Quantum Simulation and Hardware Codesign

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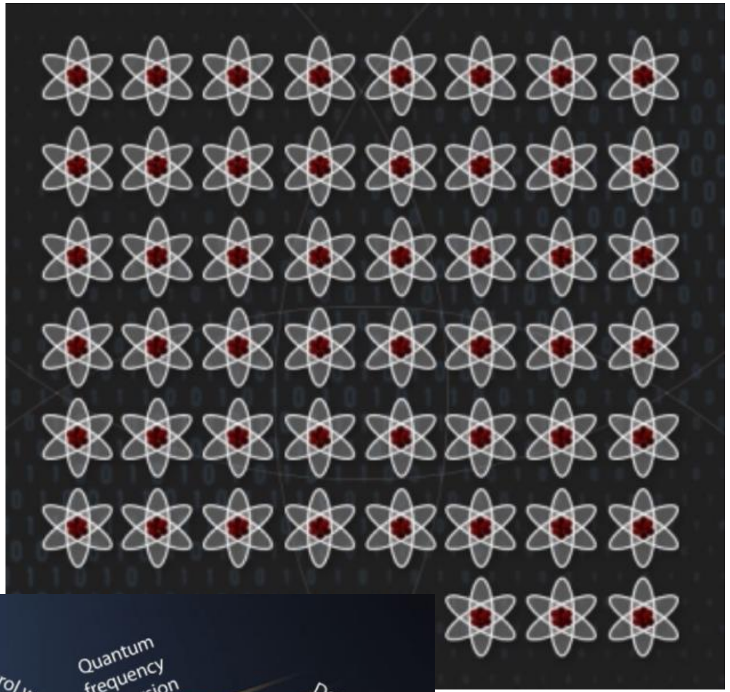
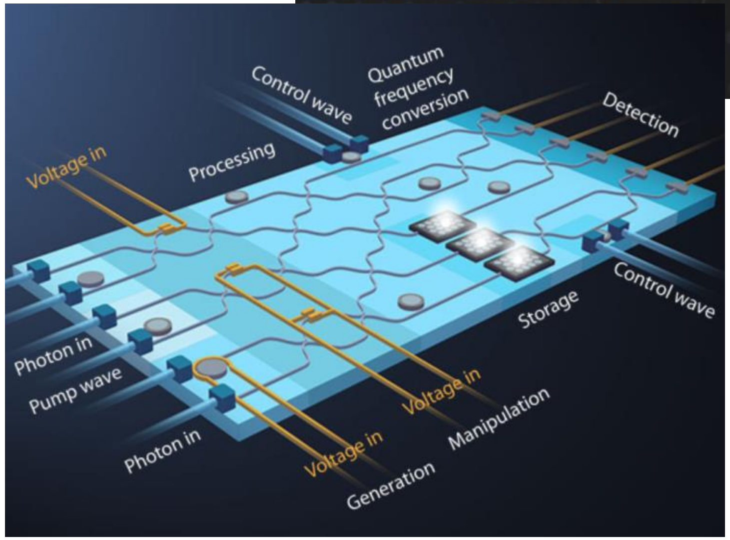
QUANTUM INFORMATION SCIENCE

Basic idea

- Quantum Simulators can be built for specific tasks
- A purpose-built device might have higher fidelity for specific operations than a universal device does
- Candidates include (not limited to)
  - Neutral atoms
  - Trapped ions
  - Optical fields
  - Superconducting qudits
- Analog quantum simulation may make sense in the NISQ era



MIT



U. Rochester

Analog quantum simulation

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Digital-Analog Quantum Simulation of Spin Models in Trapped Ions

Iñigo Arrazola[1], Julen S. Pedernales[1], Lucas Lamata[1] & Enrique Solano[1,2]

We propose a method to simulate spin models in trapped ions using a digital-analog approach, consisting in a suitable gate decomposition in terms of analog blocks and digital steps. In this way, we show that the quantum dynamics of an enhanced variety of spin models could be implemented with substantially less number of gates than a fully digital approach. Typically, analog blocks are built of multipartite dynamics providing the complexity of the simulated model, while the digital steps are local operations bringing versatility to it. Finally, we describe a possible experimental implementation in trapped-ion technologies.

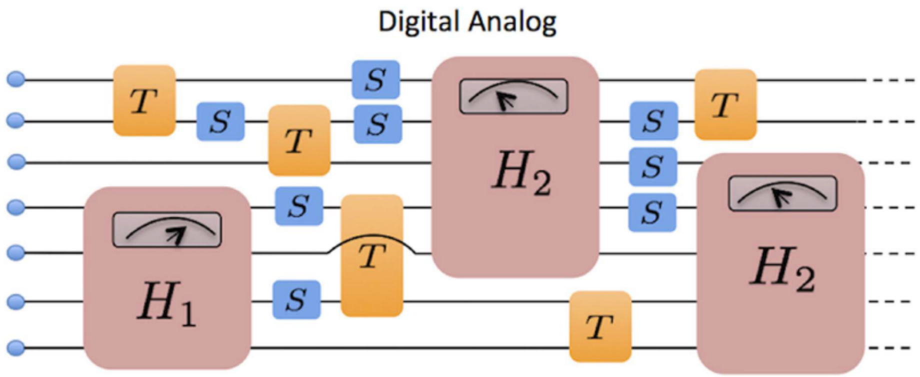


Figure 1. Fully Digital vs. Digital-Analog. We depict the circuit representation of the digital and digital-analog approaches for quantum simulation. The fully digital approach is composed exclusively of single-qubit (S) and two-qubit (T) gates, while the digital-analog one significantly reduces the number of gates by including analog blocks. The latter, depicted in large boxes (H_1 and H_2), depend on tunable parameters, represented by an analog indicator, and constitute the analog quantum implementation of a given Hamiltonian dynamics.

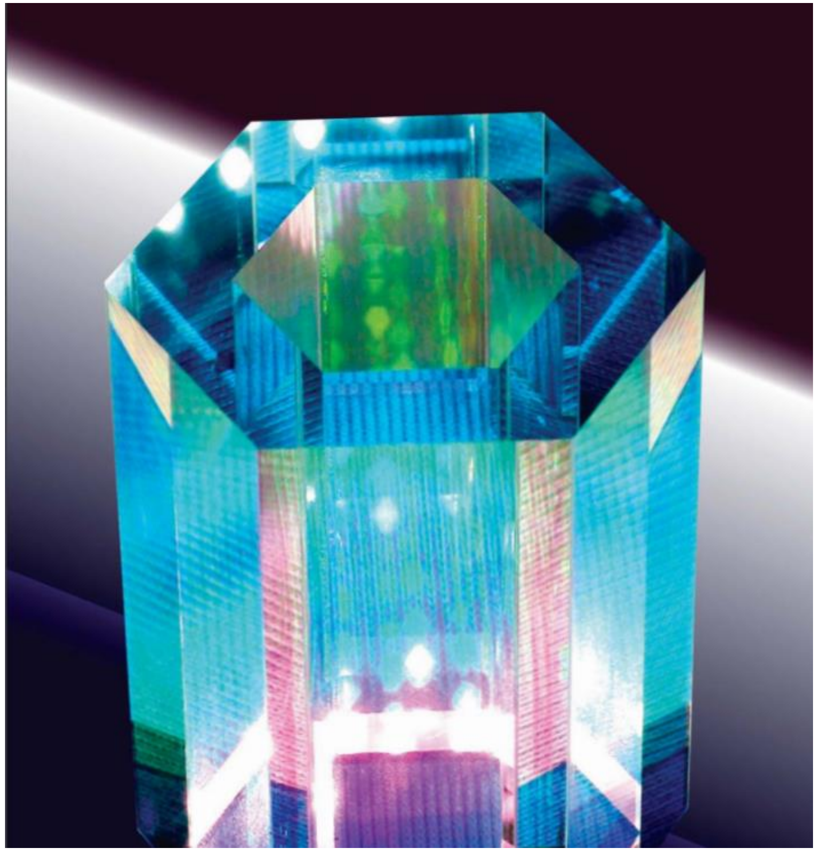
- Simulate Trotter steps $U^{\mathrm{H}}(t/l) = e^{-iH_{XY}t/l} R_y e^{-iH_{XX}t/l} R_y^{\dagger}$, via direct implementation of H_{ij}

Neutral atom quantum simulators

- Trap atoms in 2D arrays, optical tweezers, quantum gas microscopes
- Natural Hamiltonians:
  - Ising model $$\mathcal{H}(t) = \frac{\hbar}{2}\Omega(t)\sum_j \sigma_j^x - \hbar\delta(t)\sum_j n_j + \sum_{i\neq j}\frac{C_6}{r_{ij}^6} n_i n_j,$$

    (simulating magnets, solving optimization problems)
  - Transverse field (spin exchange) $$\mathcal{H}(t) = \frac{\hbar}{2}\Omega(t)\sum_j \sigma_j^x - \frac{\hbar}{2}\delta(t)\sum_j \sigma_j^z + 2\sum_{i\neq j}\frac{C_3}{r_{ij}^3}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)$$

https://arxiv.org/pdf/2006.12326.pdf



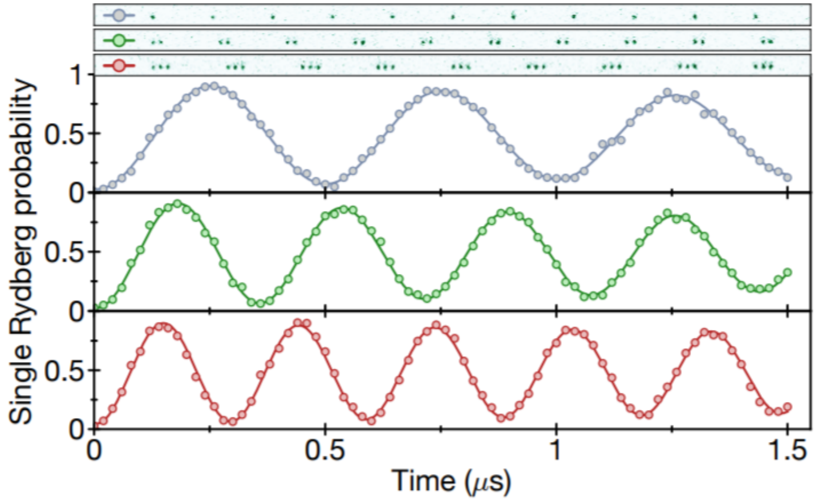
U Wisconsin; Physics Today

Neutral atom quantum simulators

Probing many-body dynamics on a 51-atom quantum simulator

Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

Controllable, coherent many-body systems can provide insights into the fundamental properties of quantum matter, enable the realization of new quantum phases and could ultimately lead to computational systems that outperform existing computers based on classical approaches. Here we demonstrate a method for creating controlled many-body quantum matter that combines deterministically prepared, reconfigurable arrays of individually trapped cold atoms with strong, coherent interactions enabled by excitation to Rydberg states. We realize a programmable Ising-type quantum spin model with tunable interactions and system sizes of up to 51 qubits. Within this model, we observe phase transitions into spatially ordered states that break various discrete symmetries, verify the high-fidelity preparation of these states and investigate the dynamics across the phase transition in large arrays of atoms. In particular, we observe robust many-body dynamics corresponding to persistent oscillations of the order after a rapid quantum quench that results from a sudden transition across the phase boundary. Our method provides a way of exploring many-body phenomena on a programmable quantum simulator and could enable realizations of new quantum algorithms.



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

Observe transition to crystalline phases

Optical quantum simulators

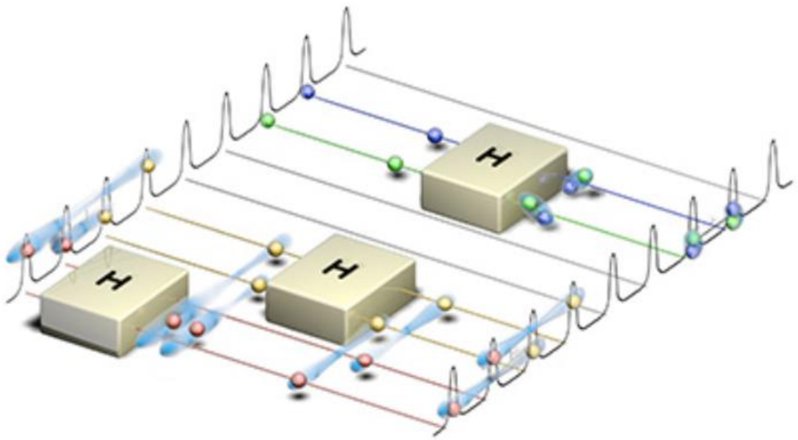
PHYSICAL REVIEW A **100**, 012320 (2019)

Simulations of subatomic many-body physics on a quantum frequency processor

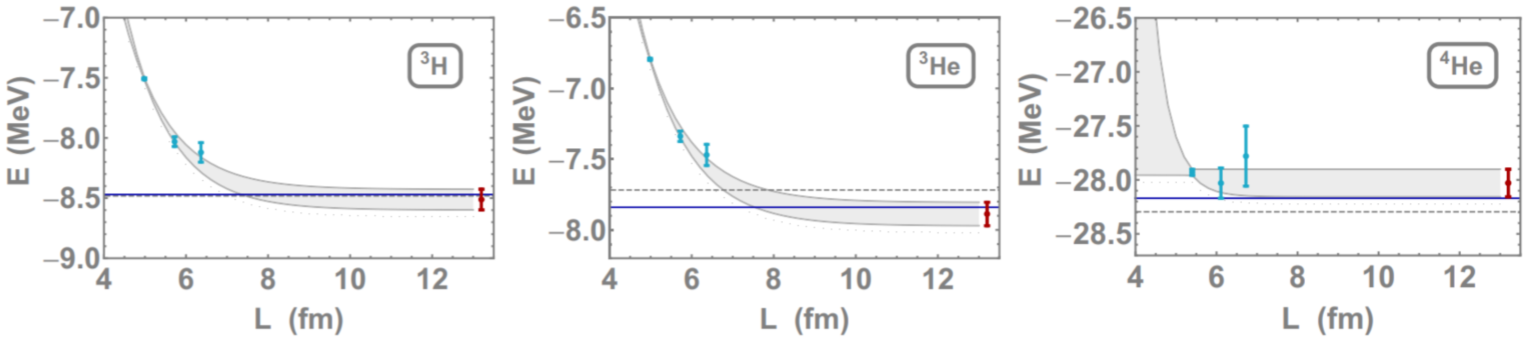
Hsuan-Hao Lu,[1,*] Natalie Klco,[2,*] Joseph M. Lukens,[3] Titus D. Morris,[4,3] Aaina Bansal,[5] Andreas Ekström,[6] Gaute Hagen,[4,5] Thomas Papenbrock,[5,4] Andrew M. Weiner,[1] Martin J. Savage,[2] and Pavel Lougovski[3,†]

Simulating complex many-body quantum phenomena is a major scientific impetus behind the development of quantum computing, and a range of technologies are being explored to address such systems. We present the results of the largest photonics-based simulation to date, applied in the context of subatomic physics. Using an all-optical quantum frequency processor, the ground-state energies of light nuclei including the triton (^{3}H), ^{3}He, and the alpha particle (^{4}He) are computed. Complementing these calculations and utilizing a 68-dimensional Hilbert space, our photonic simulator is used to perform subnucleon calculations of the two- and three-body forces between heavy mesons in the Schwinger model. This work is a first step in simulating subatomic many-body physics on quantum frequency processors—augmenting classical computations that bridge scales from quarks to nuclei.

DOI: 10.1103/PhysRevA.100.012320



- VQE of nuclei and lattice gauge theories



Continuous variable optical quantum simulators

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VOLUME 82, NUMBER 8 PHYSICAL REVIEW LETTERS 22 FEBRUARY 1999

Quantum Computation over Continuous Variables

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(Received 27 October 1998)

This paper provides necessary and sufficient conditions for constructing a universal quantum computer over continuous variables. As an example, it is shown how a universal quantum computer for the amplitudes of the electromagnetic field might be constructed using simple linear devices such as beam splitters and phase shifters, together with squeezers and nonlinear devices such as Kerr-effect fibers and atoms in optical cavities. Such a device could in principle perform "quantum floating point" computations. Problems involving noise, finite precision, and error correction are discussed. [S0031-9007(99)08418-5]

Continuous variable optical quantum simulators

PRL **118**, 080501 (2017) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2017

Quantum Machine Learning over Infinite Dimensions

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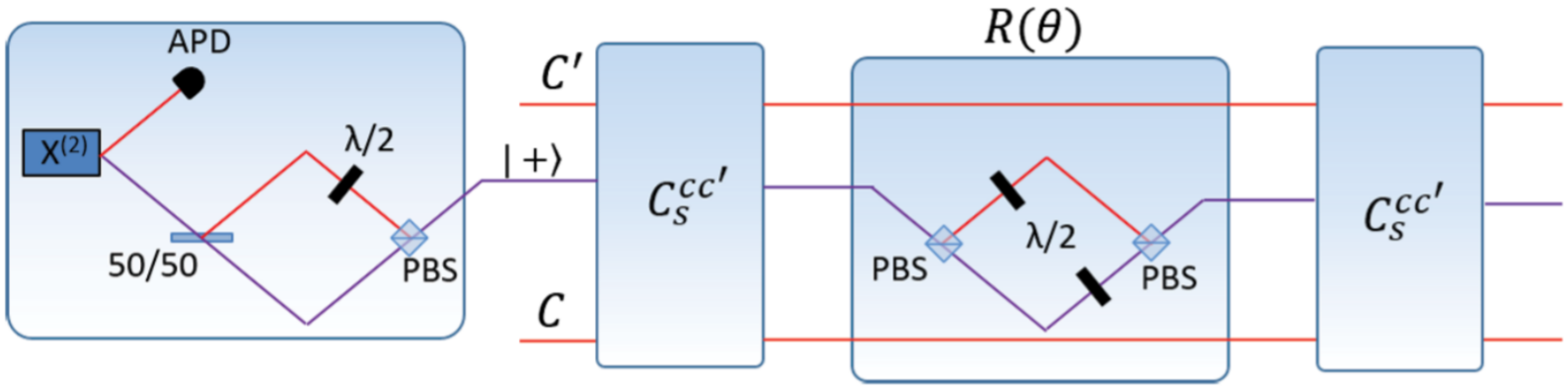
(Received 20 March 2016; published 21 February 2017)

Machine learning is a fascinating and exciting field within computer science. Recently, this excitement has been transferred to the quantum information realm. Currently, all proposals for the quantum version of machine learning utilize the finite-dimensional substrate of discrete variables. Here we generalize quantum machine learning to the more complex, but still remarkably practical, infinite-dimensional systems. We present the critical subroutines of quantum machine learning algorithms for an all-photonic continuous-variable quantum computer that can lead to exponential speedups in situations where classical algorithms scale polynomially. Finally, we also map out an experimental implementation which can be used as a blueprint for future photonic demonstrations.

DOI: 10.1103/PhysRevLett.118.080501

FIG. 1. All-photonic implementation schematic of the operator $\exp(i\theta\mathcal{S}) = C_S^{cc'}R(\theta)C_S^{cc'}$. We initially have an ancillary input mode $|+\rangle = (|01\rangle + |10\rangle)/\sqrt{2}$ with two (swap) modes C and C' used to implement the operators given in Eq. (4). The method for generating $|+\rangle$ is one of many possibilities, e.g., preparing a heralded superposition of polarization states is illustrated. $\chi^{(2)}$, nonlinear crystal source; APD, avalanche photodiode detector; 50/50, balanced beam splitter; $\lambda/2$, half wave plate; PBS, polarizing beam splitter; $C_S^{CC'}$, controlled-swap operator; $R(\theta)$, rotation operator; see the text for an explanation of the operators.

Principle component analysis
Matrix inversion



Continuous variable optical quantum simulators

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PHYSICAL REVIEW A **92**, 063825 (2015)

Quantum simulation of quantum field theory using continuous variables

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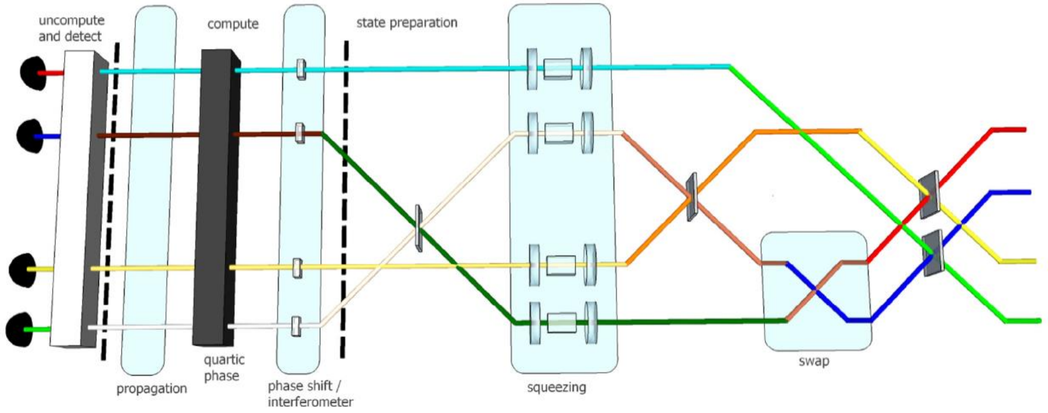
(Received 31 March 2015; published 14 December 2015)

The year 1982 is often credited as the year that theoretical quantum computing was started with a keynote speech by Richard Feynman, who proposed a universal quantum simulator, the idea being that if you had such a machine you could in principle "imitate any quantum system, including the physical world." With that in mind, we present an algorithm for a continuous-variable quantum computing architecture which gives an exponential speedup over the best-known classical methods. Specifically, this relates to efficiently calculating the scattering amplitudes in scalar bosonic quantum field theory, a problem that is believed to be hard using a classical computer. Building on this, we give an experimental implementation based on continuous-variable states that is feasible with today's technology.

DOI: 10.1103/PhysRevA.92.063825 PACS number(s): 03.67.Ac, 03.67.Lx, 03.70.+k, 42.50.Ex



Discretize space, but not the field and time variables

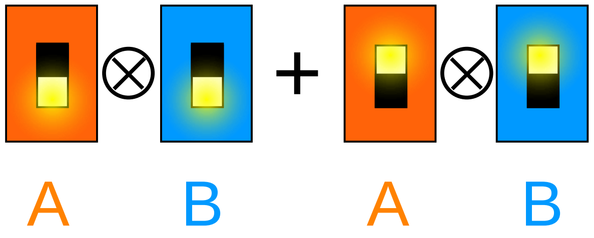
$$H_0 = \frac{1}{2}\int_0^L dx\left[\pi^2 + \left(\frac{\partial\phi}{\partial x}\right)^2 + m^2\phi^2\right],$$

$$H_0 = \sum_{n=0}^{N-1}\frac{P_n^2 + m^2 Q_n^2}{2} + \frac{1}{2}\sum_{n=0}^{N-1}(Q_n - Q_{n+1})^2$$

Quantum Entanglement

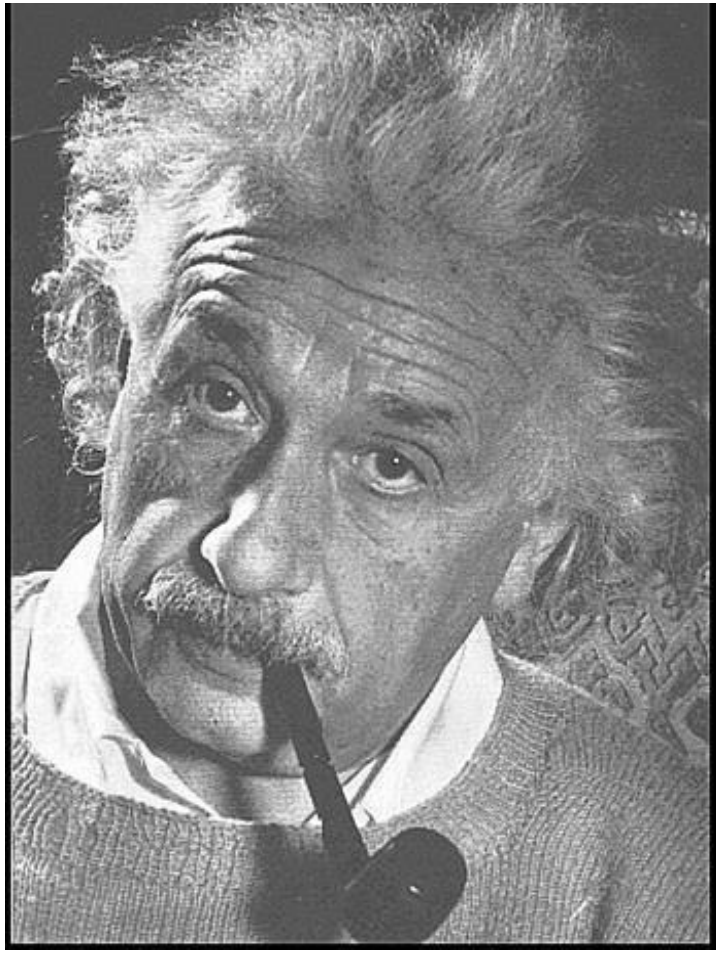
- Einstein, Podolsky, and Rosen, 1935: quantum mechanics predicts entanglement

- Variables like position and momentum can be entangled between two particles:



$$\longrightarrow \quad \int | x\rangle_A \, | x\rangle_B dx;$$

$$\int | p\rangle_A \, | -p\rangle_B dp$$



Quantum Sensing and Quantum Computing Across Quantum Networks

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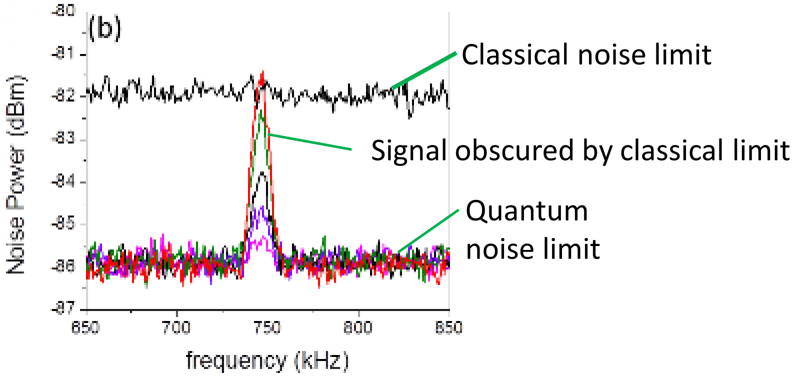
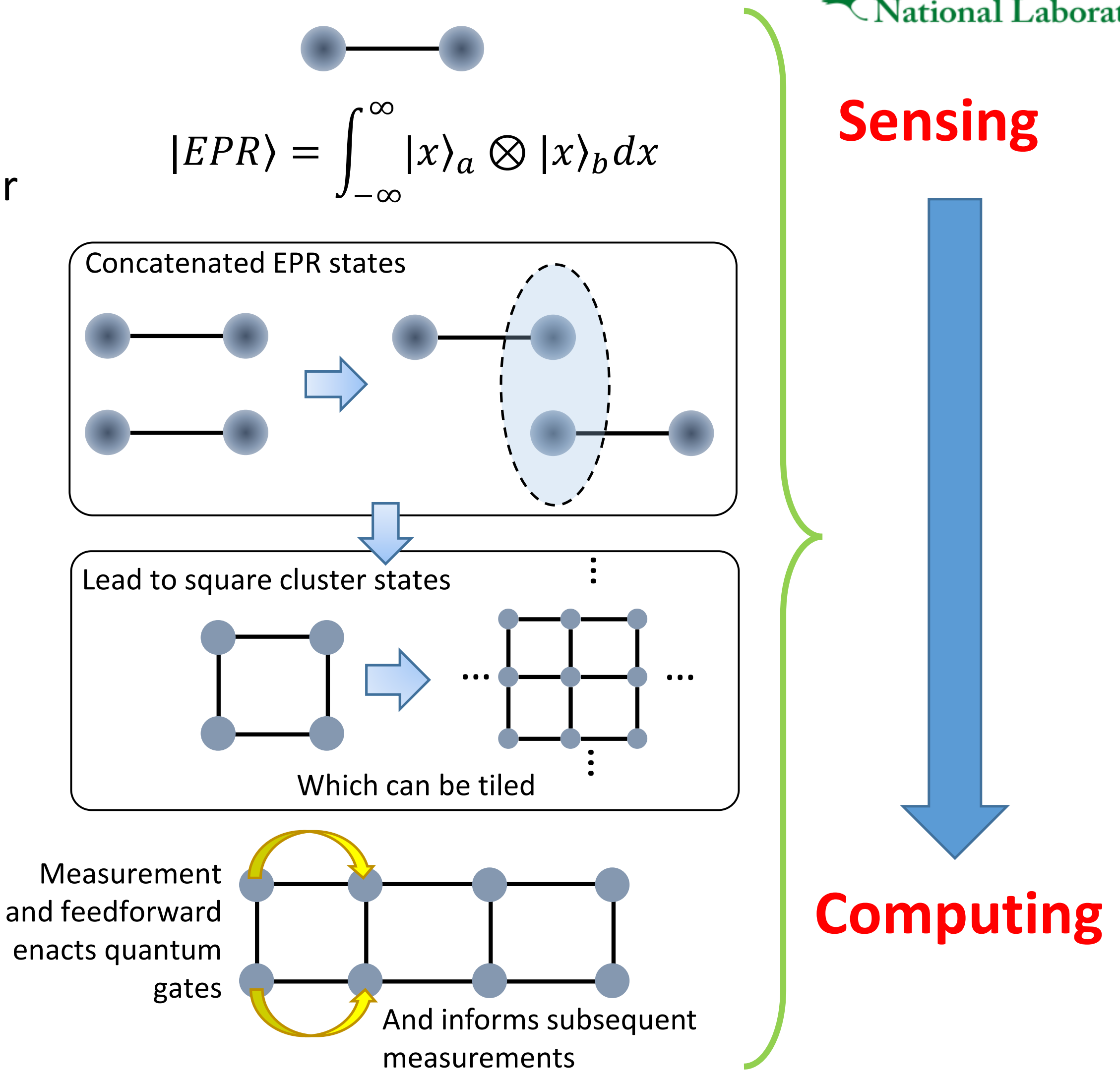
- Quantum networks are collections of qubits (nodes) connected by interactions, or quantum gates (edges)
- Simplest quantum network is the two qubit EPR state or Bell state, *which is a workhorse in quantum sensing*
  - The quantum correlations in EPR quantum networks can be used to *reduce the noise floor in measurements* – **quantum metrology**



- Indefinitely large quantum networks can be built by concatenating EPR states – *the same network is a resource for measurement-based quantum computing and distributed quantum sensors*

$$|EPR\rangle = \int_{-\infty}^{\infty} |x\rangle_a \otimes |x\rangle_b \, dx$$



The know-how in generating long range entanglement for quantum sensing lends itself to building quantum computers. This is because in order to make these quantum sensors, one must build a *quantum network* with a *two qubit gate* interaction between the nodes.