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Quantum Computing Data Centers, Current Trends and Future Outlook

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You have probably heard, the next generation AI models are expected to require many large data centers

- **"Colossus" (one example of a modern AI data center)**
  - Built by x.ai to train cutting-edge large language models (LLM) [1]
  - Based in Memphis, Tennessee

- **System Specification**
  - ~200k NVIDIA H100 Chips [1]
  - ~300 MW of Energy (at peak) [2]
  - Water cooled servers

Colossus

- **Infracututre Impacts**
  - The power grid could not support immediately, using 10-30 natural gas turbine generators to supplement
  - Water consumption estimated at 1 million gallons per day, wastewater is a viable option [3]

[1] https://x.ai/colossus
[2] https://www.tomshardware.com/tech-industry/artificial-intelligence/musks-colossus-is-fully-operational-with-200-000-gpus...
[3] https://en.wikipedia.org/wiki/Colossus_(supercomputer)

Bottom Line Up Front

- ***Data center requirements for large quantum computers are expected to be very different than AI data centers***

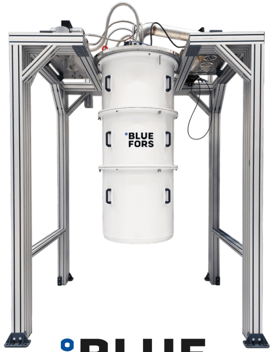
- **Quantum Computer Requirements**
  - Modest amounts of power
  - Minimal amounts of water
  - Cutting-edge cooling technologies **(examples on right)**
  - Vibration isolation
  - Cosmic ray protection (maybe)

- **Quantum Computer requirements also vary by the type of quantum technology**
  - e.g., superconducting, atomic, photonic, …

Quantum Computer Chandelier Example (Google)

[1]

Dilution Refrigerator Examples



BLUE FORS [2]

Maybell [3]

[1] https://quantumai.google/quantumcomputer
[2] https://bluefors.com/
[3] https://www.maybellquantum.com/about

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Quantum Computers of Today

Some US Based Quantum Computing Companies

- **Atlantic Quantum** — Cambridge, Massachusetts
- **Atom Computing** — Boulder, Colorado
- **Google** — Mountain View, California
- **Hewlett Packard Enterprise** — Houston, Texas
- **IBM** — Yorktown Heights, New York
- **IonQ** — College Park, Maryland
- **Infleqtion** — Louisville, Colorado
- **Microsoft** — Redmond, WA
- **PsiQuantum** — Palo Alto, California
- **Quantinuum** — Broomfield, Colorado
- **QuEra Computing** — Boston, Massachusetts
- **Rigetti Computing** — Berkeley, California

Note, this is not a comprehensive list.

Examples of Quantum Computers Today

IBM, System Two
superconducting technology [1]

IonQ, Forte
atomic technology [2]

Quandela, Belenos
photonic technology [3]

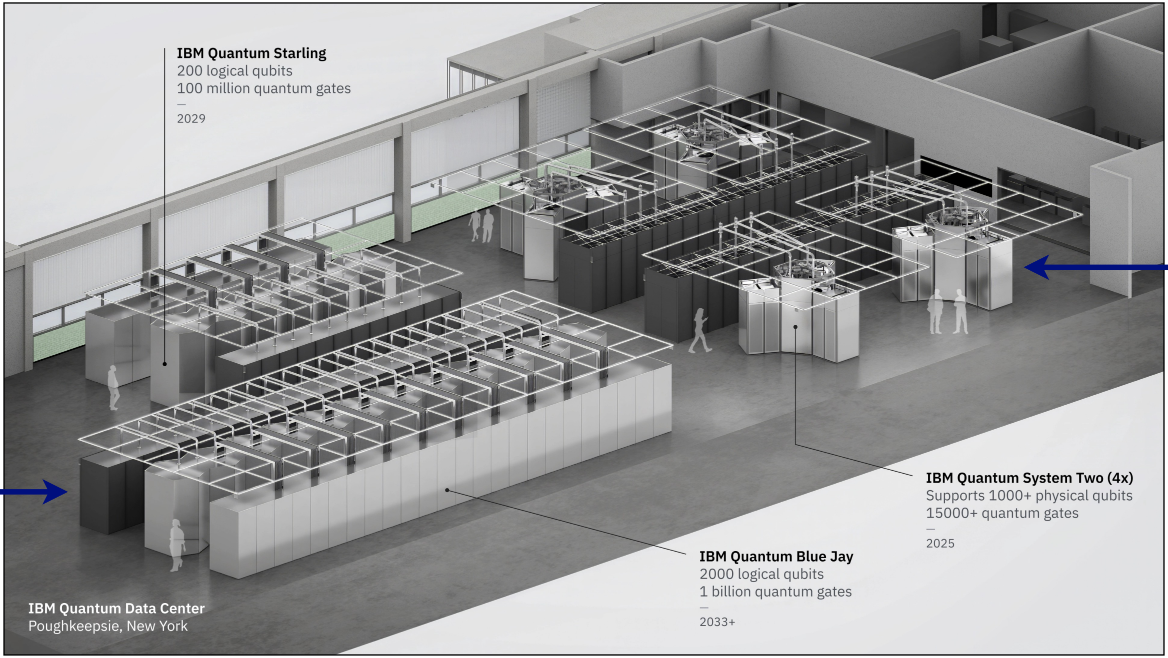
- All are available for purchase today
- Can be sited in many types of commercial buildings
- Require a very reliable supply of power, water, liquid nitrogen

[1] https://mediacenter.ibm.com/media/IBM+Quantum+System+Two
[2] https://ionq.com/resources/ionq-forte-first-configurable-quantum-computer
[3] https://www.quandela.com/about-us/newsroom/belenos-the-worlds-most-powerful-photonic-quantum-computer-launched-by-quandela/

Quantum Computers of the Future (~2030)

IBM's Quantum Computing Roadmap

Size of the quantum computer in ~2033



[1]

Size of the quantum computer today

[1] https://www.ibm.com/quantum/technology#roadmap

PsiQuantum's Quantum Computing Plan

- **Illinois Quantum and Microelectronics Park (IQMP)**
  - Lots more info at iqmp.org

QUANTUM BUSINESS PARK COMING TO CHICAGO, BACKED BY $700M FROM STATE OF ILLINOIS

FORMER U.S. STEEL PLANT WILL HOST 'QUANTUM CAMPUS' DEVELOPMENT

Andrew Adams, Capitol News Illinois Jul 29, 2024 Updated Jul 29, 2024 0

[1]

- **PsiQuantum Building-Scale Deployment**
  - "The Illinois state budget for the fiscal year 2025 includes $500M committed to the development of the Quantum Park, including $200M for the build-out of a Cryogenic Plant to serve the cooling needs for PsiQuantum and other potential users." [2]

[2]

[1] https://capitolnewsillinois.com/news/quantum-business-park-coming-to-chicago-backed-by-700m-from-state-of-illinois/
[2] https://www.psiquantum.com/news-import/illinois-iqmp

Summary of Key Points

- **Today's quantum computers do not require dramatic changes to critical infrastructure**
  - Existing commercial buildings often have sufficient — Space, Power, Water, …
  - Very-high reliability of this existing infrastructure is important

- ***Future*** **quantum computers may require specialized facilities, but upgrades to critical infrastructure appear to be modest**
  - Cryogenic capabilities appear to be the most novel potential infrastructure need
  - A robust supply of liquid nitrogen and helium may be important

- ***Now*** **is a good time to engage with the quantum computing industry to understand future requirements for quantum data centers (~2030) and put the foundations in place for those needs**

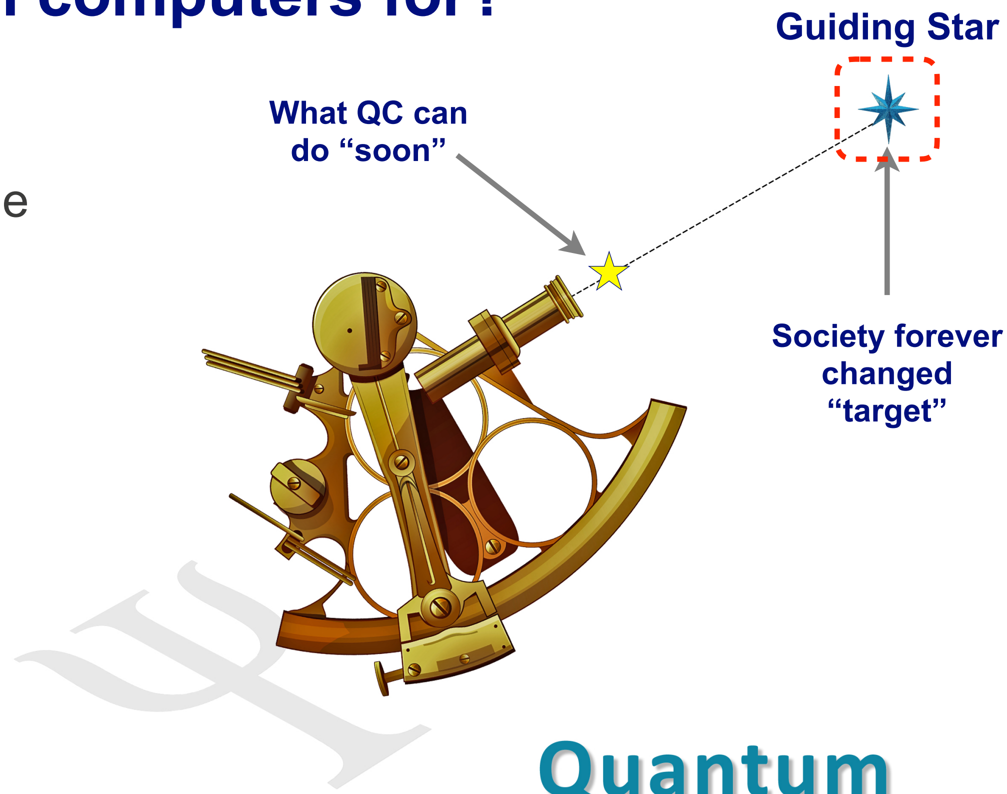
Thanks!

Backup Slides

What will we use quantum computers for?

- **Thought Experiment**
  - “After all the Quantum Advantage demos are done, then what?”

- **A much more fundamental question than you might expect**



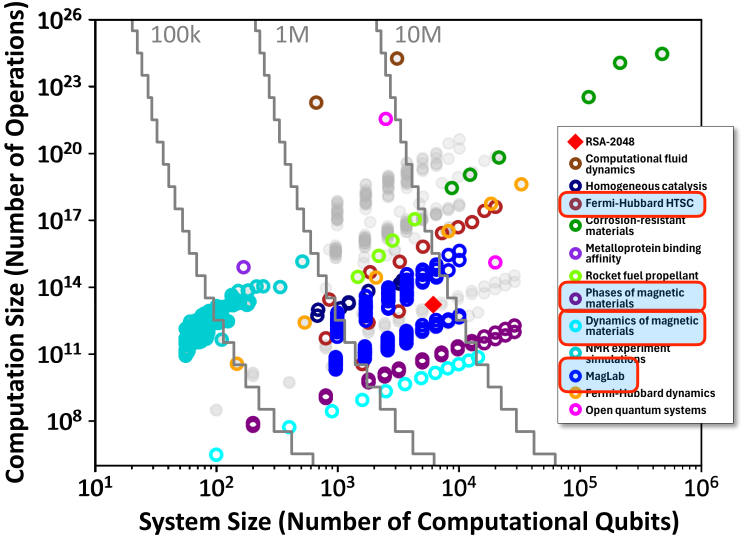
DARPA

Quantum Benchmarking

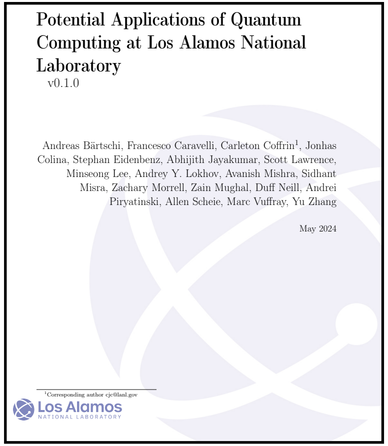
Preliminary Results from a Previous DARPA Program

Applications that could benefit from a quantum coprocessor:

- Simulating correlated materials
- Developing corrosion resistant materials
- Developing new rocket fuels and explosive materials
- Dynamical simulations (for new solar cells, better understanding of biological processes, and magnetic materials)
- New methods to compile algorithms to fault-tolerant quantum architectures



Grey solid circles represent pessimistic resource estimates. Colored circles are optimistic resource estimates based on known improvements. All points supported by detailed published pre-prints.



Potential Applications of Quantum Computing at Los Alamos National Laboratory

v0.1.0

Andreas Bärtschi, Francesco Caravelli, Carleton Coffrin[1], Jonhas Colina, Stephan Eidenbenz, Abhijith Jayakumar, Scott Lawrence, Minseong Lee, Andrey Y. Lokhov, Avanish Mishra, Sidhant Misra, Zachary Morrell, Zain Mughal, Duff Neill, Andrei Piryatinski, Allen Scheie, Marc Vuffray, Yu Zhang

May 2024

[1]Corresponding author cjc@lanl.gov

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~150 pages of technical descriptions
~470 references
Large software supplement

arXiv:2406.06625

Preliminary evidence suggests that large-scale quantum computers could be industrially useful

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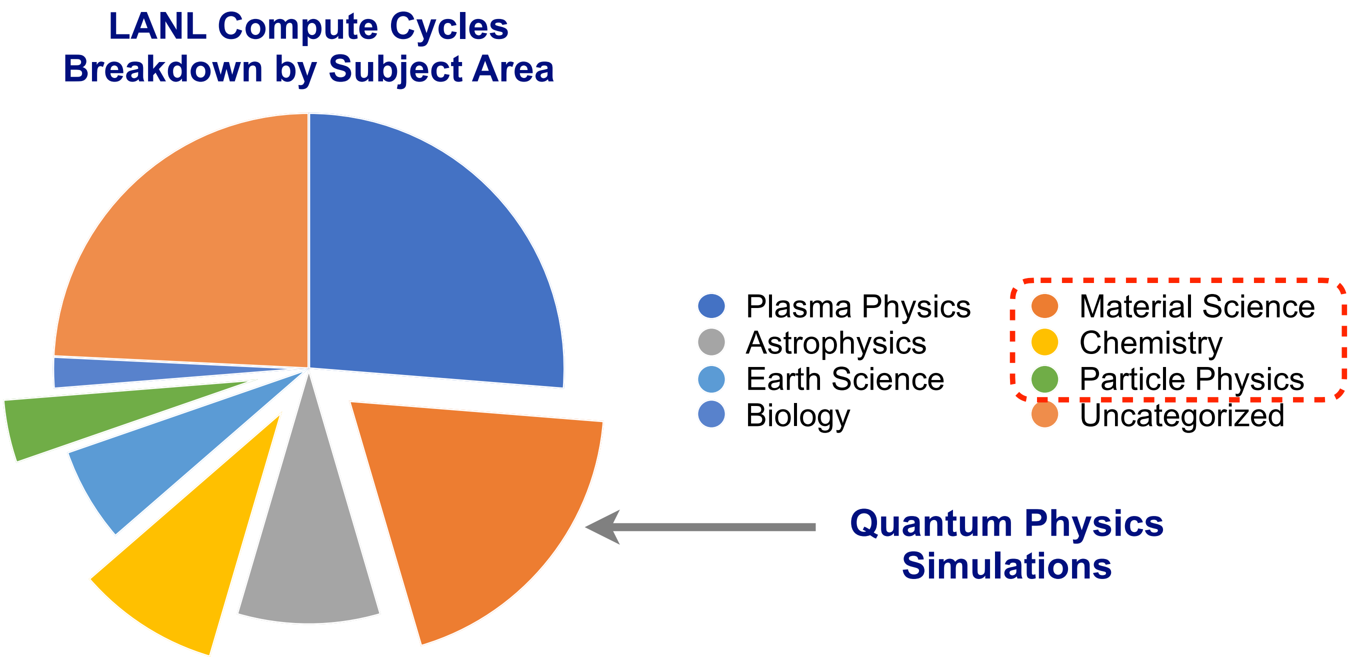
[1] https://www.darpa.mil/work-with-us/quantum-benchmarking-initiative

LANL does a lot of Physics Simulation. What will be the first workloads to be *transformed* by quantum computation?

- **We estimate around 33% of compute at LANL in FY22 was clearly "Quantum Computer Amenable"**



Some potential applications for quantum computing that will *impact scientific discovery at LANL*

18 staff from across the lab working for 18 very intense months…

- **Spin Materials**
  - Spin Liquids (MAGLAB)
  - Multiferroic Materials
  - Neutron Scattering
- **Super Conducting Materials**
  - Theoretical reproduction of super conductivity
- **Quantum Chemistry**
  - Catalysis for Carbon Capture and Combustion
- **Quantum Optics**
  - Super radiant phase transition
- **Nuclear Physics**
  - Parton physics in colliders
  - Neutrino physics flavor distributions
- **Maybe Classical Simulation (in development)**
  - Plasma, Turbulence
  - Oscillator networks

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The current gap between quantum hardware performance and application requirements projected to close by *2030**

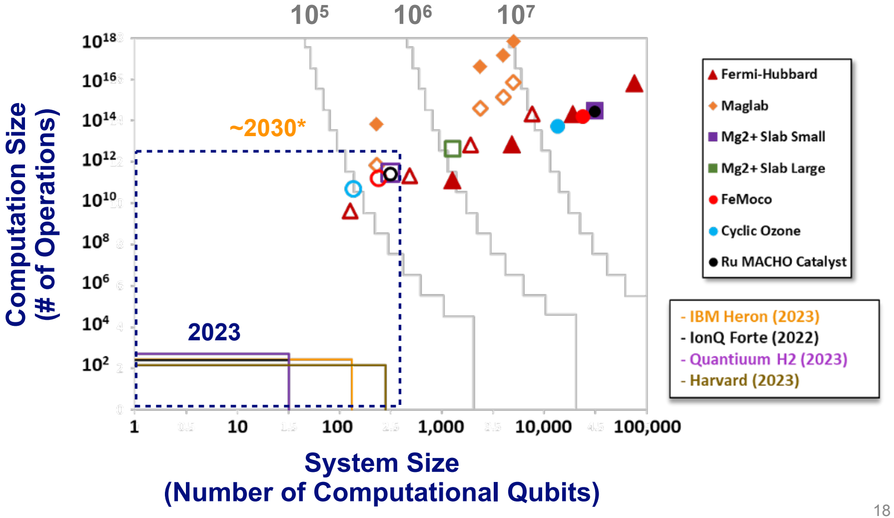
- **What type of quantum computer will it take to achieve *transformational-impact* on quantum computing applications?**

- **Very limited understanding until DARPA's Quantum Benchmarking program**

- **Preliminary findings from Quantum Benchmarking (right)**
  - Initial application impact occurs around ~100 logical qubits
  - Wide application impact occurs around ~1000 logical qubits
  - Number of required gates $>10^8$ a good target is something like $\sim10^{14}$

Quantum Benchmarking

FTQC Staircases



* according to public vendor roadmaps

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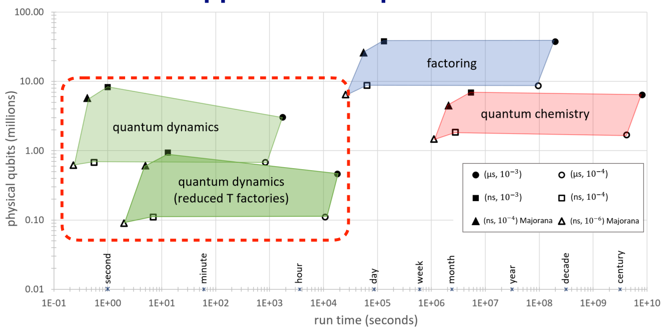
What would LANL do with *100 Logical Qubits*? There are useful theoretical models that can be studied at this scale.

- **Simulation of the dynamics of quantum spin systems is widely believe to the be first useful scientific computations that one use a quantum computer for**

- **MS "Quantum Dynamics" application**
  - "Assessing requirements to scale to practical quantum advantage" [arXiv:2211.07629]

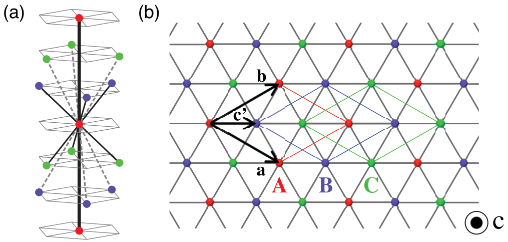
- **IBM's "Quantum Utility" demo**
  - "kicked Ising" experiment
  - [s41586-023-06096-3]

Application Requirements

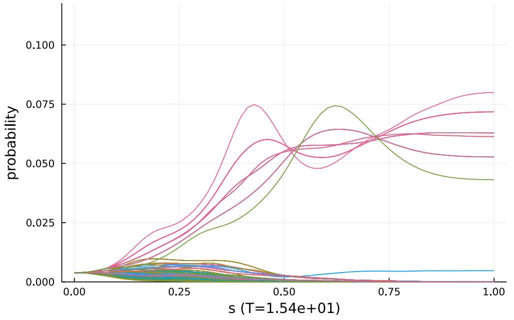


"Assessing requirements to scale to practical quantum advantage" arXiv:2211.07629.pdf

Quantum Lattice Model



"Simple" 8 Qubit System



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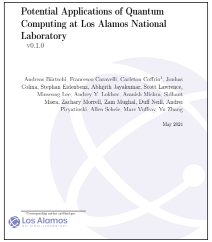
These theoretical models will directly support *frontier scientific discovery* at LANL in the context of Quantum Magnets

- Quantum spin dynamics computations have direct applicability to the experimental material science research at MPA-MAGLAB and MPA-Q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Chapter 3 (MPA-Q)

3 Exploring exotic phases of magnetic materials near instabilities

This chapter presents applications related to the study of exotic phases in magnetic materials. For many Hamiltonians, either of theoretical importance or those proclaimed to be effective models for certain compounds, there are regions in the parameter space of the exchange interactions that defy classical or semi-classical description. This phenomenon often arises from the presence of long range entanglement that prevents understanding and prediction of properties of such phases. The computational capabilities required to enable the study of these exotic phases is the ability to compute specified observables either from the ground state or after simulating simulate the time-dynamics for a spin Hamiltonian defined on a lattice. Existing classical methods cannot be scaled to large lattice sizes, where a fault tolerant quantum computer can provide utility by computing these observables at the desired scale and accuracy. The following table provides a condensed summary of the computational requirements of the applications.

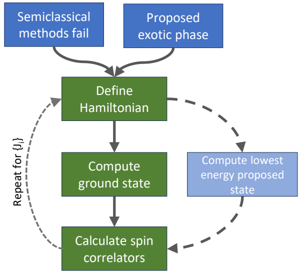
Hamiltonian Type: Heisenberg spin Hamiltonian.
Quantum Computational Kernels: Ground State Preparation, Hamiltonian simulation.

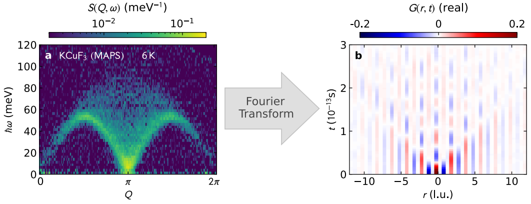
Chapter 2 (MPA-MAGLAB)

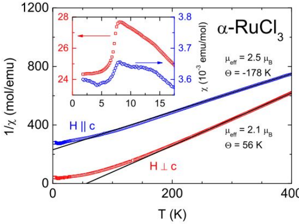
2 Experimental analysis of magnetic materials at the MAGLAB user facility

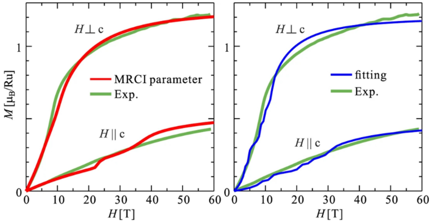
This chapter presents several applications relevant to the MAGLAB user facility. The MAGLAB is an experimental facility that analyzes several magnetic materials of interest. These include Kitaev quantum spin liquids (KQSLs), multi-ferroic materials for memory and high temperature superconductivity. We focus on the applications of quantum computing in the study of KQSLs, where the broad research goal is to identify the effective spin Hamiltonian and search for the existence of the KQSL phase in the phase space. The computational capabilities required are methods for quantum Hamiltonian simulation and computation of ground states for spin Hamiltonians on given regular two-dimensional lattices. Current classical approaches cannot be scaled to sufficiently large system sizes (> 10000 sites) that are required to avoid significant errors from finite size effects. Consequently, the primary potential benefit of a quantum computer is the ability to perform these computations at a scale where the results accurately represent experimental observables and properties of the material. The following table summarizes the computational requirements that must be met to be of value to research at the MAGLAB.

Hamiltonian Type: Spin Kitaev/Heisenberg Hamiltonian.
Quantum Computational Kernels: Ground State Preparation, Hamiltonian simulation.









This is just the tip of the iceberg for LANL applications benefiting from Quantum Computing

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