Simulating False Vacuum Decays in a 2D Mesoscopic Quantum System Using Programmable Quantum Annealing

JÜLICH Forschungszentrum

J. Vodeb[1,2,3], M. Diego[2], Y. Vaskivskyi[2], L. Logaric[2], Y. A. Gerasimenko[2], V. V. Kabanov[2], B. Lipovsek[4], M. Topic[4], Dragan Mihailovic[2,3,5]

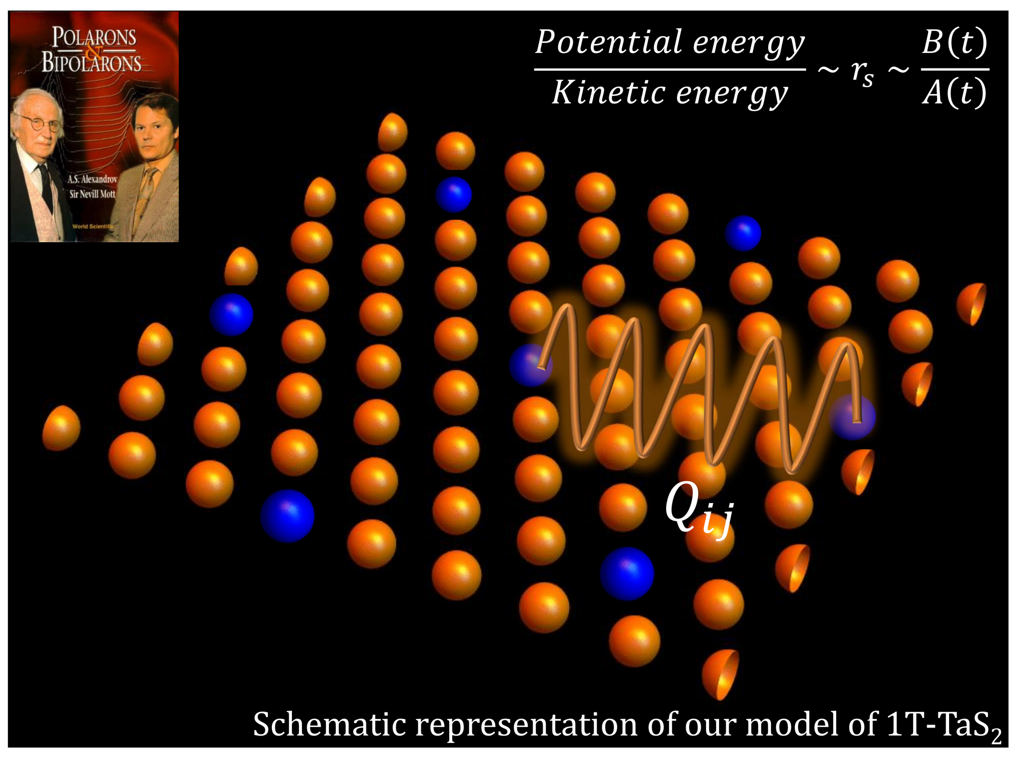
1. Institute for Advanced Simulation, Jülich Supercomputing Centre, Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52425 Jülich, Germany
2. Department of Complex Matter, Jozef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia
3. Department of Physics, Faculty for Mathematics and Physics, Jadranska 19, University of Ljubljana, 1000 Ljubljana, Slovenia
4. Faculty for Electrical Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia
5. Center of Excellence on Nanoscience and Nanotechnology—Nanocenter (CENN Nanocenter), 1000 Ljubljana, Slovenia

j.vodeb@fz-juelich.de

ABSTRACT

- Investigation of domain reconfiguration dynamics in an electronic charge density-wave crystal ($1T\text{-}TaS_2$) by means of scanning tunnelling microscopy.
- Observing quantum domain melting and simulating it using D-Wave's quantum annealer.
- Demonstrating the remarkable value of quantum simulators for modeling the dynamics of emergent mesoscopic inhomogeneities on the basis of fundamental interactions.
- The presented quantum simulation of a real system would not be possible with a state-of-the-art conventional computer.

POLARONIC WIGNER CRYSTAL



Schematic representation of our model of $1T\text{-}TaS_2$

Tight binding interacting electron band with phonons

$$H = \sum_{i,j,s,s'} (t_{i,j} - \mu\delta_{i,j})\delta_{s,s'} c^\dagger_{i,s} c_{j,s'} + \sum_{q,i,s} \omega_{\boldsymbol{q}} n_{i,s}(u_{i,s}(\boldsymbol{q}) d_{\boldsymbol{q}} + h.c.) + \frac{1}{2}\sum_{i,j,s,s'} V_c(i,j) n_{i,s} n_{j,s'} + \sum_{\boldsymbol{q}} \omega_{\boldsymbol{q}}(d^\dagger_{\boldsymbol{q}} d_{\boldsymbol{q}} + 1/2)$$

Polarons

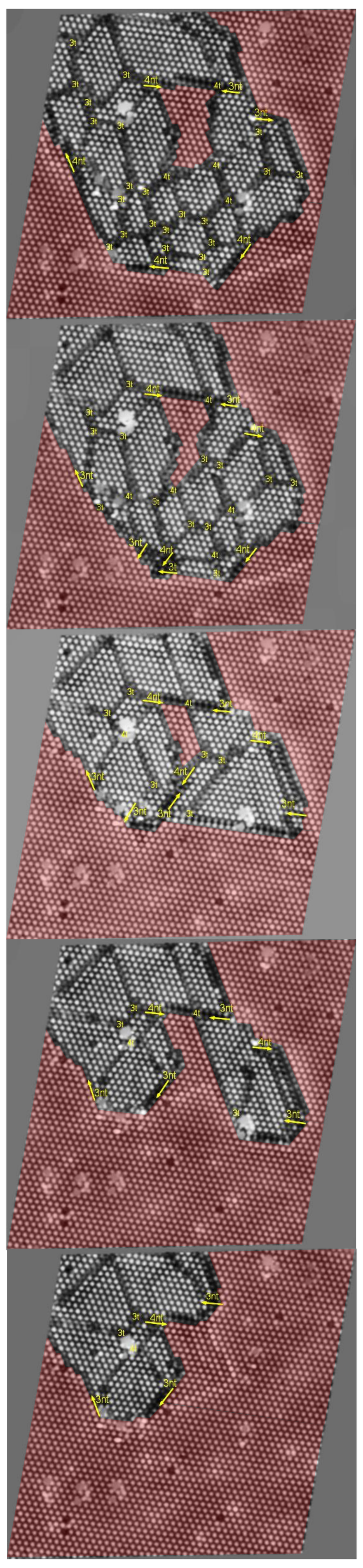
$$\widetilde{H} = \sum_{i,j,s,s'} T_{i,s,j,s'} \tilde{c}^\dagger_{i,s} \tilde{c}_{j,s'} + \frac{1}{2}\sum_{i,j,s,s'} v_{i,s,j,s'} \tilde{n}_{i,s} \tilde{n}_{j,s'} - E_p \sum_{i,s} \tilde{n}_{i,s} + \sum_q \omega_q (\tilde{d}^\dagger_q \tilde{d}_q + \frac{1}{2})$$

D − Wave Hamiltonian | *2D Jordan − Wigner* | *Final model*

$$H_{DW} = -\frac{A(t)}{2}\sum_{i=1}^{N} \sigma_i^x + \frac{B(t)}{2}\left(\sum_{i=1}^{N} h_i \sigma_i^z + \sum_{i<j}^{N} J_{ij}\sigma_i^z \sigma_j^z\right)$$

$$\mathcal{H} = -\frac{A(t)}{4}\sum_i \left(c_i^\dagger e_i^{-i\alpha_i} + c_i e^{i\alpha_i}\right) + \frac{B(t)}{2}\left(\sum_{i<j} Q_{i,j} n_i n_j\right)$$

QUANTUM DOMAIN MELTING

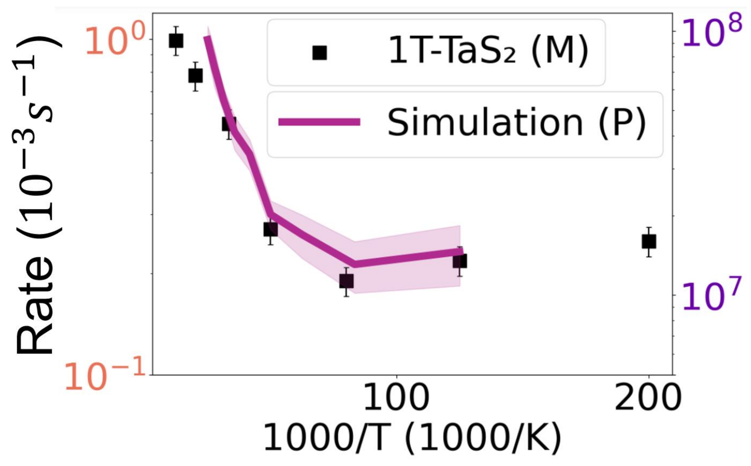


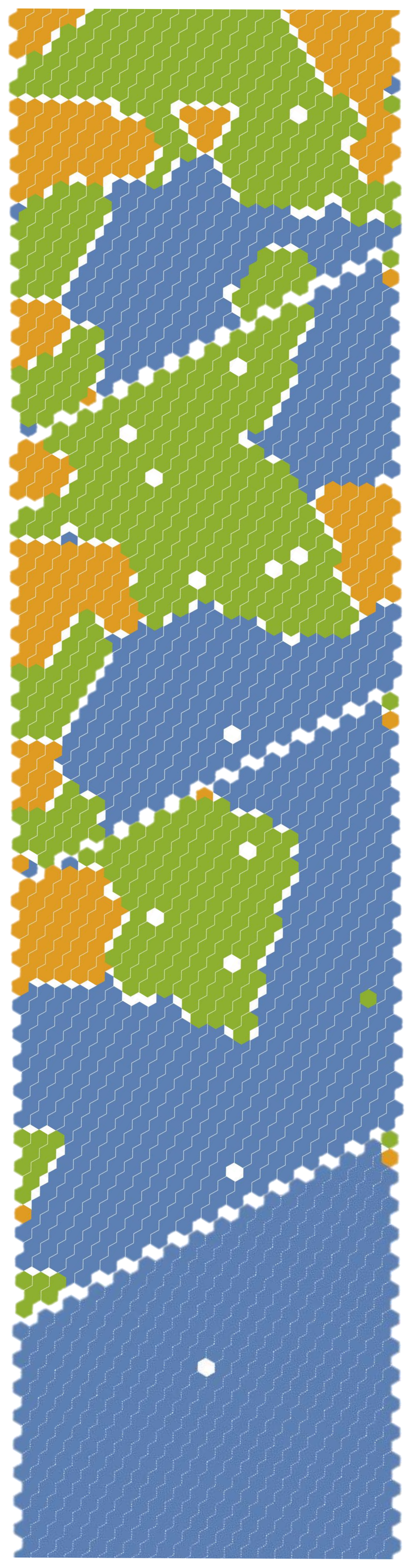
Experimental (left) and theoretical (right) relaxation of an inital domain configuration.

Time (mins)

The relaxation mechanism is dissipative configurational quantum tunnelling.

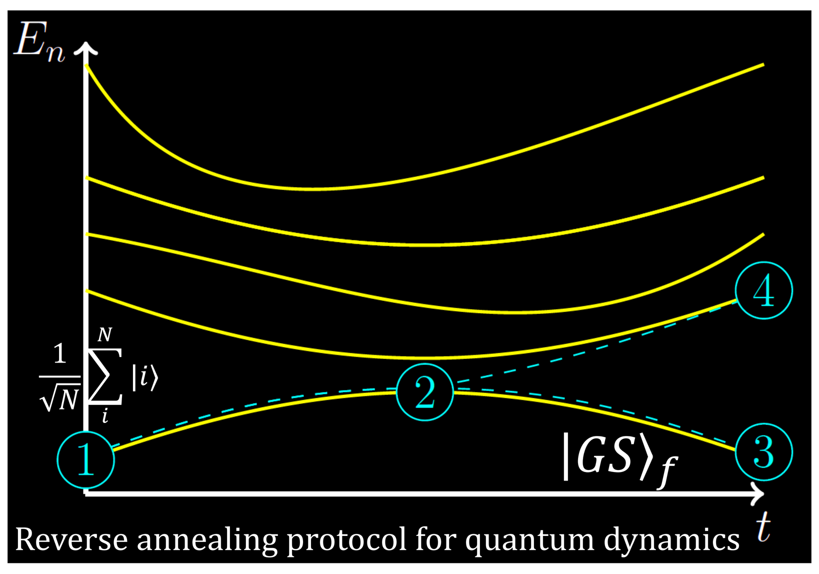
Rate versus temperature.





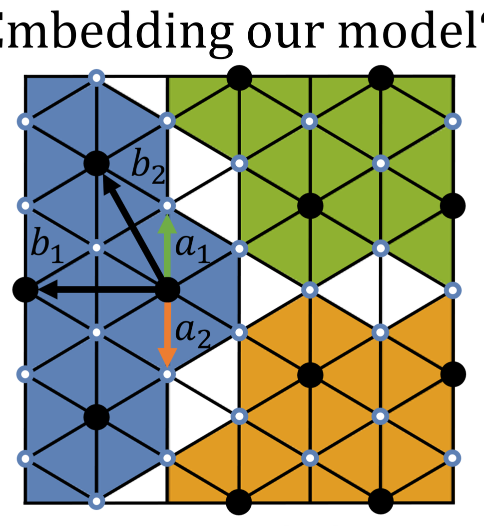
QUANTUM ANNEALING WITH 2008 QUBITS


The D-Wave Advantage quantum annealer

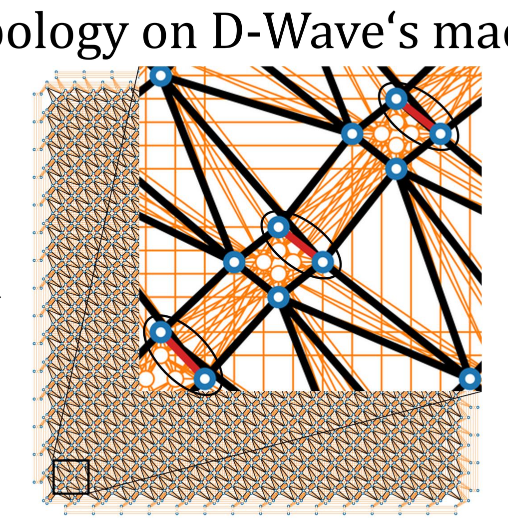


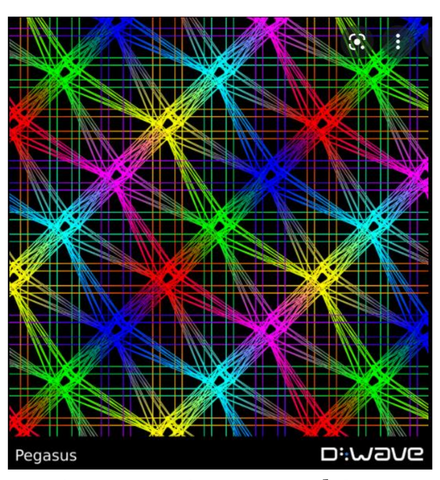
Reverse annealing protocol for quantum dynamics

Embedding our model's topology on D-Wave's machine:



$1T\text{-}TaS_2$ triangular lattice


Embedding



D-Wave Pegasus chip

By varying the energy scale, we can vary the temperature of the system.

CONCLUSION

- Relaxation dynamics of the non-equilibrium hidden state in $1T\text{-}TaS_2$ can be mapped onto D-Wave's quantum computing model.
- Quantum dynamics are responsible for low-temperature relaxation and involve multi-qubit tunnelling processes.
- We simulated a real-world experiment on a quantum computer and therefore developed one of the first useful applications of quantum computing.

LITERATURE

- T. Kibble, "Topology of Cosmic Domains and Strings", Journal Of Physics A-Mathematical And General 9, 1387 (1976).
- W. Zurek, "Cosmological experiments in superfluid helium?", Nature 317, 505 (1985).
- A. Legget, "Dynamics of the dissipative two-state system", Reviews of Modern Physics 59, 1 (1987).
- K. Hong and N. Giordano, "Evidence for domain wall tunneling in a quasi-one dimensional ferromagnet", Journal of Physics: Condensed Matter 8, L301 (1996).
- E. M. Chudnovsky and L. Gunther, "Quantum Tunneling of Magnetization in Small Ferromagnetic Particles", Physical Review Letters 60, 661 (1988).
- J. Brooke, T. F. Rosenbaum, and G. Aeppli, "Tunable quantum tunnelling of magnetic domain walls", Nature 413, 610 (2001)

erc · COMPLEXmatter · Institut "Jožef Stefan" Ljubljana, Slovenija · Nanocenter · Slovenian Research Agency