Geneva university

QUANTUM COMPUTING SIMULATION OF QUANTUM SPIN LIQUIDS

- Larbaoui Yasmine Badr Elhouda
- Shehata Samah
- Win Thawdar Aung
- Carson Glines
- Nikita Missiri
- Antoine Sedoh

What is Quantum Spin Liquid?

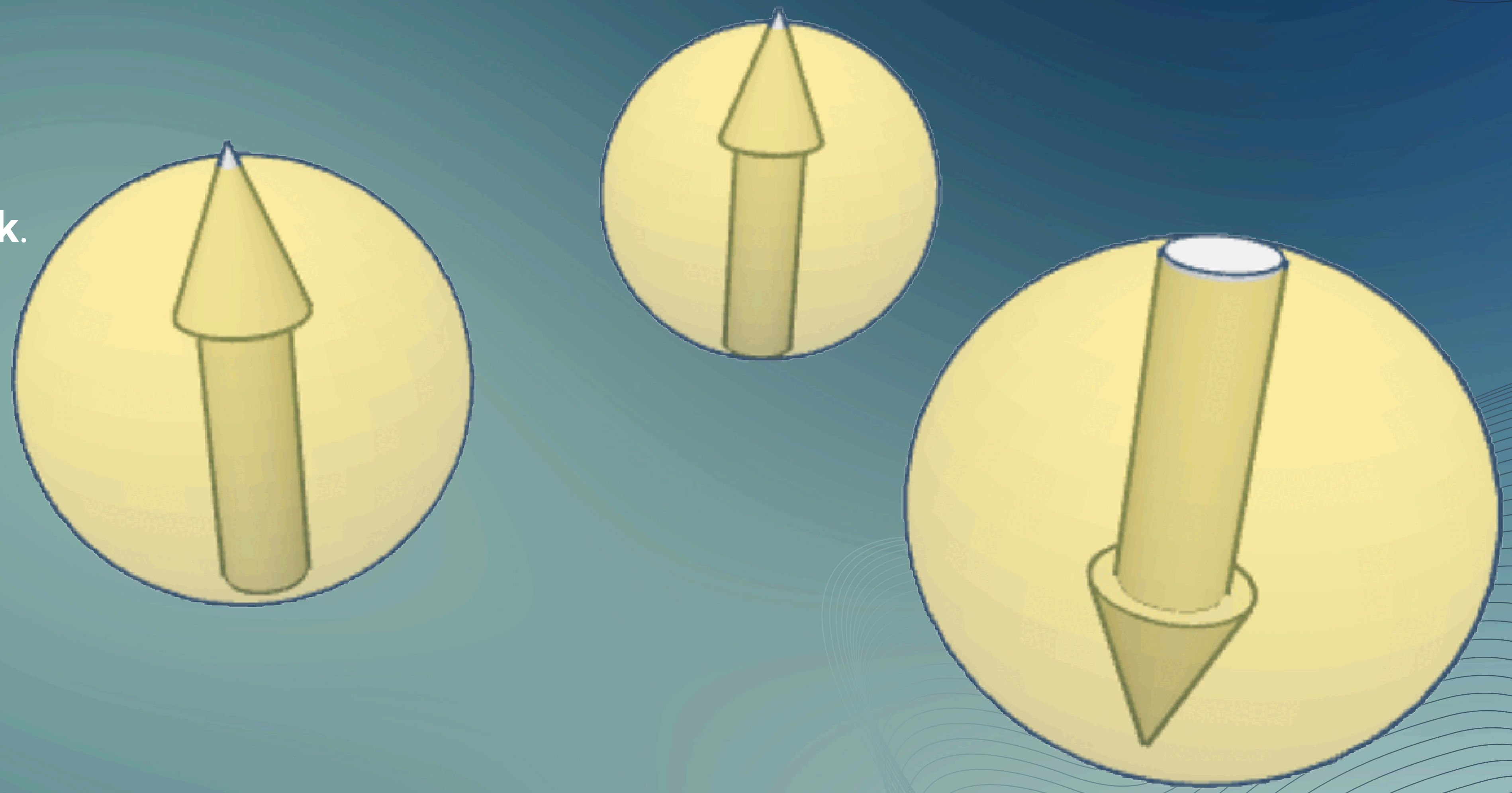
Frustrated magnets where electron spins remain in a constantly fluctuating, entangled state with no long-range magnetic order even at absolute zero.

They are a **theoretical concept** that we don’t have a concrete example of.

In order to find them in real life, we need to **simulate them.**

Simulation helps us determine identifiers of QSLs and **where to look**.

It is **exponentially costly** to simulate a QSL classically.

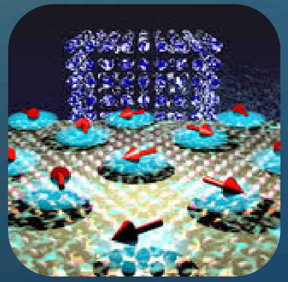


Why Does it Matter ?

Topological quantum computing

- **Drug Discovery Acceleration**
  - **SDG 9, SDG 3 – Good Health & Well-being**
- Simulate molecular interactions at quantum level → faster breakthroughs
- Classical computers can't model quantum bonding/entanglement in complex drugs

- **Autonomous Material Design**
  - **SDG 9, SDG 7 – Affordable & Clean Energy**
- AI + TQC to invent new superconductors, batteries, etc.
- QSLs simulate strongly correlated systems beyond classical limits



- **Climate Modeling 2.0**
  - **SDG 9, SDG 13 – Climate Action**
- High-precision simulations of Earth systems (atmosphere, oceans)
- Classical models break with too many entangled variables

- **Next-Gen Manufacturing**
  - **SDG 9, SDG 12 – Responsible Consumption & Production**
- Quantum-optimized production lines & smart factories
- Quantum-enhanced optimization requires stable qubits only QSLs enable

- **Secure Industrial AI**
  - **SDG 9, SDG 16 – Peace, Justice & Strong Institutions**
- Run encrypted AI computations for sensitive R&D
- Topological Qubits resist decoherence → protect models & IP

Existing Research

- Topological spin liquids on a programmable quantum simulator
- Crystalline compound cerium zirconium oxide ($Ce_2Zr_2O_7$)

Explored Approaches

Adiabatic Quantum Computing

Adiabatic quantum computing is an analog quantum computing technique where you start with a ground state energy simulation of a simple Hamiltonian, and then modify the simulation while it remains in a ground state until it evolves to the desired hamiltonian.

Material Centric Strategy

Instead of only developing computational methods abstractly, you choose a realistic material candidate close to QSL behavior and:

1. Map its physical Hamiltonian.
2. Simulate its properties
3. Validate and predict its quantum spin liquid characteristics.

Quantum Annealing

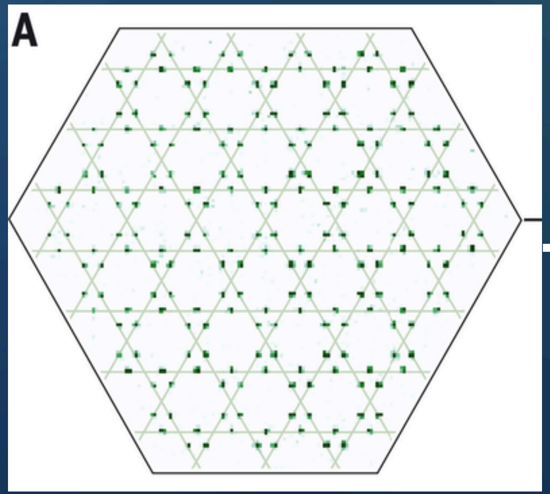
A practical application of adiabatic quantum computing that use thermal fluctuations to decohere the system and allow the system to quantum tunnel to the solution.

Trotterization

Using digital quantum computing to simulate analog quantum computing techniques, such as quantum annealing. Would allow us to use more available computing techniques, but is computationally complex to implement.

PIPELINE: Digital Quantum Computing

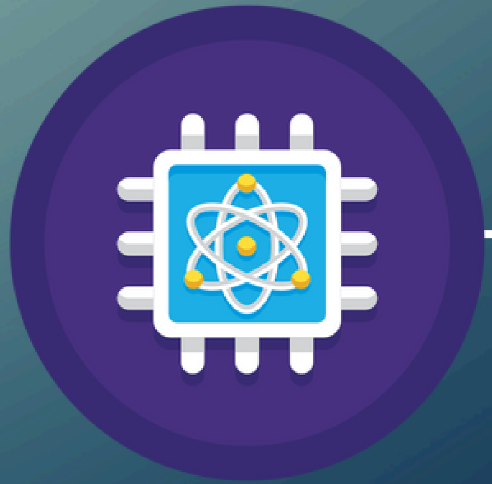
Kagome Lattice



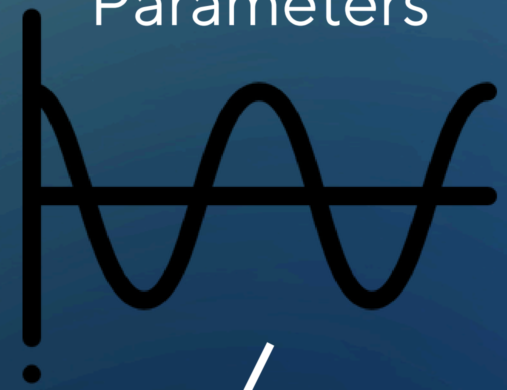
Hamiltonian

$$\frac{H}{\hbar} = \frac{\Omega(t)}{2} \sum_i \sigma_i^x - \Delta(t) \sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

VQE

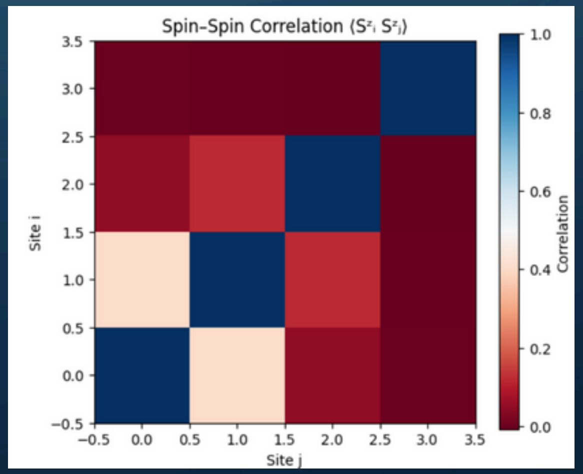


Ground State Parameters

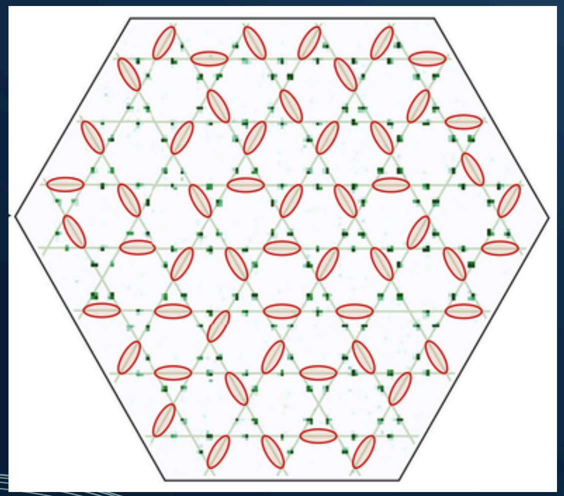


Quantum Circuit Simulation and Spin Sampling

Spin Corellation Matrix



QSL Indicator



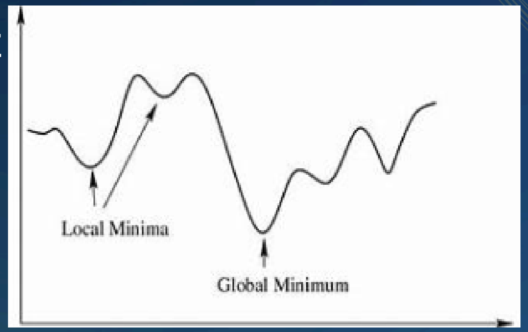
Main Challenges

Limited Time & Domain Knowledge

- Mostly CS background, learning physics & quantum computing under time pressure

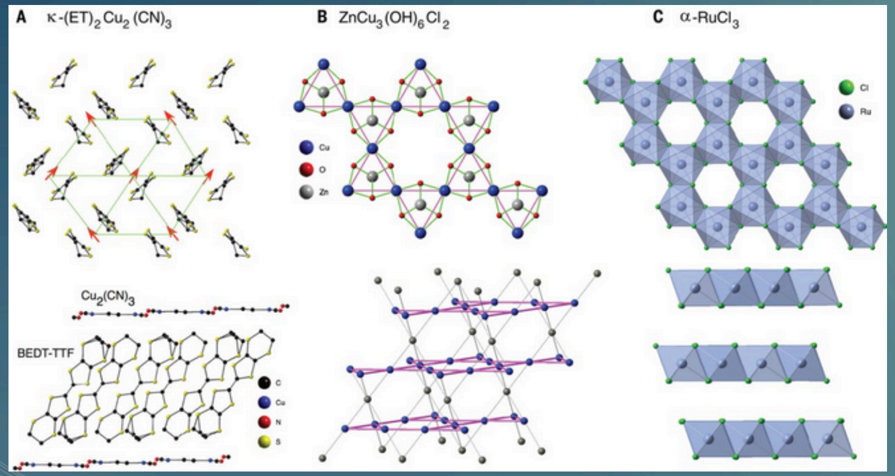
Algorithmic Complexity (VQE)

- Requires expressive ansatz and robust optimization
- Thousands of circuit evaluations per iteration



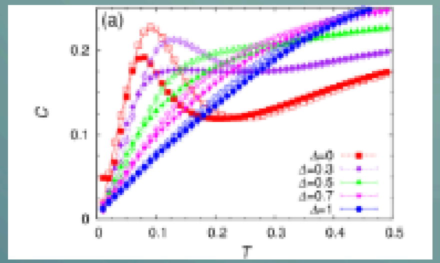
Modeling QSL Systems

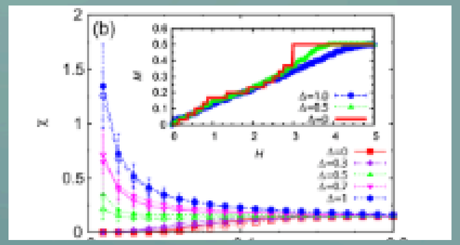
- Translating complex, frustrated lattices into simplified Hamiltonians risks omitting essential physics



Verification Difficulty

- No definitive metric for confirming QSL behavior
- Spin correlation functions were analyzed but remain inconclusive
- Simulations constrained to small system sizes due to resource limits





Computational Limitations

- 20+ qubits require >1 TB RAM classically
- Quantum hardware: shallow depth, limited qubits, noisy

Future: Next Steps

Access to experts to **verify** our research and methods.

Simulating a smaller **Kagome Lattice** structure.

Increasing **computational power** to run Hamiltonians with more complexity.

Looking at a potential **quantum housing function** that could parallelize this quantum search process

THANK YOU