Neuromorphic and Quantum Computing

Specialized Architectures for Science

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CCS – LBNL Collaborative Workshop 2016
May 12, 2016

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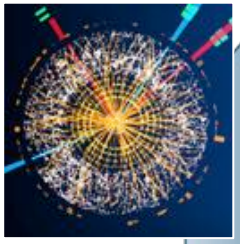
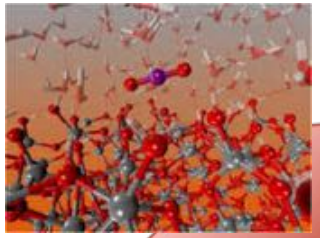
BERKELEY LAB

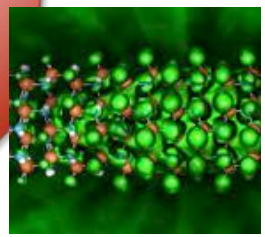
U.S. DEPARTMENT OF ENERGY | Office of Science

Explore novel computing technologies and apply them to science challenges.





Strongly correlated systems



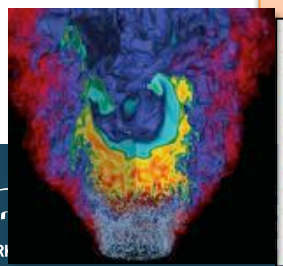
Real time, very low power, machine learning

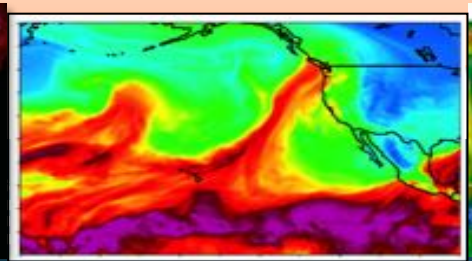
Neuromorphic

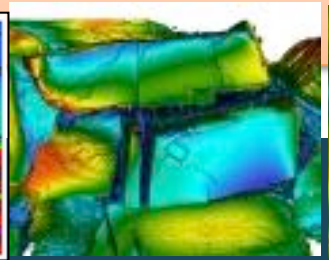
Quantum

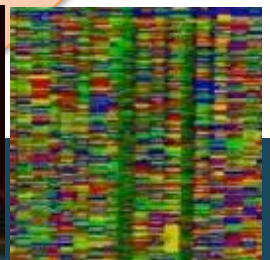
Exascale

High Performance Modeling and Simulation for Broad DOE science mission



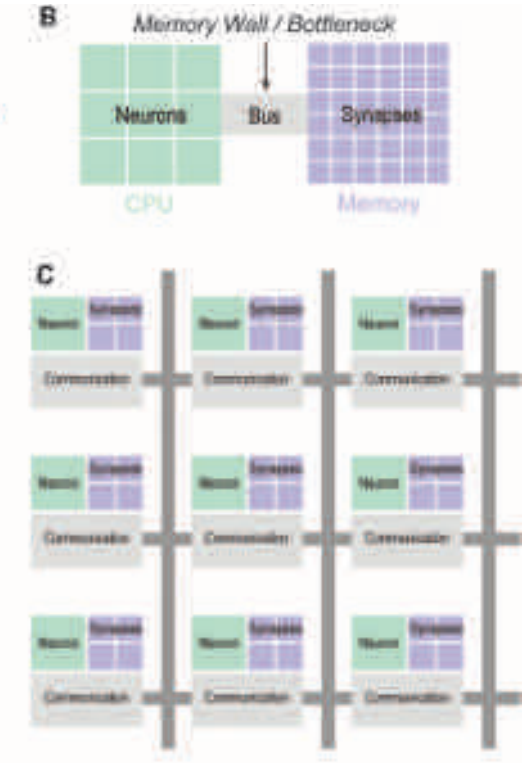






Explore and evaluate the use of neuromorphic computing technology on applications in image analysis and event detection

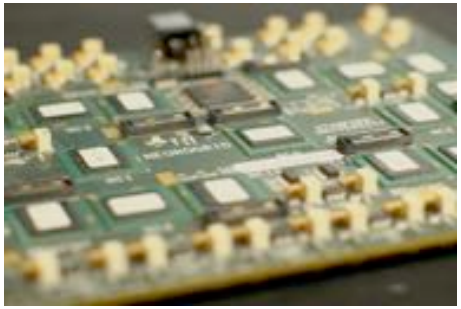
- "Brain-inspired" non-Von Neumann architecture
- Implement scalable, efficient, and flexible spiking neural networks



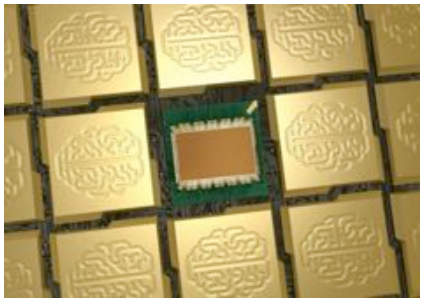
Neuromorphic Computing Platforms

“Spikey” from Electronic Visions group in Heidelberg

Qualcomm’s NPU’s for robots.

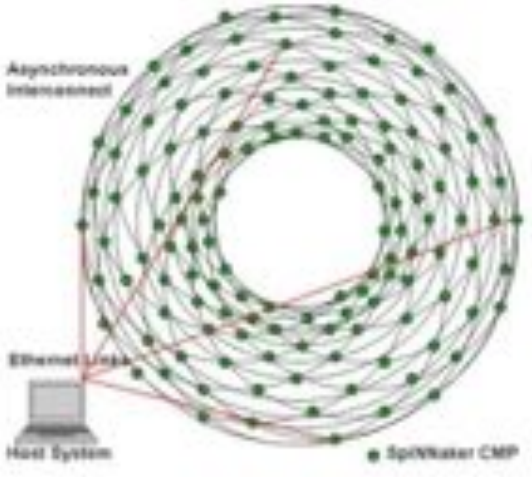


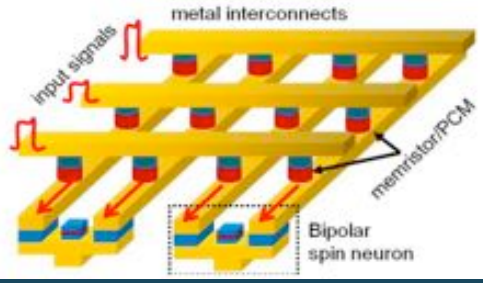
Stanford’s Neurogrid



IBM’s TrueNorth

SpiNNaker’s 1B neuron machine

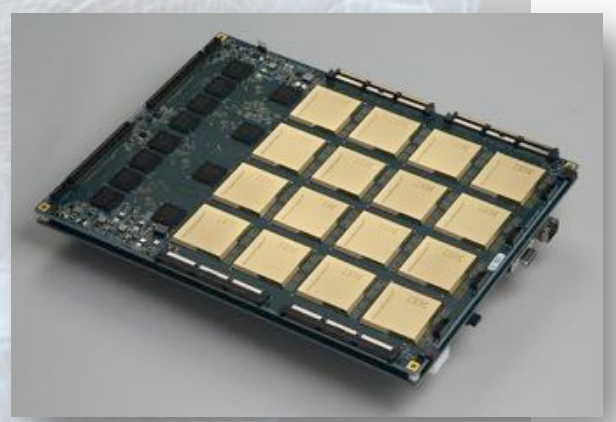




Intel’s concept design...

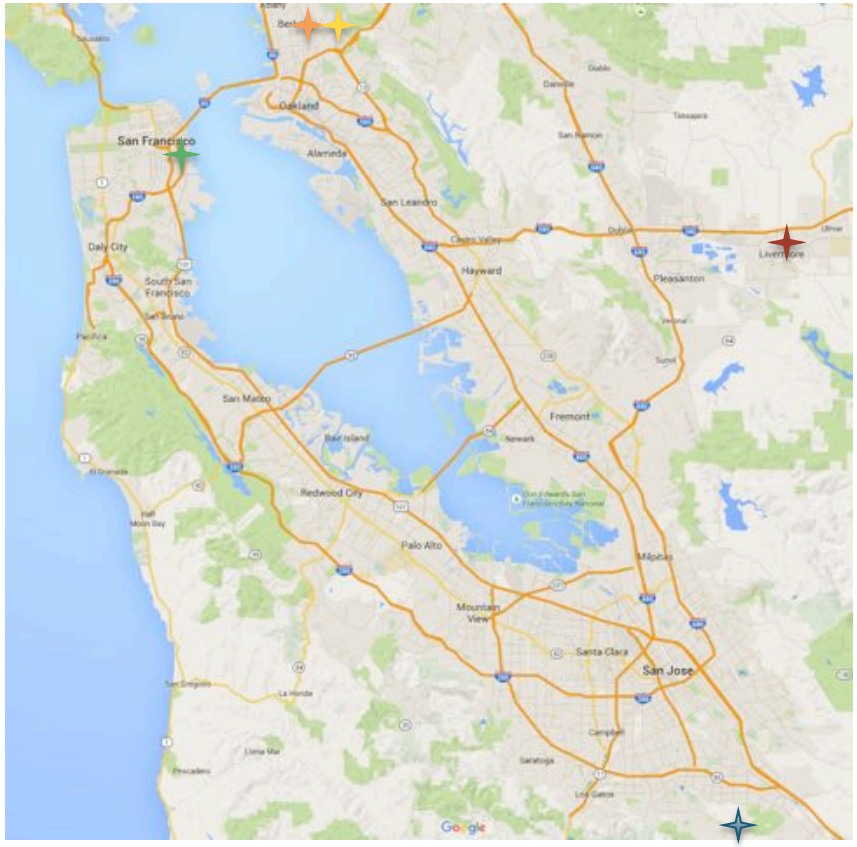
IBM SyNAPSE Project (D. Modha)

- 5.4 B transistor chip TrueNorth, 4096 neurosynaptic cores, 1M spiking neurons, 256 M configurable synapses
- 63 mW power per chip, significantly less energy per event (176,000) when compared to a simulator
- Scalability to large system
- Corelet programming model



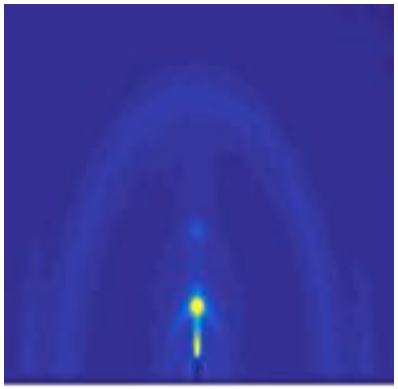
Neuromorphic Computing Collaboration

- **LBNL**
- **UC Berkeley**
  - Redwood Center for Theoretical Neuroscience
  - Berkeley Institute for Data Science (BIDS)
- **LLNL**
- **IBM Almaden**
- **BrainSEED – LBNL, UC Berkeley, UCSF**

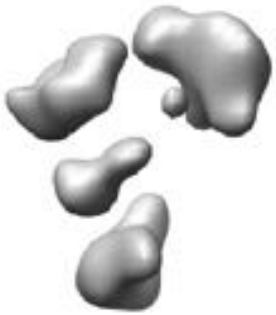


Neuromorphic Image Classification

- **Recognize patterns in images using convolutional neural networks for low-power, high throughput, real-time data feedback in material science, biology and cosmology**



GISAXS (Materials)



Cryo-EM (Biosciences)

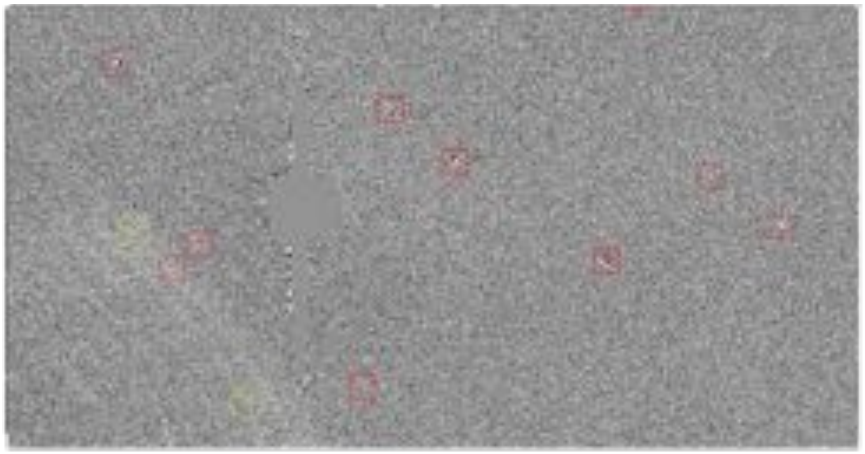
Telescope (Cosmology)

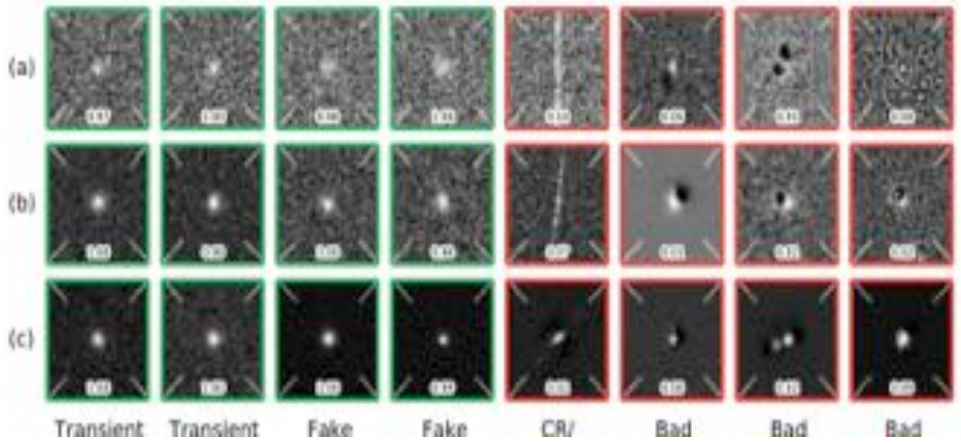
Micro-CT (Energy Technologies)

Supernova Detection - Candidate Detection

- Goal: detecting SN candidates in sky surveys as early as possible (otherwise observation becomes too faint or scientifically useless)
- basic idea: subtract images from two points in time and look for brighter spots

- After difference merging, ~93% images background
- CCD defects, cosmic rays, bad alignments, poorly subtracted galaxies, etc.



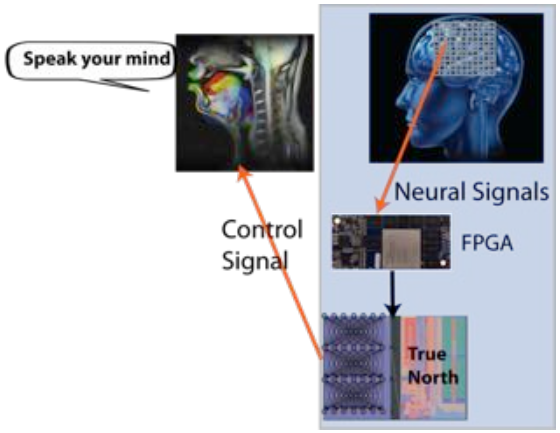


Kessler et al 2015

Neuromorphic Kalman Filters

- **Implement Kalman filters on neuromorphic architecture for low-power, high-throughput, real-time data processing**

Brain-machine interfaces

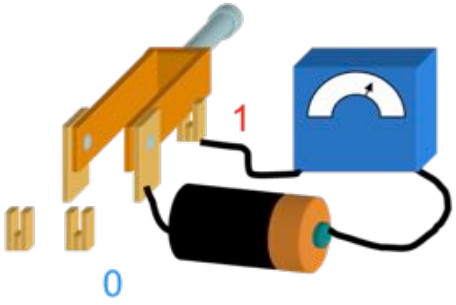


Charged particle tracking

Quantum Computing

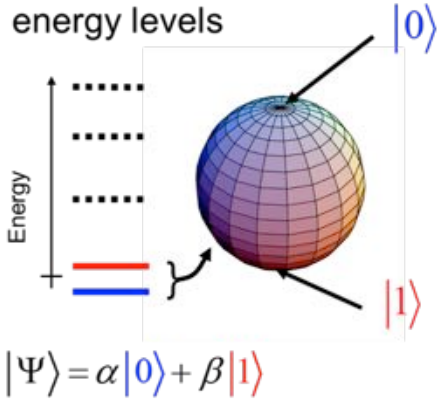
"Shrinking the bit"

classical
equilibrium states



"Redefining the bit"

quantum
energy levels

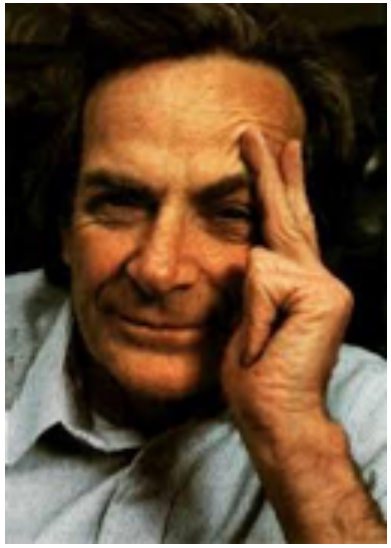


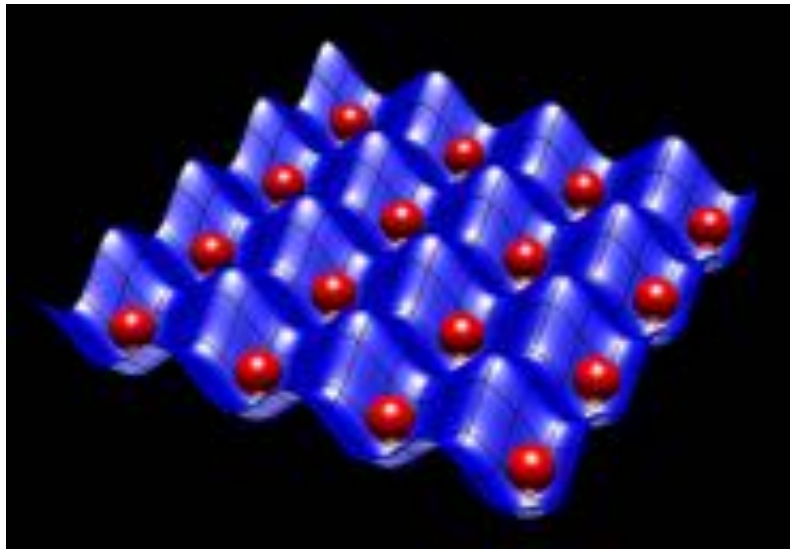
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

write: 0 OR 1
read: 0 OR 1

write: |0> AND |1>
read: |0> OR |1>

Quantum Simulators





- **Quantum Mechanics on classical computers is hard**
  - Simulate one kind of quantum mechanical system with another

Simulating Physics with Computers, R.P. Feynman, *Int. J. Theor. Phys.,* 21:467 (1982)
Universal Quantum Simulators. S. Lloyd, *Science*, 273:1073 (1996)

Quantum Computing Collaboration

- **Advanced Quantum-Enabled Simulation**
  - CRD & MSD
  - UC Berkeley Physics & Chemistry

Deploy 10-qubit system as a *quantum simulator*

Computing (~100-100,000)

- Gate Based: Shor, Grover,…
- Adiabatic Quantum Computing
- Quantum Annealing

Simulations (~1-100)

- Fundamental CS, Math, Info.Thy.,…
- Chemical & Materials Science
- Theoretical Physics: Cosmology,...

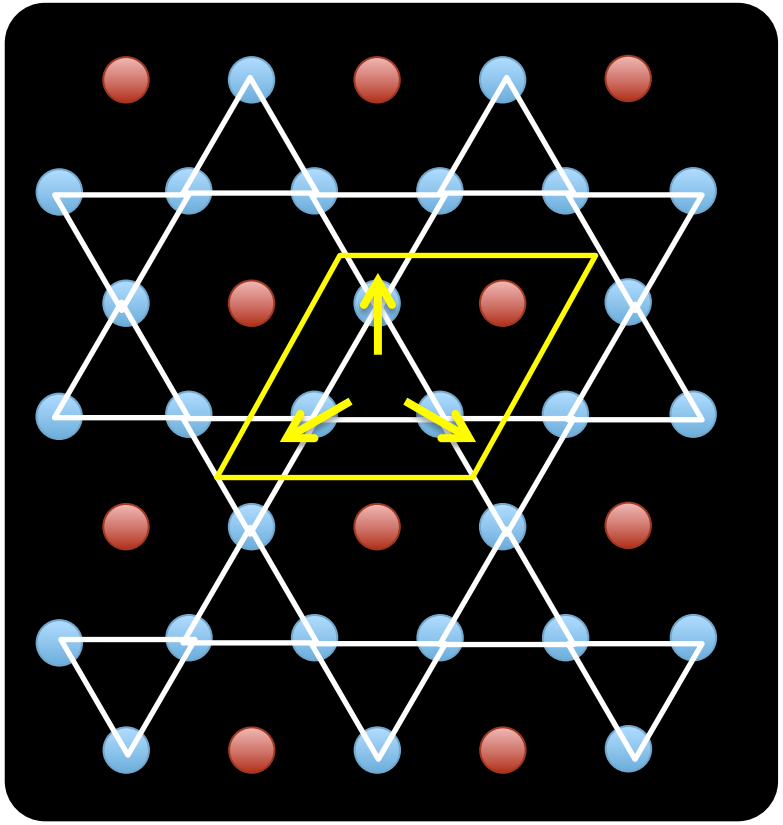
Communication (~1, flying)

- Quantum Key Distribution
- Quantum Commitment

Metrology (~1-10)

- Precision measurements, squeezing
- Sensors (Magnetic, Charge, Light)

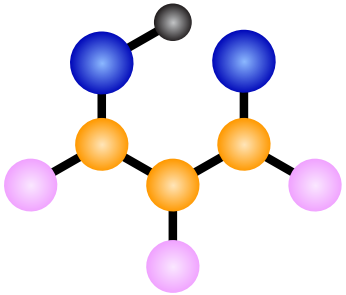
Modeling Frustrated Systems with Ultracold Atoms



- **Magnetic properties of minerals with Kagome lattice often unusual or poorly understood, e.g. Herbertsmithite, $ZnCu_3(OH)_6Cl_2$**
- **Ultracold atoms trapped in a similar lattice can interact analogously to atoms in a solid**

Simulating Quantum Chemistry

quantum chemical system of interest



quantum model

$$\hat{H}|\Psi\rangle = E|\Psi\rangle$$

$$\hat{H}|\Psi\rangle = i\hbar\frac{d|\Psi\rangle}{dt}$$

classical (super)computer

classical information

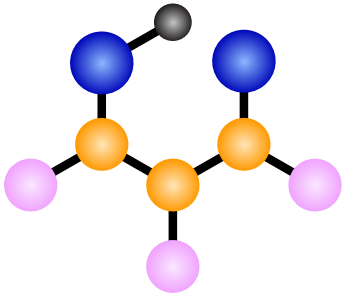
$$E_0 = \ldots$$

$$|\Psi|^2(t) = \ldots$$

- Exact methods are exponentially expensive!
  - Full configuration interaction (FCI) (time-independent): ~10 electrons
  - Quantum dynamics (time-dependent): ~3 atoms
- Approximate methods are computable but insufficient for many applications

Simulating Quantum Chemistry

quantum chemical system of interest

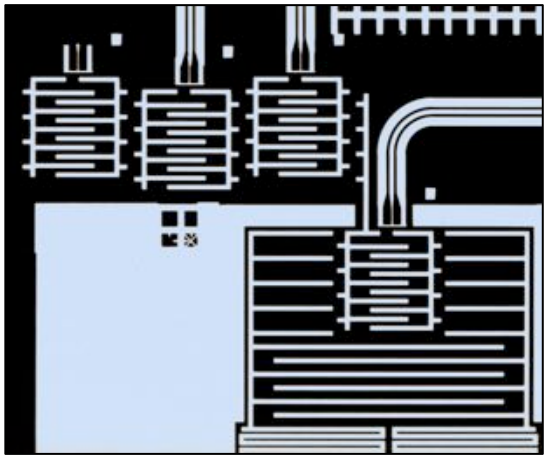


quantum model

$$\hat{H}|\Psi\rangle = E|\Psi\rangle$$

$$\hat{H}|\Psi\rangle = i\hbar\frac{d|\Psi\rangle}{dt}$$

Quantum simulator



classical information

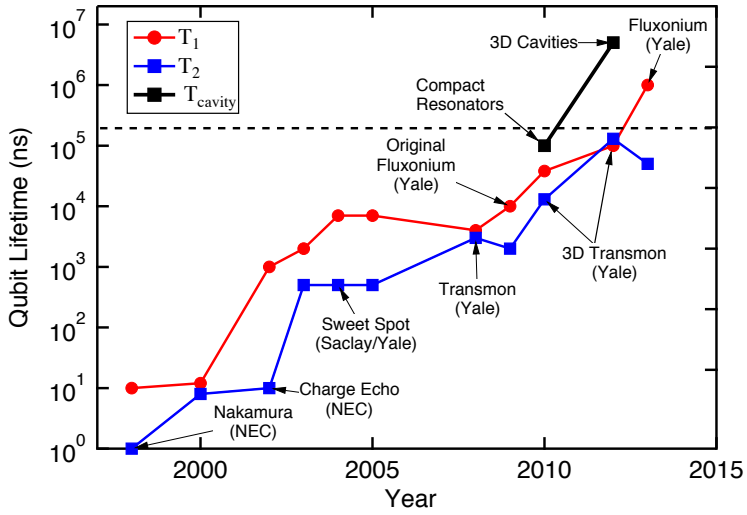
$$E_0 = \ldots$$

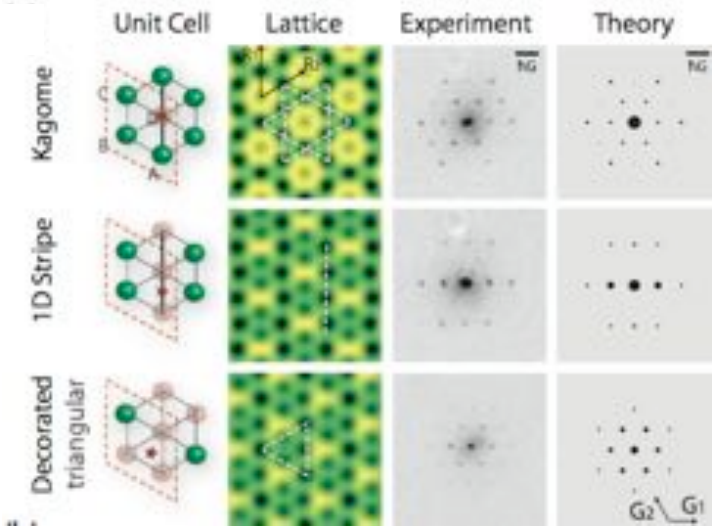
$$|\Psi|^2(t) = \ldots$$

- **Encode quantum chemical systems in polynomial number of qubits.**
- **Solve quantum model using polynomial number of operations.**

Simulators that will realize progress over classical computers

- "Quantum Supremacy" that you care about
- Deploy a 10-100 superconducting qubit testbed for circuit-based computing
- Deploy ultracold atoms in distinct confinement topologies as quantum simulators





Devoret and Schoelkopf Groups, Yale.
Stamper-Kurn Group, Berkeley

Design quantum algorithms for strongly correlated systems

- **Electronic properties of metallo-enzymes incompletely described by mean-field models**
  - Mixed classical/quantum algorithm, error tolerant, and circuit-based
- **Magnetic properties of minerals with Kagome lattice poorly understood, e.g. possible spin liquid**
  - Ultracold atoms trapped in a similar lattice can interact analogously to atoms in a solid