Statement of Research Interests — Dorian Rudolph

My research is on *quantum complexity theory* and broadly follows two directions: (1) Variants of QMA (i.e. the quantum analogue of NP), and (2) foundations of continuous-variable quantum computation (i.e. the CV analogue of BQP).

I am greatly interested in research that connects computer science, quantum physics, and mathematics. In [**AGR26**][*], we connect TFNP, the quantum satisfiability problem, and Bézout's theorem (algebraic geometry). In [**CGM+25**], we also connect these topics in an entirely different way by proving (among many other results) the undecidability of self-adjointness of physically relevant continuous-variable Hamiltonians.

I have contributed to twelve papers on quantum computing. My work has been presented at many leading venues such as QIP (2 talks), TQC (5 talks), ITCS (5 papers), ICALP (2 papers), AQIS, MFCS, and npj Quantum Information. I have independently developed multiple international collaborations [**URC26**; **GR25**; **MPR26**], as well as student-only work [**KR26**] (QIP 2025, ITCS 2026), [**GR25**] (TQC and ICALP 2026), and also single-author work [**Rud25**] (AQIS 2025).

Organization. Section 1 discusses the QMA direction with future work in Section 1.2. Section 2 discusses the continuous-variable direction with future work in Section 2.1. Figure 1, placed after the main text, connects the complexity classes I have worked on into a single diagram.

1. Variants of QMA

Perhaps the most fundamental question in (classical) complexity theory is "P vs. NP". NP is the class of decision problems whose YES instances can be efficiently *verified* on a classical computer, given a suitable witness. Drawing from quantum mechanics, we have many problems that are believed to be hard to solve on a quantum computer, but that are still efficiently verifiable on a quantum computer given a suitable witness. The most "canonical" such problem is the *local Hamiltonian problem*. Feynman first realized that computation can be embedded into the evolution of a local Hamiltonian [Fey86]. Later Kitaev modified Feynman's Hamiltonian construction so that the ground state energy roughly corresponds to the best acceptance probability of a quantum verification circuit with a quantum witness [KSV02], thereby proving a quantum analogue of the Cook–Levin theorem, i.e., the local Hamiltonian problem is QMA-complete, where QMA is the most studied quantum analogue of NP and has both a quantum verifier and a quantum witness.

1.1 Completed Research.

My research spans a wide variety of different complexity classes (refer to Fig. 1), each with its own physical motivation. The general directions are the following:

Unentanglement. QMA(2) is QMA with an unentangled witness $|\psi_1\rangle \otimes |\psi_2\rangle$ (or equivalently two Merlins that do not share any entanglement) [KMY03]. Unentangled witnesses can be surprisingly powerful: logarithmic-size unentangled quantum proofs suffice to verify NP [BT09]. Equivalently, one can think of QMA(2) as QMA where Merlin receives multiple copies of the witness, i.e., $|\psi\rangle^{\otimes \mathrm{poly}(n)}$ [HM13]. The multi-copy setting is quite natural: quantum learning algorithms like classical shadows generally use multiple copies, and multi-copy measurements provide a learning advantage over single-copy measurements [HKP21]. Despite great research interest, the complexity of QMA(2) remains elusive, with NEXP being the best known classical upper bound. I have multiple works on QMA(2), e.g., in [**GR23**] (QIP 2022) we study how to embed MIP (multi-prover interacting) or streaming proof systems into QMA(2). One work I would like to focus on here is:

> **The Pure-State Consistency of Local Density Matrices Problem [KR26].**[†] QIP 2025, ITCS 2026, joint work with J. Kamminga. Given a list of reduced density matrices, does there exist a consistent *(pure)* state? For mixed states, this problem is QMA-complete [Liu06; BG22], but for pure states only a QMA(2) upper bound was known for a long time [LCV07]. Our work gives a circuit-based complexity class, which we call PureSuperQMA, for which this problem is complete, and also gives a PSPACE upper bound by using methods from real algebraic geometry to construct polynomial-depth circuits for solving certain quadratic systems. Our methods even work for the exact version of this problem, which is generally not possible with SDP-based techniques.
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> Hence, the pure-state consistency problem is not complete for QMA(2), unless QMA(2) $\subseteq$ PSPACE.

Classically, NP generalizes to the polynomial hierarchy, which can be defined in terms of quantified Boolean formulas with a constant number of alternating quantifiers. This can be interpreted as a game in which the $\exists$-prover tries to convince the verifier that the input is a YES-instance, and the $\forall$-prover tries to convince the verifier that the input is a NO-instance. This interpretation gives a clean extension from QMA(2) to the quantum polynomial hierarchy [GSS+22], where alternating provers send unentangled proofs to the verifier.

[*] Citations to my own work are printed in bold green.
[†] All authors were students at the time of writing.

> **Pure Quantum Polynomial Hierarchy [GR25].**† ICALP 2026, TQC 2026, joint work with S. Grewal. *Should one define the quantum polynomial hierarchy in terms of mixed or pure states?* This is far from obvious. In [AGKR24], we give a one-sided amplification for pureQPH that fails for (mixed) QPH. In this work, we show that $\mathsf{QMA}(2) \subseteq \mathsf{pureQ}\Sigma_2 \subseteq \mathsf{pureQ}\Sigma_3 \subseteq \mathsf{NEXP}$, i.e., two competing unentangled provers can solve QMA(2). We also finally give a two-sided amplification for QPH (this is already highly non-trivial for QMA(2) [HM13]), and prove that QPH = pureQPH. However, level-for-level, pureQPH is more powerful than QPH, unless $\mathsf{QMA}(2) \subseteq \mathsf{PSPACE}$, which is a major open problem. We also give a complete problem for each level of pureQPH, arguing that pureQPH is the "right" QPH definition.

The quantum satisfiability problem and QMA_1. The k-local Hamiltonian problem (k-LH) can be seen as a quantum analogue of MAX-k-SAT, since the task is to find the lowest energy state, i.e., the state that satisfies the most constraints. Then the *Quantum k-SAT* problem is the quantum analogue of the k-SAT problem, where the task is to decide whether a given local Hamiltonian is *frustration-free*, i.e., there exists a state that has energy 0 with respect to each (non-negative) local term. Paralleling the classical world, 2-QSAT is in P [Bra06], whereas 2-LH is QMA-complete [KKR06], and 3-QSAT is complete for QMA with perfect completeness (QMA_1), i.e., in the YES-case, there exists a witness that is accepted with probability 1. In [RGN25], we study the hardness of bipartite 2-QSAT systems on qudits, and show that the problem remains QMA_1-complete even if each constraint acts on one qubit and one qu-5-it.

> **Towards a universal gate set for QMA_1 [Rud25].**† AQIS 2025. Recently, a sequence of works by Crichigno and Kohler [CK24], as well as King and Kohler [KK24], has shown that the gapped clique homology problem is QMA_1-hard and contained in QMA. The problem is to decide whether the clique complex, a certain topological structure associated with a graph, has a high-dimensional hole; this is motivated by topological data analysis [LGZ16]. The gap between QMA_1-hardness and QMA-containment was due in part to the fact that QMA_1 has to be defined relative to a gate set, since Solovay–Kitaev compilation does not necessarily preserve perfect completeness. My work closes this gap by providing an exact gate synthesis algorithm inside certain cyclotomic field extensions of the rationals. Additionally, I develop a kernel-testing algorithm that sidesteps quantum phase estimation to test whether a given state is in the kernel of a sparse Hamiltonian with perfect completeness. With these tools, I prove that the gapped clique homology problem is complete for QMA_1. Finally, I show that the decision version of the clique homology problem is PSPACE-complete, substantially improving the previous lower bound of #P for the harder problem of counting the number of holes [SL23].

An interesting special case of QSAT is *QSAT with SDR* (system of distinct representatives or *dimer covering*), which guarantees the existence of a product ground state (cf. *mean-field ansatz*) [LLM+10]. The classical analogue is a CNF-SAT instance with a matching between clauses and variables, giving a trivial solution.

> **An Unholy Trinity: TFNP, Polynomial Systems, and the Quantum Satisfiability Problem [AGR26].** ITCS 2026, TQC 2024, joint work with M. Aldi and S. Gharibian. First, we extend [LLM+10] to QSAT on qudit systems. Then, we define two new subclasses of TFNP borne of the study of complex polynomial systems: Multi-homogeneous Systems (MHS) and Sparse Fundamental Theorem of Algebra (SFTA). The first of these is based on Bézout's theorem from algebraic geometry, marking the first TFNP subclass based on an algebraic-geometric principle. We show that QSAT with SDR is MHS-complete, thus giving not only the first link between quantum complexity theory and TFNP, but also the first TFNP problem whose classical variant (SAT with SDR) is easy but whose quantum variant is hard. We also show how to embed the roots of a sparse, high-degree, univariate polynomial into QSAT with SDR, obtaining that SFTA is contained in a zero-error version of MHS.

1.2 Ongoing and Future Research.

What is the power of QMA(2)? We still do not fully understand the power of two unentangled quantum provers. I would like to prove oracle separations involving QMA(2). It is easy to show $\mathsf{coNP} \not\subseteq \mathsf{QMA}(2)$ relative to a classical oracle. Can we give an oracle separation from AM? Or does QMA(2) perhaps contain problems like graph *non*-isomorphism that are not known to be in QMA? Note that an oracle separation would also imply progress on the *disentangler conjecture*, which says that any efficient quantum channel that maps potentially entangled states to separable states cannot approximate all separable states.

In current work, I can prove that two provers do not help achieve perfect completeness by giving a quantum oracle separation between BQP and $\mathsf{QMA}(2)_1$. Surprisingly, the same problem can be solved with perfect completeness if the witness is restricted to real amplitudes, which suggests that considering $\mathbb{R}\mathsf{QMA}(2)$ may be a good step toward potential NEXP-hardness.

Does QMA_1 have a universal gate set? While my paper [Rud25] made significant progress in terms of universal gate sets for all gate sets inside cyclotomic field extensions of $\mathbb{C}$, a fully universal gate set still seems out of reach. Of course, proving $\mathsf{QMA}_1 = \mathsf{QMA}$ would resolve this question. This raises the question of whether one can show a classical oracle separation between QMA_1 and QMA.

Recently, two oracle separations between QCMA and QMA have been published [BHNZ26; BHV26]. Both oracle problems are not (trivially) in QMA_1. So these problems may also be candidates to separate QMA_1 from QMA. On the other hand, in recent work [**MPR26**], we give a classical oracle separation between QCMA and QMA_1, with the limitation that our separation requires in-place access to a classical permutation. With standard oracle access, the QCMA lower bound only holds up to n^k (for fixed k) rounds of queries.

Improving circuit-to-Hamiltonian gap (toward Quantum PCP). Much of my work on QSAT involves different circuit-to-Hamiltonian constructions [**Rud25**; **RGN25**; **GR22**; **KRM+25**]. Currently, the best we can do is a spectral gap that scales with $\Omega(n^{-3})$ relative to the norm of the Hamiltonian when embedding a circuit with n gates [BC18]. Can we use a novel clock construction to improve the gap? The quantum PCP conjecture [AAV13] would be proven by achieving a constant gap. But even achieving a constant gap for a sparse Hamiltonian would be novel and require a deviation from the "history state" concept. I would like to consider shallow circuits or commuting circuits.

2. Foundations of Continuous-Variable Quantum Computing

We usually consider quantum algorithms in the *discrete-variable (DV)* setting (i.e. on qubits). However, many physical systems are *continuous-variable (CV)* (i.e. infinite-dimensional with continuous degrees of freedom). CV systems are especially relevant for near-term quantum system design, such as quantum photonics (e.g. Gaussian Boson Sampling [HKS+17]) and hybrid CV-DV systems (e.g. trapped-ion, neutral-atom, and superconducting qubits [LSS+26]). In 1999, Lloyd and Braunstein [LB99] proposed a model of quantum computation in terms of CV gates, where each gate is of the form $\exp(-itH)$, where H is a polynomial of position and momentum operators $\hat{X}, \hat{P}$. Chabaud et al. [CJMM26] initiate the study of CVBQP, the continuous-variable analogue of BQP. They consider the physically motivated gate set of linear optics, Gaussian nonlinear gates, and the $\hat{X}^3$ gate (a $\chi^{(3)}$ interaction). Surprisingly, the best classical upper bound on this variant of CVBQP is EXPSPACE. This is because it is possible to create states with an energy (i.e. average photon number) that scales as *doubly exponential* in the circuit size. In [**URC26**], we give a PSPACE upper bound assuming the energy is at most exponential. Brenner et al. [BCCK25] also use energy to show the surprising result that a constant number of oscillators suffice to execute a variant of Shor's algorithm. These computations are in a CV-DV model and also require exponential energy. Hence, the following paper studies energy explicitly as a computational resource.

> **Energy, Bosons and Computational Complexity.** TQC 2026, joint work with U. Chabaud, S. Gharibian, S. Mehraban, A. Motamedi, H. Naeij, and D. Sambrani [**CGM+25**]. First, we show that even deciding whether a given Hamiltonian constructed from position and momentum operators is self-adjoint is undecidable; this is due to unbounded-operator issues, where Hermiticity is not equivalent to self-adjointness. This already shows that CV gate synthesis is fundamentally different from DV gate synthesis, and we cannot hope for a straightforward Solovay–Kitaev analogue.
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> We then construct a fixed gate set for which exponential-energy computations on $O(1)$ modes can solve not only factoring but any problem in NP. By allowing unbounded energy, we can even solve problems in EEXPSPACE, i.e., doubly exponential space, within constant time; this class is provably harder than EXPSPACE by the space hierarchy theorem. Hence *energy* is a computational resource, and complexity theory can identify Hamiltonians that are unlikely to be physically realizable.
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> Additionally, we improve the classical upper bound on CVBQP with $\hat{X}^3$ and exponential energy from PSPACE [**URC26**] to PP.

These results motivate further research on the capabilities of CV quantum systems. Fundamental questions such as gate synthesis and decidability are currently still open.

2.1 Ongoing and Future Research

CV gate synthesis. In an upcoming work with the same coauthors as [**CGM+25**], we will give additional concrete counterexamples to the proposed gate synthesis of [LB99]. We will propose a different gate synthesis algorithm that can synthesize fixed, general gates (under certain energy conditions) into just linear optics and Kerr gates (e.g. [FFFA21]). The synthesis has polynomial complexity in terms of the energy cutoff and the inverse precision ϵ^{-1}. While polynomial dependence on energy may be unavoidable, I would like to show a genuine Solovay–Kitaev for CV systems that has only polylogarithmic dependence on ϵ^{-1}. Further directions include efficient synthesis of many-mode Fock space unitaries (extending [ABC25]), and fault-tolerant computation in our model.

Decidability of generalized CVBQP. In [**CGM+25**], we give a gate set of essentially self-adjoint gates so that CVBQP can simulate Turing machines whose runtime is given by a power tower of height poly(n). Can we give a matching upper bound on CVBQP for general gate sets? The task is fundamental. Given a circuit of CV Hamiltonians $H_1, \ldots, H_n$, compute the probability of some measurement outcome on the output state $e^{-iH_n} \cdots e^{-iH_1}|0\rangle$ obtained after applying all gates to the vacuum state.

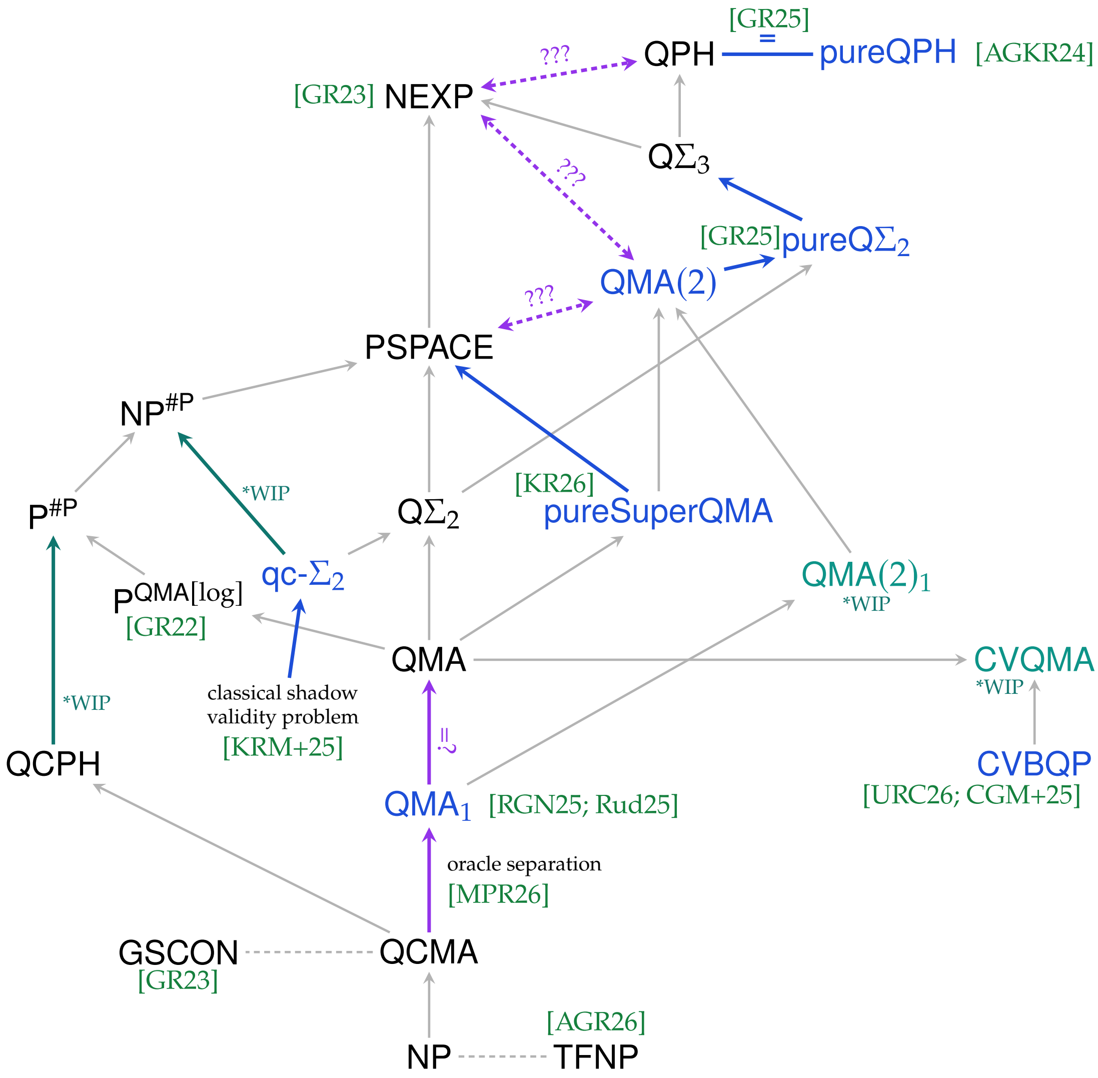

Figure 1: A complexity-theoretic map of the classes and relationships most relevant to my research, including references. The main classes involved in my work are blue, as are the proven containments. Classes and (tentative) containments I am currently working on are teal and marked "WIP". Known/trivial containments are gray. Interesting open problems are marked in purple.

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