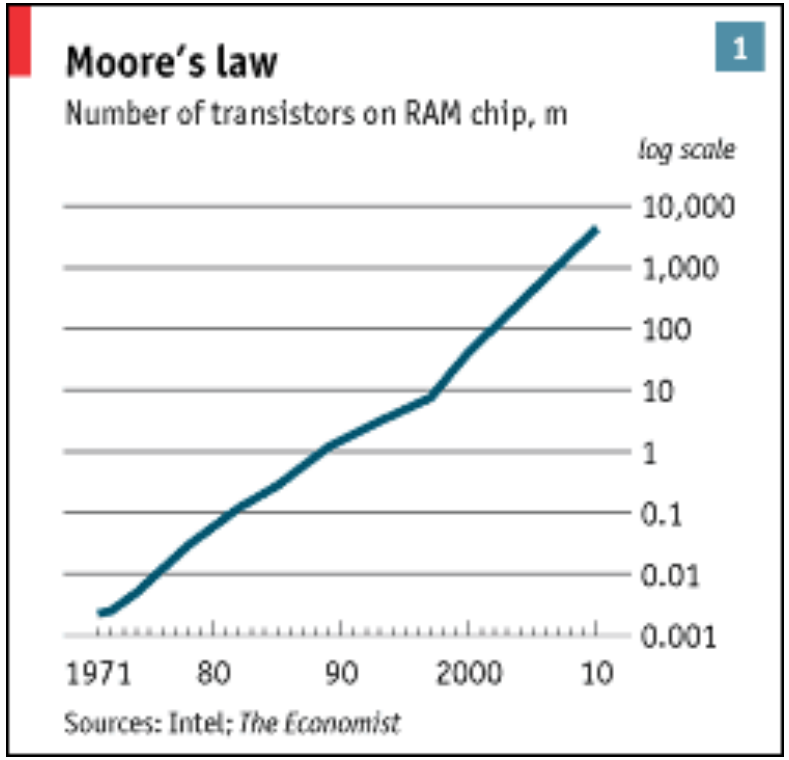
More generally, QIT studies what happens when one tries to

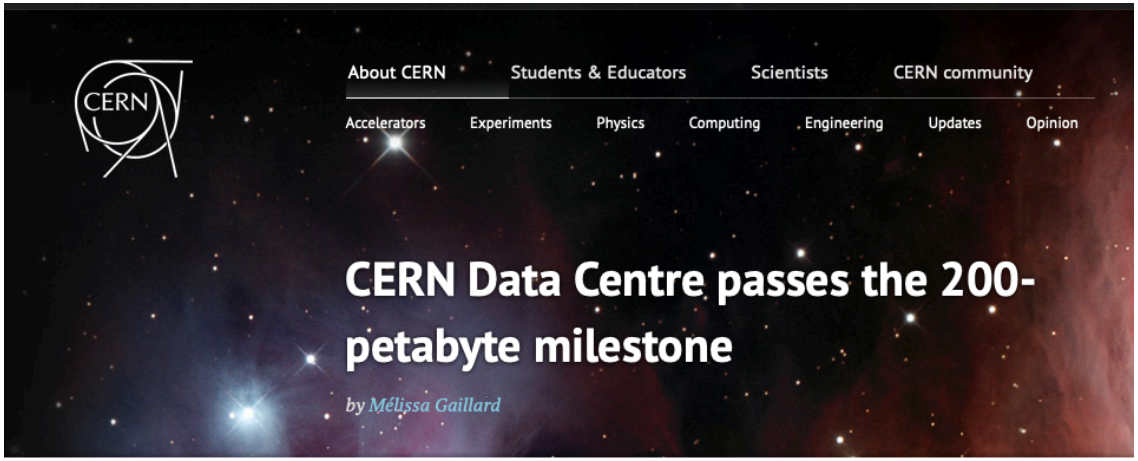
PROCESS INFORMATION VIA QUANTUM SYSTEMS

QUANTUM SCALE

Touching the quantum limit

MINIATURIZATION & BIG DATA





Posted by Stefania Pandolfi on 6 Jul 2017. Last updated 7 Jul 2017, 11.18.
Voir en français

Quantum effects will have to be taken into account,

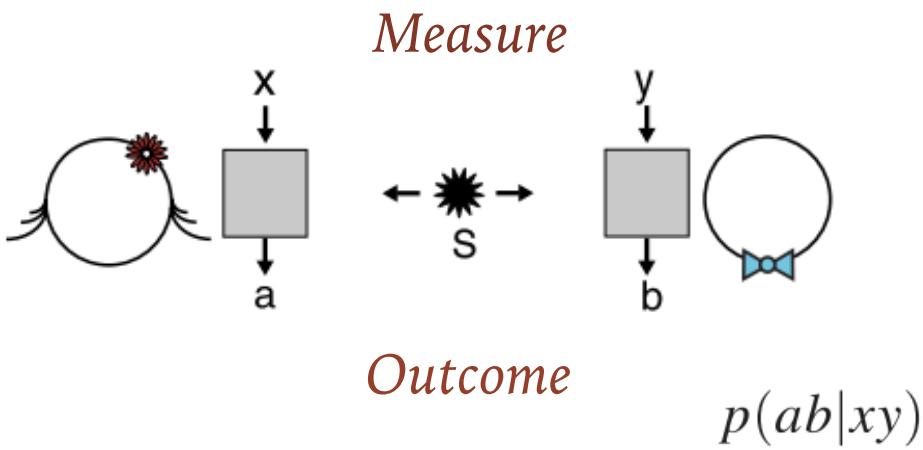
better exploit them!

HIGHLY CORRELATED STATES

Entanglement

QUANTUM VS CLASSICAL CORRELATIONS

Clauser-Horne-Shimony-Holt (CHSH) inequality



Locality (no influence between space-time separate regions)

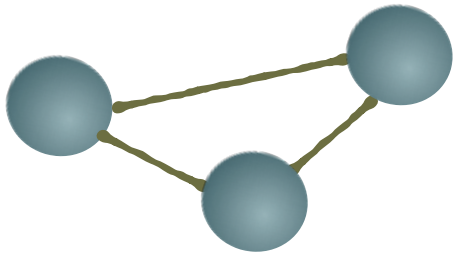
$$S = \langle a_0 b_0 \rangle + \langle a_0 b_1 \rangle + \langle a_1 b_0 \rangle - \langle a_1 b_1 \rangle \leq 2$$

Bell state (singlet):

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \qquad S = 2\sqrt{2} > 2$$

N. Brunner et al. RMP 2014

INEFFICIENT COMPRESSIBILITY OF ENTANGLEMENT



$$|\psi\rangle = \sum \psi_{\alpha_1\alpha_2\alpha_3}|\alpha_1\alpha_2\alpha_3\rangle$$

For spins 1/2, if

$$\psi_{\alpha_1\alpha_2\alpha_3} = \frac{1}{2\sqrt{2}} \quad \Rightarrow \quad |\psi\rangle = \left(\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\right)^{\otimes 3} = \left(\sum \psi_\alpha|\alpha\rangle\right)^{\otimes 3}$$

8 coefficients

Separable state
6 coefficients!

In general,

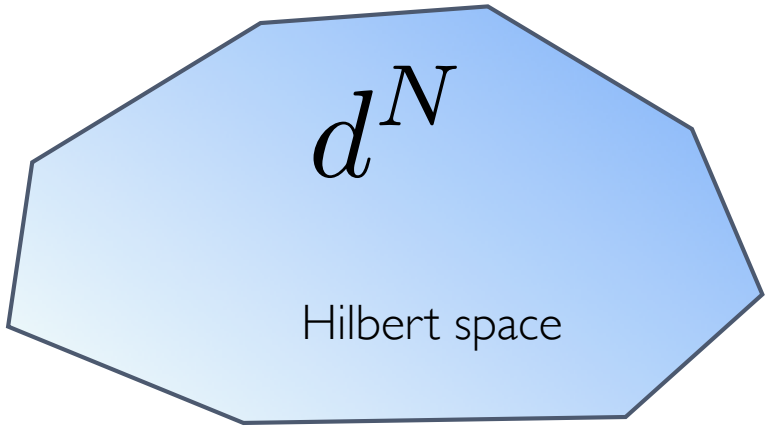
d^N coefficients

$$|\psi\rangle = \sum \psi_{\alpha_1\alpha_2\ldots\alpha_N}|\alpha_1\alpha_2\ldots\alpha_3\rangle$$

$$|\psi^{MF}\rangle = \left(\sum \psi_\alpha|\alpha\rangle\right)^{\otimes N}$$

dN coefficients

ENTANGLED STATES



1. *Live in an exponentially large Hilbert space*

2. *Are highly correlated*

3. *Cannot be compressed efficiently*

4. *Cannot be prepared by LOCC*

ENTANGLEMENT

HEISENBERG

THEORY

LIMIT

QUANTUM

QUANTUM CHANNEL

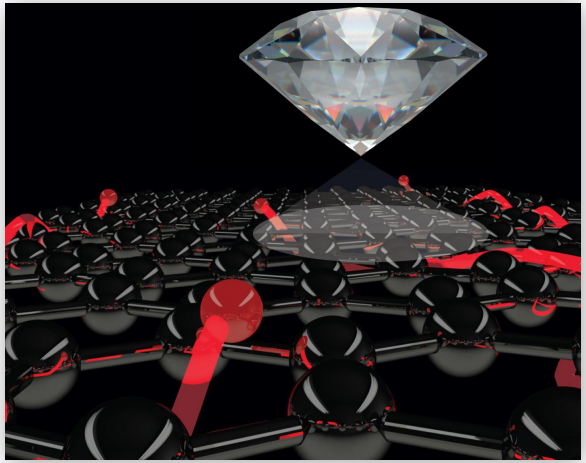
QUANTUM COMPLEXITY

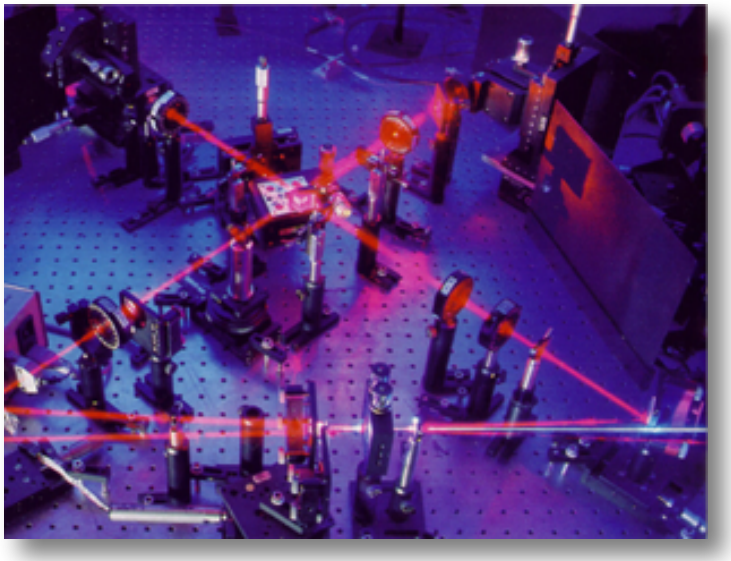
ADVANTAGE?

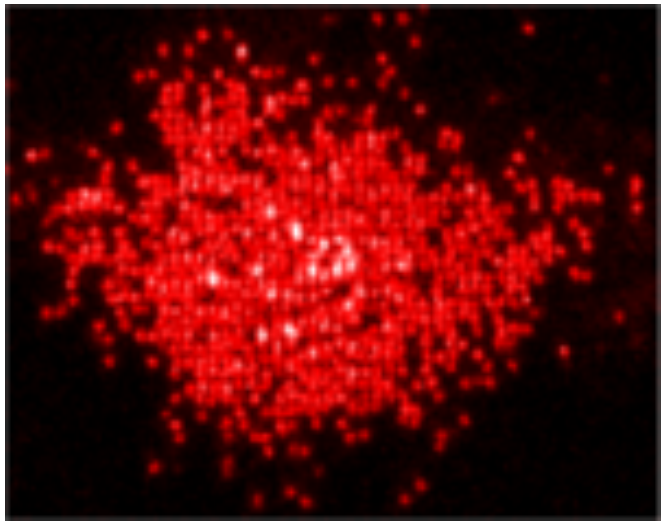
CAPACITY

CLASSES

QUANTUM SCIENCE

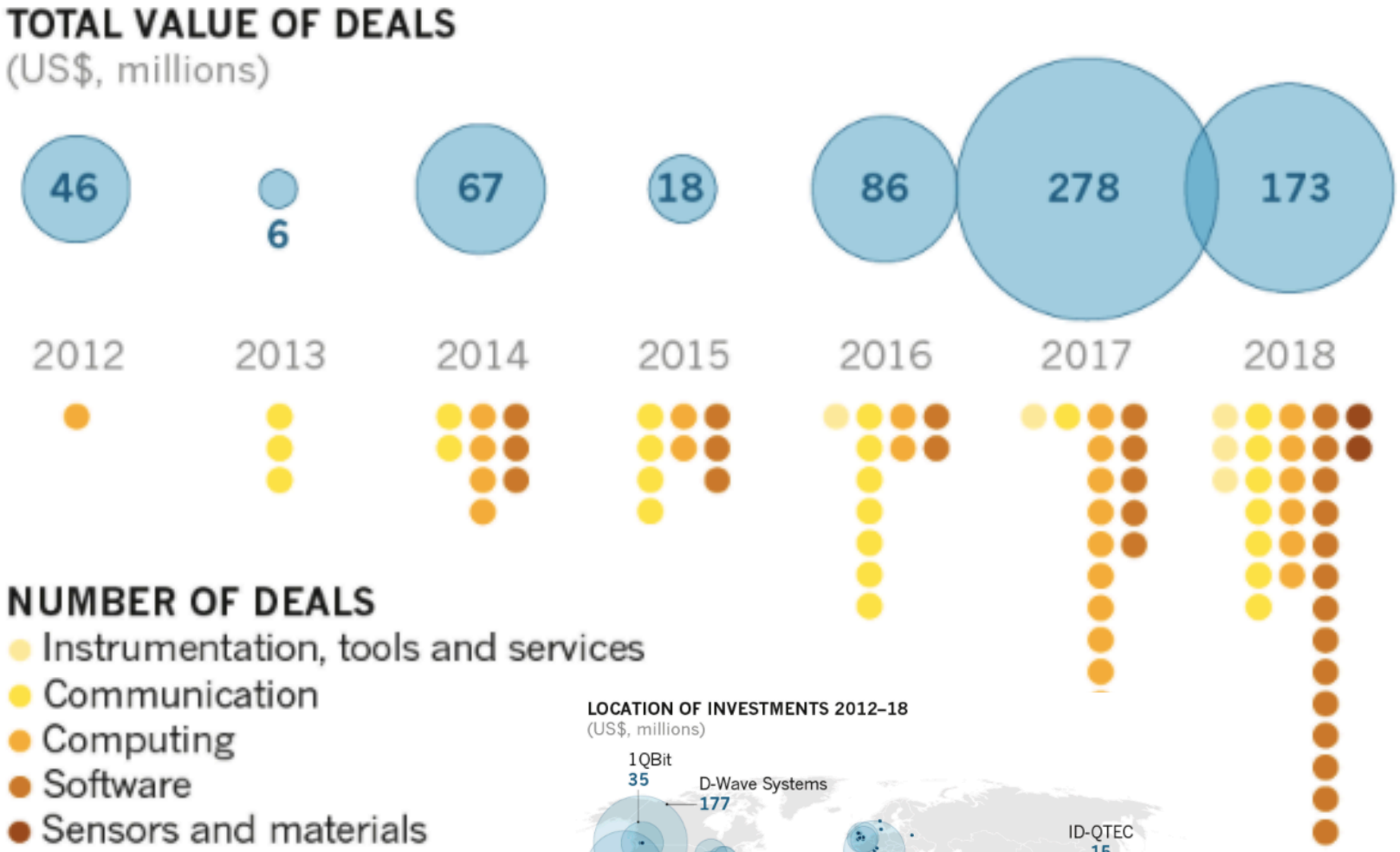






QUANTUM TECHNOLOGIES

PRIVATE INVESTMENTS



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*Includes unspecified contribution from the Australian government alongside private investors.

Nature news October 2019

EU QUANTUM INITIATIVES

www.qt.eu

www.quantera.eu

Quantum Flagship in a nutshell.

04
140
Research and Innovation Actions (RIA) proposals submitted in response of the first Quantum Flagship call

01
1b €
Quantum Technology will be funded with at least one billion Euro by the European Commission.

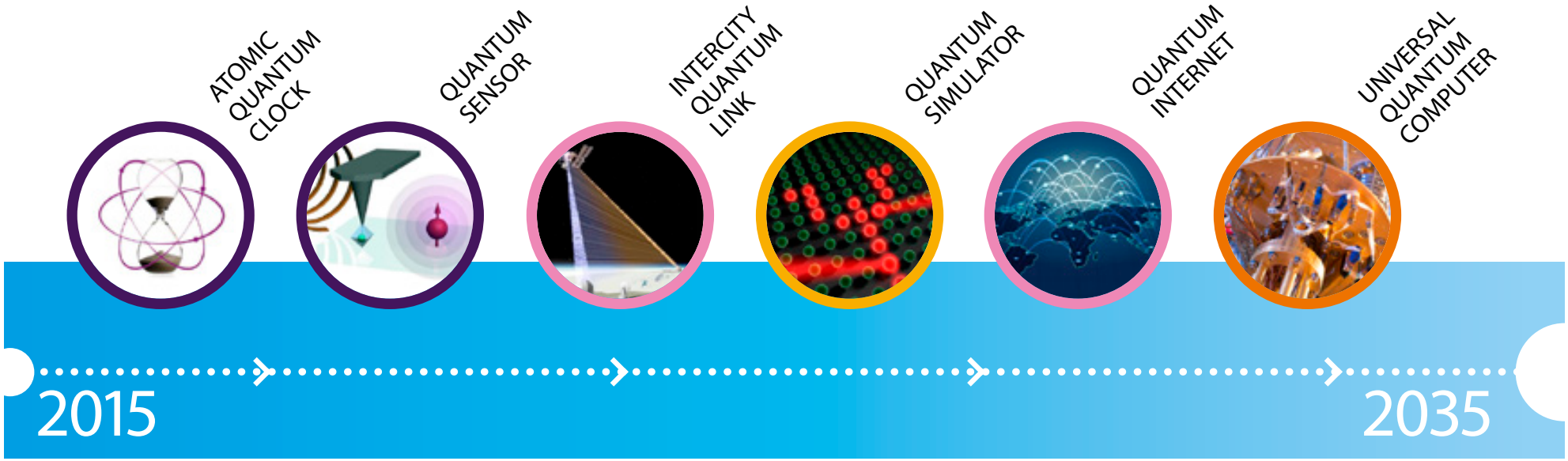
02
10+ yrs
Flagship's timescale

03
5000+
researchers residing in all EU and associated countries involved

QuantERA ERA-NET Cofund in Quantum Technologies

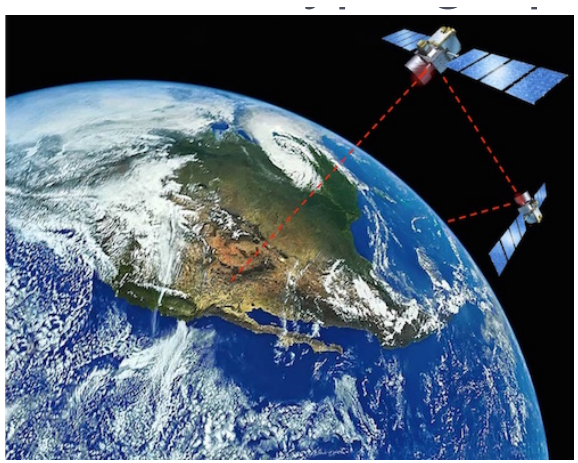
2ND QUANTUM REVOLUTION

Quantum Technologies Timeline

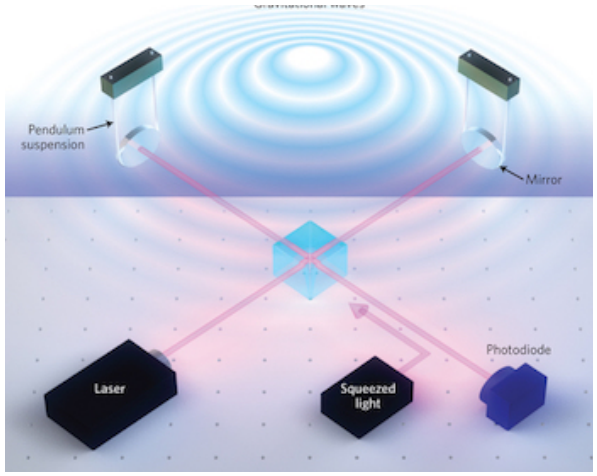


Quantum Manifesto (2015)

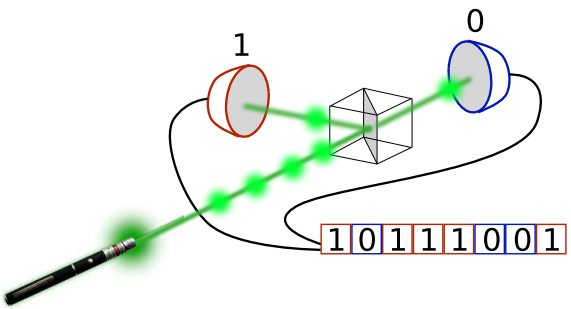
QUANTUM COMMUNICATIONS



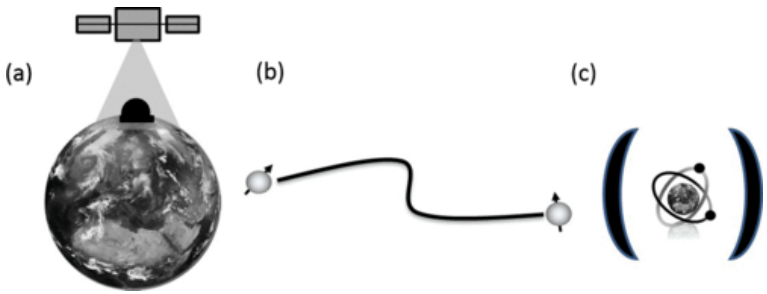
Quantum cryptography



Quantum metrology

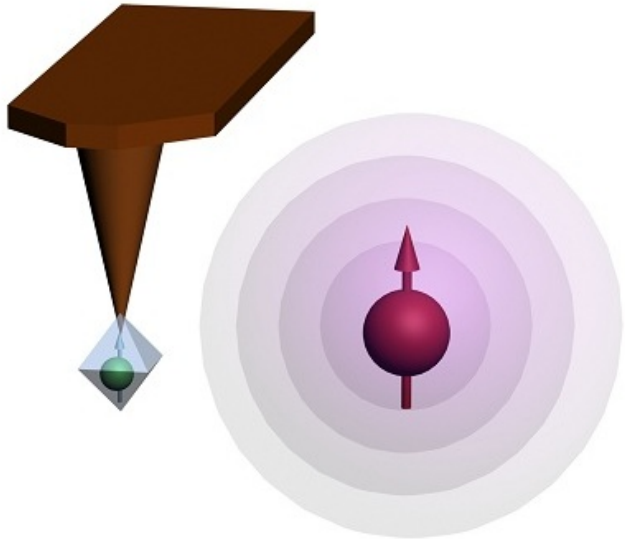


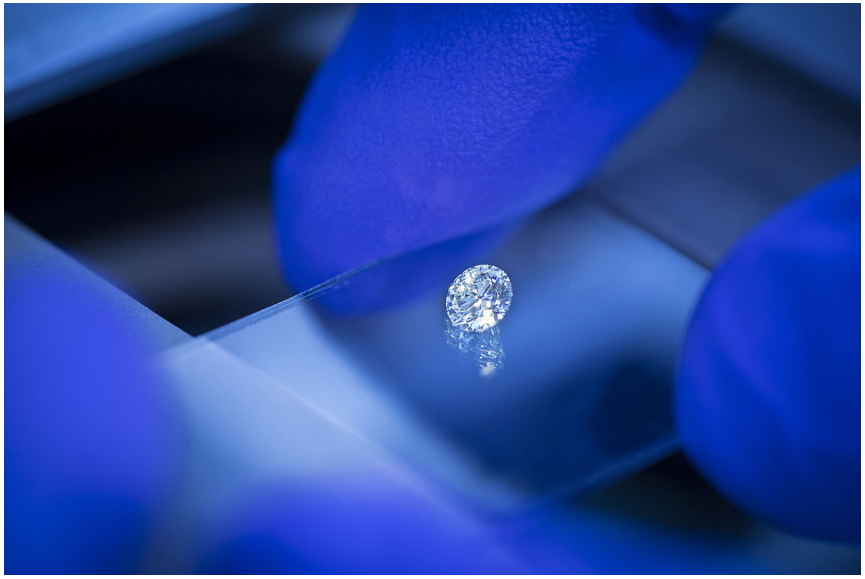
Quantum random numbers



Quantum channels

QUANTUM SENSING





credits: F. Jelzko IQST

Quantum sensing is typically used to describe:

(I) Use of a quantum object to measure a physical quantity (classical or quantum).

(II) Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity.

(III) Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.

Spin qubits, NV-centres in diamonds, trapped ions, flux qubits…

Degen et al. RMP 2017

HIGH-PRECISION NANOSCALE TEMPERATURE SENSING

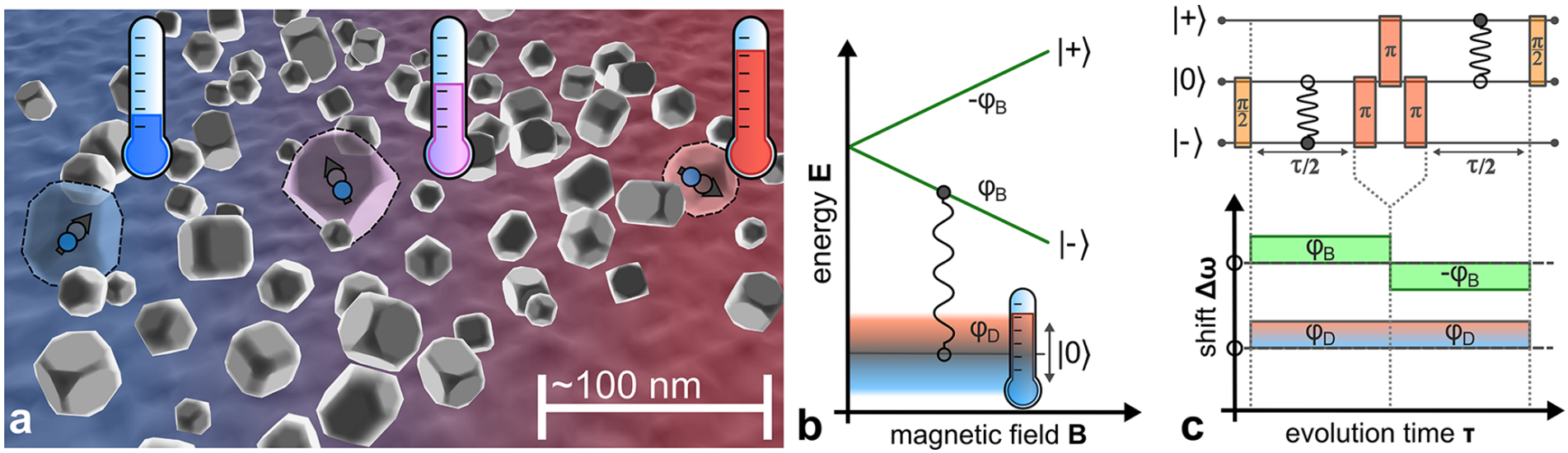
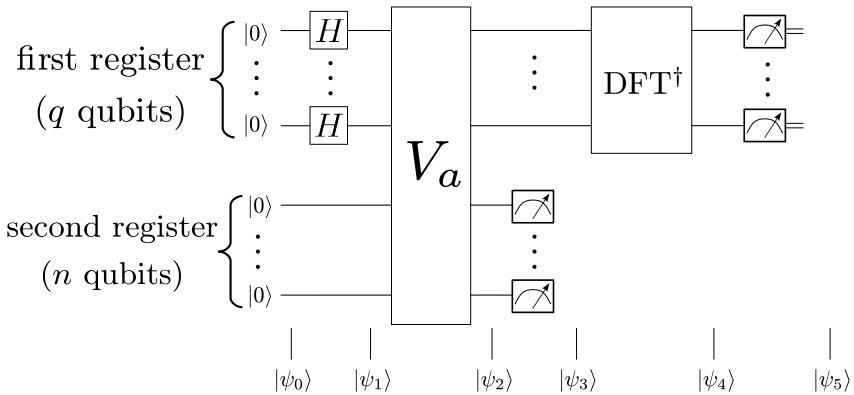


Figure 1. NV thermometer operation scheme. (a) Nanodiamonds containing single NV centers can serve as distributed probe temperature sensors. (b) Electron spin energy levels are mainly influenced by applied axial magnetic fields B_z and the temperature T. B_z splits the levels $|\pm\rangle$ and the temperature shifts level $|0\rangle$ with respect to $|\pm\rangle$. During free evolution the spin states acquire phases φ_D, φ_B, and $-\varphi_B$. The initial superposition state $|0\rangle+|-\rangle$ of our excitation sequence is depicted. (c) D-Ramsey sequence to cancel the magnetic signal. The upper part shows mw pulses for spin control and the resulting spin coherences. The lower part shows phase cancellation and accumulation for magnetic (B) and temperature (T) contributions.

"Accuracies down to 1 mK for nanocrystal sizes and therefore length scales of a few tens of nanometers. This combination of precision and position resolution, [..] should allow the measurement of the heat produced by chemical interactions involving a few or single molecules even in heterogeneous environments like cells.

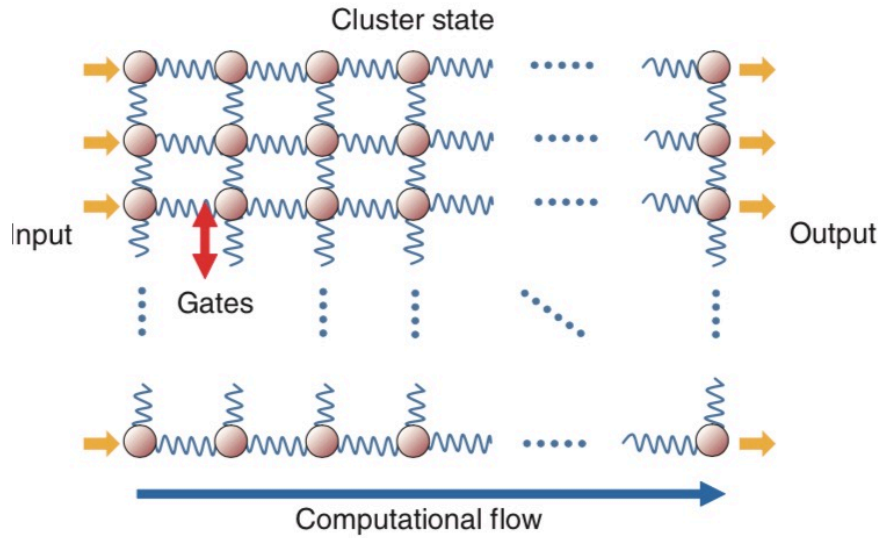
P. Neumann et al. Nano letters (2013)

QUANTUM COMPUTING

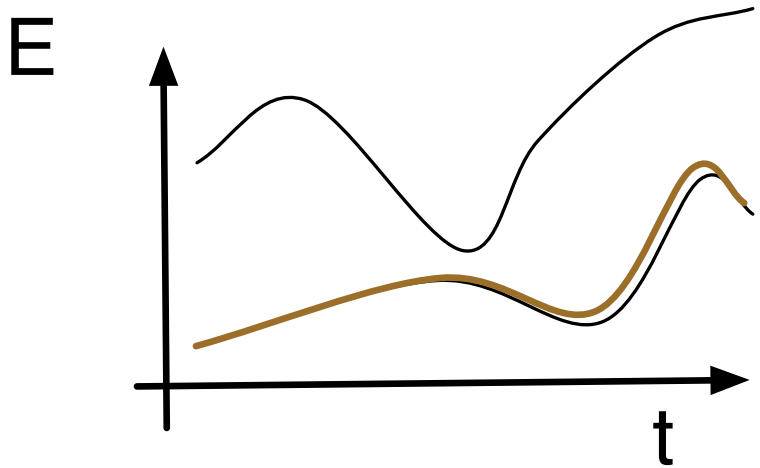


$$V_a : |x\rangle|y\rangle \rightarrow |x\rangle|y \oplus a^x \mod N\rangle$$

Circuit model

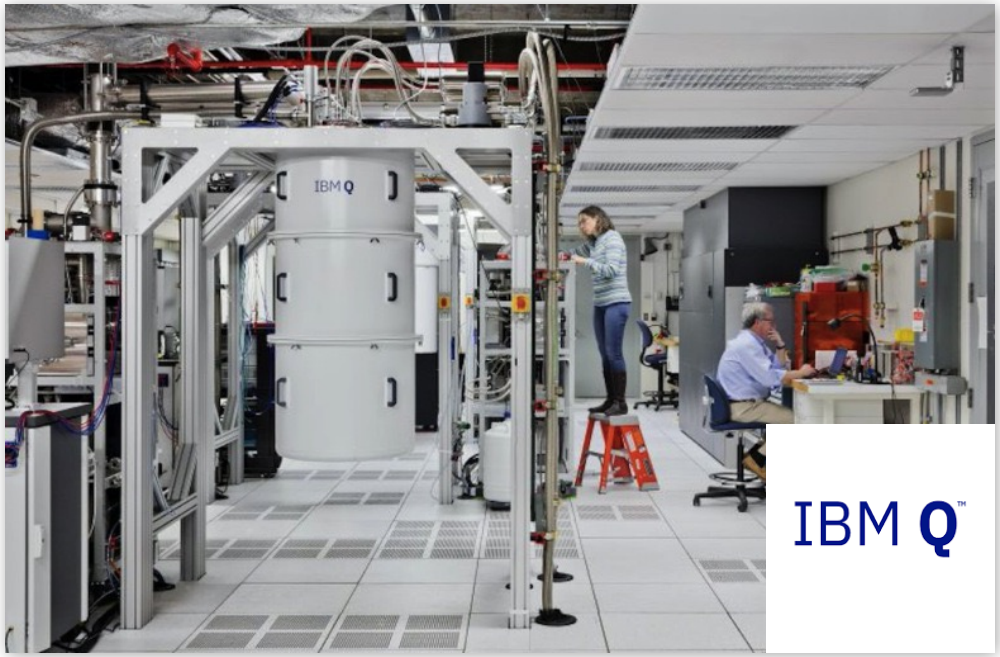


One-way



Adiabatic - Quantum Annealing

QUANTUM COMPUTERS



Google

rigetti

IBM Q™

QUANTUM COMPUTERS AND SIMULATORS

RESEARCH ARTICLES

Universal Quantum Simulators

Seth Lloyd

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.

Table 1. The asymptotic scaling of the number of quantum gates needed to simulate scattering in the strong-coupling regime in $d = 1, 2$ spatial dimensions is polynomial in p (the momentum of the incoming pair of particles), $\lambda_c - \lambda_0$ (the distance from the phase transition), and n_{out} (the maximum kinematically allowed number of outgoing particles). The notation $f(n) = \tilde{O}(g(n))$ means $f(n) = O(g(n) \log^c(n))$ for some constant c.

	$\lambda_c - \lambda_0$	p	n_{out}
$d = 1$	$\left(\frac{1}{\lambda_c - \lambda_0}\right)^{9+o(1)}$	$p^{4+o(1)}$	$\tilde{O}(n_{out}^5)$
$d = 2$	$\left(\frac{1}{\lambda_c - \lambda_0}\right)^{6.3+o(1)}$	$p^{6+o(1)}$	$\tilde{O}(n_{out}^{7.128})$

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1*] Keith S. M. Lee,[2] John Preskill[3]

Quantum field theory reconciles quantum mechanics and special relativity, and plays a central role in many areas of physics. We developed a quantum algorithm to compute relativistic scattering probabilities in a massive quantum field theory with quartic self-interactions (ϕ^4 theory) in spacetime of four and fewer dimensions. Its run time is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. In the strong-coupling and high-precision regimes, our quantum algorithm achieves exponential speedup over the fastest known classical algorithm.

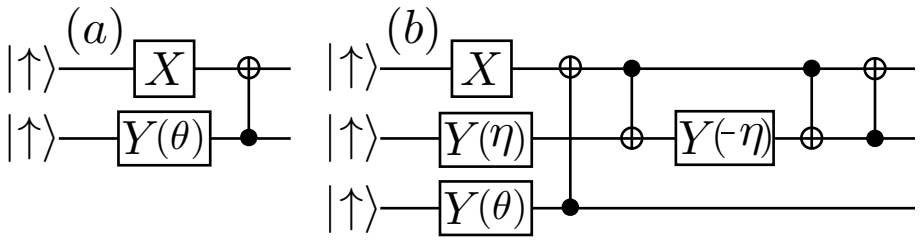
S.P. Jordan et al., Science (2012)

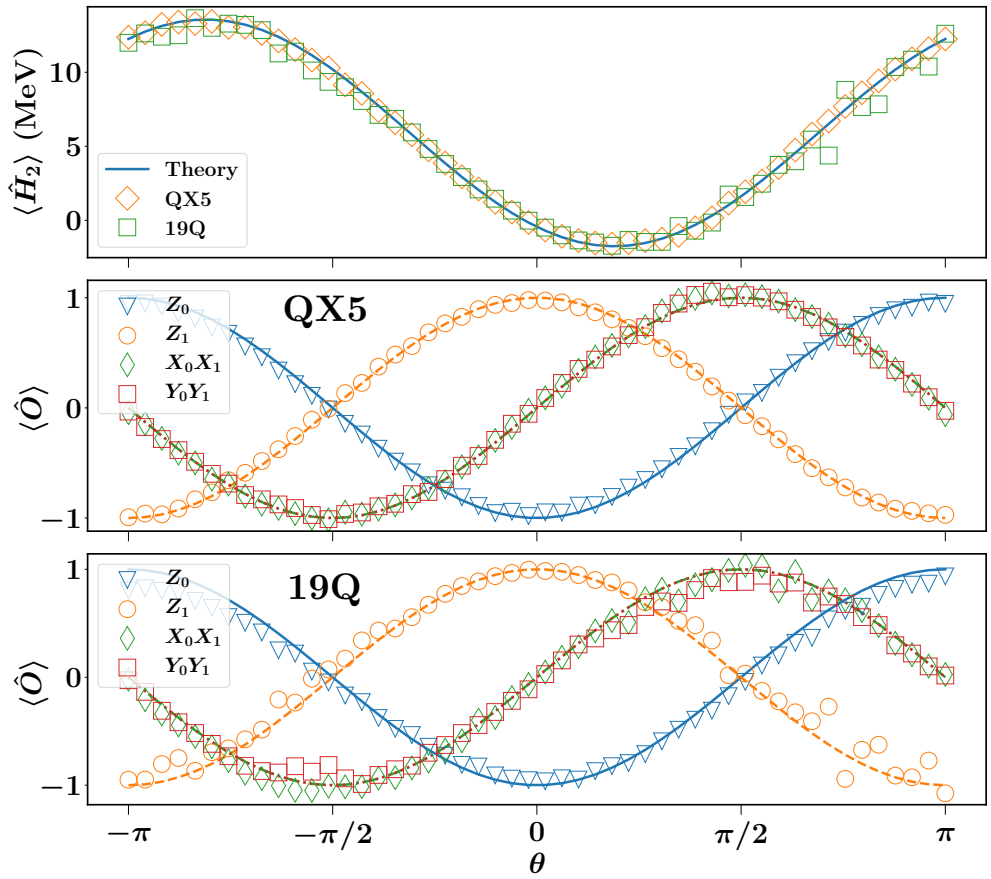
CLOUD QUANTUM COMPUTING OF AN ATOMIC NUCLEI

$$H_N = \sum_{n,n'=0}^{N-1} \langle n'|(T+V)|n\rangle a^\dagger_{n'} a_n$$

$$H_2 = 5.906709I + 0.218291Z_0 - 6.125Z_1 - 2.143304\left(X_0X_1 + Y_0Y_1\right),$$

Computation of the deuteron ground state energy via quantum variational eigensolver algorithm





E.F. Dumitresku PRL (2018)

Quantum supremacy using a programmable superconducting processor

Google, Nature 2019

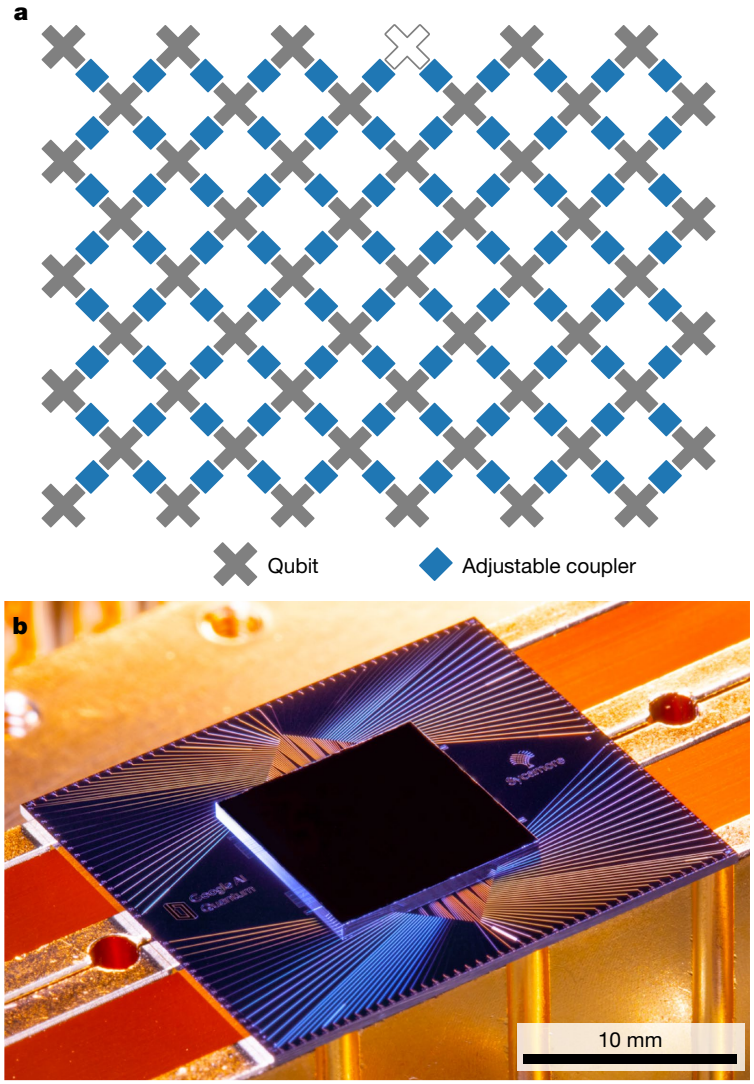
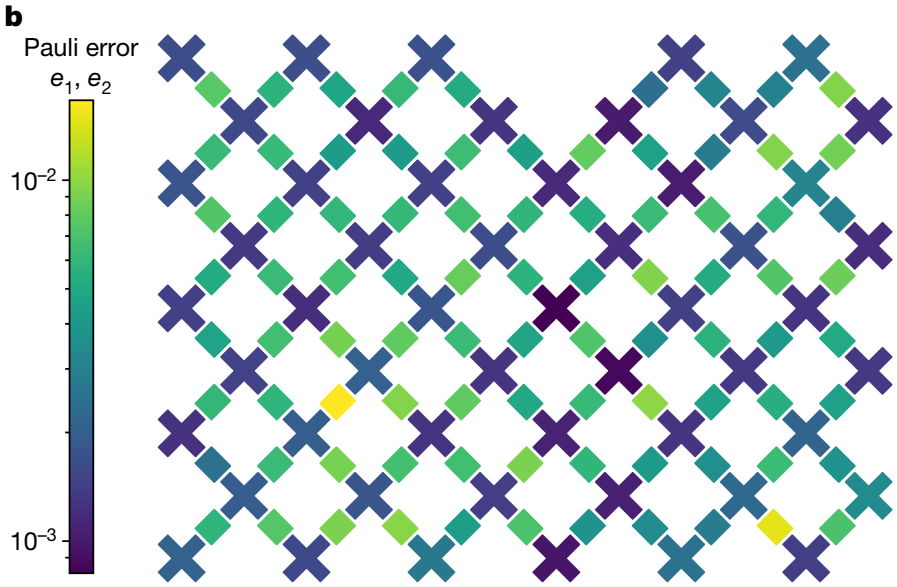


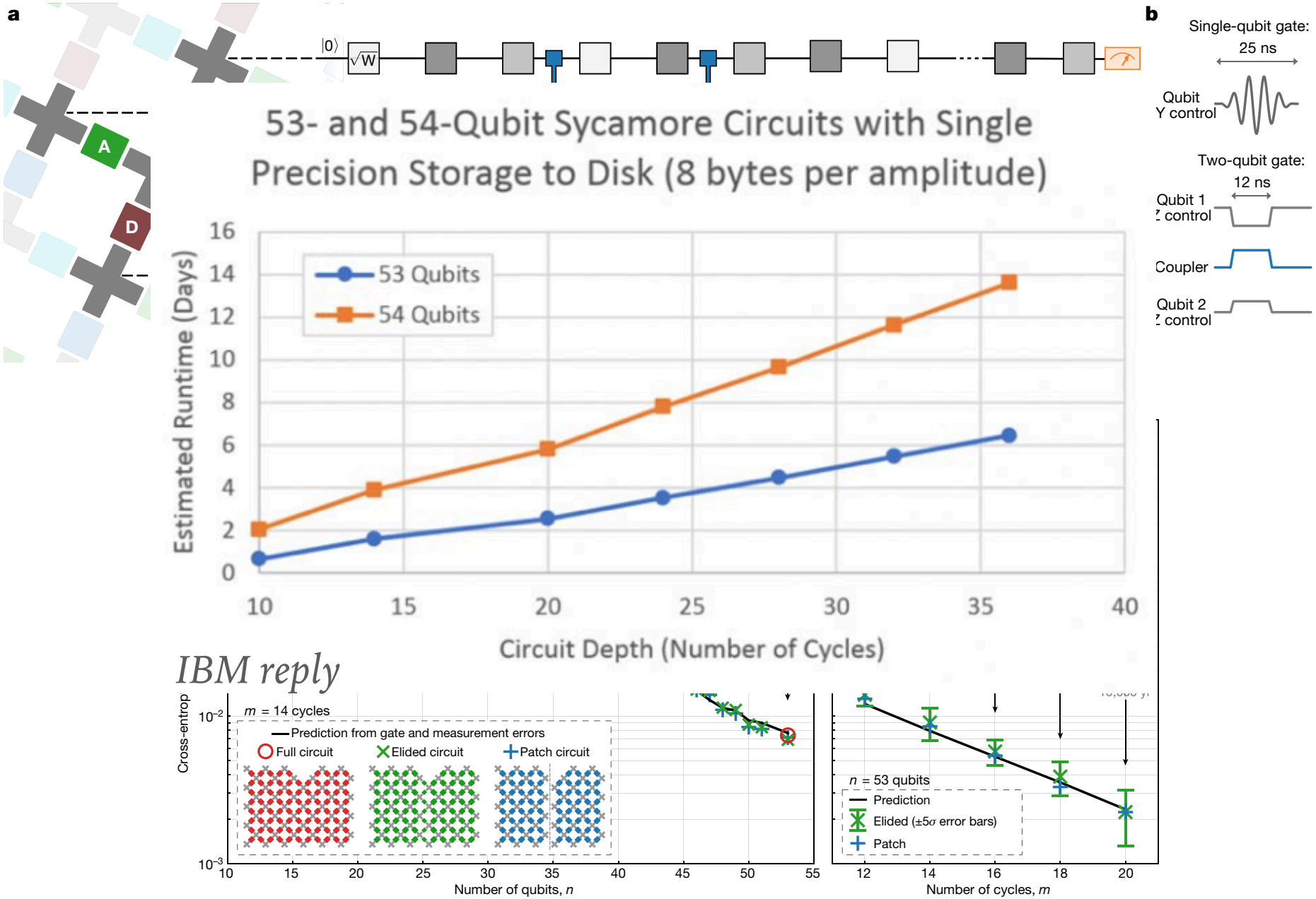
Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Pauli and measurement errors

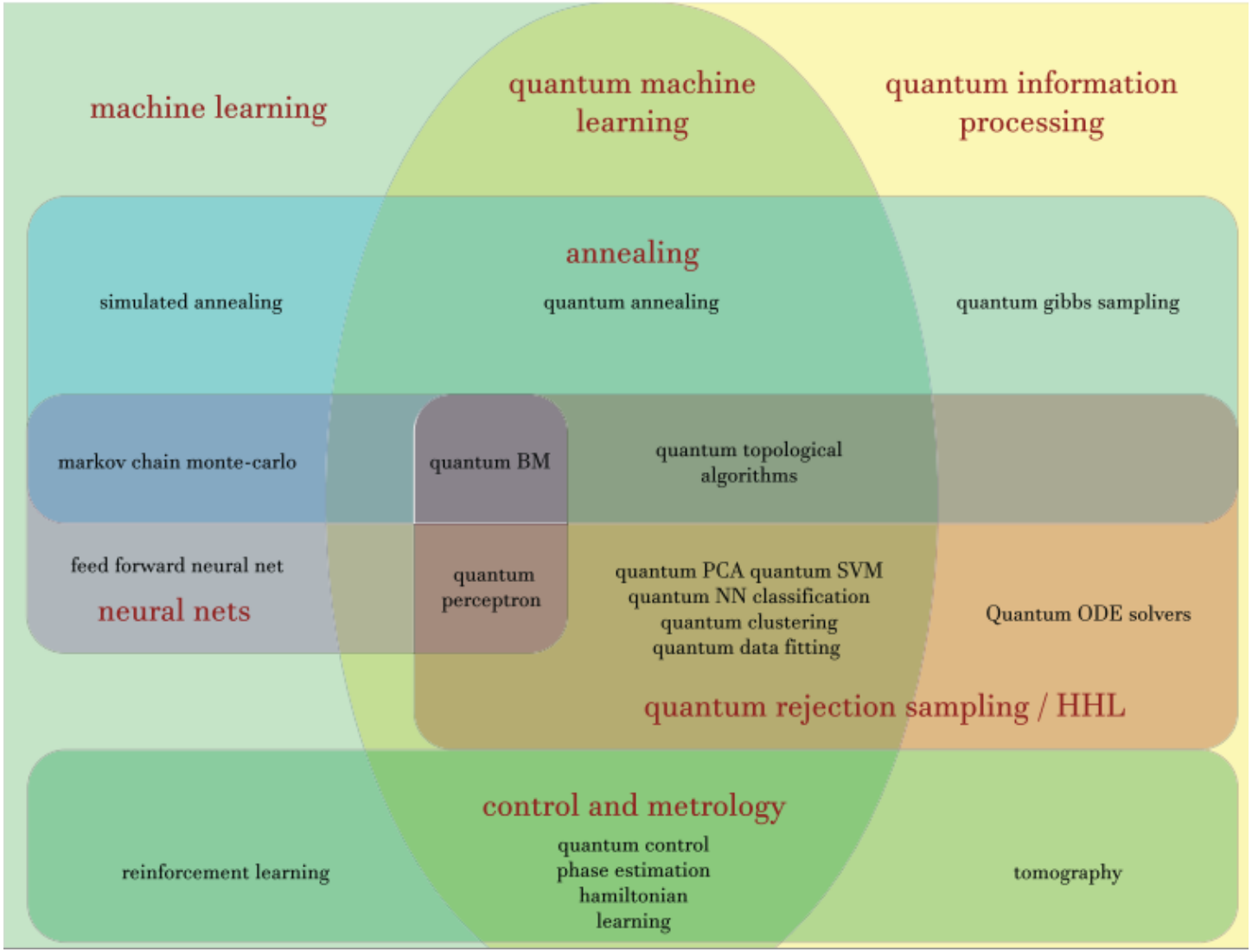
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



RANDOM CIRCUIT SAMPLING



QUANTUM MACHINE LEARNING



J. Biamonte et al. Nature (2017)

QUANTUM ALGORITHMS FOR BIG DATA

Speed up

Grover like	*SQRT(N)*
Shor algorithm (QFT)	*Exponential*

Tasks

Solving sets of linear equations $Ax=b$

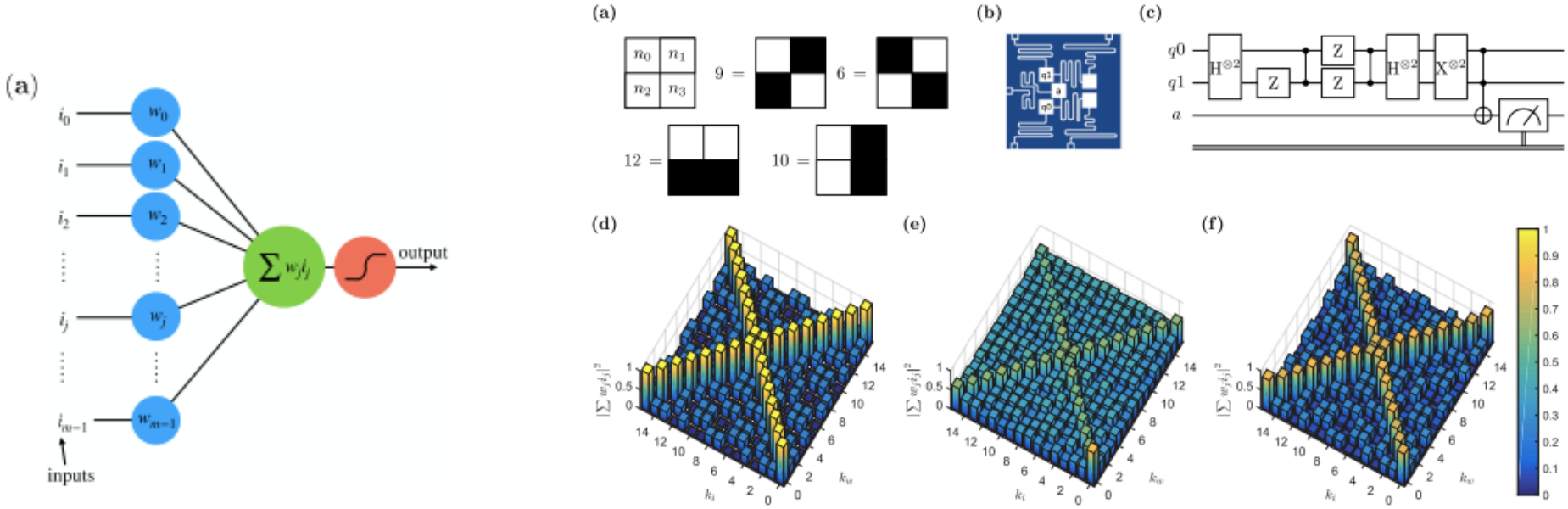
Find a concise function that approximates the data to be fitted and bound the approximation error

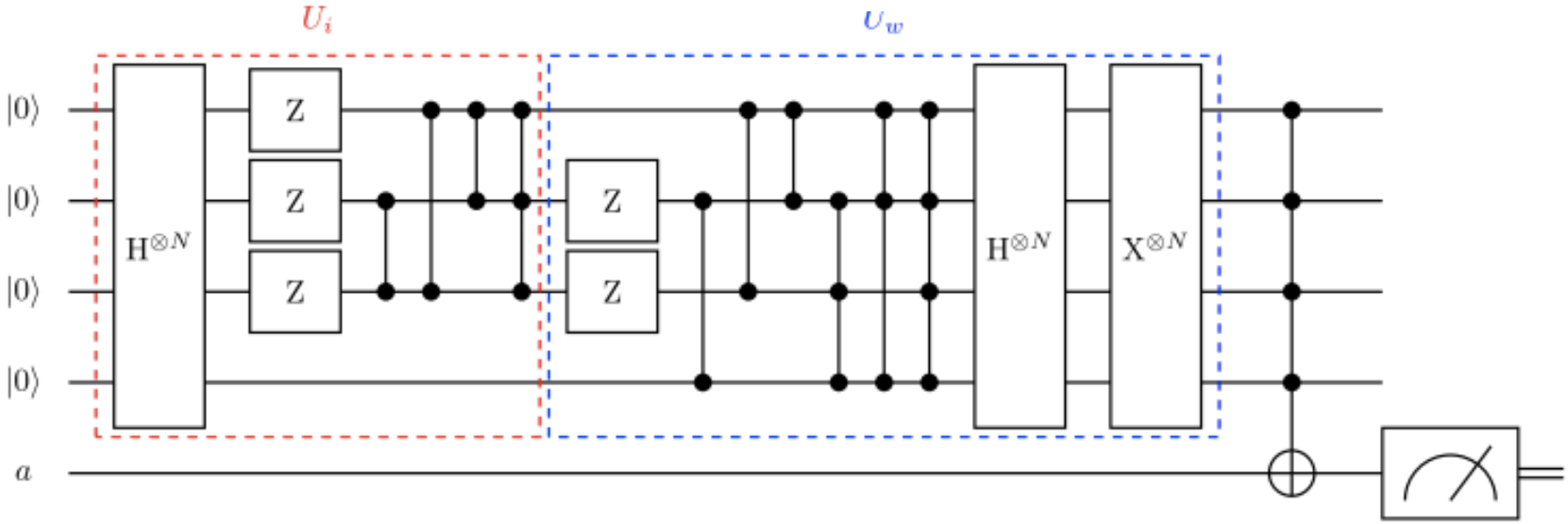
Support vector machine

Cluster assignment and finding

…

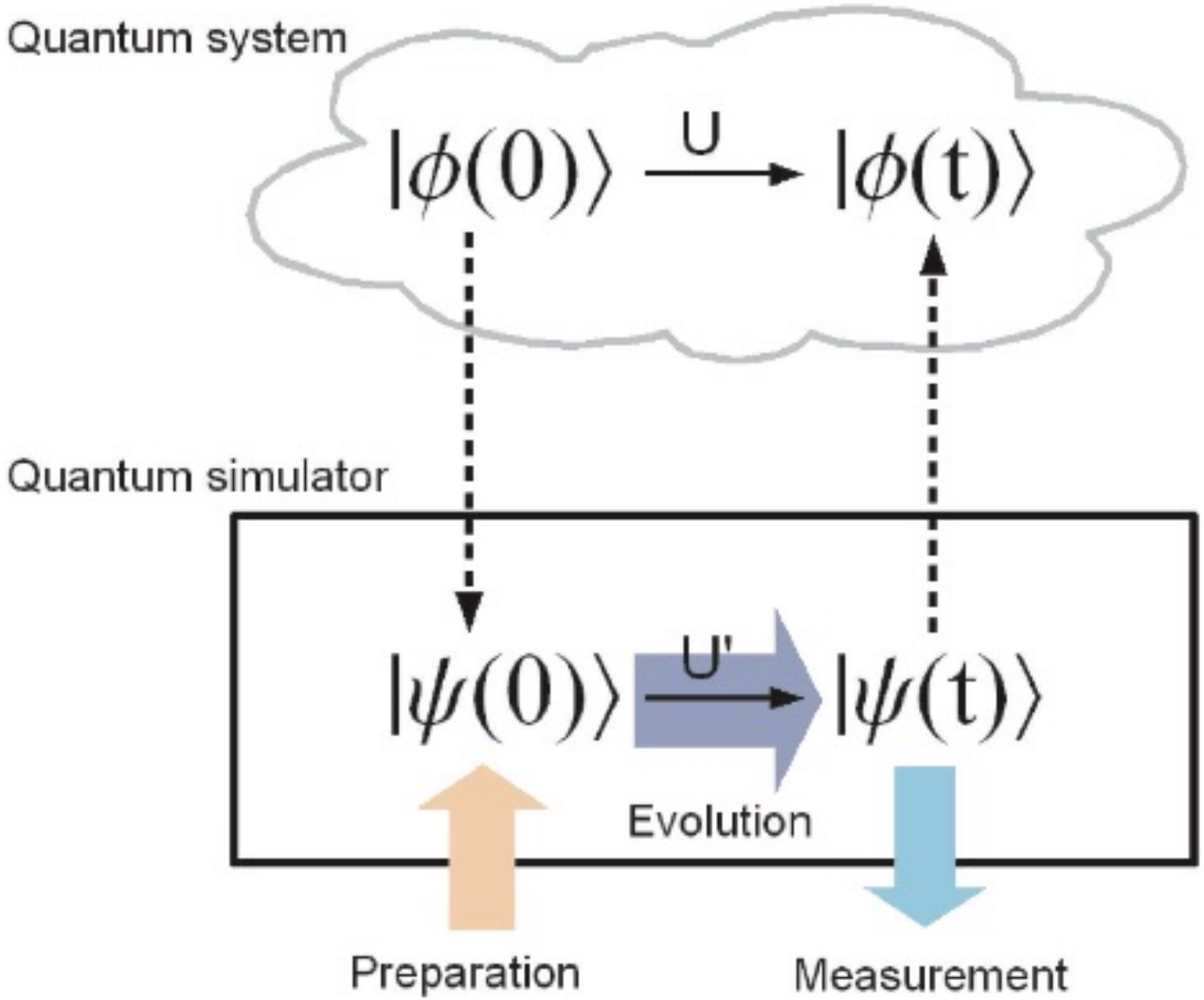
QUANTUM PERCETRON





F. Tacchino et al. arXiv:1811.02266

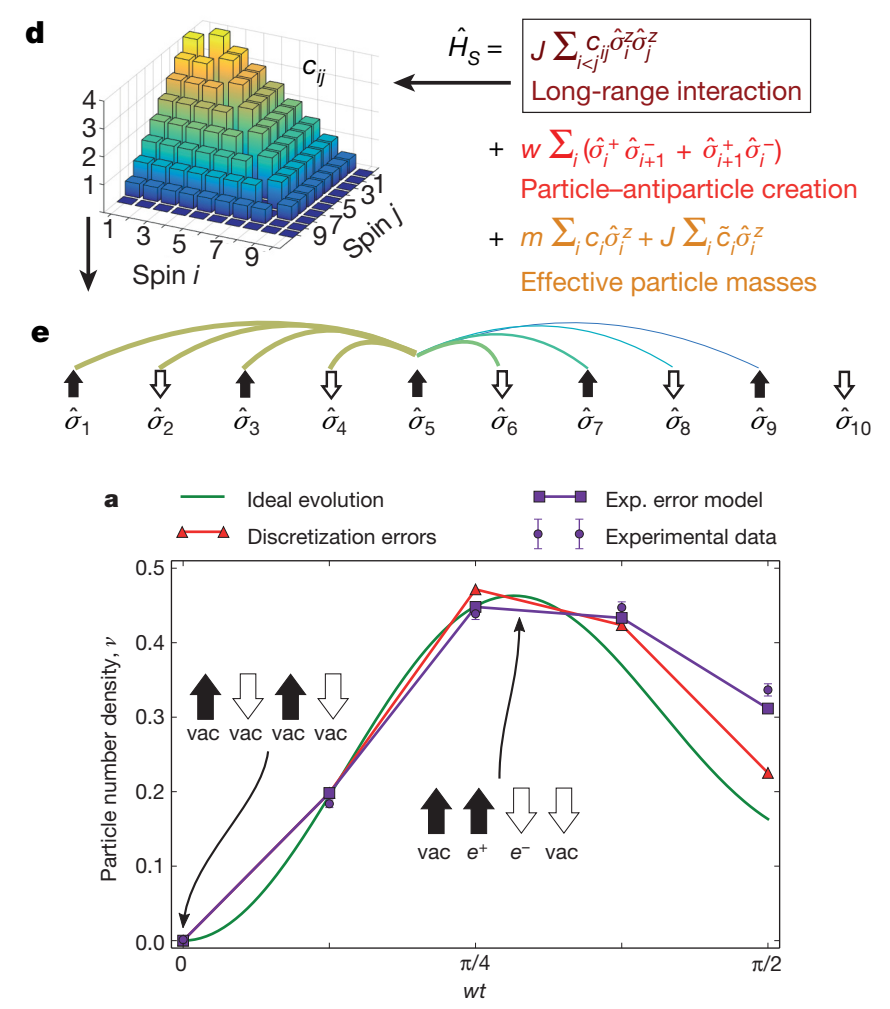
QUANTUM SIMULATIONS

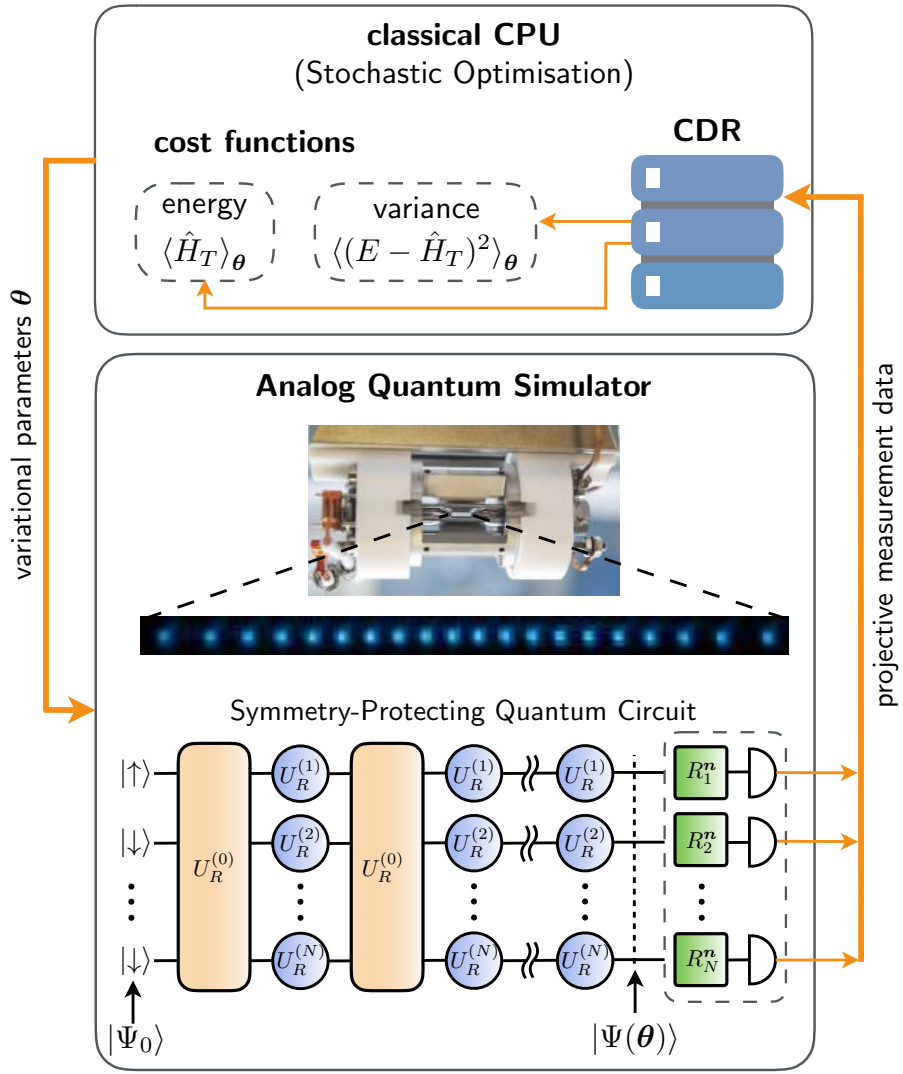


Quantum Simulation, *Rev. Mod. Phys.(2014)*

QUANTUM SIMULATION OF HEP PROCESS

QUANTUM SIMULATIONS OF THE SCHWINGER MODEL





IQOQI Innsbruck

R. Blatt and P. Zoller's groups

20 lattice sites!

Nature (2016), Nature (2018)

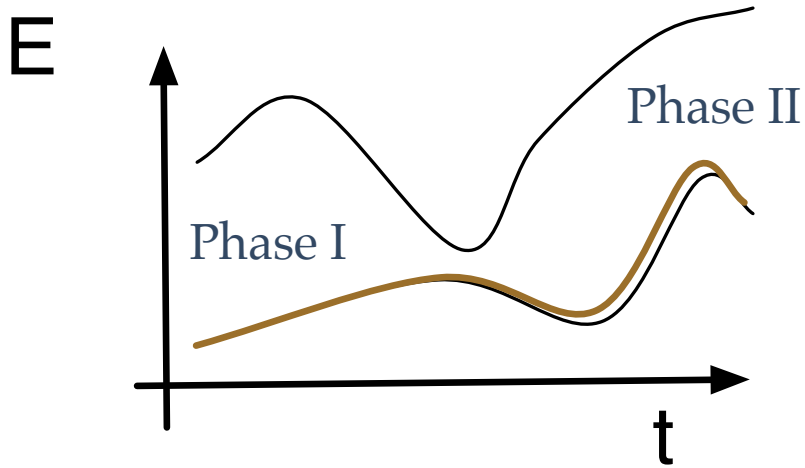
ADIABATIC QUANTUM COMPUTING

- *Preparation of the system in an "easy" state* $\downarrow\downarrow\downarrow \ldots \downarrow\downarrow\downarrow$

- *Slowly change the system Hamiltonian to reach another ground state which encodes the solution of the problem* $\downarrow\uparrow\downarrow \ldots \downarrow\downarrow\uparrow$

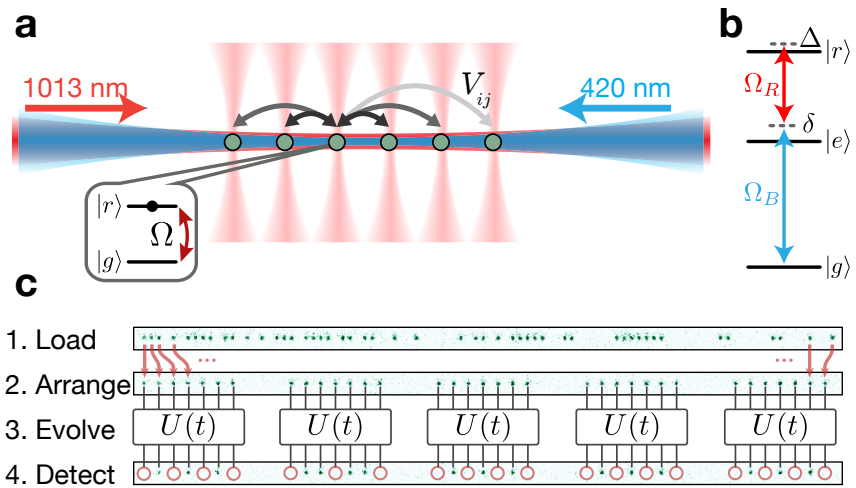
$$H_0 = -h_0 \sum_{i=1}^{N} s_i \qquad s_i = \{\uparrow, \downarrow\} \qquad H(t) = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_P$$

Slow



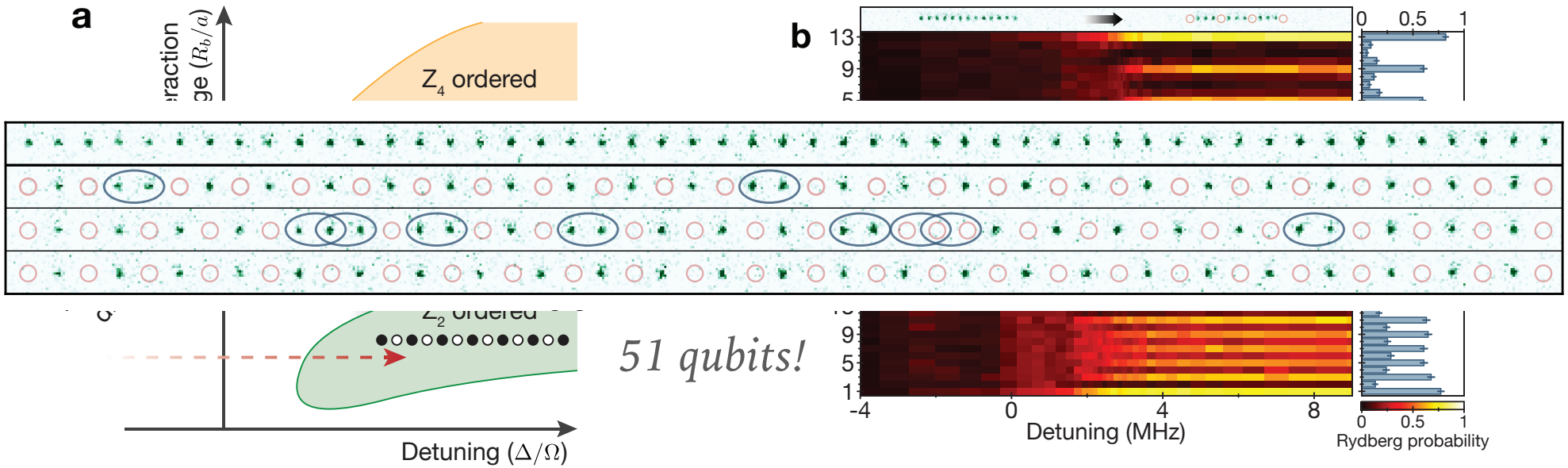
Adiabatic strategy

QUANTUM SIMULATION OF MANY-BODY CORRELATED DYNAMICS



$$\frac{\mathcal{H}}{\hbar} = \sum_i \frac{\Omega_i}{2}\sigma_x^i - \sum_i \Delta_i n_i + \sum_{i<j} V_{ij} n_i n_j,$$

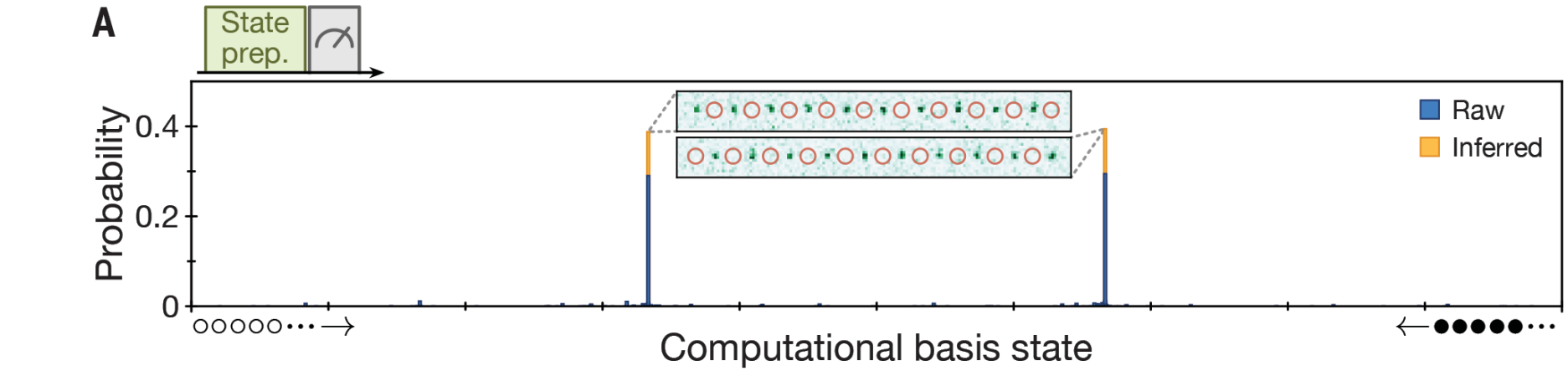
Rydberg Blockade

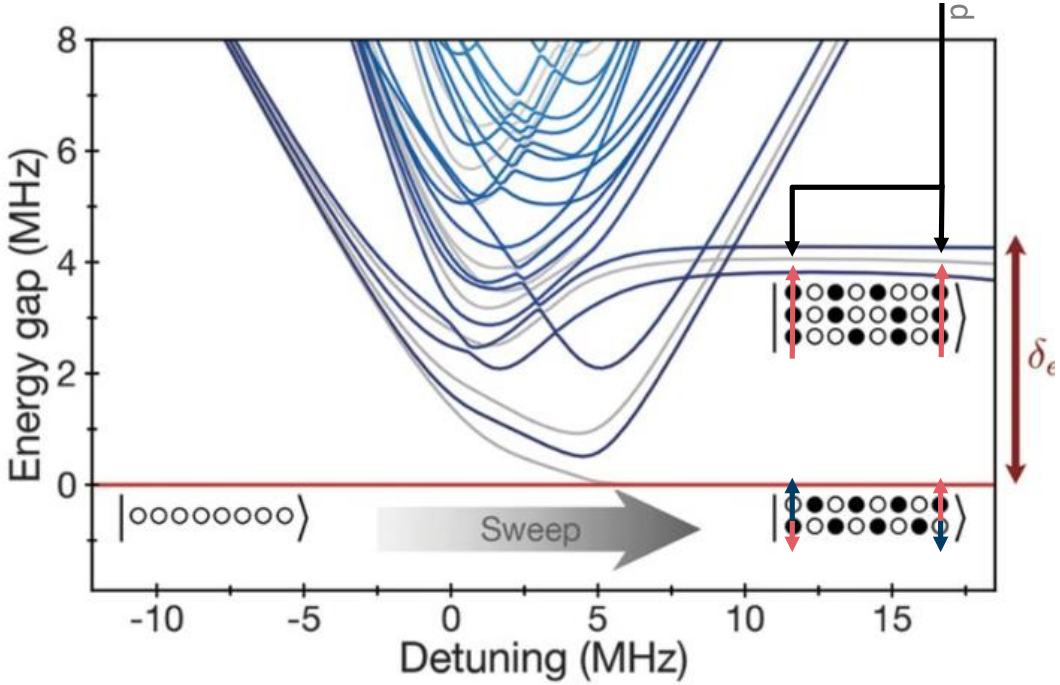


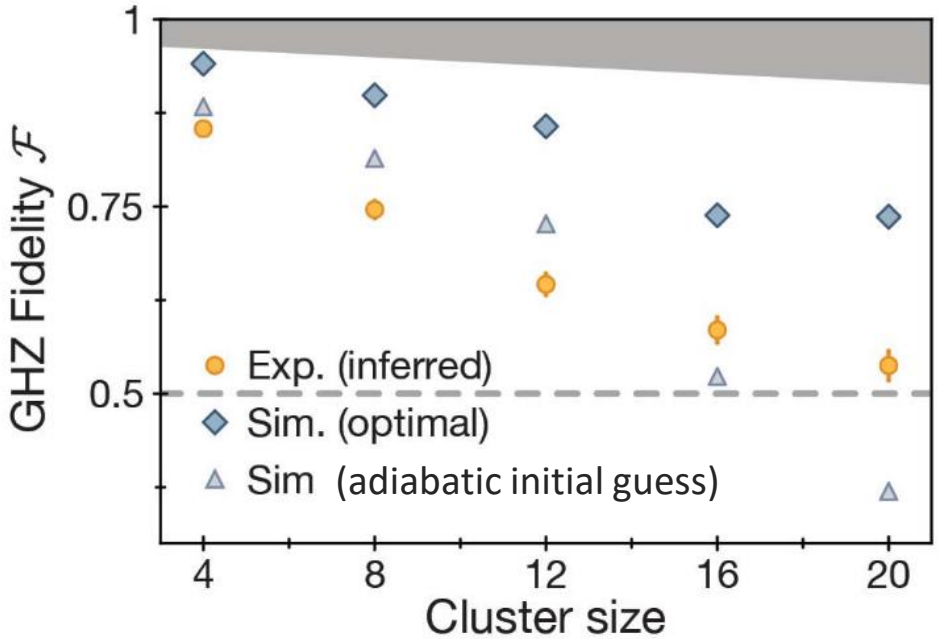
51 qubits!

M. Lukin's group ***Nature*** *(2017)*

GHZ STATE PREPARATION ON RYDBERG





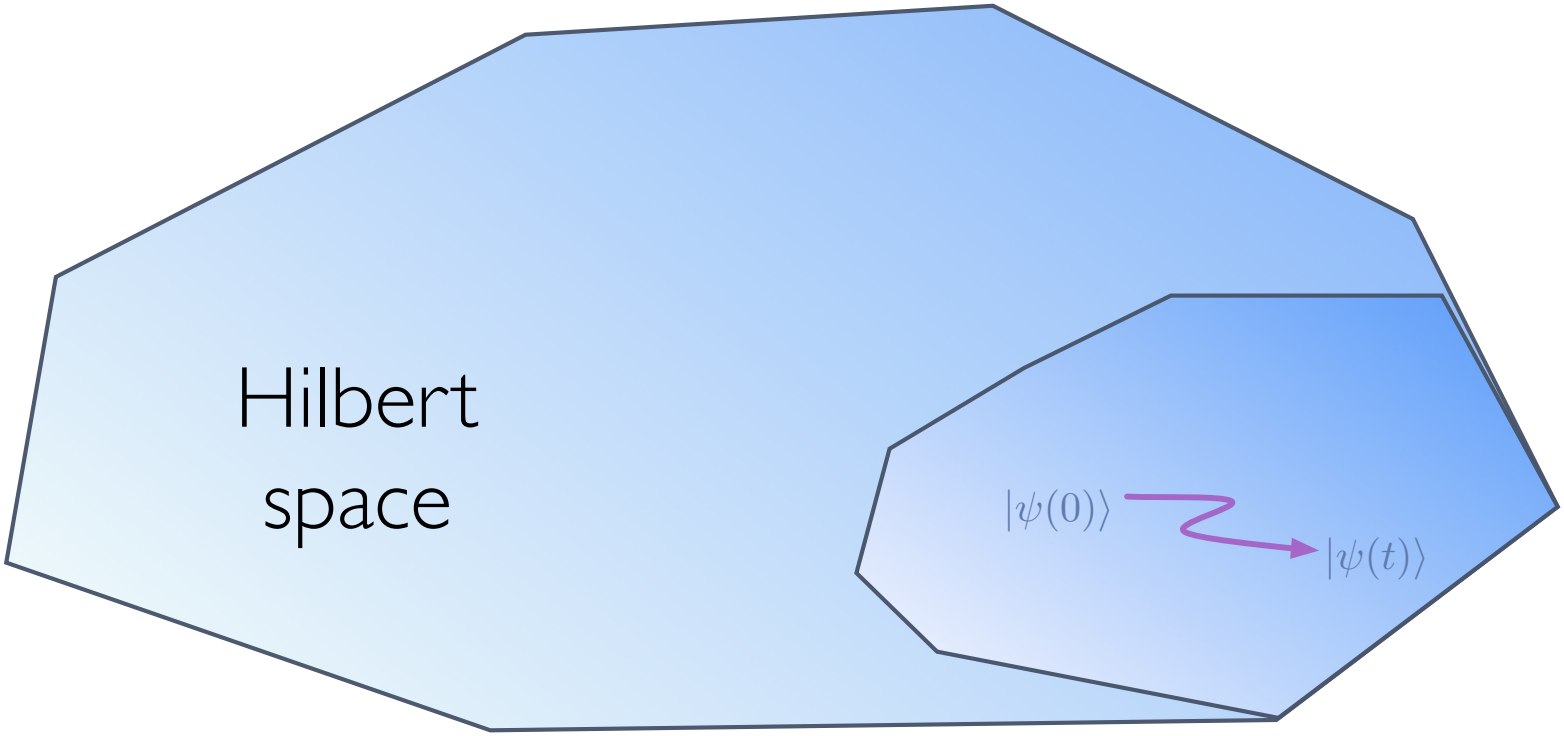


Omran et al Science (2019)

SCHRÖDINGER CAT

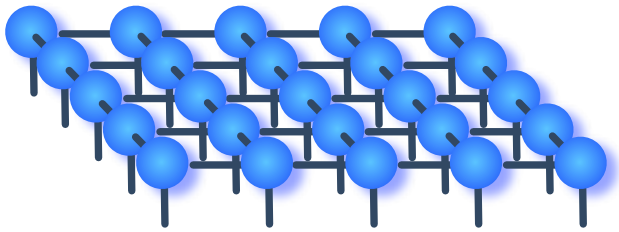
“

When do we really need a quantum simulation/computation?


Hilbert
space
$|\psi(0)\rangle$
$|\psi(t)\rangle$

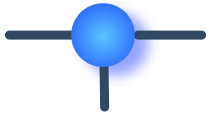
TENSOR NETWORKS STATES

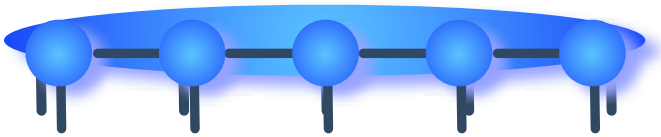
$$\psi_{\alpha_1,\alpha_2,\ldots\alpha_N} \qquad \mathcal{O}(d^N)$$



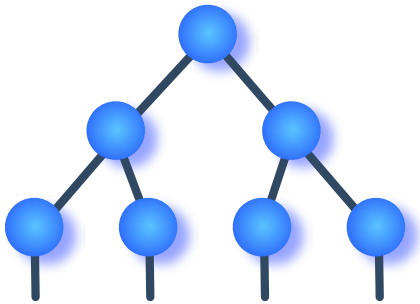
PEPS

$$A_{\alpha_i}^{\beta_i,\beta_{i+1}} \equiv$$





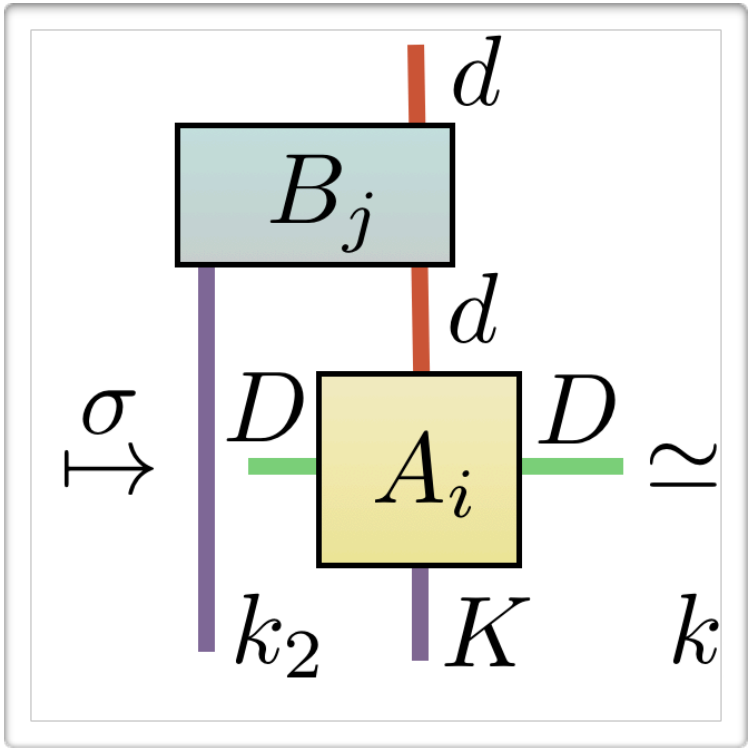
$$A_{\alpha_1}^{\beta_1} A_{\alpha_2}^{\beta_1\beta_2} \ldots A_{\alpha_N}^{\beta_{N-1}} \qquad \mathcal{O}(Ndm^2)$$



Tree Tensor Network

Tensor networks states are a faithful adaptive description of the system tunable between mean field and exact

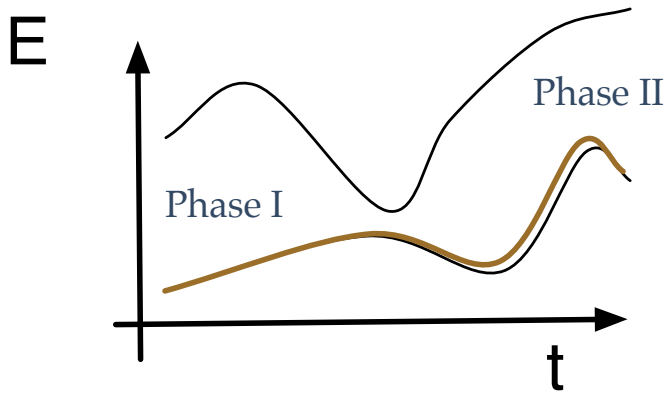
TENSOR NETWORK ALGORITHMS



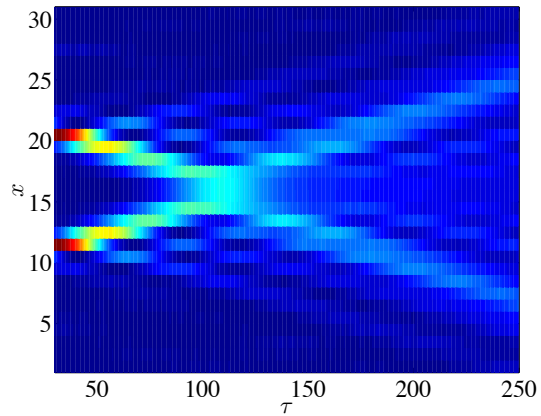
- *State of the art in 1D (poly effort)*
- *No sign problem*
- *Extended to open quantum systems*
- *Machine learning*
- *Data compression (BIG DATA)*
- *Extended to lattice gauge theories*

U. Schollwock, RMP (2005) *A. Cichocki, ECM (2013)* *I. Glasser, et al. PRX (2018)*

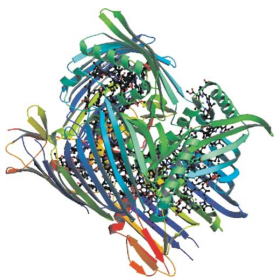
APPLICATIONS



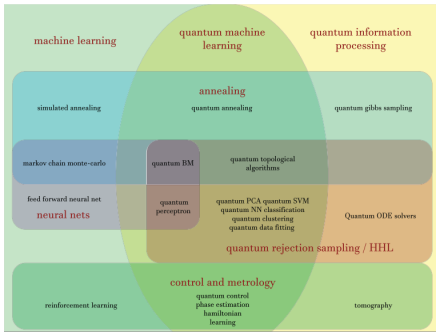
Quantum annealing



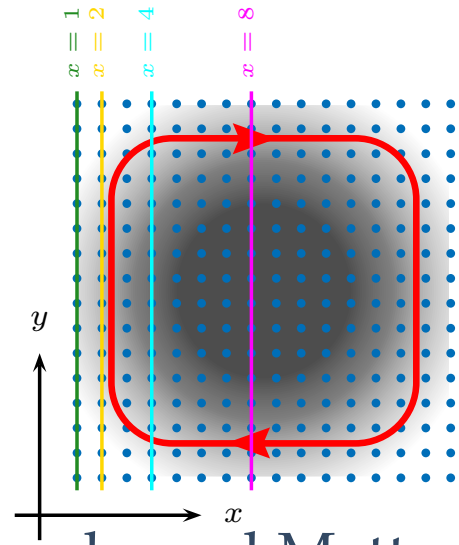
Lattice gauge theories



Quantum Chemistry



Computer Science



Condensed Matter

DATA ANALISYS

Tensor decomposition for Big Data and Optimization

TABLE II: Similarities and links between tensor networks (TNs) and graphical models used in Machine Learning (ML) and Statistics. The categories are not exactly the same, but they closely correspond.

Tensor Networks	Graphical Models in ML/Statistics
TT/MPS	Hidden Markov Models (HMM)
HT/TTNS	Gaussian Mixture Model (GMM)
TNS/PEPS	Markov Random Field (MRF) and Conditional Random Field (CRF)
MERA	Deep Belief Networks (DBN)
DMRG and MALS Algs.	Forward-Backward Algs., Block Nonlinear Gauss-Seidel Methods

A. Cichocki, ECM (2013).

Tensor networks for image processing

FIG. 3: Comparison of the original 512x512 8-bit grayscale image (upper-left) with images compressed with the MPS algorithm (upper-right, DCR=17.97, SSIM=0.8311, and lower-left, DCR=7.64, SSIM=0.9014) and JPEG (lower-right, DCR=33.14, SSIM=0.8311). Note how the compression artifacts are characteristic of each algorithm, even though the quality measure is the same.

A. Bloque and J.I Latorre

MACHINE LEARNING

$$\psi_w(\mathbf{s}) = \prod_i \cosh\left(b_i + \sum_j w_{ij} s_j\right)$$

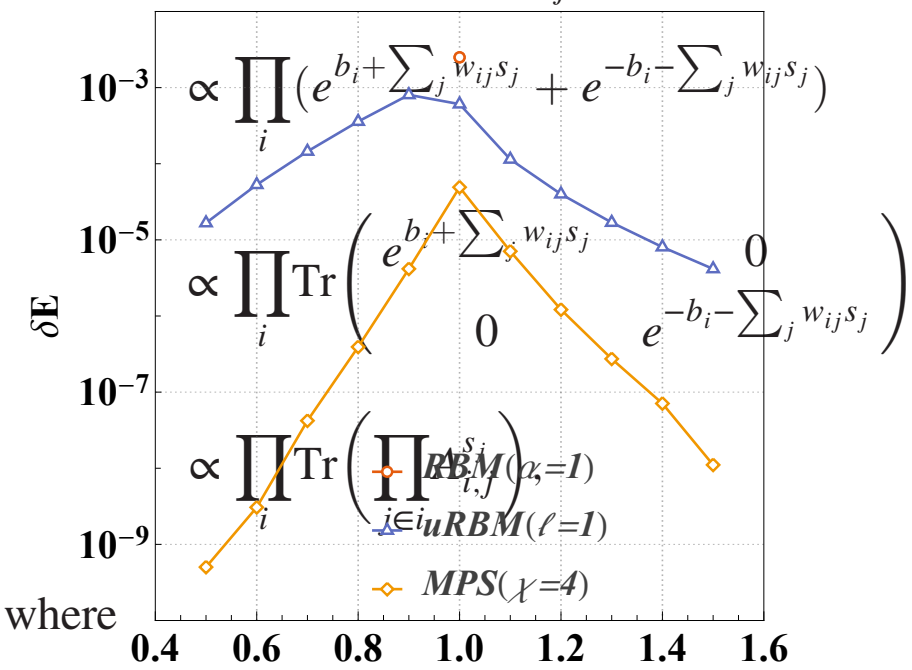
$$\propto \prod_i \left(e^{b_i + \sum_j w_{ij} s_j} + e^{-b_i - \sum_j w_{ij} s_j}\right)$$

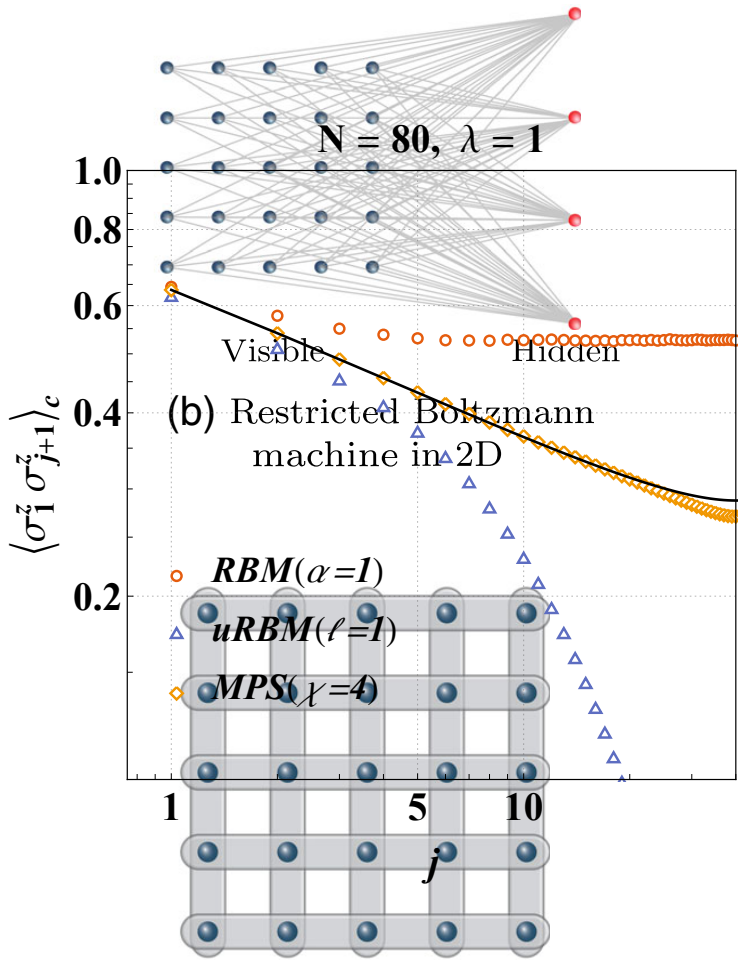
$$\propto \prod_i \mathrm{Tr}\begin{pmatrix} e^{b_i + \sum_j w_{ij} s_j} & 0 \\ 0 & e^{-b_i - \sum_j w_{ij} s_j} \end{pmatrix}$$

$$\propto \prod_i \mathrm{Tr}\left(\prod_{j \in i} A_{i,j}^{s_j}\right)$$

where

$$A_{i,j}^{s_j} = \begin{pmatrix} e^{b_i/\lambda N + w_{ij} s_j} & 0 \\ 0 & e^{-b_i/N - w_{ij} s_j} \end{pmatrix}$$





(d) SBS

Ivan Glasser et al PRX (2018)

M. Collura et al, arXiv:1905.11351

LGT HAVE APPLICATIONS IN

High-energy physics

QED,
QCD, …

Condensed matter

Quantum spin ice,
Kitaev model, …

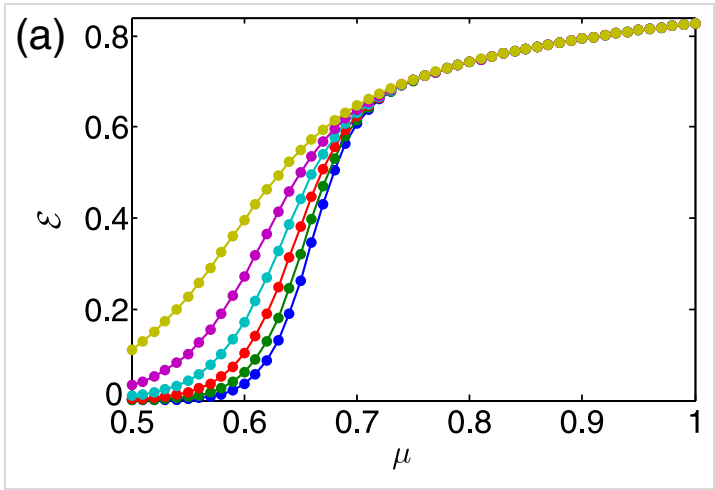
Computer science

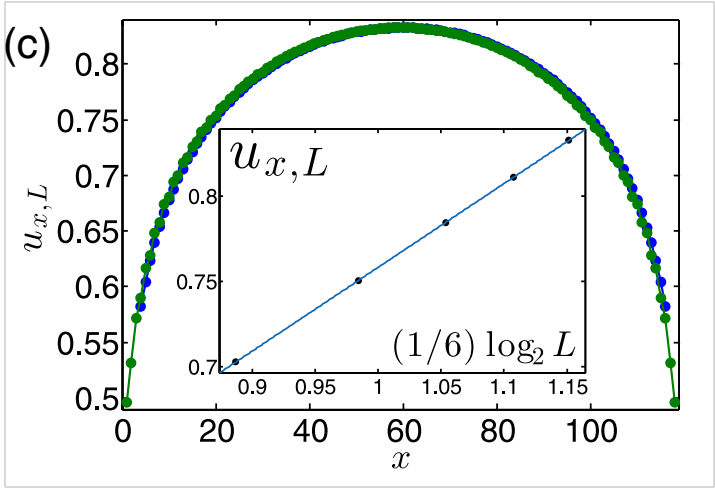
Adiabatic
computation

Quantum science

Quantum
simulations, …

U(1) LATTICE GAUGE THEORY IN 1+1D



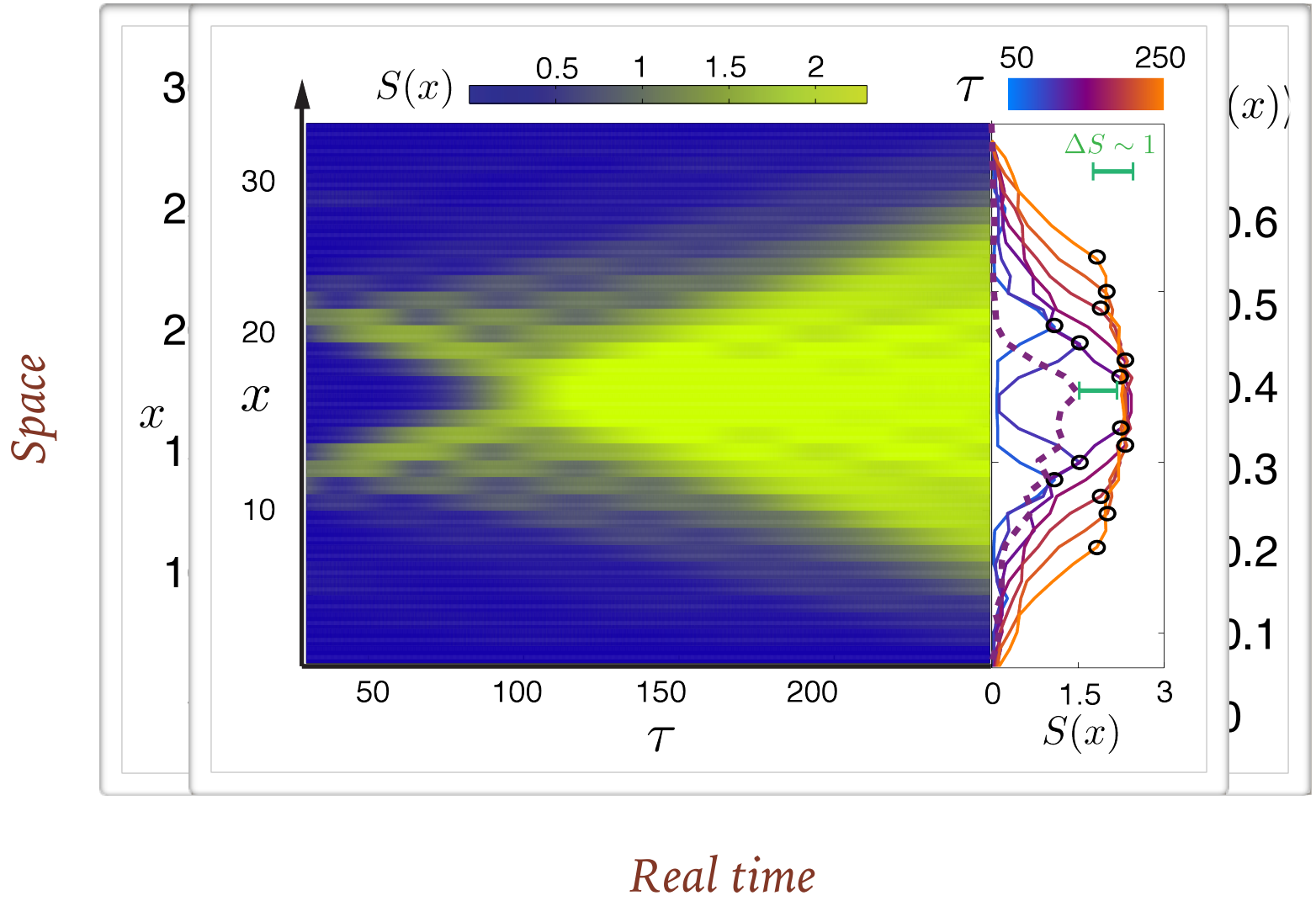


$$H = -t\sum_x \left[\psi_x^\dagger U_{x,x+1}^\dagger \psi_{x+1} + \psi_{x+1}^\dagger U_{x,x+1}\psi_x\right] + m\sum_x (-1)^x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_x E_{x,x+1}^2 .$$

$$\mathcal{E} = \sum_x \langle E_{x,x+1}\rangle / L$$

- *Quantum link representation*
- *Staggered fermions*
- *Ising universality class*
- *Central charge* $c = 0.49 \pm 0.01$
- *Confirmed by higher-link representation*

E. Rico, T. Pichler, M. Dalmonte, P. Zoller, and SM, PRL (2014)

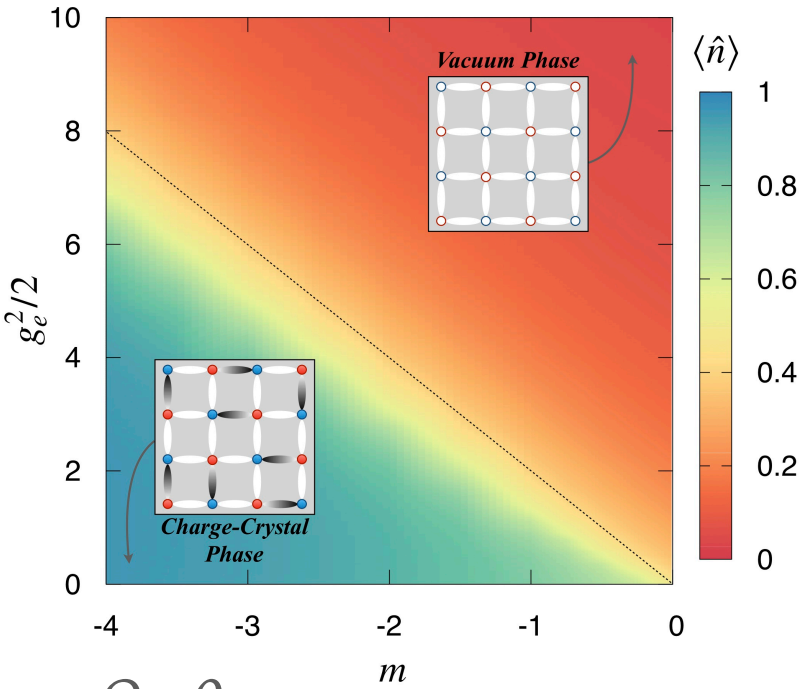


MESONS SCATTERING

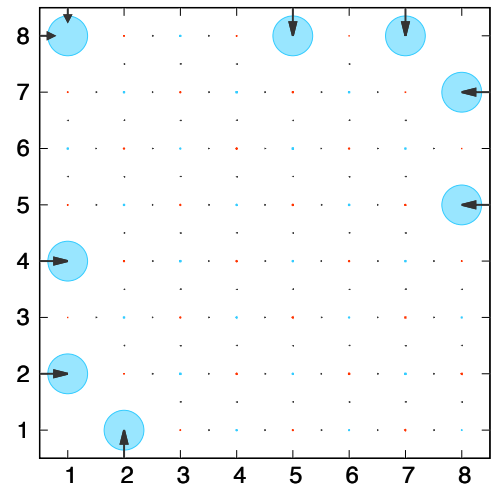
T. Pichler, E. Rico, M. Dalmonte, P. Zoller, and SM, PRX (2016)

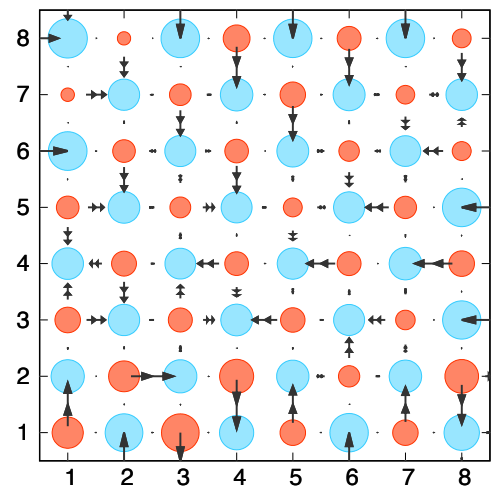
TWO DIMENSIONAL SIMULATION OF A LGT AT FINITE DENSITY

$$\hat{H} = -t \sum_{x,\mu} \left(\hat{\psi}_x^\dagger \hat{U}_{x,\mu} \hat{\psi}_{x+\mu} + h.c. \right)$$
$$+ m \sum_x (-1)^x \hat{\psi}_x^\dagger \hat{\psi}_x + \frac{g_e^2}{2} \sum_{x,\mu} \hat{E}_{x,\mu}^2$$
$$- \frac{g_m^2}{2} \sum_x \left(\hat{U}_{x,\mu_x} \hat{U}_{x+\mu_x,\mu_y} \hat{U}_{x+\mu_y,\mu_x}^\dagger \hat{U}_{x,\mu_y}^\dagger + h.c. \right)$$



Q=0





Q= - 8

arXiv:1911.09693

TAKE HOME MESSAGE

- Quantum technologies are fast developing, hybrid solutions will play a fundamental role
- Tensor network algorithms can be used to benchmark, verify, support and guide quantum simulations/computations
- Synergies between quantum technologies and high-energy physics can lead to unexpected developments:
    - Sign-problem-free solutions
    - Machine learning
    - Quantum sensing
    - Optimized protocols
- Quest for quantum advantage is still open

Thank you for your attention!

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