

¹ QuaRT: A toolkit for the exploration of quantum methods for radiation transport

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Summary

⁸ QuaRT is a Python library for quantum simulation of radiative transfer in astrophysical and
⁹ cosmological problems.

¹⁰ The source code for QuaRT is available on [GitHub](#). It can be installed via pip from the [pypi](#)
¹¹ index. Its [documentation](#) is hosted publicly.

Statement of need

¹³ Computational cosmology, the use of simulations to study the evolution of the universe, is
¹⁴ a rapidly-growing field of research, driven largely by the exponential increase in computing
¹⁵ power following Moore's law. Numerous codes ([Brummel-Smith et al., 2019](#); [Bryan et al., 2014](#);
¹⁶ [Davis et al., 2012](#); [Hayes & Norman, 2003](#); [Ilian T. Iliev et al., 2006](#); [Ilian T. Iliev et al., 2009](#);
¹⁷ [Jiang et al., 2014](#); [Rahul Kannan et al., 2019](#); [R. Kannan et al., 2021](#); [O'Shea et al., 2015](#)) have been written to study questions about the early universe and to obtain
¹⁸ a better understanding of the plethora of observational results which have come with new
¹⁹ telescopes such as the James Webb Space Telescope ([Adams et al., 2024](#)). However, classical
²⁰ high-performance computing hardware is slowly approaching the fundamental quantum limit
²¹ where electronics cannot be scaled down any further ([Powell, 2008](#)). Quantum computers
²² present a potential path for further scaling of physical simulations by taking advantage of
²³ quantum phenomena such as superposition and entanglement which enable new models of
²⁴ computation. Many quantum algorithms have already been developed for the simulation of
²⁵ cosmological problems ([Joseph et al., 2021, 2022](#); [Kaufman et al., 2019](#); [Liu & Li, 2021](#);
²⁶ [Mocz & Szasz, 2021](#); [Wang & Wu, 2024](#); [Yamazaki et al., 2025](#)). Such simulations must
²⁷ model physical processes such as radiation transport from stars, magnetohydrodynamics of
²⁸ matter, gravitation between massive particles, gas chemistry, and the formation of structures
²⁹ such as stars, black holes, halos, and galaxies (e.g., [Brummel-Smith et al., 2019](#); [Hopkins et al., 2023](#)). Of these, radiation transport tends to be one of the most expensive steps due to
³⁰ the high dimensionality of the problem, but it also the most difficult to develop because of
³¹ the lack of problems with analytical solutions ([Ilian T. Iliev et al., 2006](#); [Ilian T. Iliev et al., 2009](#)).
³² Quantum algorithms have been formulated for radiation transport, such as those based
³³ on ray tracing ([Lu & Lin, 2022a, 2022b, 2023](#); [Mosier, 2023](#); [Santos et al., 2025](#)), random
³⁴ walks ([Lee et al., 2025](#)), and other novel differential equations solvers ([Gaitan et al., 2024](#)).
³⁵ Classical lattice Boltzmann methods (LBMs), which track the distribution of a quantity on
³⁶ a grid with discretized propagation directions ([McNamara & Zanetti, 1988](#)), have already
³⁷ been applied extensively to study radiation transport ([Bindra & Patil, 2012](#); [McCulloch & Bindra, 2016](#); [Mink et al., 2020](#); [Olsen & Rezzolla, 2025](#); [Weih et al., 2020](#)) and radiation
³⁸ hydrodynamics ([Asahina et al., 2020](#)). Quantum LBMs have also been constructed to study
³⁹ hydrodynamics ([Budinski, 2021](#); [Ljubomir, 2022](#); [Wawrzyniak, Winter, Schmidt, Indiniger,](#)
⁴⁰

et al., 2025; Wawrzyniak, Winter, Schmidt, Indinger, et al., 2025) and radiation transport (Igarashi et al., 2024). These quantum LBMs reduce the memory constraints of classical simulations by storing information in quantum state amplitudes, the number of which grows exponentially with the number of qubits, enabling the storage of data with only logarithmic scaling with problem size. Individual simulation steps can thus be made very high resolution and only the necessary amount of data needs to be stored classically. However, existing quantum LBMs are not suited for cosmological problems because such simulations are typically non-scattering, but isotropic sources under stars are not accurately resolved angularly by LBMs due to their discretized angular structure. QuaRT features the first known implementation of a quantum LBM which accurately resolves isotropic sources in non-scattering media; it does so via a novel methodology which we refer to as “angular redistribution”, where radiation is redistributed between angular directions based on the expected angular distribution. This can even be done globally for an entire simulation domain with no increase in computational complexity, enabling larger and more accurate simulations of the evolution of the universe than currently possible.

58 **Functionality**

59 QuaRT uses Qiskit for circuit construction and Qiskit Aer for circuit execution (Javadi-Abhari
60 et al., 2024).

61 The qlbm_rt module features the simulate method which is called to perform simulations
62 with the lattice Boltzmann method. This method constructs the full quantum circuit for each
63 timestep of the simulation and returns the lattice data.

64 The qlbm_circuits module features constructors for the necessary circuits for radiative transfer
65 simulation in 1D, 2D, and 3D, including a constructor for the novel angular redistribution step.
66 These constructors are called by the simulate method which composes them to construct the
67 full quantum circuit.

68 QuaRT features a variety of utility methods for both general and quantum lattice Boltzmann
69 methods in lbm_utils and qlbm_utils, respectively. It also features analysis utilities in the
70 analysis module. These utilities are used by the simulate method for problem setup and
71 analysis.

72 The test module features a variety of common test cases used for radiative transfer codes,
73 including the isotropic source, opaque cloud shadow, and crossing radiation beams tests. These
74 tests demonstrate the general correctness of the codebase, with a particular emphasis on the
75 performance of the angular redistribution methodology.

76 There is also a set of demo notebooks including a fully-classical implementation for comparison
77 with the quantum algorithm and some unit tests of experimental features.

78 **Scholarly Work**

79 QuaRT is currently being used to study lattice Boltzmann methods for radiative transfer (Devkota
80 & Wise, 2025, in prep.).

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